Future Circular Collider e^+e^- overview

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Thanks to Michael Benedikt (CERN), Anke-Susanne Müller (KIT), Frank Zimmermann (CERN)

2020 International Workshop on the High Energy Circular Electron Positron Collider
Shanghai, October 26-28, 2020

on behalf of the FCC collaboration

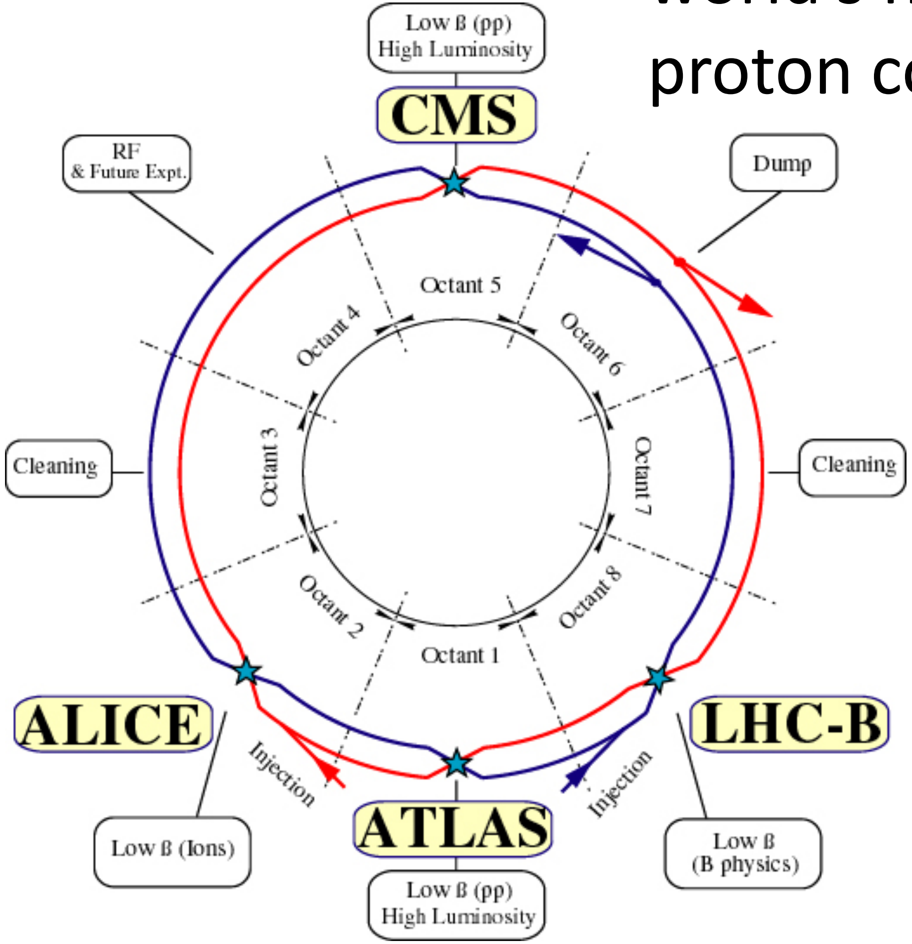
http://cern.ch/fcc

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*

photo: J. Wenninger

Large Hadron Collider (LHC) – present flagship

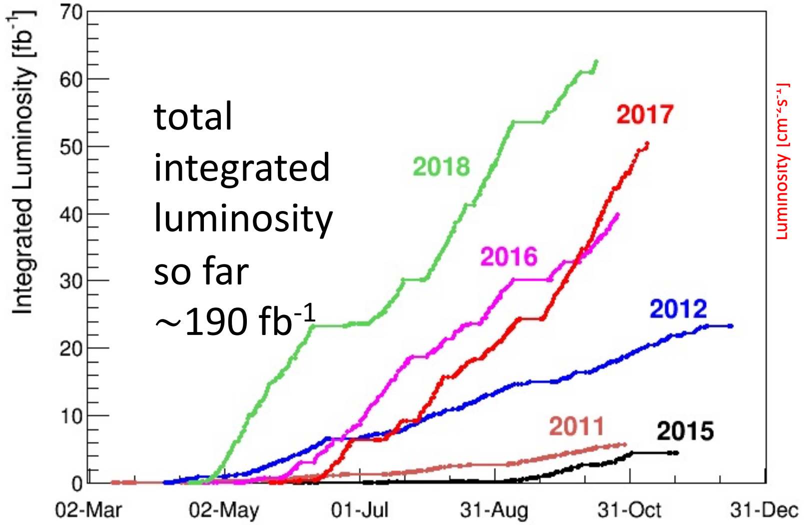
circumference 27 km



world's highest energy proton-proton collider at CERN/Geneva

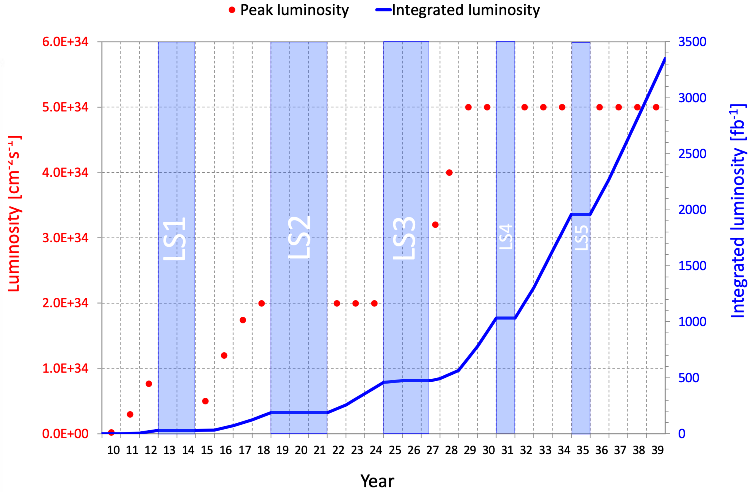
running extremely well

peak luminosities up to **~2.2x10^{34} cm^{-2}s^{-1}**, levelled to 1.5x10^{34} cm^{-2}s^{-1}



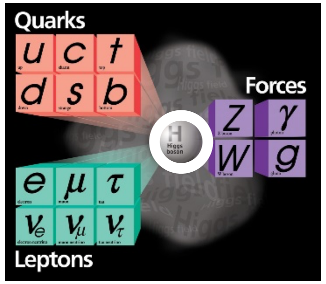
Followed by HL-LHC

levelled luminosities up to **~7.5x10^{34} cm^{-2}s^{-1}** , with ultimate integrated luminosity up to ~ **4000 fb^{-1}**

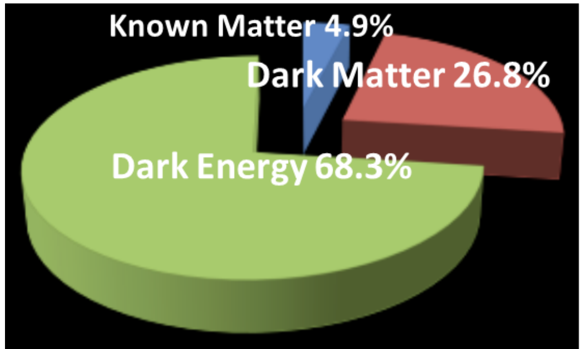


succeeded Large Electron-Positron Collider (LEP), operated 1989-2000, in the same tunnel; ALEPH, DELPHI, L3, OPAL exp.'s: no. ν families, mass of *t* & *H*

discovery of the Higgs boson at LHC has completed the Standard Model of Particle Physics



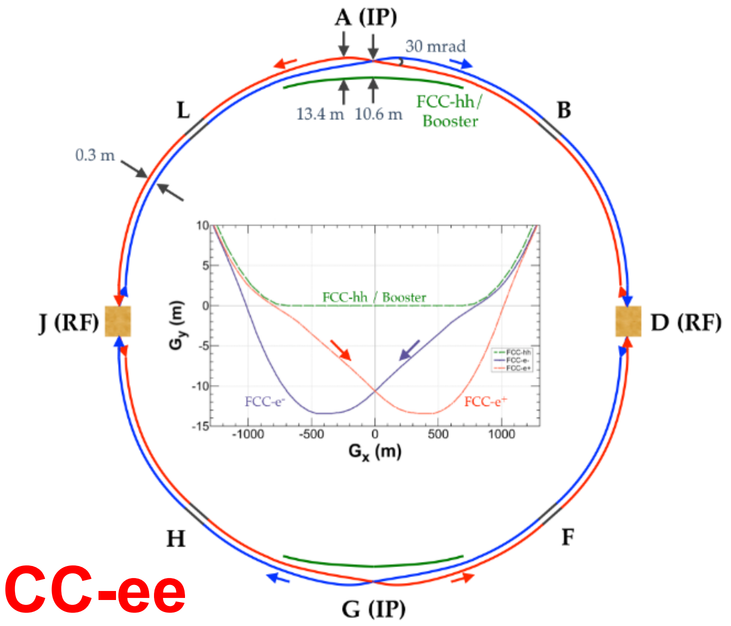
but still many open questions



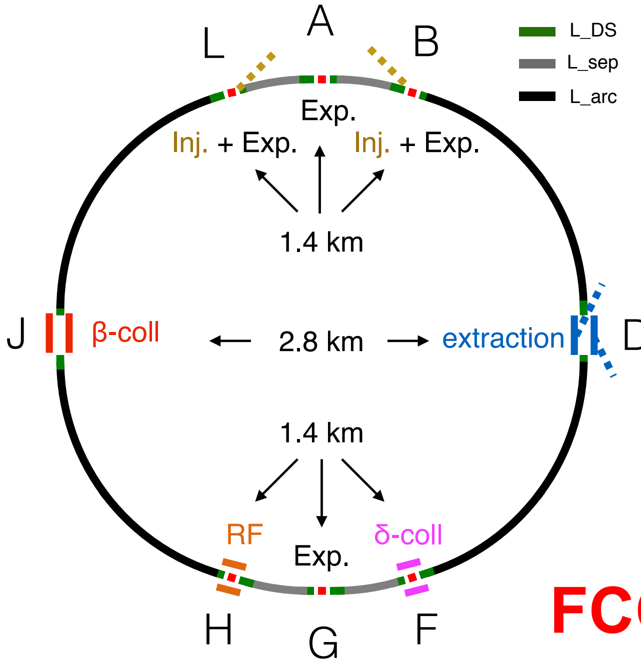
Succeeding the HL-LHC?: The FCC integrated program inspired by successful LEP – LHC programs at CERN

Comprehensive cost-effective program maximizing physics opportunities

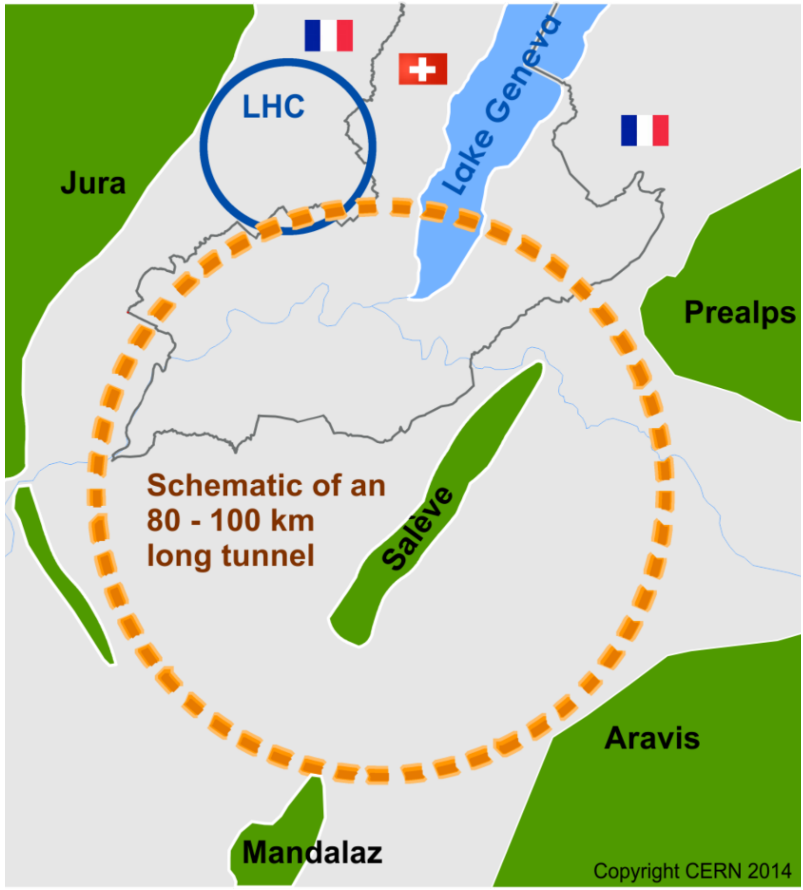
- **Stage 1: FCC-ee (Z, W, H, $t\bar{t}$) as Higgs factory, electroweak & top factory at highest luminosities**
- **Stage 2: FCC-hh (~100 TeV) as natural continuation at energy frontier, with ion and eh options**
- Complementary physics
- Common civil engineering and technical infrastructures
- Building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



FCC-ee



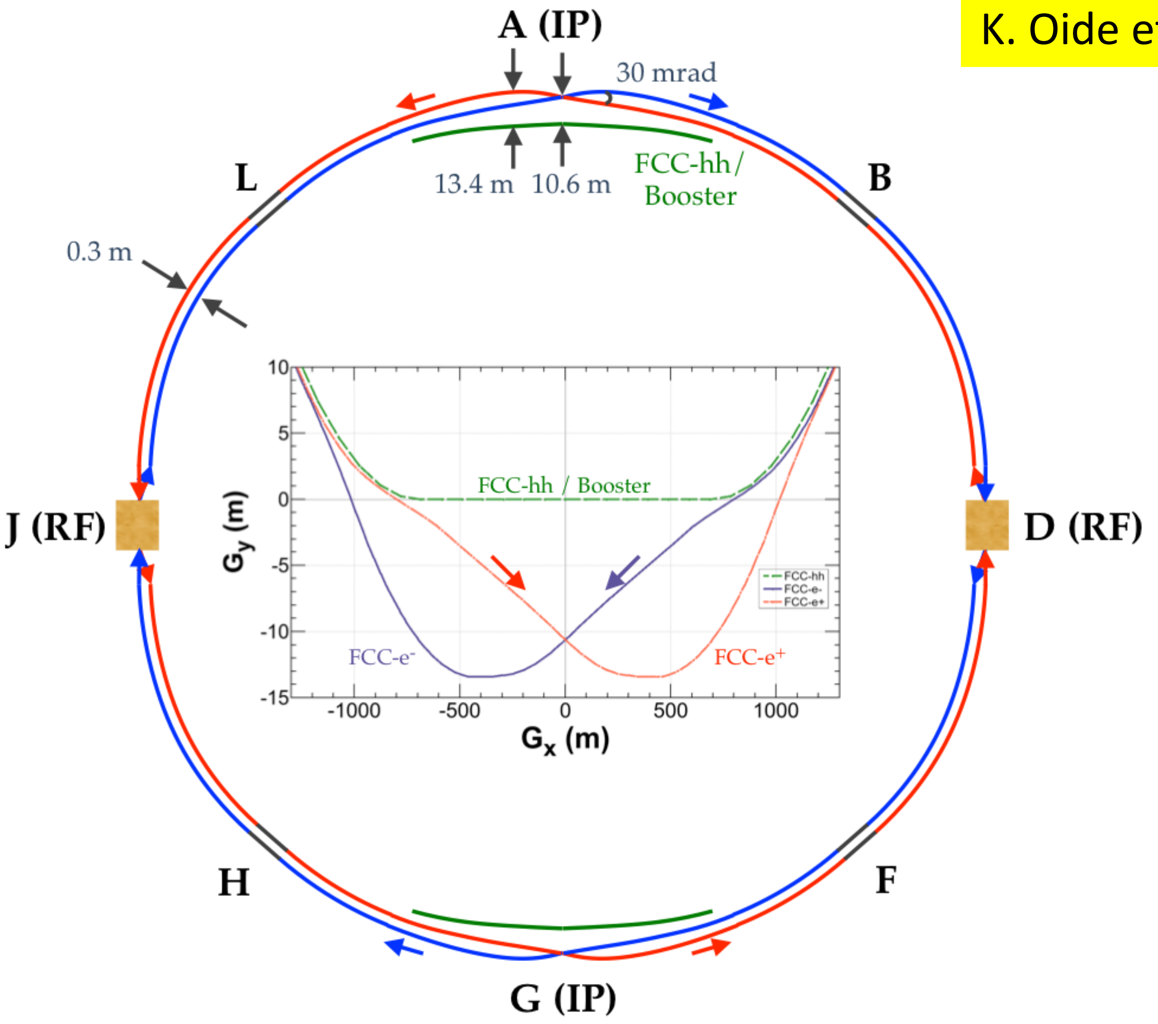
FCC-hh



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.

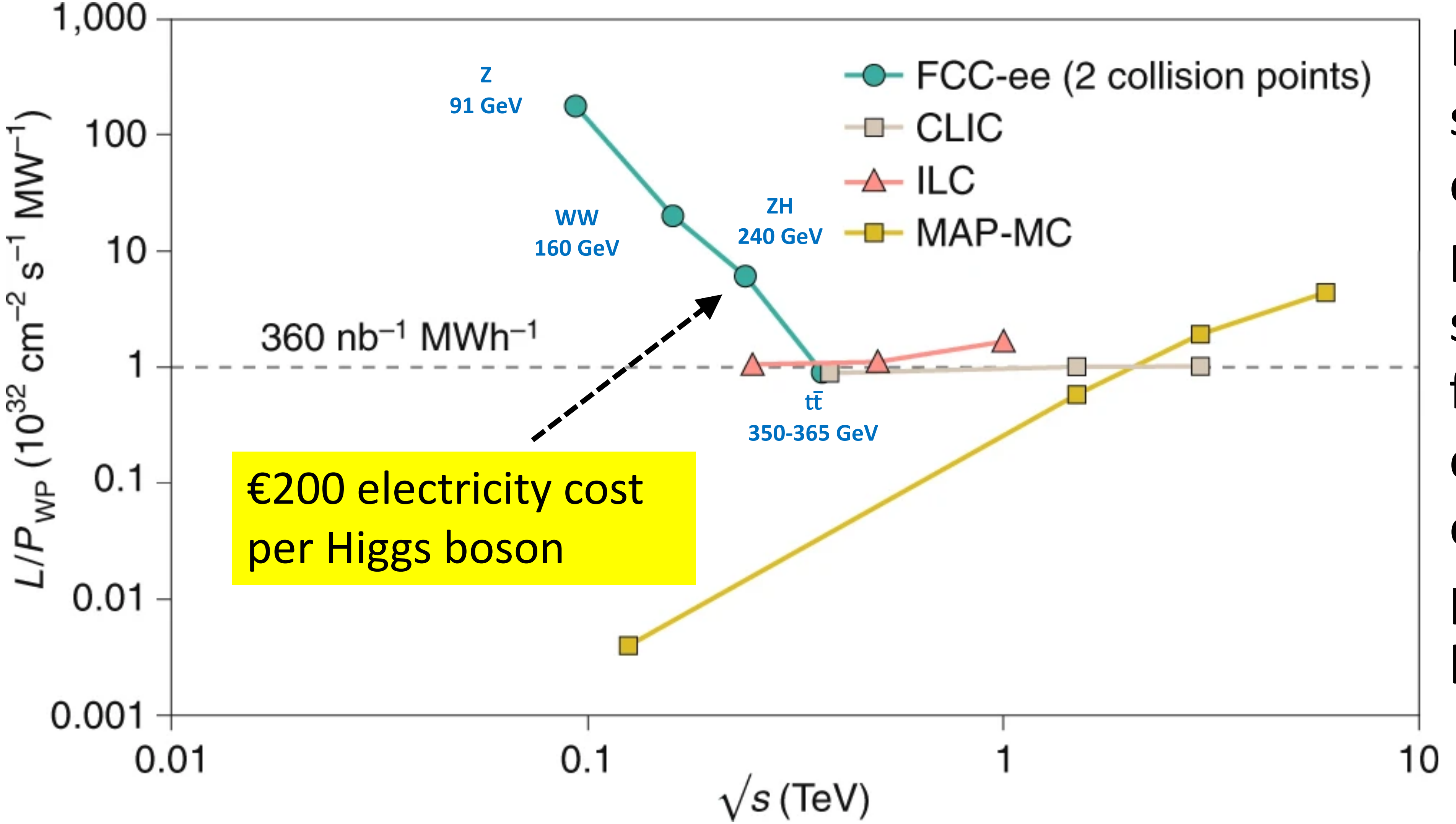


FCC-ee: The Lepton Collider, **Eur. Phys. J. Spec. Top. 228**, 261–623 (2019)
K. Oide et al., **Phys. Rev. Accel. Beams 19**, 111005 (2016)

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

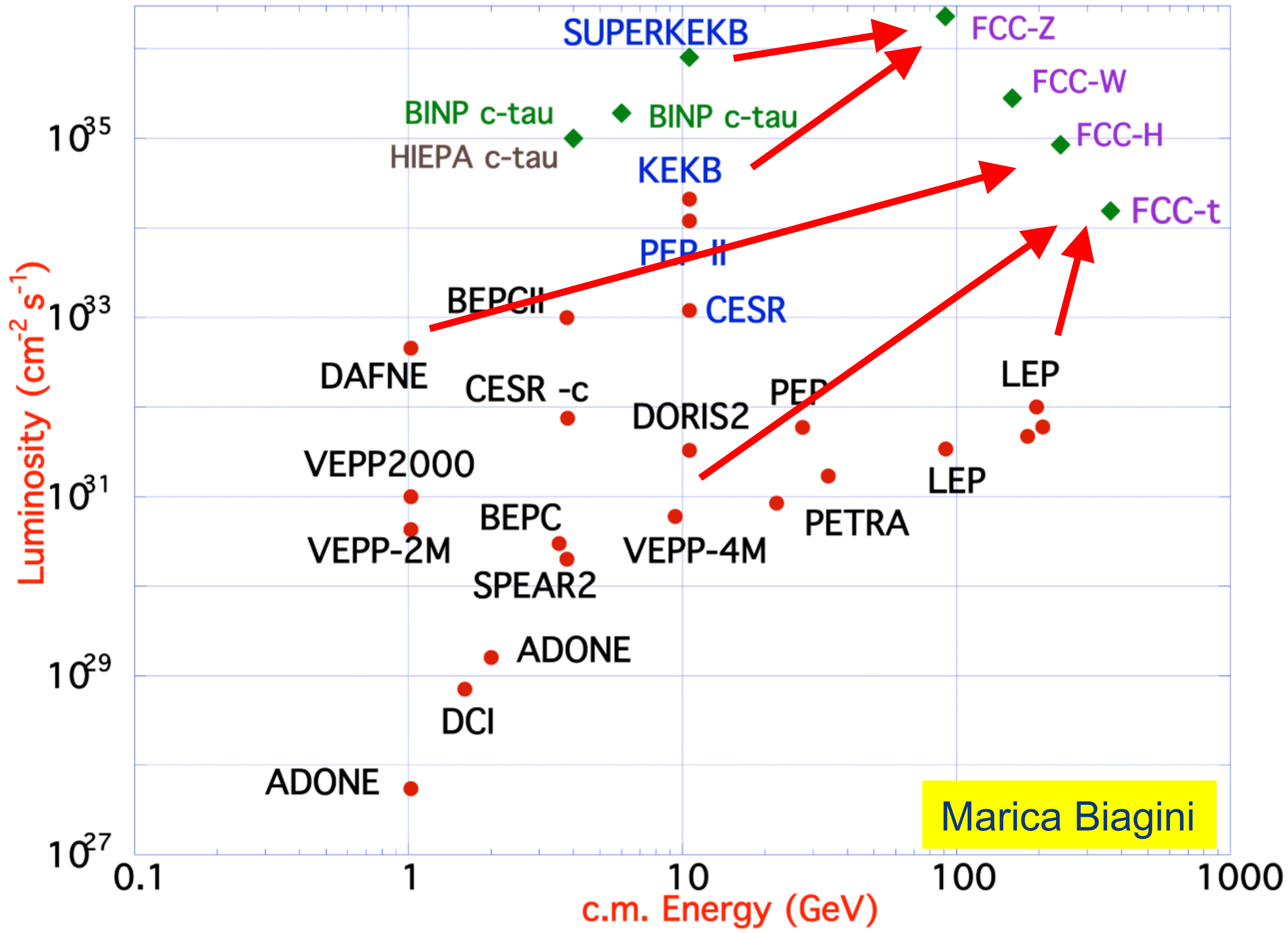


Luminosity L per supplied electrical wall-plug power P_{WP} is shown as a function of centre-of-mass energy for several proposed future lepton colliders.

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

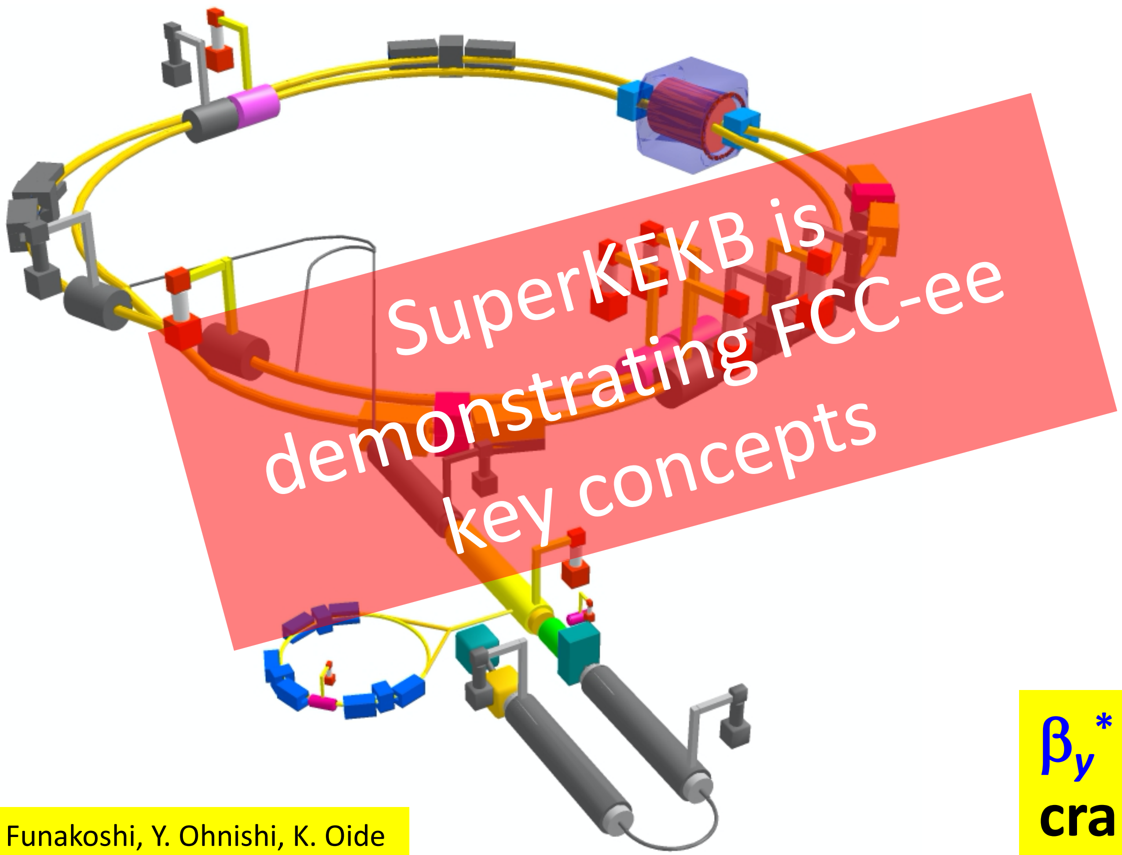
KEKB: *e^+* source

HERA, LEP, RHIC: spin gymnastics

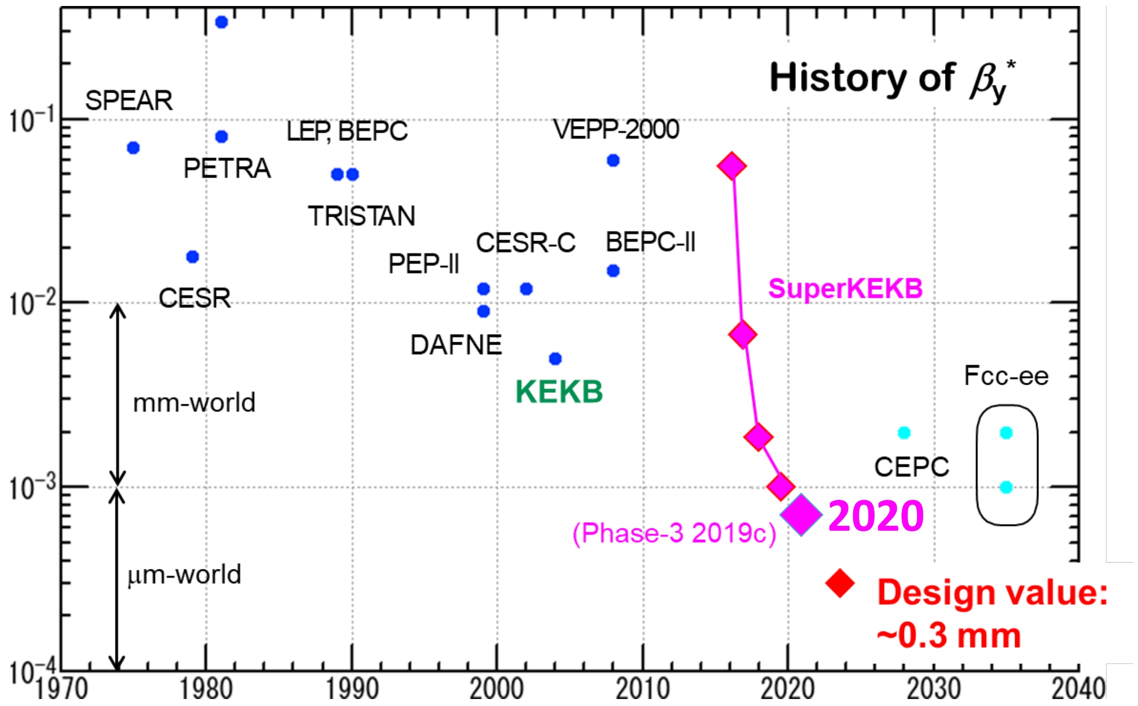
combining successful ingredients of several recent colliders → highest luminosities & energies

SuperKEKB – pushing luminosity and β*

<u>Design</u>: **double ring e⁺e⁻ collider as *B*-factory** at 7(e⁻) & 4(e⁺) GeV; **design luminosity ~8 x 10^{35} $cm^{-2}s^{-1}$; $\beta_y^* \sim 0.3$ 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**

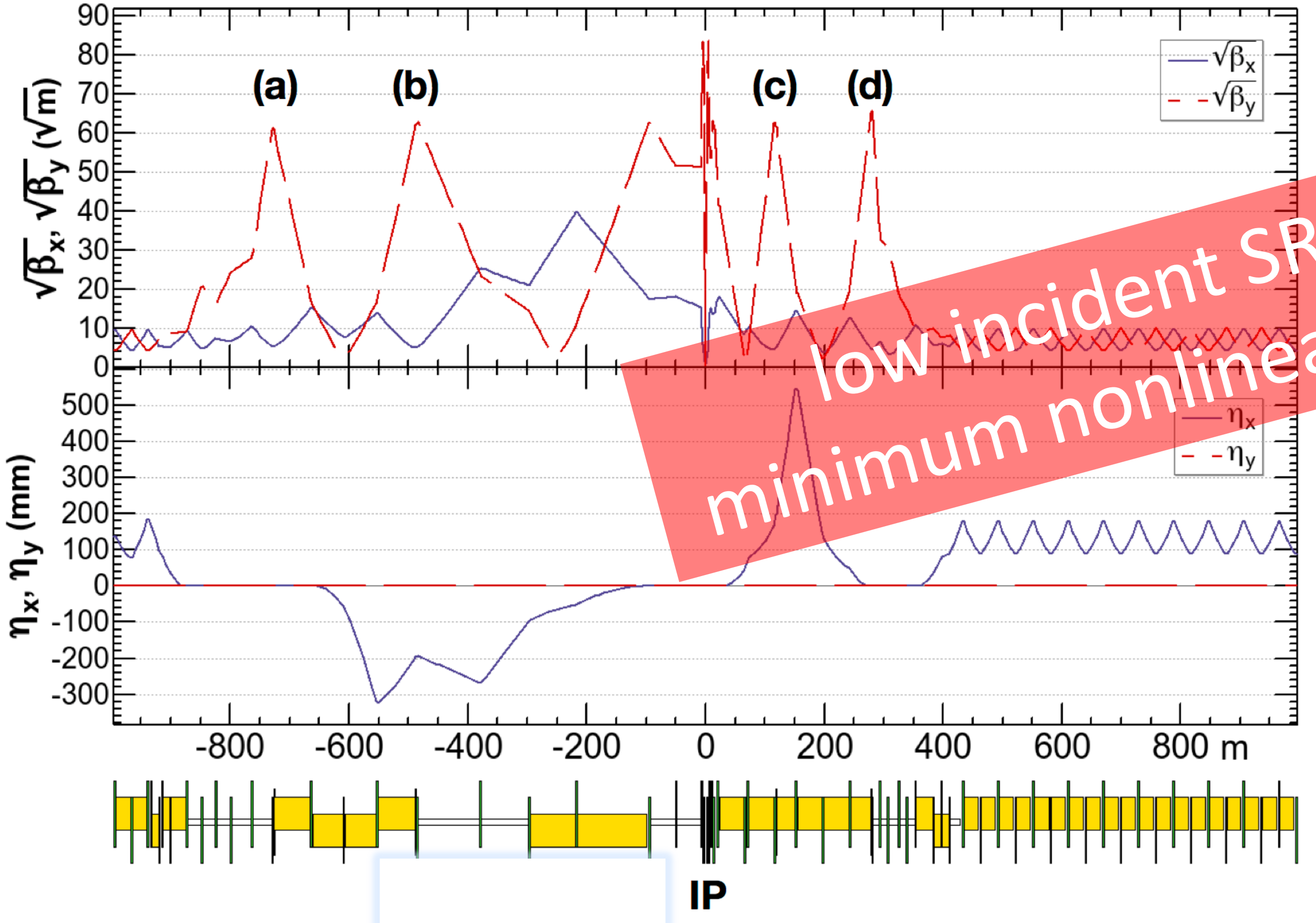


Y. Funakoshi, Y. Ohnishi, K. Oide



β_y^* = 0.8 mm achieved in both rings - world record
crab-waist collisions implemented recently

FCC-ee asymmetric crab-waist IR optics



yellow boxes: dipole magnets

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

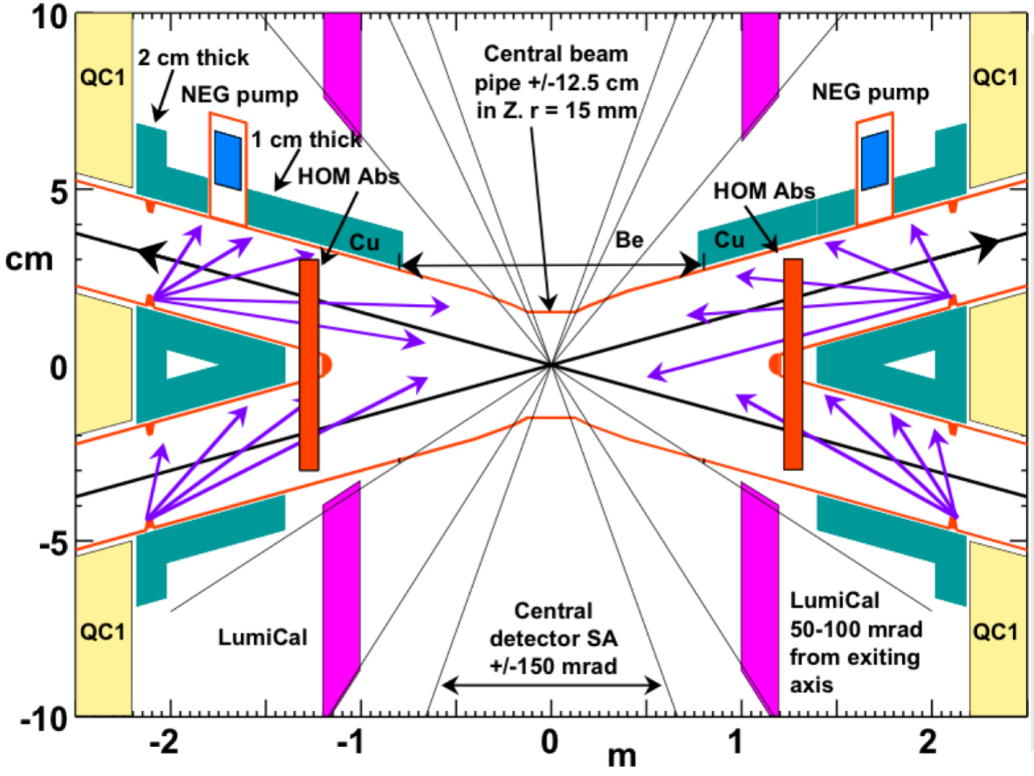
H. Burkhardt, A. Blondel, M. Koratzinos, K. Oide, et al.

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

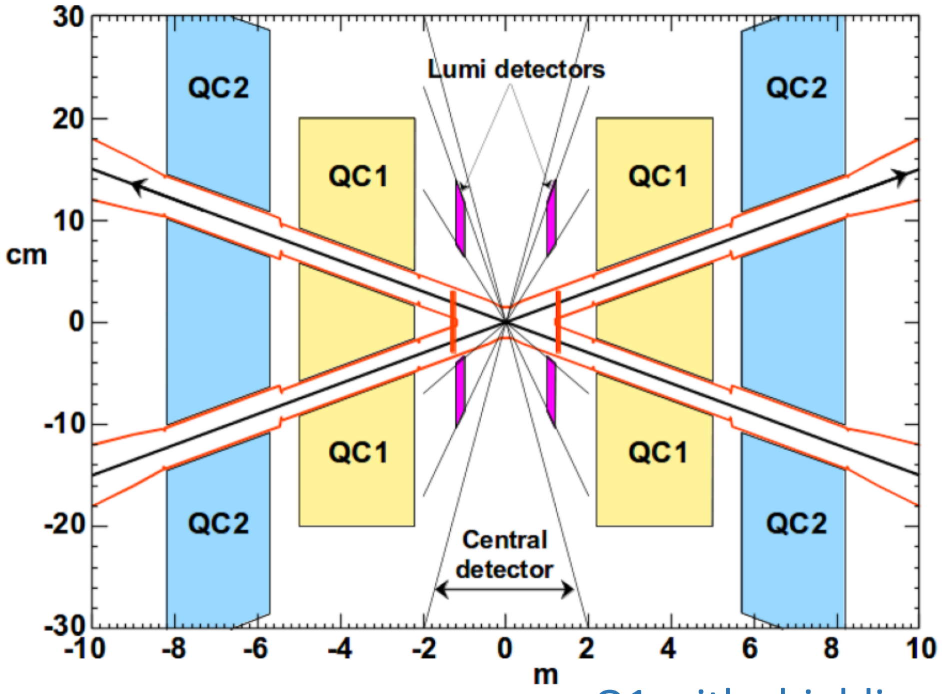
4 sextupoles (a–d) for local vertical chromaticity correction combined w. crab waist, optimized for each working point – **novel "virtual crab waist"**, **standard crab waist demonstrated at DAFNE**

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

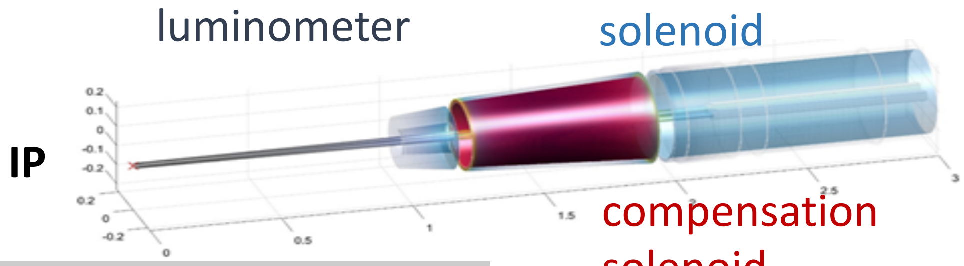
FCC-ee Interaction Region Design



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



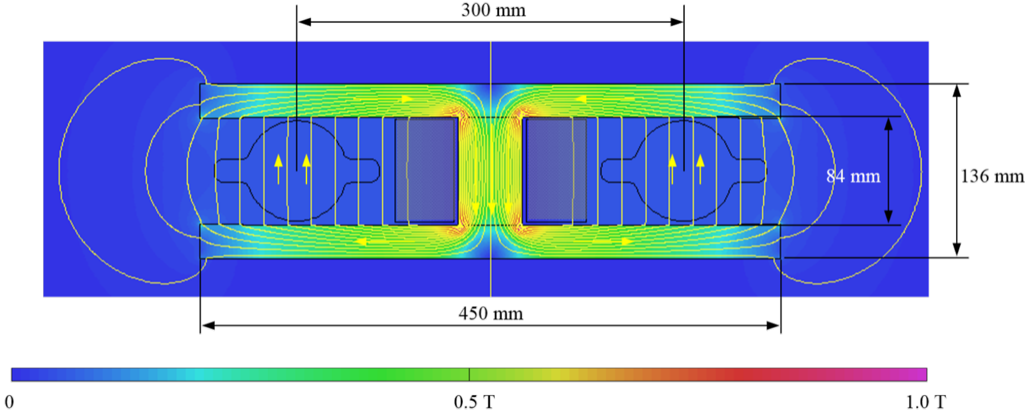
stiff-skeleton cryostats?

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.

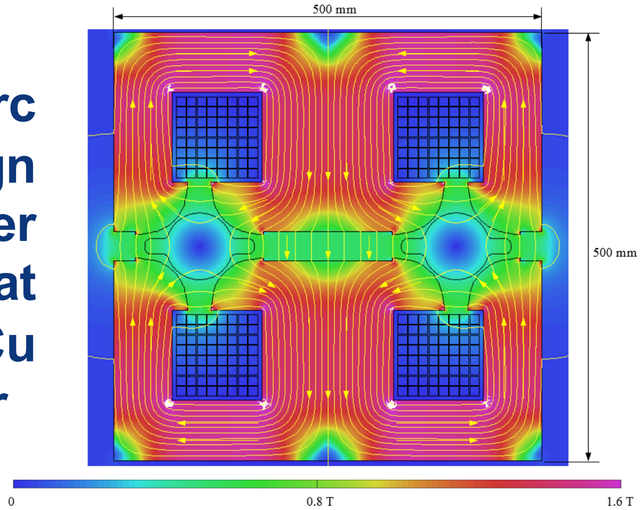
M. Boscolo, H. Burkhardt, and M. Sullivan, **Phys. Rev. Accel. Beams 20**, 011008 (2017)
A. Novokhatski, M. Sullivan, E. Belli, M. Gil Costa, and R. Kersevan, **Phys. Rev. Accel. Beams 20**, 111005 (2017)

FCC-ee low-cost, energy-efficient arc magnets

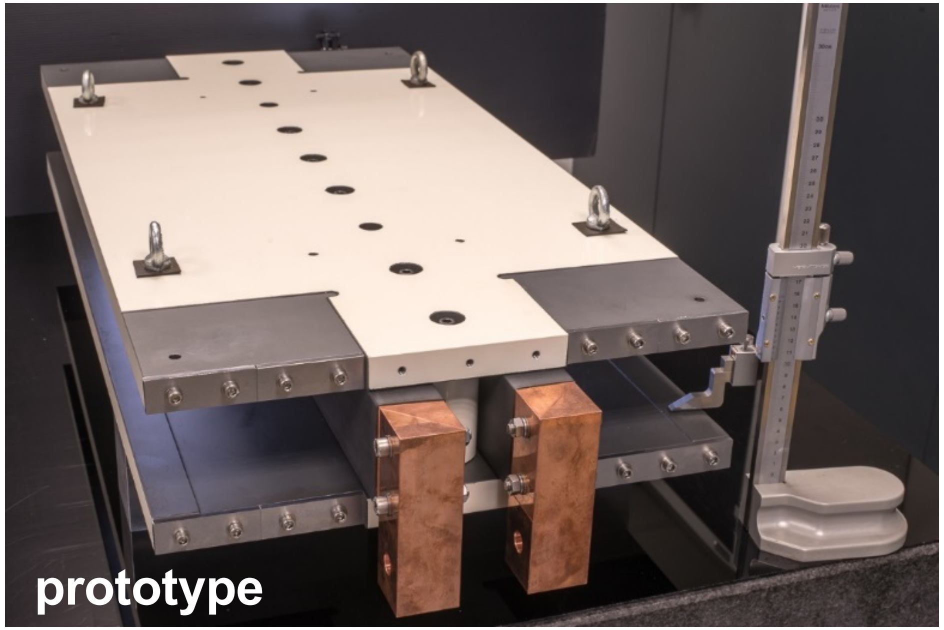
twin-dipole magnet design with 2× power saving 16 MW (at 175 GeV), with Al busbars



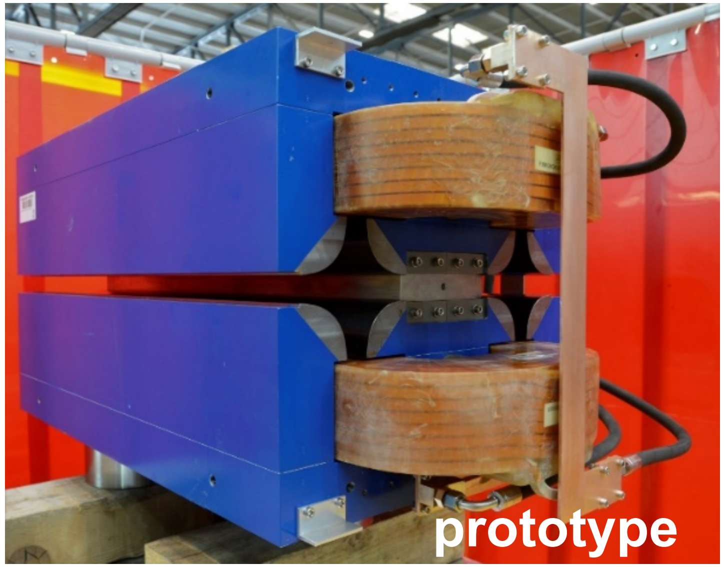
twin F/D arc quadrupole design with 2× power saving; 25 MW (at 175 GeV), with Cu conductor



2900 units, 0.057 T, ~22 m



2900 units, 10 T/m, 3.1 m

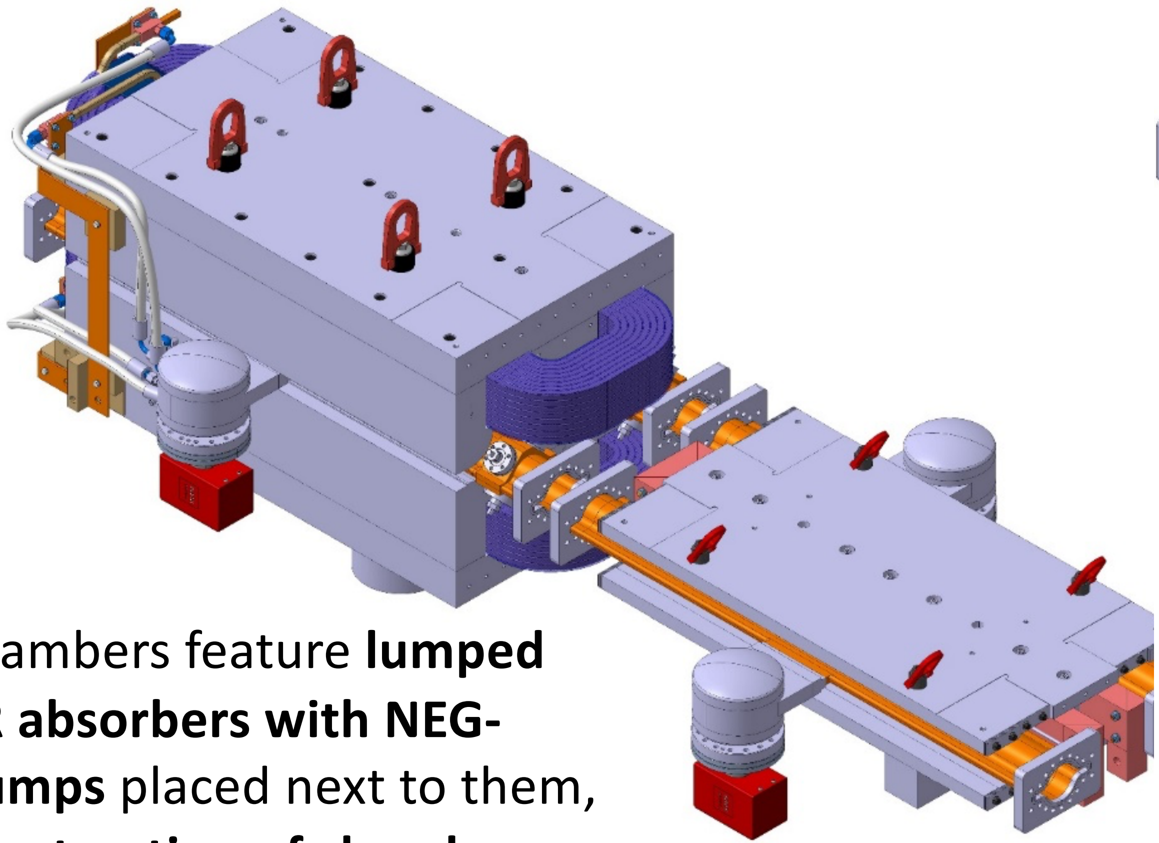


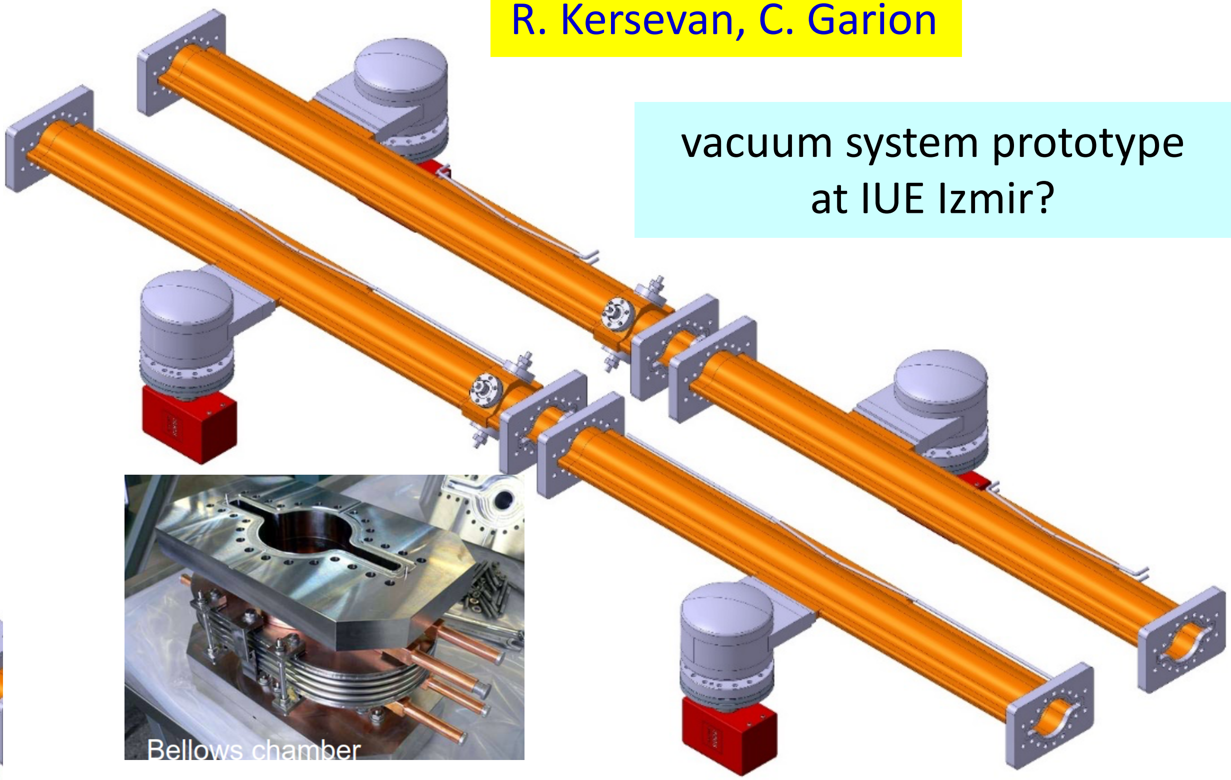
A. Milanese, *Efficient twin aperture magnets for the future circular e+/e- collider*, **Phys. Rev. Accel. Beams 19**, 112401 (2016)

FCC-ee arc vacuum chambers and integration

R. Kersevan, C. Garion

vacuum system prototype at IUE Izmir?



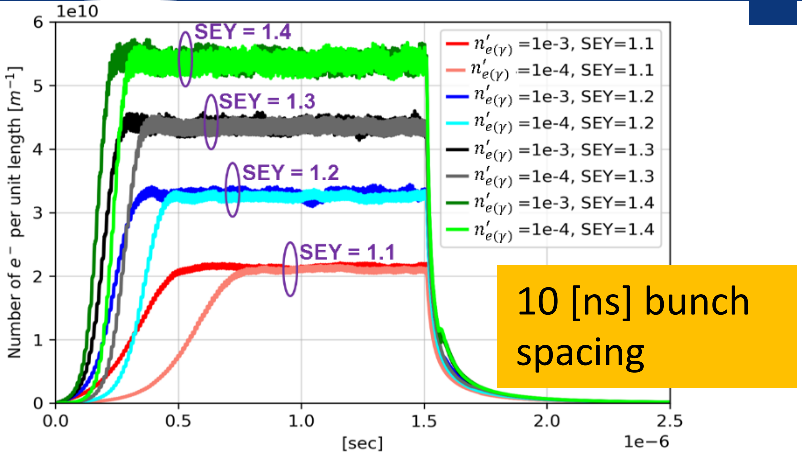


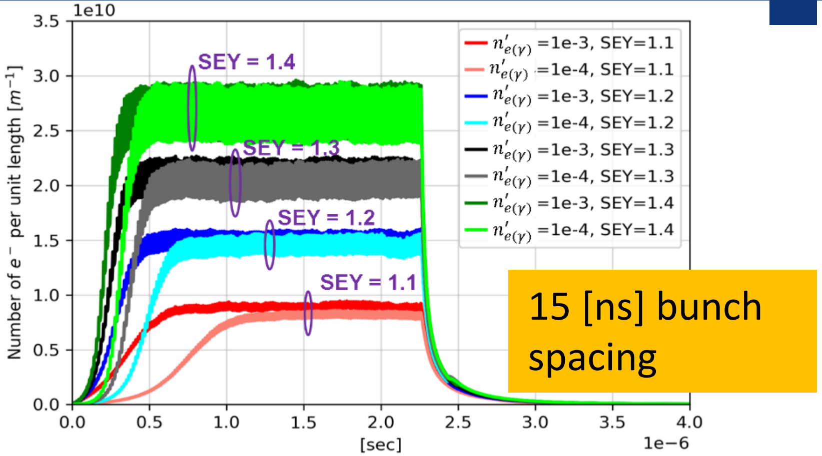
chambers feature **lumped SR absorbers with NEG-pumps** placed next to them, **construction of chamber prototypes and integration with twin magnets**

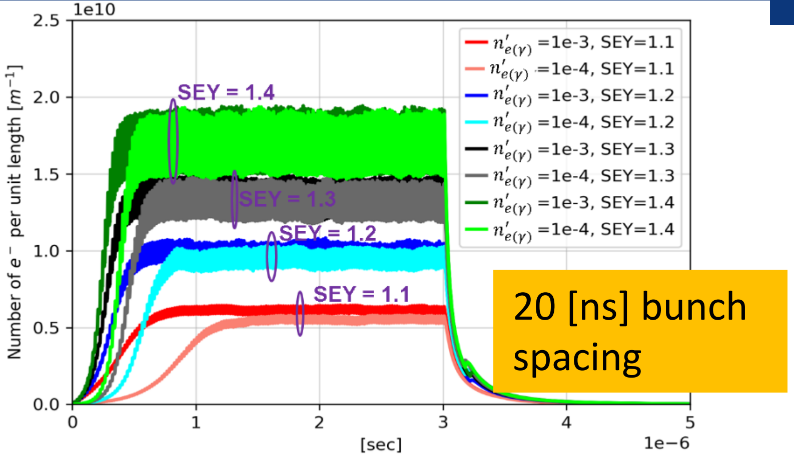
vacuum chamber cross section: 70 mm ID with ”winglets” in the plane of the orbit (SuperKEKB-like)

FCC R&D: e-cloud mitigation

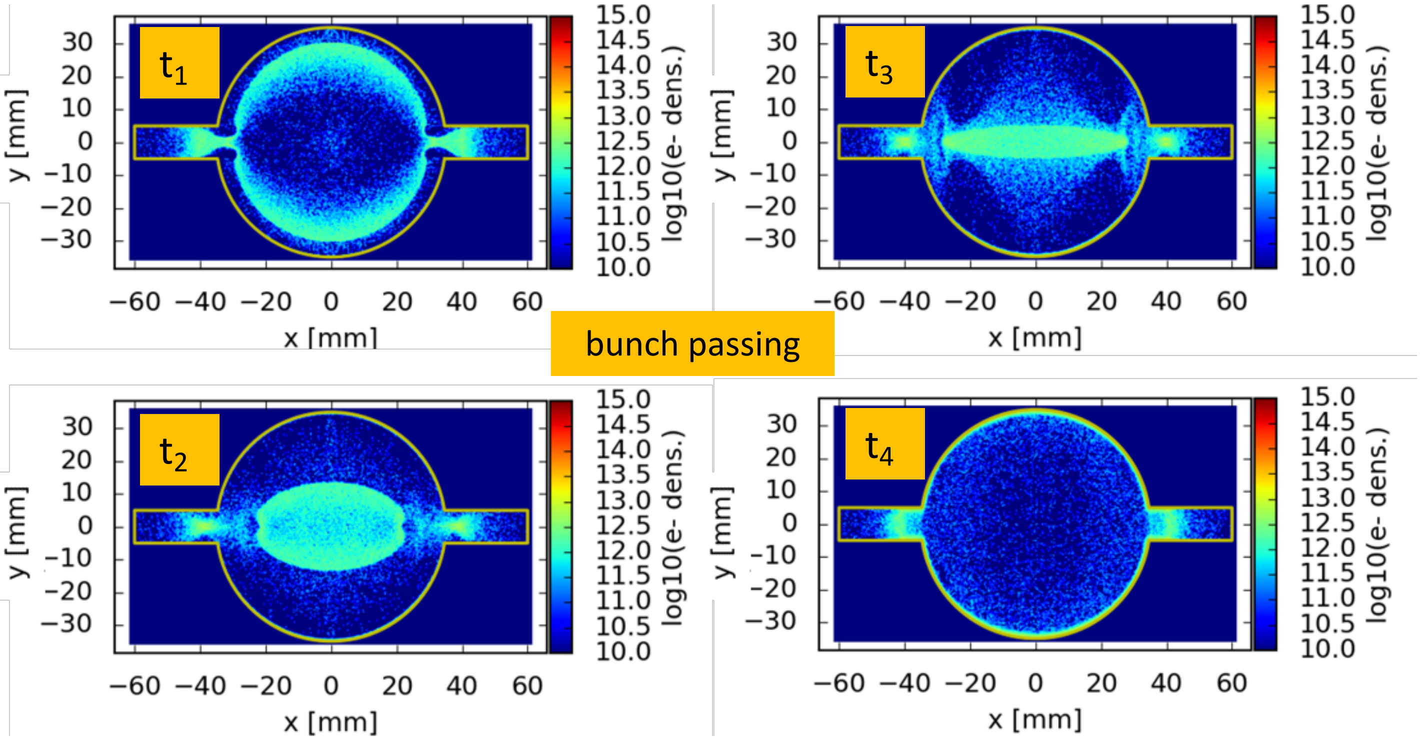
circular beam pipe results







ECloud distribution for circular beam pipe with winglets



precision electron-cloud simulations with realistic models, to identify target beam & surface parameters

F. Yaman, IYTE, Izmir

Fatih Yaman, 'Electron-Cloud Simulations for the FCC-ee Collider Arcs and for the e+ Damping Ring' 121st FCC-ee Optics Design Meeting, July, 2020

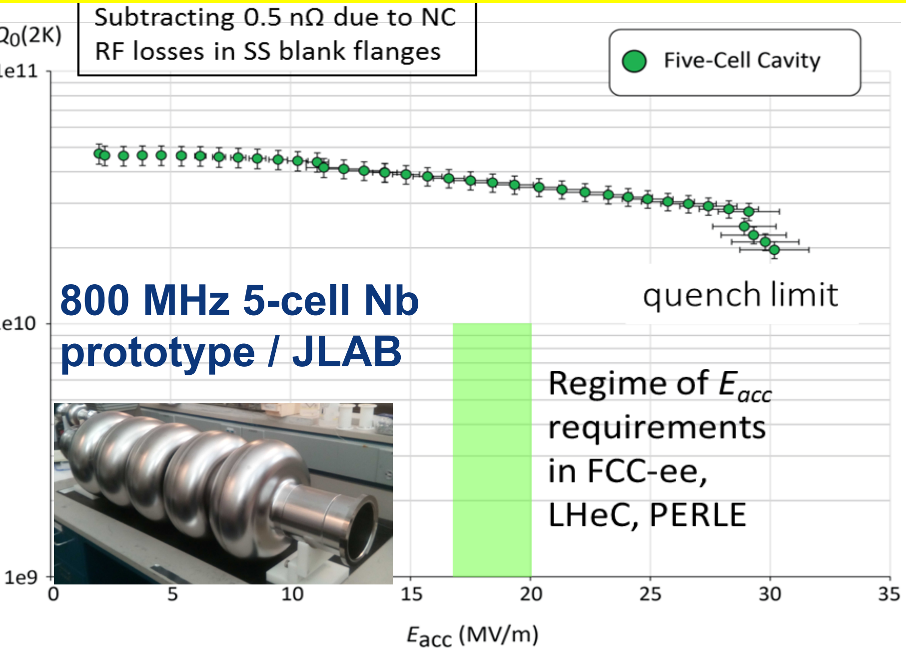
Fatih Yaman, 'Electron cloud build up in the collider: towards lower density', 123rd FCC-ee Optics Design Meeting, July, 2020

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

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

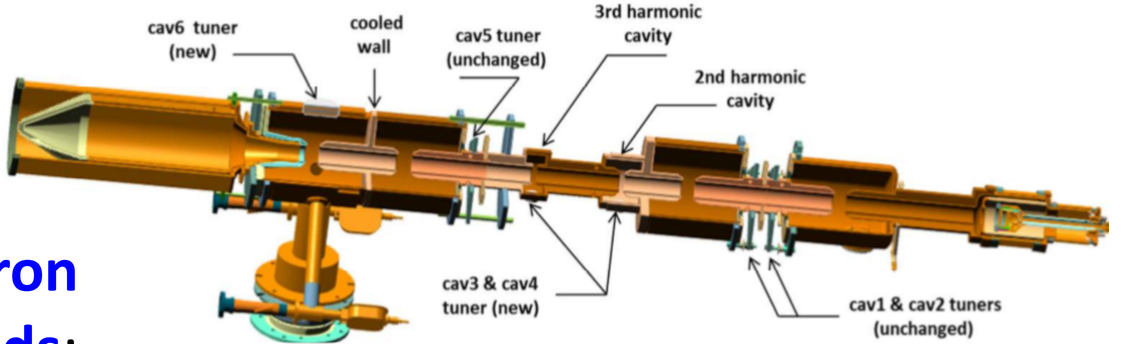
- improved Nb/Cu coating/sputtering (e.g. ECR fibre growth, HiPIMS)
- new cavity fabrication techniques (e.g. EHF, improved polishing, seamless…)
- coating of A15 superconductors (e.g. Nb_3Sn), · cryo-module design optimisation
- bulk Nb cavity R&D at FNAL, JLAB, Cornell, also KEK and CEPC/IHEP
- MW-class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

prototype FCC SRF cavities at JLAB



Jefferson Lab

high-efficiency klystron at CERN

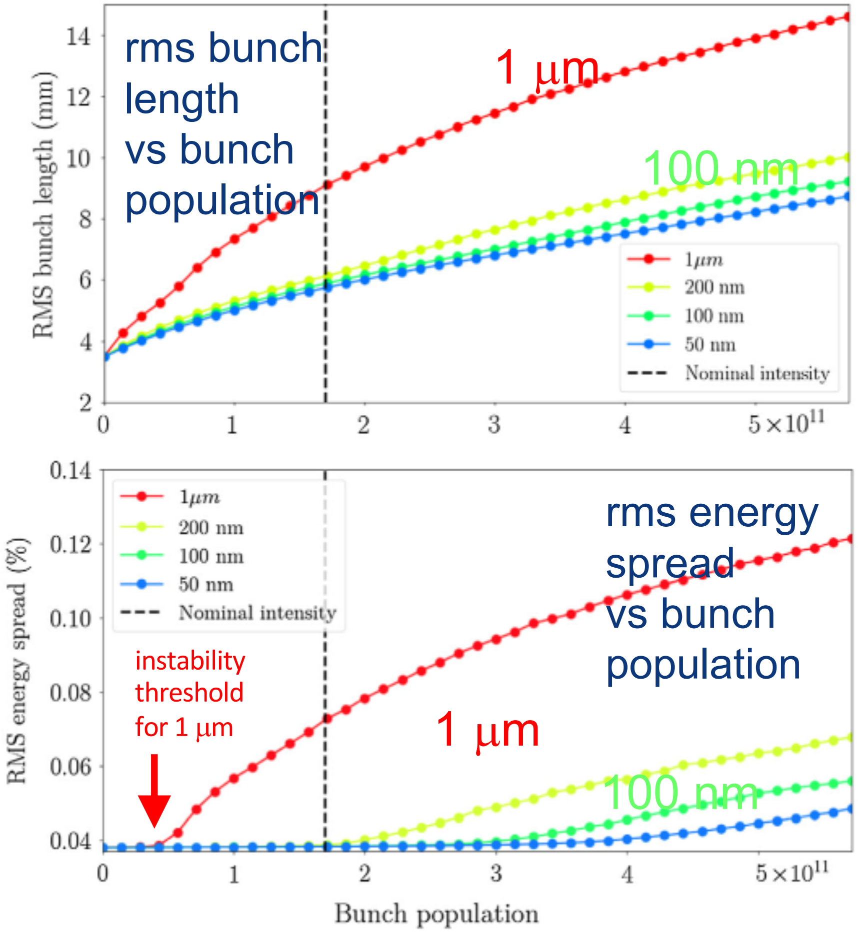


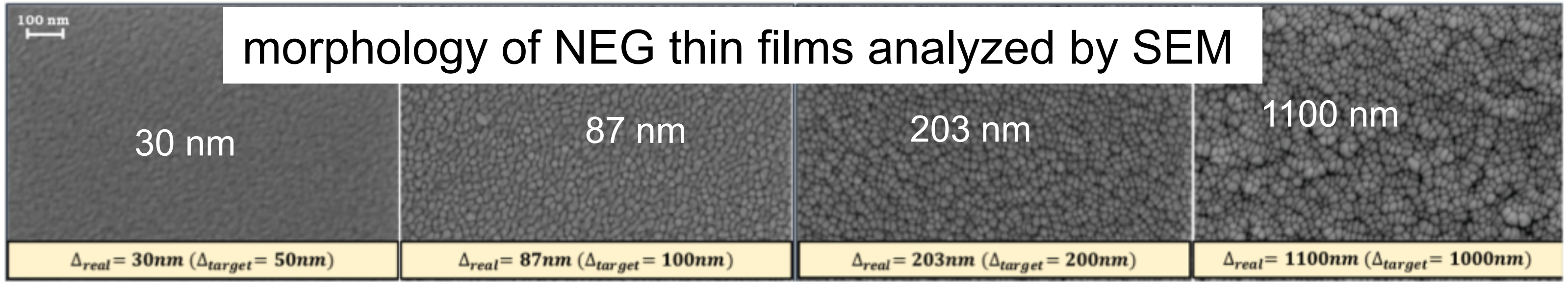
New klystron bunching methods: **LHC klystron retrofit** as proof of principle for FCC

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

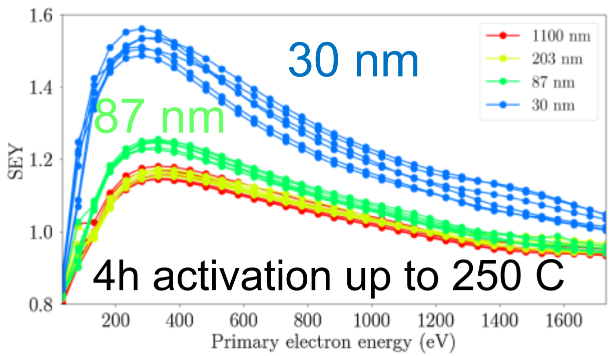
FCC-ee R&D: impedance mitigation

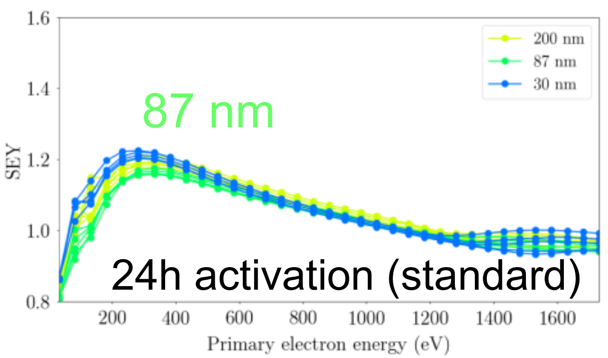
resistive wall impedance of 98 km long collider → **microwave instability** for standard 1 μm NEG coating → **development & qualification of ultrathin NEG coating** for FCC-ee (pumping, SEY, activation, impedance...)





SEY vs primary e-energy for varying NEG thickness



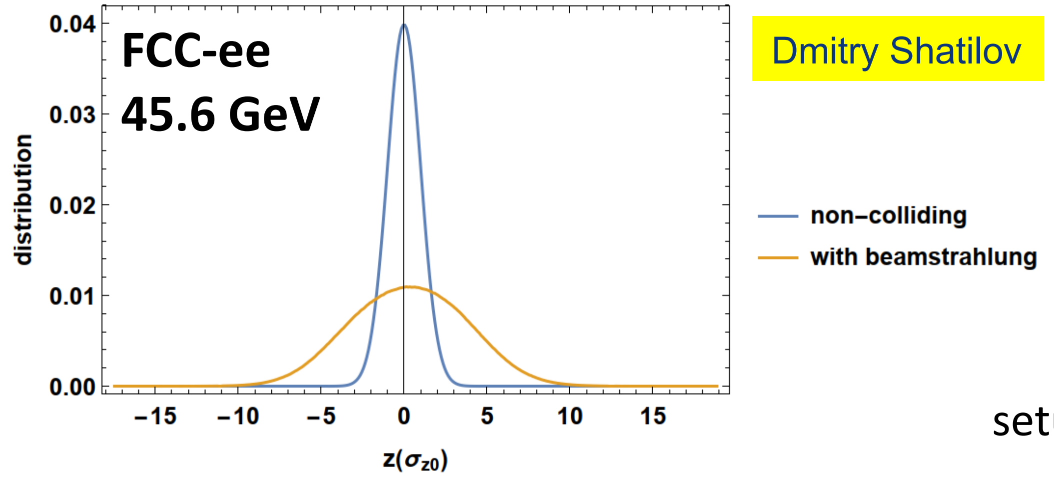


M. Migliorati, E. Belli, M. Zobov, **Phys. Rev. Accel. Beams 21**, 041001 (2018)

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

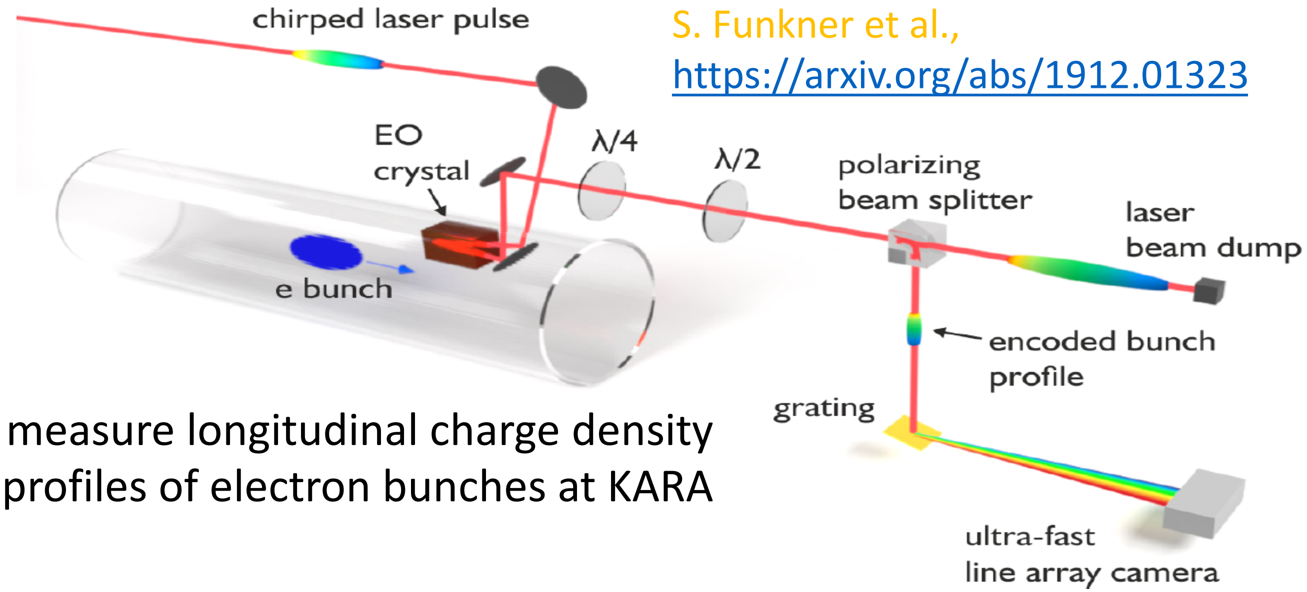
Dmitry Shatilov



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

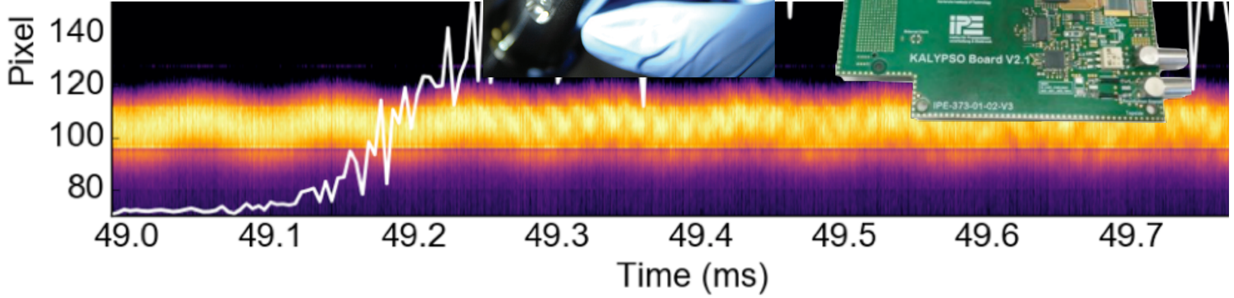
high-throughput electro-optical single-shot diagnostics developed at KIT

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



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

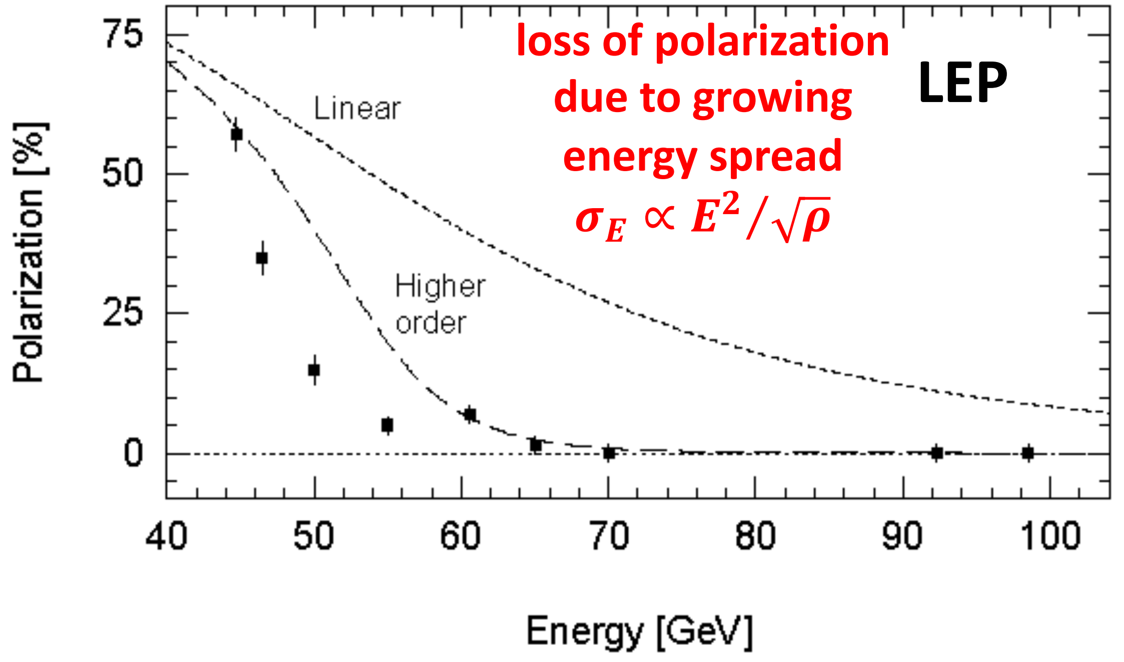
longitudinal bunch profiles recorded with the KALYPSO-based electro-optical spectral decoding setup



Karlsruhe Institute of Technology

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

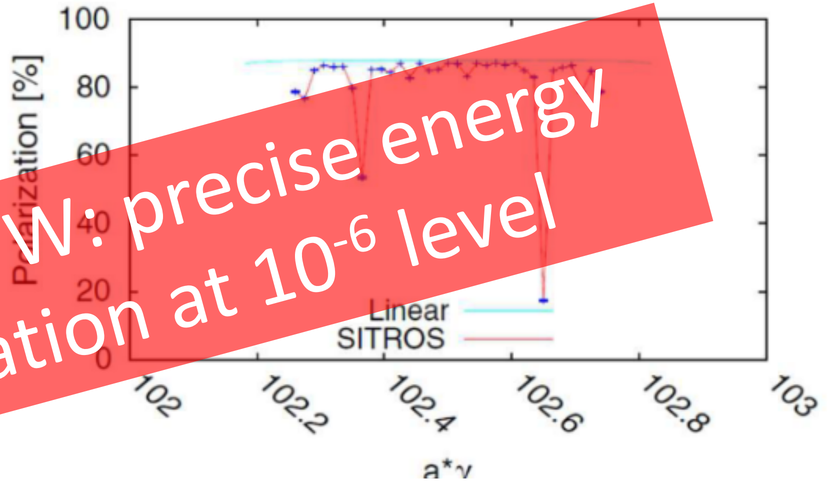


loss of polarization due to growing energy spread $\sigma_E \propto E^2/\sqrt{\rho}$

LEP

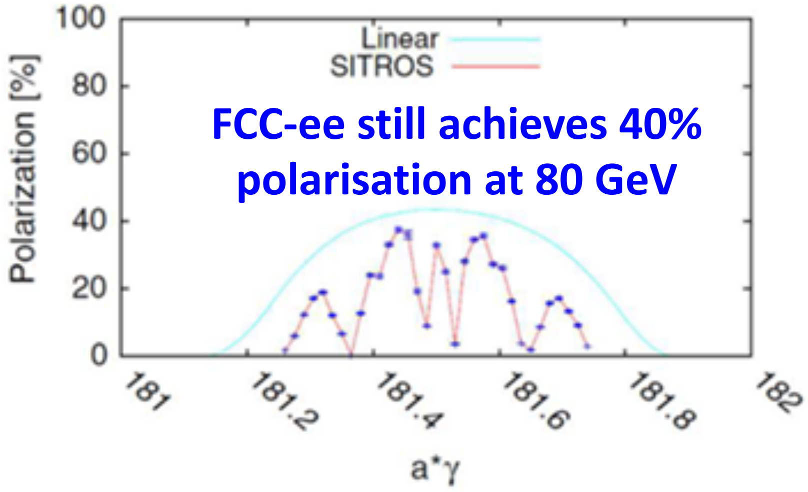
LEP had no polarisation above ~65 GeV

FCC-ee 45.6 GeV (Z)



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

FCC-ee 80 GeV (WW)



FCC-ee still achieves 40% polarisation at 80 GeV

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

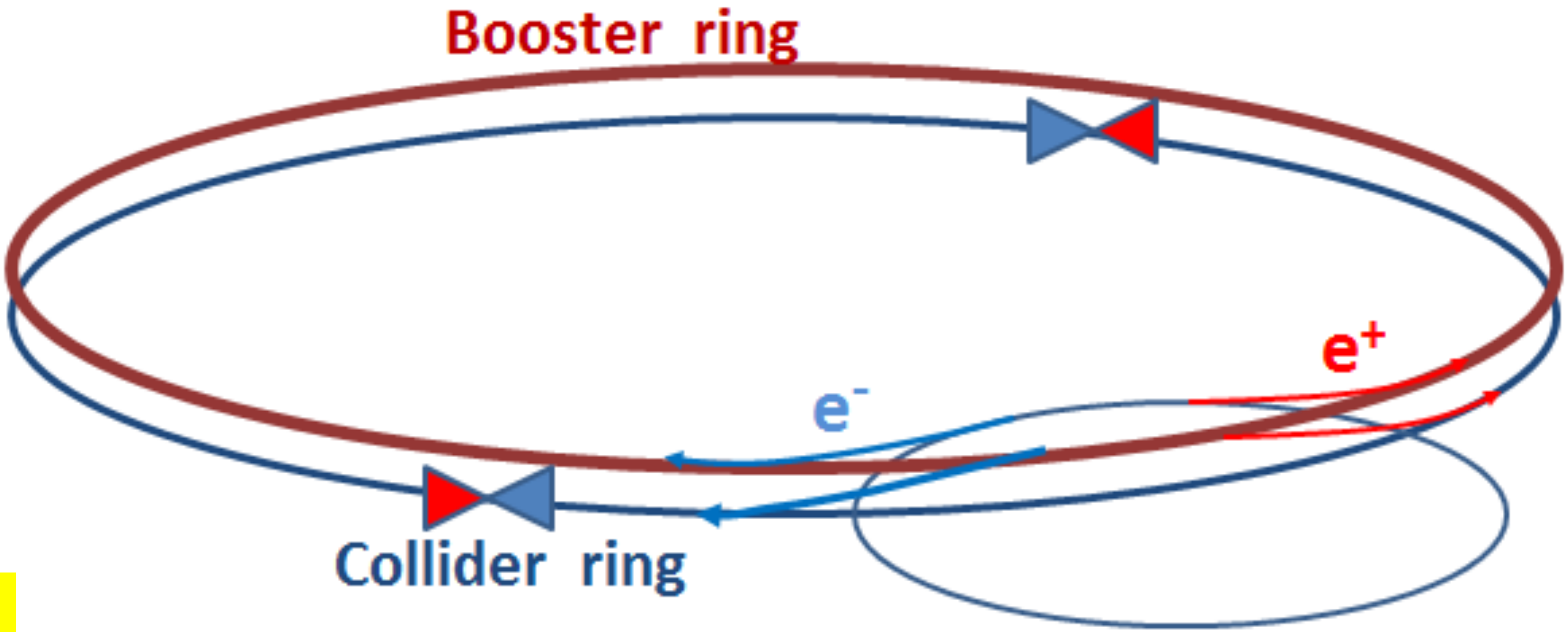
R. Assmann, M. Lamont, S. Myers,
Nucl. Phys. B, Proc. Suppl. 109 (2002) 17-31

Fermilab

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

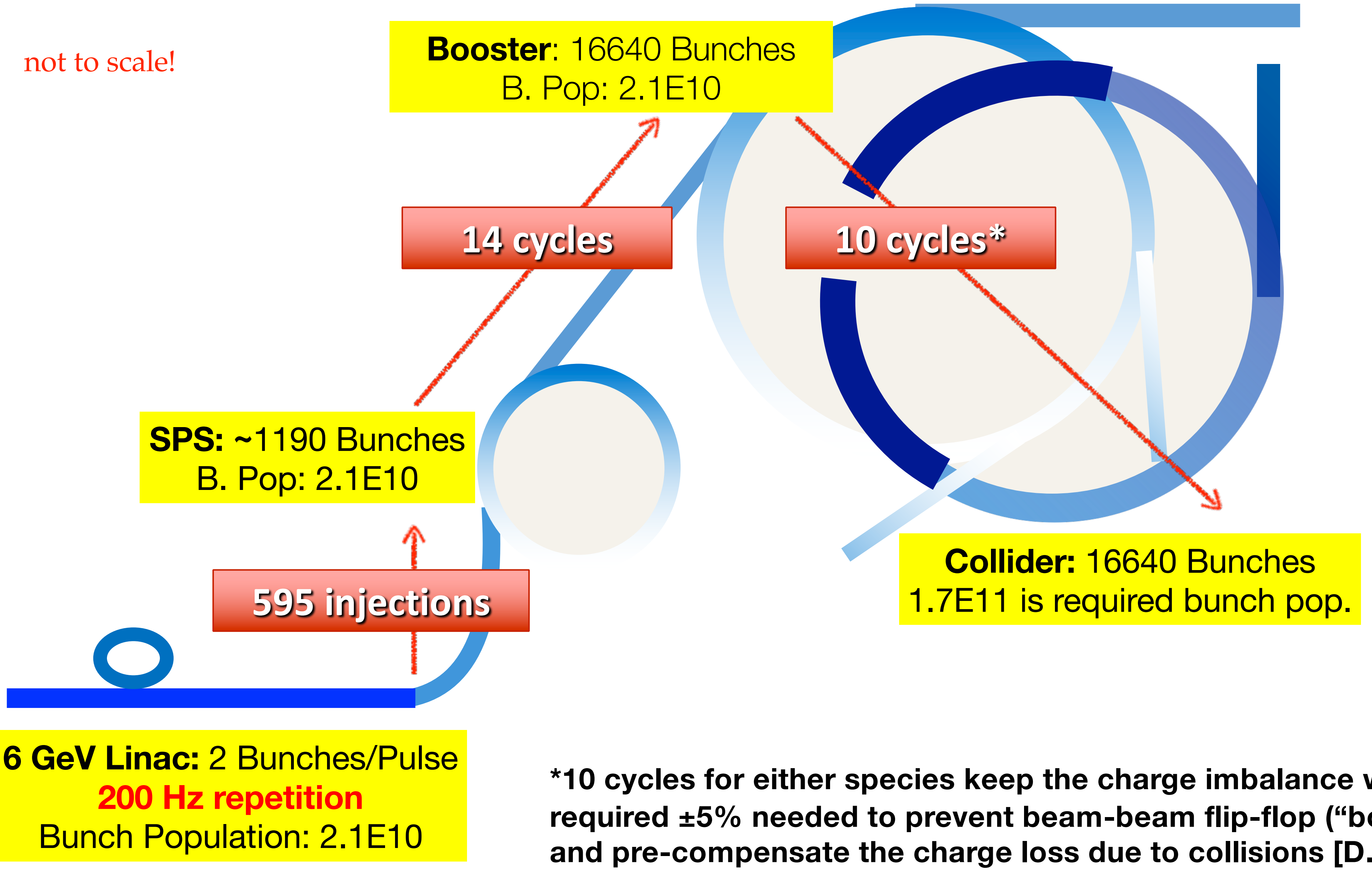
FCC-ee Top-Up Injection

due to extremely high luminosity, **beam lifetime is limited** to ≤ 20 minutes (radiative Bhabha scattering, beamstrahlung) ; maintaining constant luminosity and beam current requires quasi-continuous "**top-up injection**" (demonstrated at PEP-II, KEKB, SuperKEKB, many light sources) → **full-energy booster** (same tunnel)



A. Blondel

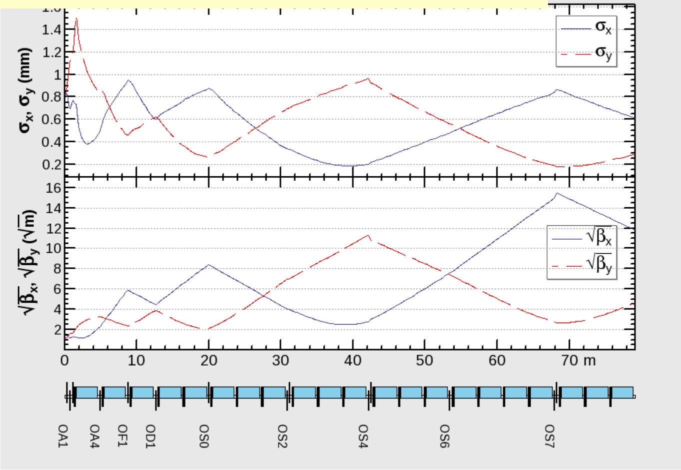
challenge: filling collider in Z mode



***10 cycles for either species keep the charge imbalance within the required ±5% needed to prevent beam-beam flip-flop ("bootstrapping") and pre-compensate the charge loss due to collisions [D. Shatilov]**

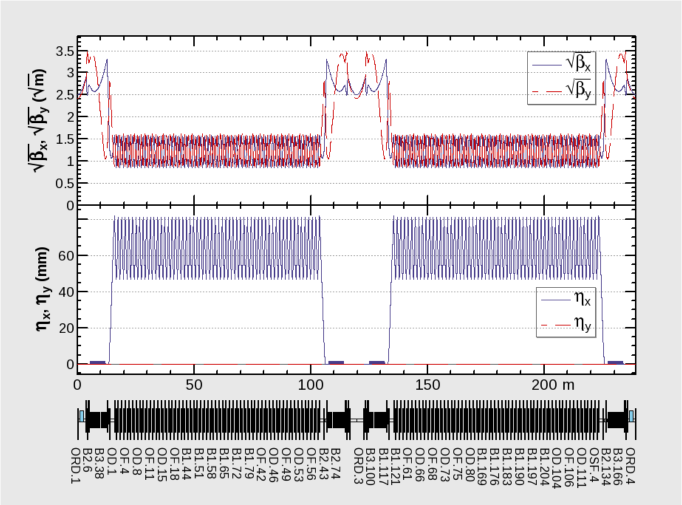
ee linac & damping ring design

S. Ogur



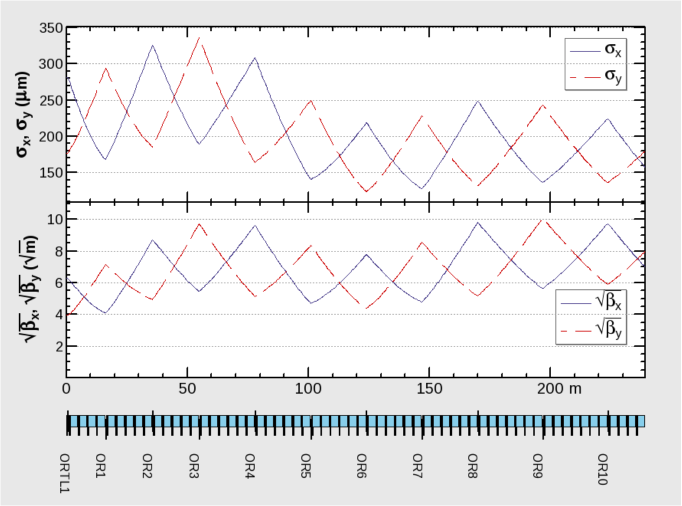
0-1.54 GeV S-band Linac

Parameter	Value
Length (m)	79.1
Transmission for 2.2E10 part.	100%
Number of Cavities	21
Number of Quadrupoles	14
Emit. with no blow	2.7/3.8 nm
Avg. Extracted Emit.	6.4/5.0 nm



1.54 GeV Damping Ring

Parameter	Value
$\tau_x/\tau_y/\tau_z$	10.5/10.9/5.5 ms
equilibrium emittance (x/y/z)	0.96 nm/- /1.46 µm
circumference	241.8 m (for 50 ns)
# of FODO cells	114
dipole field	0.66 T
no. of wigglers, field	4, 1.80 T
ring tunes	24.189/23.580



1.54-6 GeV S-band Linac

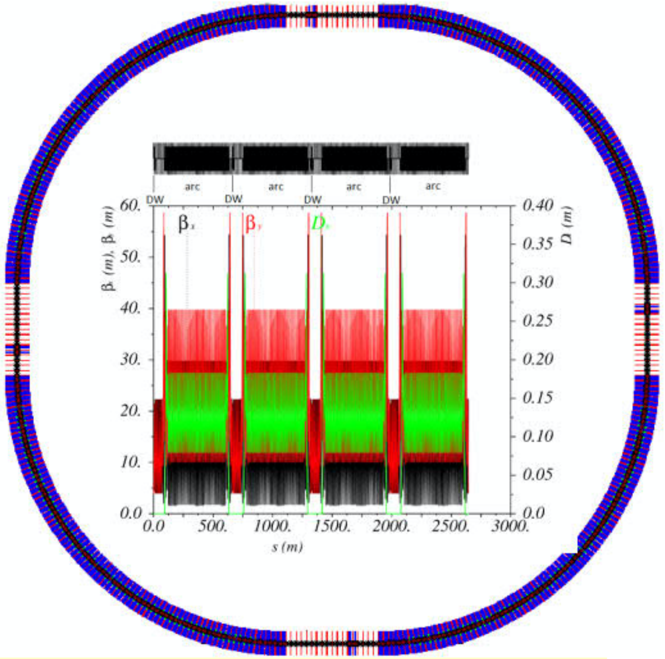
Parameter	Value
Length (m)	239.1
Transmission for 2.2E10 part.	100%
Number of Cavities	60
Number of Quadrupoles	12
Emit. with no blow	0.48/0.10 nm
Avg. Extracted Emit.	0.55/0.11 nm

FCC-ee pre-booster ring design

Two options for pre-booster synchrotron: existing SPS (baseline) or a new ring.

- **SPS** poses challenges related to machine availability, synchrotron radiation power and RF system requirements.
- A new design has been developed: the **alternative pre-booster ring**

Alternative ring



The design of the PBR composes of 4 arcs and 4 straight sections.

Straight sections:

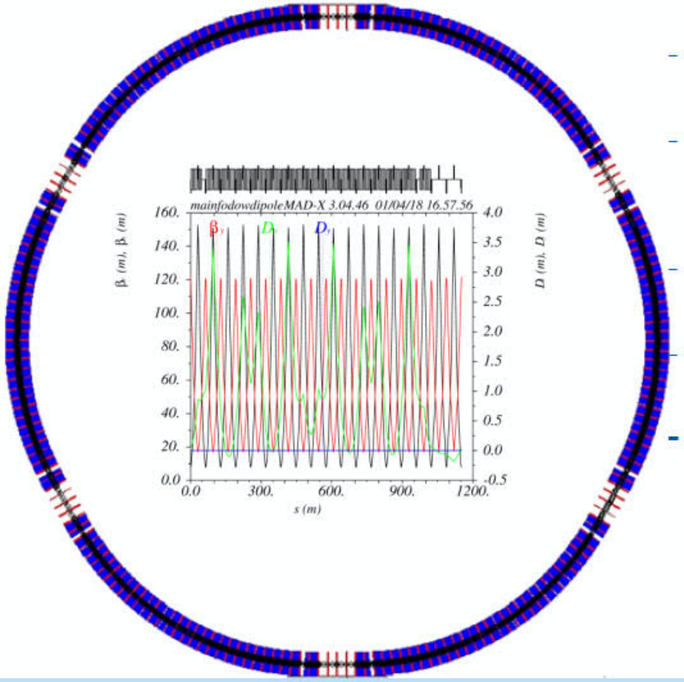
- 5 cells,
- Allocated for
    - Wiggler magnets,
    - RF elements,
    - Injection and extraction elements.

1 FODO with wiggler magnet is used to reduce the damping time at the injection energy in each straight section (same wiggler structure with CLIC DR).

O. Etisken, Ankara U.

For detailed information, please follow Ozgur Etisken's presentation on Wednesday in Hall - 3 at 17:00.

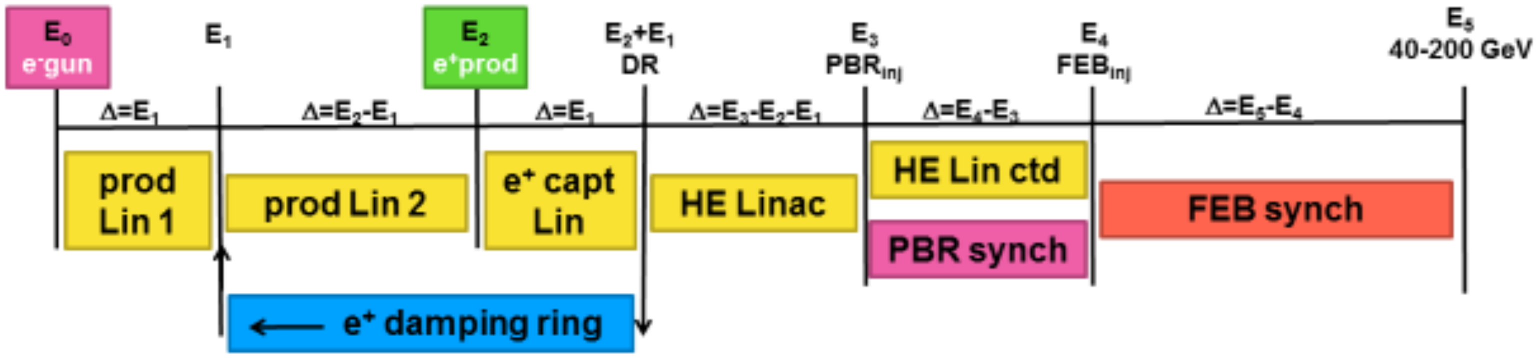
SPS

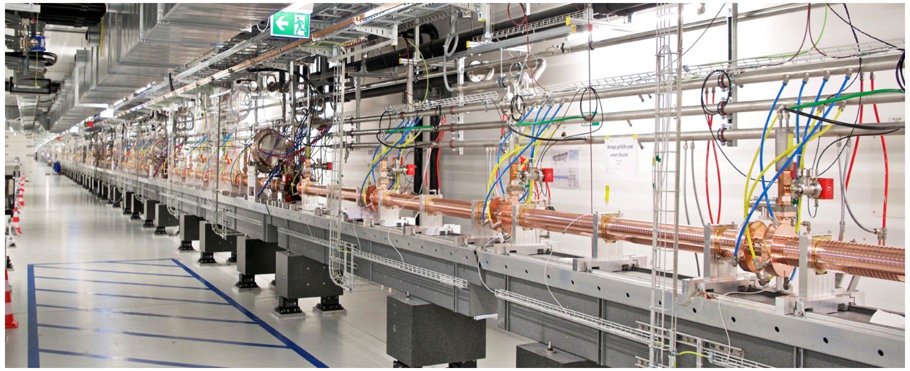


- The ring consist of **6 arcs and 6 straight** sections,
- 6 identical periods; each **super period** is composed of **18 FODO** cells,
- Each super-period is around **1.15 km**,
- The circumference is around **6.9 km**,
- **744 dipoles** with **6.26 m** length.

Two main challenges were revealed for the SPS: the extraction emittance is ten times larger than the required one and the synchrotron radiation damping time at injection for the SPS is 1.7 s which is much longer than the 0.1 s required for the pre-booster ring. In order to overcome the aforementioned challenges, it is proposed: to move horizontal phase advance to **3π/4 (Q40)**, to insert **wiggler** magnets (Damping wiggler and Robinson wiggler).

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

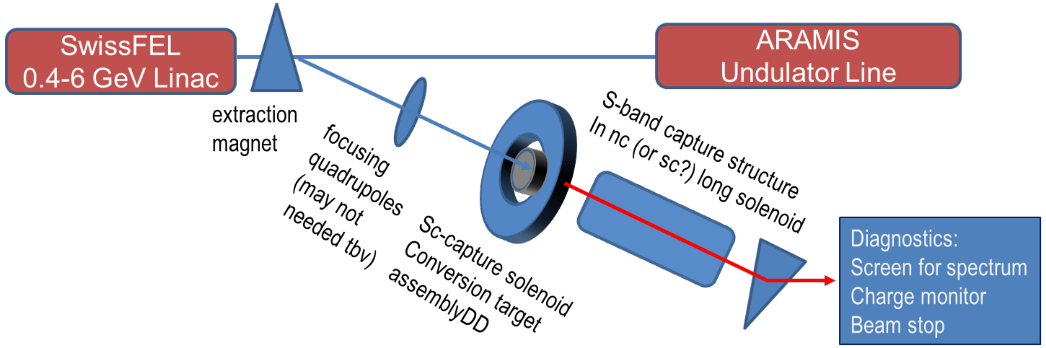
Task 2 e+ and e- Linac extension study (Linac 4) - PSI/CERN

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

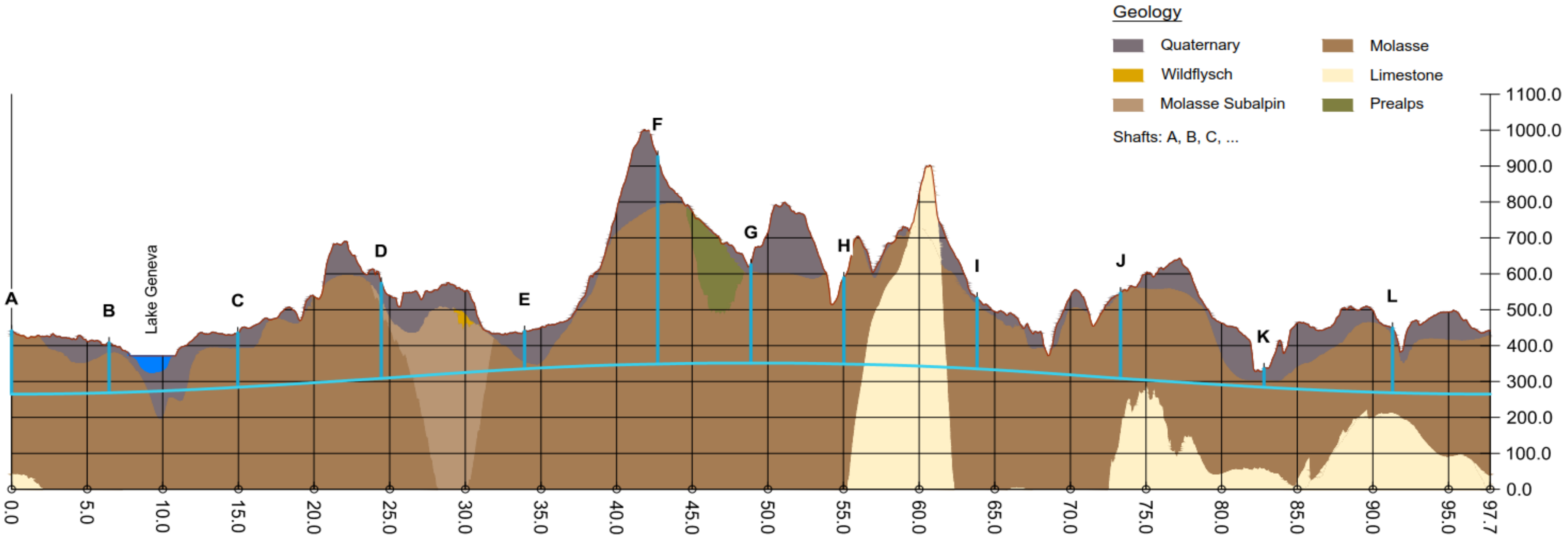
Task 6 PoP e+ source in SwissFEL – PSI/CERN/IJClab/BINP

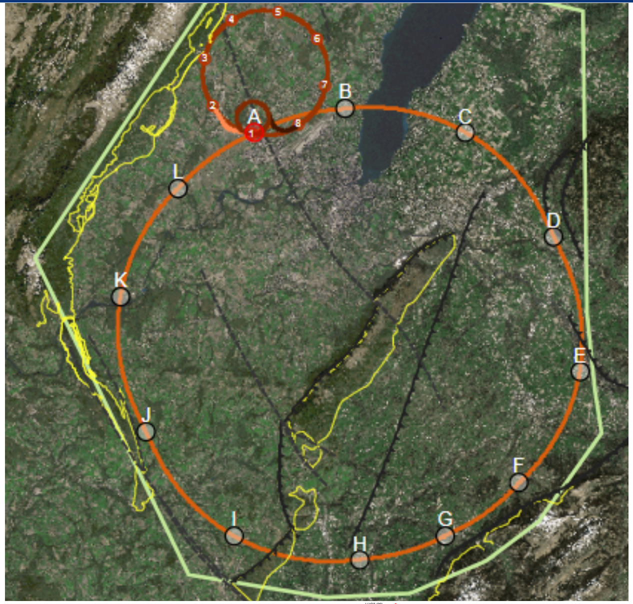


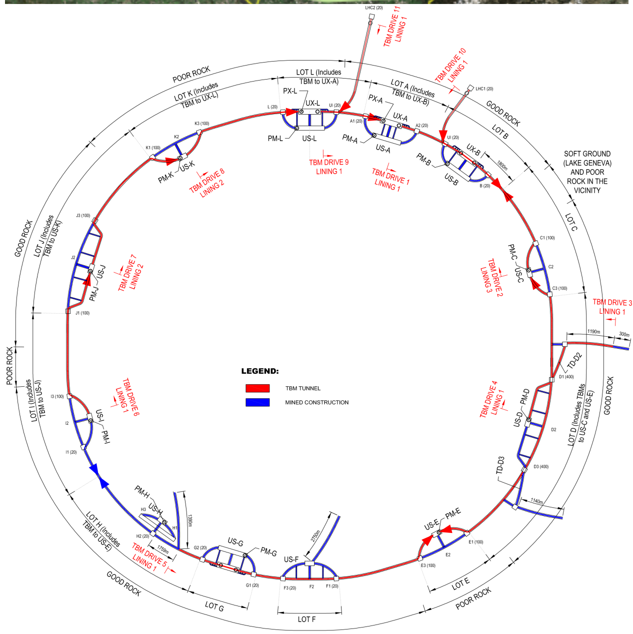
FCC-ee demonstrator e+ source at SwissFEL for e^-/e^+ conversion & capture efficiency

P. Craievich., A. Grudiev

FCC implementation - footprint baseline



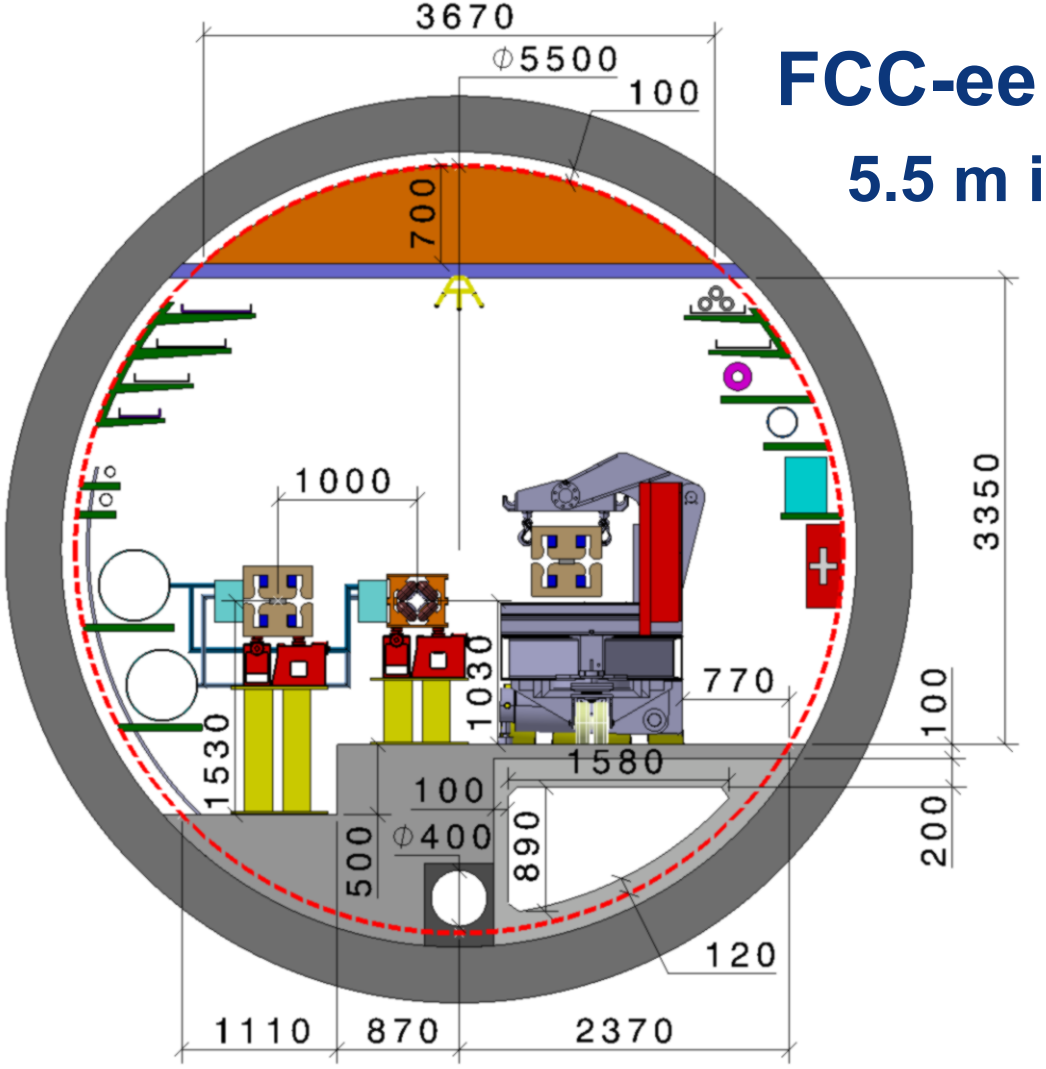




- **Present baseline position was established considering:**
- lowest risk for construction, fastest and cheapest construction
- feasible positions for large span caverns (most challenging structures)

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

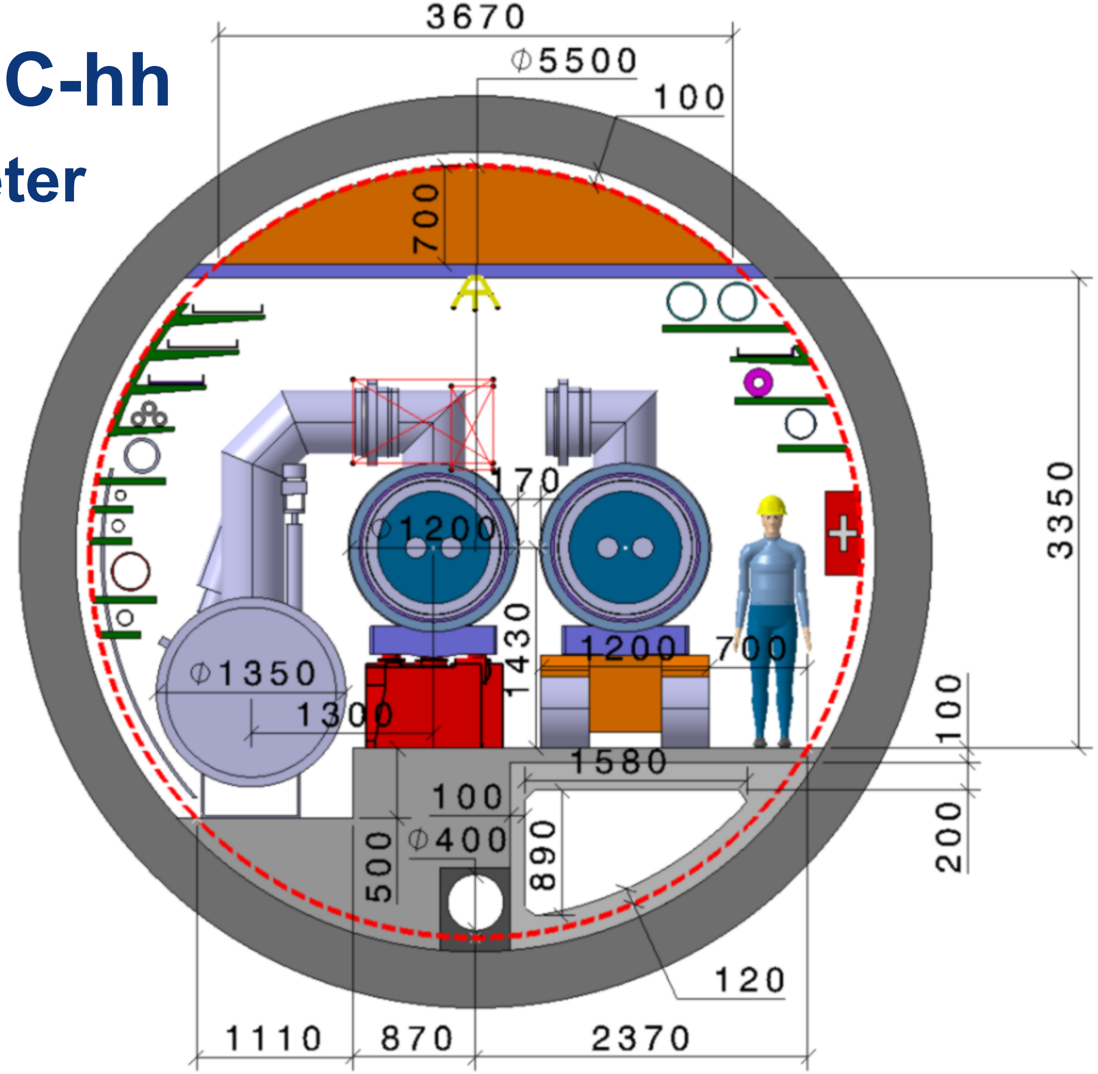
FCC-tunnel integration in arcs



FCC-ee

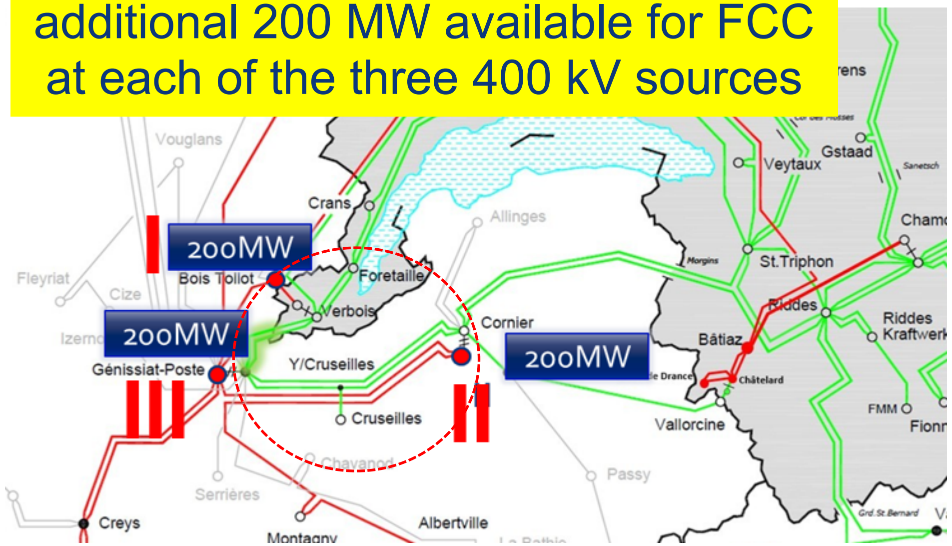
FCC-hh

5.5 m inner diameter



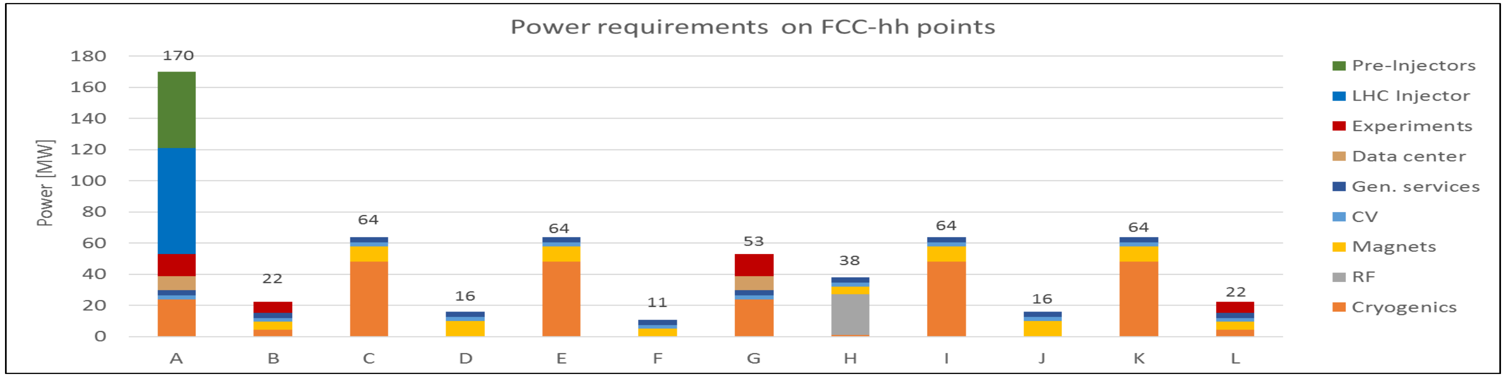
Supply & distribution of electrical energy

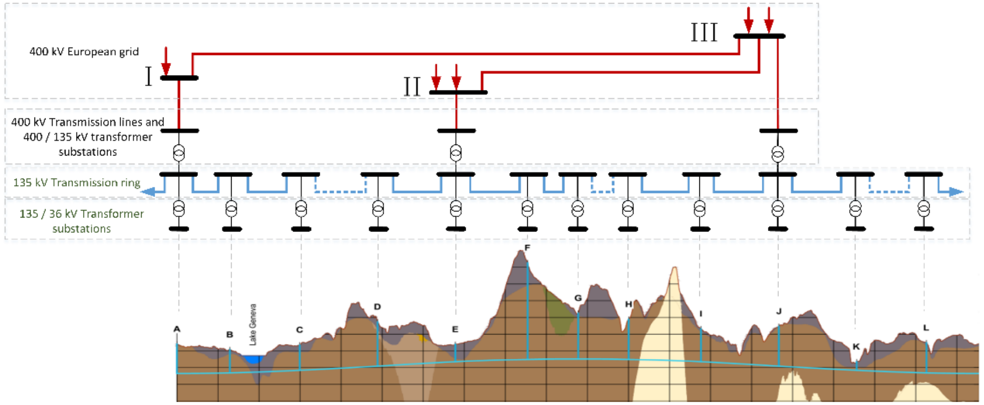
additional 200 MW available for FCC at each of the three 400 kV sources



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

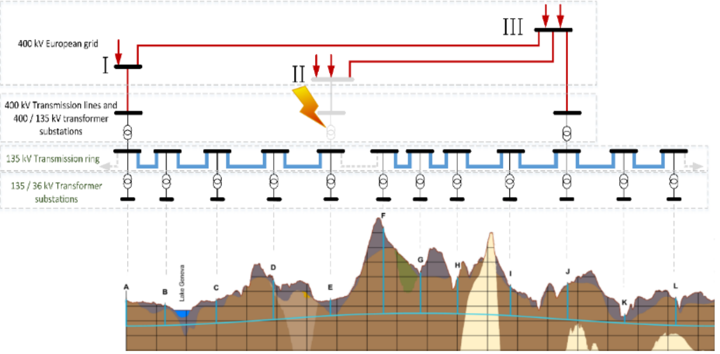
per-point power requirements as input for infrastructure-optimized conceptual design (peak FCC-ee: 260-340 MW, total FCC-hh: 550 MW)

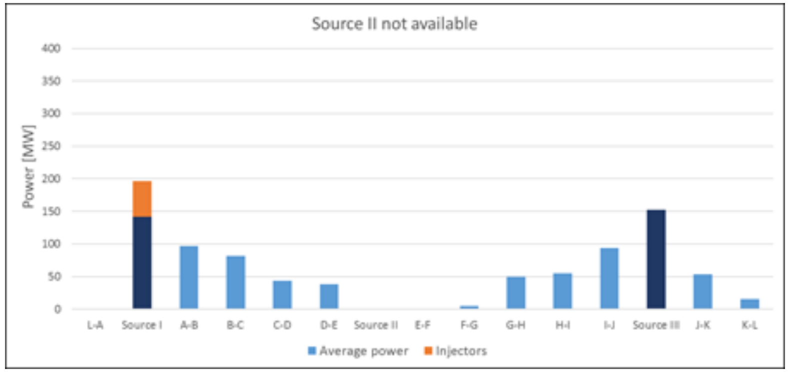




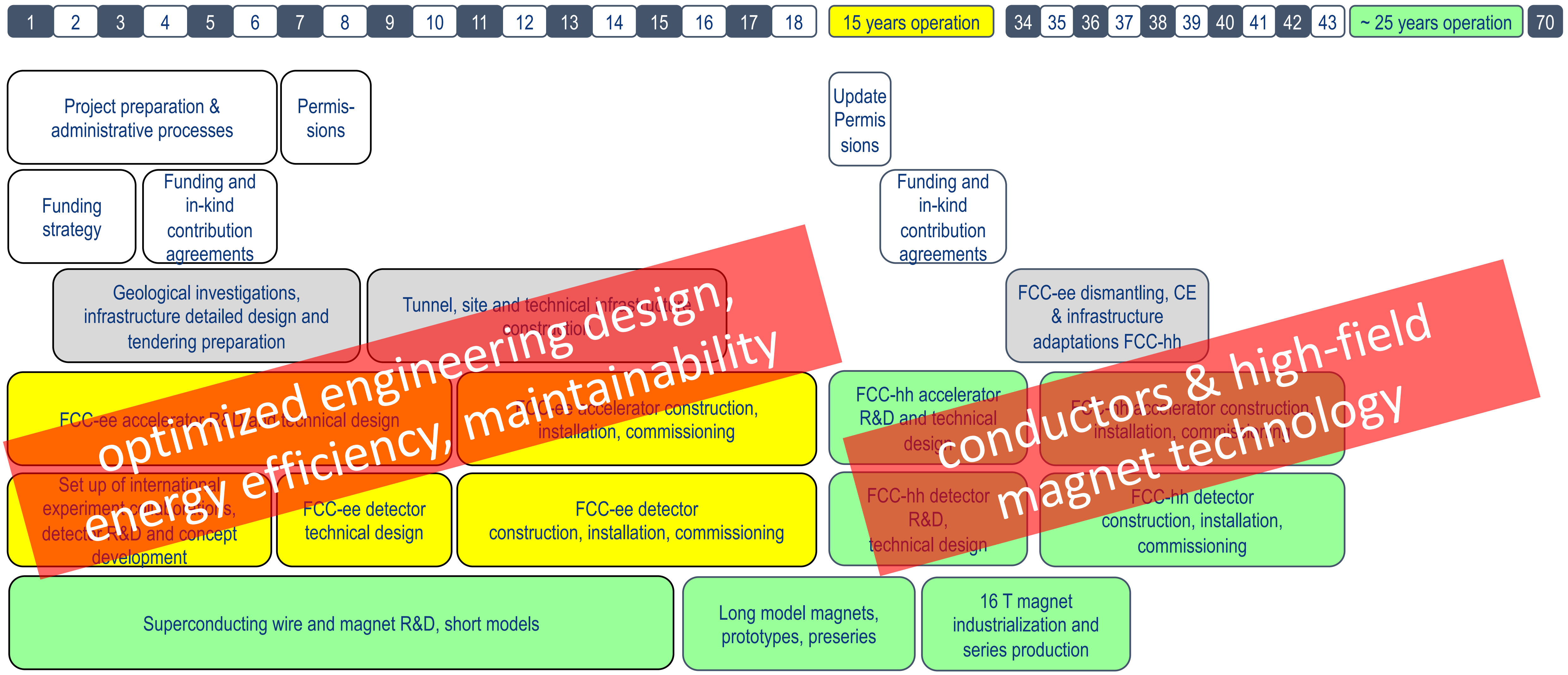
3 x 400 kV connections
+ 135 kV underground power distribution (NC)

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

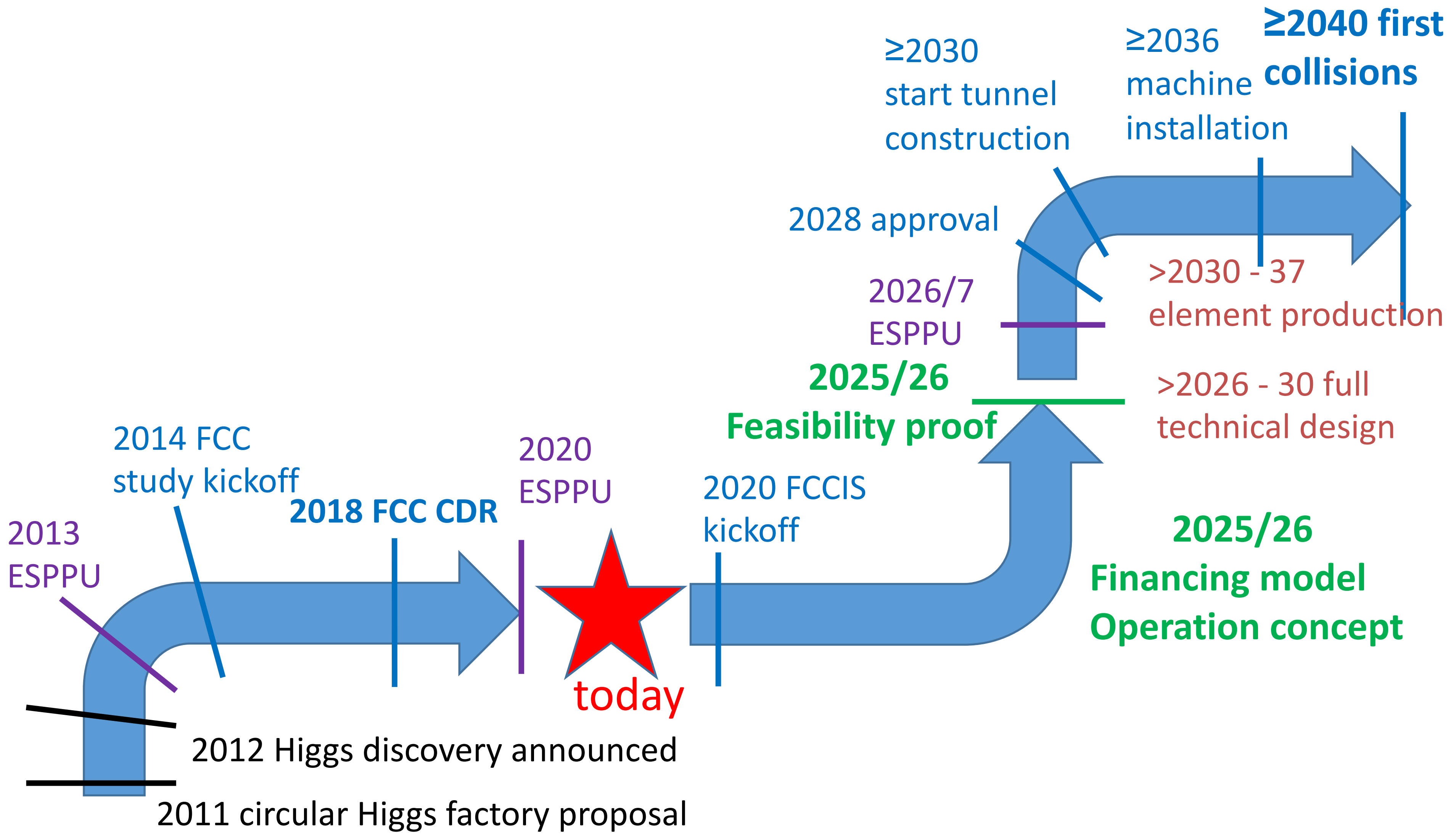




FCC integrated project technical schedule



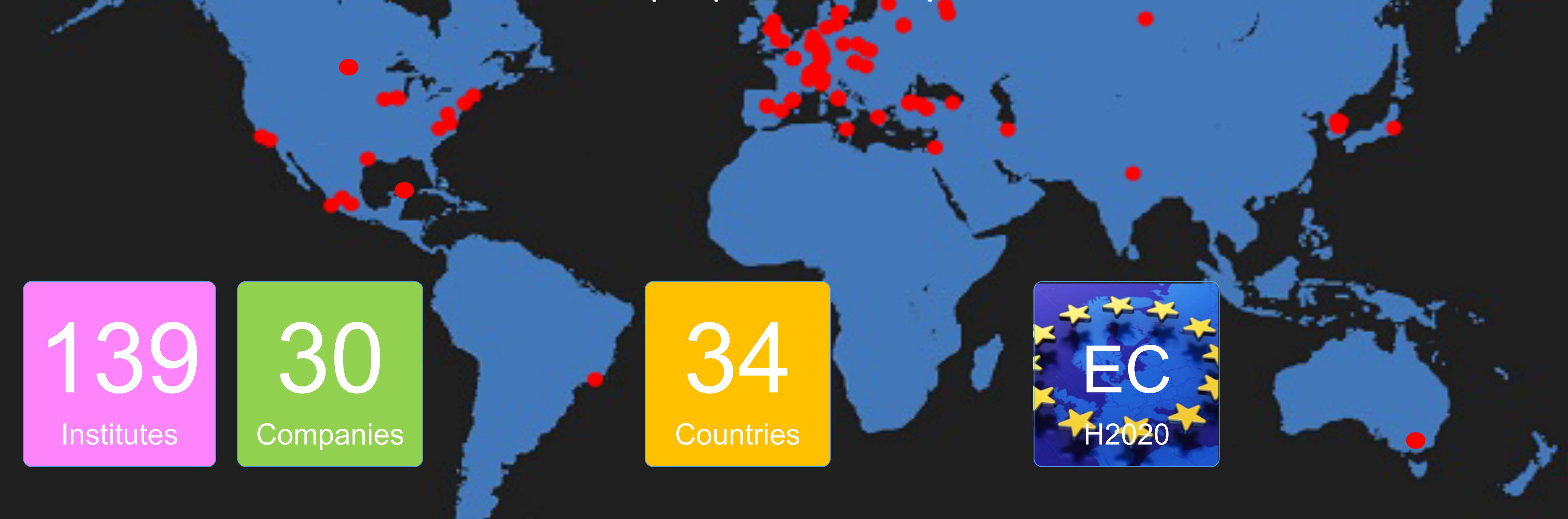
Roadmap to first FCCee collisions



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



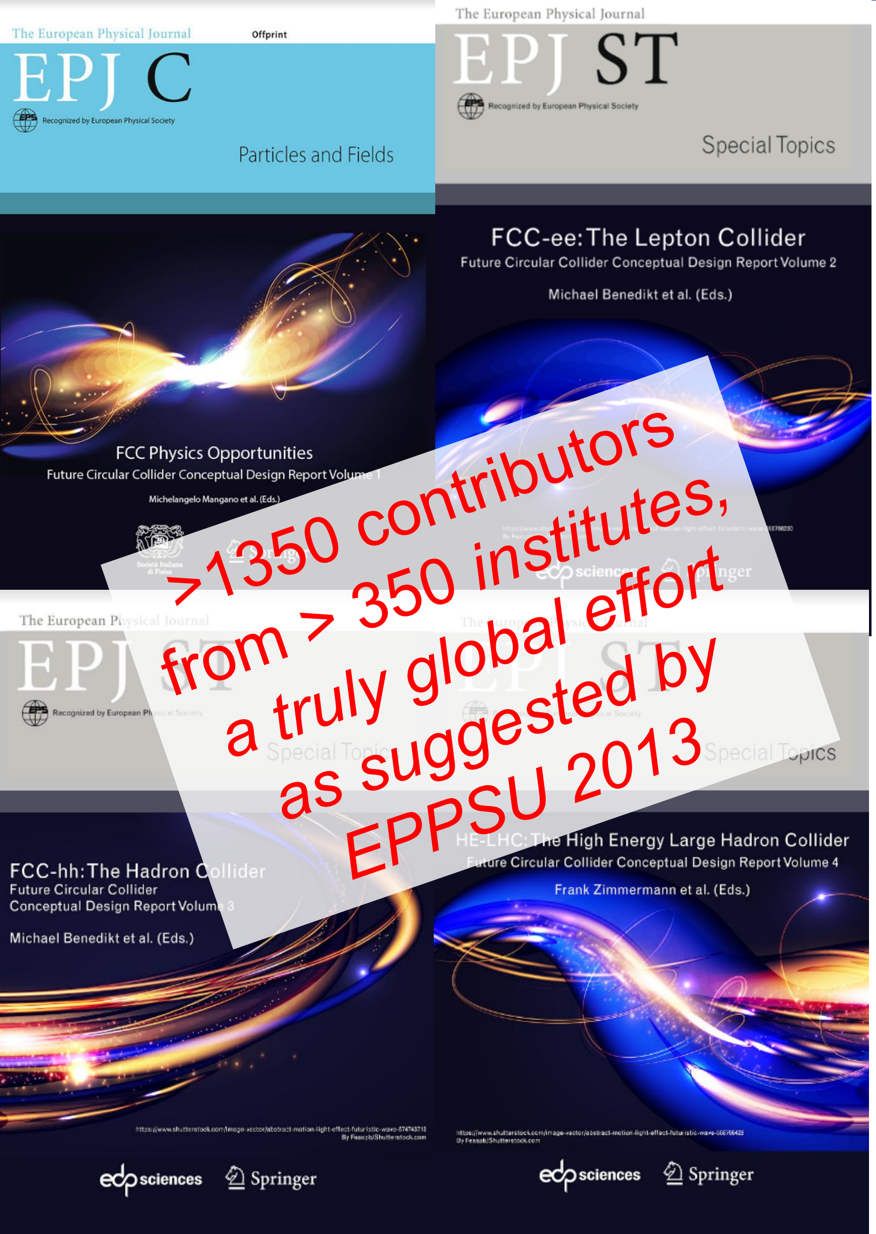
139 Institutes

30 Companies

34 Countries

EC H2020

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)**

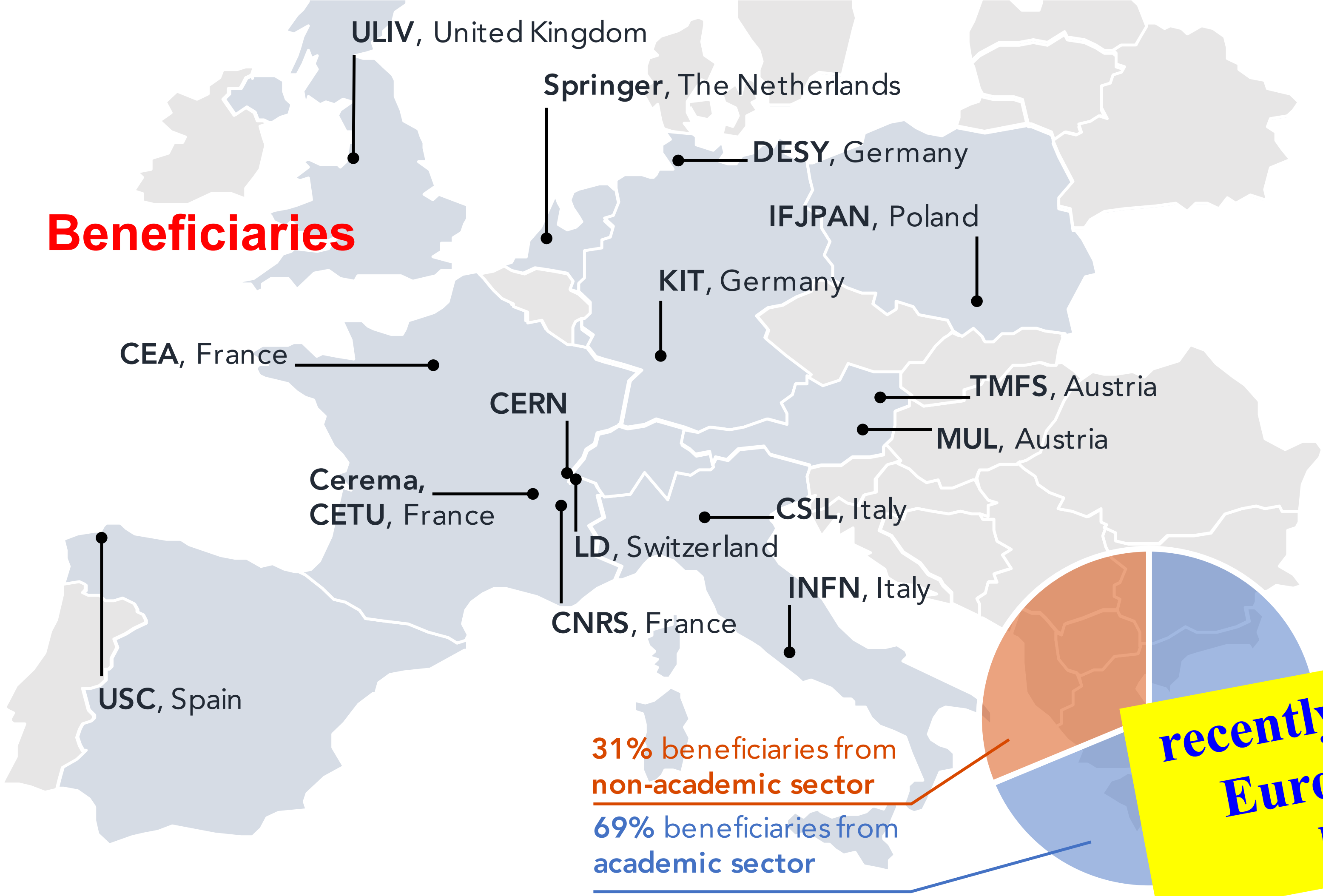
    EPJ C 79, 6 (2019) 474 , EPJ ST 228, 2 (2019) 261-623 ,

    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/

H2020 DS FCC Innovation Study 2020-24

Beneficiaries



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

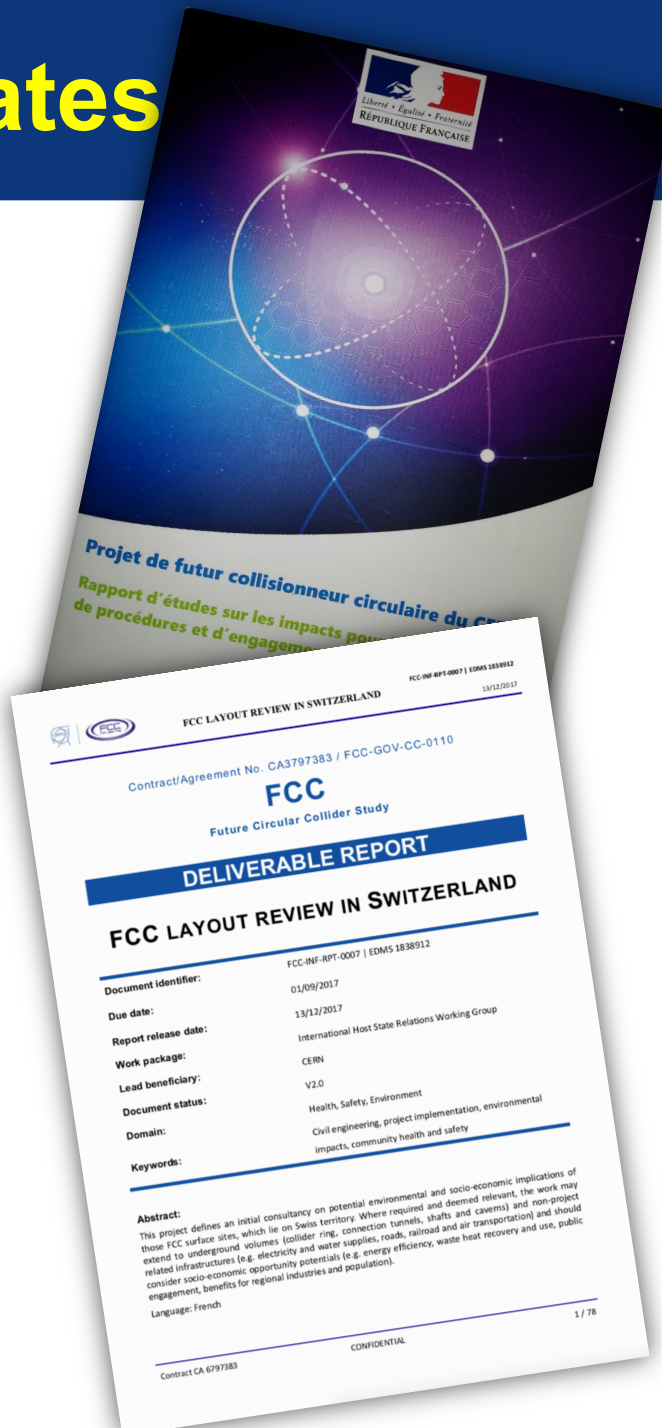
Design optimisation, construction planning, environmental impact assessment, management of excavation materials, user community building and public engagement, socio-economic impact,…

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

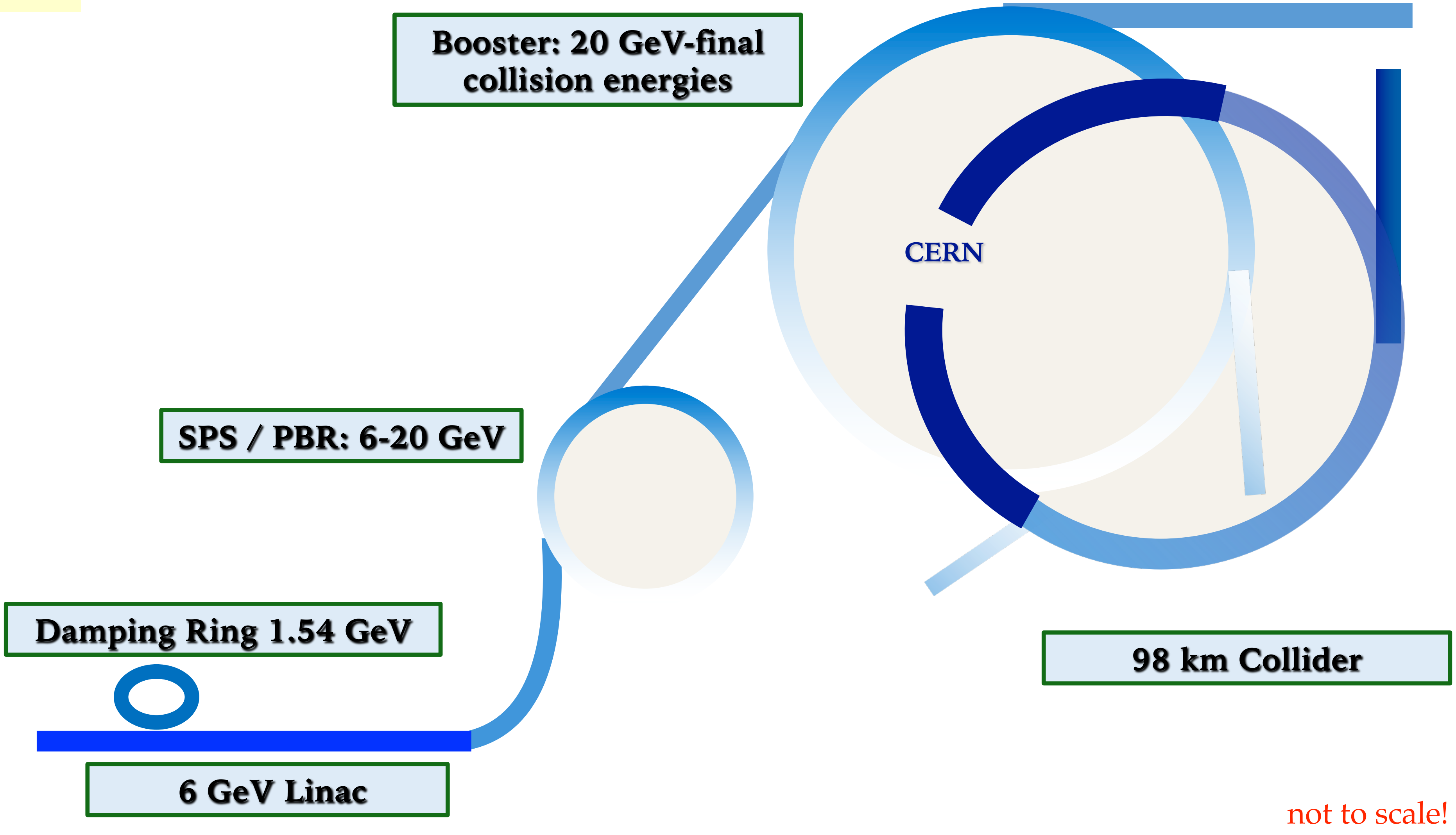
Status and Outlook

- **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

backup slides

FCC-ee injector complex

S. Ogur, O. Etisken



FCC - Next steps

Plan for 2020–2025:

1. Financing strategy including in-kind contributions
2. Governance model for construction & operation
3. Host states / Civil-engineering preparation including site investigations
4. Technical design study for accelerator and infrastructure

2020 Update European Particle-Physics Strategy (CERN-ESU-013/014)

"Investigate technical and financial feasibility of future hadron collider at CERN with c.o.m. energy of ≥ 100 TeV and with e^+e^- Higgs and electroweak factory as possible first stage.

… It is important therefore to launch feasibility study for such collider to be completed in time for the next Strategy update [~2026], so that a decision … can be taken on that timescale. The feasibility study should involve the following aspects: the possibility of constructing such a large infrastructure in the vicinity of CERN, the financial plan to complete and operate project of this scale with international partners, its governance, and handling of energy consumption."