Future Colliders

Jan. 7, 2019

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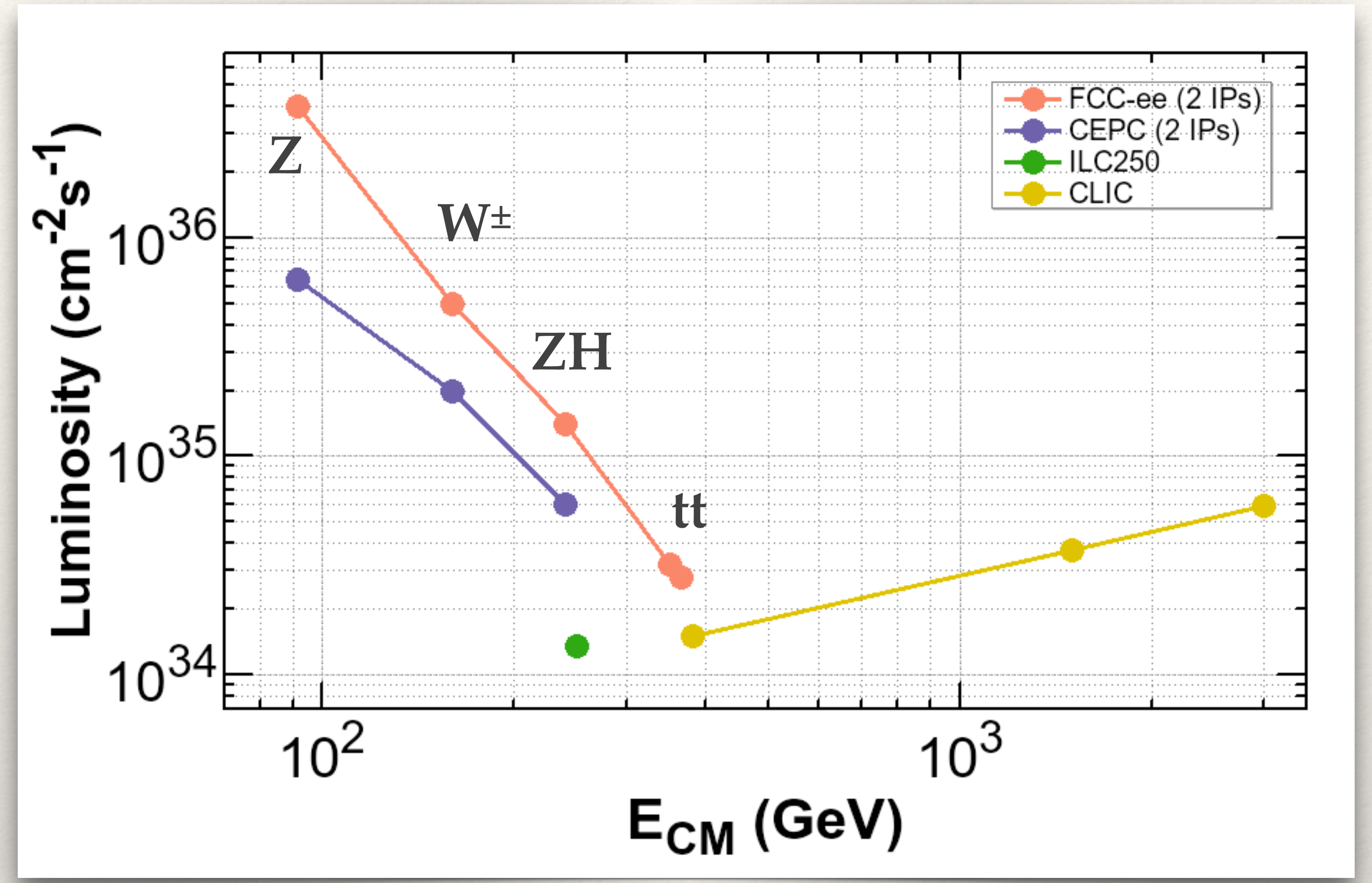
Joint Kavli IPMU — ICEPP Workshop
on Future Directions for HEP
@ Tokyo Univ.

Many thanks to M. Benedikt, J. Gao, D. Schulte, F. Zimmermann,
and everybody I have borrowed the materials.

Future e+e- colliders (CEPC, FCC-ee, CLIC)

Future Circular Collider, The Lepton Collider (FCC-ee) V1.5 (2018-12-17)

CEPC CDR

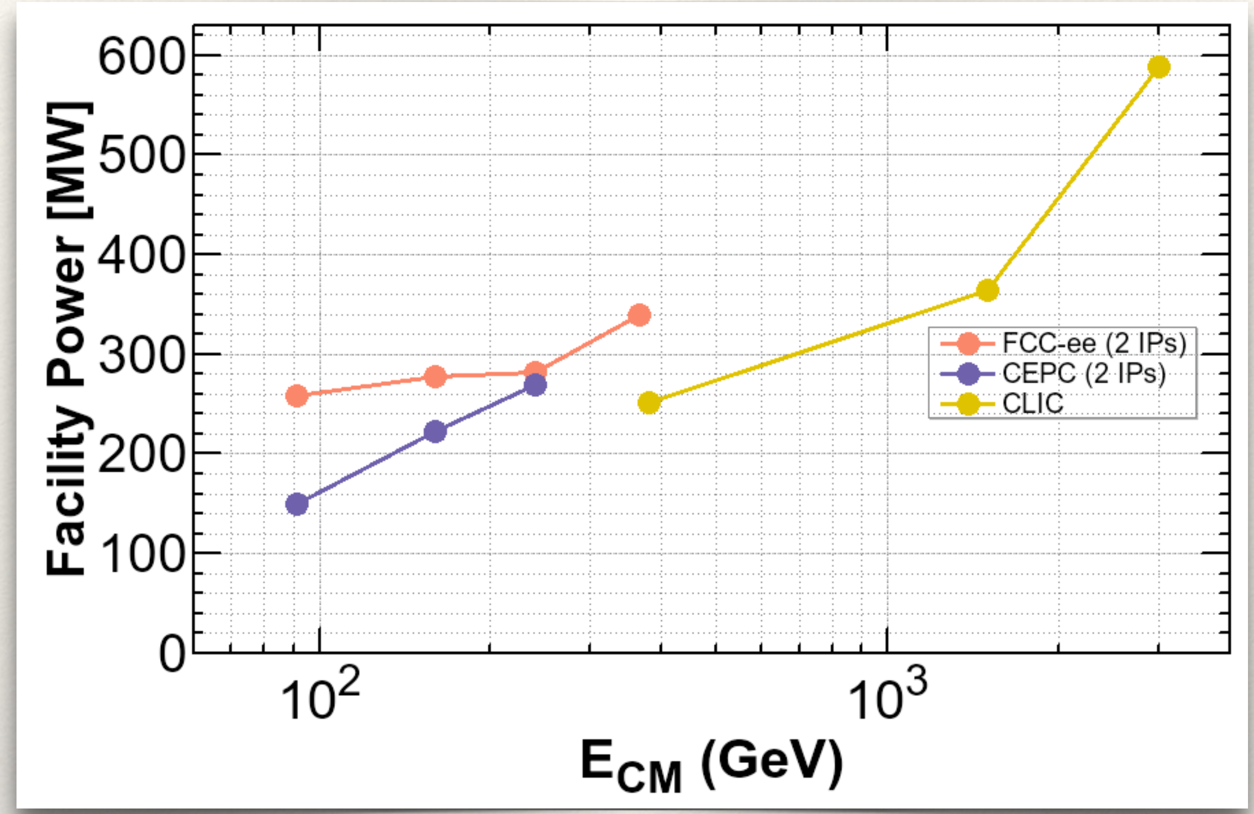


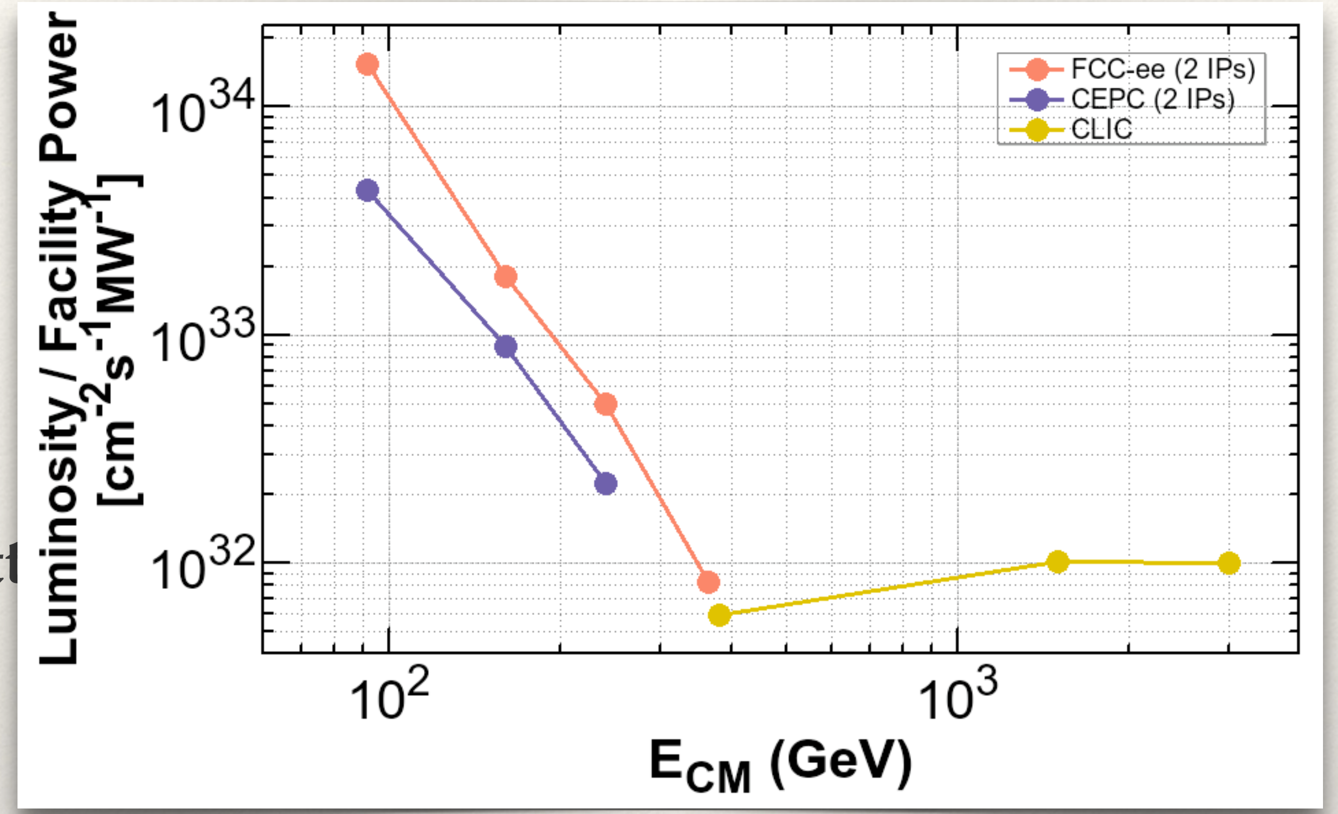
UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER, CERN–2016–004

http://newsline.linearcollider.org/2018/04/05/the-ilc-at-250-gev-an-overview-of-options/

- Circular colliders have advantage in luminosity up to 400 GeV CM. At Z, they have 2-3 orders higher luminosity than LCs.
- The steep falls in the luminosity of circular colliders are due to constraints to keep the synchrotron radiation power constant over energies.
- Beyond 400 GeV, LCs take over, and there is no chance for circular e+e- machines (for 100 km circumference & 50 MW/beam).
- More exotic energies, such as the s-channel Higgs production, may be possible at circular colliders.

Future e+e- colliders (CEPC, FCC-ee, CLIC)





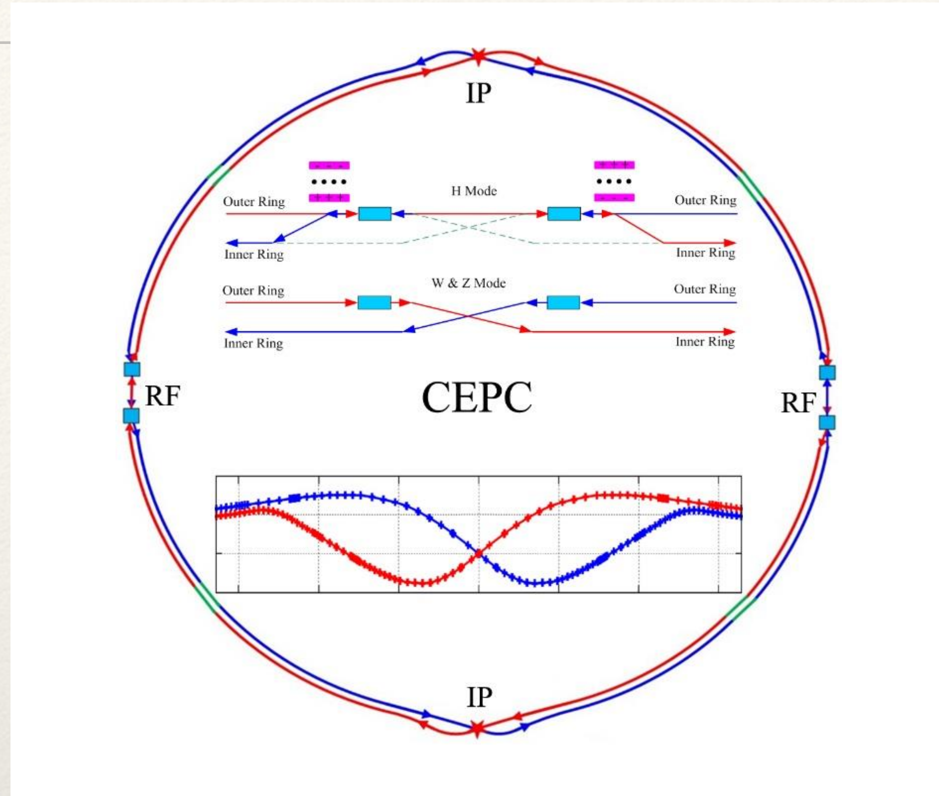
- The luminosity per unit power consumption shows the same tendency. The cross over energy between circular/linear colliders is around 400 GeV CM.

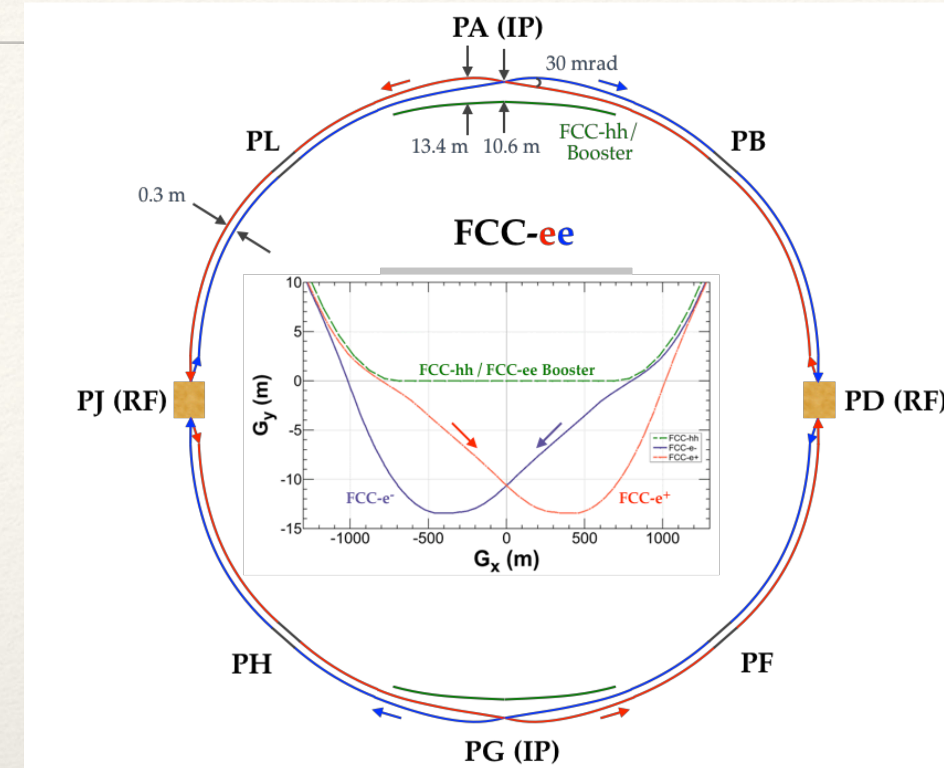
Future Circular Collider, The Lepton Collider (FCC-ee) V1.5 (2018-12-17)

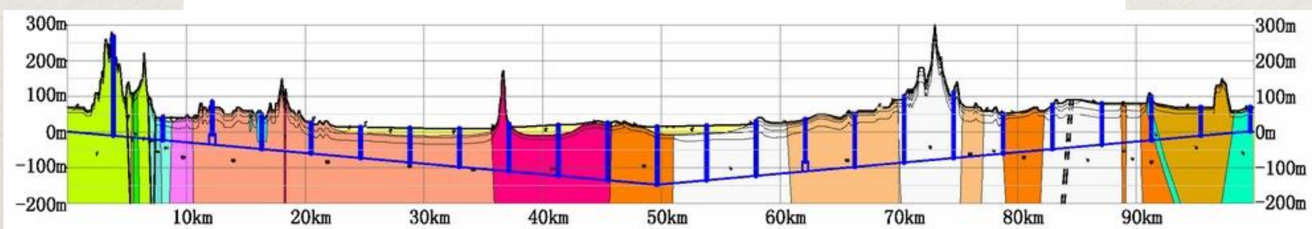
CEPC CDR

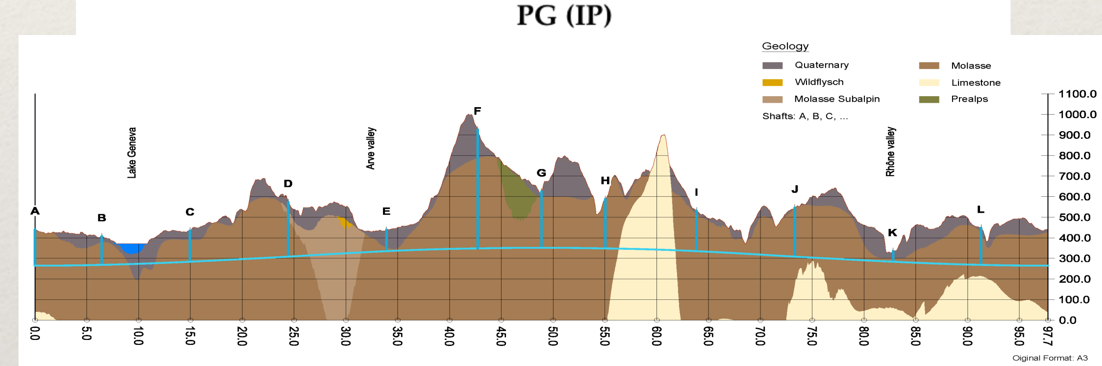
UPDATED BASELINE FOR A STAGED COMPACT LINEAR COLLIDER, CERN–2016–004

Circular e+e- colliders (CEPC, FCC-ee)

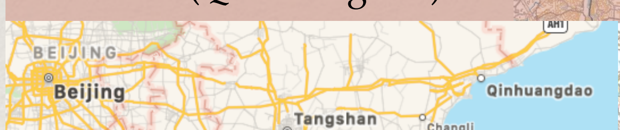


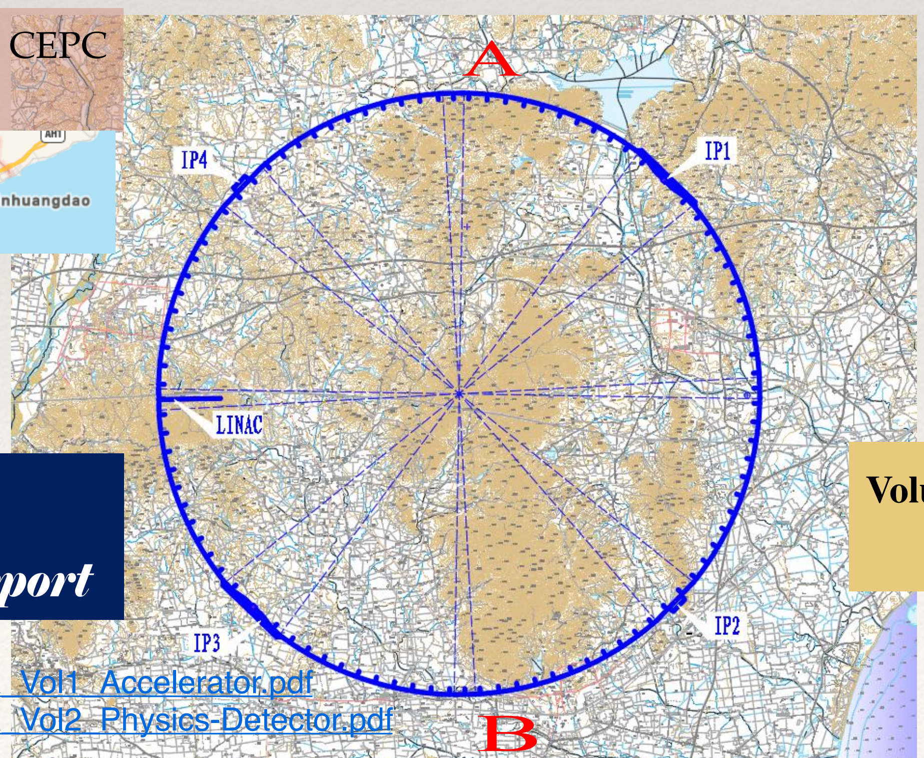






One of the candidate sites for CEPC (Qinhuangdao)





CEPC

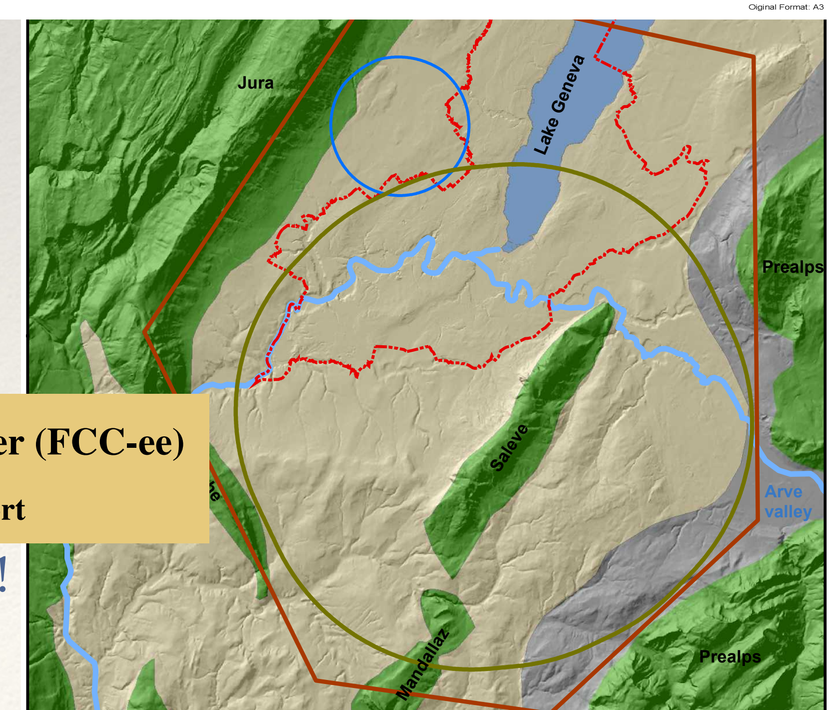
Conceptual Design Report

http://cepc.ihep.ac.cn/CEPC_CDR_Vol1_Accelerator.pdf
http://cepc.ihep.ac.cn/CEPC_CDR_Vol2_Physics-Detector.pdf

Volume 2 - The Lepton Collider (FCC-ee)

Conceptual Design Report

coming next week!

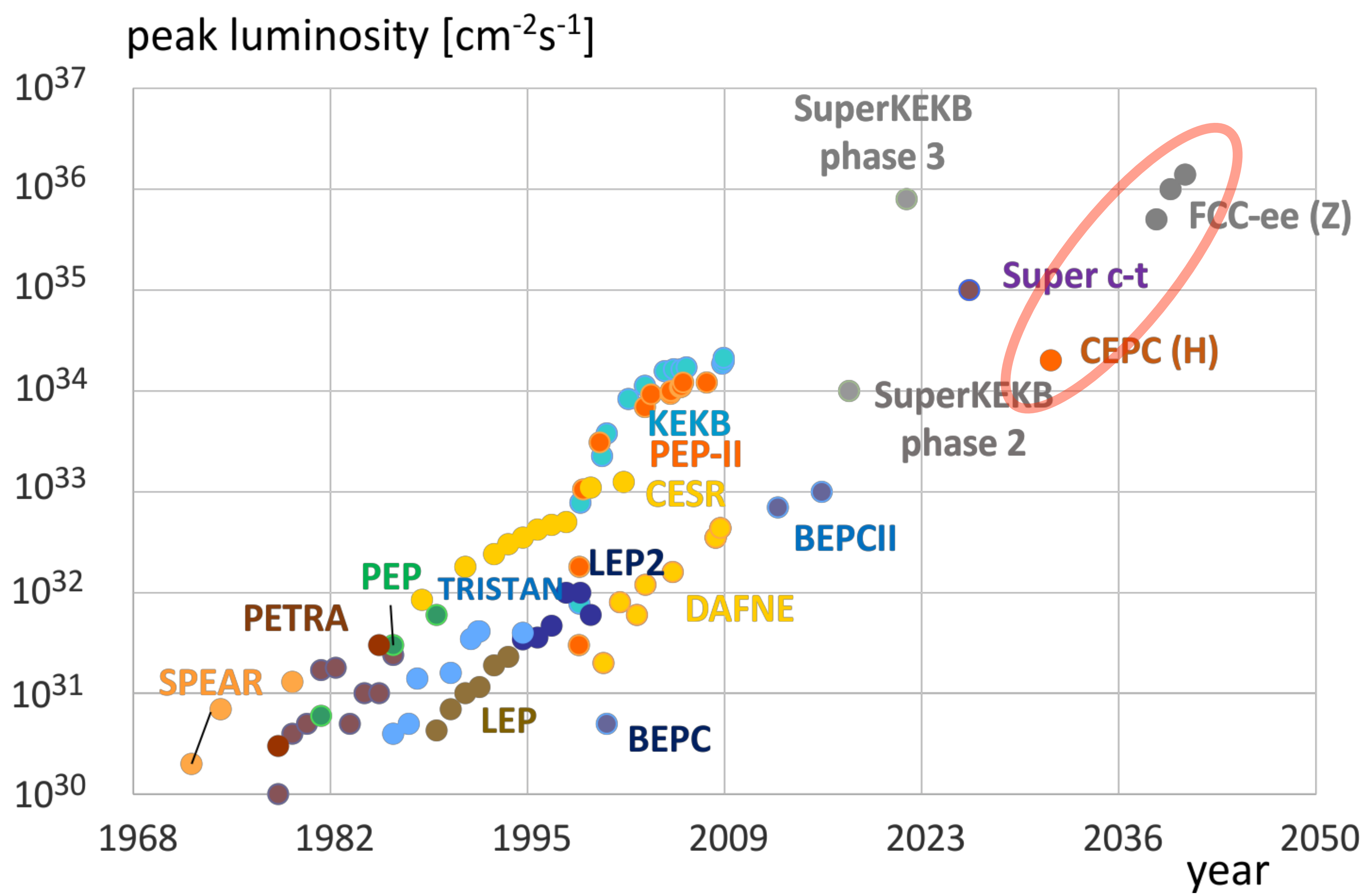


Circular e+e- colliders (CEPC, FCC-ee)

- 100 km, double ring, 2 IPs.
- Limit total synchrotron radiation (SR) power < 60/100 MW (CEPC/FCC-ee) at all energies.
- "Crab-waist" scheme with a large crossing angle at the IP for higher luminosity performance, as verified at DAFNE.
- Advantages in luminosity over linear colliders. in the range below 400 GeV CM.
- Based on existing accelerator technologies experienced in all e+e- colliders in the world for over a half century including:
  - normal/superconducting magnets & RF systems
  - vacuum system with SR/e-cloud/impedance mitigations
  - linac and e+e- production/injection devices including e+ damping ring
  - beam diagnostics and control
  - alignments, civil engineering with safety considerations
  - beam polarization
  - beam dynamics and handling, incl. collective effects, e-cloud, beam-beam, etc.
- Synergies with light sources and linear colliders.

Circular e+e- colliders (CEPC, FCC-ee)

circular e^+e^- colliders: 50 year success story



Peak luminosity of circular e^+e^- colliders as a function of year – for past, operating, and proposed facilities including the Future Circular Collider

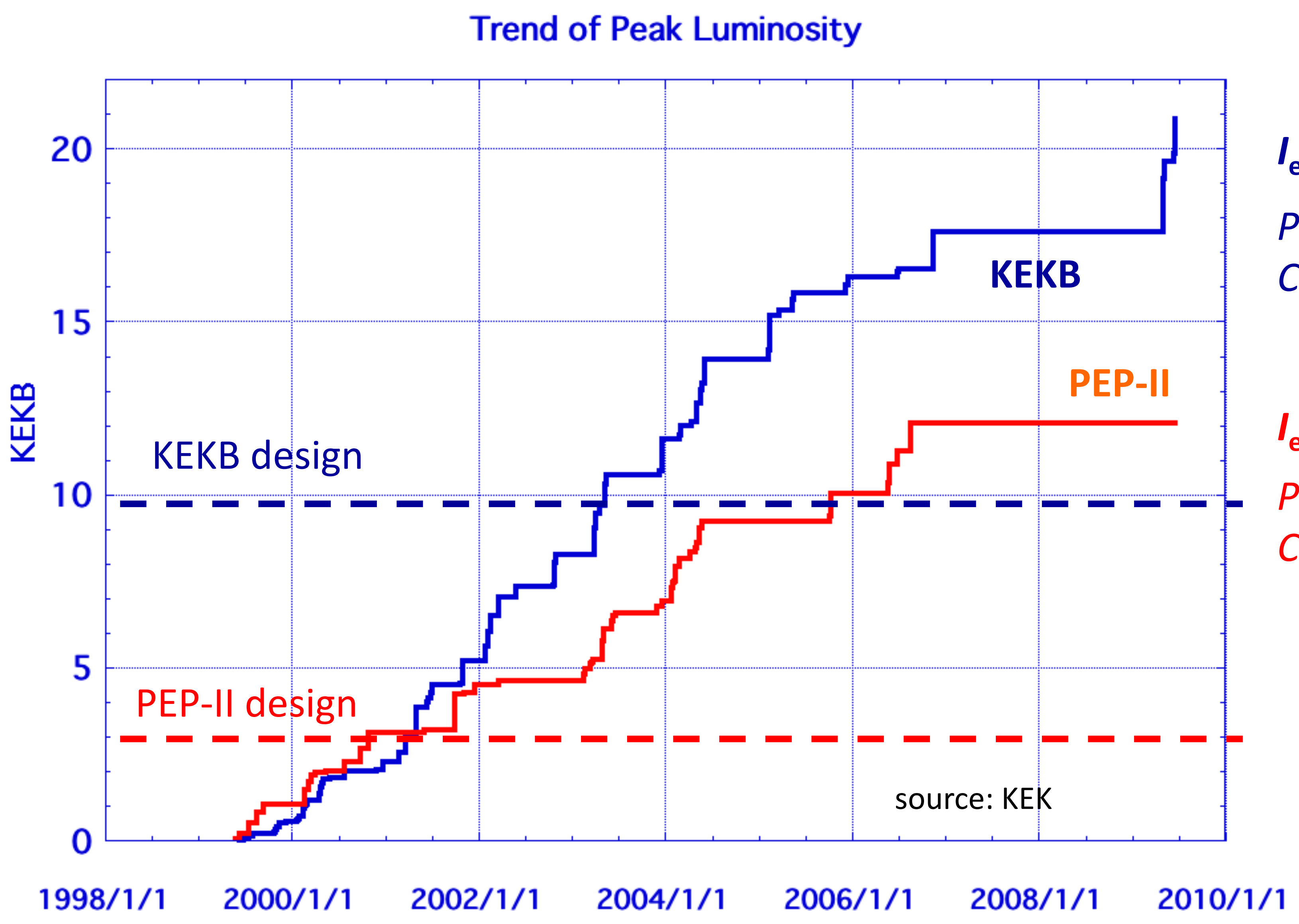
[historical data courtesy Y. Funakoshi]

F. Zimmermann

Circular e+e- colliders (CEPC, FCC-ee)

B factories: high current, high luminosity

+ top-up injection



I_{e+}=1.6 A, I_{e-}=1.2 A

P_{SR} ~ 5 MW

C = 3 km

I_{e+}=3.2 A, I_{e-}=2.1 A

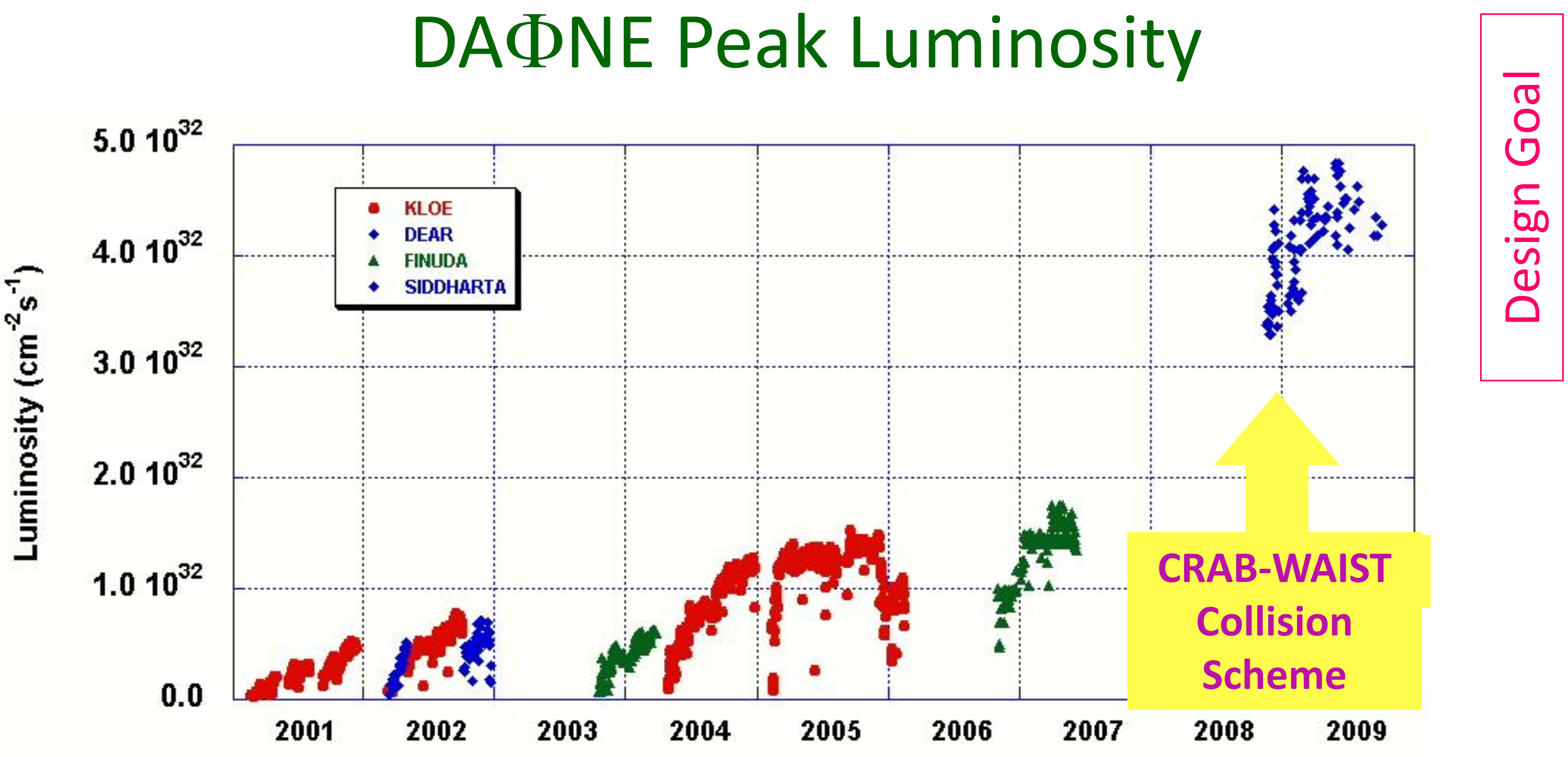
P_{SR} ~ 8 MW

C = 2.2 km

F. Zimmermann

Circular e+e- colliders (CEPC, FCC-ee)

DAΦNE: crab waist collisions

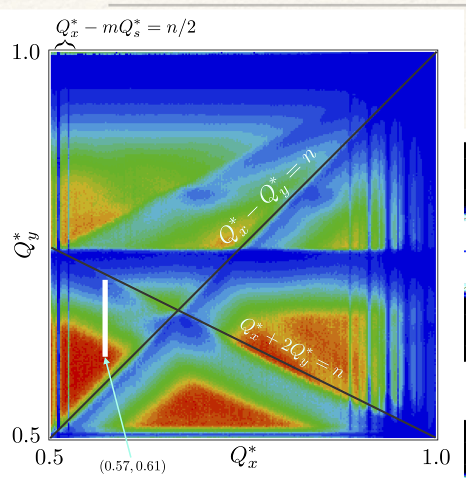


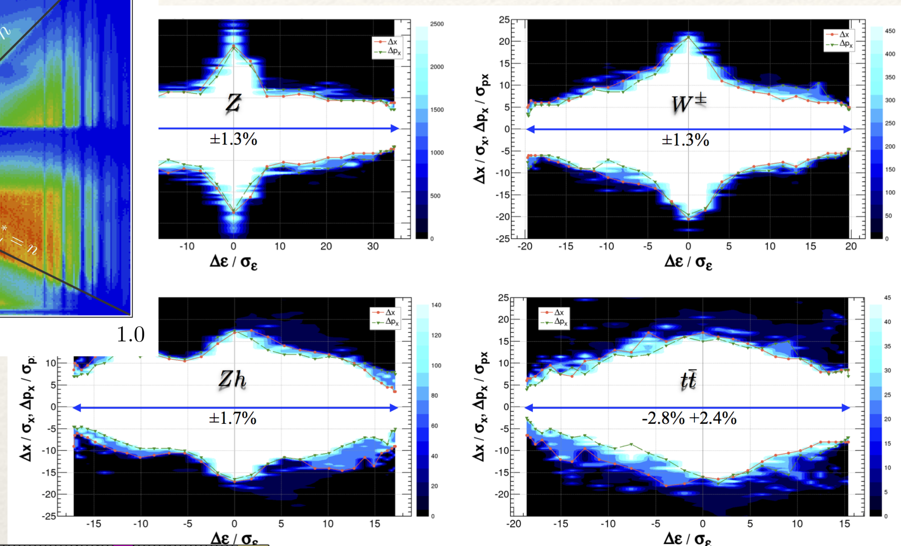
small β_y^*, large beam-beam tune shift

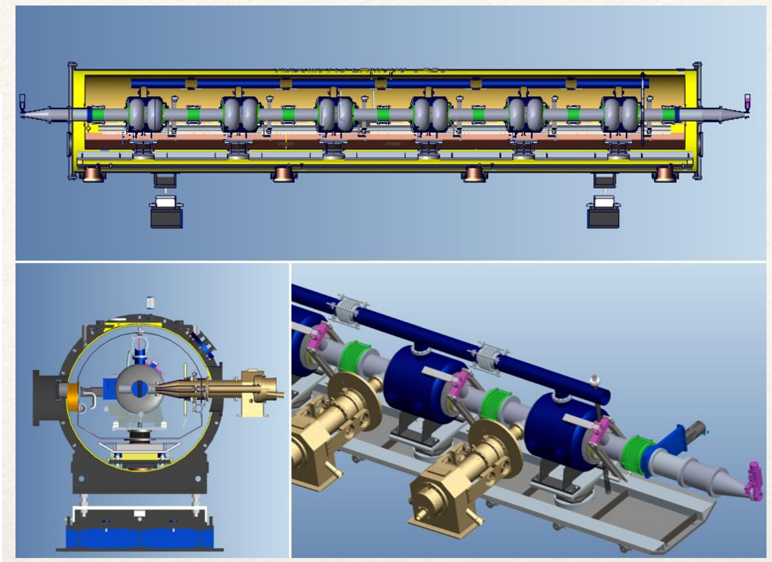
M. Zobov

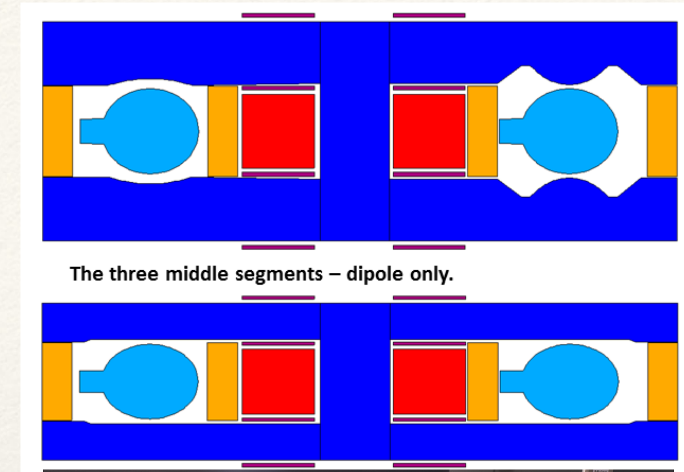
F. Zimmermann

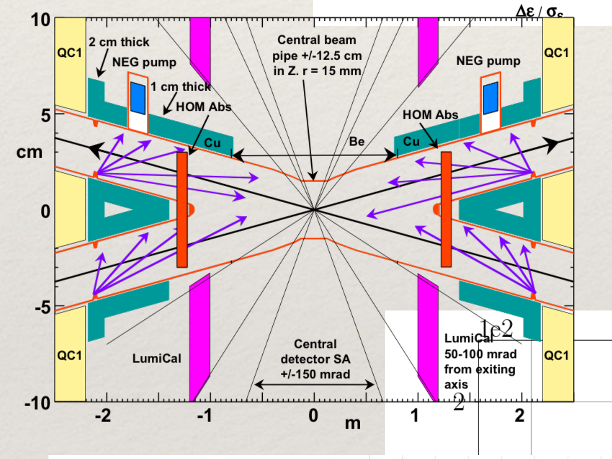
Circular e+e- colliders (CEPC, FCC-ee)

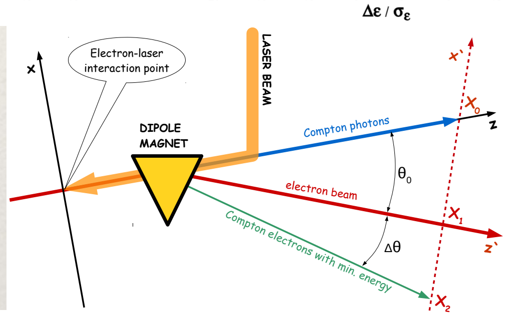


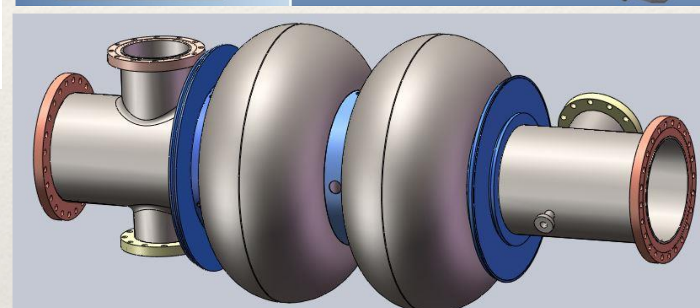


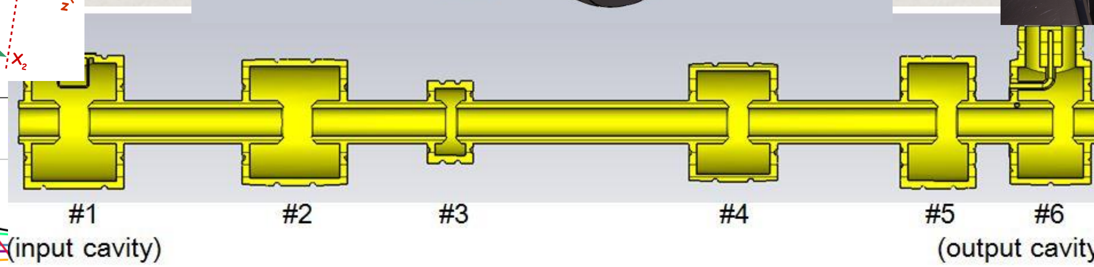


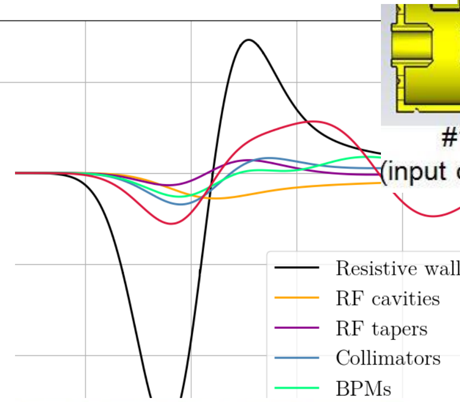


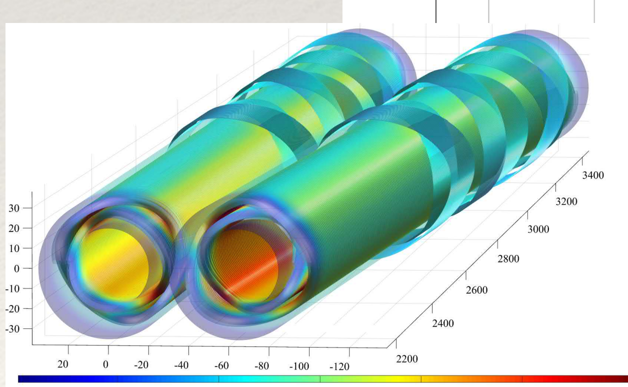


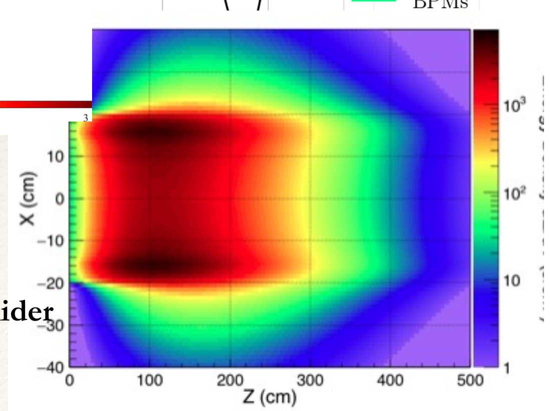


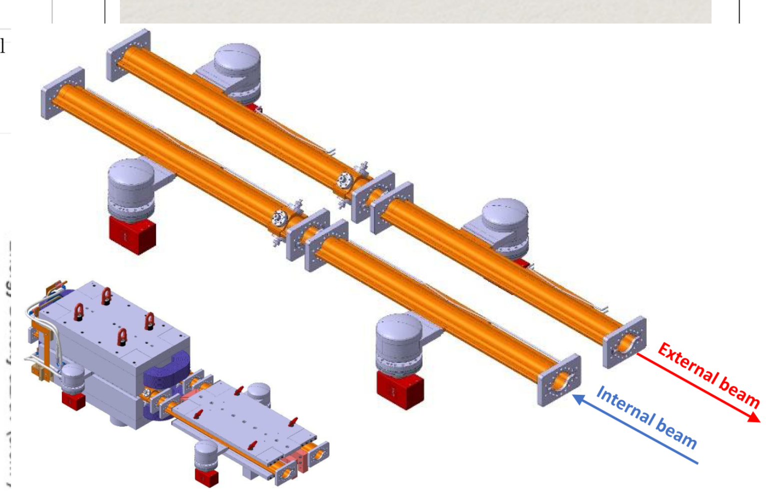


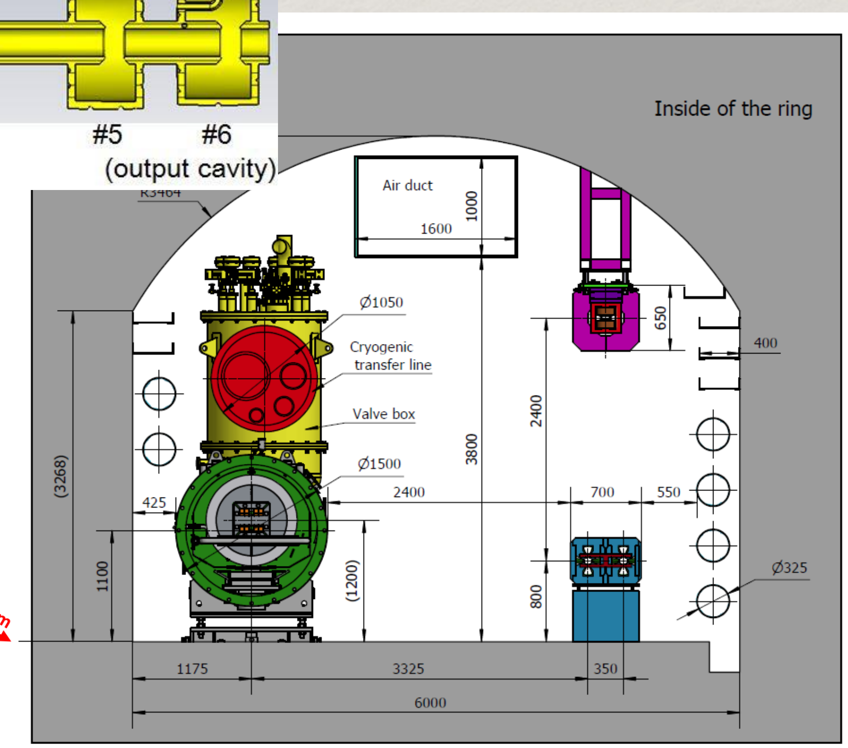












CEPC CDR

Future Circular Collider, The Lepton Collider (FCC-ee) V1.5 (2018-12-17)

Circular e+e- colliders (CEPC, FCC-ee)

Parameters	CEPC		FCC-ee		
	Z	ZH	Z	ZH	$t\bar{t}$
E_{beam} [GeV]	45.6	120	45.6	120	182.5
Circumference [km]	100		97.756		
Current / beam [mA]	461	17.4	1390	29	5.4
SR power / beam [W}	16.5	30	50		
Crossing angle at IP [mrad]	33		30		
β-functions at IP (x/y) [m/mm]	0.2/1.0	0.36/1.5	0.15/0.8	0.3/1.0	1/1.6
Emittance (x/y) [nm/pm]	0.18/1.6	1.21/2.4	0.27/1.0	0.63/1.3	1.46/2.9
Beam sizes at IP [μm/nm]	6.0/40	20.9/60	6.4/28	13.7/36	38.2/68
Bunch length (SR/BS)* [mm]	2.4/8.5	2.7/4.4	3.5/12.1	3.2/5.3	2.0/2.5
Energy spread (SR/BS) [10^{-4}]	3.8/8.0	10.0/13.4	3.8/13.2	9.9/16.5	15.0/19.2
Particles/bunch [10^{11}]	0.8	1.5	1.7	1.8	2.3
Bunches/beam	12000	242	16640	328	48
Beam-beam parameters (x/y)	0.004/0.079	0.018/0.109	0.004/0.133	0.016/0.118	0.099/0.126
Luminosity/IP [10^{34}/cm^{2}s]	**32**	**3.0**	**230**	**8.5**	**1.55**

* SR = synch. rad. only, BS = synch. rad. + beamstrahlung

CEPC CDR

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Circular e+e- colliders (CEPC, FCC-ee)

CEPC

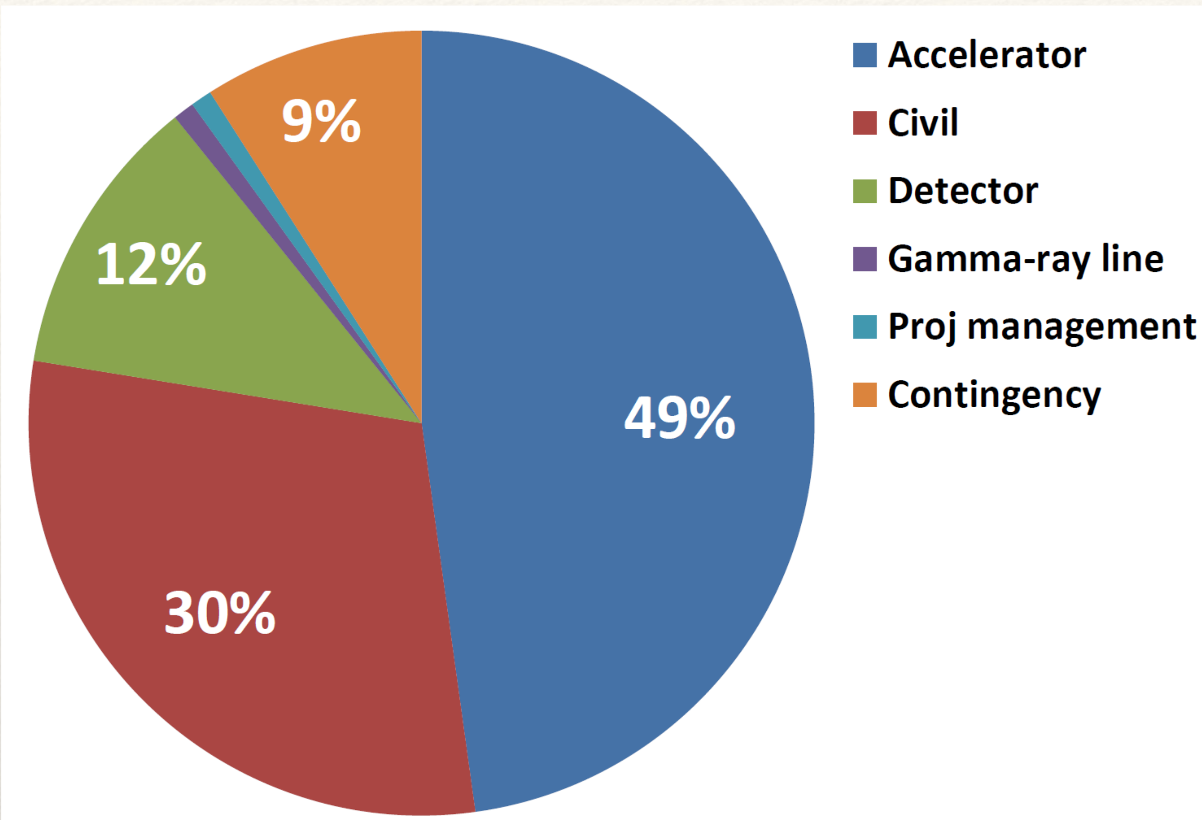
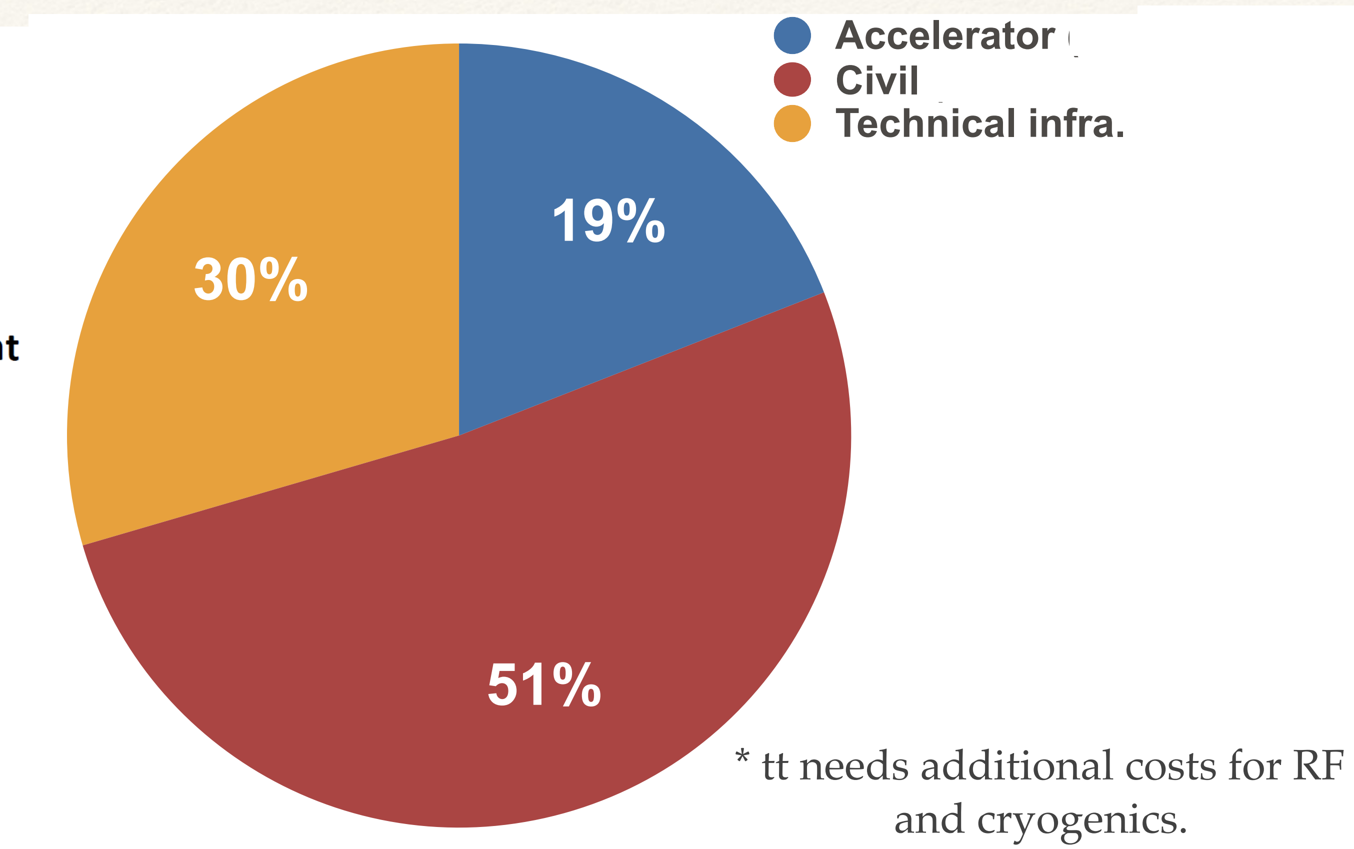


Figure 12.1: Relative cost of the CEPC project constituents.

FCC-ee (detectors not included)



- Note that the relative portion for civil engineering and technical infrastructure is much smaller in CEPC than FCC-ee.
- CEPC-CDR saids "The cost saving is more than 50%", compared to FCC-ee.
- The cost for FCC-ee roughly agrees with scaling from LEP (1/3.5) including ~150% escalation of CHF since 1985. http://fxtop.com/en/inflation-calculator.php?A=100&C1=CHF&INDICE=CHCPI2011&DD1=01&MM1=01&YYYY1=1985&DD2=04&MM2=01&YYYY2=2019&btnOK=Compute+actual+value

CEPC CDR

Future Circular Collider, The Lepton Collider (FCC-ee)

V1.5 (2018-12-17)

Circular e+e- colliders (CEPC, FCC-ee)

CEPC CDR

CEPC

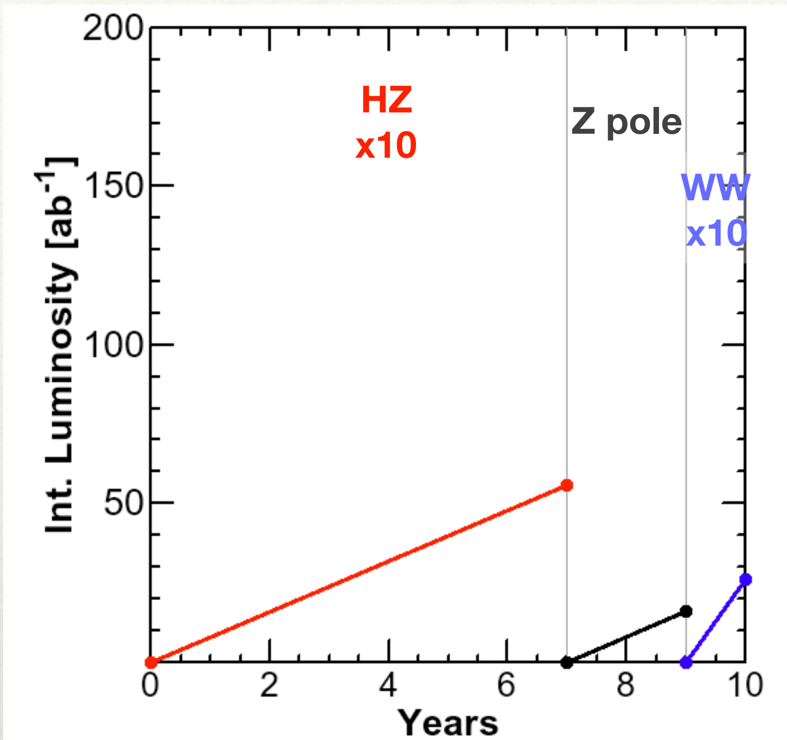


Table 3.1: CEPC 10-year operation plan

Particle	$E_{c.m.}$ (GeV)	L per IP (10^{34} cm^{-2}s^{-1})	Integrated L per year (ab^{-1}, 2 IPs)	Years	Total Integrated L (ab^{-1}, 2 IPs)	Total no. of particles
H	240	3	0.8	7	5.6	1×10^6
Z	91	32 (*)	8	2	16	7×10^{11}
W^+W^-	160	10	2.6	1	2.6	1.5×10^7

(*) Assuming detector solenoid field of 2 Tesla during Z operation

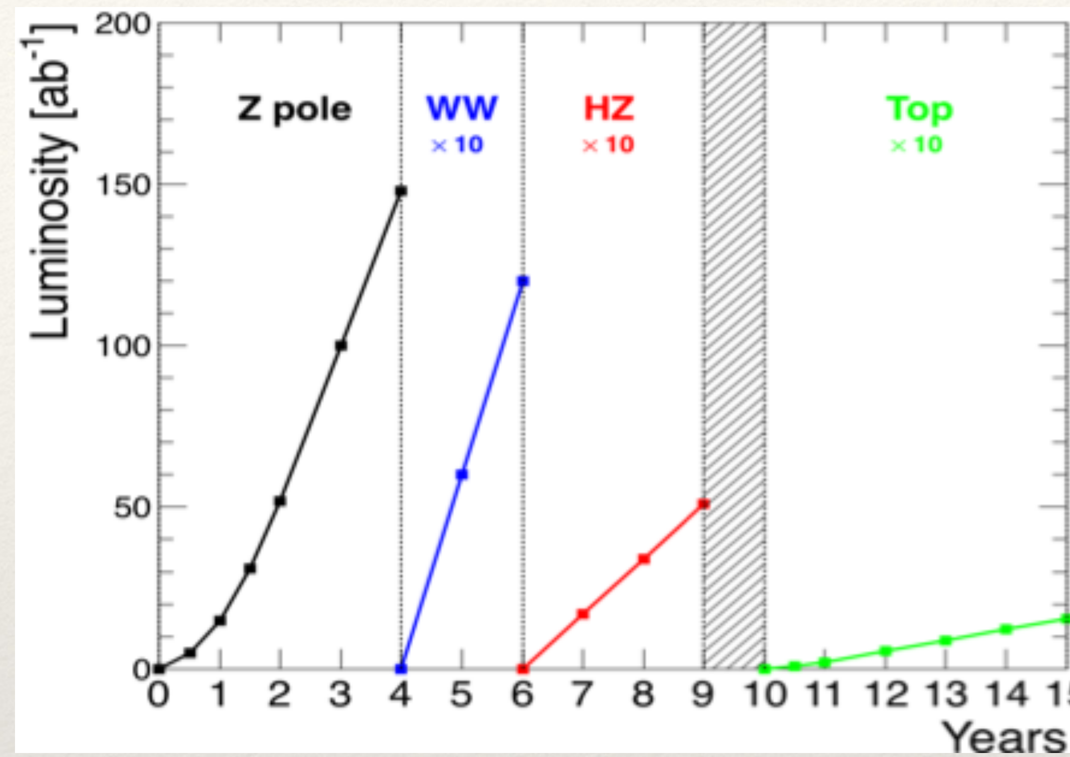
Figure 12.5: A possible timeline.

SppC installation

CEPC can co-exist with SppC.

FCC-ee

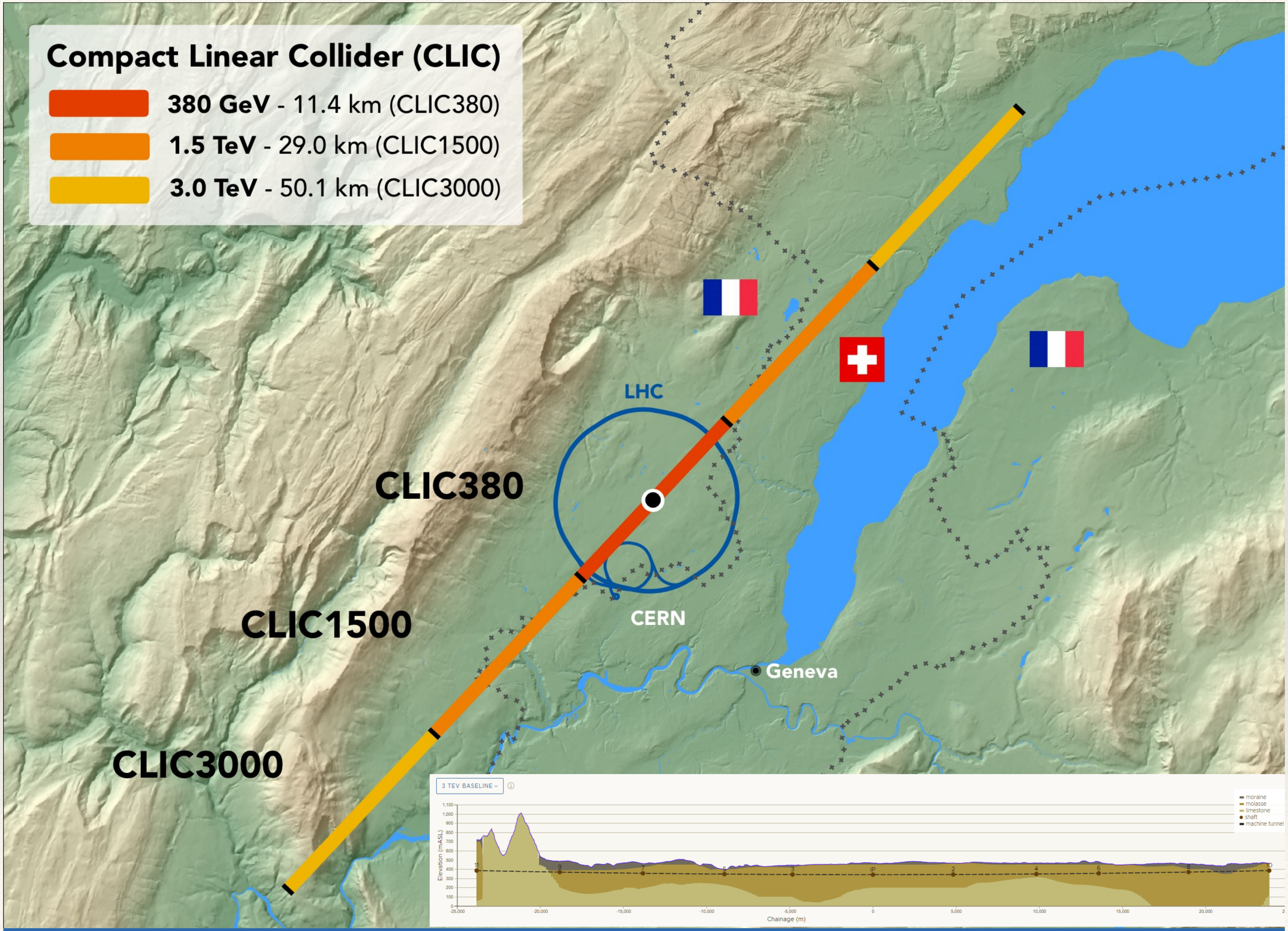
Future Circular Collider, The Lepton Collider (FCC-ee) V1.5 (2018-12-17)



FCC-hh

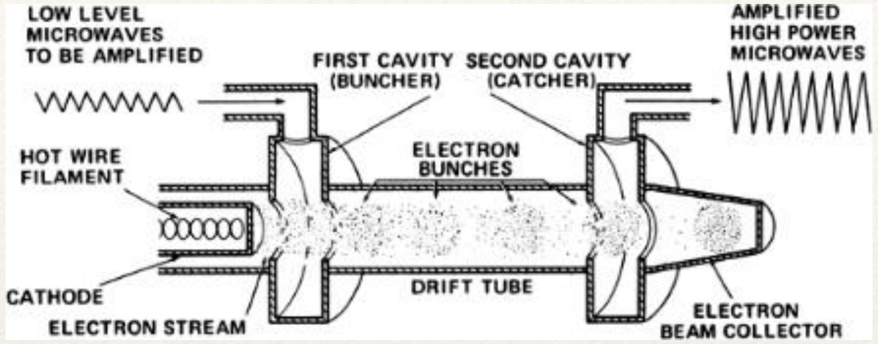
- CEPC starts at ZH production, then goes back to lower energies.
- FCC-ee installs more RF units as the energy increases.
- FCC-ee will be removed when FCC-hh comes in.

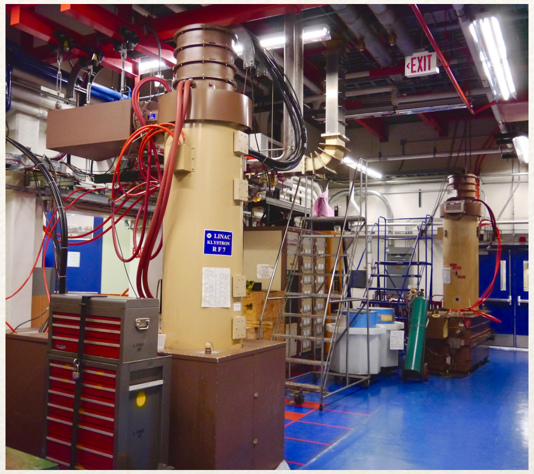
The Compact Linear Collider (CLIC)



The Compact Linear Collider (CLIC)

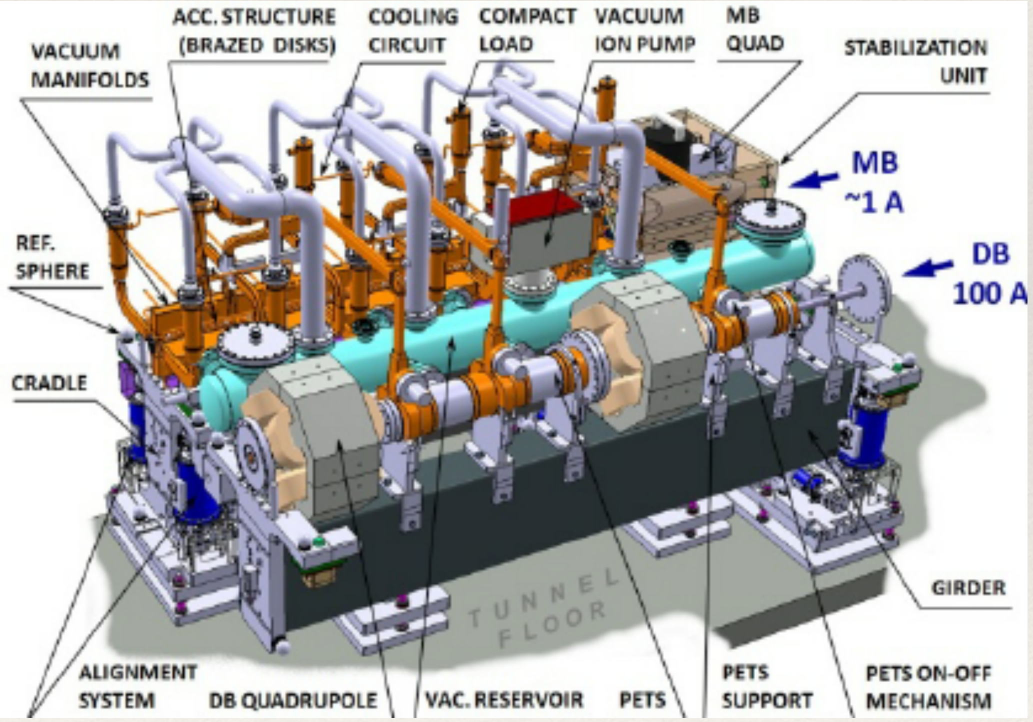
- Klystron driven accelerating structure (usual linac): extracts the energy of beam inside the klystron as RF and feeds it to an accelerating structure.





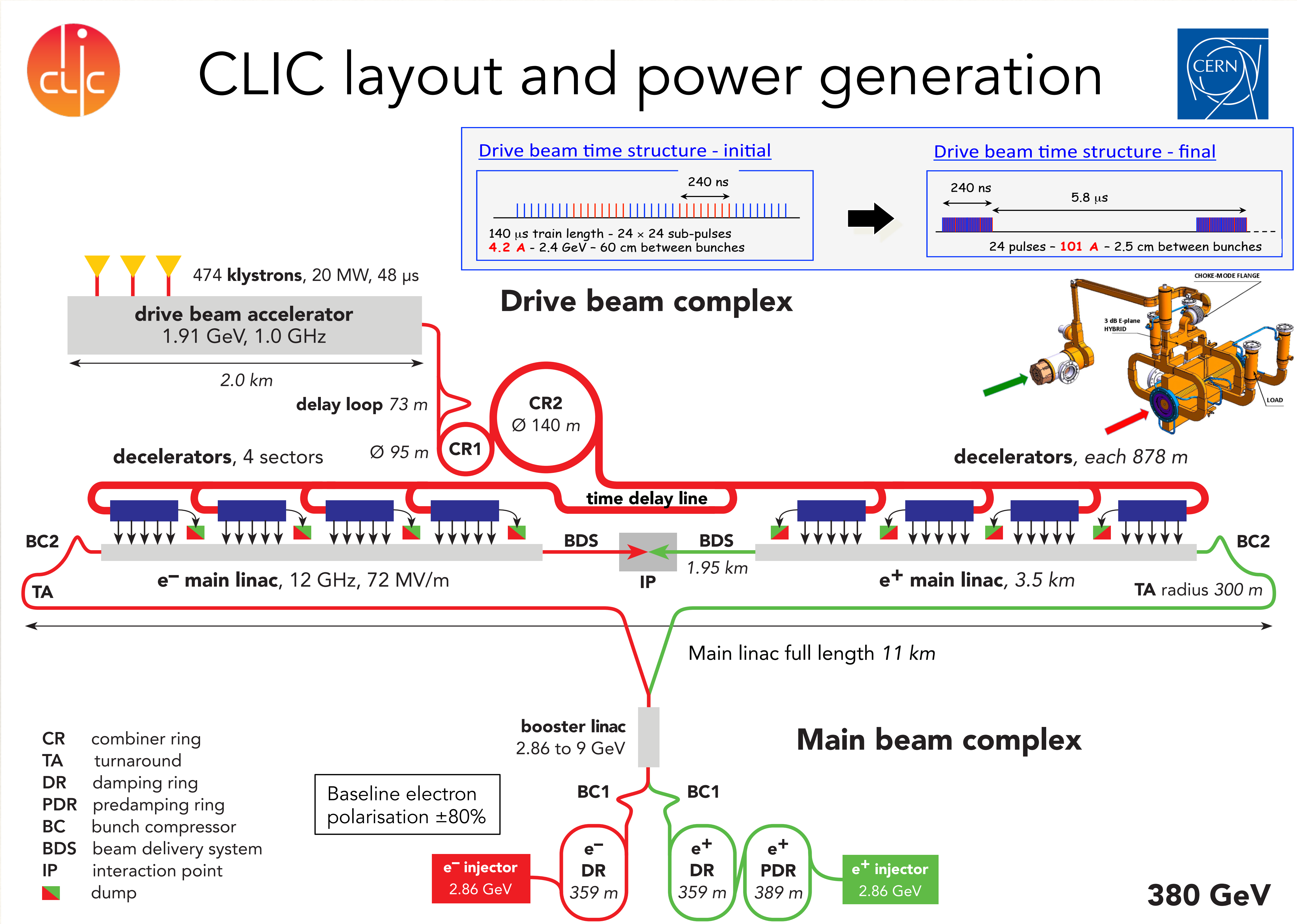
Fermilab Linac

- Two beam accelerator: instead of many small klystrons, use a small number of two beam structures, which extracts energy of the drive beam and feed to the driven beam. So it is a sort of huge klystron placed along the beam.



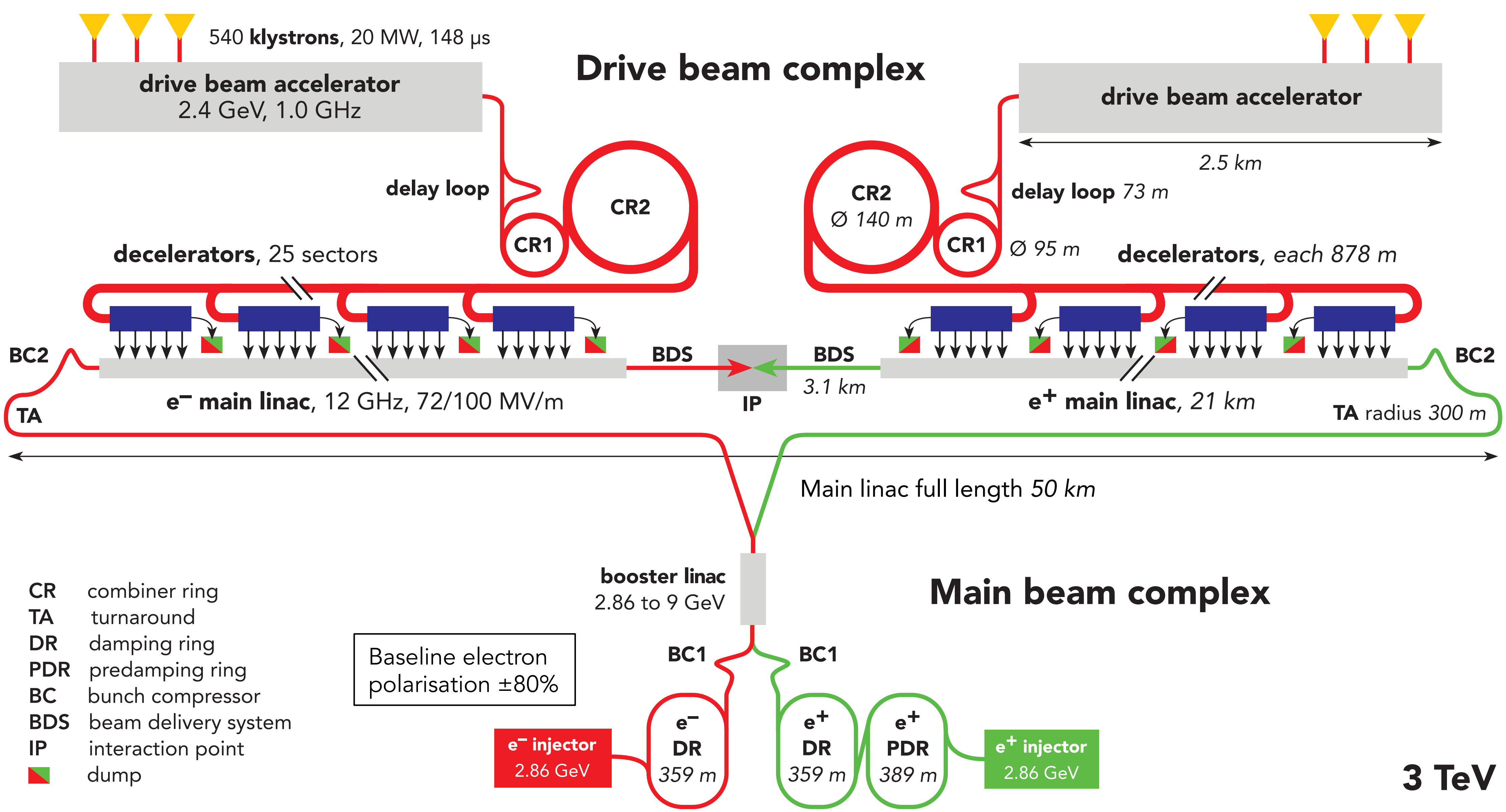
- Very high accelerating gradient is possible, up to 150 MV/m.
- Very high energy efficiency from the drive beam to driven beam is expected.

The Compact Linear Collider (CLIC)



The Compact Linear Collider (CLIC)

CLIC layout – 3TeV



The Compact Linear Collider (CLIC)

Accelerator challenges

Four challenges:

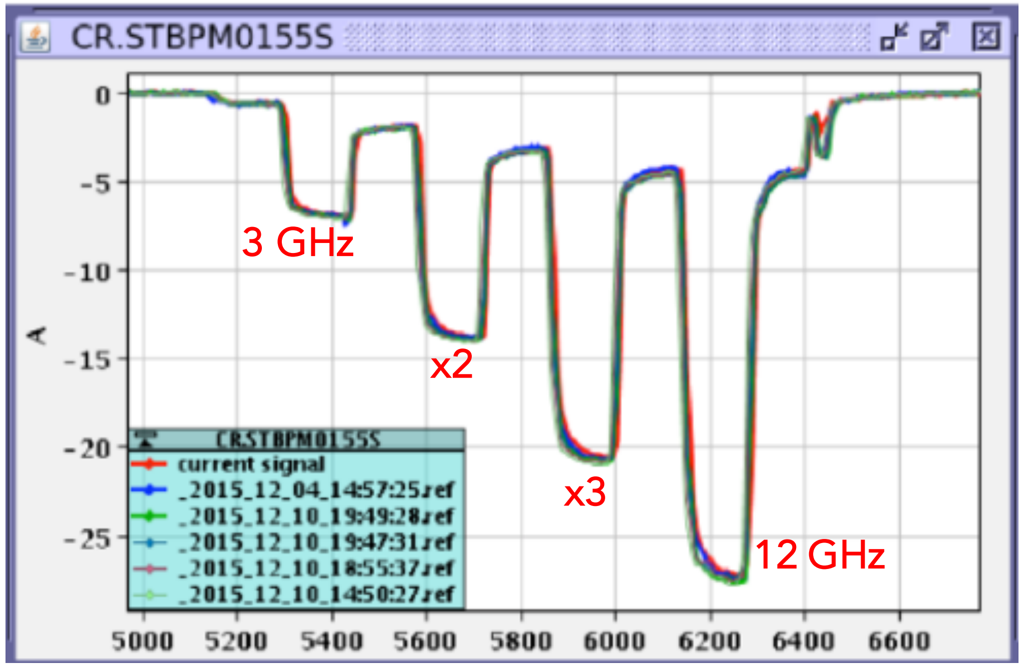
High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

~100 MV/m gradient in main-beam cavities

Alignment & stability

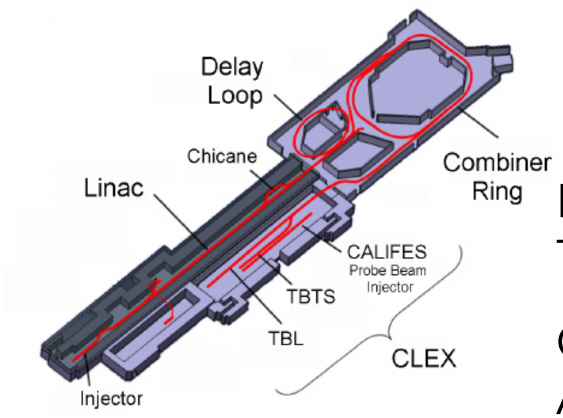
Drive beam quality:
Produced high-current drive beam bunched at 12GHz



Current in combiner ring

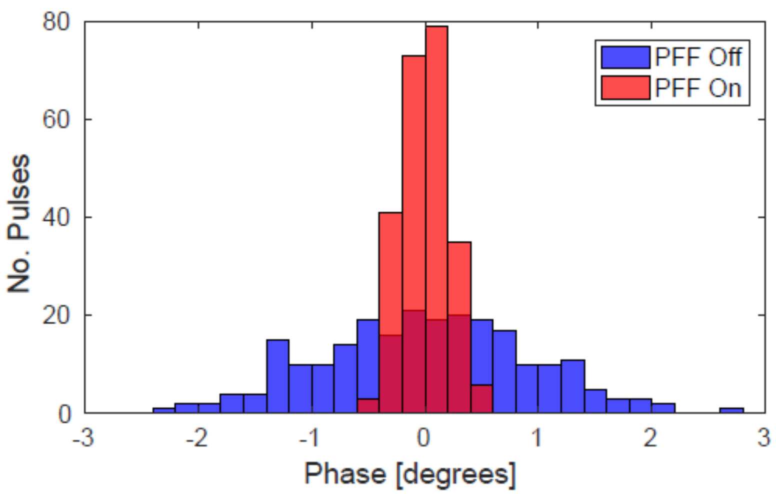
28A

Drive beam arrival time stabilised to CLIC specification of 50fs:



Examples of measurements from CLIC Test Facility, CTF3, at CERN.

CTF3 now the 'CERN Linear Electron Accelerator for Research' facility, CLEAR



The Compact Linear Collider (CLIC)

Accelerator challenges

Demonstrated 2-beam acceleration

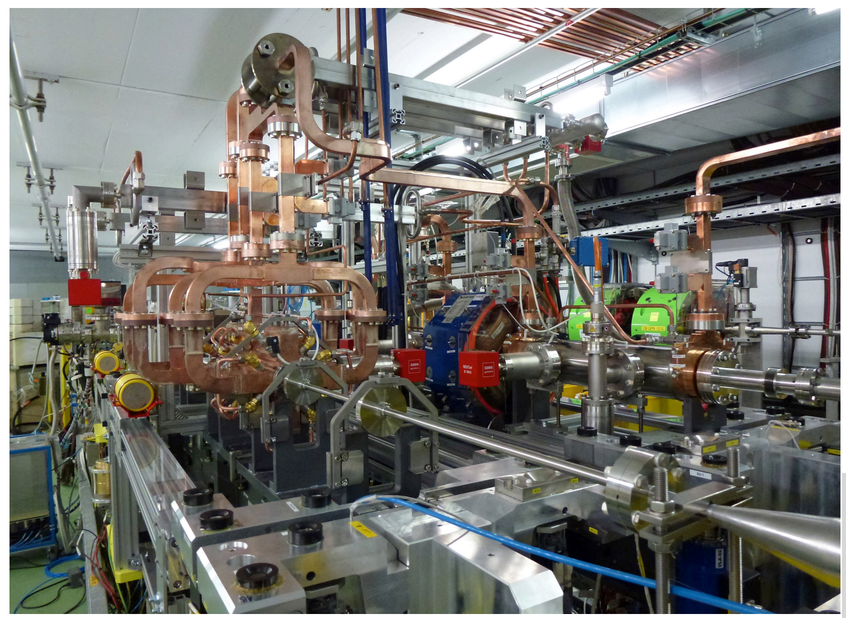
Four challenges:

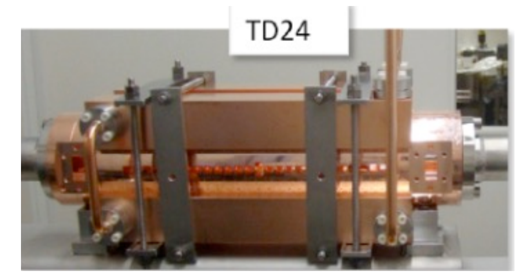
High-current drive beam bunched at 12 GHz

Power transfer + main-beam acceleration

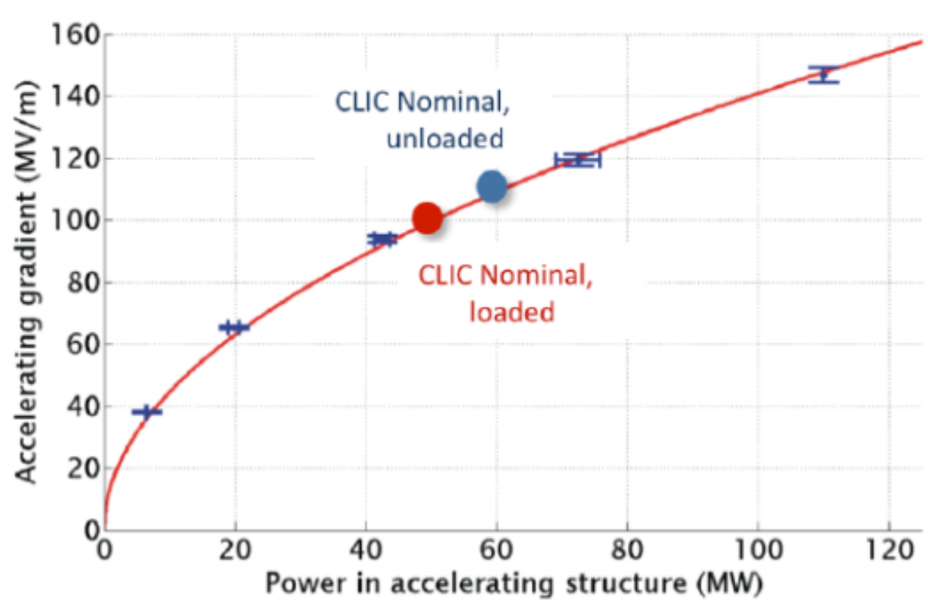
~100 MV/m gradient in main-beam cavities

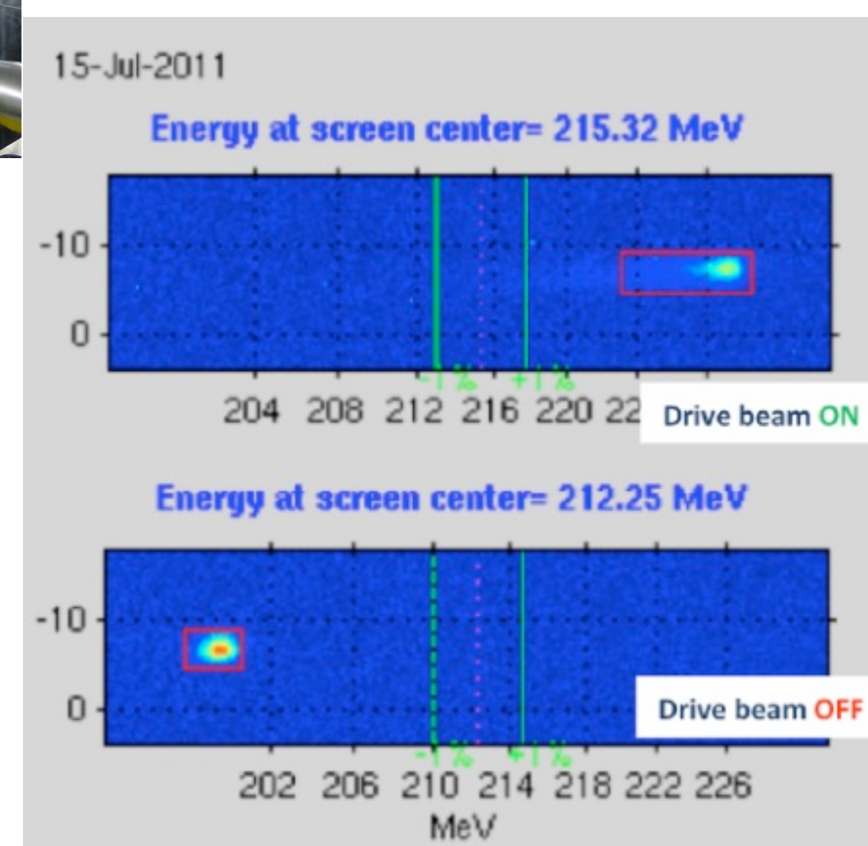
Alignment & stability





31MeV = 145MV/m





The Compact Linear Collider (CLIC)

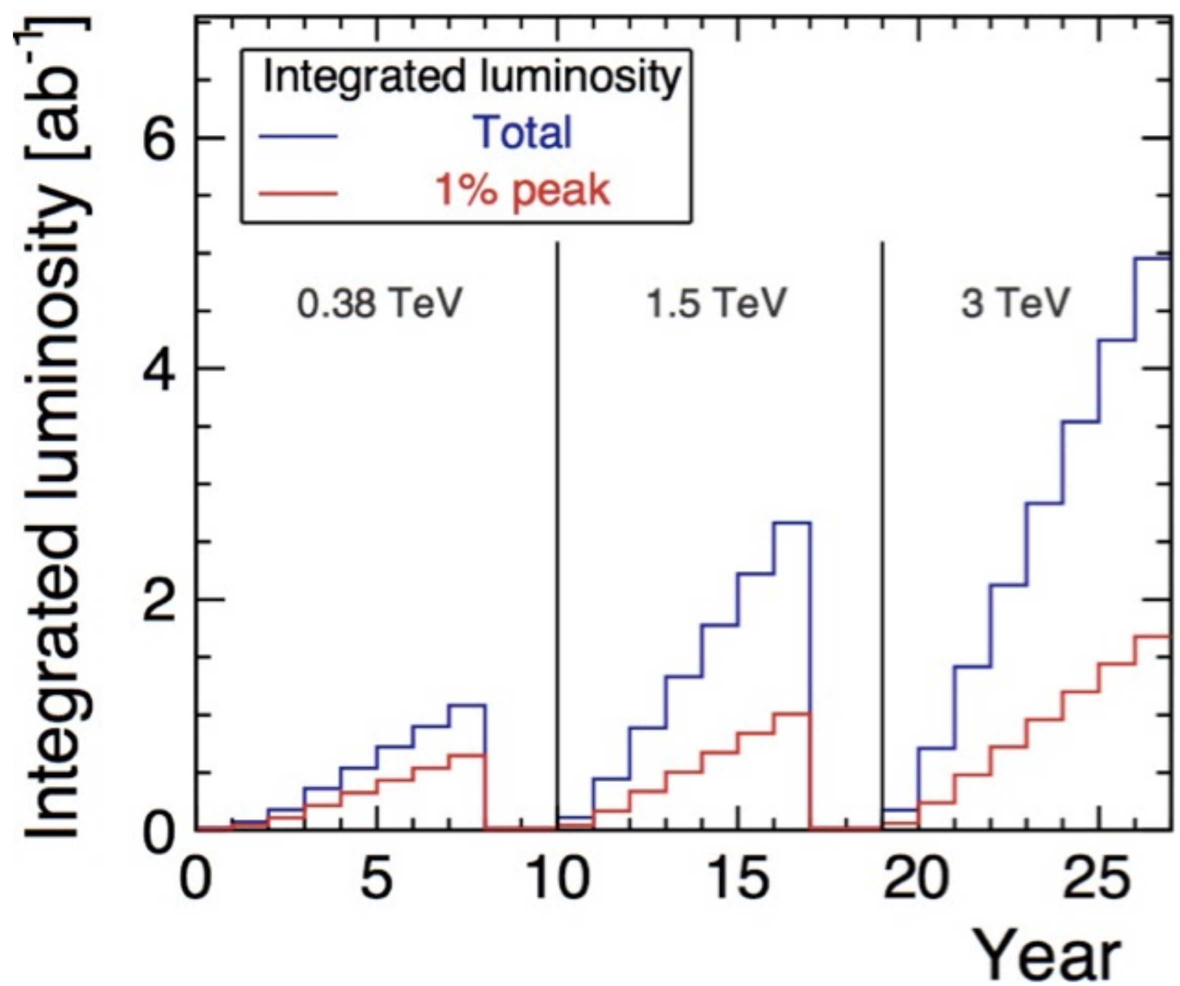
Schedule

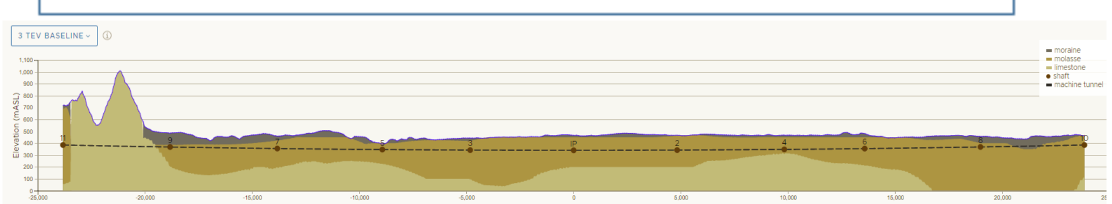
Updated schedule:
Construction + commissioning: 7 years, followed by 25–30 year physics programme

Civil Eng.
- Tunnel excavation TBM Good rock
- Inner lining

Infrastr. + Machine Inst.
- Survey works
- General services installation
- CV Installation works
- Electrical installation and cabling
- Machine transport
- Machine Installation

- Commissioning period
- Physics





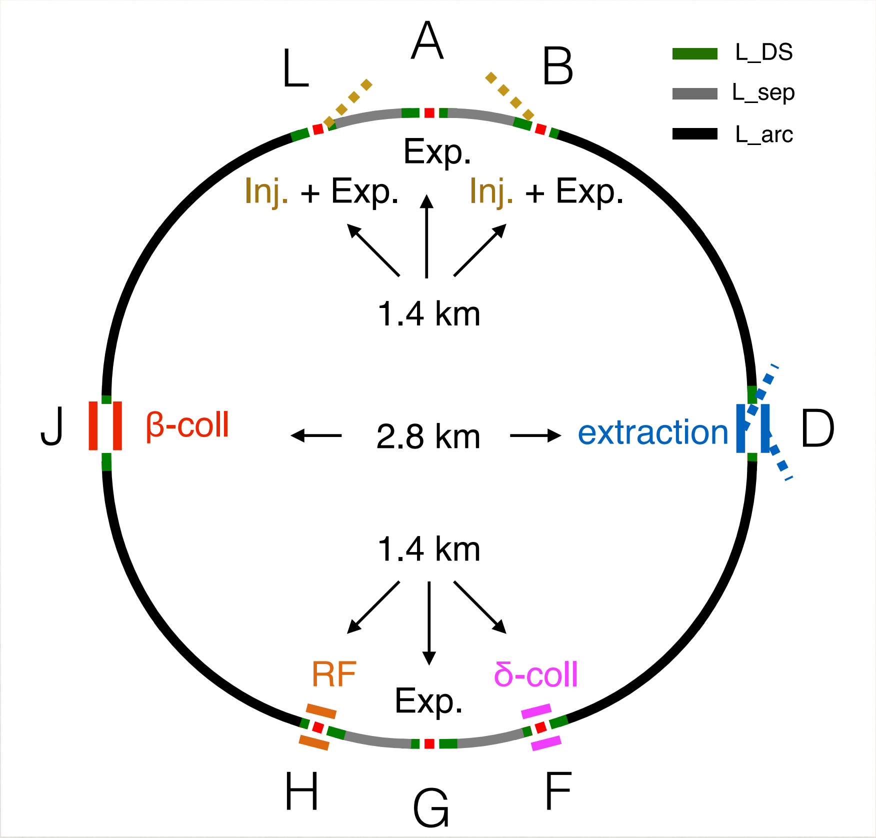
Future pp Colliders (FCC-hh, SppC, HE-LHC)

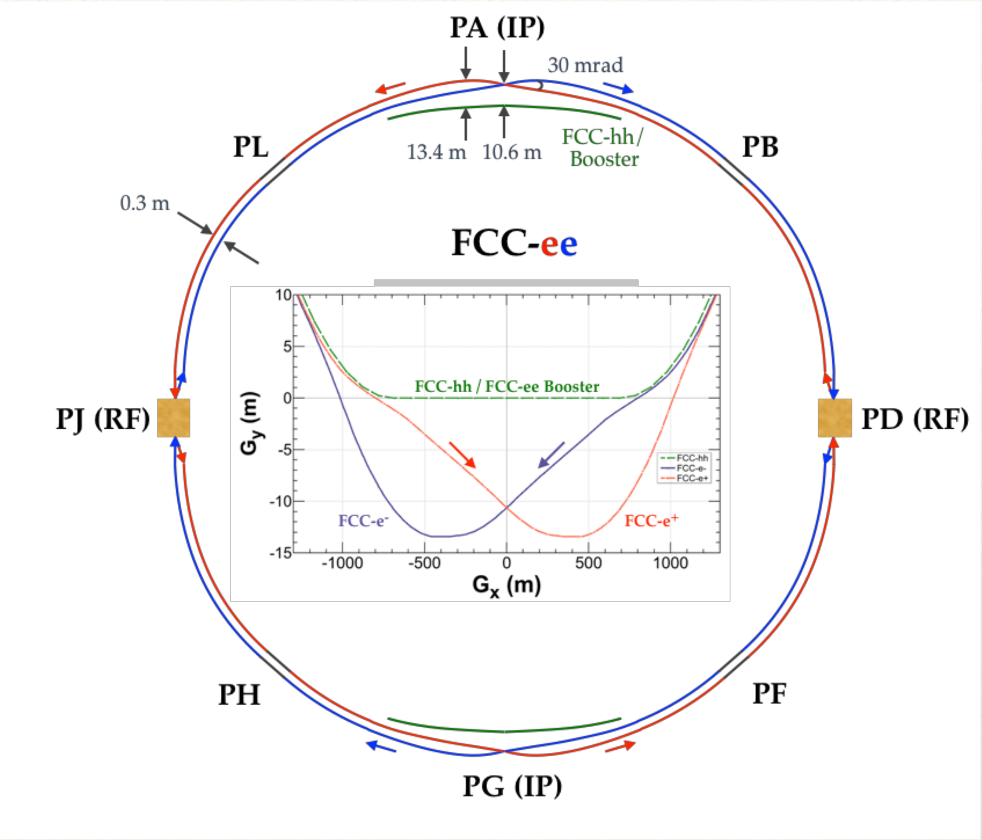
parameter	FCC-hh Initial	FCC-hh Nominal	SppC Baseline	HE-LHC	HL-LHC
collision energy cms [TeV]	100		75	27	14
dipole field [T]	16		12	16	8.33
dipole magnet	Nb_3Sn		Fe-HTS	Nb_3Sn	NbTi
circumference [km]	97.75		100	26.7	26.7
beam current [A]	0.5		0.75	1.1	1.1
bunch intensity [10^{11}]	1	1	1.5	2.2	2.2
bunch spacing [ns]	25	25	25	25	25
synchr. rad. power / ring [kW]	2400		1100	101	7.3
SR power / length [W/m/ap.]	28.4		12.8	4.6	0.33
long. emit. damping time [h]	0.54		1.28	1.8	12.9
beta* [m]	1.1	0.3	0.75	0.45	0.15
normalized emittance [μm]	2.2		2.4	2.5	2.5
peak luminosity / IP [10^{34} $cm^{-2}s^{-1}$]	5	30	10	16	5 (lev.)
events/bunch crossing	170	1000	500	460	132
stored energy/beam [GJ]	8.4		9.1	1.3	0.7

- FCC-hh has two modes of operation with different β*. No change in the hardware between two modes.
- FCC-hh also thinks a possibility of energy upgrade toward 150 TeV CM with HTS magnets.
- SppC mentions "ultimate energy", 125 - 150 TeV, in the CEPC CDR, by stronger (20 - 24 T) dipole magnets.

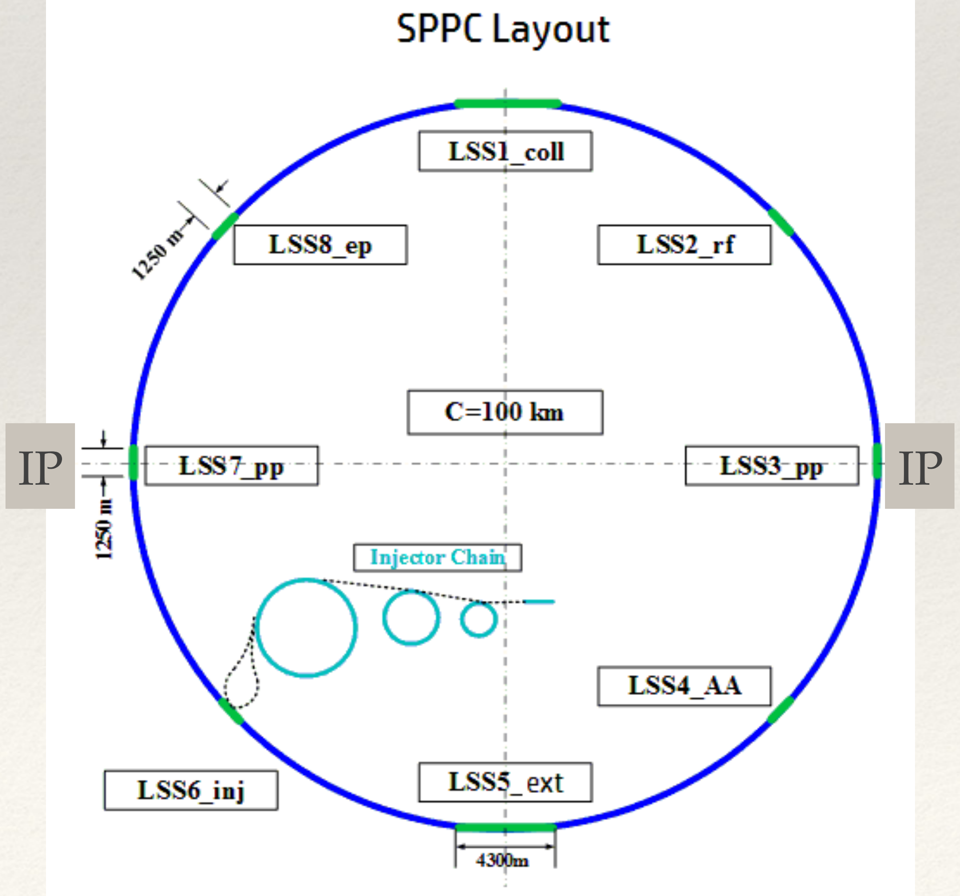
Future pp Colliders (FCC-hh, SppC, HE-LHC)

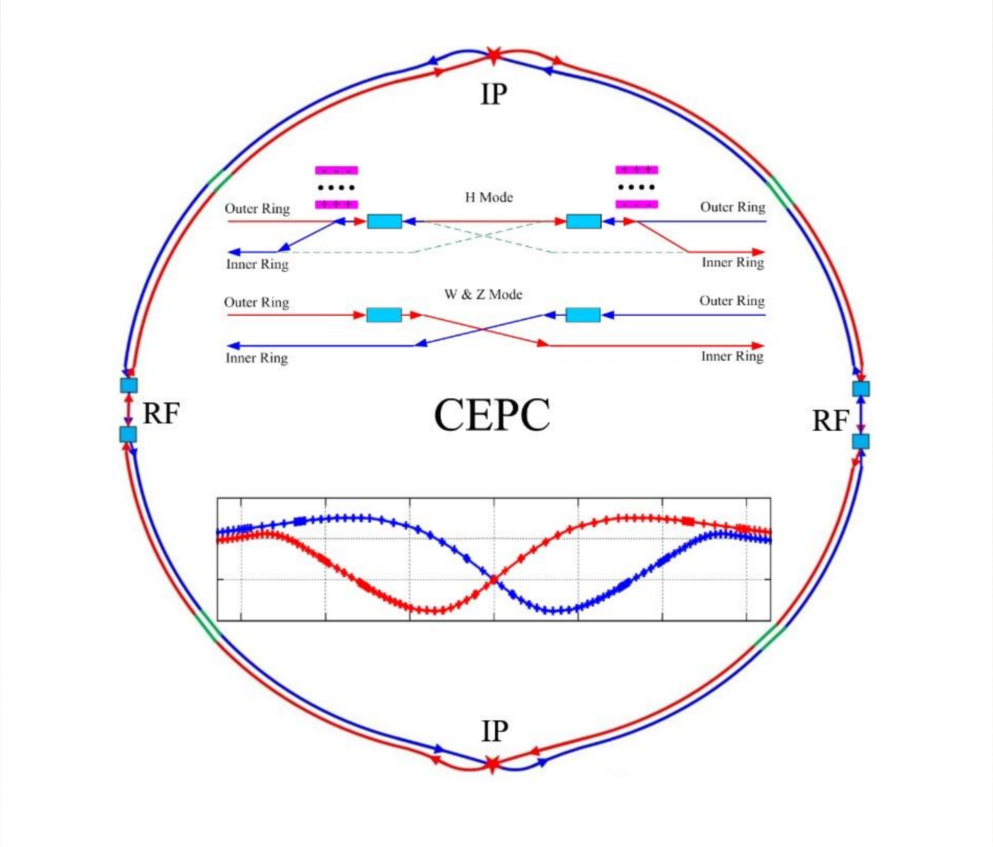
FCC-hh's detectors are placed in the same cavern as FCC-ee's.





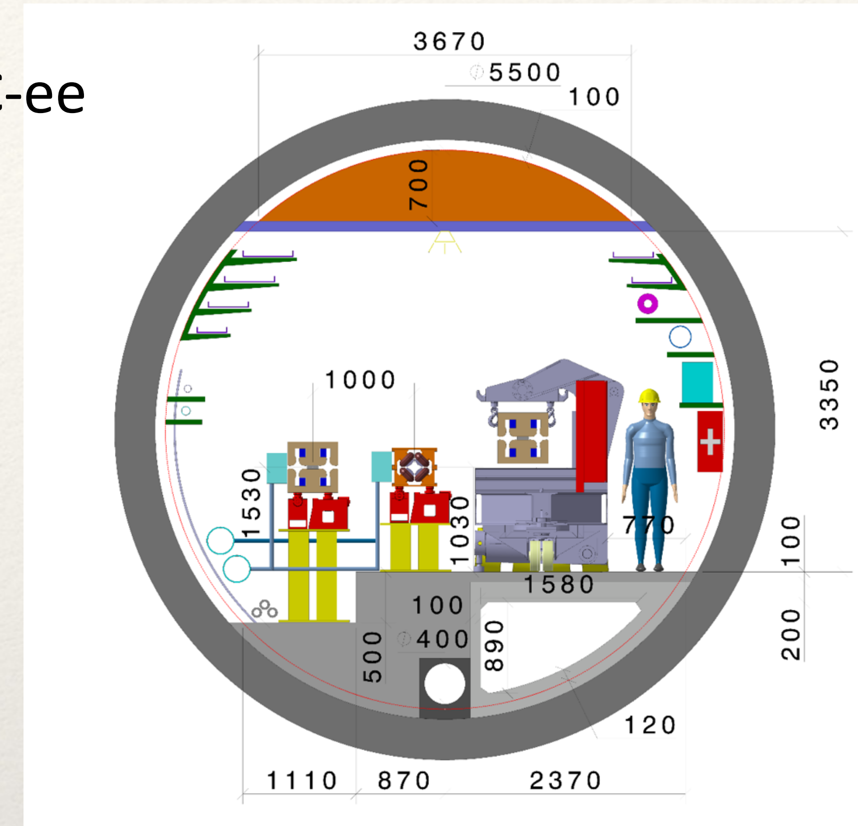
SppC's detectors are placed at 90°/270° relative to CEPC's.





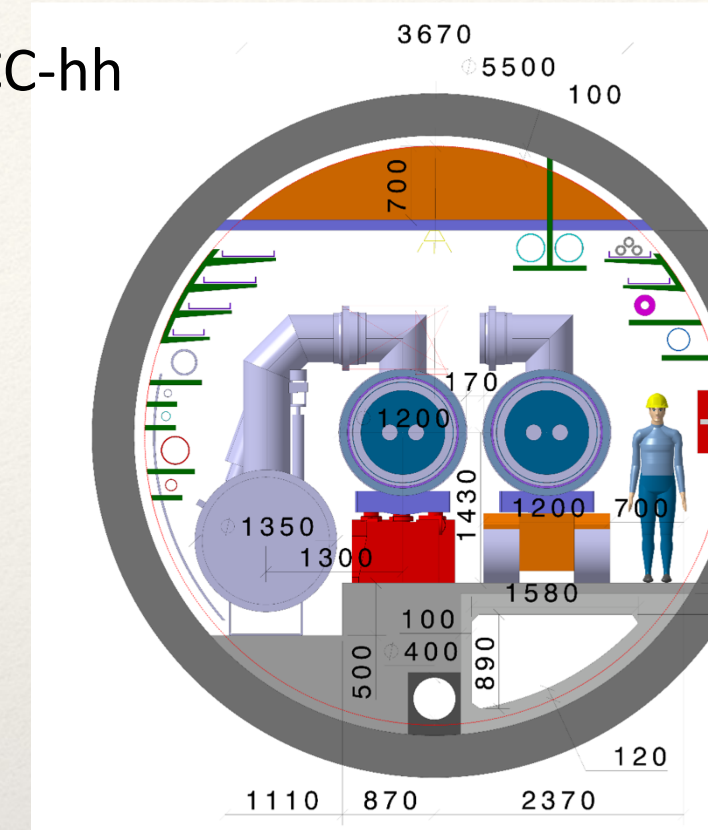
Future pp Colliders (FCC-hh, SppC, HE-LHC)

FCC-ee

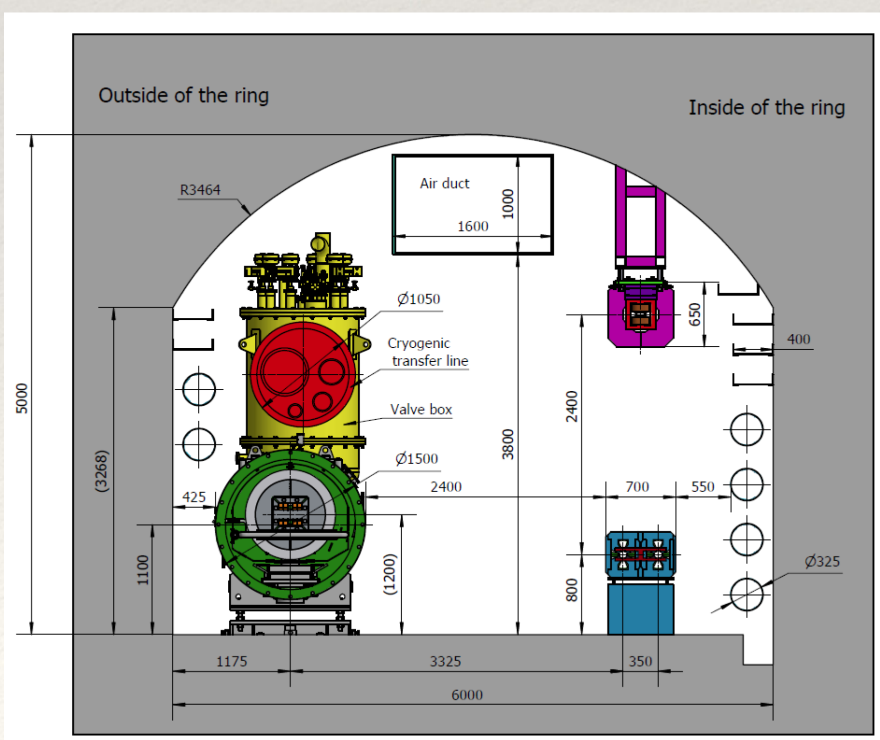


FCC-hh

5.5 m diameter



CEPC/SppC



6 m wide

HE-LHC

3.8 m diameter

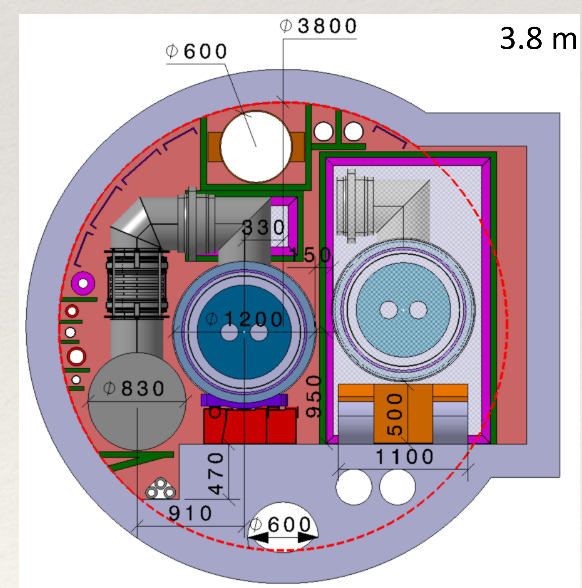


Figure 4.9: Tunnel cross section at fire compartment separation wall.

4.4 Tunnel Enlargements

Separation walls need to be installed every 548 m to create fire compartments to implement the new fire safety concept. Given the size of the magnets, it is not possible to fit the doors of these separations in the existing tunnel envelope, as shown in Fig. 4.9. Therefore, parts of the lining must be broken out.

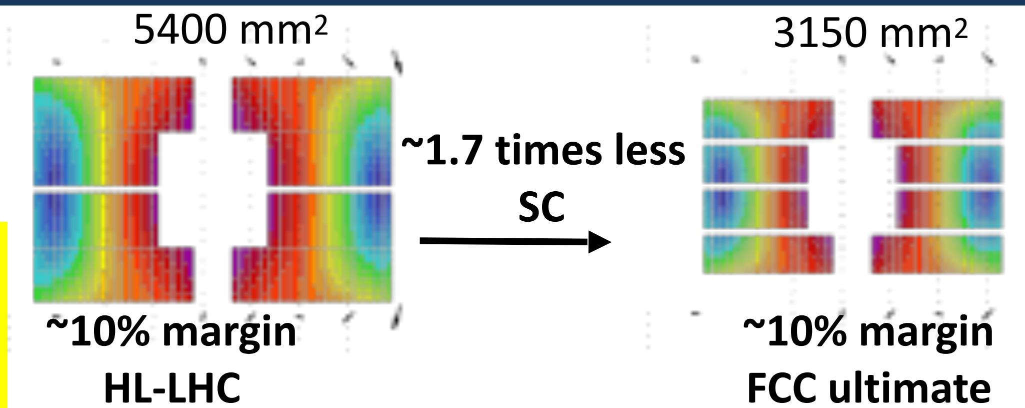
High field magnets (FCC-hh, HE-LHC)

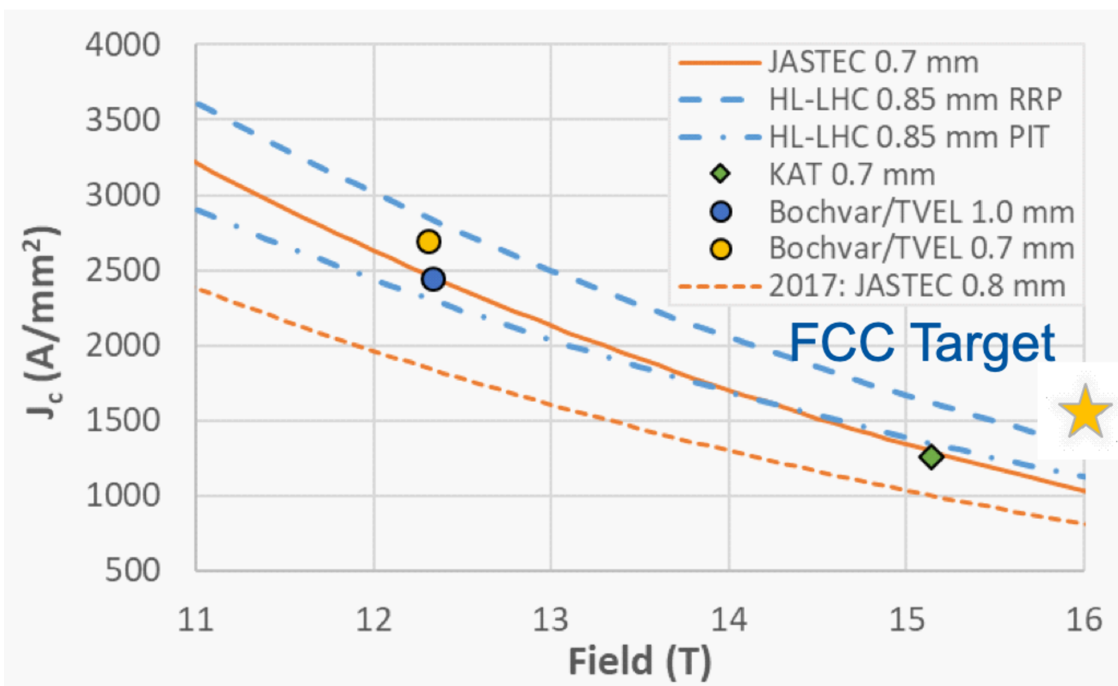
Worldwide FCC Nb_3Sn Program

Main development goal is wire performance increase:

- J_c (16T, 4.2K) > 1500 A/mm² → 50% increase wrt HL-LHC wire
- Reduction of coil & magnet cross-section

After only one year development, **prototype Nb_3Sn wires from several new industrial FCC partners already achieve HL-LHC performance in current density J_c**





Conductor activities for FCC started in 2017:

- **Bochvar Institute** (production at **TVEL**), **Russia**
- **KEK** (**Jastec** and **Furukawa**), **Japan**
- **KAT**, **Korea**
- **Columbus**, **Italy**
- **University of Geneva**, **Switzerland**
- **Technical University of Vienna**, **Austria**
- **SPIN**, **Italy**
- **University of Freiberg**, **Germany**
- **Bruker**, **Germany**
- **Luvata Pori**, **Finland**

November 2018 103rd Plenary ECFA Meeting — M. Aleksa (CERN) 26

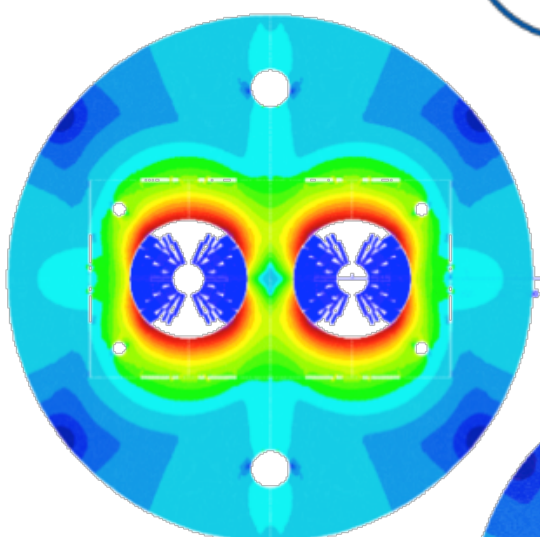
- Higher current density means smaller amount of superconductors and reduced cost.
- Not only the field strength, but the field quality is another issue to limit the dynamic aperture. A uniformity of 10^{-4} is required.
- HE-LHC assumes the same (or even more difficult) magnets as FCC-hh.

High field magnets (FCC-hh, HE-LHC)

16T Dipole Design Activities and Options

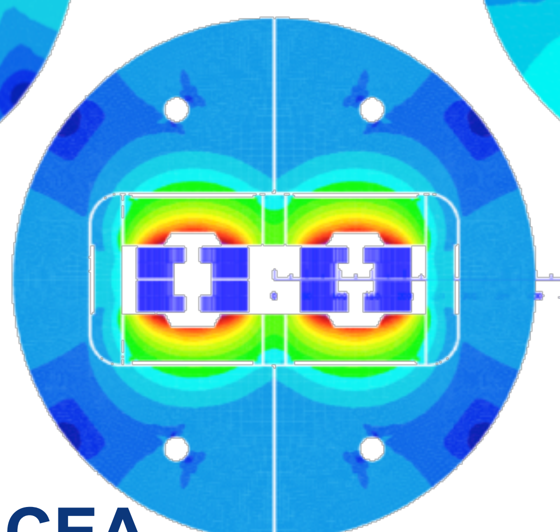
H2020
EuroCirCol
A key to New Physics

Cos-theta



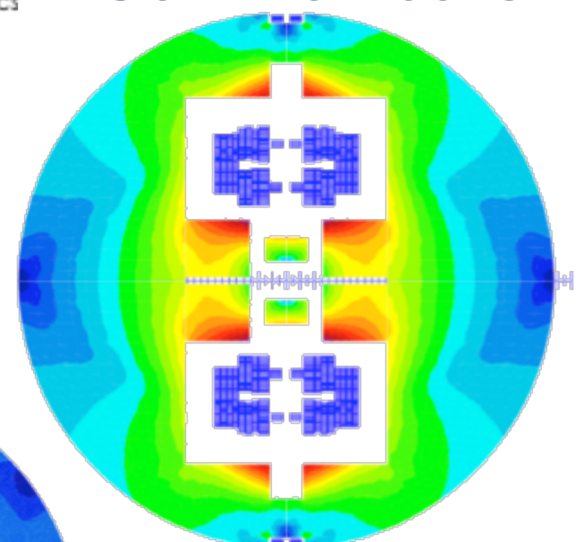
INFN

Blocks



CEA

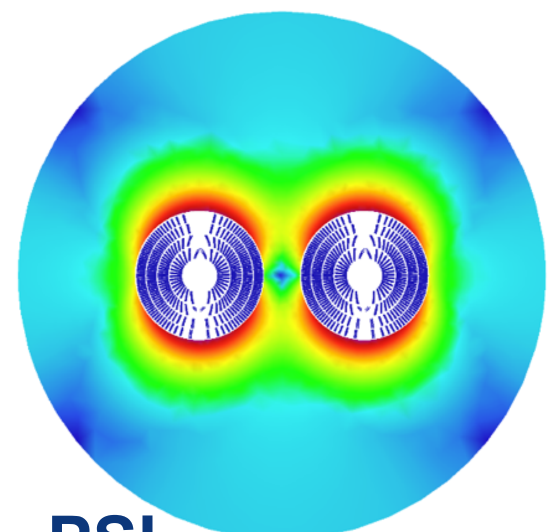
Common coils



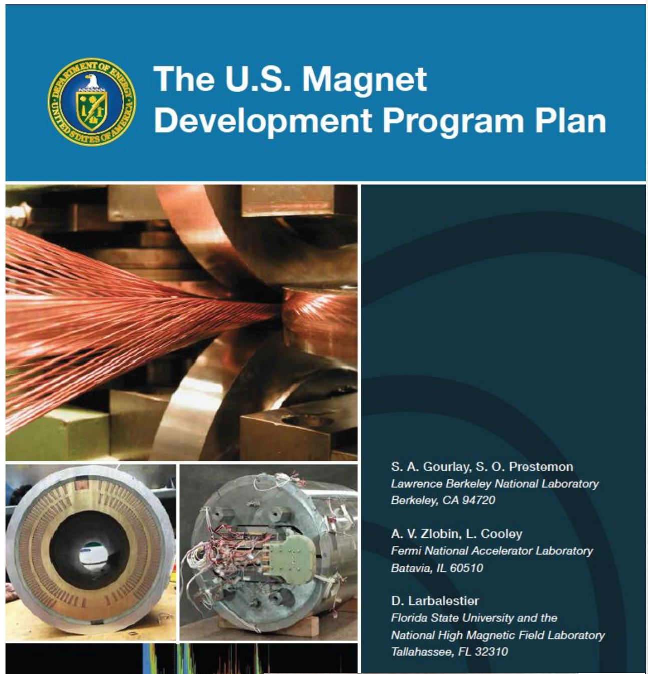
CIEMAT

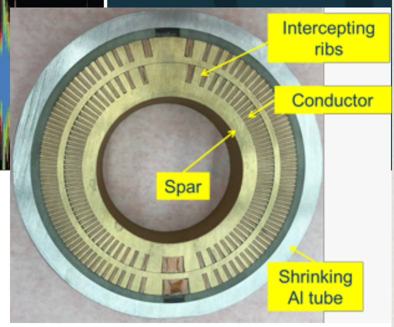
Swiss contribution

Canted Cos-theta

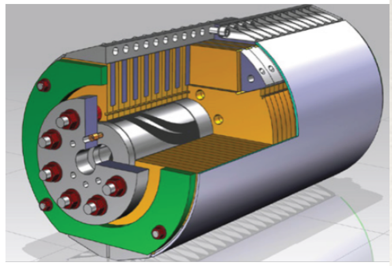


PSI





LBNL



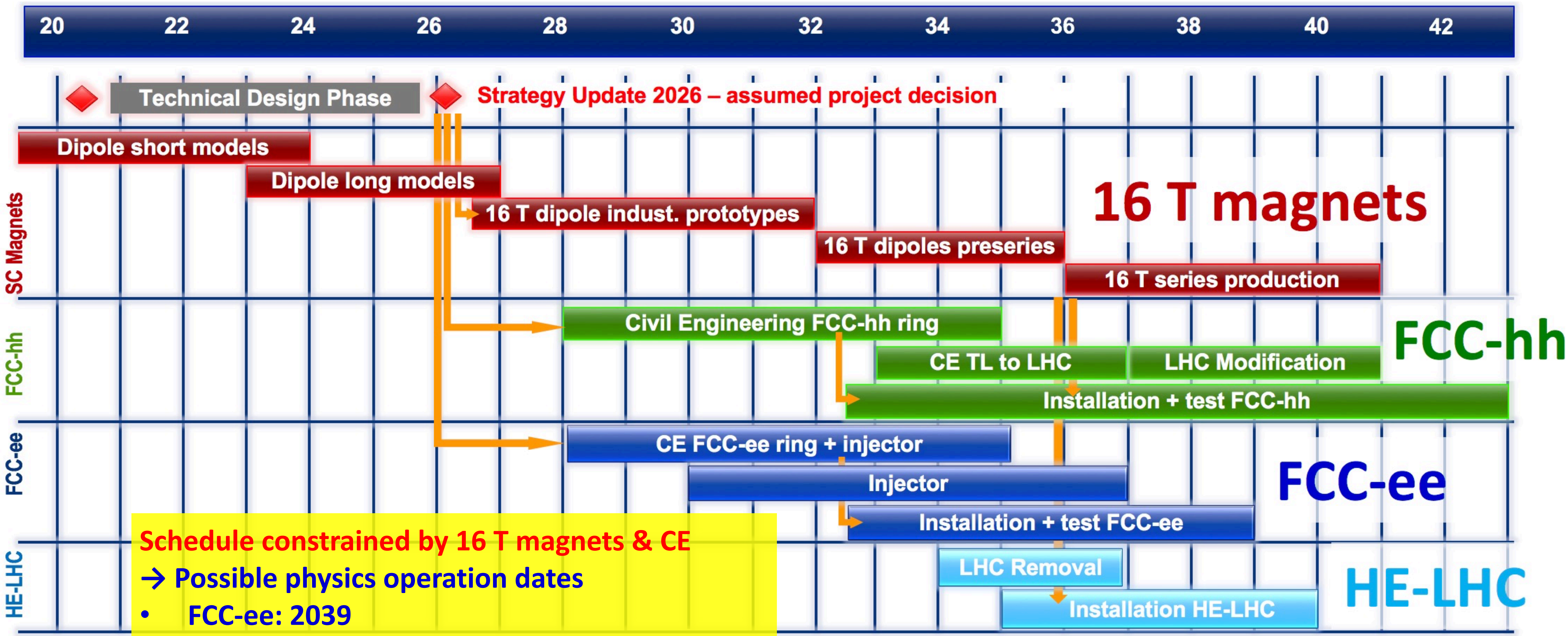
FNAL

Short model magnets (1.5 m lengths) will be built from 2018 – 2022

Russian 16T magnet program launched by BINP recently

High field magnets (FCC-hh, HE-LHC)

Technical Schedules

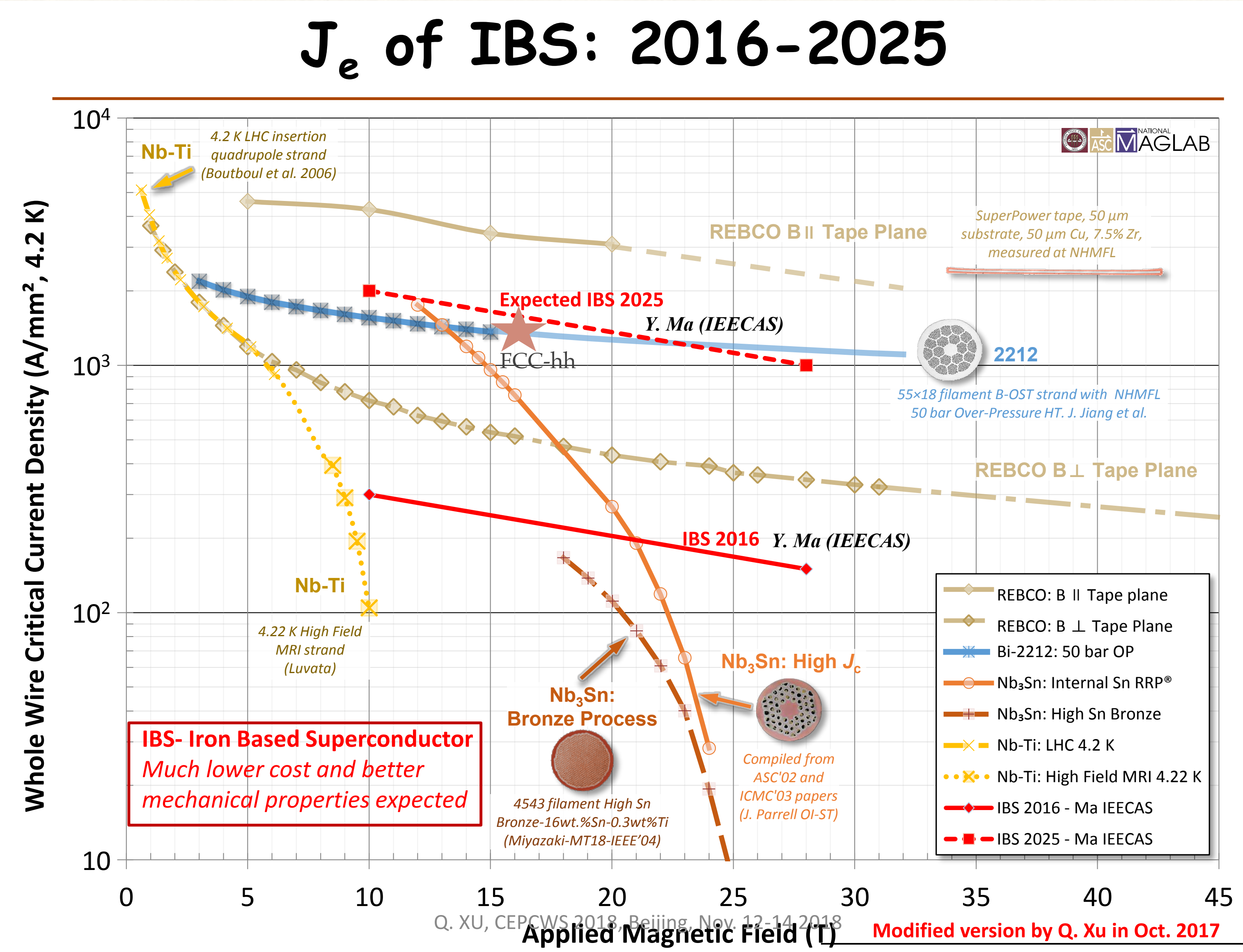


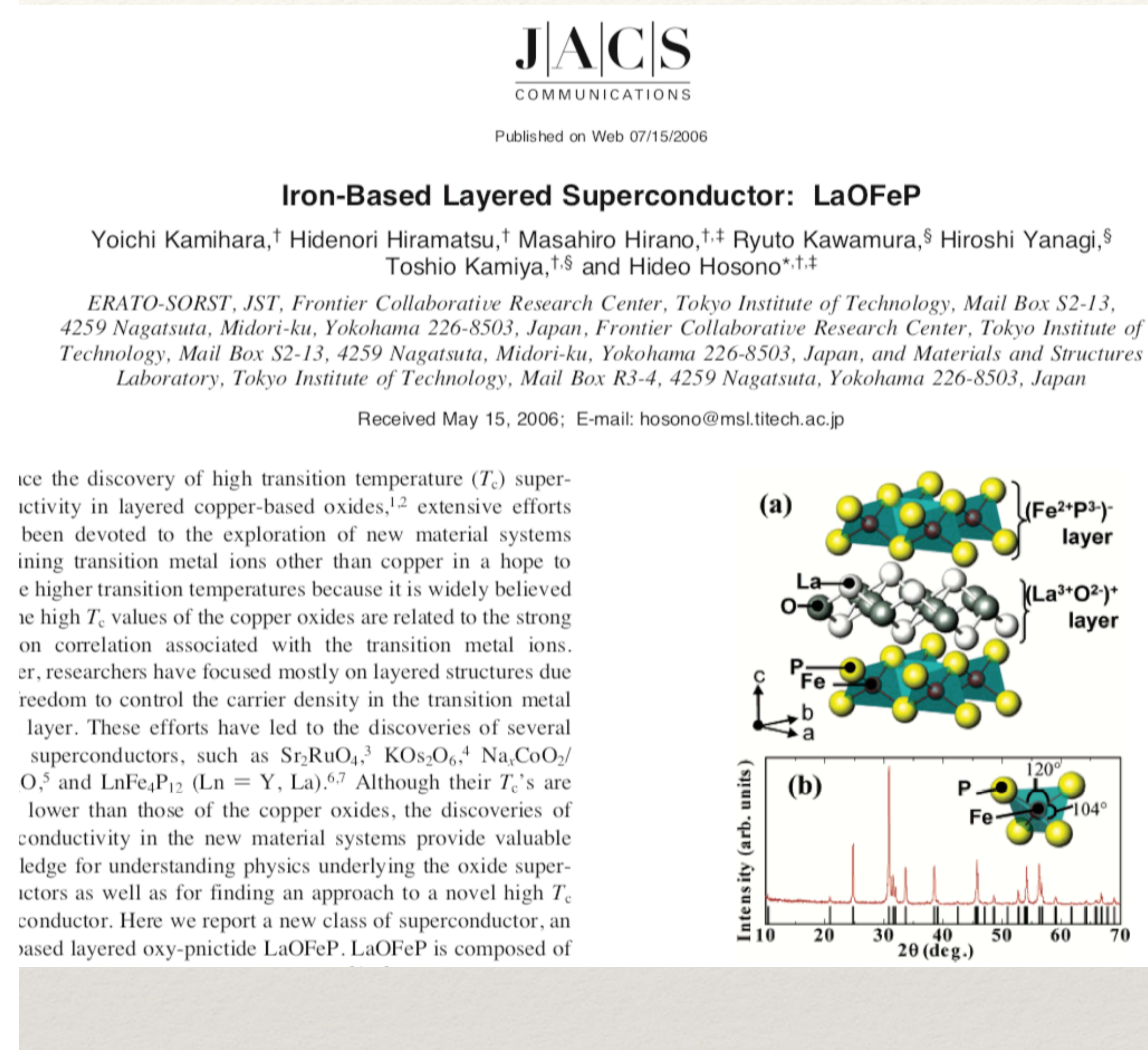
Schedule constrained by 16 T magnets & CE

→ Possible physics operation dates

- **FCC-ee: 2039**
- **FCC-hh: 2043**
- **HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)**

High field magnets, Fe-HTS (SppC)





J|A|C|S COMMUNICATIONS

Published on Web 07/15/2006

Iron-Based Layered Superconductor: LaOFeP

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ıce the discovery of high transition temperature (T_c) superıctivity in layered copper-based oxides,[1,2] extensive efforts been devoted to the exploration of new material systems ining transition metal ions other than copper in a hope to e higher transition temperatures because it is widely believed ıe high T_c values of the copper oxides are related to the strong on correlation associated with the transition metal ions. er, researchers have focused mostly on layered structures due reedom to control the carrier density in the transition metal layer. These efforts have led to the discoveries of several superconductors, such as Sr_2RuO_4,[3] KOs_2O_6,[4] Na_xCoO_2/ O,[5] and $LnFe_4P_{12}$ (Ln = Y, La).[6,7] Although their T_c's are lower than those of the copper oxides, the discoveries of conductivity in the new material systems provide valuable ledge for understanding physics underlying the oxide superıctors as well as for finding an approach to a novel high T_c conductor. Here we report a new class of superconductor, an ɔased layered oxy-pnictide LaOFeP. LaOFeP is composed of

H. Hosono, Materials Today Volume 21, Number 3 April 2018

Comparison of three representative high-T_c superconductors.

	IBSCs	MgB_2	Cuprates
Parent material	AFM semimetal (T_N ~ 150 K)	Pauli paramagnetic metal	AFM Mott insulator (T_N ~ 400 K)
Fermi level	Fe 3d 5-orbitals	B 2p 2-orbitals	Cu 3d single orbital
Maximum T_c (K)	55 (for 1111 type), 38 (for 122 type)	39	93 (YBCO), 110 (Bi2223)
Impurity	Robust	Sensitive	Sensitive
SC gap symmetry	Extended s-wave	s-wave	d-wave
Upper critical field at 0 K, $H_{c2}(0)$ (T)	100–200 (for 1111 type) 50–100 (for 122 type) ~50 (for 11 type)	40	>100
Irreversibility field, H_{irr} (T)	>50 (4 K) >15 (20 K)	>25 (4 K) >10 (20 K)	>0 (77 K,YBCO)
Anisotropy, γ	4–5 (for 1111 type) 1–2 (for 122- and 11-types)	2	5–7 (YBCO), 50–90 (Bi-system)
Crystallographic symmetry in SC state	Tetragonal	Hexagonal	Orthorhombic (Y- and Bi-systems)
Critical GB angle, θ_c (deg.)	8–9	No data	3–5 (YBCO)
Advantage	High $H_{c2}(0)$, Easy fabrication	Easy fabrication	High T_c and $H_{c2}(0)$
Disadvantage	Toxicity	Low $H_{c2}(0)$	High cost due to 3D alignment of crystallites

- SppC is developing 12 T dipole with iron-based superconductor (discovered by H. Hosono *et al.*,TITECH in 2006).
- Fe-HTS has advantages both in high Jc and easier fabrication compared to other materials such as MgB2 or cuprates.
- Toxic arsenic might be an issue for the cable production.

High field magnets, Fe-HTS (SppC)

SPPC Magnet Design Scope

Top priority: reducing cost!
Instead of increasing field

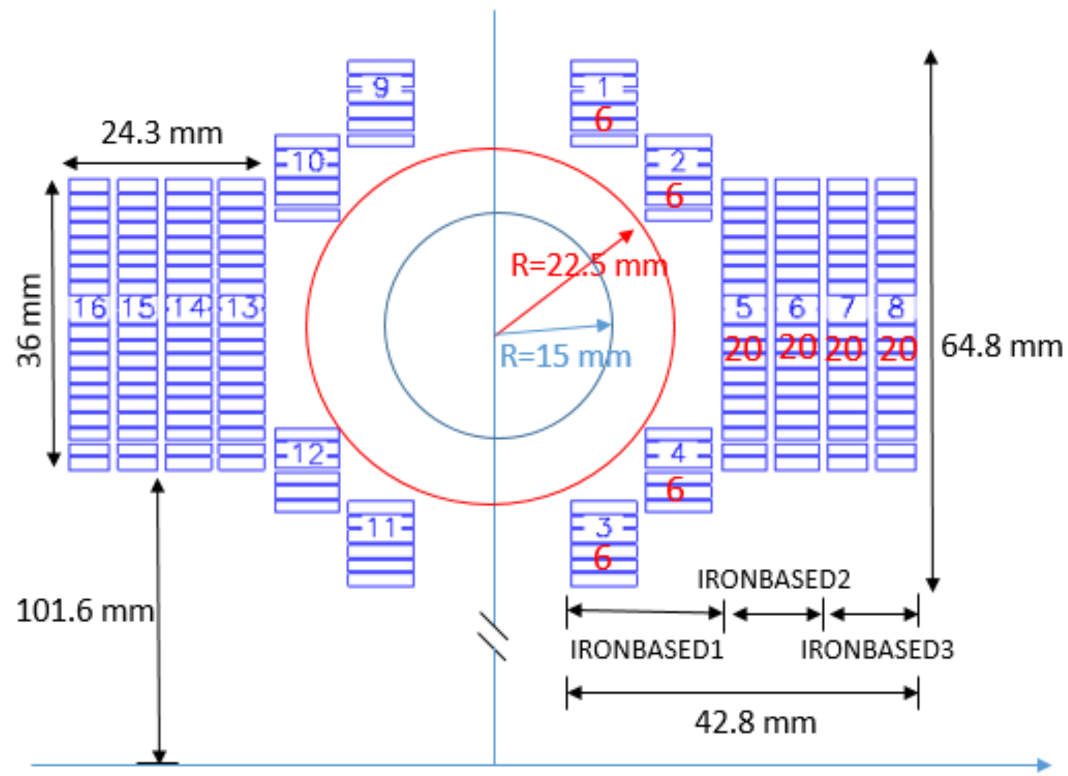
- **Baseline design**
  - Tunnel circumference: 100 km
  - Dipole magnet field: 12 T, iron-based HTS technology (IBS)
  - Center of Mass energy: >70 TeV
  - Injector chain: 2.1 TeV

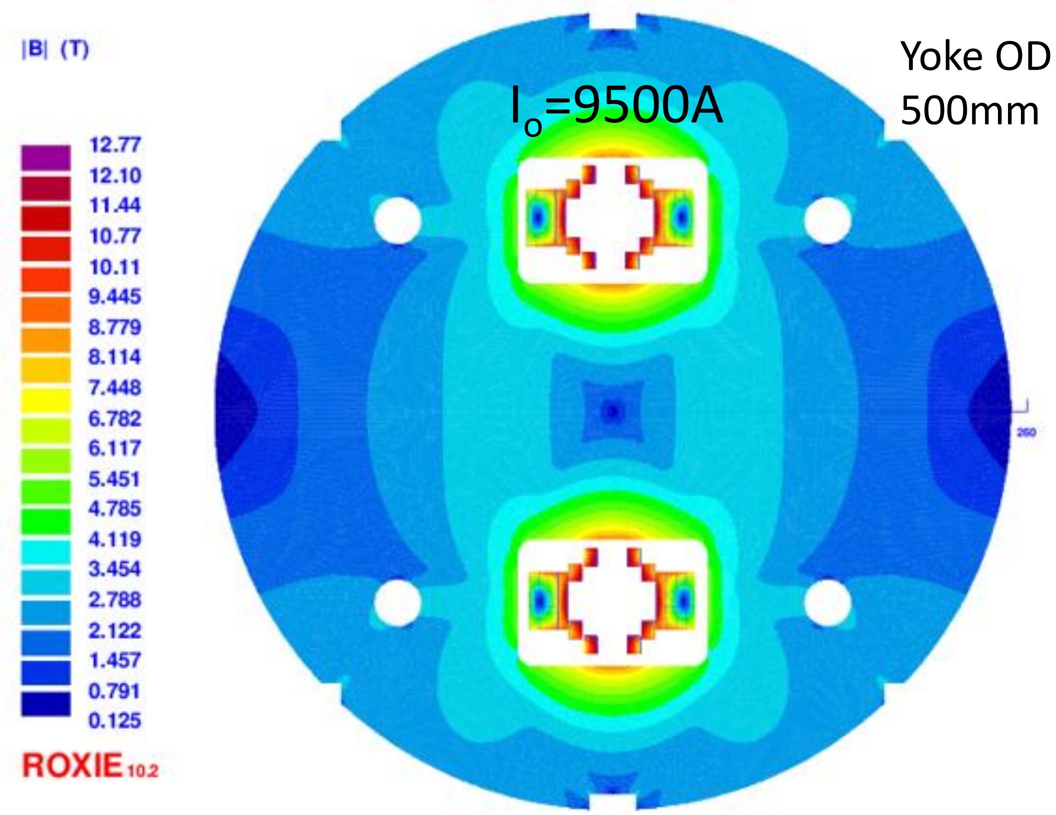
Make IBS the High-T_c and High-Field "NbTi" superconductor in 10 years!

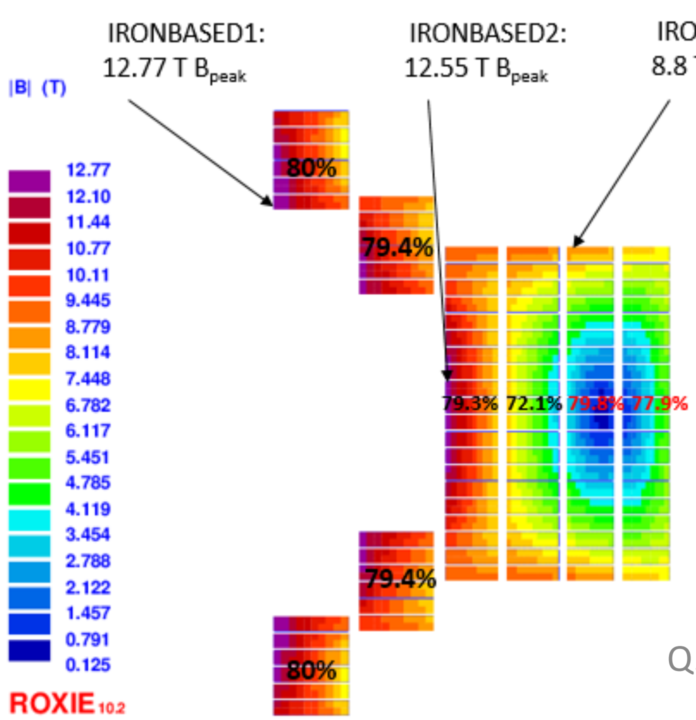
- **Upgrading phase**
  - Dipole magnet field: 20 -24T, IBS technology
  - Center of Mass energy: >125 TeV
  - Injector chain: 4.2 TeV (adding a high-energy booster ring in the main tunnel in the place of the electron ring and booster)
- **Development of high-field superconducting magnet technology**
  - Starting to develop HTS magnet technology before applicable IBS wire is available
  - ReBCO & Bi-2212 and LTS wires be used for model magnet studies and as options for SPPC: stress management, quench protection, field quality control and fabrication methods

High field magnets, Fe-HTS (SppC)

The 12-T Fe-based Dipole Magnet







Design with expected J_e of IBS in 2025

Strand	diam.	cu/sc	RRR	Tref	Bref	Jc@ BrTr	dJc/dB
IBS	0. 802	1	200	4. 2	10	4000	111

- **The required length of the 0.8 mm IBS is 6.1 Km/m**
- **For 100-km SPPC, 3000 tons of IBS is needed**
- **Target cost of IBS: 20 RMB (~2.6 Eur) /kAm @12 T**

Injector Chain (SppC)

FCC-hh

SppC

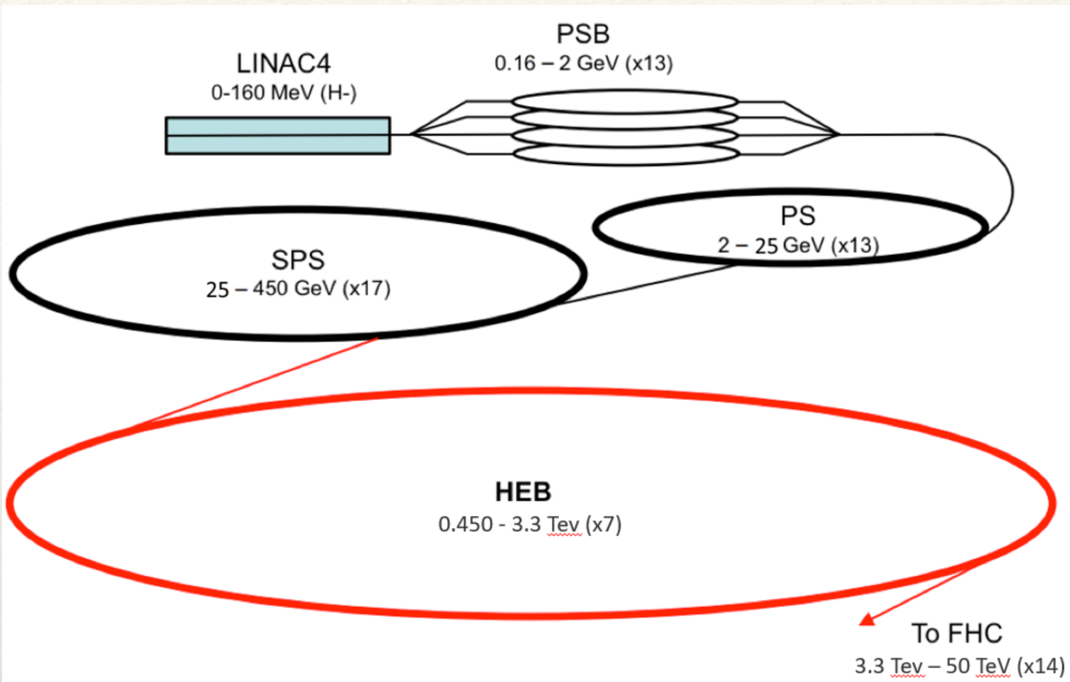


Figure 6.1: FCC-hh injector chain, based on the existing LHC injector chain and a 3.3 TeV High Energy Booster HEB.

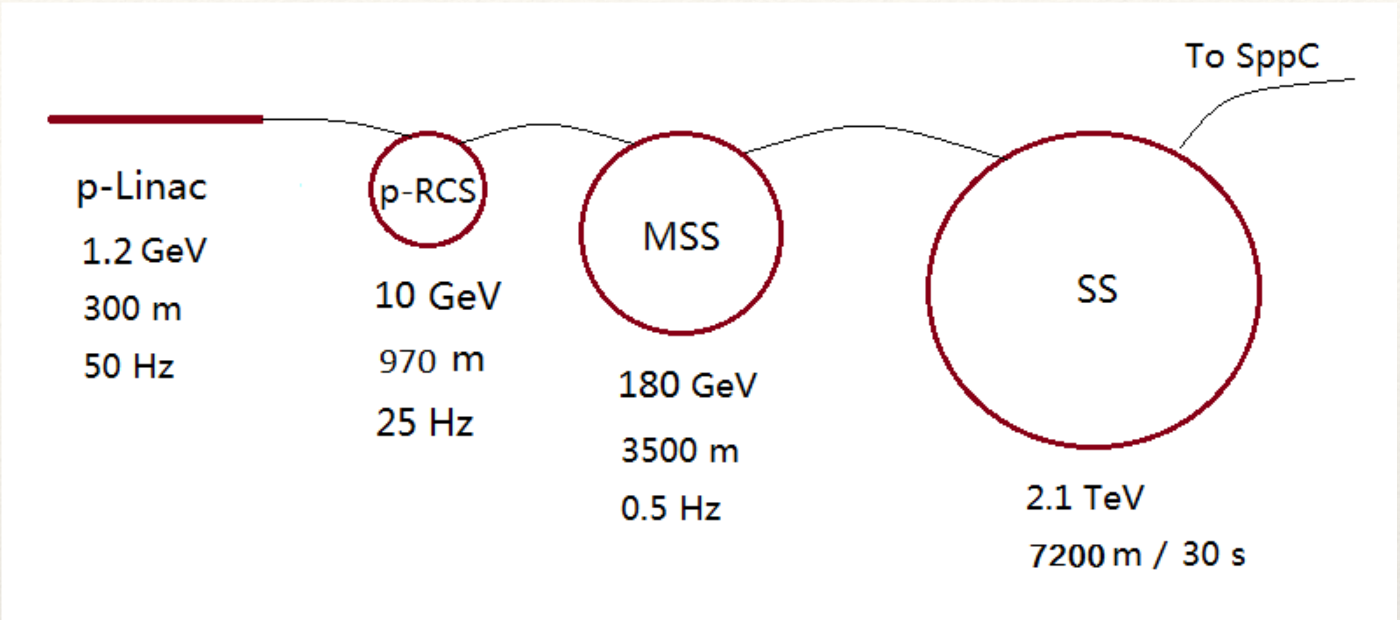
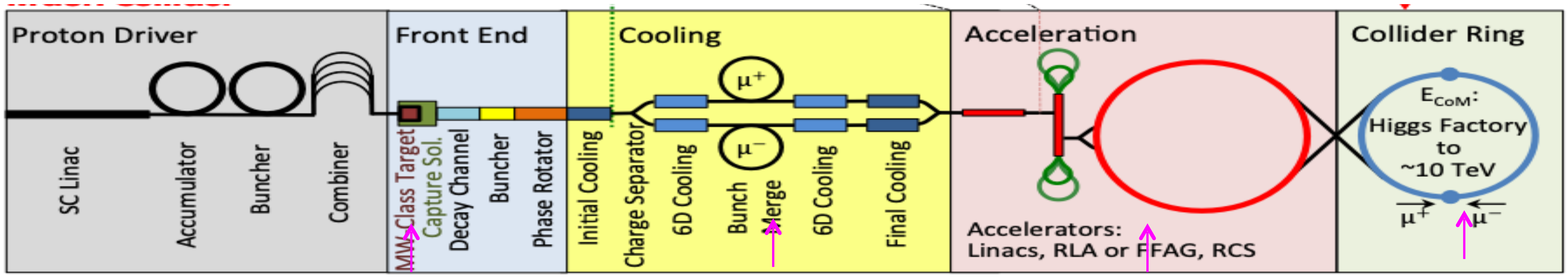


Figure 8.4.1: Injector chain for the SPPC

- SppC has to build an injector chain, which is more than CERN is currently using for LHC injection, *from scratch*. The “SS” booster looks similar to “superconducting SPS”.
- FCC-hh can convert the existing LHC for the “HEB” booster.
- HE-LHC may need “superconducting SPS” to assure enough aperture in the collider at injection.

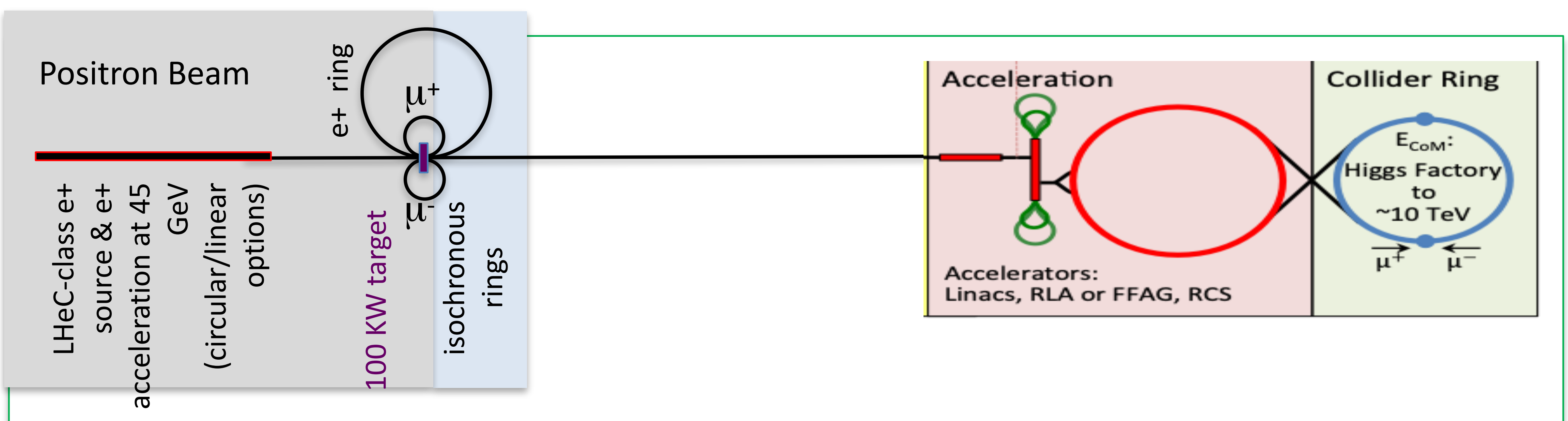
Muon colliders

from US-MAP (2015) to LEMMA scheme (2017)



key challenges

~10^{13}-10^{14} μ / sec tertiary particle *p*→π→μ:	fast cooling (τ=2μs) by 10^6 (6D)	fast acceleration mitigating μ decay	background from μ decay



key challenges

~10^{11} μ / sec from $e^+e^- \to \mu^+\mu^-$

key R&D

10^{15} e^+/sec, 100 kW class target, NON destructive process in e+ ring

M. Antonelli, M. Boscolo, P. Raimondi et al.

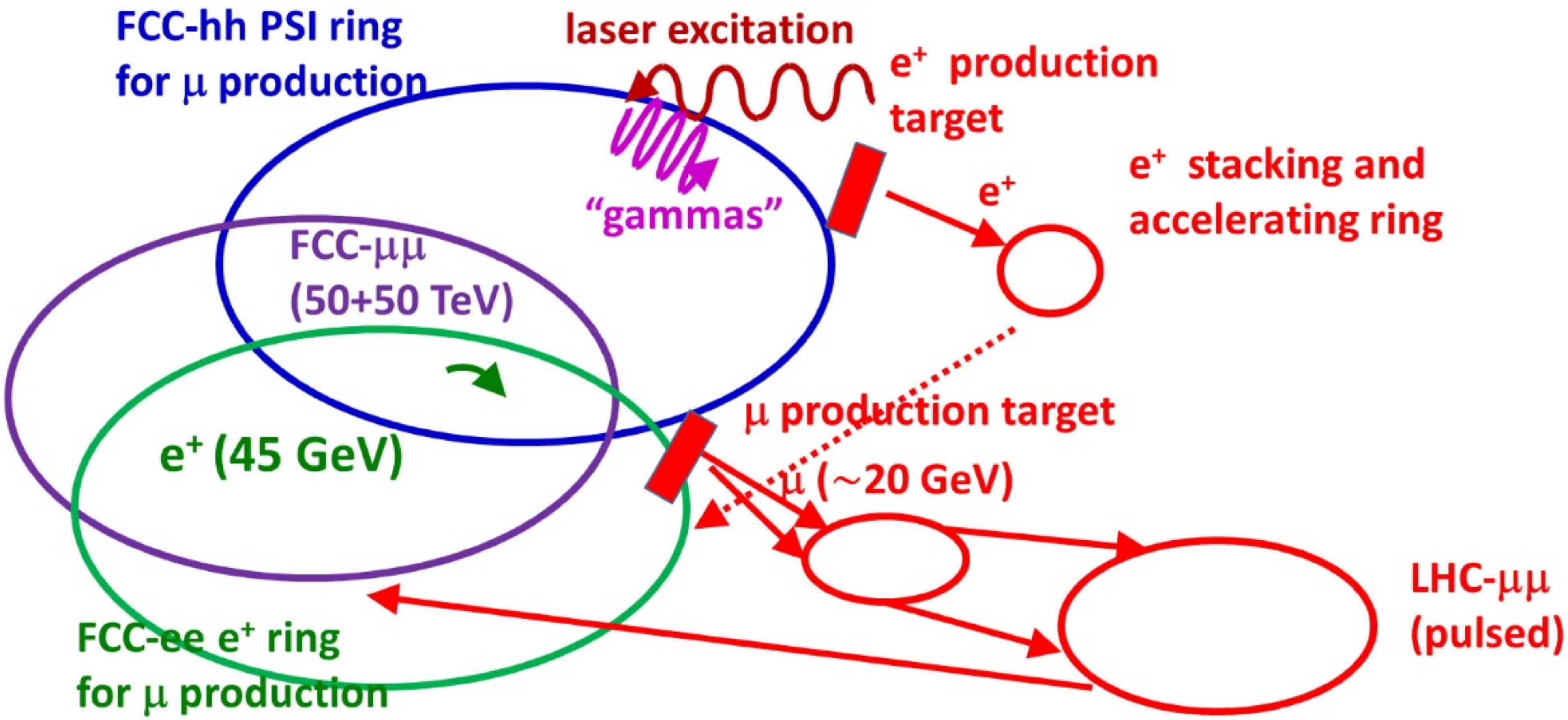
More ideas/options for muon colliders

- **LEMMA**
- Manuela Boscolo (INFN Frascati): first proposed together with Pantaleo Raimondi (ESRF) and Mario Antonelli (INFN); **45 GeV positrons circulating in a storage ring annihilate on a thin internal target, resulting in muon production**; target survival is open question. Liquid targets or rotating targets among the options; **need for experimental target tests**
- Oscar Blanco (INFN-LNF): **LEMMA muon accumulator ring**; muon beam emittance limited by multiple scattering in annihilation target
- Simone Liuzzo (ESRF): for LEMMA, more than 120 MW of **synchrotron radiation** in 6.2 km positron ring; <30 MW in 27 km ring; even lower in 100 km FCC-ee ring (F. Zimmermann), which already offers the right beam energy
- Francesco Collamati (INFN Roma): abundant bremsstrahlung photons emitted from target can be used to generate more positrons, leading to a **self-amplification of the positron beam**
- Daniel Schulte (CERN): experimental programme using electron beams from the CERN SPS, with a CLIC like injector; plasma acceleration as a perfect match for muons, which typically are of low intensity and fairly large emittance - "***if it is not suitable here, plasma acceleration probably cannot be used for any other type of collider***".
- Scott Berg (BNL) and Alex Bogacz (JLAB): options for muon acceleration, including FFA accelerator prototype **CBETA** under construction at Cornell (see also first ever experimental demonstration of muon radiofrequency acceleration at J-PARC, CERN Courier 9 July 2018; https://cerncourier.com/muons-accelerated-in-japan/).
- Daniel Kaplan (IIT): limits from neutrino radiation. Concerning next steps: "***you don't get tenure by saving government money***".
- Alain Blondel (U Geneva): **luminosity measurement techniques** for muon colliders to be worked out; Mario Greco (Roma Tre): QED radiative effects for a precision study of the Higgs pole line shape and the signal-to-background ratio

Summarized by F. Zimmermann on
Muon collider workshop 2018: https://indico.cern.ch/event/719240

Muon collider (FCC-μμ)

FCC: the ideal basis for constructing future 100 TeV muon collider



100 TeV muon collider, "**FCC-μμ**", in one of the FCC-hh rings, with e^+ production from a Gamma Factory using partially stripped ion beams circulating in the other FCC-hh ring, and with LEMMA type muon production from a positron beam stored in one of the 45 GeV FCC-ee rings (Frank Zimmermann), >100 years of FCC

* For this purpose the arc of FCC-ee must coexist with FCC-hh.

F. Zimmermann