Future Circular Colliders (FCC) - Status and Parameters

Frank Zimmermann, CERN

many thanks to FCC coordination group, esp. M. Benedikt, O. Brüning, M. Klein, to FCC collaboration, to BNL colleagues, and to all other contributors

photo: J. Wenninger

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starting points / motivations :

2010 HE-LHC’10 EuCARD workshop, Malta

→ larger proton ring

Proc. HE-LHC’10, ed. by E. Todesco & F.Z. arXiv:1111.7188 ; CERN-2011-003 (2011)

→ launch of 80 km tunnel study

2011 signs of a Higgs boson around 126 GeV

→ proposal of circular Higgs factory

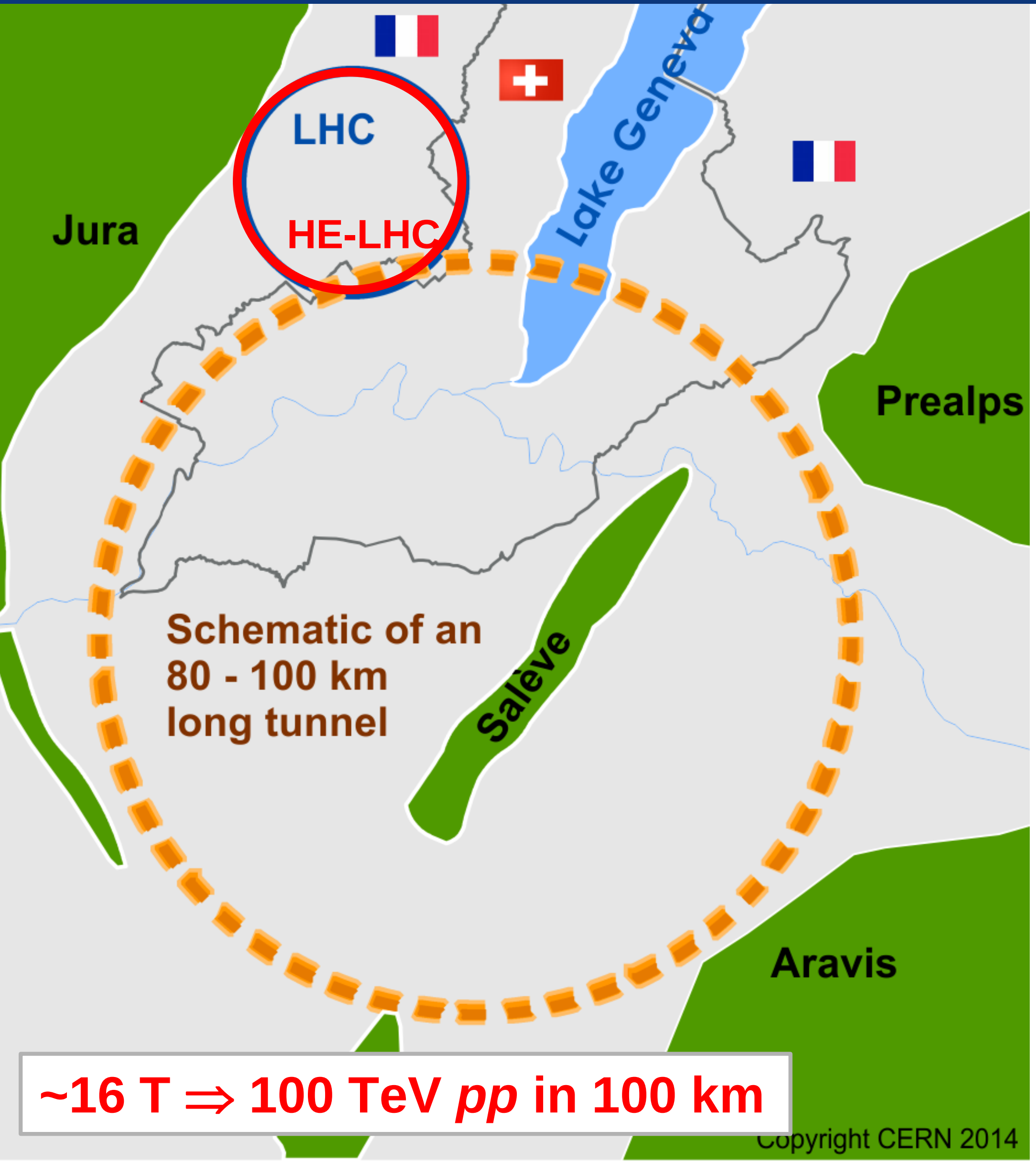
LEP3, DLEP, TLEP,...

A. Blondel, F.Z., CERN-OPEN-2011-047 ; arXiv:1112.2518 (2011)

2013 update of European Strategy

CERN-Council-S-0106 (2013)

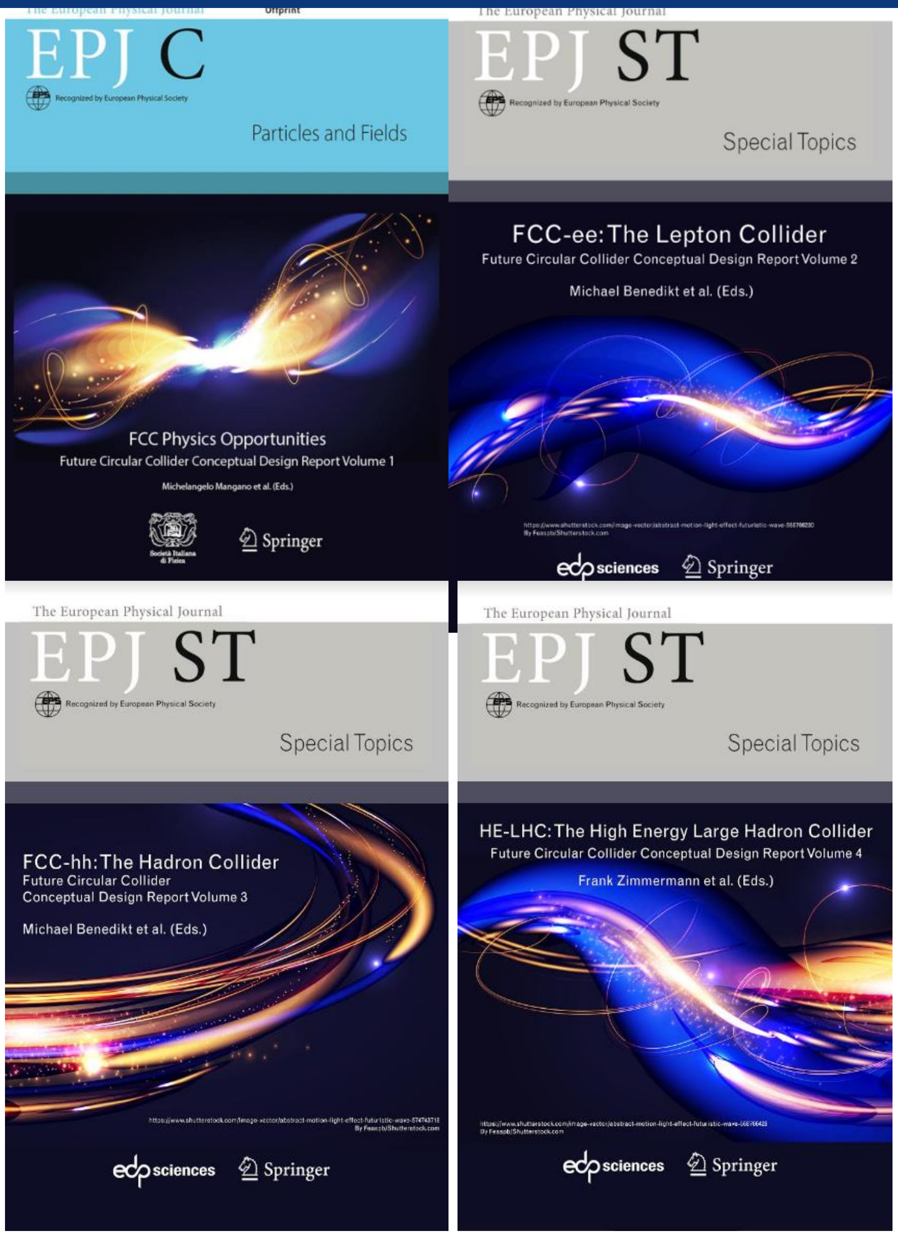
Future Circular Collider Study since 2014 - Scope



International FCC collaboration w. CERN as host laboratory to study:

- **~100 km tunnel infrastructure** in Geneva area, linked to CERN
- ***e*⁺*e*⁻ collider (*FCC-ee*),** → 1st step?
- ***pp*-collider (*FCC-hh*)** → long-term goal, defining infrastructure requirements
- **p-e option (*FCC-eh*)**
- **HE-LHC** with *FCC-hh* technology, with ***HE-LHeC*** option
- + heavy ion & **e-A** options with all hadron colliders

FCC Conceptual Design Reports Published



Study Documentation:

- 4 CDR volumes published in EPJ
  - FCC Physics Opportunities
    Eur. Phys. J. C (2019) **79**: 474
    https://doi.org/10.1140/epjc/s10052-019-6904-3
  - FCC-ee
    Eur. Phys. J. Spec. Top. (2019) 228: 261
    https://doi.org/10.1140/epjst/e2019-900045-4
  - FCC-hh + FCC-eh
    Eur. Phys. J. Spec. Top. (2019) 228: 755
    https://doi.org/10.1140/epjst/e2019-900087-0
  - HE-LHC + HE-LHeC
    Eur. Phys. J. Spec. Top. (2019) 228: 1109
    https://doi.org/10.1140/epjst/e2019-900088-6
- paper copies can be requested at
  - http://get-fcc-cdr.web.cern.ch

more than 1350 contributors from 350 institutes, a truly global collaboration and effort as suggested by the EPPSU 2013

FCC-eh & HE-LHeC *ep* baselines

FCC-hh CDR, Table 2.9

Parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-eh	LE-FCC-eh
E_p [TeV]	7	7	12.5	50	20
E_e [GeV]	60	60	60	60	50
$\sqrt{s}$ [TeV]	1.3	1.3	1.7	3.5	2.0
Bunch spacing [ns]	25	25	25	25	25
Protons per bunch [10^{11}]	1.7	2.2	2.5	1	1.2
$\gamma\epsilon_p$ [μm]	3.7	2	2.5	2.2	2.2
Electrons per bunch [10^9]	1	2.3	3.0	3.0	3.0
Electron current [mA]	6.4	15	20	20	20
IP beta function β_p^* [cm]	10	7	10	15	15
Hourglass factor H_{geom}	0.9	0.9	0.9	0.9	0.9
Pinch factor H_{b-b}	1.3	1.3	1.3	1.3	1.3
Proton filling H_{coll}	0.8	0.8	0.8	0.8	0.8
Luminosity [10^{33}cm^{-2}s^{-1}]	1	8	12	15	7

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

Oliver Brüning, John Jowett, Max Klein, Dario Pellegrini, Daniel Schulte, Frank Zimmermann

simulated FCC-eh performance

Parameter	Unit	Protons	Electrons
Beam energy	GeV	50000	60
Normalised emittance	µm	$2.2 \to 1.1$	10
IP beta function	mm	150	$42 \to 52$
Nominal RMS beam size	µm	$2.5 \to 1.8$	$1.9 \to 2.1$
Waist shift	mm	0	$65 \to 70$
Bunch population	10^{10}	$10 \to 5$	0.31
Bunch spacing	ns	25	25
Luminosity	$10^{33}\text{cm}^{-2}\text{s}^{-1}$	$18.3 \to 14.3$	
Int. luminosity per 10 years	$[\text{ab}^{-1}]$	1.2	

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

FCC-hh CDR Table 2.10

Daniel Schulte

FCC-eh & HE-LHeC *eA* baselines

Parameter [unit]	LHeC (HL-LHC)	eA at HE-LHC	FCC-eh
E_{Pb} [PeV]	0.574	1.03	4.1
E_e [GeV]	60	60	60
$\sqrt{s_{eN}}$ electron-nucleon [TeV]	0.8	1.1	2.2
Bunch spacing [ns]	50	50	100
No. of bunches	1200	1200	2072
Ions per bunch [10^8]	1.8	1.8	1.8
$\gamma\epsilon_A$ [μm]	1.5	1.0	0.9
Electrons per bunch [10^9]	4.67	6.2	12.5
Electron current [mA]	15	20	20
IP beta function β_A^* [cm]	7	10	15
Hourglass factor H_{geom}	0.9	0.9	0.9
Pinch factor H_{b-b}	1.3	1.3	1.3
Bunch filling H_{coll}	0.8	0.8	0.8
Luminosity [$10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$]	7	18	54

EDMS 17979910 FCC-ACC-RPT-0012 V1.0, 6 April, 2017, "A Baseline for the FCC-he"

FCC-hh CDR Table 2.11

John Jowett, F.Z.

FCC-eh key design questions

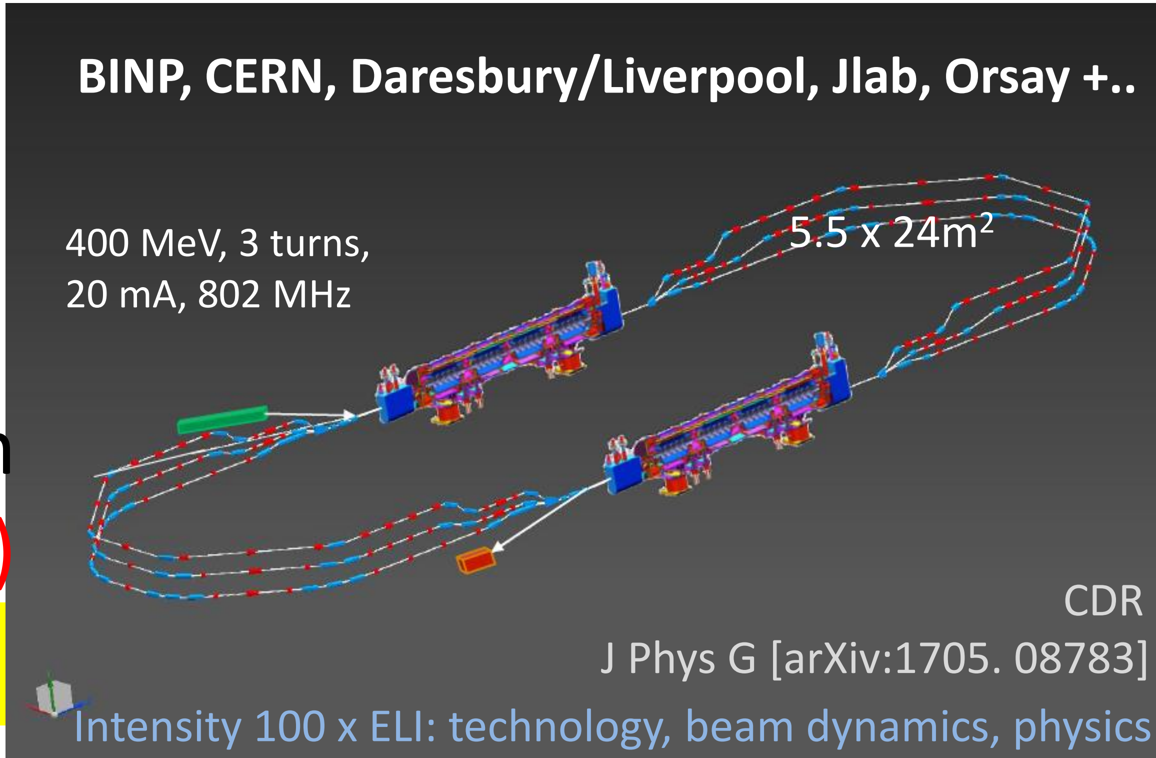
- beam current limit in multi-turn ERL
- interaction-region design: final quadrupole magnets, synchrotron-radiation inside detector, machine-detector interface
- IP choice for FCC not fixed, IP tentatively FCC point L; detailed integration study depends on location

Oliver Brüning, John Osborne, Max Klein

FCC-eh option and ERL

5-cell 800 MHz cavity, JLAB prototype for FCC-ee (top mode) & FCC-eh; also single-cell cavities for all FCC's

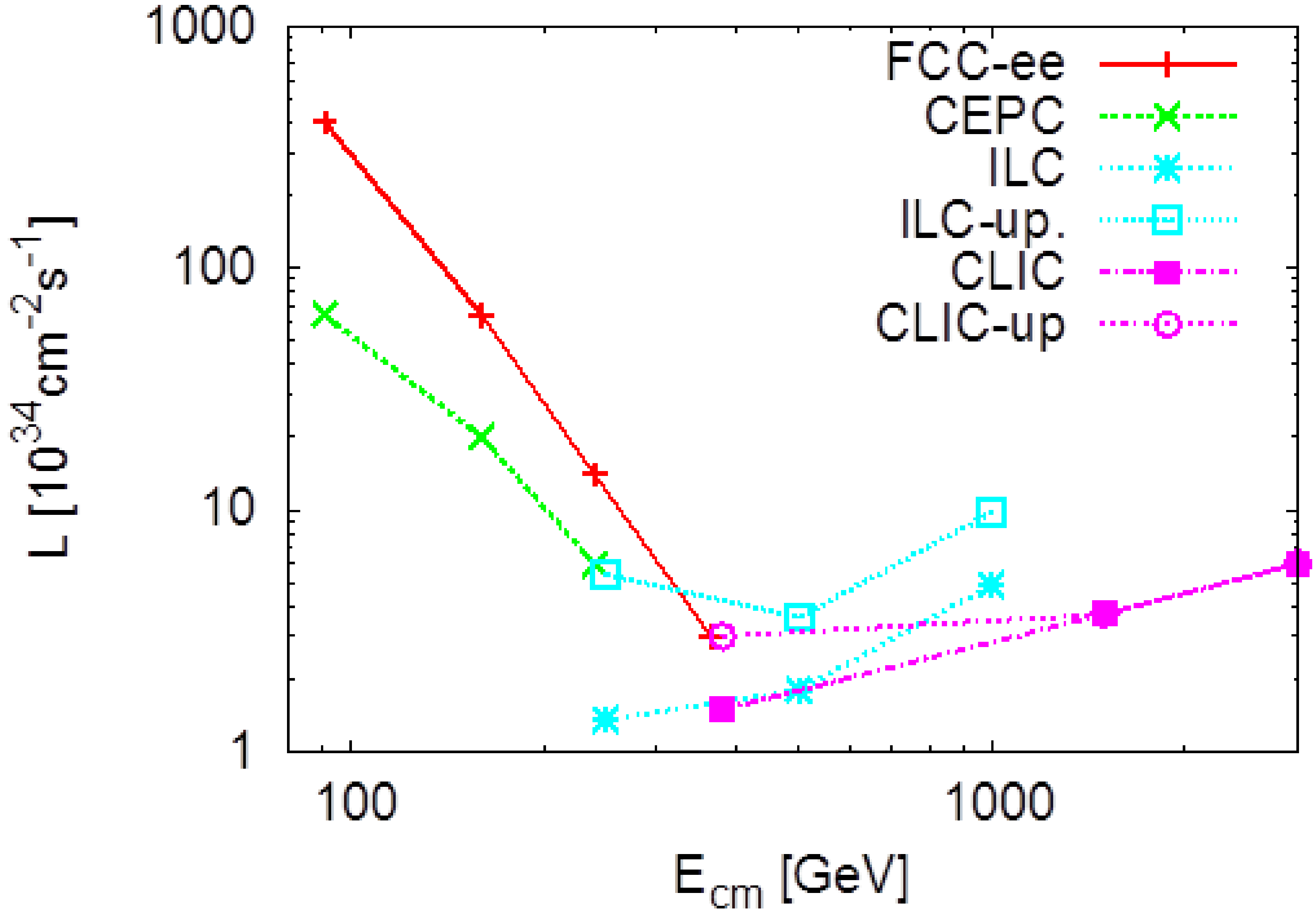
optimized for high current operation



FCC-eh: 60 GeV e^- from
Energy Recovery Linac (ERL)

PERLE@Orsay ERL test facility

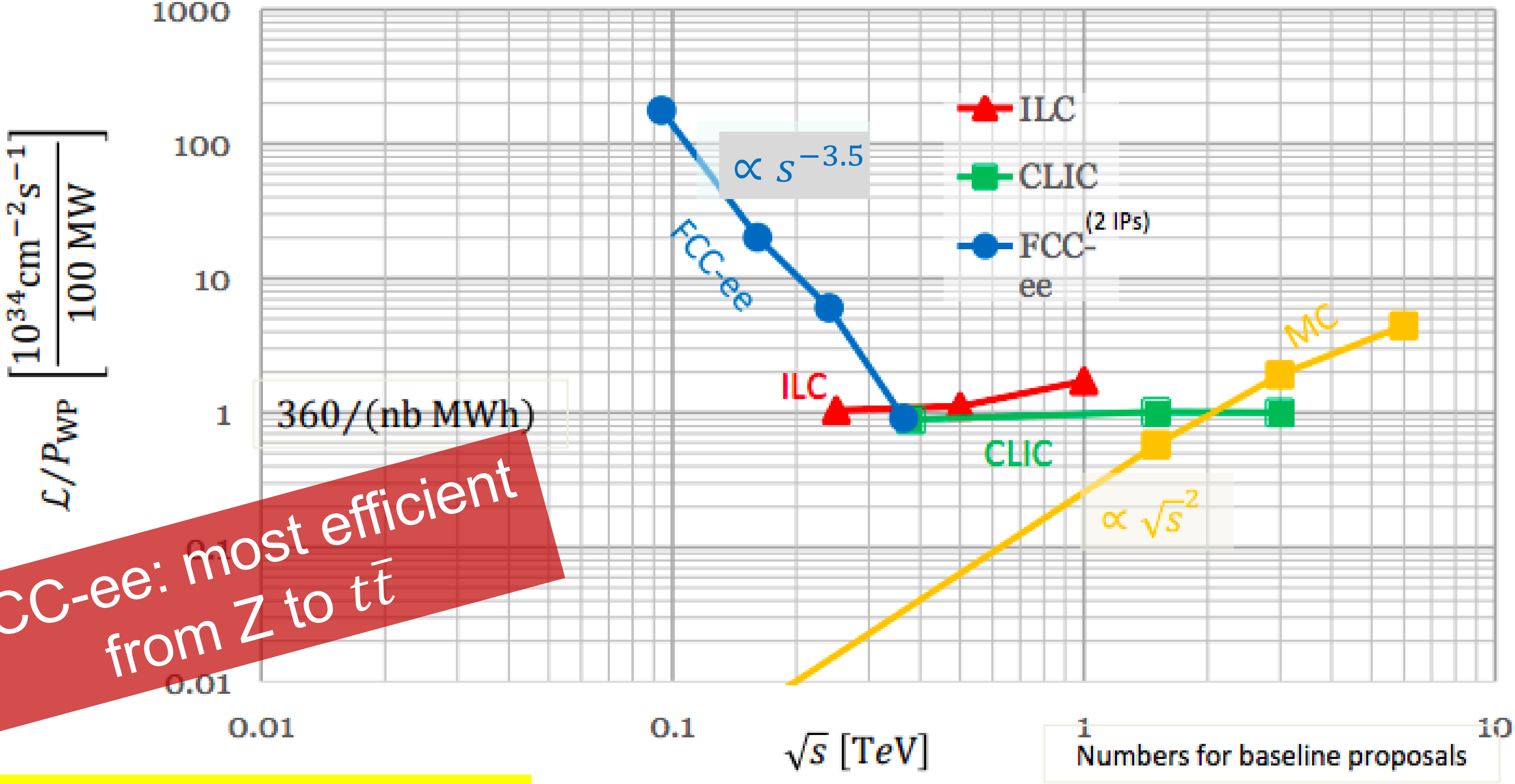
FCC-ee | e^+e^- Higgs factory luminosity vs c.m. energy



two IPs are assumed for the circular colliders FCC-ee and CEPC

D. Schulte, B. List

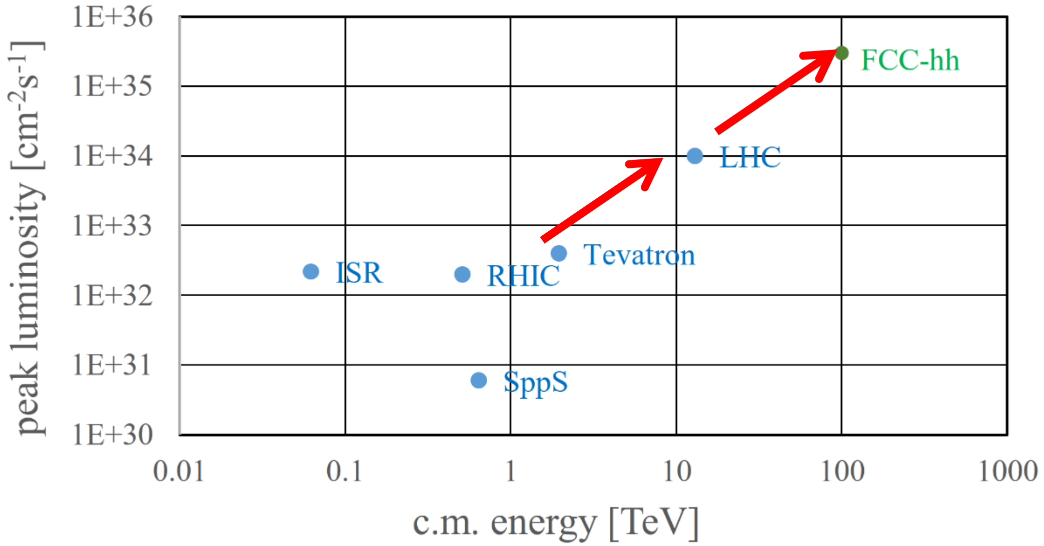
FCC-ee | figure of merit for lepton colliders



FCC-ee: most efficient from Z to $t\bar{t}$

ESU2019 Briefing Book, CERN/ESG/04

FCC-hh: performance & technology

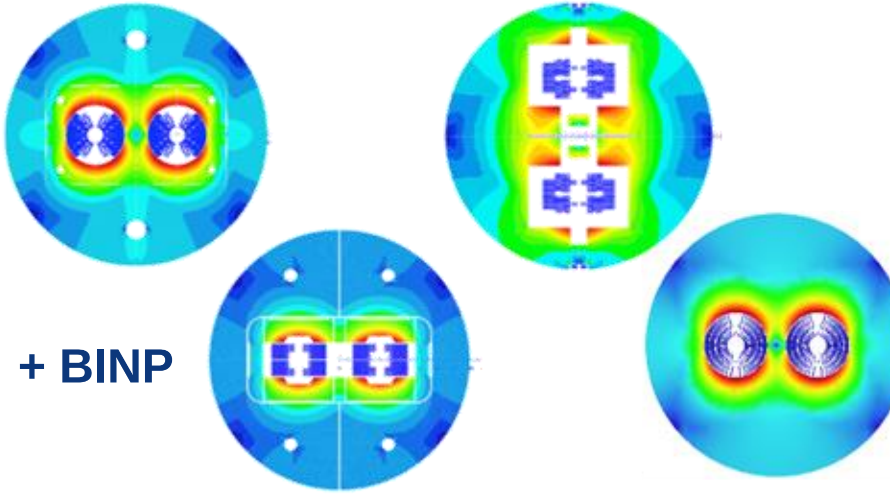


- Aim at **~one order of magnitude performance increase** in both **energy and luminosity w.r.t LHC**
- **100+ TeV cm collision energy** (vs 14 TeV for LHC)
- **20 ab^{-1} per experiment collected over 25 years** of operation time (vs 3 ab^{-1} for LHC).
- Similar performance increase as from Tevatron to LHC.
- **Key technology: High-field magnets**

From LHC technology
8.3 T NbTi

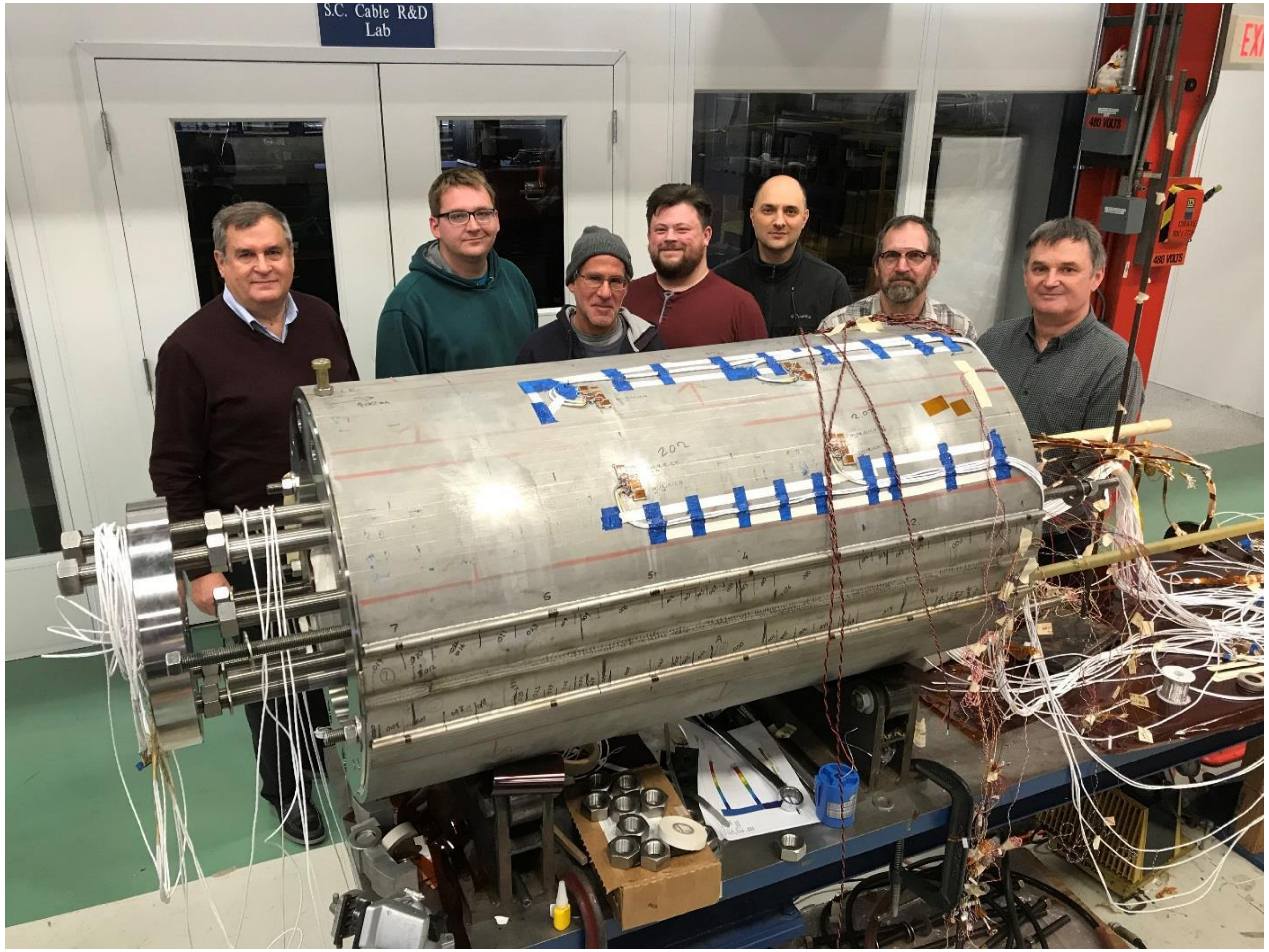
via HL-LHC technology
11 T Nb_3Sn

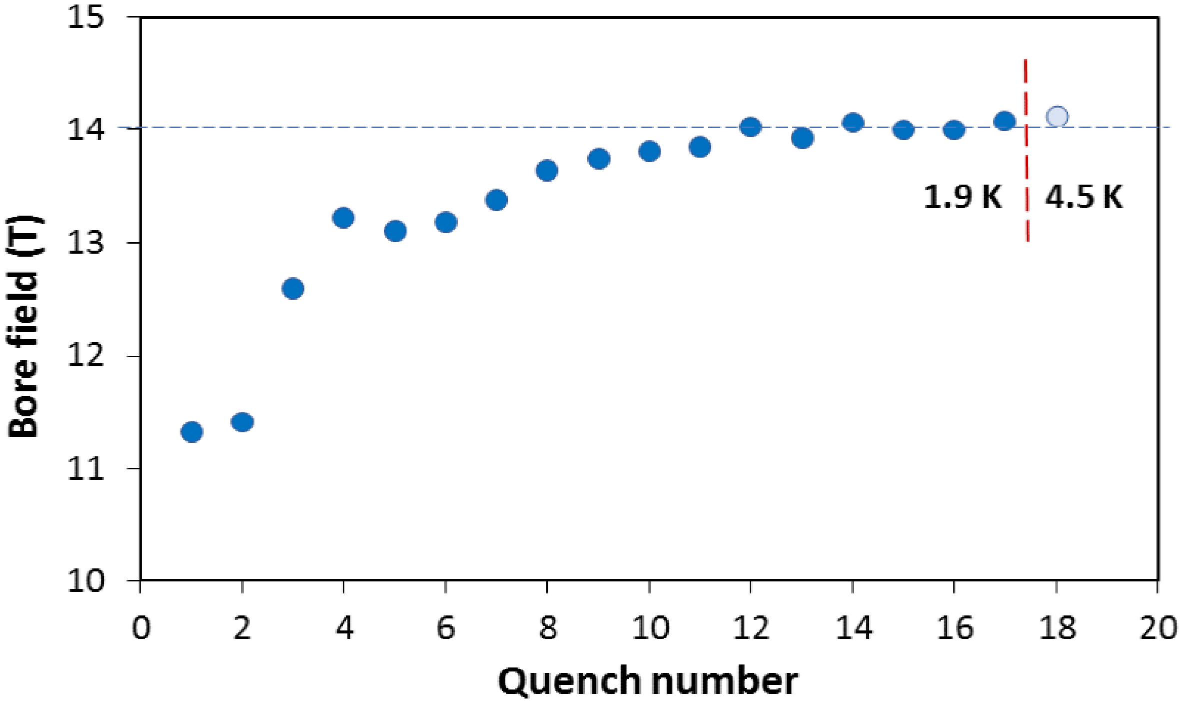
to 16 T Nb_3Sn
EuroCirCol, Chart, US MDP



+ BINP

2019: FNAL demonstrator dipole exceeded 14 T at 4.5 K





60-mm aperture
4-layer graded coil

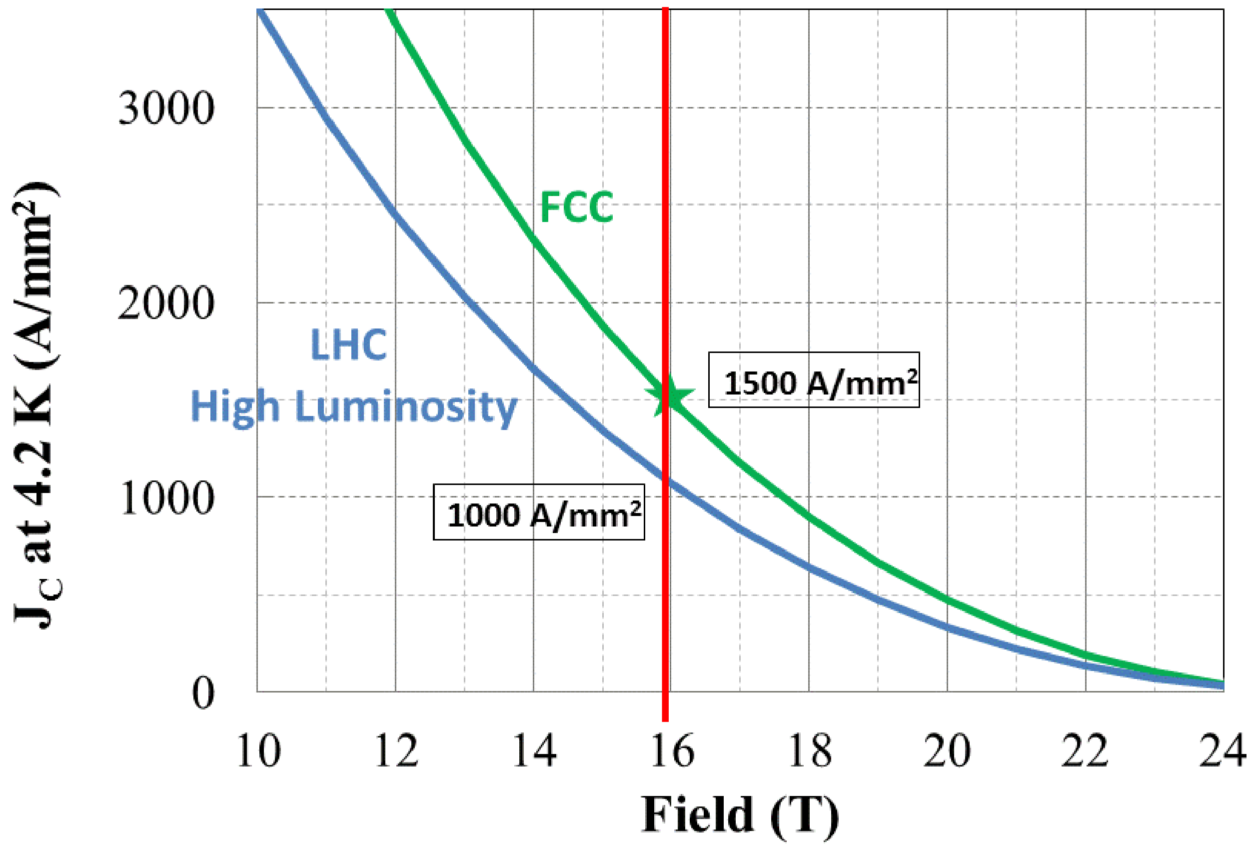
- 15 T dipole demonstrator
- Staged approach: In first step pre-stressed for 14 T
- Second test in fall 2019 with additional pre-stress for 15 T

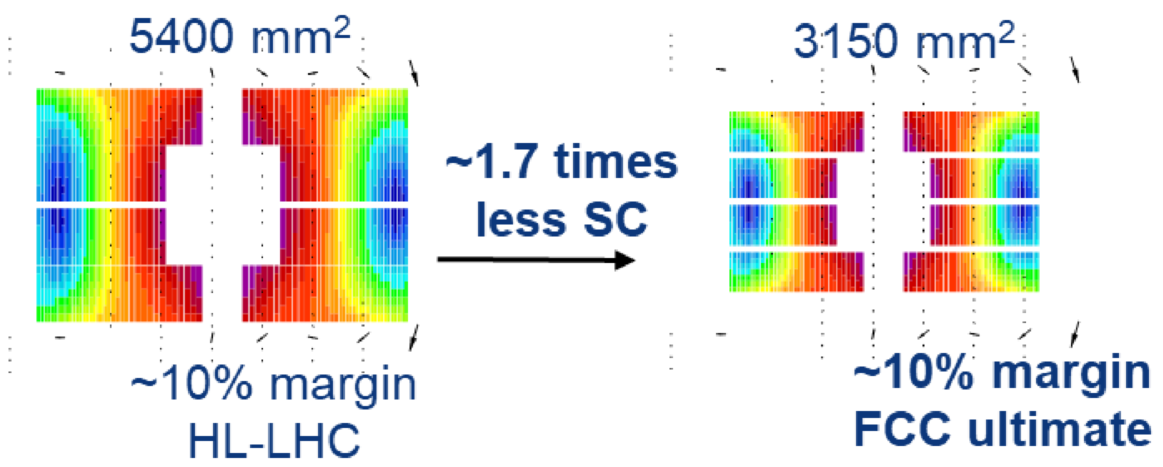
FCC Nb_3Sn conductor program

Nb_3Sn is major cost & performance driver for higher energy hadron storage rings

main development goal until 2020:

- **J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire**
- **reference wire diameter 1 mm**

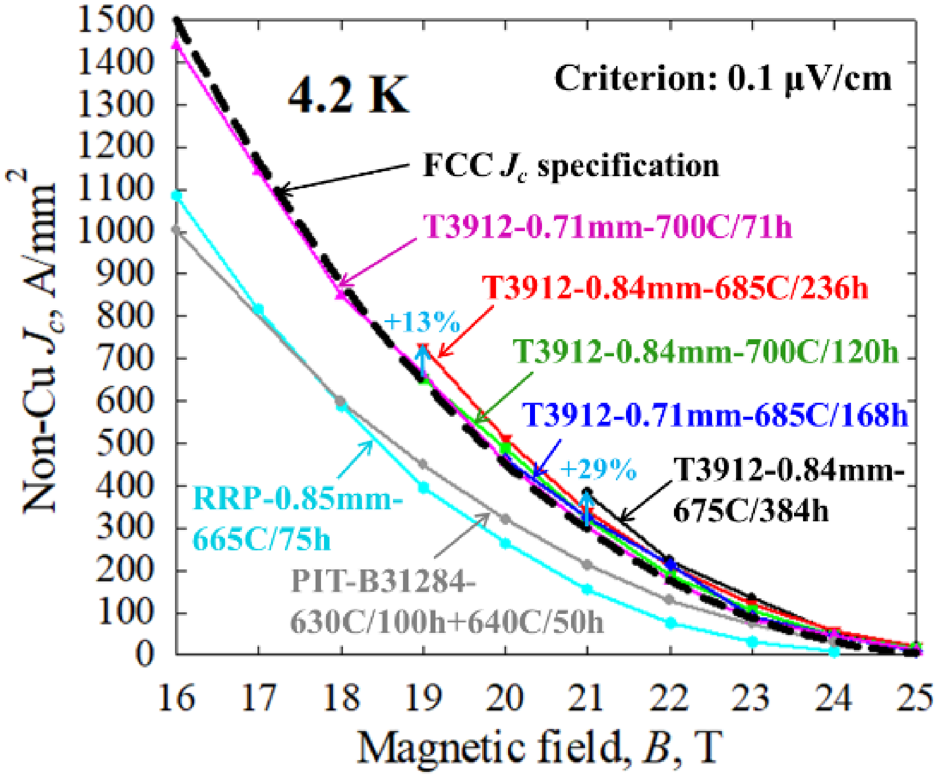




→ cost and performance

excellent progress on Nb_3Sn conductor

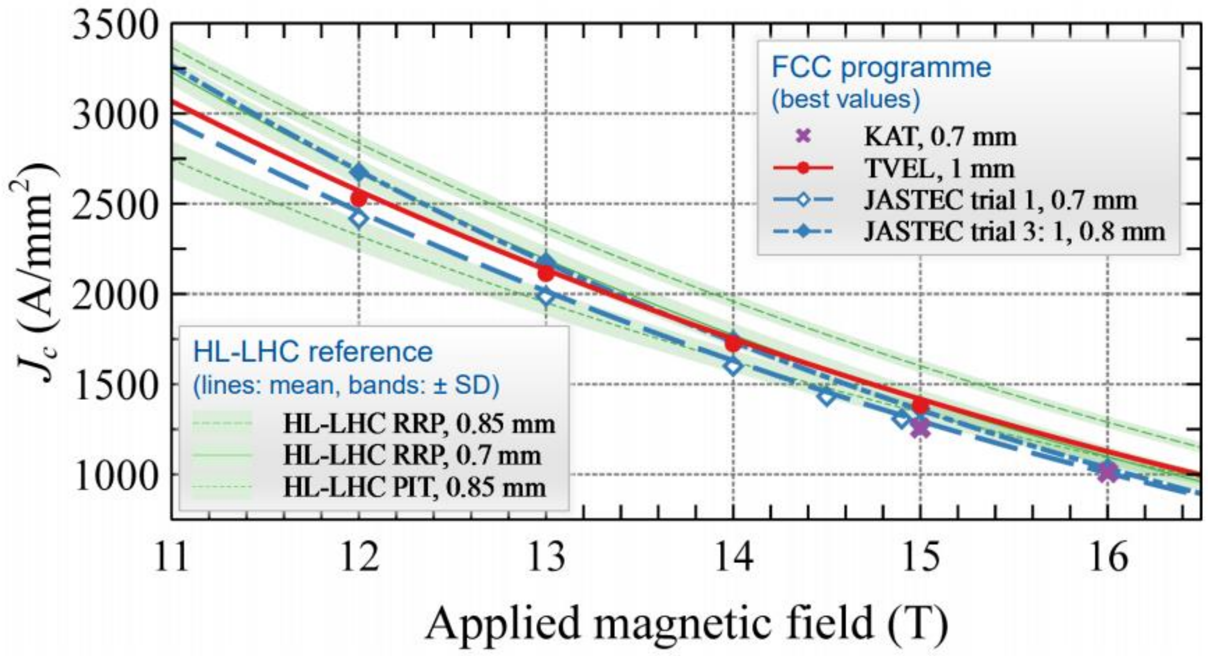
US wires with Artificial Pinning Centres (APCs) have reached FCC target J_c



X. Xu et al.

… and after less than one year, **new suppliers from Japan, Korea and Russia** already achieve HL-LHC specification

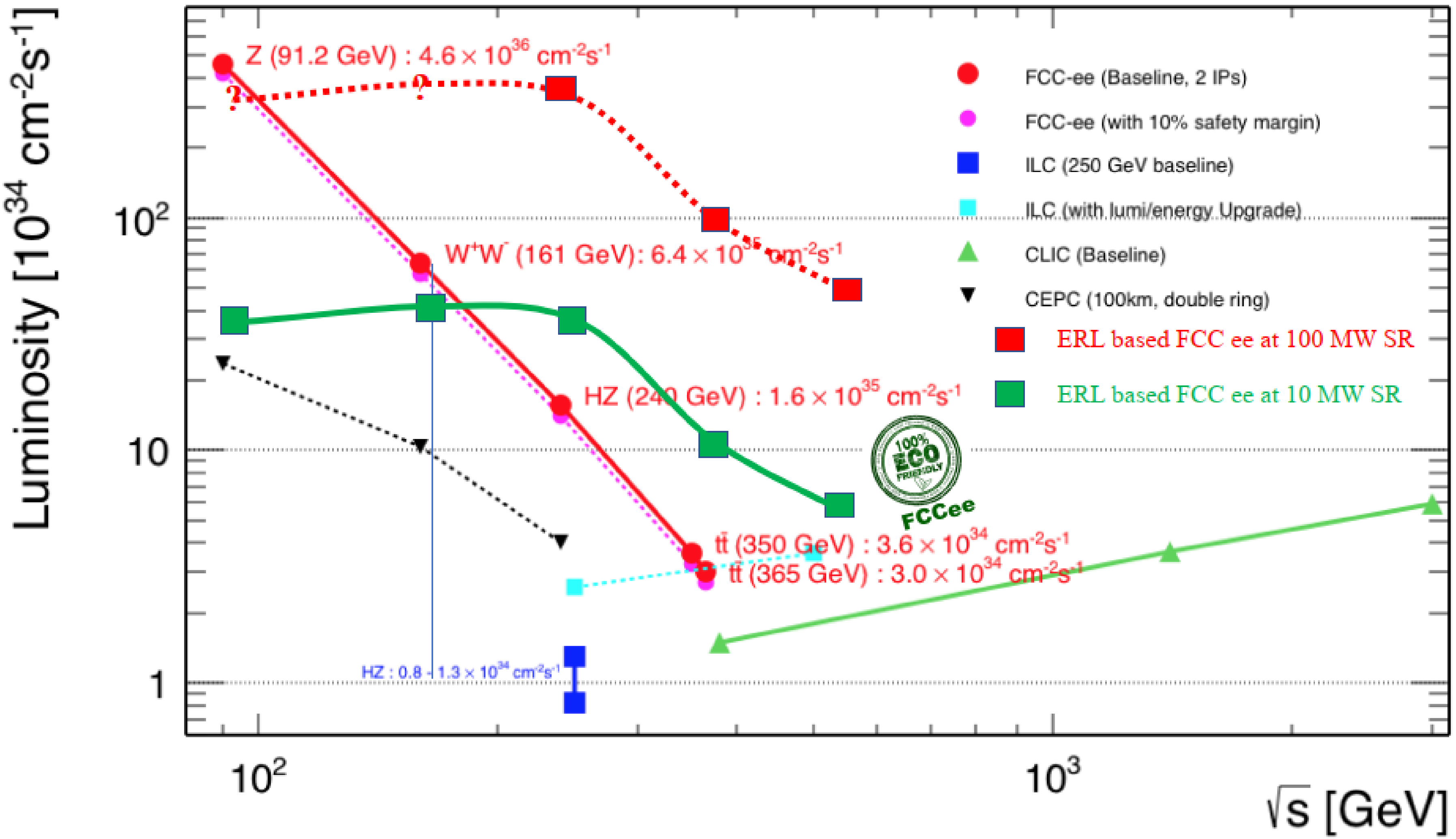
- high B_{c2} (28.8 T at 4.2 K)



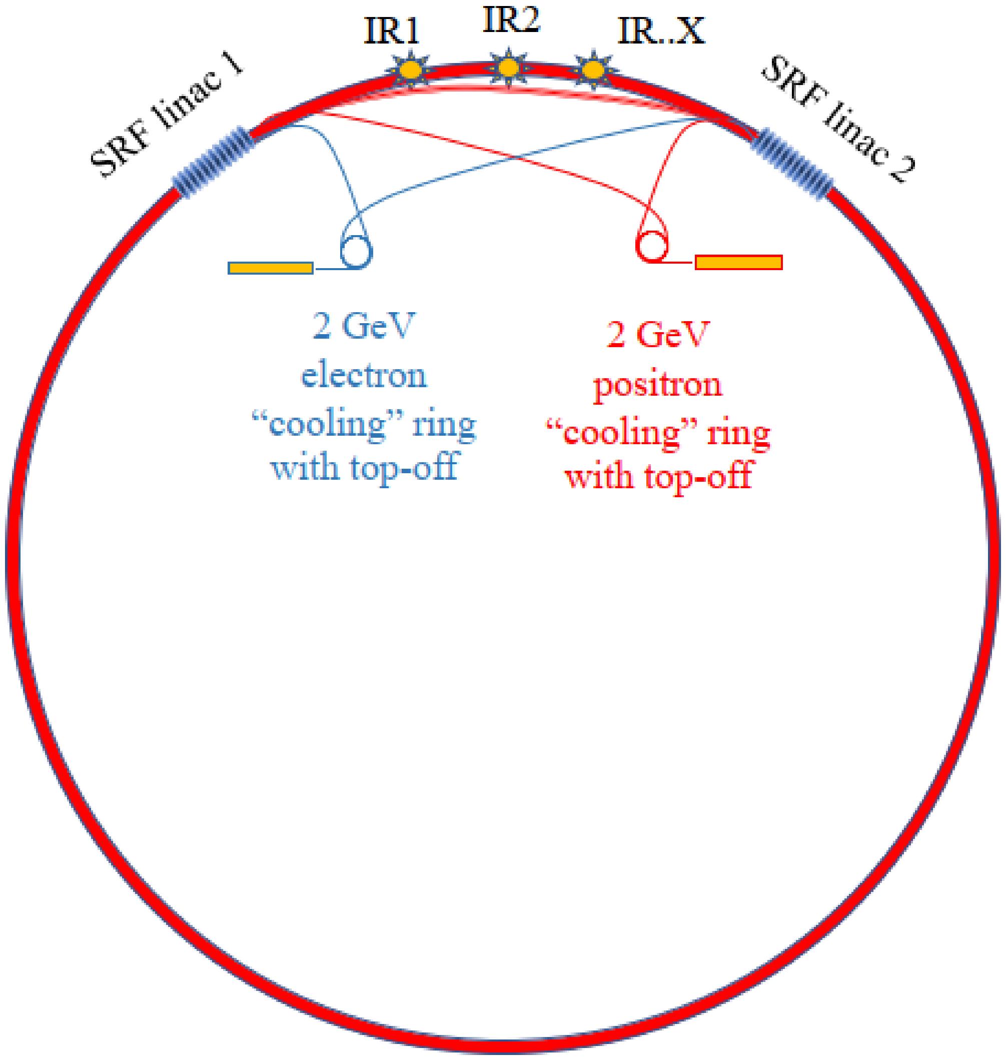
FNAL, Hyper Tech Research Inc. , and Ohio State
X. Xu et. al. 1. https://arxiv.org/abs/1903.08121 ;
Other great progress: NHMFL, FAMU/FSU: S. Balachandran et al. https://arxiv.org/ftp/arxiv/papers/1811/1811.08867.pdf (2018)

FCC-ee ERL option proposed by BNL

"Future High Energy Circular e⁺e⁻ Collider using Energy-Recovery Linacs," Vladimir N Litvinenko, Thomas Roser, Maria Chamizo Llatas, BNL, http://arxiv.org/abs/1909.04437



FCC-ee ERL option : stacked channels & damping rings



arXiv 1909.04437

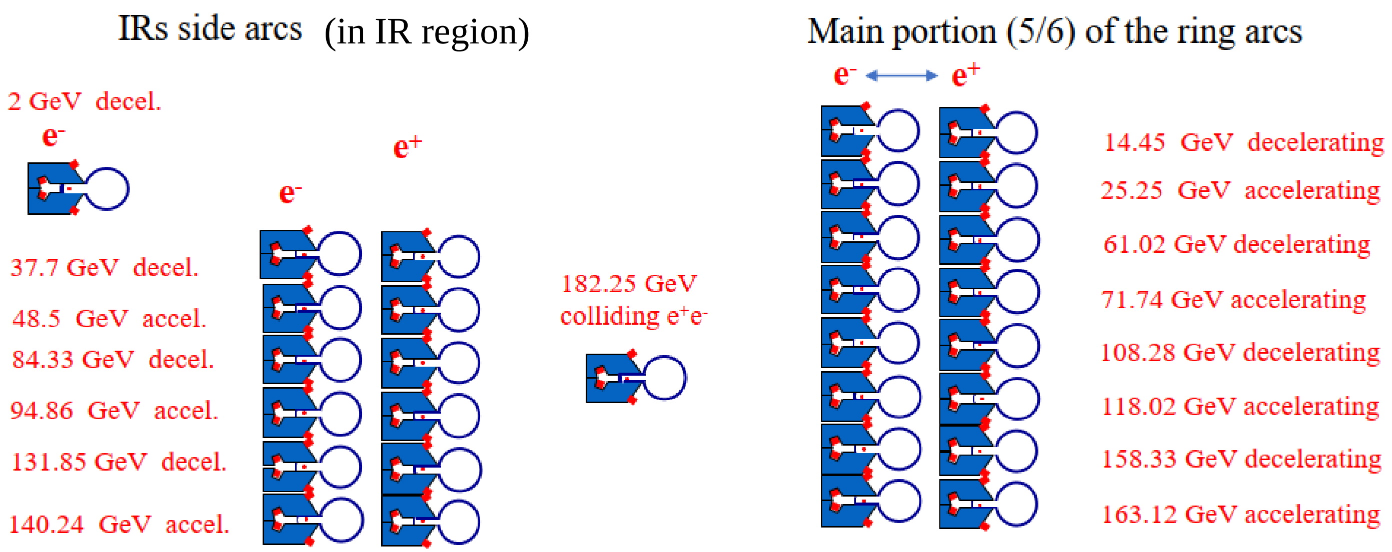


Fig. 5. Possible layout of the arcs for 4-pass ERLs with small gap electromagnets, similar to an early eRHIC linac-ring design [4]. The energies of the beams are shown for a top energy of 182.25 GeV (t-tbar).

Fig. 6. Electro-magnets with a small 5 mm gap prototyped for the eRHIC linac-ring design and tested at 0.43 T [9-10]. FCC ee needs dipoles with a magnetic field of up to 0.04 T and could be driven by a coil with low current.

FCC-ee ERL option : add paths to raise *E*, ≥500 GeV

FCC with ERLs	Z	W	H(HZ)	ttbar	HH
Beam energy, GeV	**45.6**	**80**	**120**	**182.5**	**250**
Four path ERL + Damping ring					
Energy loss per particle, GeV	**4.0**	**4.4**	**6.0**	**14.8**	**42.7**
Radiated power, MW/per beam	**5.0**	**5.0**	**5.0**	**5.0**	**4.9**
ERL linacs voltage, GV	**10.88**	**19.6**	**29.8**	**46.5**	**67.4**
Six path ERL + Damping ring					
Energy loss per particle, GeV	**4.1**	4.6	7.1	**20.4**	**64.5**
Radiated power, MW/per beam	**5.0**	5.2	5.9	**6.9**	**7.4**
ERL linacs voltage, GV	**7.25**	15.1	20	**31.6**	**47.7**
Secondary parameters					
Disruption, Dx	0.6	0.6	0.1	0.2	0.2
Disruption, Dy	183	177	129	143	121
Energy loss in IP, GeV	0.05	0.16	0.28	0.30	0.55
Tune shift, χ hor	8.9	8.9	11.7	8.0	6.8
Tune shift, χ ver	14.5	14.1	10.2	11.3	9.6
Cooler rings					
Cooler ring energy, GeV	2	2	2	2	2
Damping time, msec	2.0	2.0	2.0	2.0	2.0
Beam current, mA	534	486	356	146	49

FCC-ee (ttbar)
182.5

9.2
50
10.9

adding two passes

Table 2. FCC ee parameters for 4-path and 6-path ERL. arXiv 1909.04437

comparison: FCC-ee, FCC-ee ERL, ILC, CLIC

"combining the best of linacs and rings" (Peter Williams)

Parameter	Ring-Ring	ERL-ERL	ILC @250 GeV	CLIC @ 190 GeV
Horizontal norm ε, μm rad	518	8	10	1
Vertical norm ε, nm rad	964	8	35	30
Horizontal β, m	1.0	1.0	0.1	0.8
Vertical β, mm	2.0	2.0	0.5	0.1
RMS bunch length, mm	2.0	2.0	0.3	0.07
Beam collision rate, kHz	116.9	15.0	6.5	17.6
Bunch charge, nC	46.2	22.5	3.2	0.8
Beam current, mA	5.40	0.34	0.021	0.015
Particle energy loss, GeV	9.2	14.8	250.0	190.0
Beam losses, MW (two beams)	100.00	9.98	10.40	5.55
Energy spread in IP, %	0.18	0.16	-	-
Dx/Dy	N/A	0.2/143	0.3 / 24.3	0.24 / 12.5
Crossing angle	YES	NO	YES	YES

arXiv 1909.04437

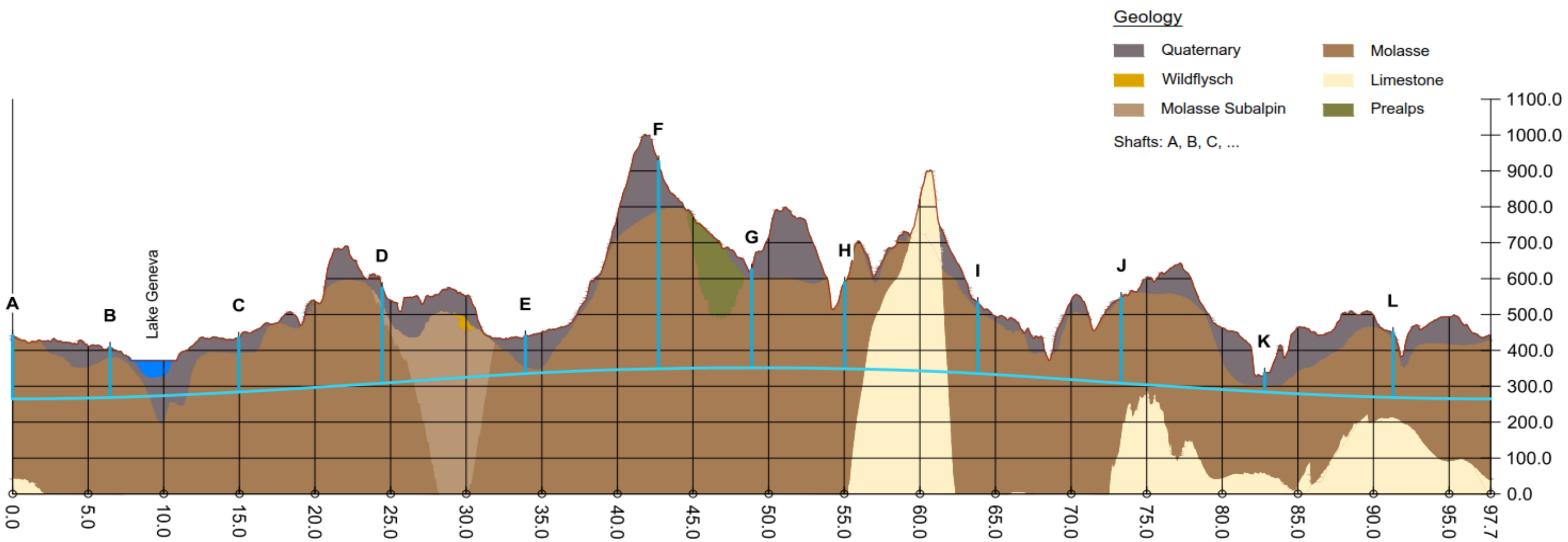
questions for ERL option:

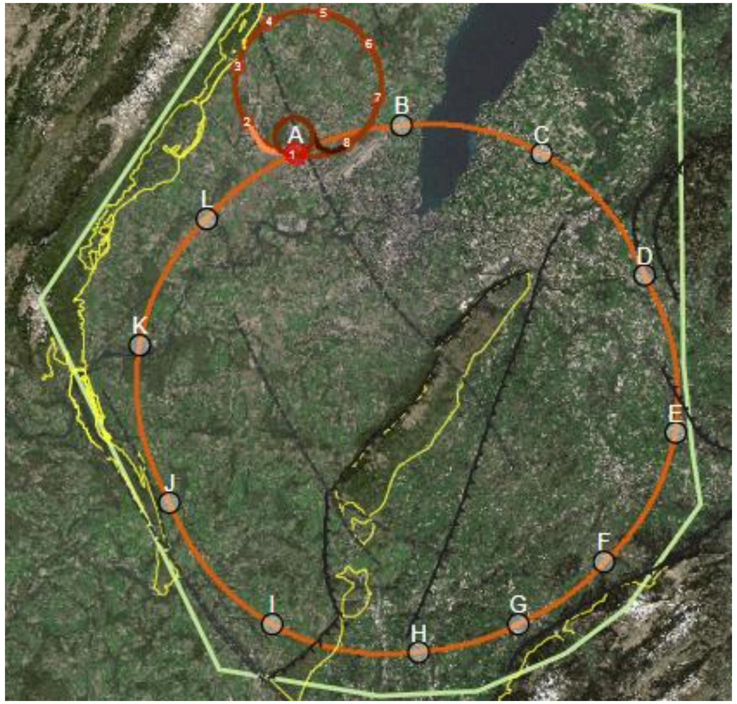
- **feasibility?** maximum current, collective effects, emittance preservation, disruption ?
- **physics interest?** energy calibration, luminosity spectrum ?
- **addt'l cost?**

FCC integrated program

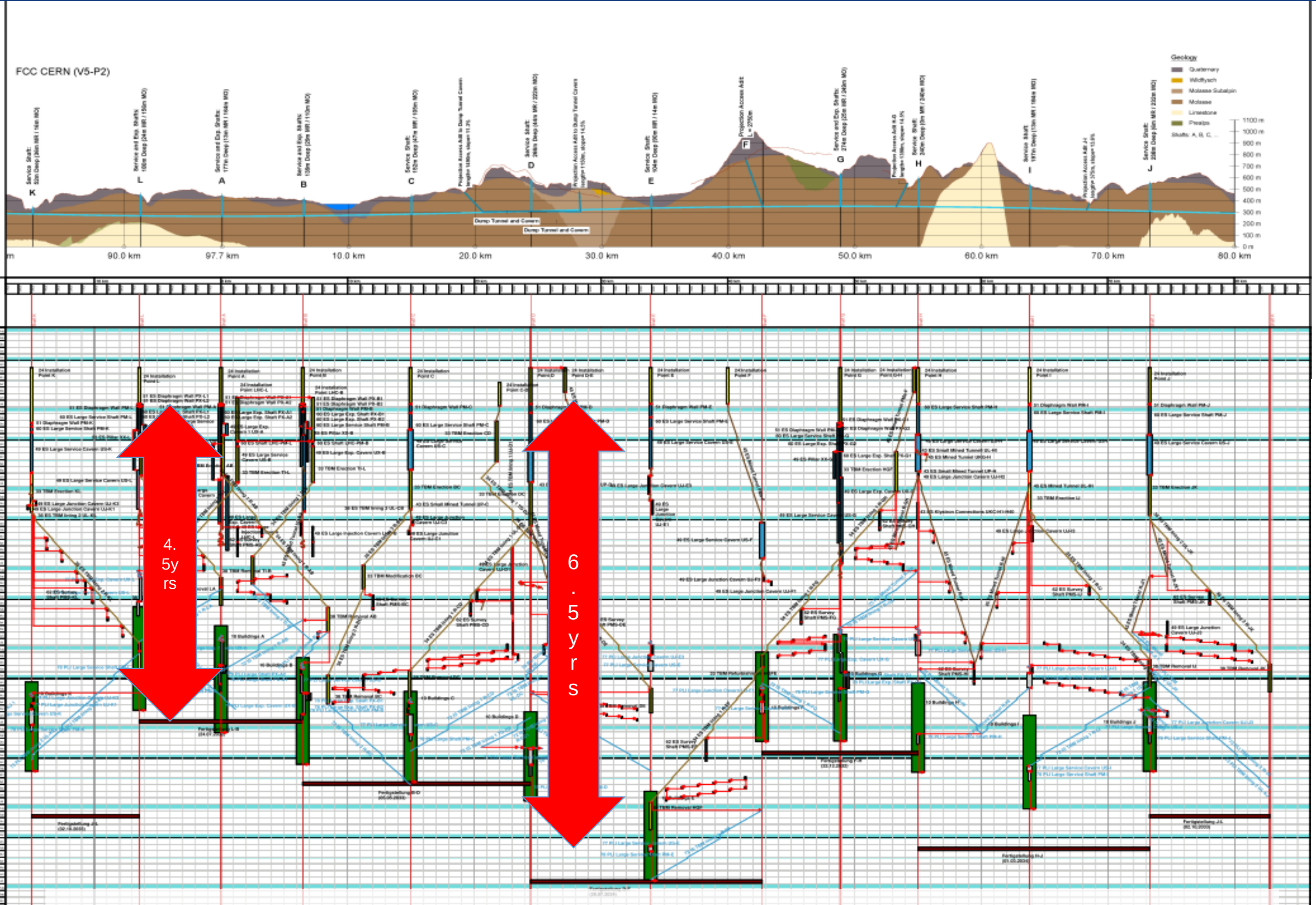
Comprehensive cost-effective program maximizing physics opportunities

- **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.

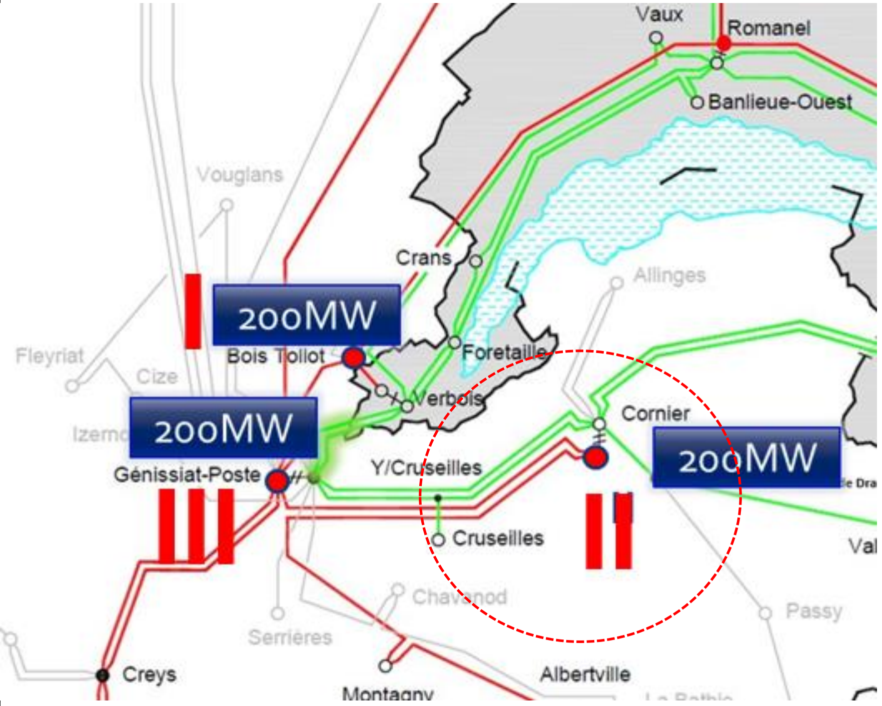




Implementation studies



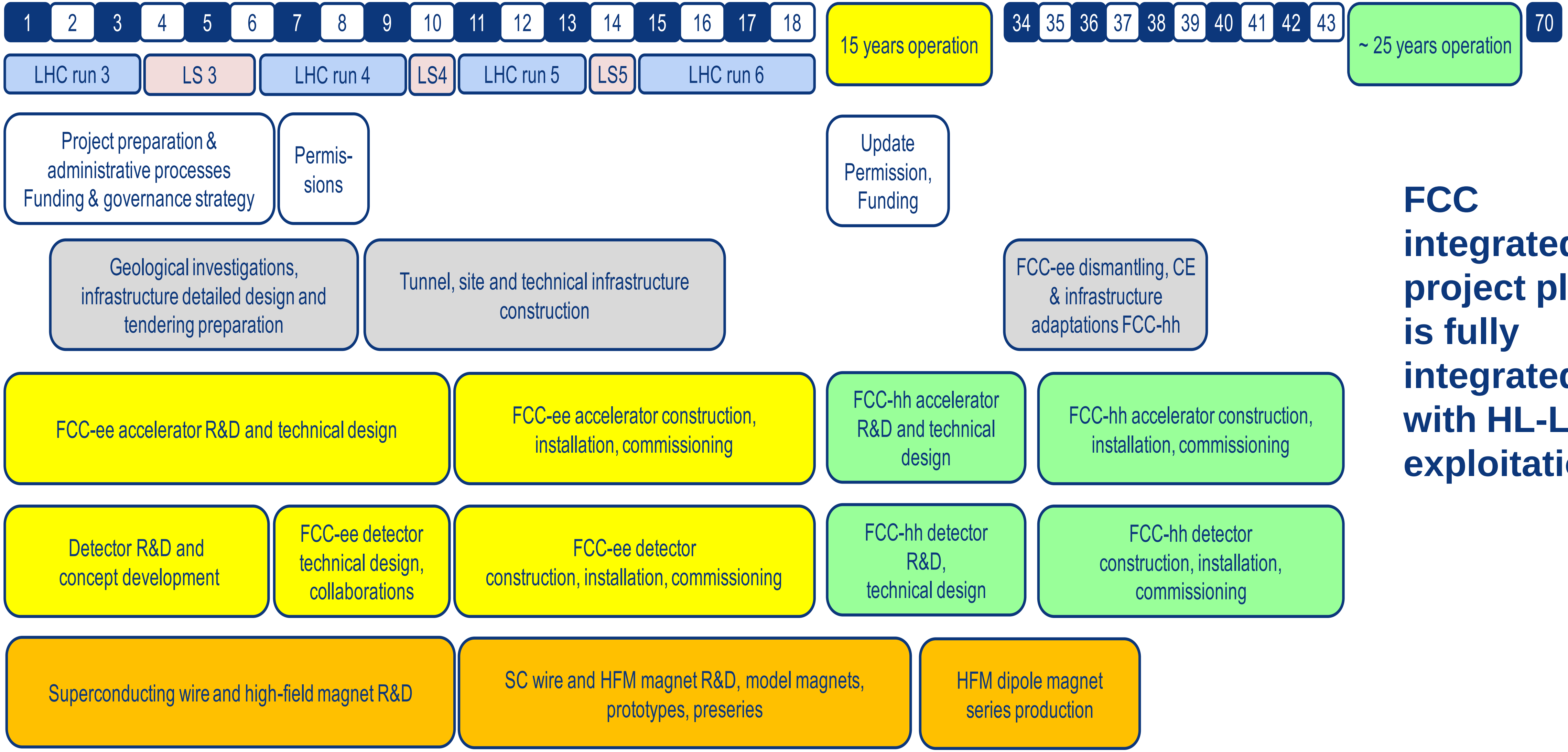
Additional 200 MW available for FCCat each of the three 400 kV sources from European grid



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

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

FCC integrated project technical schedule

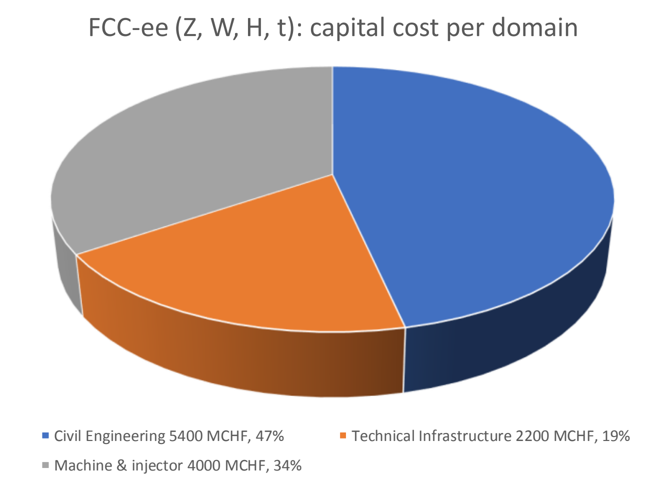


FCC integrated project plan is fully integrated with HL-LHC exploitation

FCC integrated project cost estimate

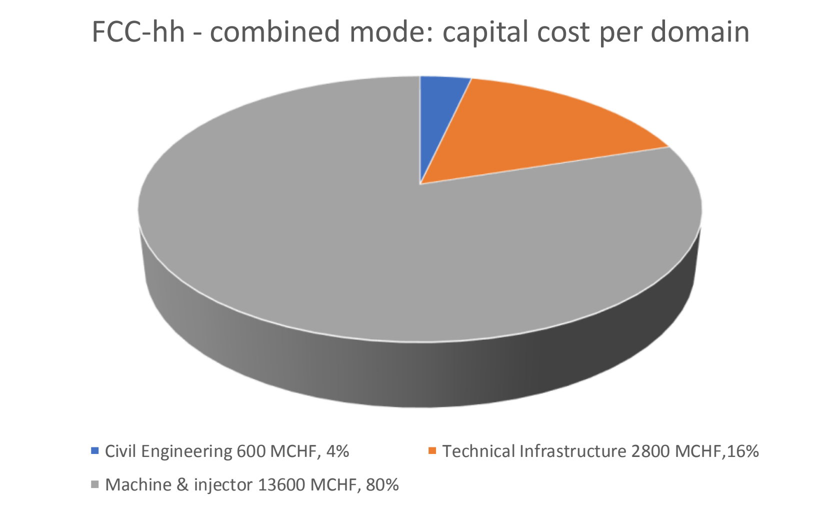
Construction cost phase1 (FCC-ee) is 11,6 BCHF

- 5,4 BCHF for civil engineering (47%)
- 2,2 BCHF for technical infrastructure (19%)
- 4,0 BCHF accelerator and injector (34%)



Construction cost phase 2 (FCC-hh) is 17,0 BCHF

- 13,6 BCHF accelerator and injector (57%)
  - Major part for4,700 Nb_3Sn 16 T main dipole magnets, totalling 9,4 BCHF, targeting 2 MCHF/magnet.
- CE and TI from FCC-ee re-used, 0,6 BCHF for adaptation
- 2,8 BCHF for additional TI, driven by cryogenics



(Cost FCC-hh stand alone would be 24,0 BCHF)

FCC work with host states

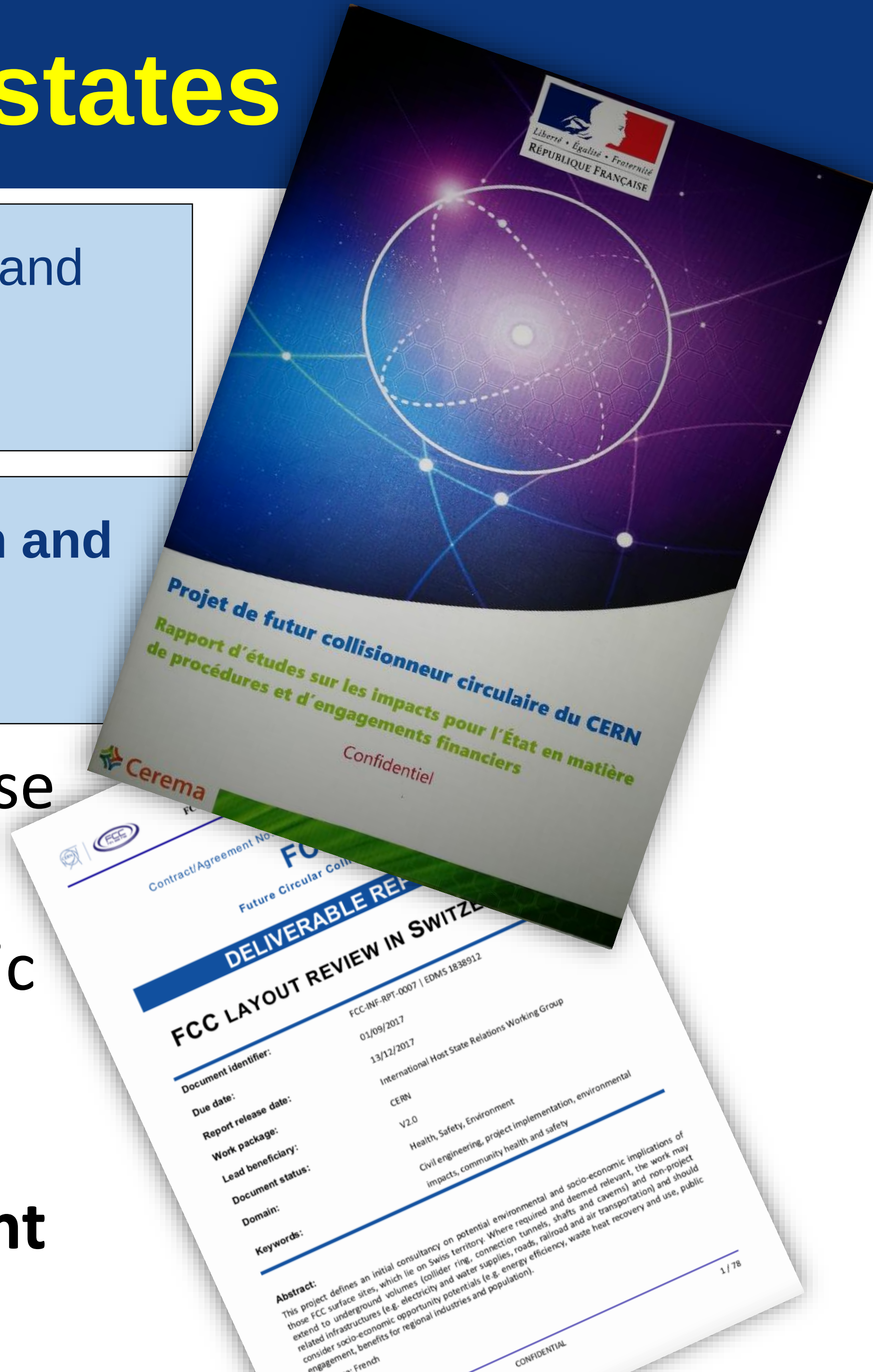
General secretariat of the region Auvergne-Rhône-Alpes and notified body “Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement”

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

requirements for urbanistic, environmental, economic impact, land acquisition and construction permit related processes defined

common review of tunnel and surface site placement ongoing



FCC - Next steps

2019-2020:

- layout **optimisation** and work on **implementation with host states**
- near-term focus on **FCC-ee as potential first step** (awaiting strategy recommendation).
- preparation of **EU H2020 DS project** (INFRADEV call November 2019), focused on infrastructure implementation

2020/21 – 2025/26: project preparation phase (if supported by EPPSU and CERN Council)

LHeC & FCC in 2019 ESU strategy scenarios

	2020-2040		2040-2060 1st gen technology	2060-2080 2nd gen technology
CLIC-all	HL-LHC	**+LHeC**	**CLIC380-1500**	CLIC3000 / other tech
CLIC-FCC	HL-LHC	**+LHeC**	**CLIC380**	FCC-h/e/A (Adv HF magnets) / other tech
FCC-all	HL-LHC	**+LHeC**	**FCC-ee (90-365)**	FCC-h/e/A (Adv HF magnets) / other tech
LE-to-HE-FCC-h/e/A	HL-LHC	**+LHeC**	**LE-FCC-h/e/A (low-field magnets)**	FCC-h/e/A (Adv HF magnets) / other tech
LHeC-FCC-h/e/A	HL-LHC	**+ LHeC**	**LHeC**	FCC-h/e/A (Adv HF magnets) / other tech

completed scenarios

LHeC/FCC-eh fits in every scenario !