The Future Circular Collider Study

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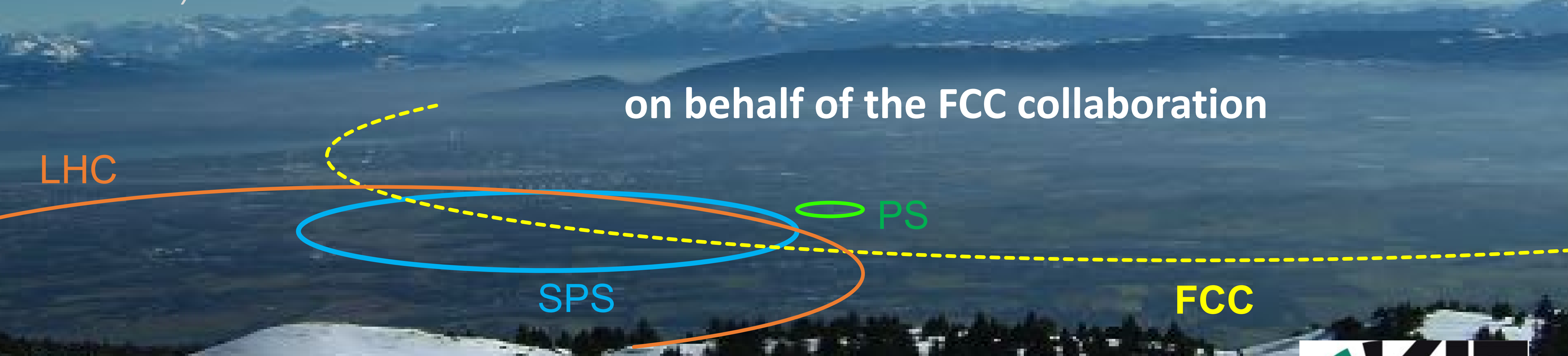
2) CERN

on behalf of the FCC collaboration



http://cern.ch/fcc

Karlsruhe Institute of Technology

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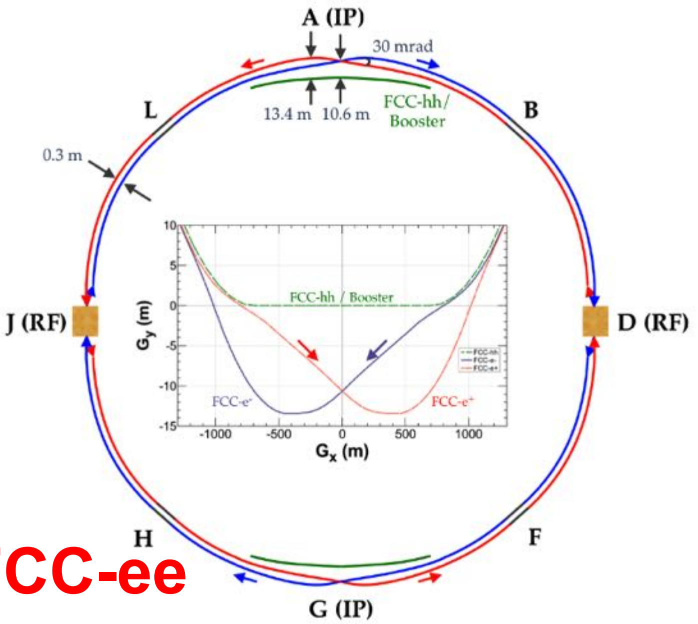
photo: J. Wenninger

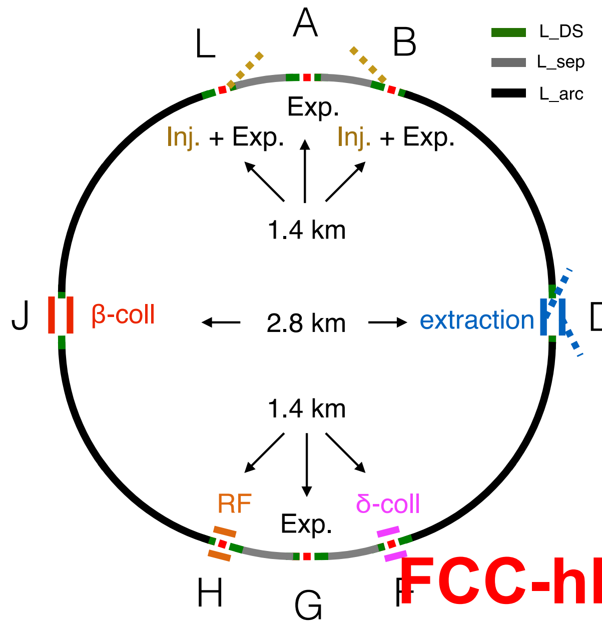
The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

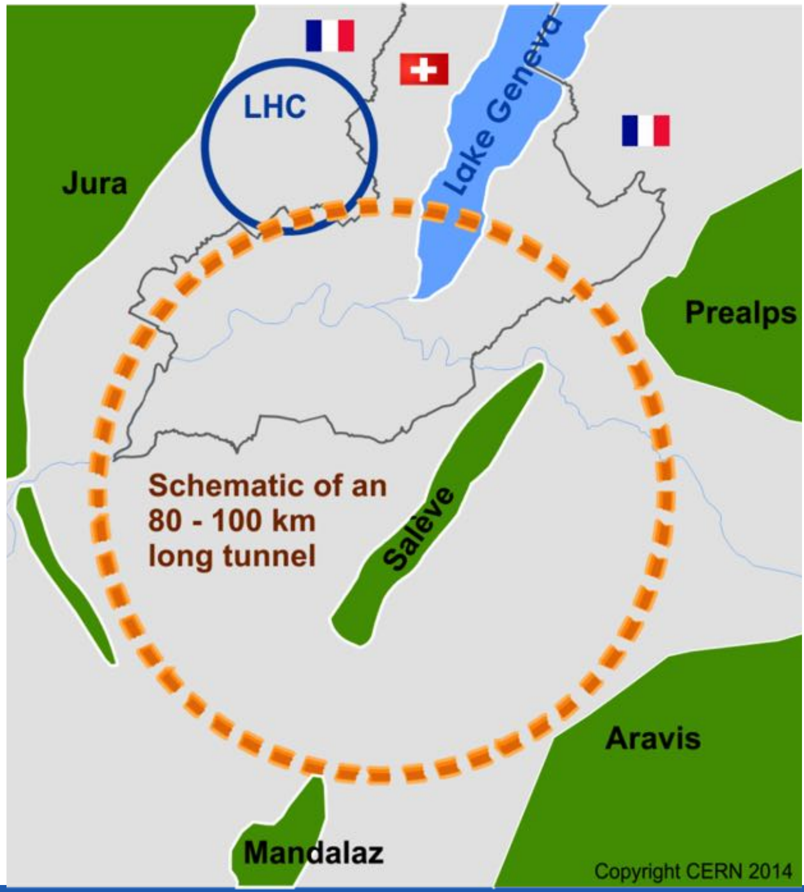
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building 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

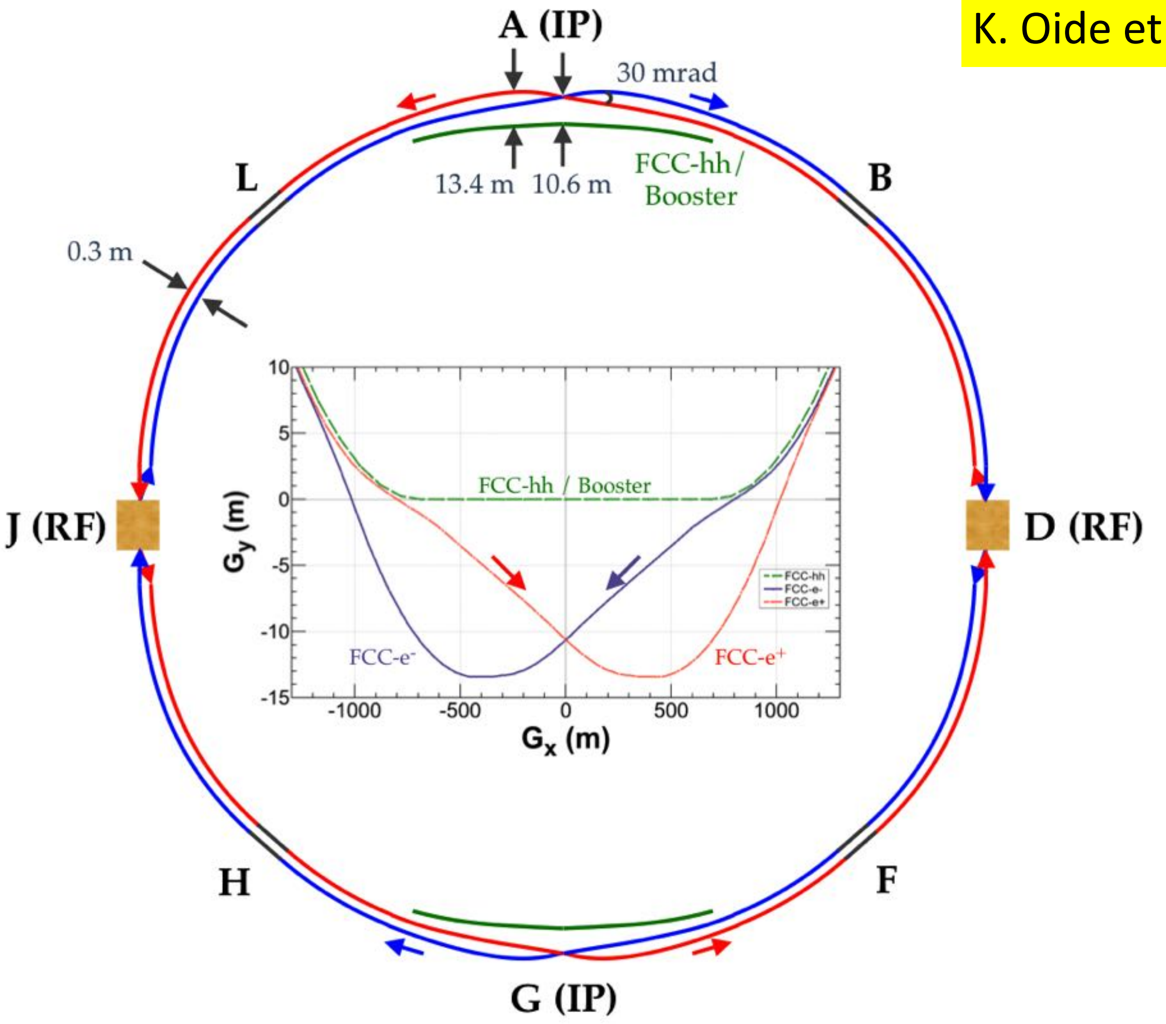
presently 2 IPs (alternative layouts with 3 or 4 IPs under study), **large** horizontal crossing angle **30 mrad, crab-waist optics**

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.

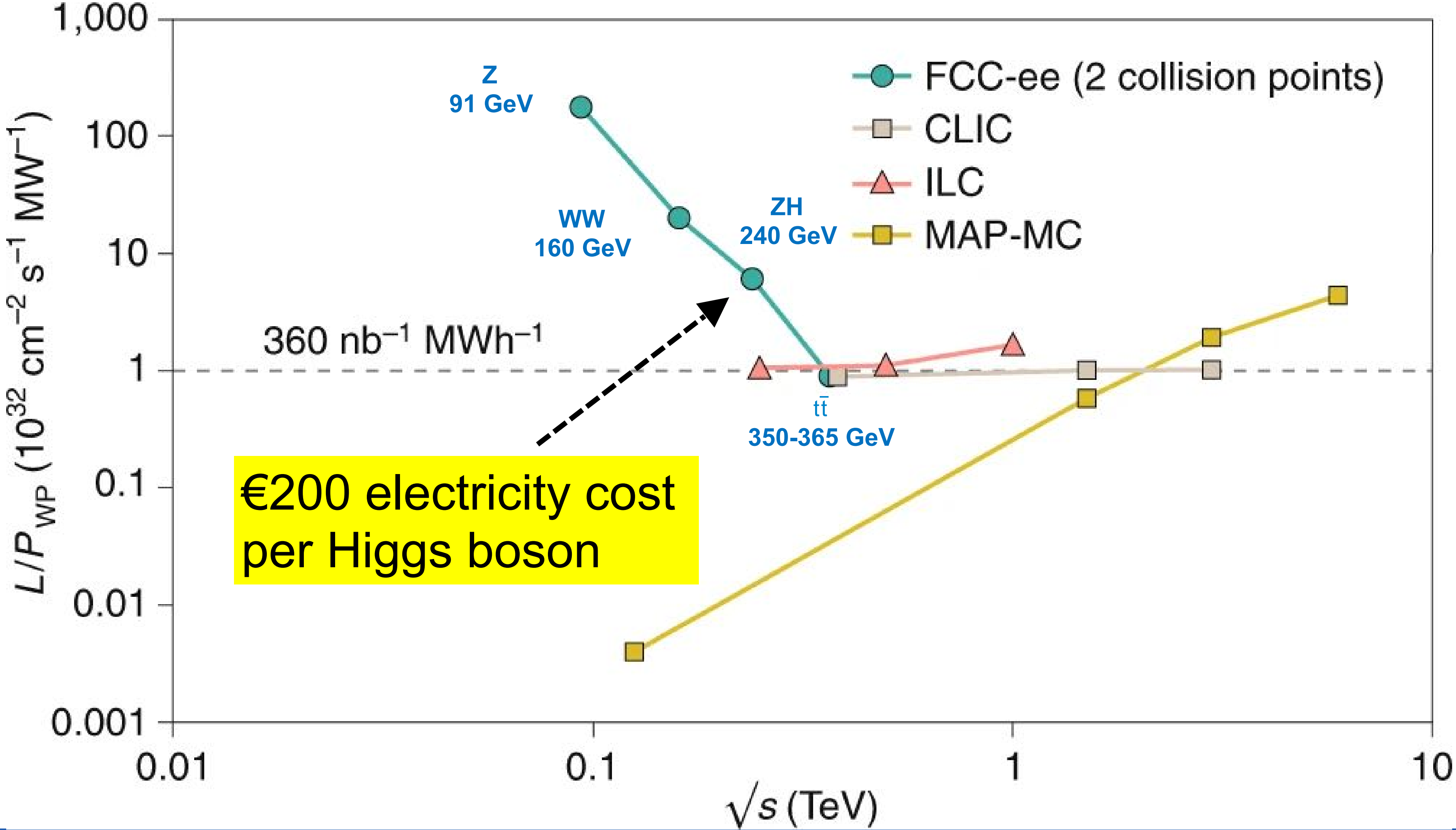


FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

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: efficient Higgs/electroweak factory

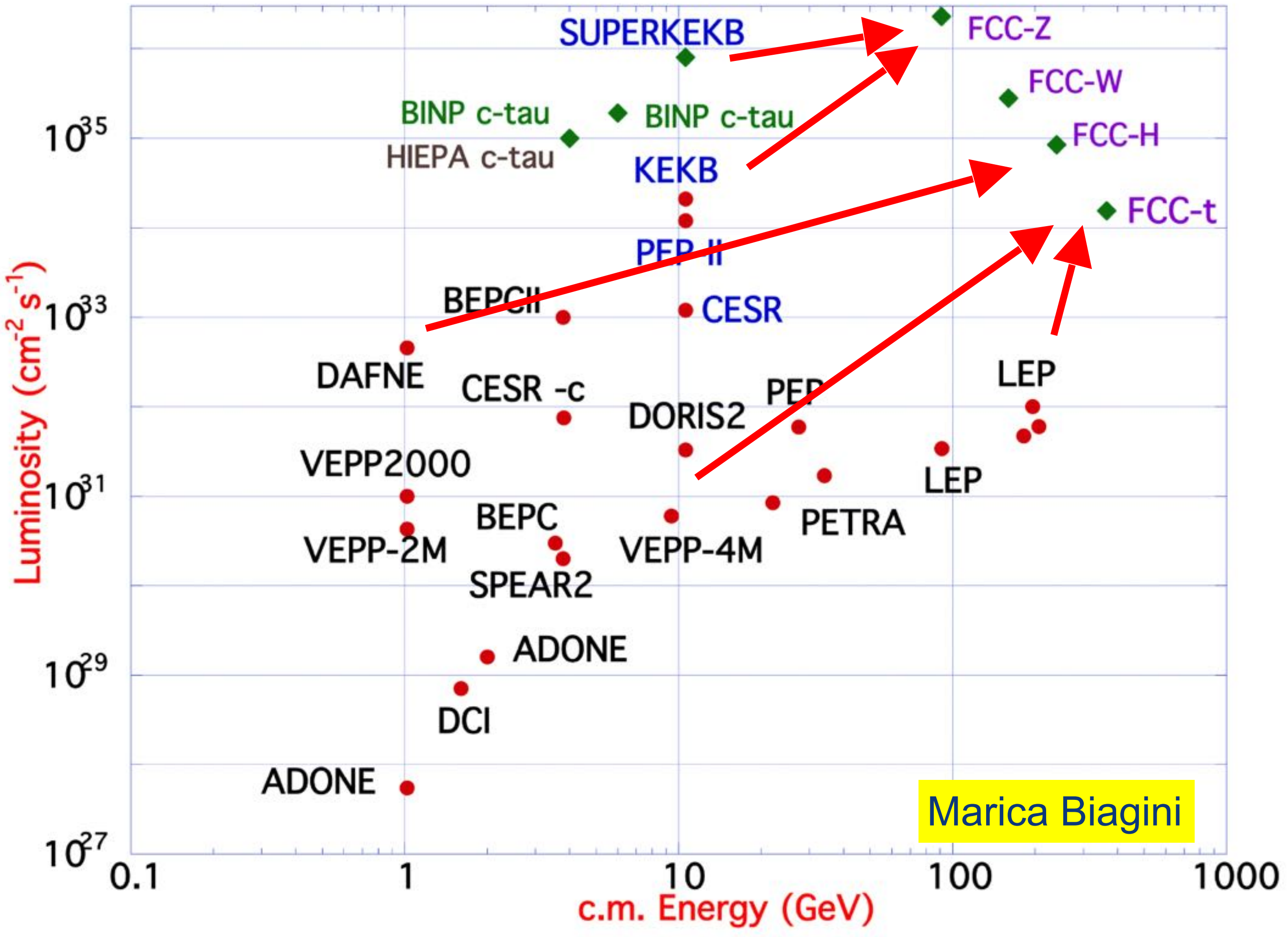


Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders.

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 design concept

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

S-KEKB: low β_y^*, crab waist

LEP: high energy, SR effects

VEPP-4M, LEP: precision E calibration

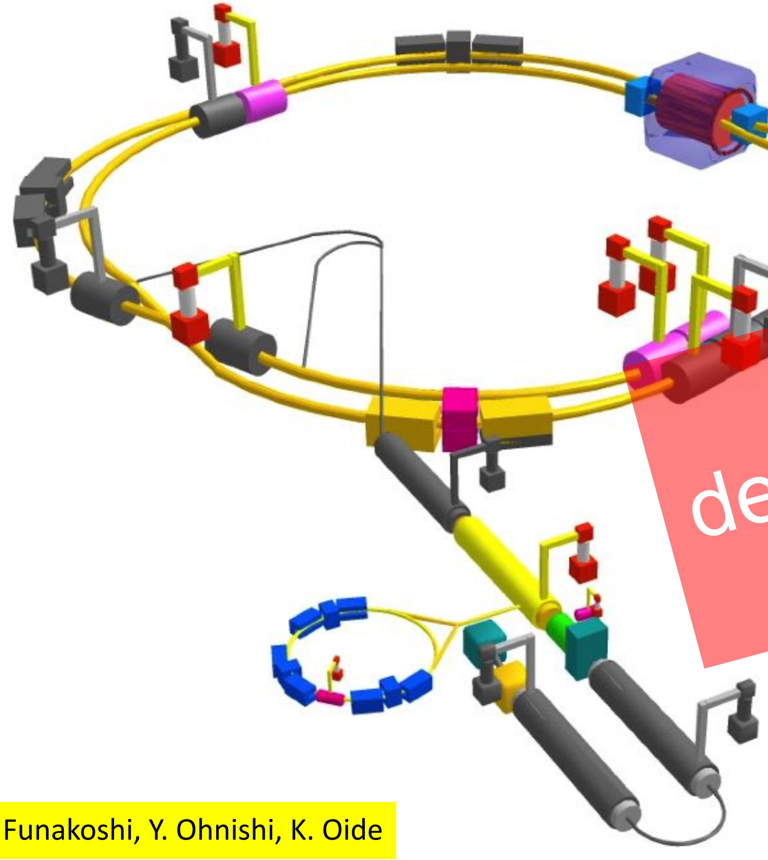
KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

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

SuperKEKB – pushing luminosity and β*

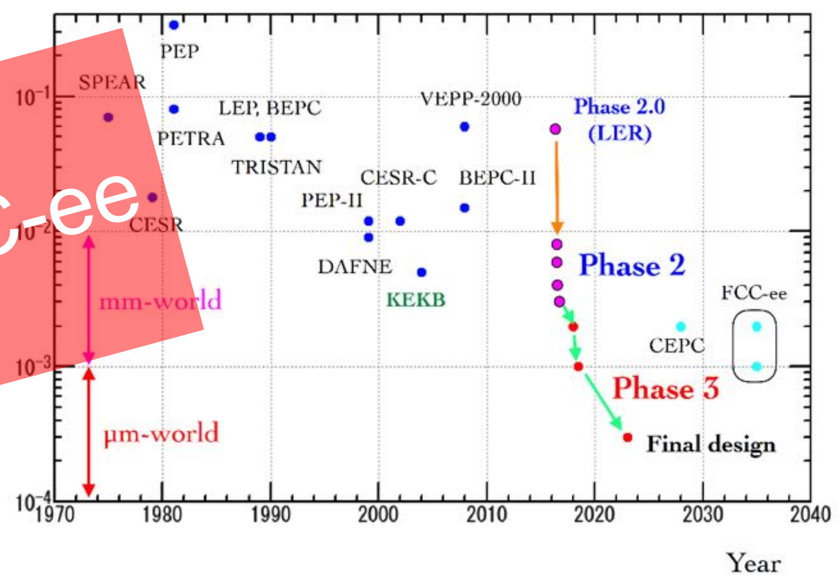
Design: double ring e^+e^- collider as *B*-factory at 7(e^-) & 4(e^+) GeV; design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; β_y^* ~ 0.3 mm; nano-beam – large crossing angle collision scheme (crab waist w/o sextupoles); beam lifetime ~5 minutes; top-up injection; e^+ rate up to ~ 2.5 10^{12} /s ; under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



Y. Funakoshi, Y. Ohnishi, K. Oide

SuperKEKB is demonstrating FCC-ee key concepts

Strategy of beta squeezing for Phase 2 and Phase 3

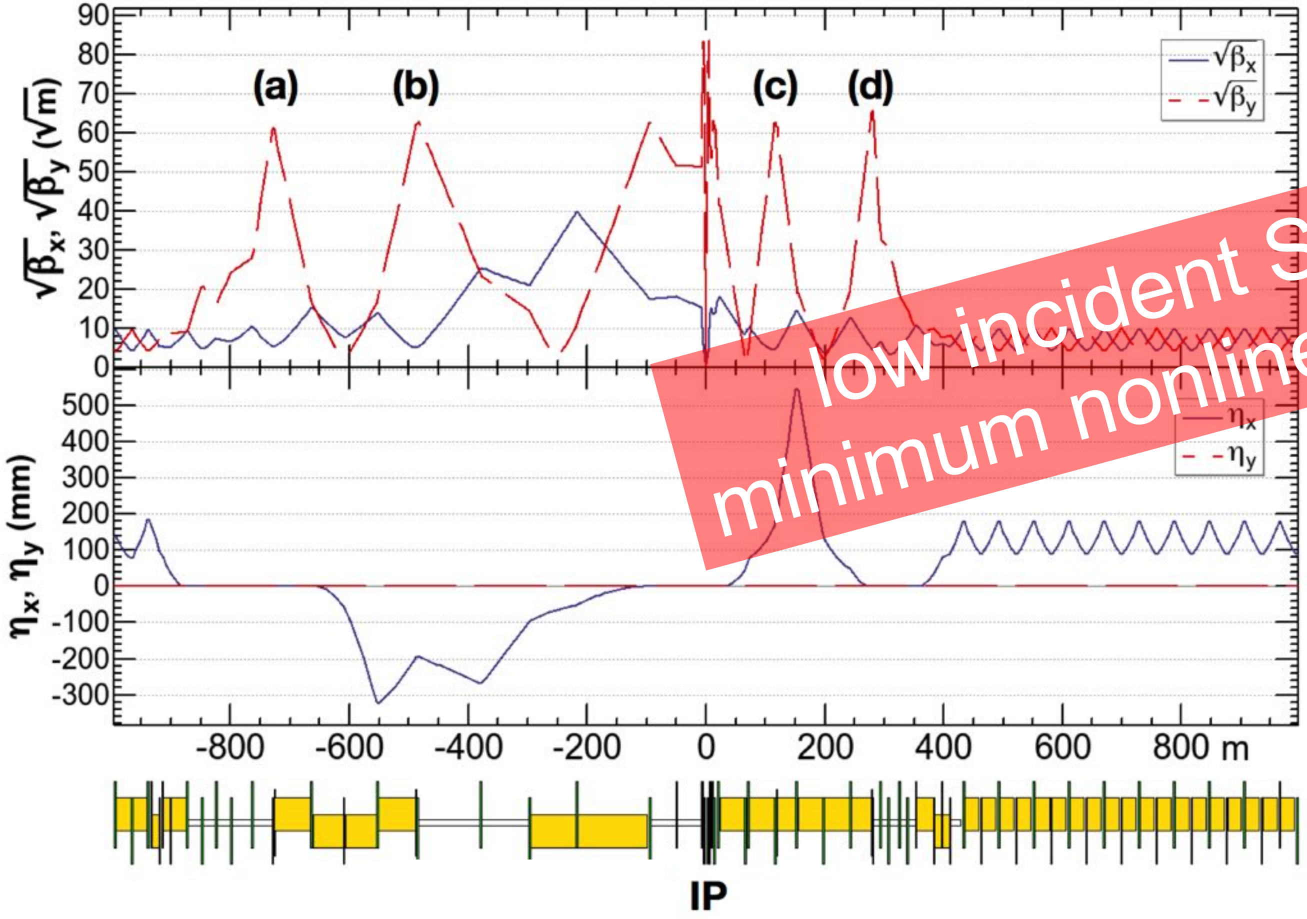


β_y^* =1 mm achieved in both rings - world record

crab-waist collisions implemented recently

→ IPAC'20 Talk by K. Shibata

FCC-ee asymmetric crab-waist IR optics



low incident SR,
minimum nonlinearities

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

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

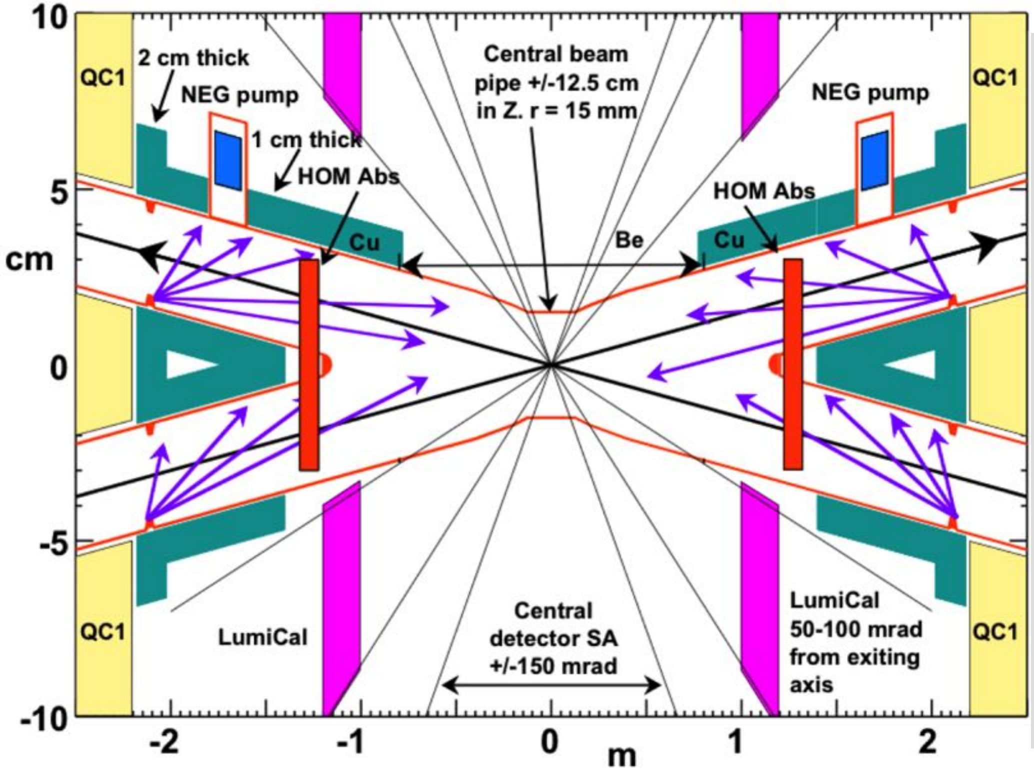
yellow boxes: dipole magnets

only two sextupoles per final focus side:
minimum nonlinearity,
large dynamic aperture

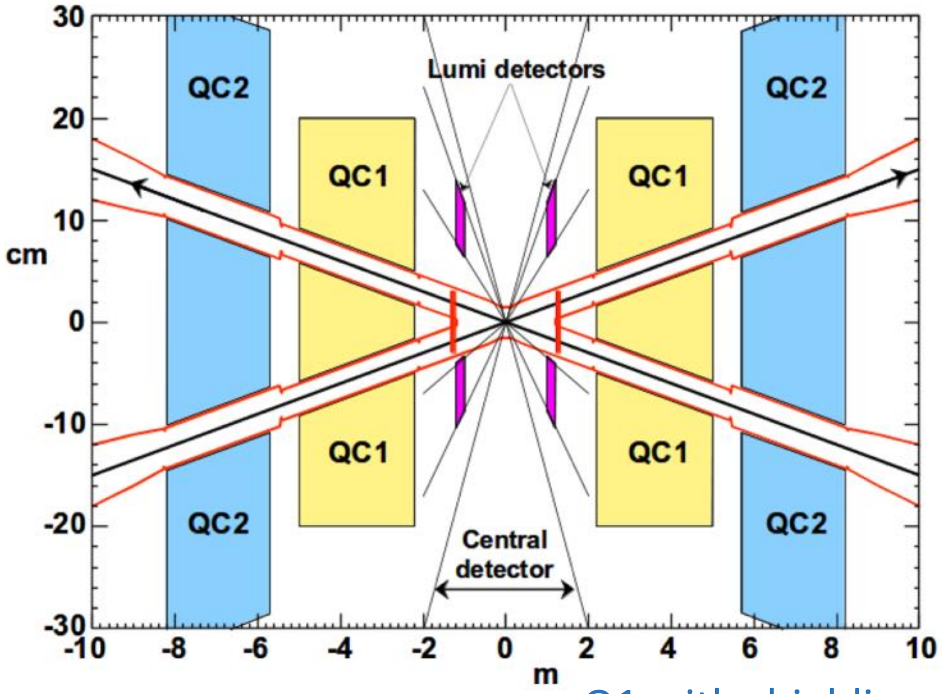
4 sextupoles (a–d) for local vertical chromaticity correction combined w. crab waist, optimized for each working point – **novel "virtual crab waist", standard crab waist demonstrated at DAFNE**

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

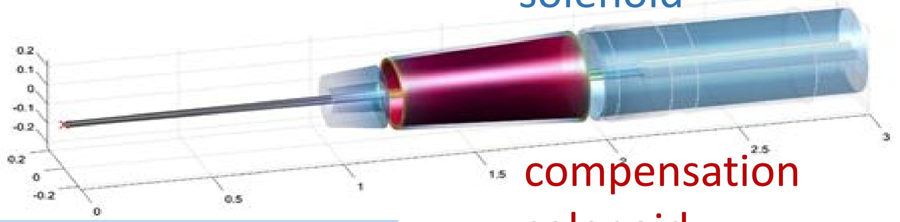
FCC-ee Interaction Region Design



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?

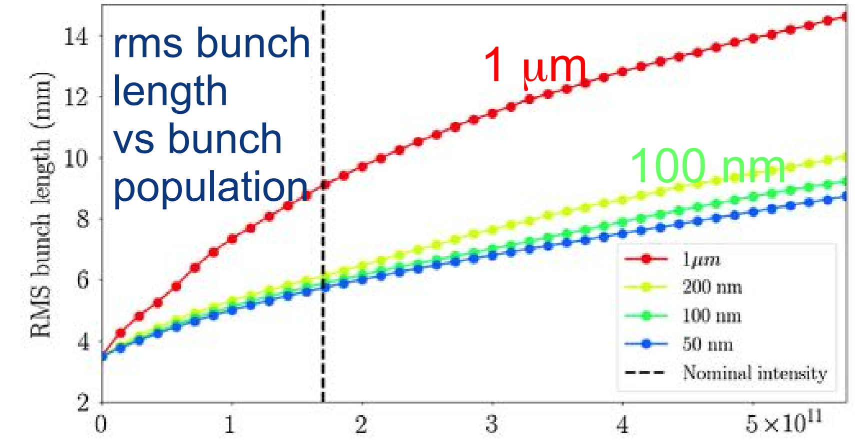
M. Boscolo, N. Bacchetta, A. Bogomyagkov, H. Burkhardt, M. Dam, D. El Khechen, M. Koratzinos, E. Levichev, M. Luckhof, A. Novokhatski, L. Pellegrino, S. Sinyatkin, M. Sullivan, et al.

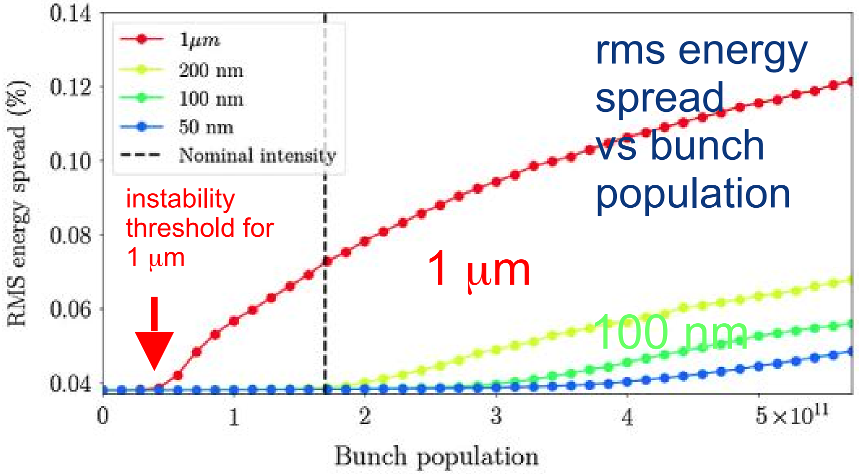
M. Boscolo, H. Burkhardt, and M. Sullivan, **Phys. Rev. Accel. Beams 20**, 011008 (2017)
A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

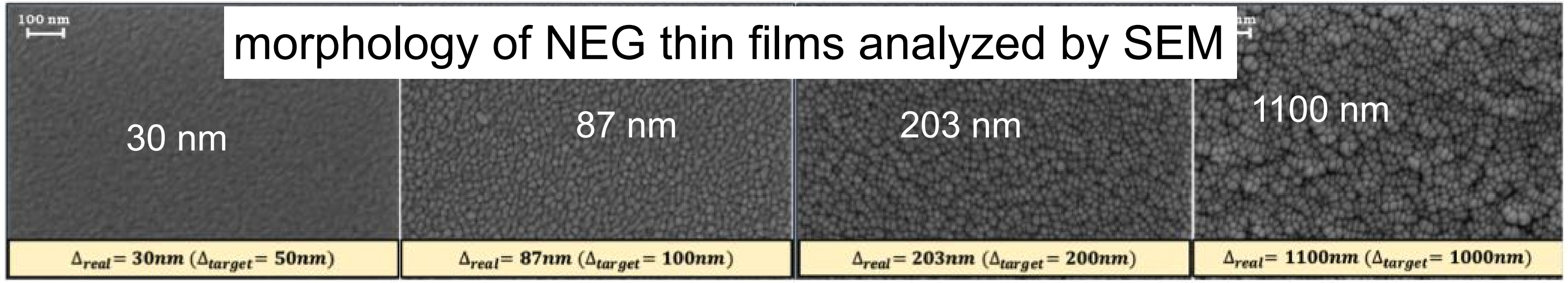
FCC-ee R&D: impedance mitigation

resistive wall impedance of 98 km long collider → **microwave instability**

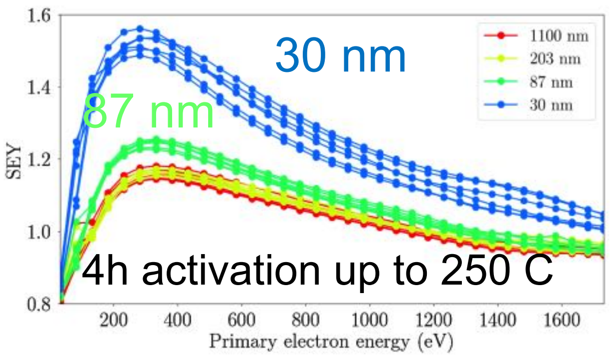
for standard 1 μm NEG coating → **development & qualification of ultrathin NEG coating** for FCC-ee (pumping, SEY, activation, impedance...)

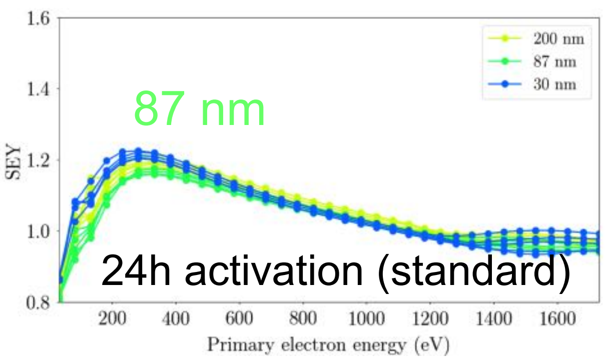






SEY vs primary e-energy for varying NEG thickness

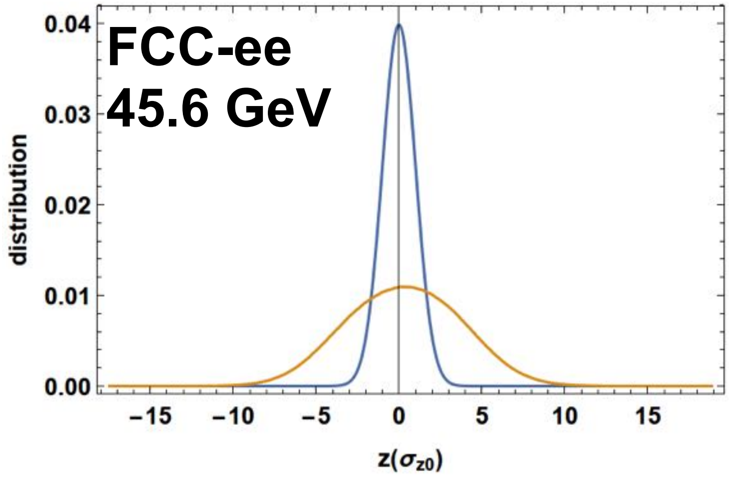




M. Migliorati, E. Belli, M. Zobov, **Phys. Rev. Accel. Beams 21**, 041001 (2018)

E. Belli et al., **Phys. Rev. Accel. Beams 21**, 111002 (2018)
E. Belli, **ARIES Monograph** vol. 53 (2018)

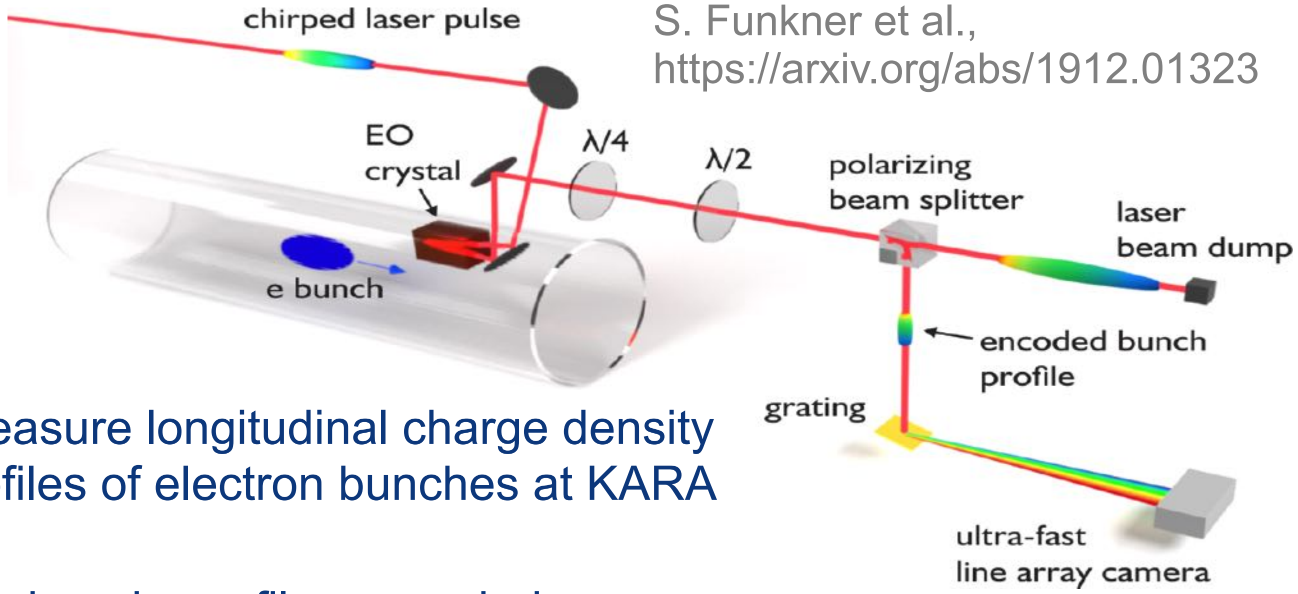
FCC-ee R&D: bunch-by-bunch diagnostics



Dmitry Shatilov

FCC-ee bunch profiles are strongly affected by beamstrahlung in collision

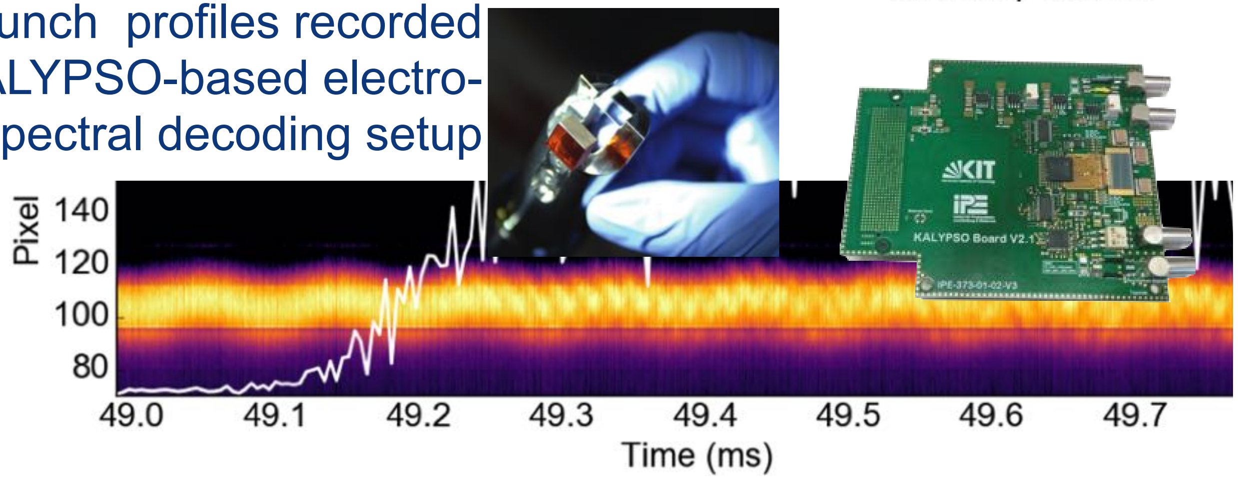
high-throughput electro-optical single-shot diagnostics developed at KIT



S. Funkner et al., https://arxiv.org/abs/1912.01323

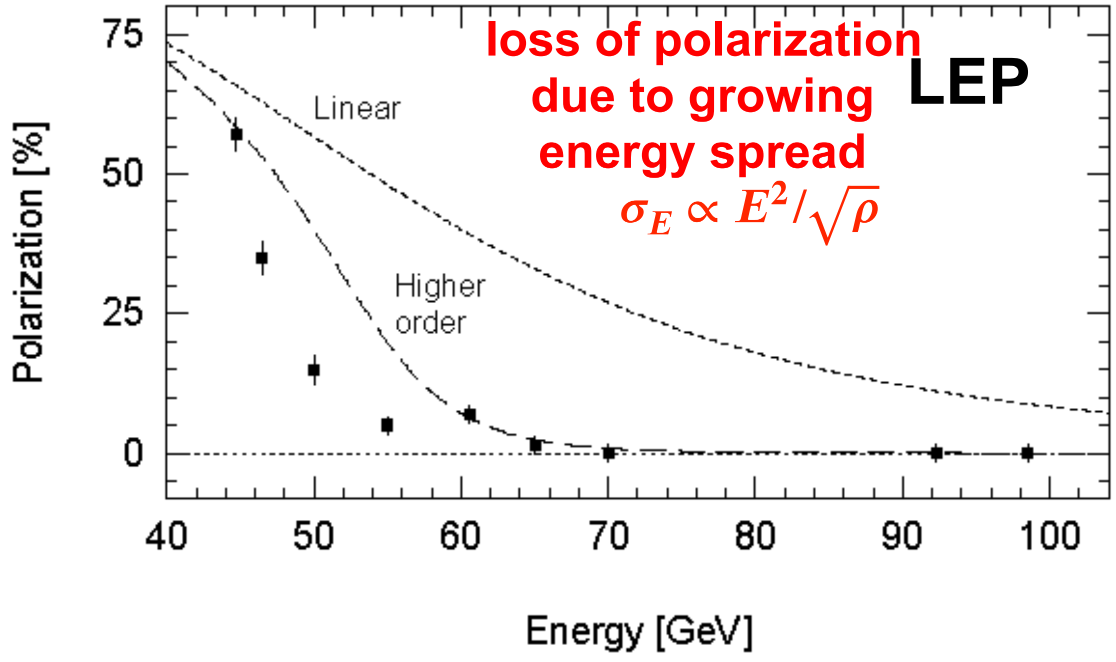
setup to measure longitudinal charge density profiles of electron bunches at KARA

longitudinal bunch profiles recorded with the KALYPSO-based electro-optical spectral decoding setup



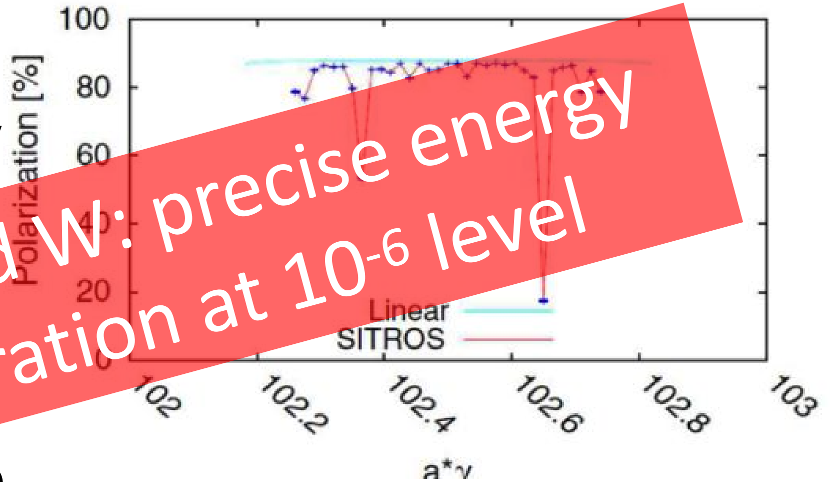
Stefan Funkner et al., **Phys. Rev. Accel. Beams 22**, 022801 (2019)
Benjamin Kehrer et al., **Phys. Rev. Accel. Beams 21**, 102803 (2018)

FCC-ee R&D: precise energy calibration



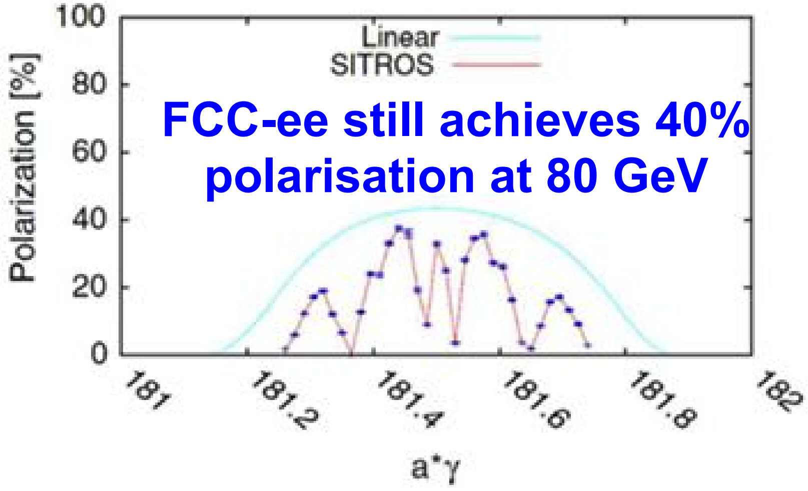
LEP had no polarisation above ~65 GeV

FCC-ee 45.6 GeV (Z)



for Z and W: precise energy calibration at 10^{-6} level

FCC-ee 80 GeV (WW)



FCC-ee *L*-averaged centre-of-mass uncertainty:
~100 keV at Z pole, ~300 keV at W pair threshold

R. Assmann, M. Lamont, S. Myers, **Nucl. Phys. B, Proc. Suppl. 109** (2002) 17-31

E. Gianfelice-Wendt, **Phys. Rev. Accel. Beams 19**, 101005 (2016)

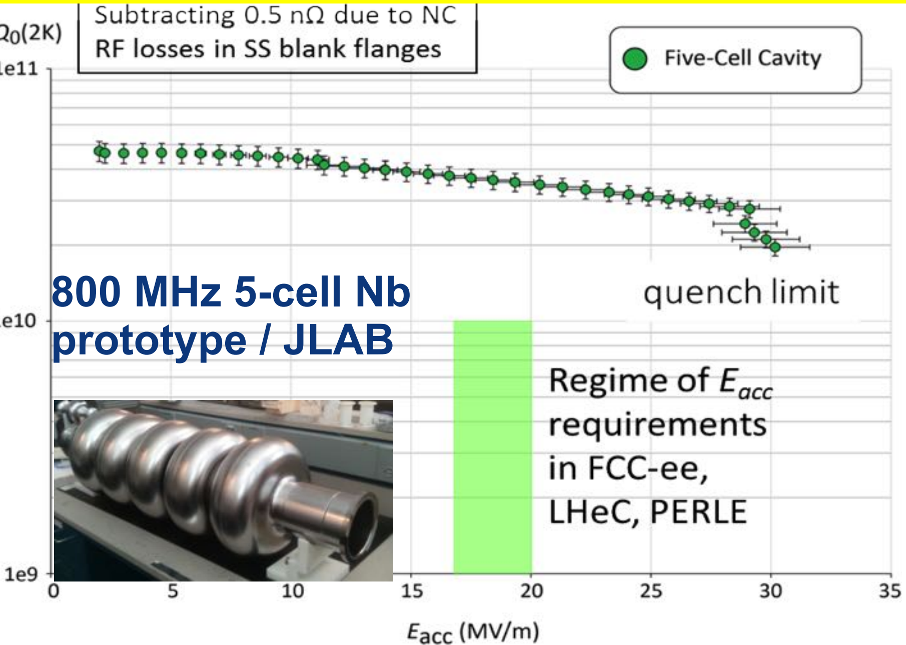
Fermilab

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

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

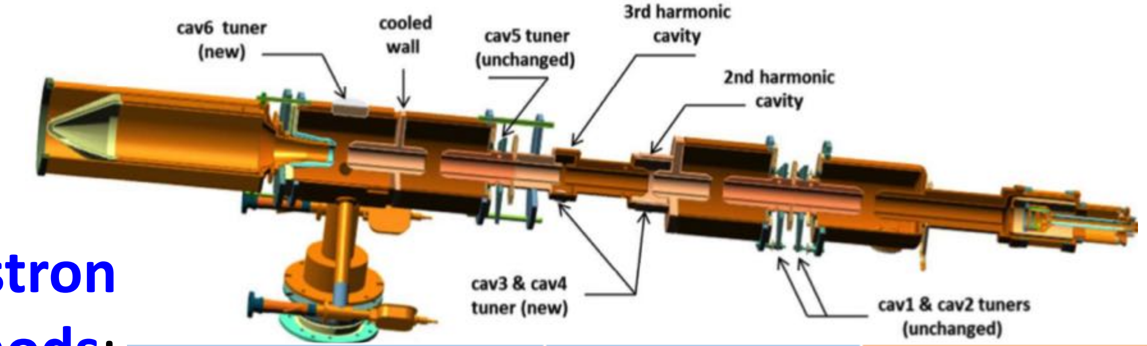
- improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)
- coating of A15 superconductors (e.g. Nb_3Sn), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- MW-class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

prototype FCC SRF cavities at JLAB



Jefferson Lab

high-efficiency klystron at CERN



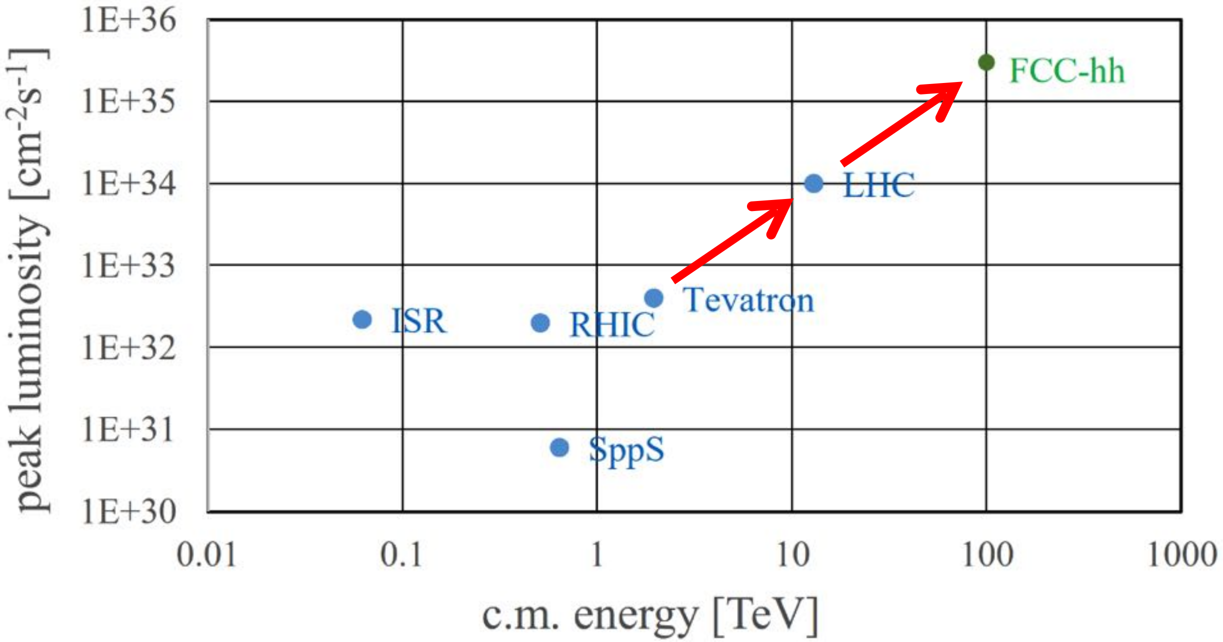
New klystron bunching methods: **LHC klystron retrofit** as proof of principle for FCC

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

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

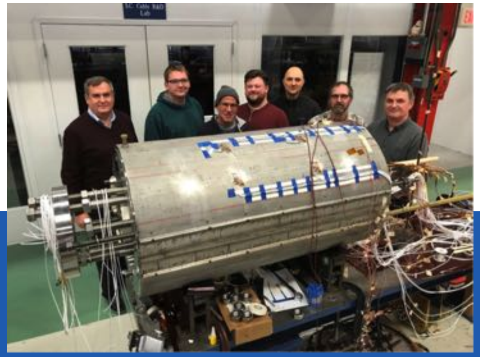
FCC-hh: performance



- **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

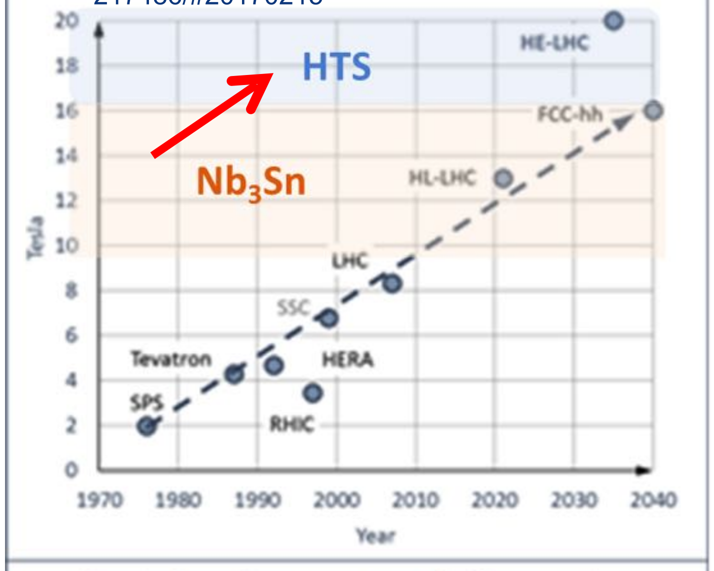


FNAL demonstrator
14.1 T Nb_3Sn
(Accelerating News)

→ IPAC'20 Talk by L. Bottura

Development of HTS high field magnets

https://indico.cern.ch/event/588810/sessions/217486/#20170215



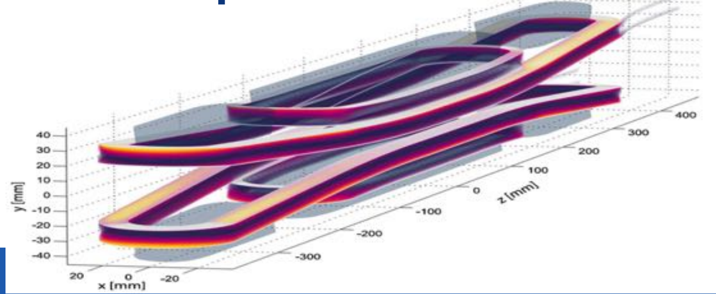
Nominal accelerator magnet field versus time

Conductor Key Technologies

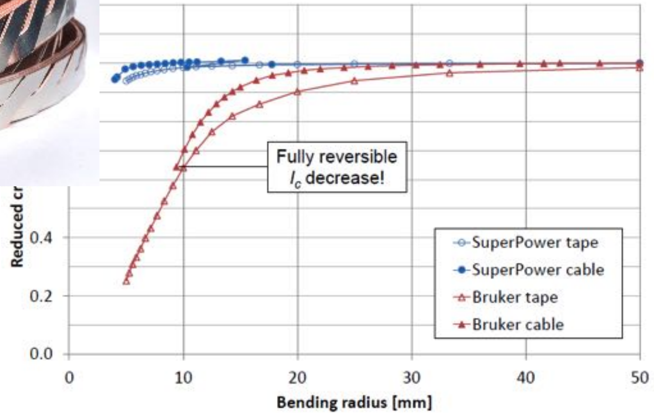
- **High field/high current Coated Conductors** (dedicated electrical + mechanical properties, stabilization, Je>600 A/mm²@20 T and 4.2 K)
- **(Roebel) Cable technology** (cable design, ac-losses, coil winding)

from
HL-LHC technology
11 T Nb_3Sn

towards
HTS based
20 T options



https://indico.cern.ch/event/588810/sessions/216289/#20170217



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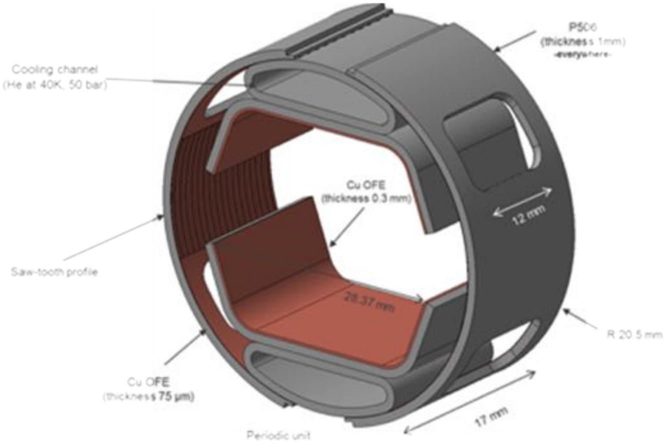
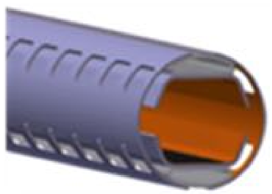
FCC-hh: synchrotron radiation (SR) challenge

synchrotron radiation (~ 30 W/m/beam @16 T field) (cf. LHC <0.2W/m)

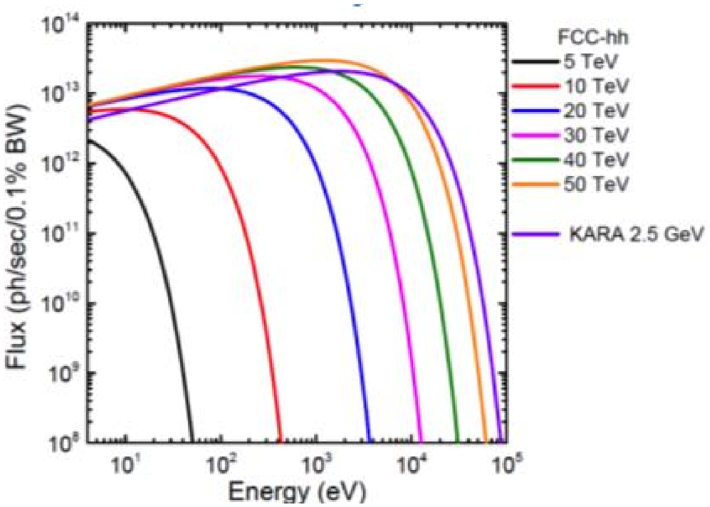
~ 5 MW total SR power in arcs from proton beams, emitted inside the cold magnets

- **strategy: absorption of synchrotron radiation on “beam screen” at higher temperature (> 1.9 K)** for cryogenic efficiency; optimum FCC-hh beam screen temperature 40-60 K (cf. LHC 5-20 K) ; beam screen also provides beam vacuum, must suppress electron cloud effect, impedance, etc.
- **novel “double” beam screen: low impedance, large cooling channels, adequate vacuum pumping, absorption of photo-electrons**





ALBA STFC ASTeC INFN



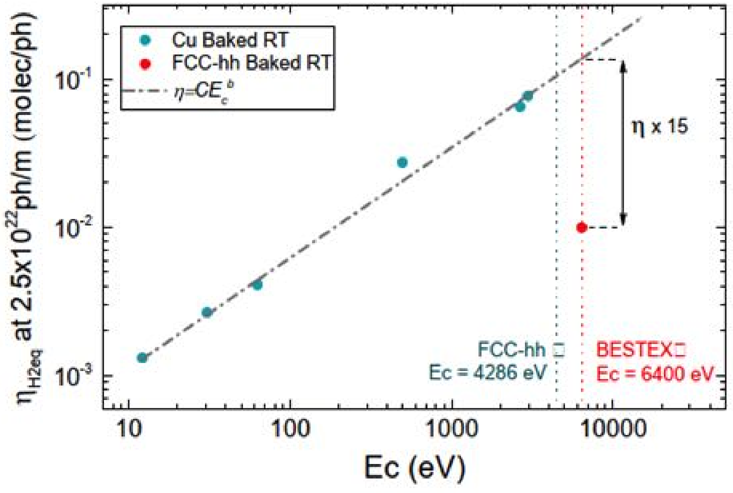
beamscreen tests with real SR at KIT

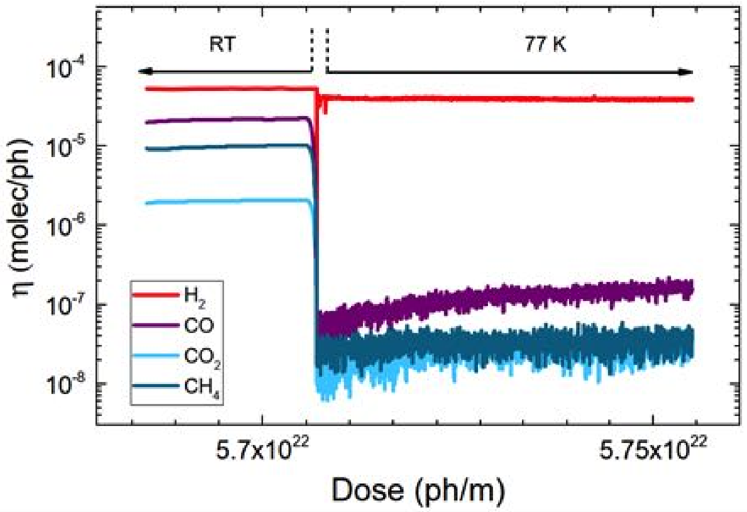
photon spectrum of ANKA/KARA light source = photon spectrum in FCC-hh arcs

CERN EuroCirCol KIT Karlsruhe Institute of Technology

I. Bellafont et al., **Phys. Rev. Accel. Beams 23**, 033201 (2020)
I. Bellafont et al, **Phys. Rev. Accel. Beams 23**, 043201 (2020)

FCC-hh cold beamscreen tests with SR at KARA





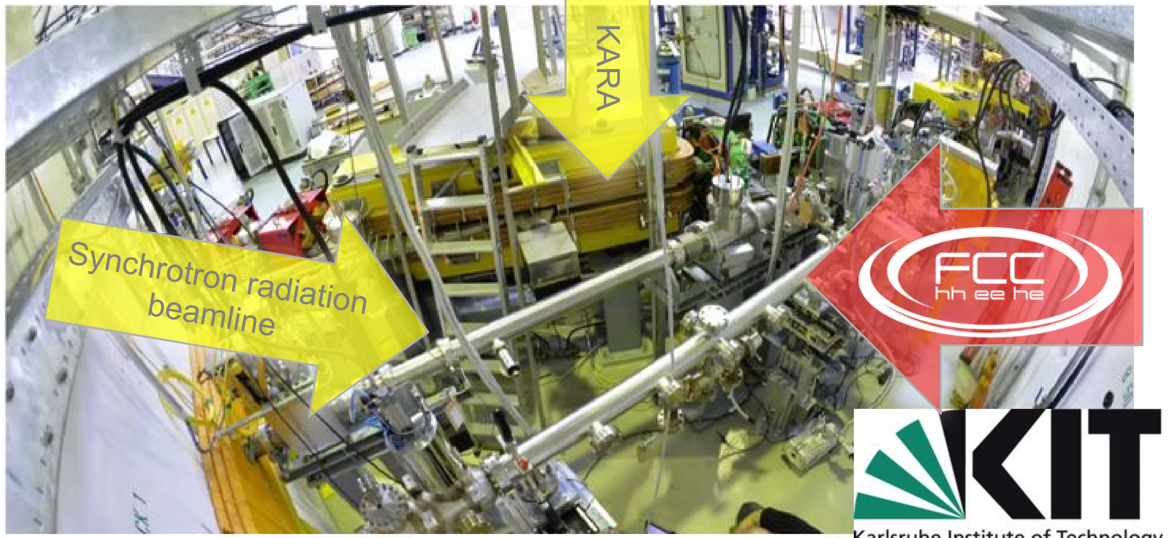
liquid Nitrogen line allows **experiments at cryogenic temperatures**:

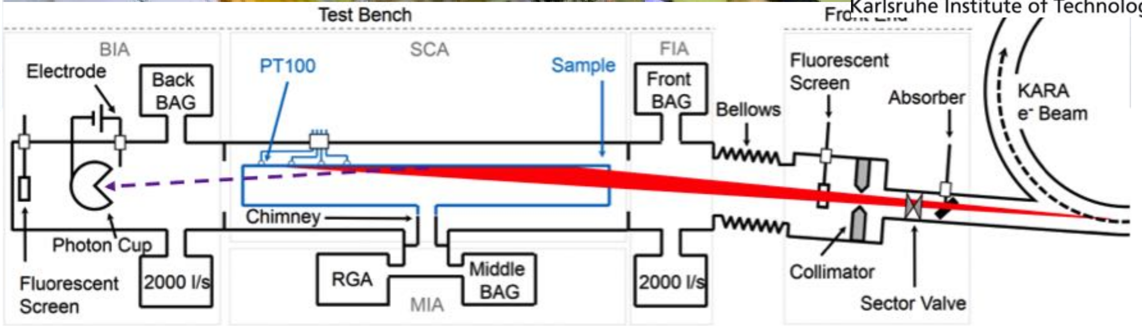
demonstrated **drastic reduction of molecular photo-desorption yield for FCC-hh BS geometry** compared with flat Cu chamber **(factor 15)**

&

when irradiating at cold (**factor 100** except H_2)

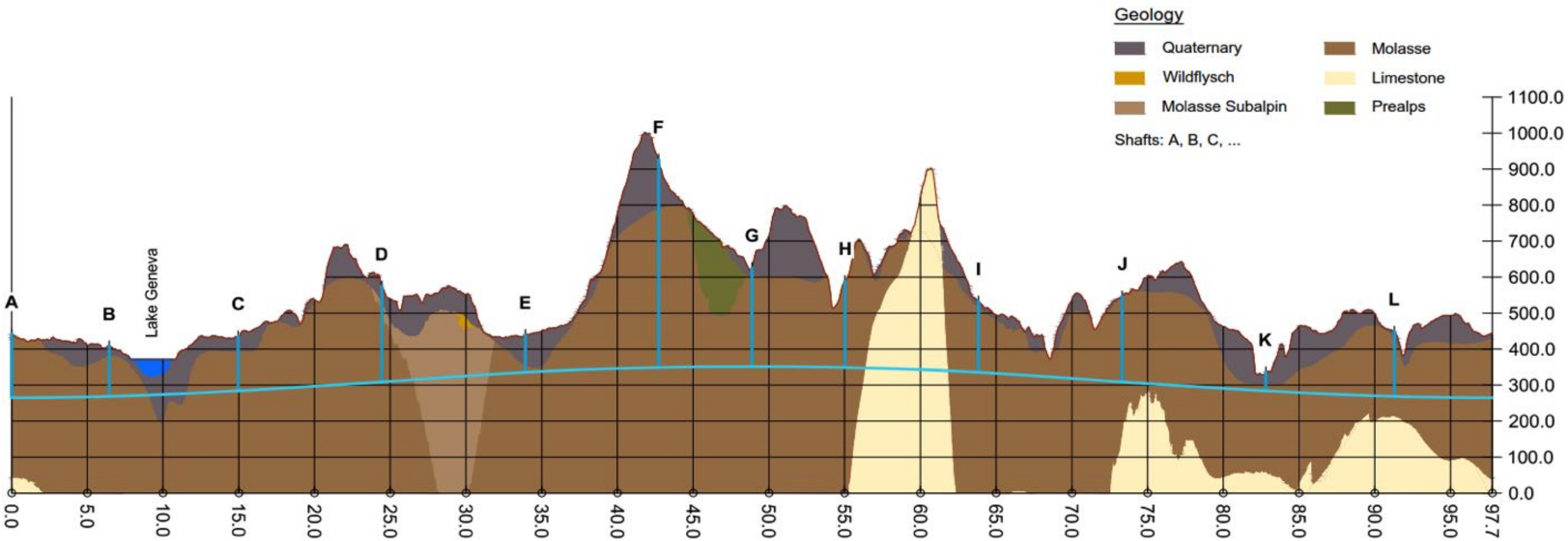
FCC vacuum chamber cryogenic test beamline at the KARA synchrotron

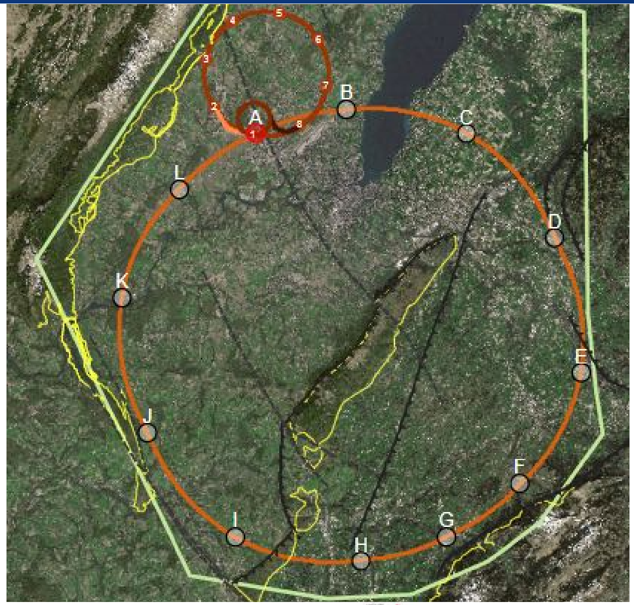


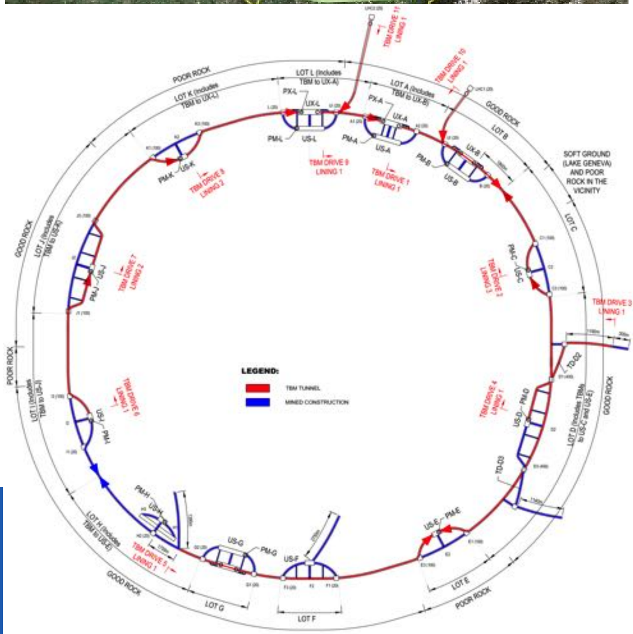


L.A. Gonzalez et al, **Phys. Rev. Accel. Beams 22**, 083201 (2019)

FCC implementation - footprint baseline







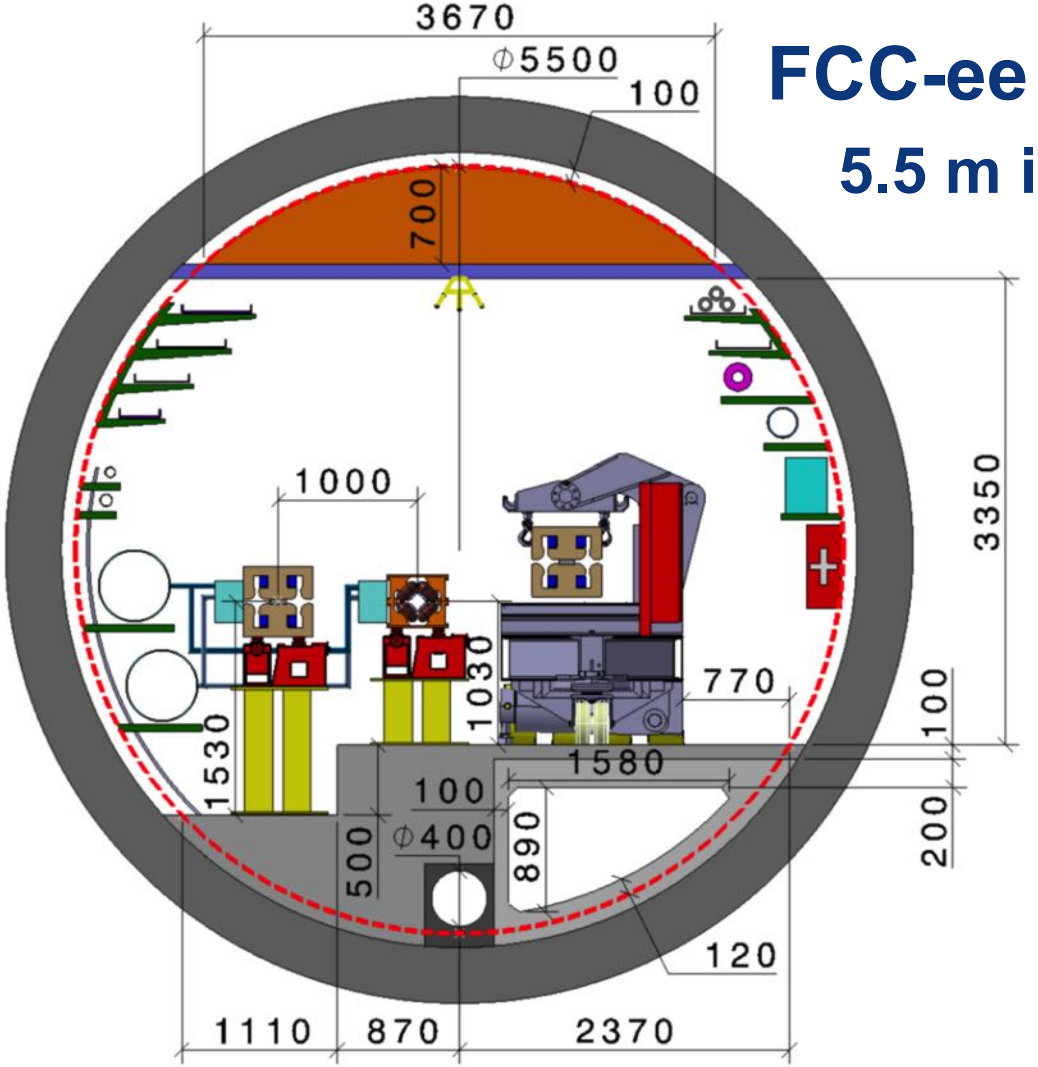
- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

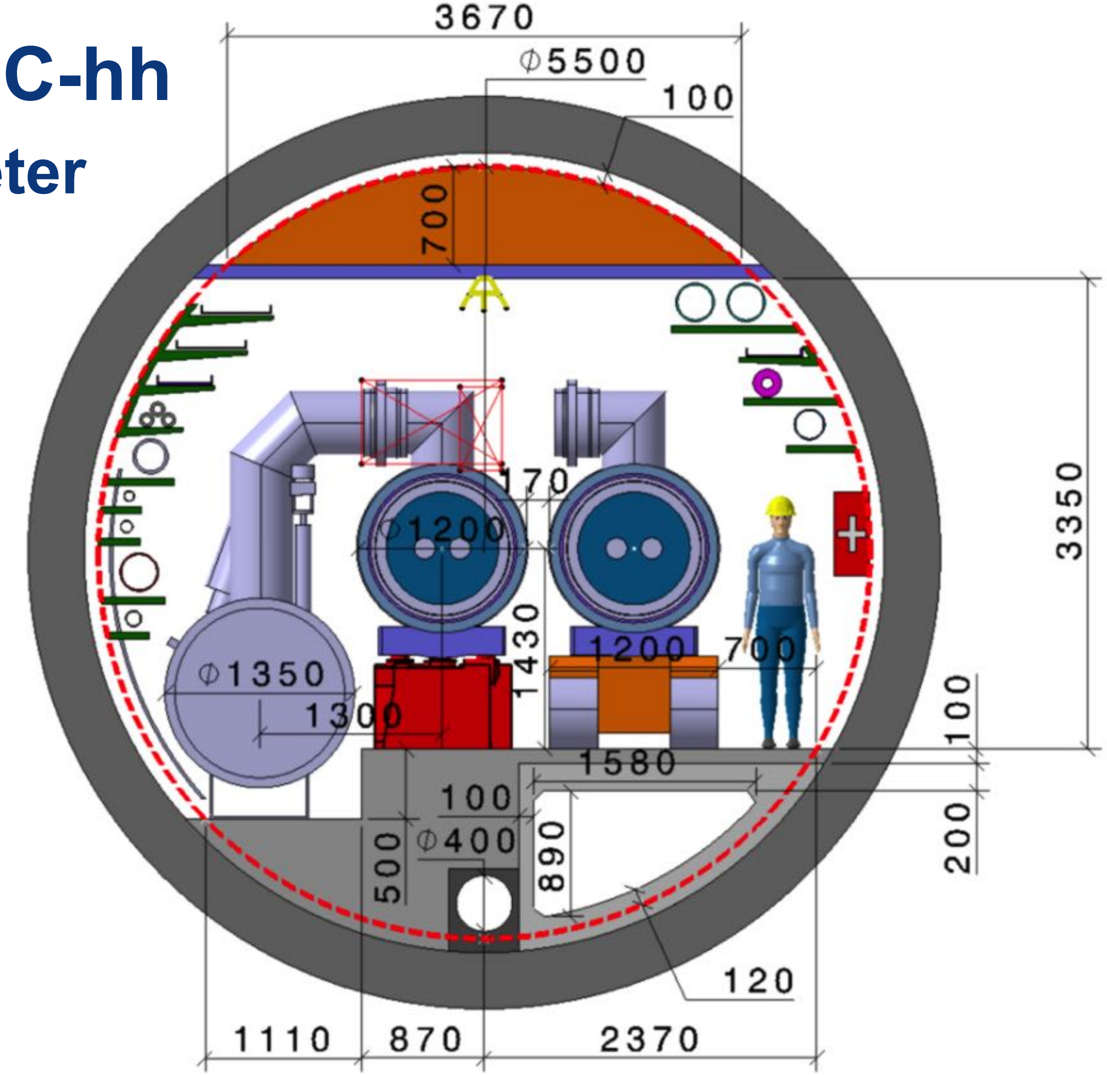
- **More than 75% tunnel in France, 8 (9) / 12 access points in France.**
- **next step: review of surface site locations and machine layout**

FCC-tunnel integration in arcs

FCC-ee FCC-hh

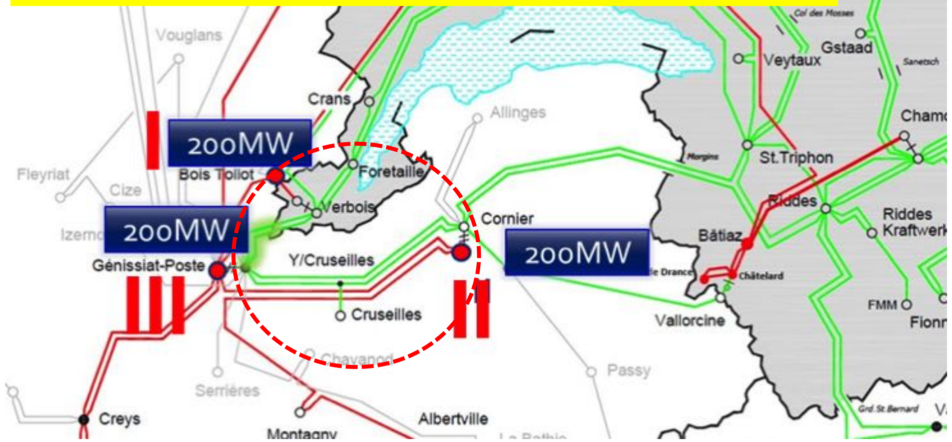
5.5 m inner diameter





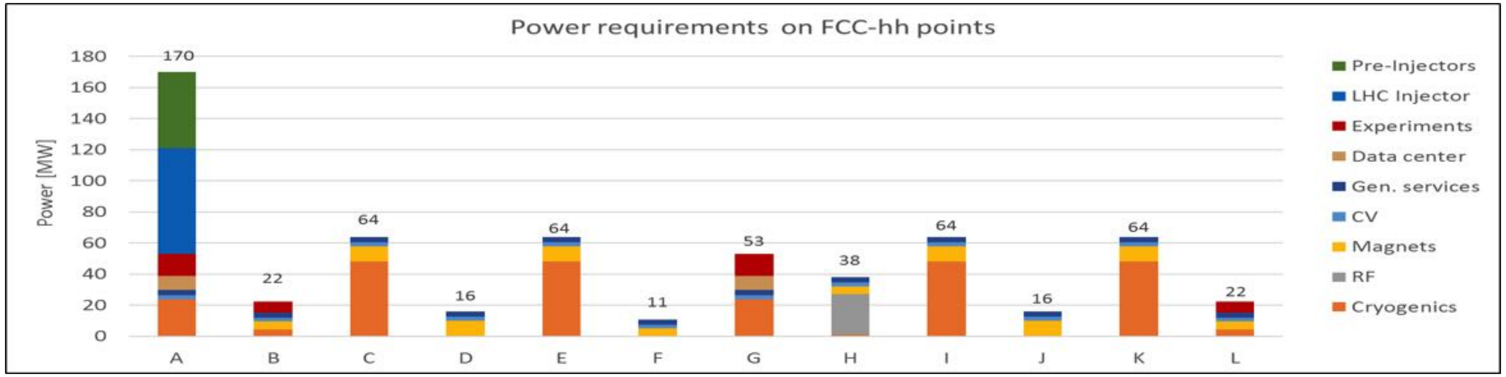
Supply & distribution of electrical energy

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

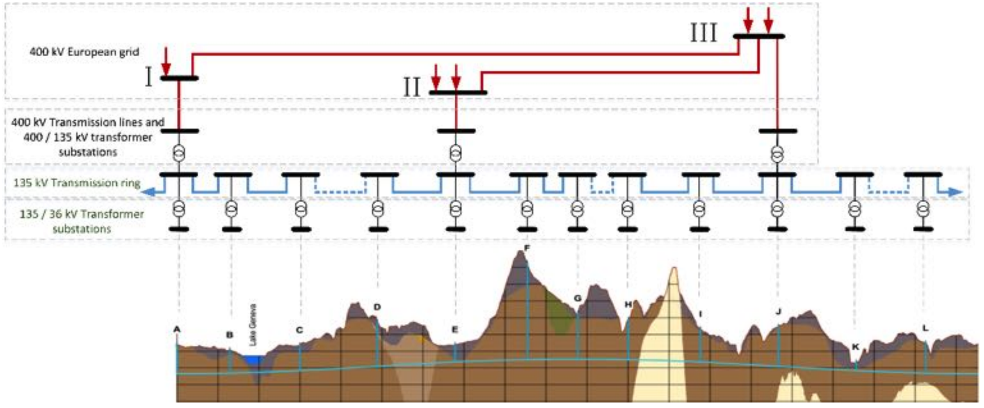


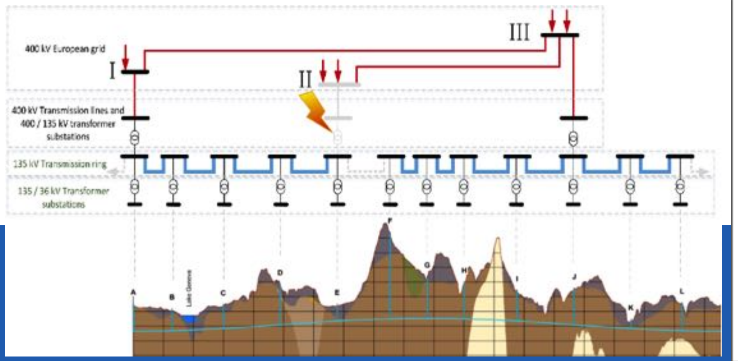
---- 400 kV ---- 230 kV

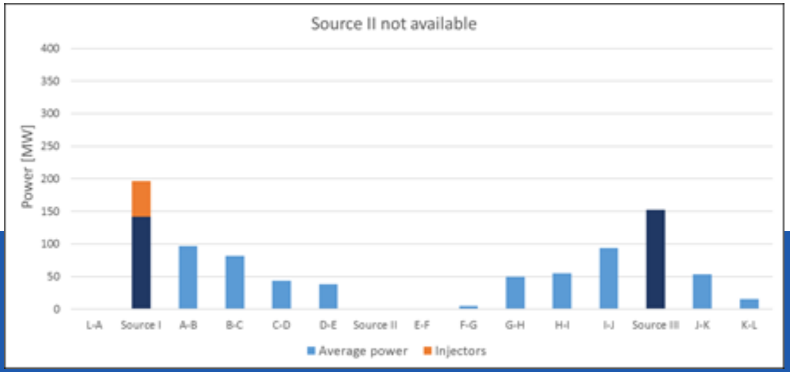
per-point power requirements as input for infrastructure-optimized conceptual design (peak FCC-ee: 260-340 MW, total FCC-hh: 550 MW)



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 integral 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

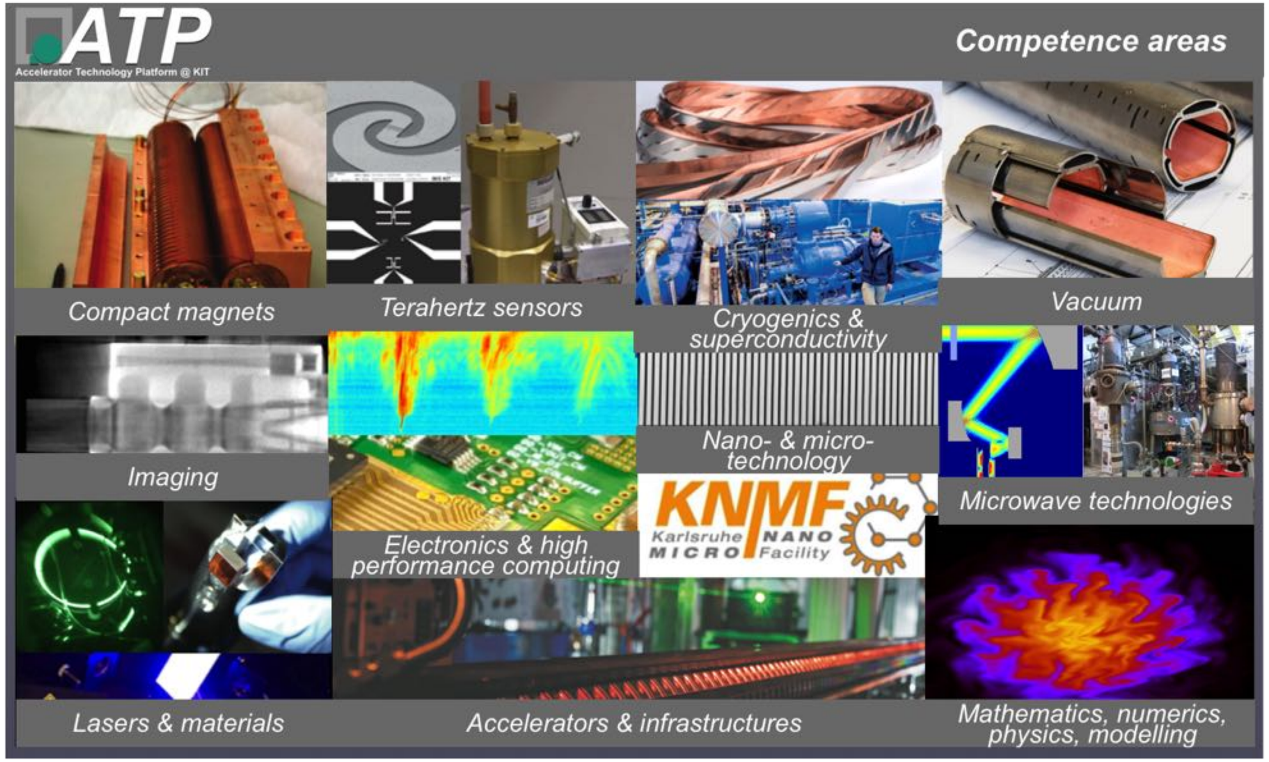
16 T magnet industrialization and series production

optimized engineering design, energy efficiency, maintainability

conductors & high-field magnet technology

FCC – a collaborative, world-wide effort

One example of many:



Technology portfolio of the Accelerator Technology Platform at KIT

KIT – The Research University in the Helmholtz Association

- 9300 employees, 24400 students
- one of the largest institutions for research and education in Germany

KIT Karlsruhe Institute of Technology

CERN

CERN Director-General Fabiola Gianotti and KIT President Holger Hanselka signed a letter of intent in 2019

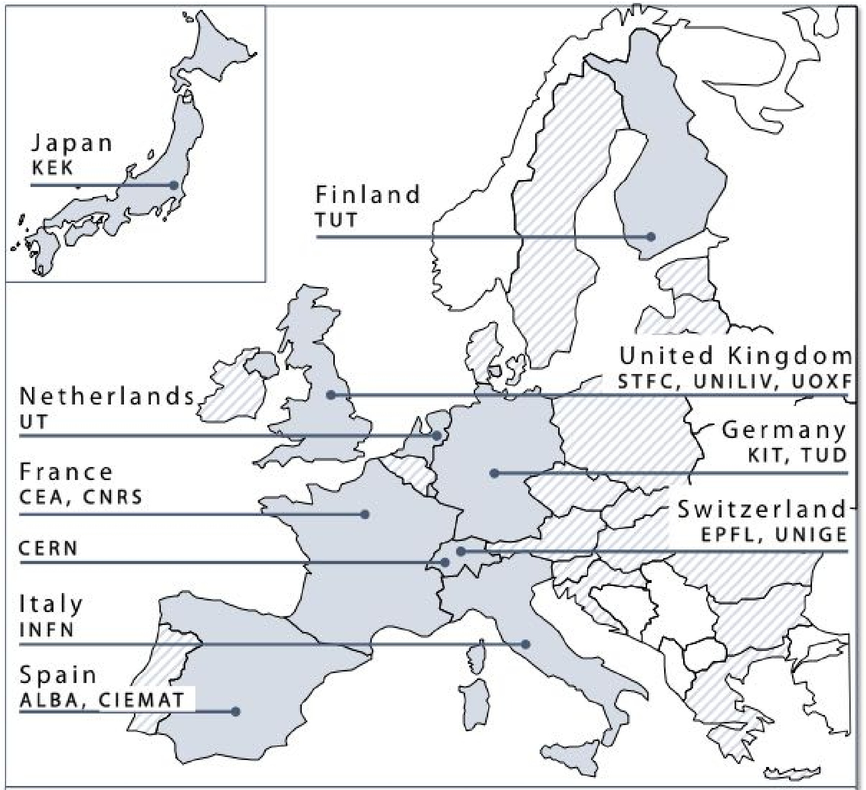
Status of Global FCC Collaboration

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

139	30	34	EC
Institutes	Companies	Countries	H2020

EU H2020 Design Study EuroCirCol



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

European Union Horizon 2020 program

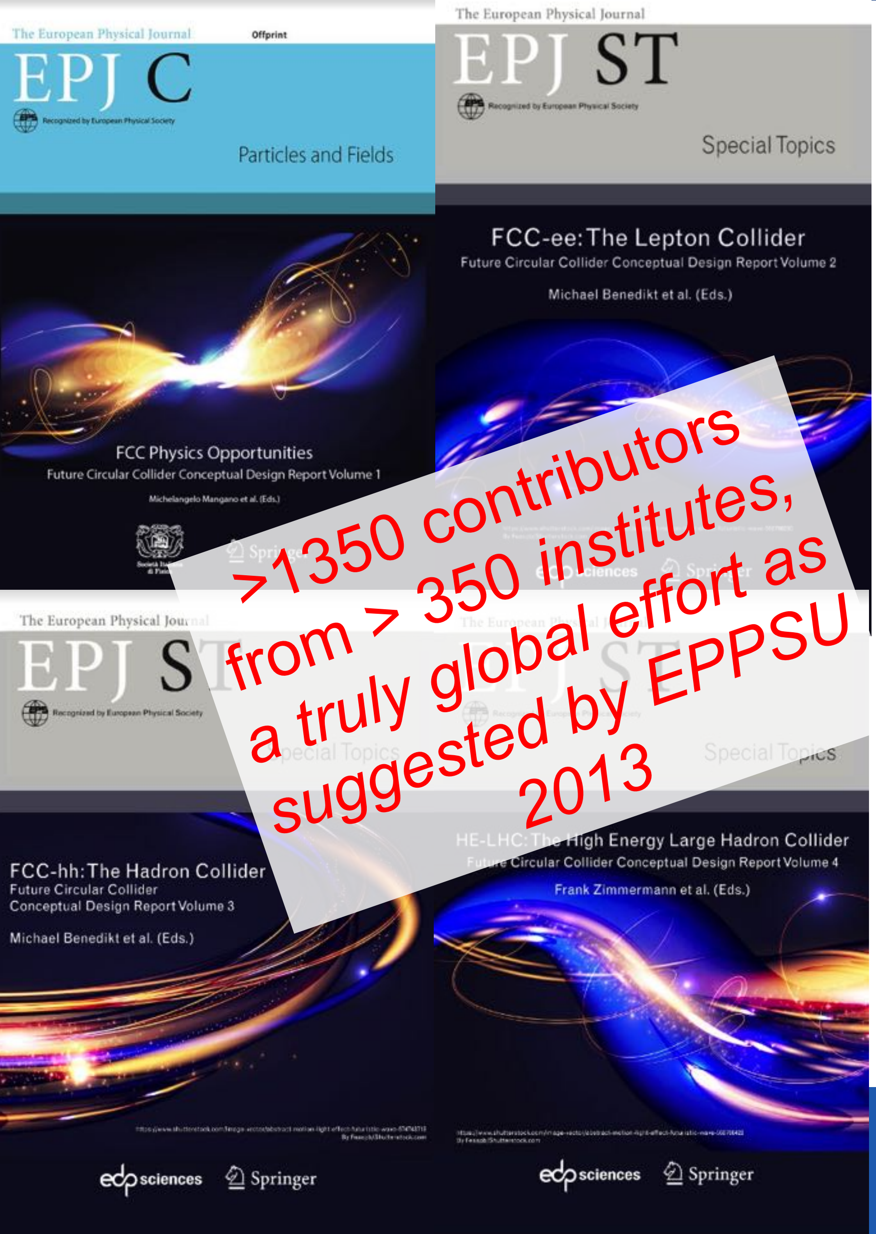
- 3 MEURO co-funding
- Completed in December 2019
- 15 European beneficiaries & KEK & associated FNAL, BNL, LBL, NHFML

Scope:

FCC-hh collider key work packages

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

FCC CDR and Study Documentation



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

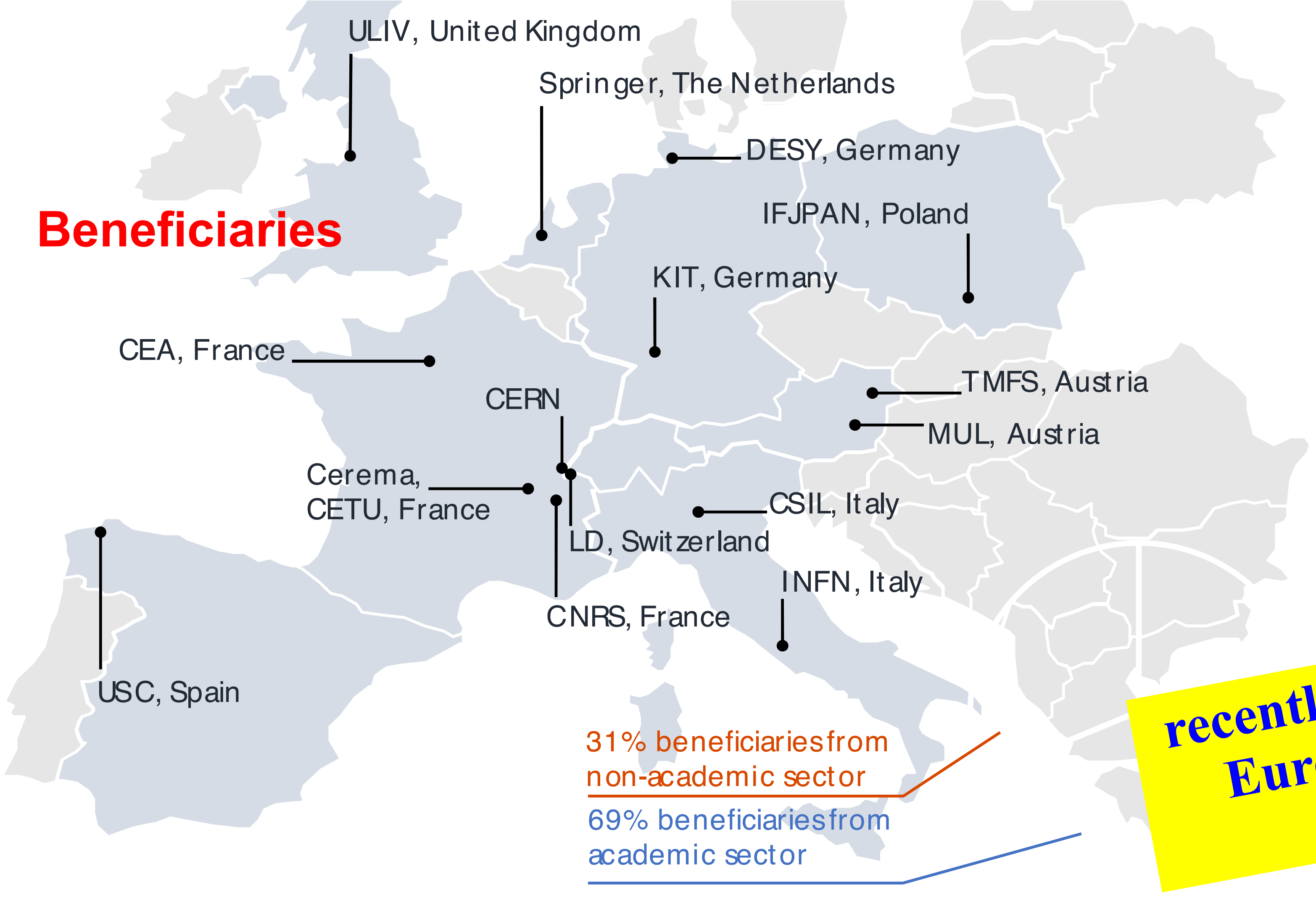
- **FCC-Conceptual Design Reports:**
  - **Vol 1 Physics, Vol 2 FCC-ee, Vol 3 FCC-hh, Vol 4 HE-LHC**
  - CDRs published in **European Physical Journal C (Vol 1) and ST (Vol 2 – 4)**

    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/

H2020 DS FCC Innovation Study 2020-24



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

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

Preparatory 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.
- **Ongoing: common optimization of collider tunnel and surface site infrastructure implementation.**

Summary

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

- **all 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, 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**
- 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