Future e+e- Higgs Factory for Asia?

Geoffrey Taylor

The University of Melbourne

AFAD Asian Forum for Accelerators and Detectors 2023

12-14 April 2023

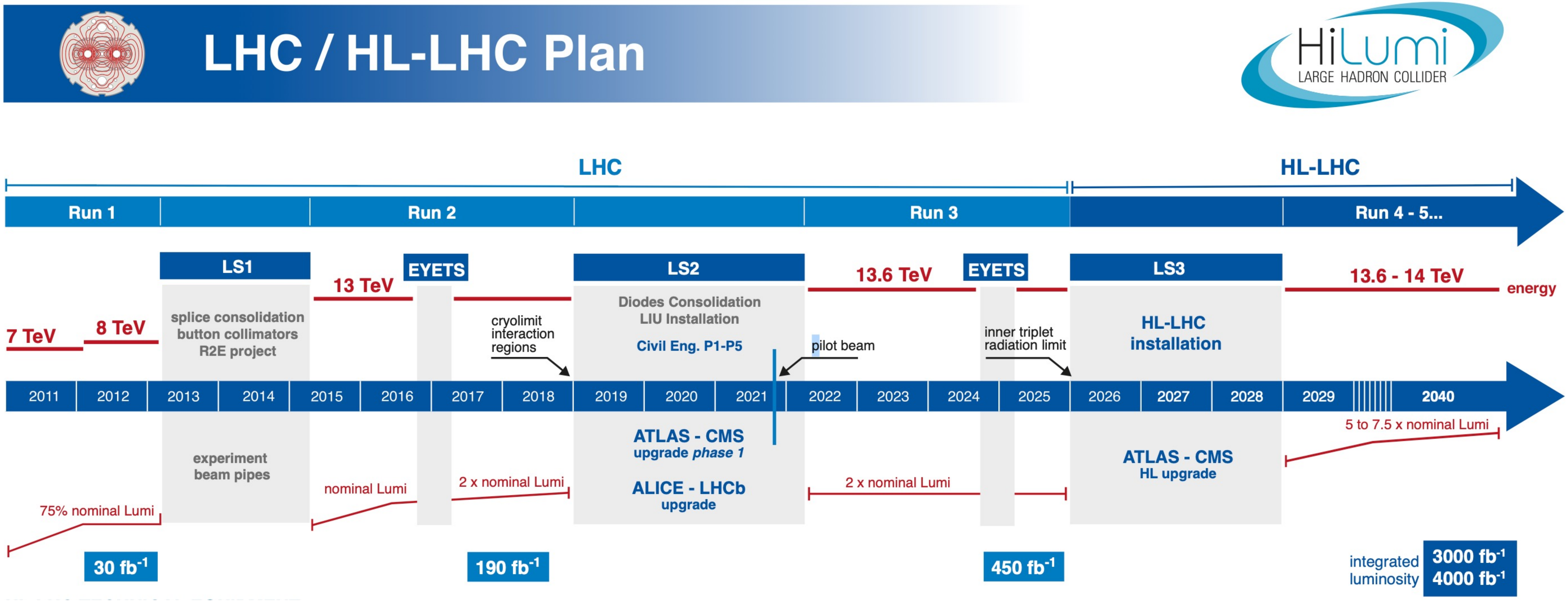
Presentation Outline

- The Higgs boson Discovery
  - The LHC and Upgrade to the HL-LHC
  - Some key questions about the Higgs boson
- The Need for an e+e- Higgs factory
  - The international "consensus"
  - The established proposals – ILC, CLIC, FCC(e+e-), CEPC
  - Some ideas for future consideration
- The International Linear Collider
  - Most advanced proposal
  - Status – progress and hurdles
- The Outlook

The LHC and the Discovery of the Higgs Boson

- High Energy Proton Colliders were Bold and Risky:
  - Following Golden Years of Particle Physics (SLAC,CERN, Fermilab, DESY, BNL, Cornell)
  - Risk → SSC Cancellation
  - Bold → LHC in LEP tunnel → Magnet technology
  - Societal benefits of CERN: the Web, … → UN Observer status
- Very difficult collision environment:
  - High rate, High particle density/radiation, High data rate, High Precision
- High Return: The Higgs boson discovery!

Future Prospect – HL-LHC



EYETS: Extended Year-End Technical Stop

https://hilumilhc.web.cern.ch/content/hl-lhc-project
February, 2022

Discovery Followed by Precision Studies

Proton Collisions → Discovery
e+e- Collisions → ”Clean”, Precision studies

A simplification (eg. LHC is a “precision” environment”), BUT:

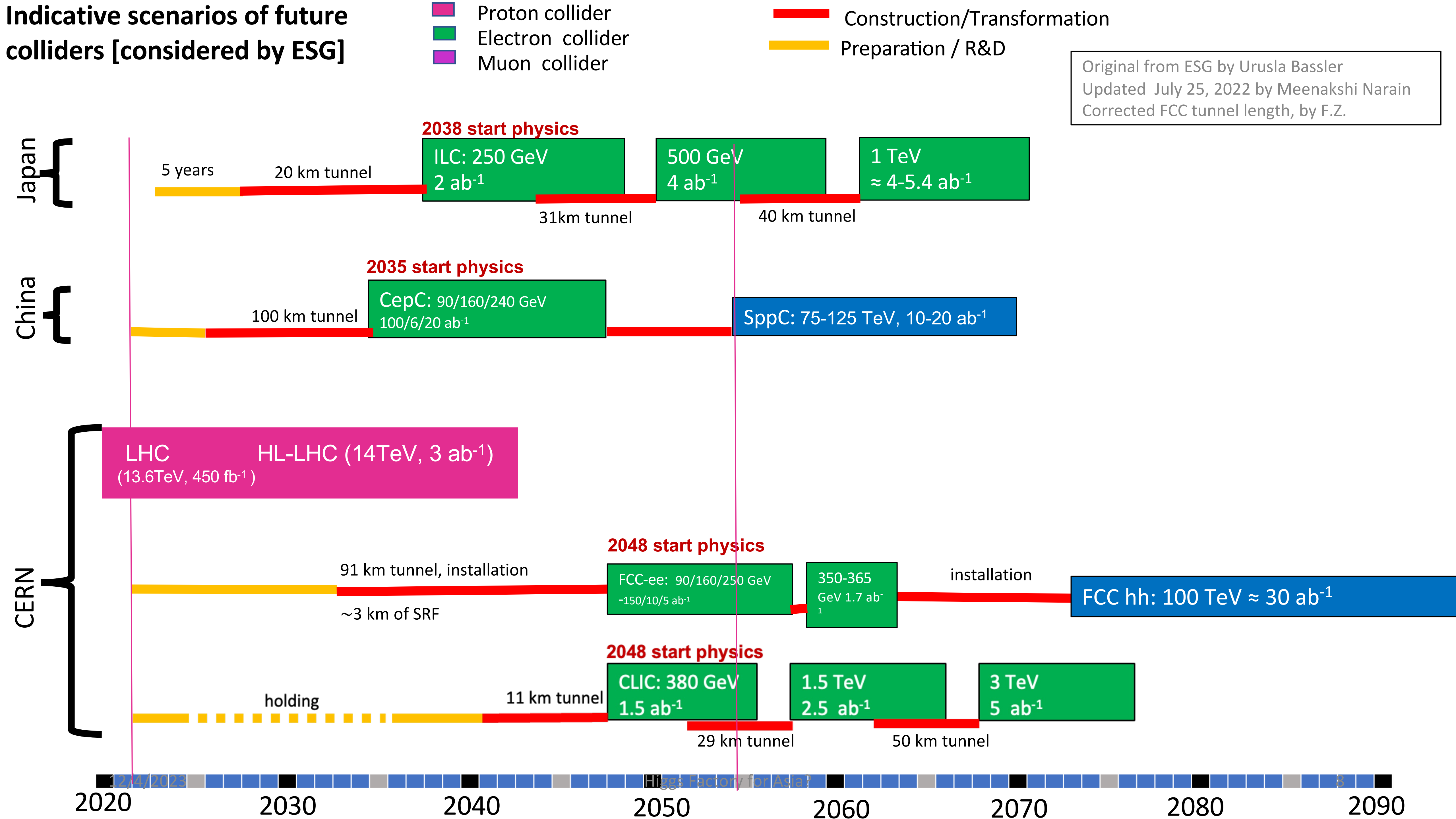
- CERN (SppS) → discovery of Z, W boson
  - LEP Precision Z-studies (→ top-quark; Higgs; via radiative corrections!!)
- But other similar history:
  - Upsilon discovery in proton interactions (Fermilab) followed by B-factories:
    - PEPII and KEKB(& SuperKEKB)
  - Even e-p scattering (SLAC) followed by “quark” factories:
    - SPEAR, DORIS/PETRA, CESR

High Energy Frontier: Circular Colliders

- Trade-off between radius (large civil works/technical infrastructure) and magnetic field.
- Next generation (?) ~100km circumference machines
  - CMS energies >100 TeV → B ~16T (Nb_3Sn) or >20T (HTS inserts)
  - Current technology (HL-LHC) ~12T (Nb_3Sn)
- CERN: FCC(hh); IHEP(China): SppC
- 100km Class machines: cost dominated by mere size:
  - e+e- collider as “stepping stone” for p-p future
  - CERN: FCC(e+e-) ; IHEP: CEPC
  - Benefit of large radius → reduce synchrotron electron energy loss
    - (Remember LEP2)
  - Synchrotron radiation “limit” ~380 GeV (cms energy)for ~100km ring
    - Power cost limitation

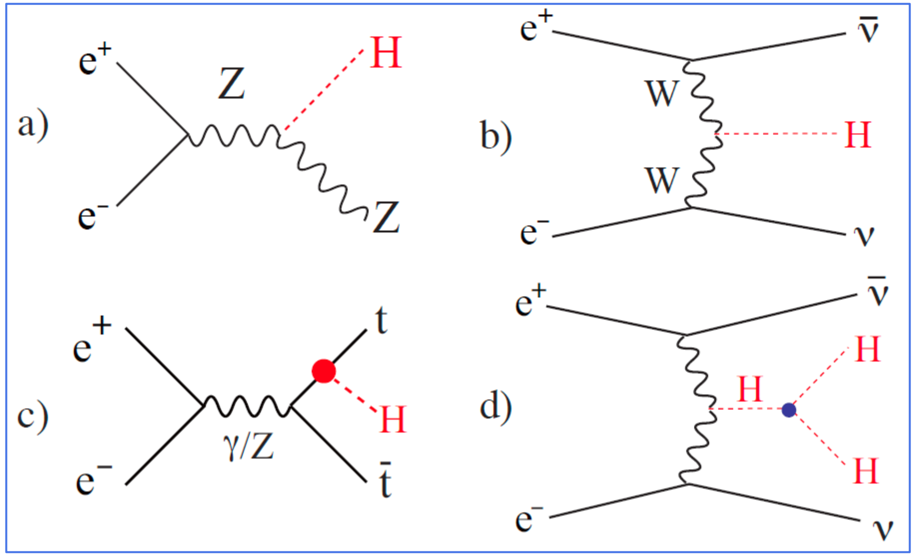
e+e- Colliding Beam Higgs Factory

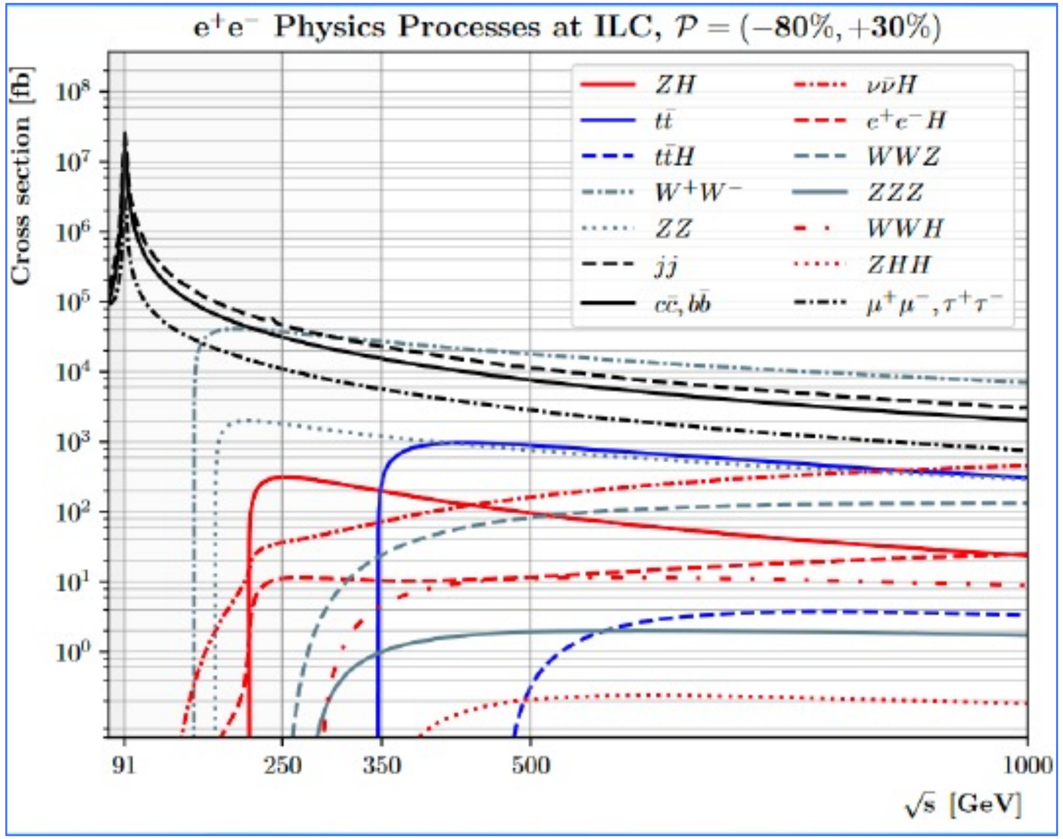
- The need for an e+e- Higgs Factory
  - The international “consensus”
    - EPPSU (2013, 2020), P5(2015)
    - ICFA (2019, 2020)
  - The established proposals – ILC, CLIC, FCC(e+e-), CEPC
    - Linear Machines - ILC, CLIC
      - Depend upon high-gradient RF capacity
      - Energy Increase Possible future upgrade (Tunnel Length, Accelerating Gradient)
    - Circular Colliders - FCC(e+e-), CEPC
      - Multiple collision points
      - Upgrade path to proton-proton collider option



Indicative scenarios of future colliders [considered by ESG]
Proton collider
Electron collider
Muon collider
Construction/Transformation
Preparation / R&D
Original from ESG by Urusla Bassler
Updated July 25, 2022 by Meenakshi Narain
Corrected FCC tunnel length, by F.Z.
Japan
5 years
20 km tunnel
2038 start physics
ILC: 250 GeV
2 ab-1
31km tunnel
500 GeV
4 ab-1
40 km tunnel
1 TeV
≈ 4-5.4 ab-1
China
100 km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab-1
SppC: 75-125 TeV, 10-20 ab-1
CERN
LHC
(13.6TeV, 450 fb-1)
HL-LHC (14TeV, 3 ab-1)
91 km tunnel, installation
~3 km of SRF
2048 start physics
FCC-ee: 90/160/250 GeV
-150/10/5 ab-1
350-365
GeV 1.7 ab-1
installation
FCC hh: 100 TeV ≈ 30 ab-1
holding
11 km tunnel
2048 start physics
CLIC: 380 GeV
1.5 ab-1
29 km tunnel
1.5 TeV
2.5 ab-1
50 km tunnel
3 TeV
5 ab-1
2020
2030
2040
2050
2060
2070
2080
2090

Energy	Reaction	Physics Goal
91 GeV	$e^+e^- \to Z$	ultra-precision electroweak
160 GeV	$e^+e^- \to WW$	ultra-precision W mass
250 GeV	$e^+e^- \to Zh$ $e^+e^- \to t\bar{t}$	precision Higgs couplings top quark mass and couplings
350–400 GeV	$e^+e^- \to WW$ $e^+e^- \to \nu\bar{\nu}h$ $e^+e^- \to f\bar{f}$ $e^+e^- \to t\bar{t}h$	precision W couplings precision Higgs couplings precision search for Z' Higgs coupling to top
500 GeV	$e^+e^- \to Zhh$ $e^+e^- \to \tilde{\chi}\tilde{\chi}$ $e^+e^- \to AH, H^+H^-$ $e^+e^- \to \nu\bar{\nu}hh$ $e^+e^- \to \nu\bar{\nu}VV$	Higgs self-coupling search for supersymmetry search for extended Higgs states Higgs self-coupling composite Higgs sector
700–1000 GeV	$e^+e^- \to \nu\bar{\nu}t\bar{t}$ $e^+e^- \to \tilde{t}\tilde{t}^*$	composite Higgs and top search for supersymmetry



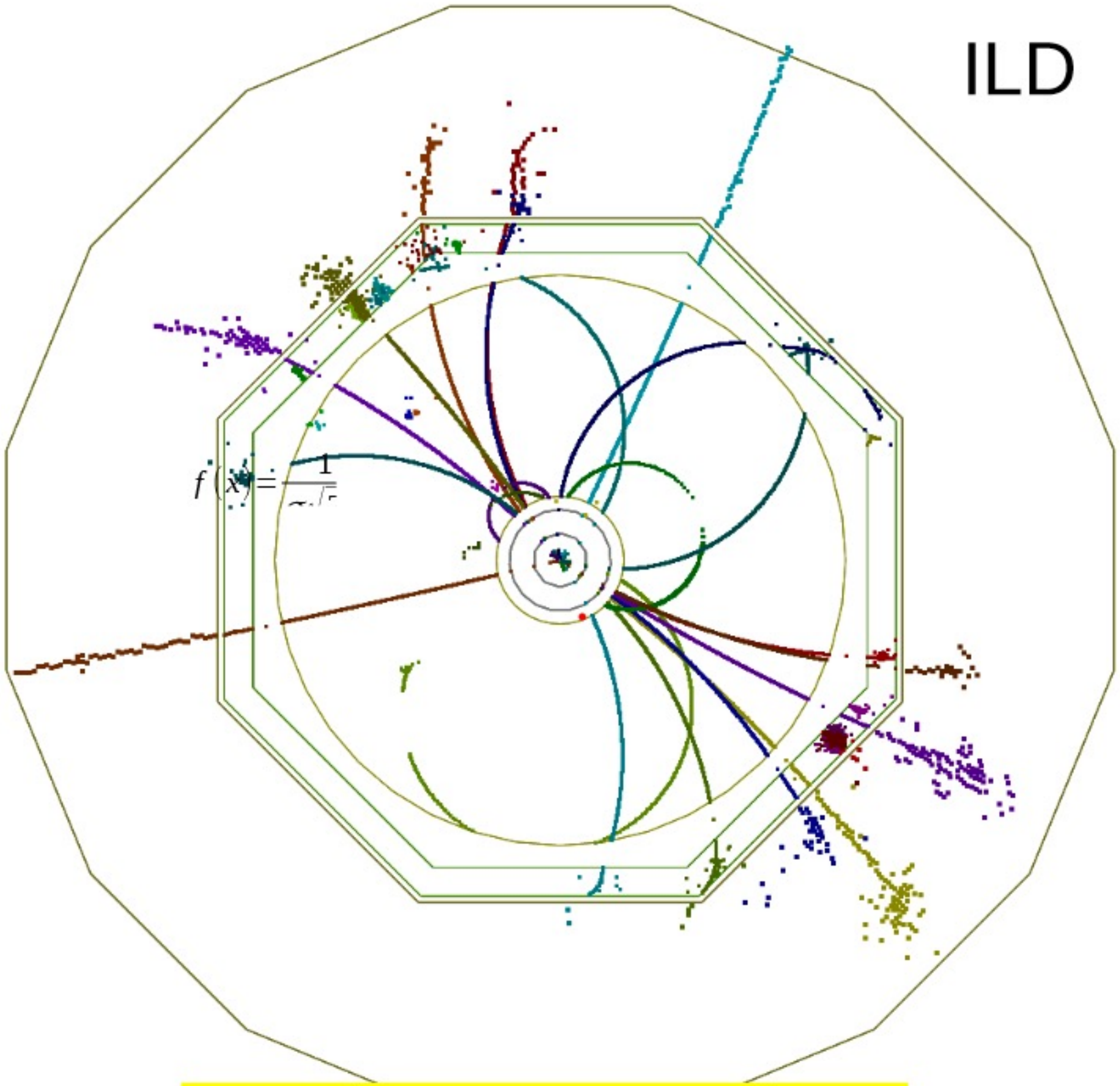


For example, "The International Linear Collider: Report to Snowmass 2021"
DESY-22-045, IFT–UAM/CSIC–22-028,
KEK Preprint 2021-61, PNNL-SA-160884,
SLAC-PUB-17662
July 14, 2022

240-250 GeV Higgs Factory

With E_{cms} =250 GeV:
$E(Z^0)$ = 110 GeV →
Recoil: Higgs boson
No need to trigger on H

Precision Higgs Studies including Invisible Higgs decays



ECM = 250 GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

Circular and Linear Options

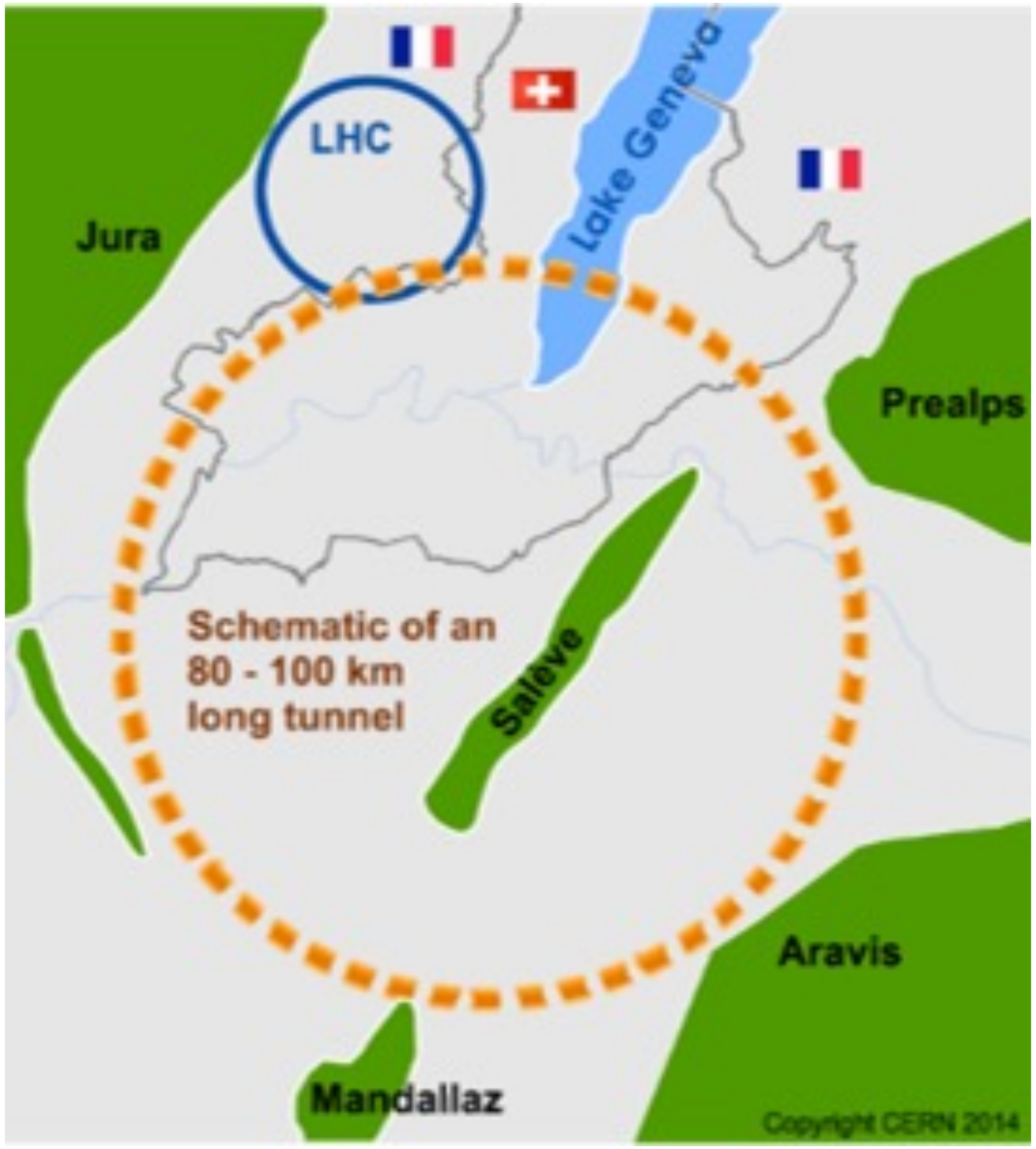
- ILC:
  - 250 GeV, Upgrades to 500 GeV (even 1 TeV possible)
- CLIC:
  - 250/380 GeV (Klystrons or Drive Beam; 1TeV and 3 TeV (Drive Beam)
- FCC(ee); CEPC:
  - 90 GeV (Tera-Z); 250 GeV (Higgs Factory); 380 GeV (t-tba)

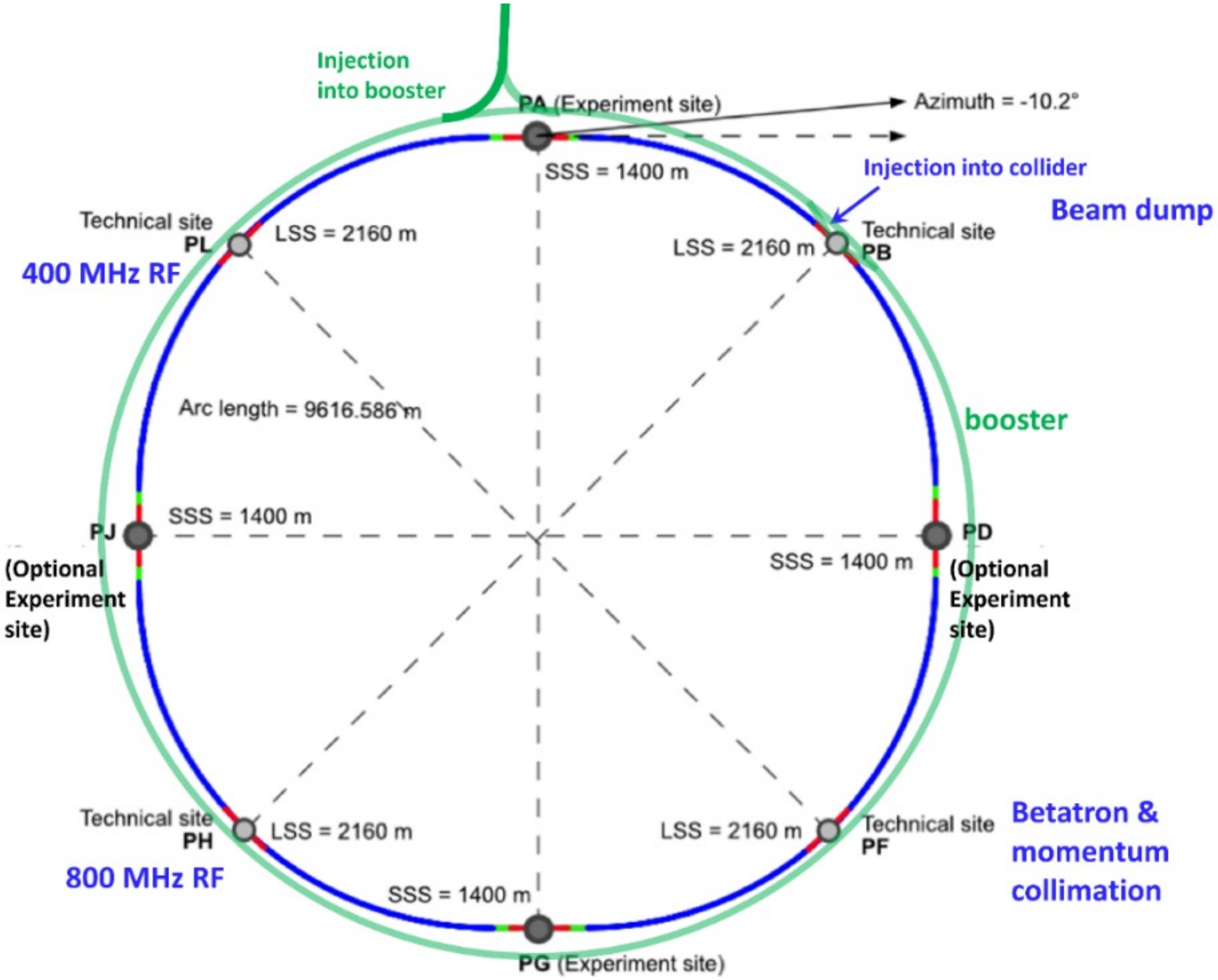
Circular Colliders – FCC, CEPC

FCC(ee)

- e+e- collider for Higgs factory as stepping-stone to very high energy (100TeV) FCC(hh)
- FCC Feasibility study to report by 2025 following 2020 update of the European Strategy for Particle Physics

Frank Zimmermann,
Future Circular Colliders (FCC),
Future Colliders Seminar Series,
CERN, 14 March 2023

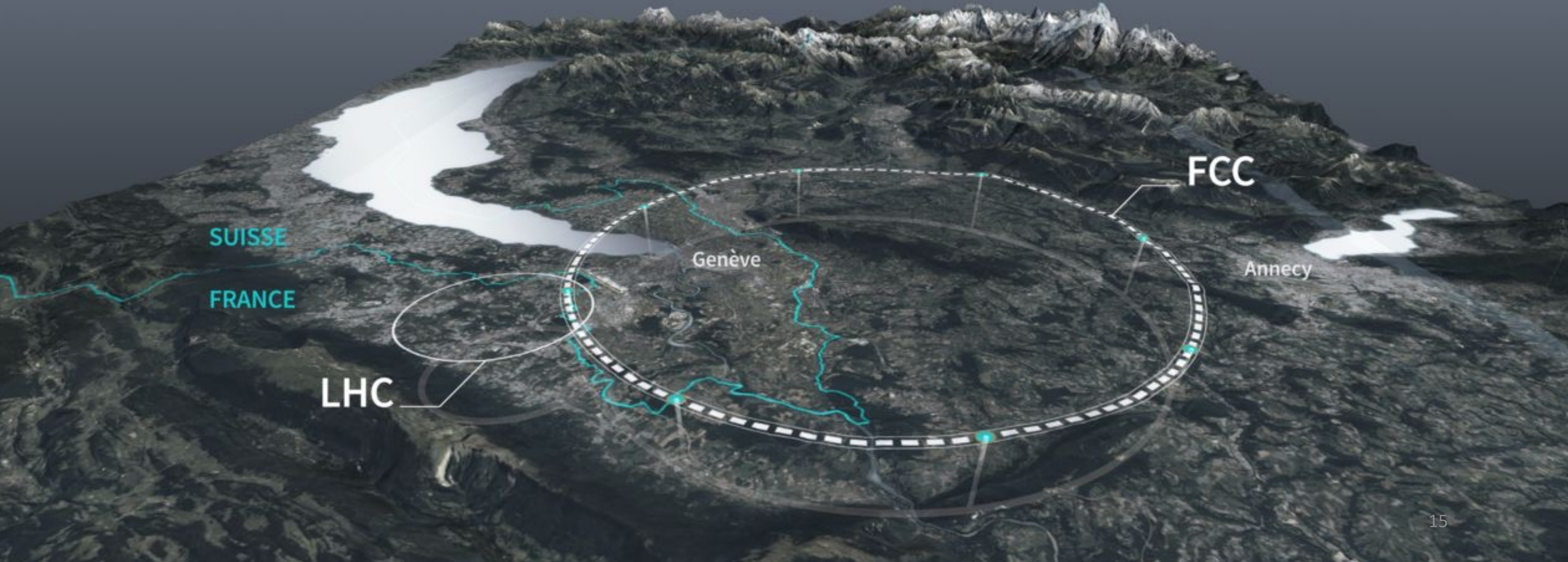

LHC
Lake Geneva
Jura
Prealps
Schematic of an 80 - 100 km long tunnel
Salève
Aravis
Mandallaz
Copyright CERN 2014


Injection into booster
PA (Experiment site)
Azimuth = -10.2°
SSS = 1400 m
Injection into collider
Beam dump
Technical site PL
LSS = 2160 m
400 MHz RF
LSS = 2160 m
Technical site PB
Arc length = 9616.586 m
booster
PJ
SSS = 1400 m
(Optional Experiment site)
PD
SSS = 1400 m
(Optional Experiment site)
Technical site PH
LSS = 2160 m
800 MHz RF
LSS = 2160 m
Technical site PF
Betatron & momentum collimation
SSS = 1400 m
PG (Experiment site)

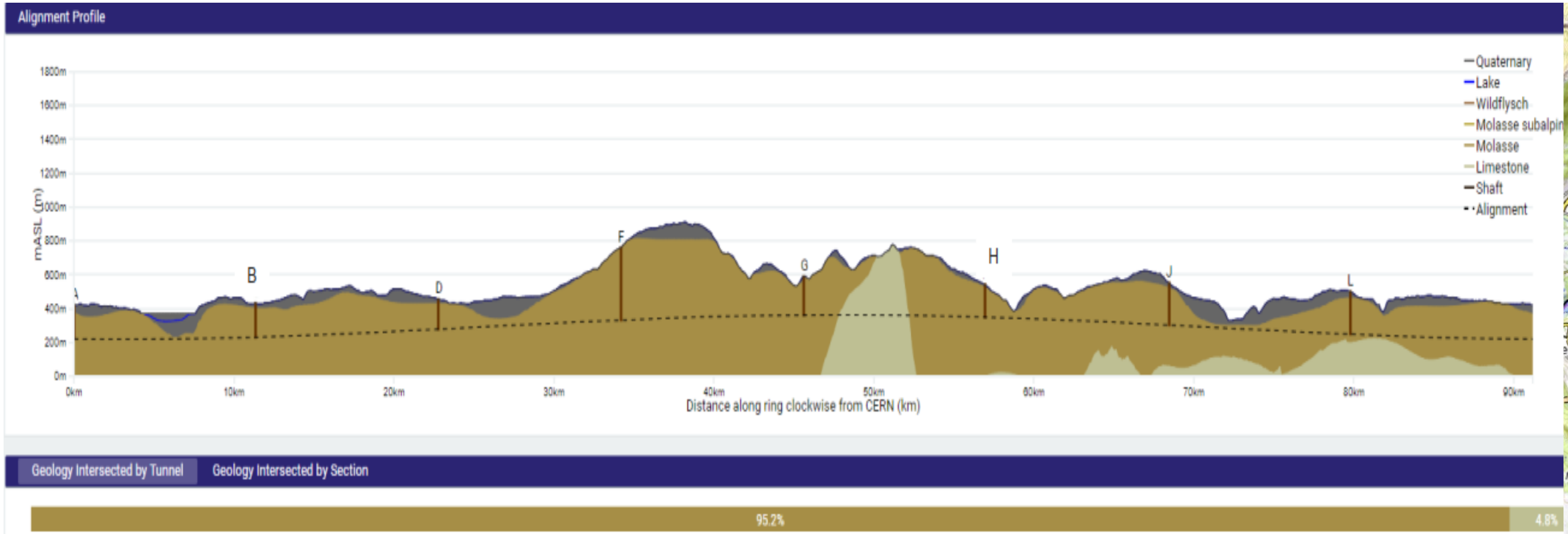
FCC(ee)

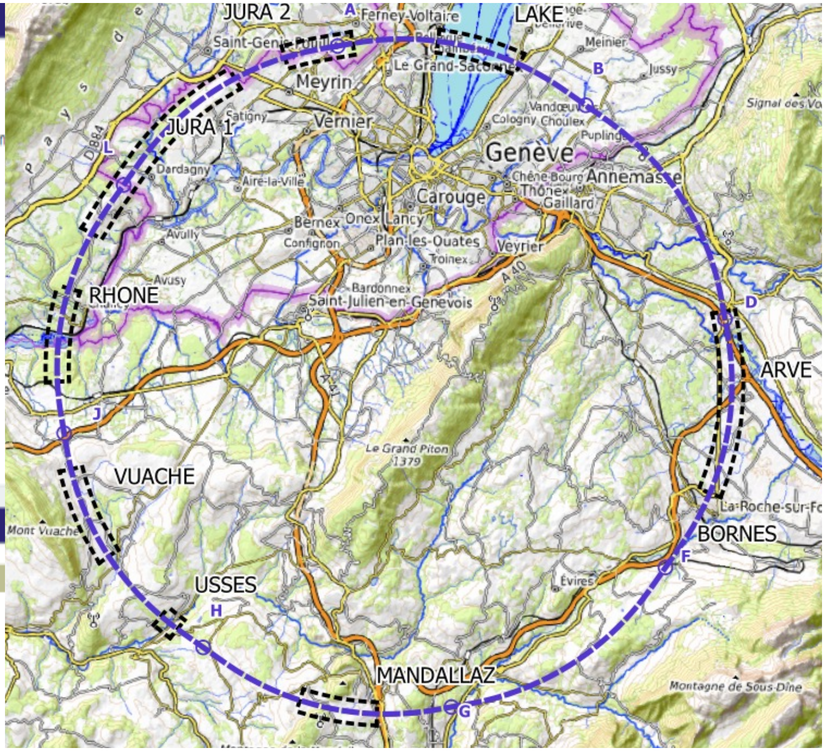
FCC research infrastructure for the 21st century

A new 91 km tunnel to host multiple colliders
100 – 300 m under ground, 8 surface sites
FCC-ee: electron-positron @ 91, 160, 240, 365 GeV
FCC-hh: proton-proton @ 100 TeV, and heavy-ions (Pb) @39 TeV
FCC-eh: electron-proton@ 3.5 TeV



FCC implementation - footprint baseline





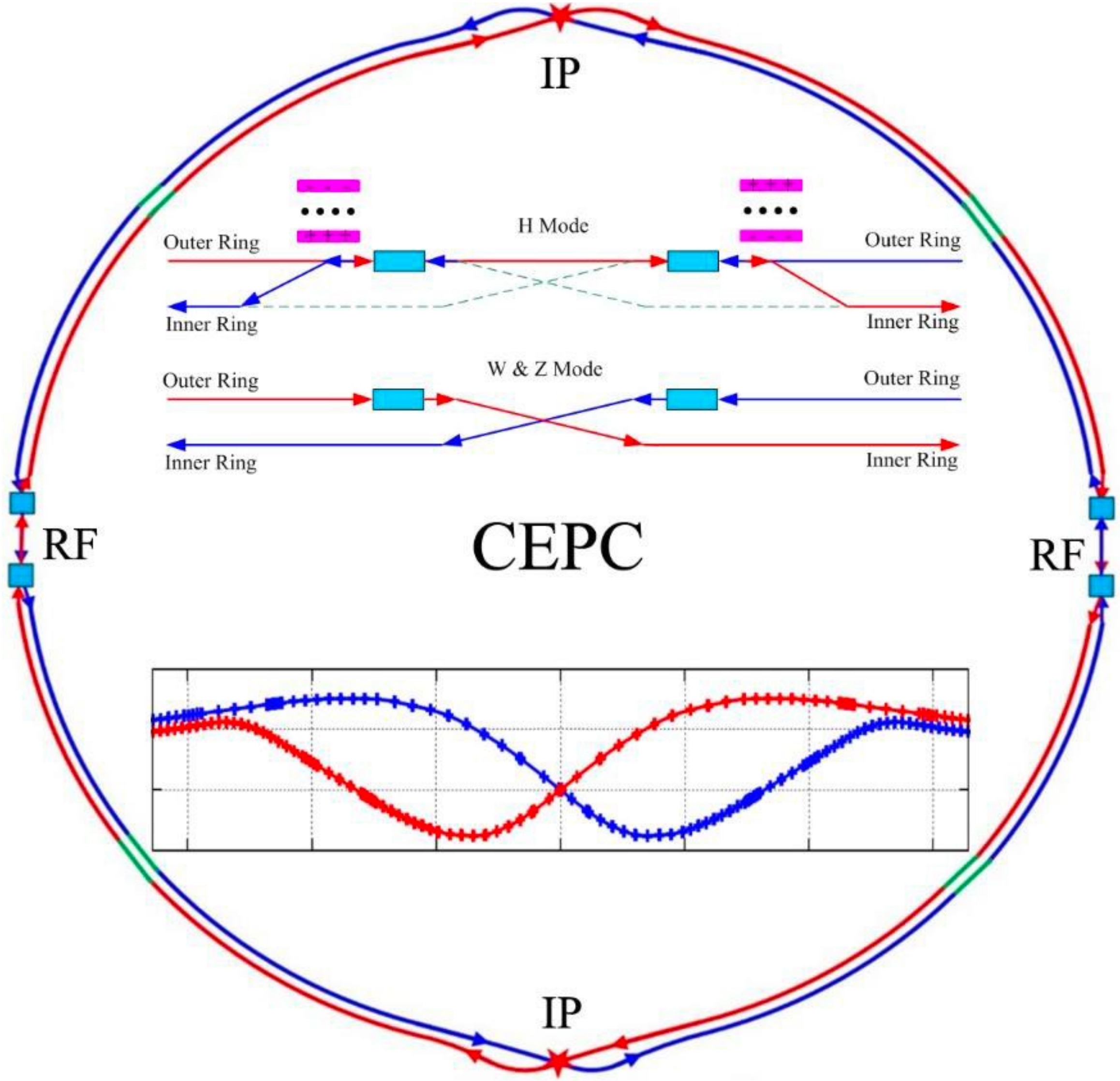
Present baseline implementation

- 91 km circumference
- 95% in molasse geology for minimising tunnel construction risks
- 8 surface sites with ~5 ha area each.

Site investigations planned for 2024 and 2025 in areas with uncertain geological conditions:

- Limestone-molasse border, karstification, water pressure, moraine properties, water bearing layers, etc.
- ~40-50 drillings, 100 km of seismic lines

CEPC - China



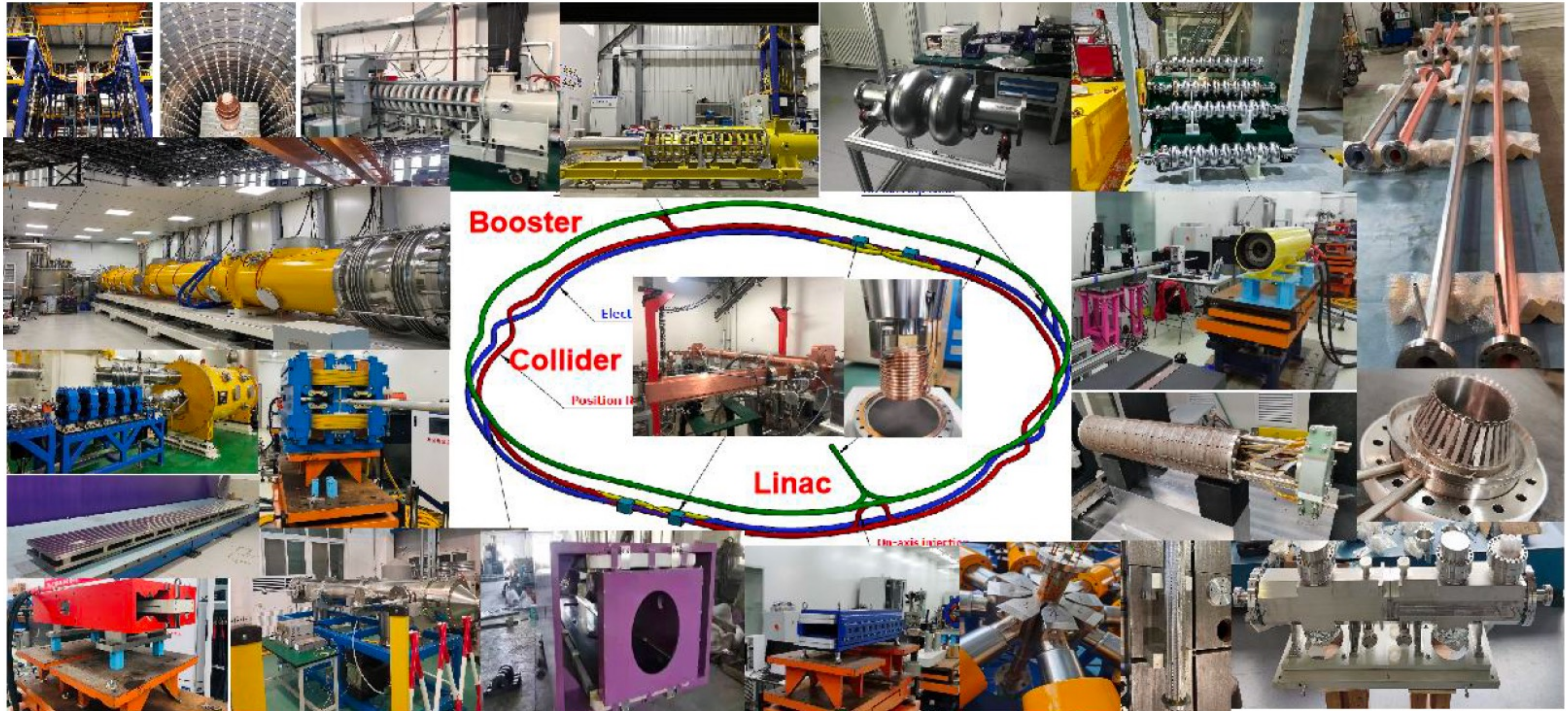
From Jie Gao, IHEP, Beijing

CEPC TDR Parameters (Upgrade)

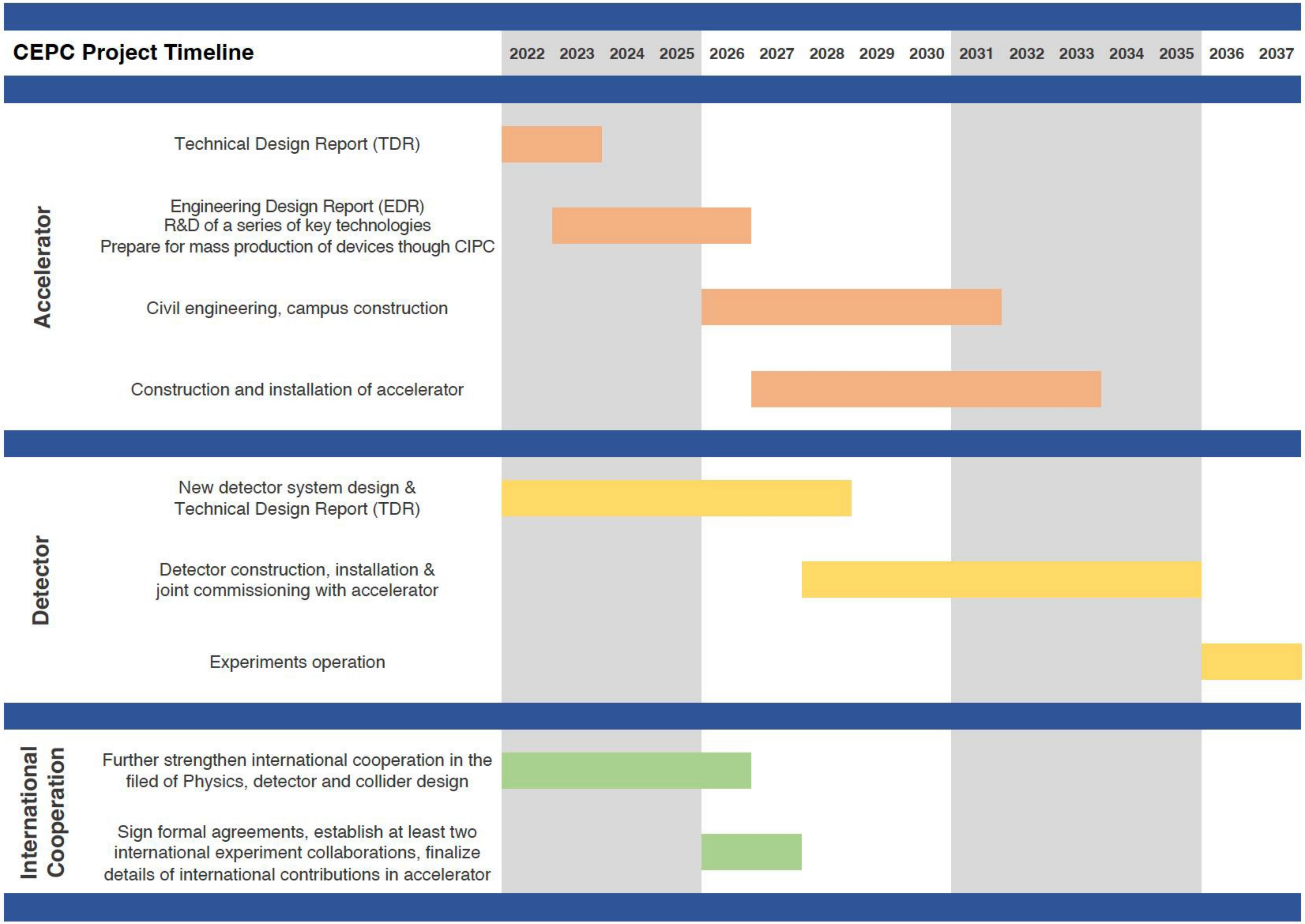
	Higgs	Z	W	$t\bar{t}$
Number of IPs	2			
Circumference (km)	100.0			
SR power per beam (MW)	**50**			
Half crossing angle at IP (mrad)	16.5			
Bending radius (km)	10.7			
Energy (GeV)	120	45.5	80	180
Energy loss per turn (GeV)	1.8	0.037	0.357	9.1
Damping time $\tau_x/\tau_y/\tau_z$ (ms)	44.6/44.6/22.3	816/816/408	150/150/75	13.2/13.2/6.6
Piwinski angle	4.88	29.52	5.98	1.23
Bunch number	446	13104	2162	58
Bunch spacing (ns)	355 (53% gap)	23 (10% gap)	154	2714 (53% gap)
Bunch population (10^{11})	1.3	2.14	1.35	2.0
Beam current (mA)	27.8	1340.9	140.2	5.5
Momentum compaction (10^{-5})	0.71	1.43	1.43	0.71
Beta functions at IP β_x^*/β_y^* (m/mm)	0.3/1	0.13/0.9	0.21/1	1.04/2.7
Emittance $\varepsilon_x/\varepsilon_y$ (nm/pm)	0.64/1.3	0.27/1.4	0.87/1.7	1.4/4.7
Betatron tune ν_x/ν_y	445/445	266/267	266/266	445/445
Beam size at IP σ_x/σ_y (um/nm)	14/36	6/35	13/42	39/113
Bunch length (natural/total) (mm)	2.3/4.1	2.7/10.6	2.5/4.9	2.2/2.9
Energy spread (natural/total) (%)	0.10/0.17	0.04/0.15	0.07/0.14	0.15/0.20
Energy acceptance (DA/RF) (%)	1.6/2.2	1.3/1.5	1.2/2.5	2.0/2.6
Beam-beam parameters ξ_x/ξ_y	0.015/0.11	0.0045/0.13	0.012/0.113	0.071/0.1
RF voltage (GV)	2.2	0.1	0.7	10
RF frequency (MHz)	650			
Longitudinal tune ν_s	0.049	0.032	0.062	0.078
Beam lifetime (Bhabha/beamstrahlung) (min)	39/40	86/400	60/700	81/23
Beam lifetime (min)	20	71	55	18
Hourglass Factor	0.9	0.97	0.9	0.89
Luminosity per IP (10^{34} cm^{-2} s^{-1})	**8.3**	**192**	**26.7**	**0.8**

From: Jie Gao IHEP

Huge CEPC R&D Underway



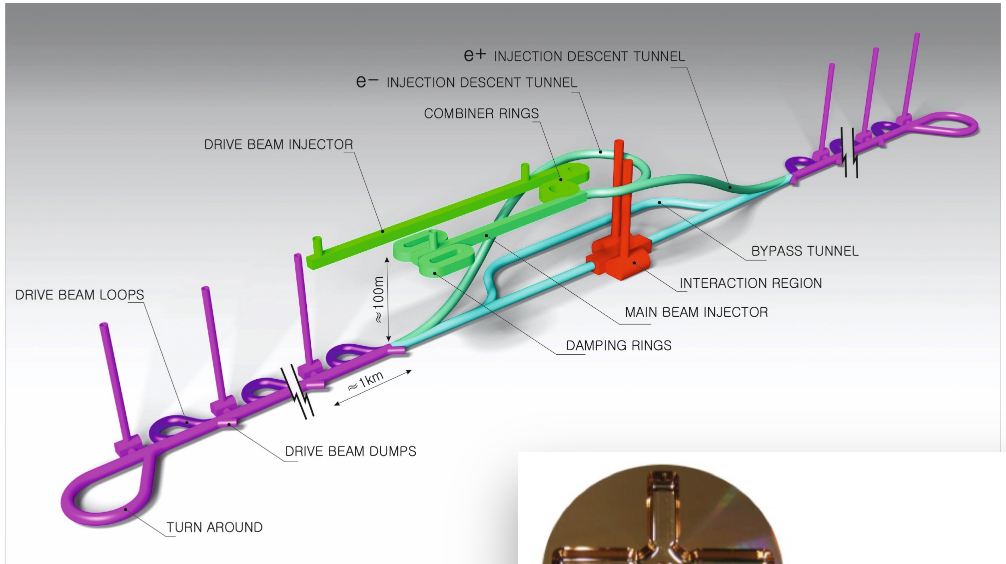
CEPC Timeline



Linear Colliders – ILC, CLIC

The Compact Linear Collider (CLIC)

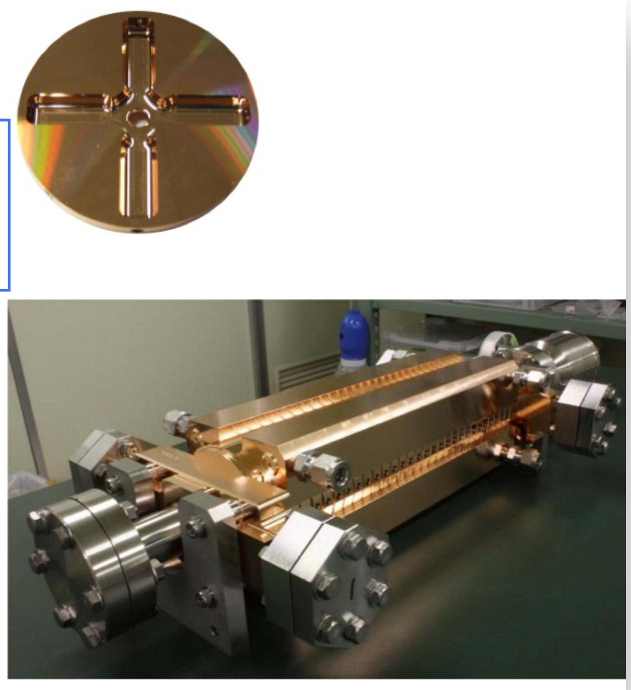
Steinar Stapnes , “Linear Colliders”
Future Colliders Seminar Series,
CERN,14 March 2023



- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision energies from 380 GeV (Higgs/top) up to 3 TeV (Energy Frontier)

(CDR in 2012 focused on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.)

Accelerating structure prototype for CLIC: 12 GHz (L~25 cm)



Klystron powered testing at Melbourne
See talk, M. Volpi

The CLIC accelerator studies are mature:
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

FCC Feasibility Study (2021-2025): high-level objectives

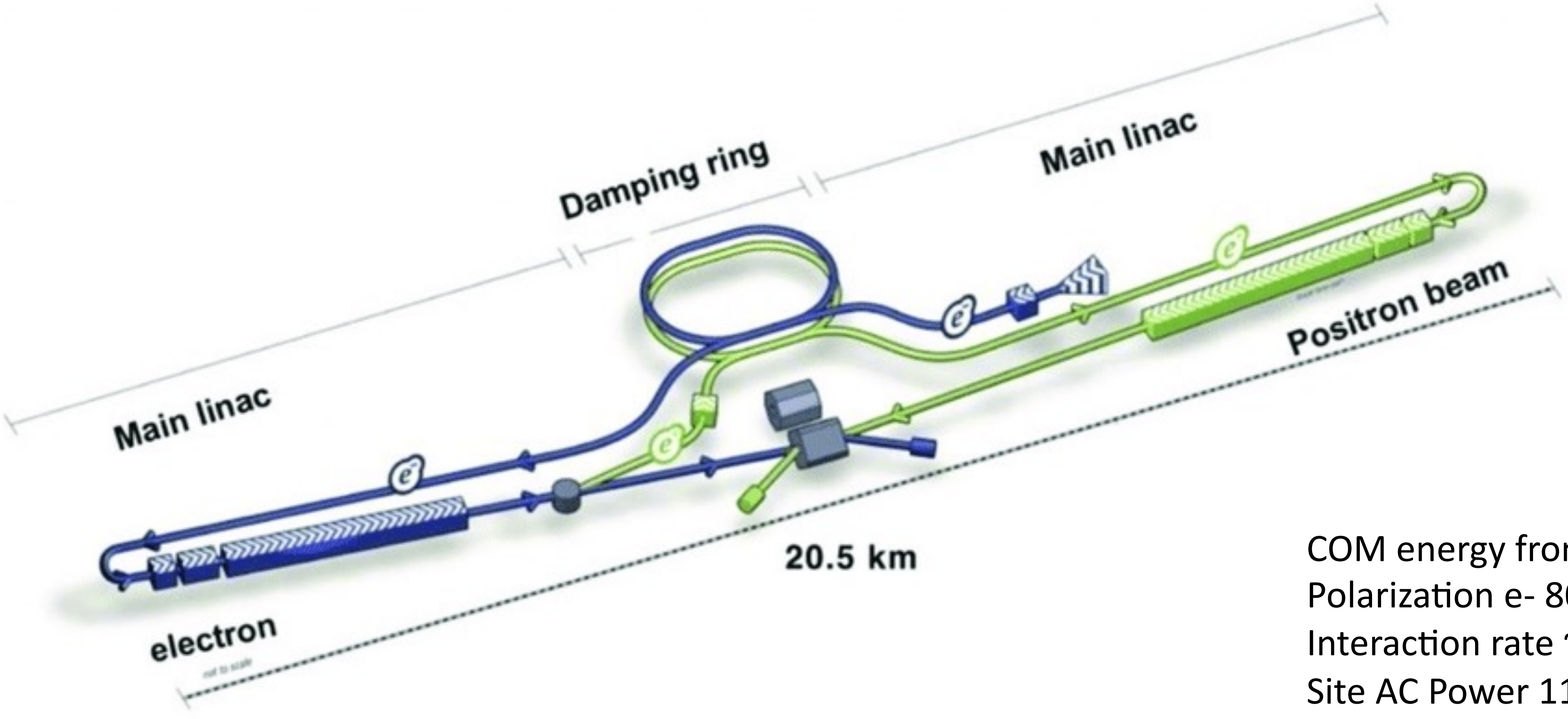
FUTURE CIRCULAR COLLIDER

- ❑ demonstration of the geological, technical, environmental and administrative feasibility of the tunnel and surface areas and optimisation of placement and layout of the ring and related infrastructure;
- ❑ pursuit, together with the Host States, of the preparatory administrative processes required for a potential project approval to identify and remove any showstopper;
- ❑ optimising design of colliders and their injector chains, supported by R&D to develop the needed key technologies;
- ❑ elaboration of a sustainable operational model for the colliders and experiments in terms of human and financial resource needs, as well as environmental aspects and energy efficiency;
- ❑ development of a consolidated cost estimate, as well as the funding and organisational models needed to enable the project's technical design completion, implementation and operation;
- ❑ identification of substantial resources from outside CERN's budget for the implementation of the first stage of a possible future project (tunnel and FCC-ee);
- ❑ consolidation of the physics case and detector concepts for both colliders.

Results will be summarised in a Feasibility Study Report to be released at end 2025

F. Gianotti

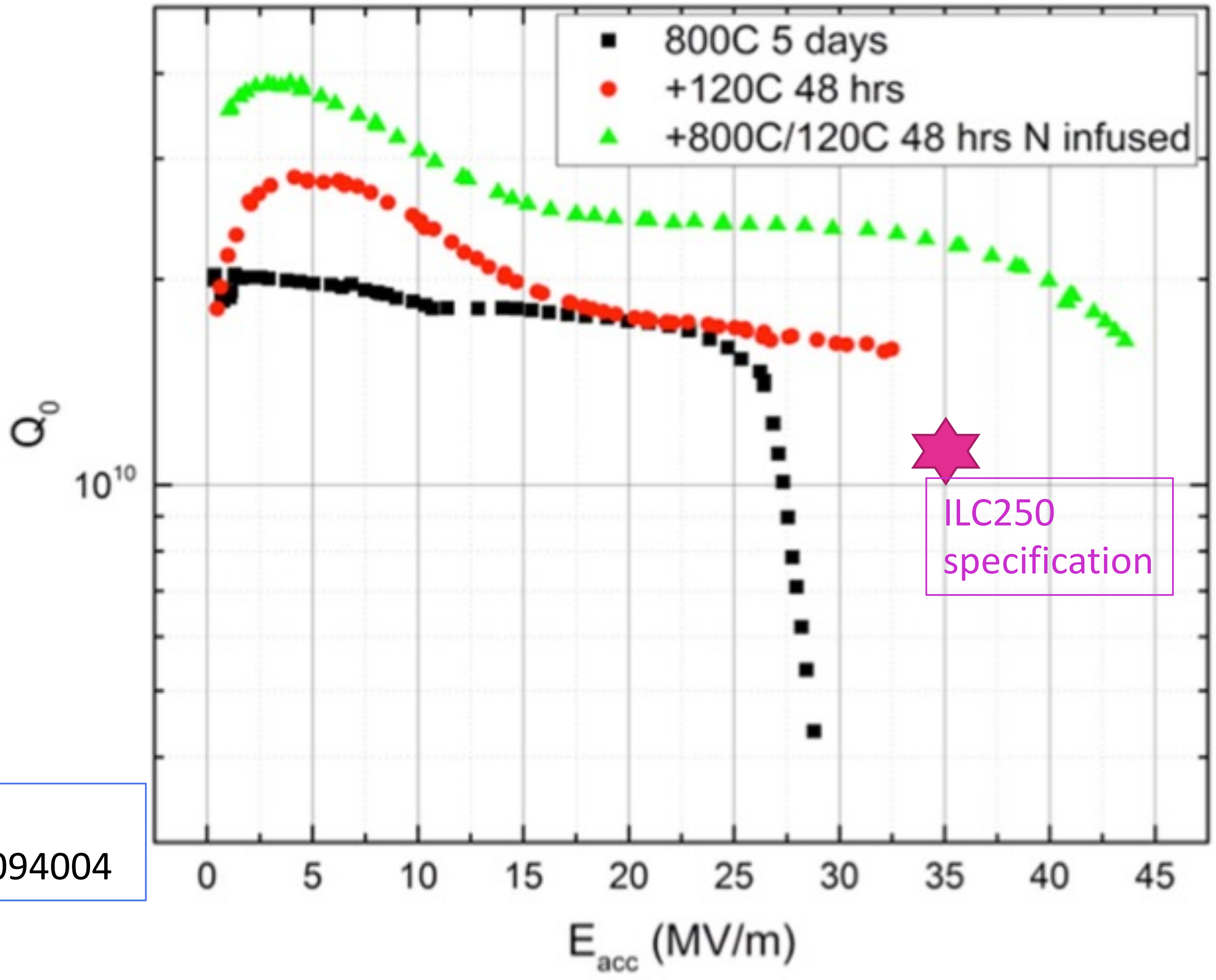
The International Linear Collider



COM energy from Z-pole to 1000 GeV
Polarization e- 80%, e+ 30%
Interaction rate ~1 Hz for e+e- → ff̄
Site AC Power 111 MW (250 GeV)

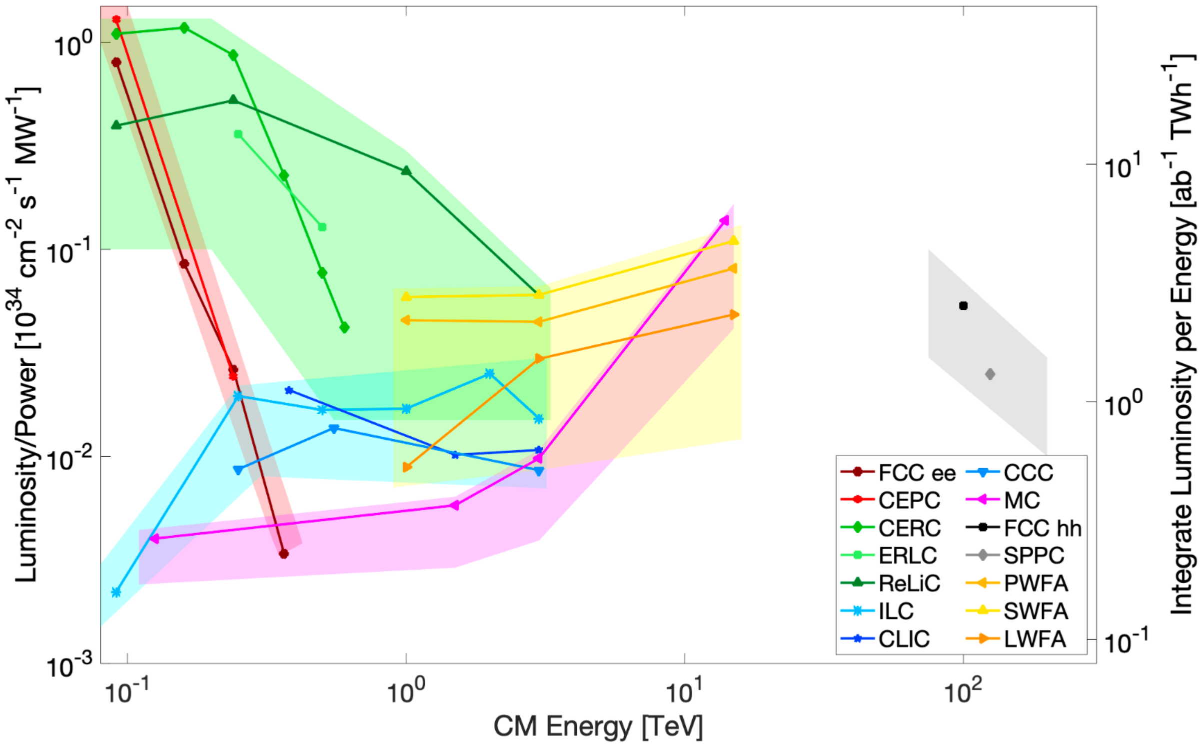
US-Japan Joint Research on ILC Cost Reduction (2017)

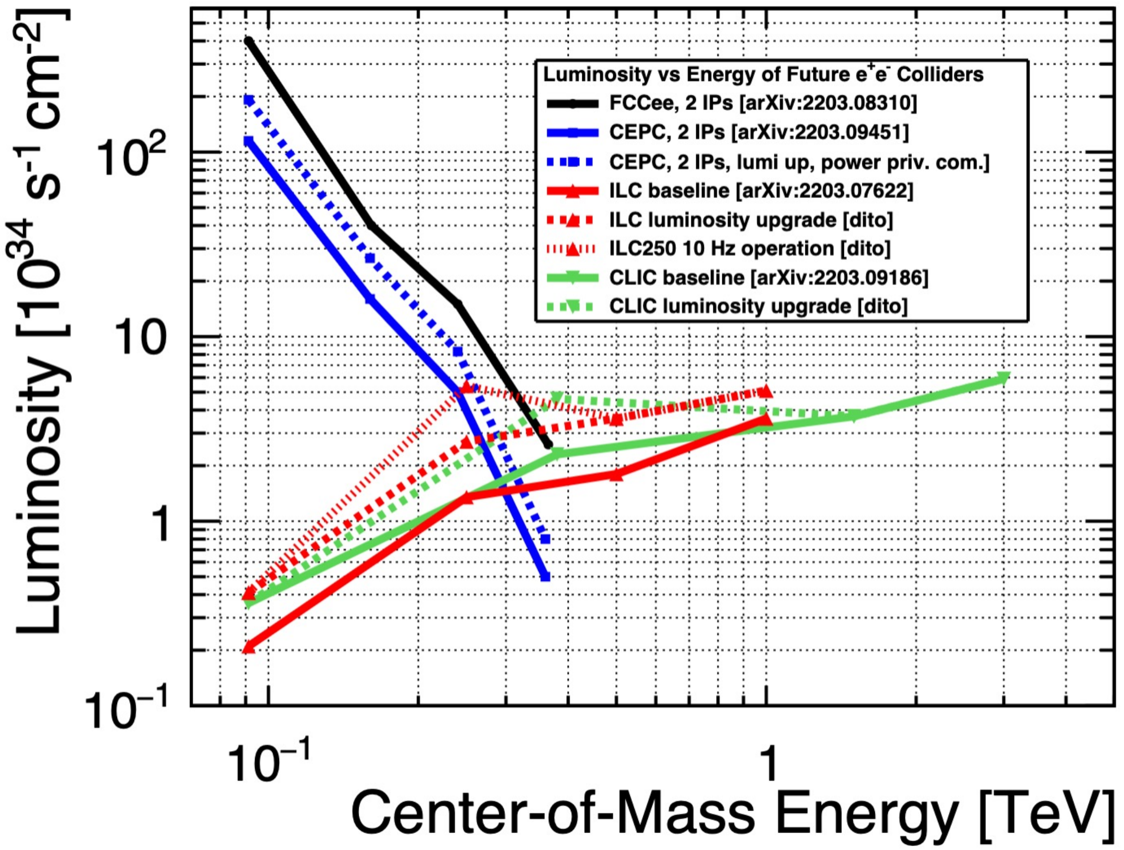
- Dramatic improvement in SRF performance



A. Grossellino, et al.,
Supercond. Sci. Technol. 30 (2017) 094004

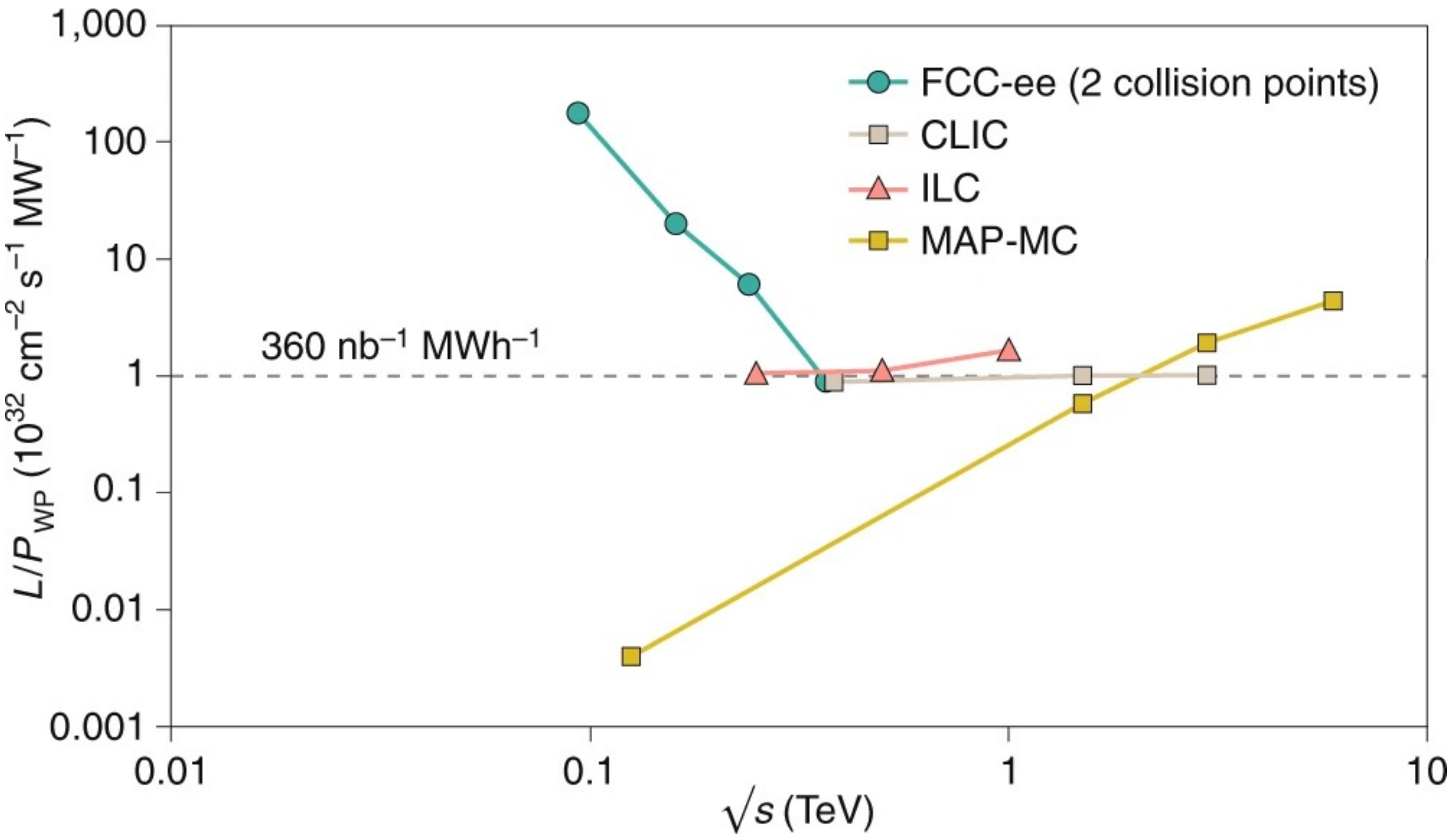
Luminosities





Per IP, from Snowmass

Luminosity vs. Electricity consumption



Nature Physics 16, 402–407 (2020)

e+e- Experiments at a Linear Collider

- Clean collisions of elementary particles at precise energies.
- Energy range extendable – full Higgs physics coverage
- Polarization for e- and e+
- No pile-up as in hadron collider experiments (Expect ~1 hadronic interaction per bunch train)
- No trigger needed – record all events
- Power pulsing possible – reduced power requirement
- Potential detector upgrade paths using new technologies

The International Linear Collider: Report to Snowmass 2021

DESY-22-045, IFT–UAM/CSIC–22-028,
KEK Preprint 2021-61, PNNL-SA-160884,
SLAC-PUB-17662
July 14, 2022

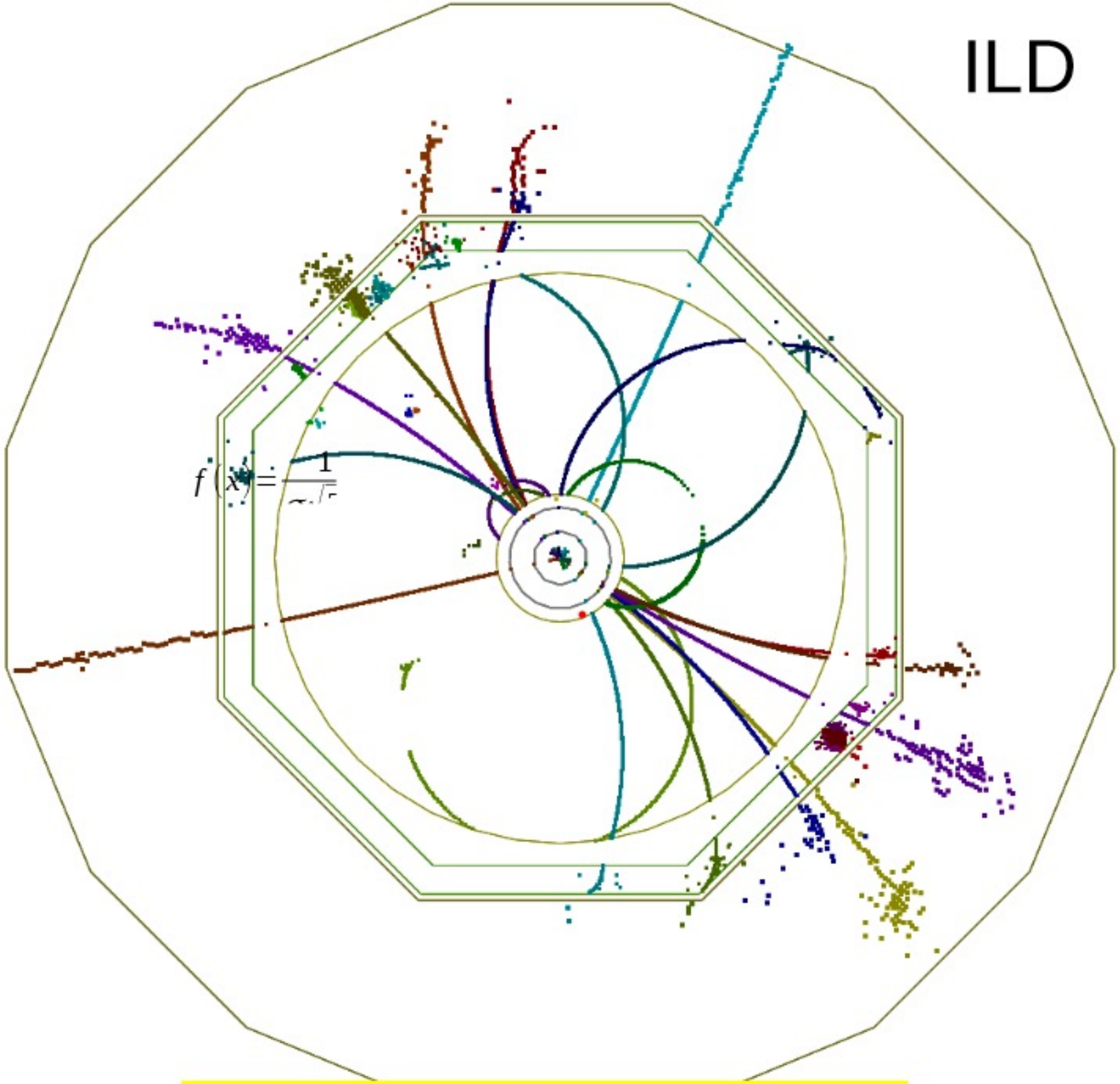
- The International Linear Collider (ILC): the global energy frontier taking data in the 2030's?
- The ILC addresses key questions for our current understanding of particle physics.
  - It is based on a proven accelerator technology.
  - Its experiments will challenge the Standard Model of particle physics and will provide a new window to look beyond it.
- The flagship program of the ILC:
  - Study the Higgs boson at much higher precision than will be possible at LHC.
  - LHC experiment: Couplings of Higgs boson agree with SM predictions at the 20% accuracy.
  - Not nearly sufficient to distinguish the SM Higgs boson from competing models.

A dedicated program required of full suite of couplings of the Higgs boson at 1% level and below.

240-250 GeV Higgs Factory

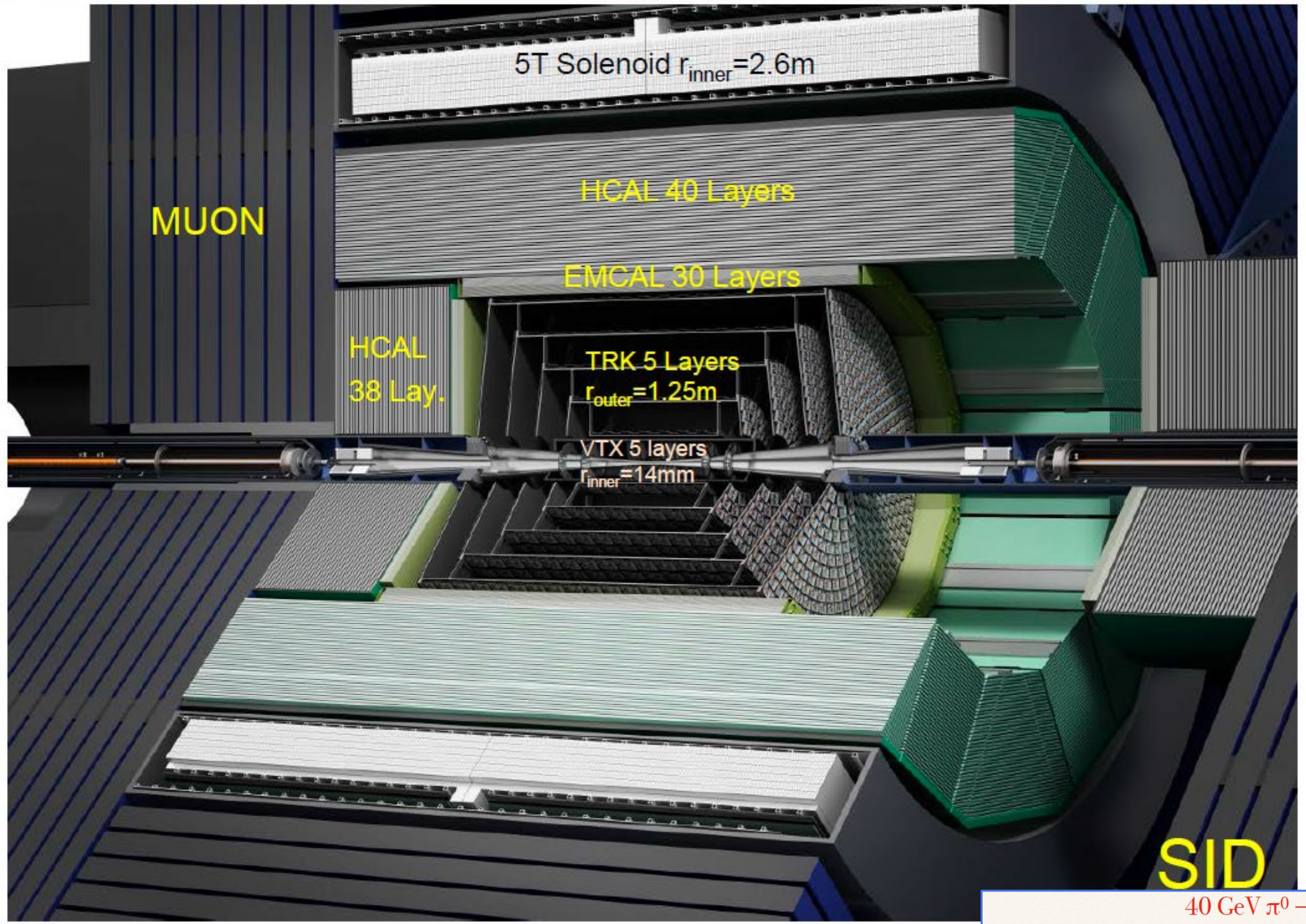
With E_{cms} =250 GeV:
$E(Z^0)$ = 110 GeV →
Recoil: Higgs boson
No need to trigger on H

Precision Higgs Studies including Invisible Higgs decays



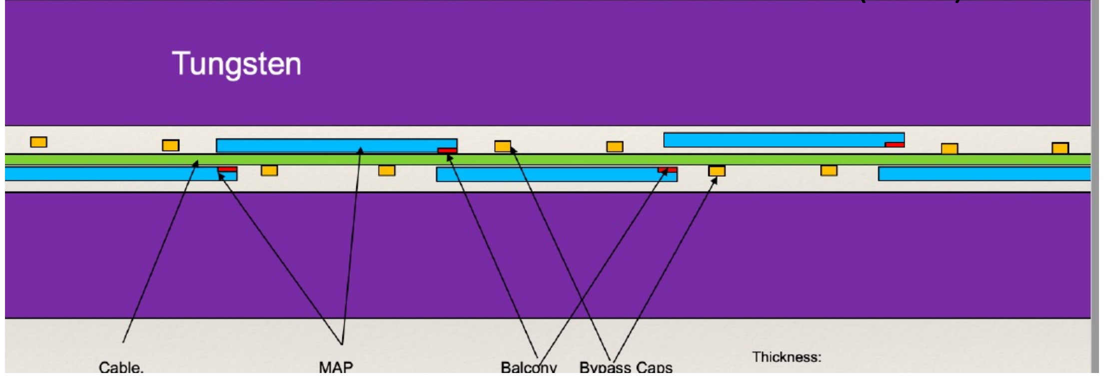
ECM = 250 GeV, $e^+e^- \rightarrow \mu^+ \mu^- H$

Example Detector: SiD

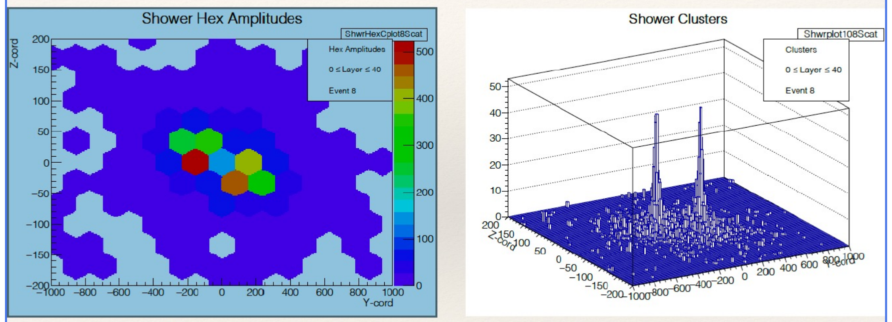


- Much room for innovation,
  - eg EM calorimetry

M. Breidenbach (SLAC)



40 GeV $\pi^0 \rightarrow$ two 20 GeV γ's



SiD TDR hexagonal sensors
13 mm² pixels

New SiD fine pixel sensors
25 μm x 100 μm pixels

J.E.Brau et al., Instruments 2022, 6(4), 51

Some History

- 2003 - International Technology Recommendation Panel (ITRP) Chaired by Barry Barish:
  - Recommended L- band superconducting RF cavity technology
- ICFA launched the Global Design Effort (GDE): cms energy 500 GeV, with upgrade possible to 1 TeV:
  - TDR - 2013 ; Site independent
- Higgs boson discovery announced on July 4, 2012, a year before the TDR:
  - Higgs mass 125 GeV ➔ linear collider for precision Higgs boson studies
- ICFA: Linear Collider Collaboration (LCC) - 2017: machine parameters and cost for a 250 GeV ILC
- Japanese Association of High-Energy Physicists (JAHEP) 2012 proposed ILC250 in Japan
- (Premature!) International discussion to build the ILC in Japan!
- European Strategy for Particle Physics Update (2013) "… the ILC, based on superconducting technology, will provide a unique scientific opportunity at the precision frontier."
- US Prioritization Panel for Particle Physics Projects (P5) (2013) "physics case is extremely strong" to use "Use the Higgs boson as a new tool for discovery" via the ILC
- Japanese government expressed interest in the ILC project - ICFA March 2019 Tokyo and again in February 2020 (SLAC)

But no commitment to hosting ILC

- 2020 European Strategy for Particle Physics Update:

"An electron-positron Higgs factory is the highest-priority next collider"

"The timely realisation of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate."

- ICFA (2020): International Development Team (IDT) ILC - Pre-Lab Proposal (2021)

IDT – ILC Prelab Proposal

Proposal for the ILC Preparatory Laboratory (Pre-lab)
International Linear Collider International Development Team
arXiv:2106.00602

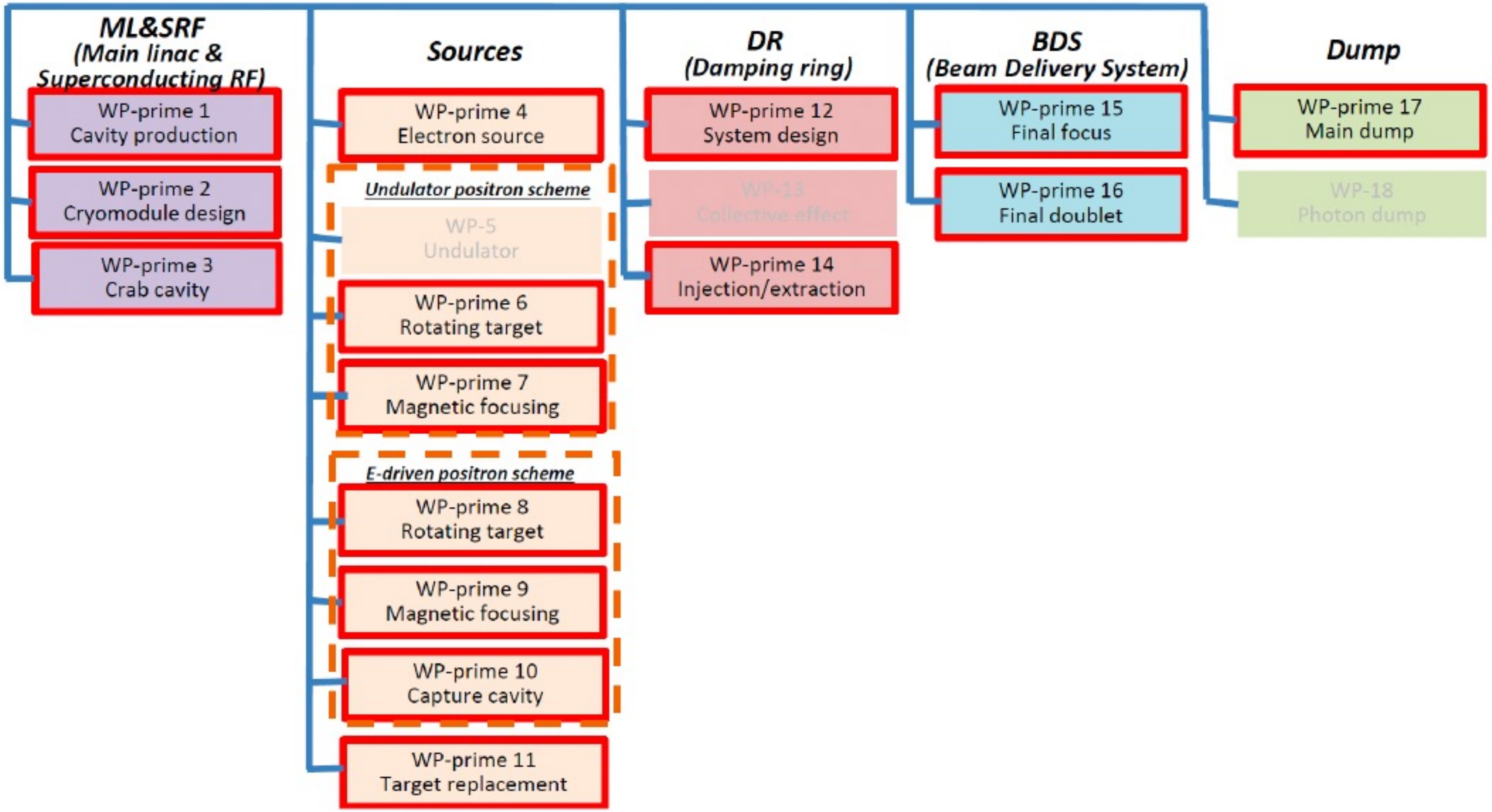
- Compilation of design studies and documentation of the civil engineering and site infrastructure work, and of the environmental impact assessment.
- Community guidance to develop the ILC physics programme that will fully exploit its potential.
- Provision of information to national authorities and to Japanese regional authorities to facilitate development of the ILC Laboratory.
- Coordination of outreach and communication work.
- Completion of technical preparations and production of engineering design documents for the accelerator complex.

MEXT Panel (2021)

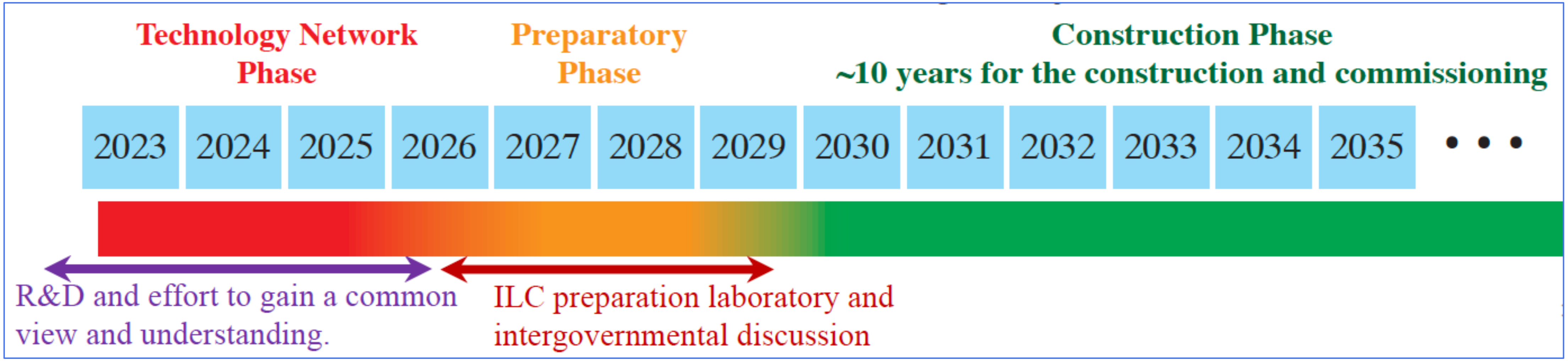
1. The panel: academic significance of particle physics and the …Higgs factory, … value of international collaborative research.
   - However, … still premature to proceed with Pre-Lab … (that is) coupled with an expression of interest to host the ILC by Japan.
2. …Increasing strain in financial situation … panel recommends ILC proponents … reflect and re-evaluate the plan ➔
   - Higgs factory as global facility, and
   - Taking into account studies such as the Future Circular Collider (FCC).
3. Development work in key technological issues for next-generation accelerator … by … strengthening the international collaboration … shelving the question of hosting the ILC.
4. … Cultivating a framework where … countries can exchange information …and discuss required steps would be important.
5. The panel recommends … to expand broad support … in Japan and abroad by building up trust and mutual understanding …

IDT Response to MEXT report:

- ILC Technology Network (ITN)
  - Funding for Critical Work Packages from Pre-Lab Proposal
  - Maintain momentum and minimise time loss



IDT (Optimistic) Potential Schedule for ILC



New Kids on the Block

- Briefly mention:
  - C^3
  - Muon Collider

C3 – Cool Copper Collider

C^3 – Cool Copper Collider – A cryogenic (80 K) high-gradient distributed coupling accelerator concept

8 km footprint for 250/550 GeV CoM $\Longrightarrow$ 70/120 MeV/m

- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

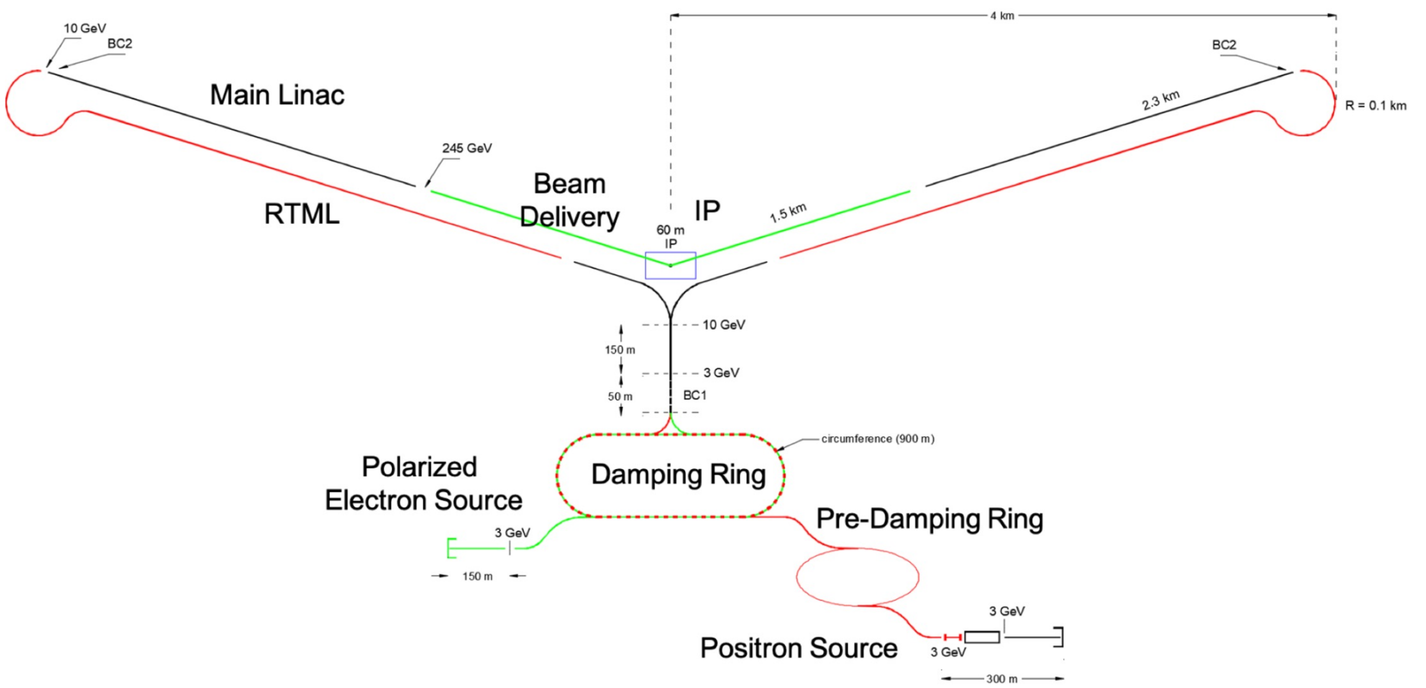
Large portions of accelerator complex are compatible between LC technologies

- Beam delivery and IP modified from ILC (1.5 km for 550 GeV CoM)
- Damping rings and injectors to be optimized with CLIC as baseline

More Details Here (Follow, Endorse, Collaborate):
https://indico.slac.stanford.edu/event/7155/

Collider	C^3	C^3
CM Energy [GeV]	250	550
Luminosity [x10^{34}]	1.3	2.4
Gradient [MeV/m]	70	120
Effective Gradient [MeV/m]	63	108
Length [km]	8	8
Num. Bunches per Train	133	75
Train Rep. Rate [Hz]	120	120
Bunch Spacing [ns]	5.26	3.5
Bunch Charge [nC]	1	1
Crossing Angle [rad]	0.014	0.014
Site Power [MW]	~150	~175
Design Maturity	pre-CDR	pre-CDR

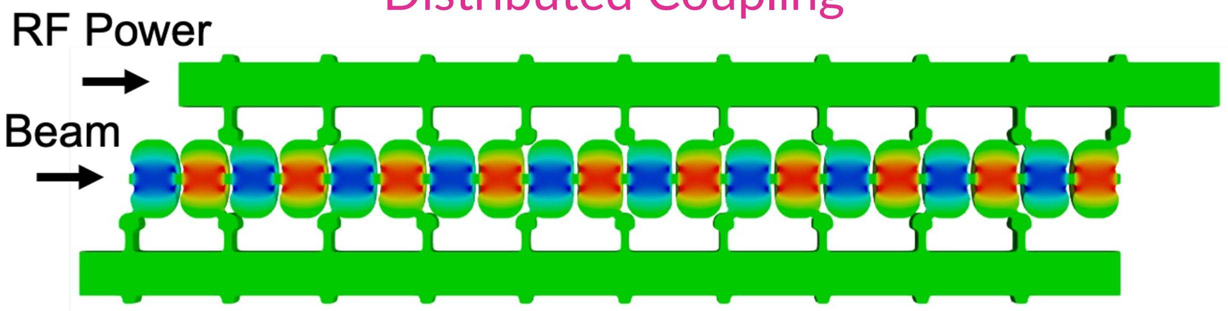
C^3 - 8 km Footprint for 250/550 GeV



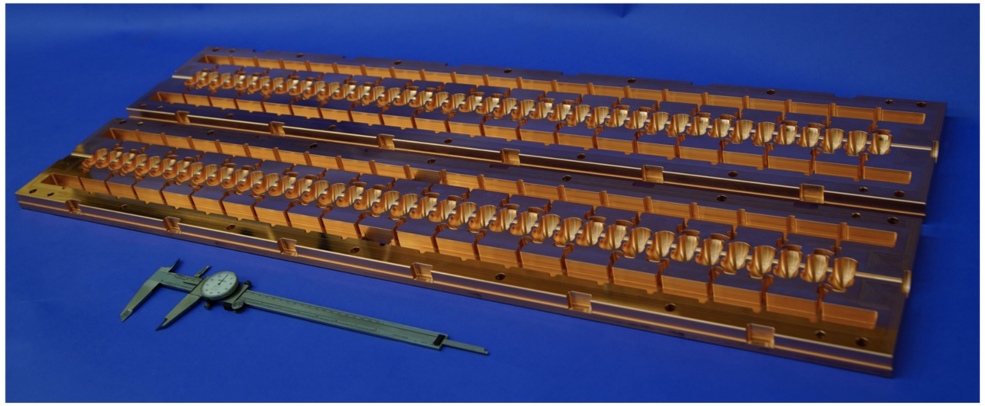
Key Technologies

Present Focus is the Main Linac
In Future Expand to Rest of Complex

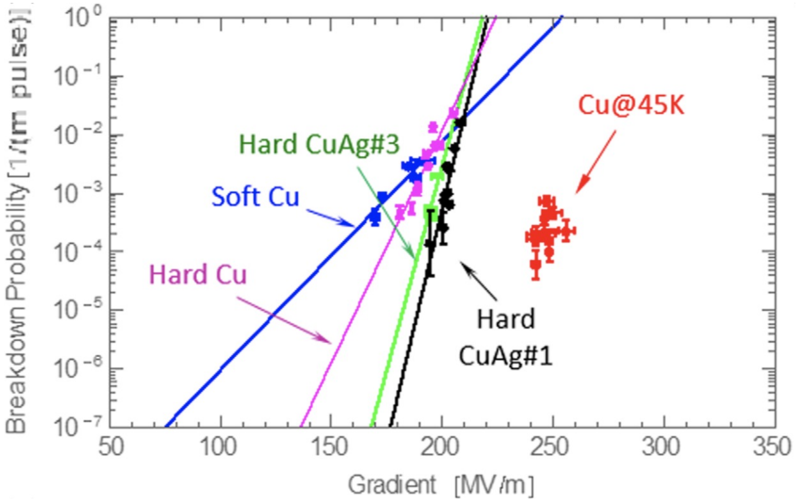
Maximize Structure Efficiency and Performance
Distributed Coupling



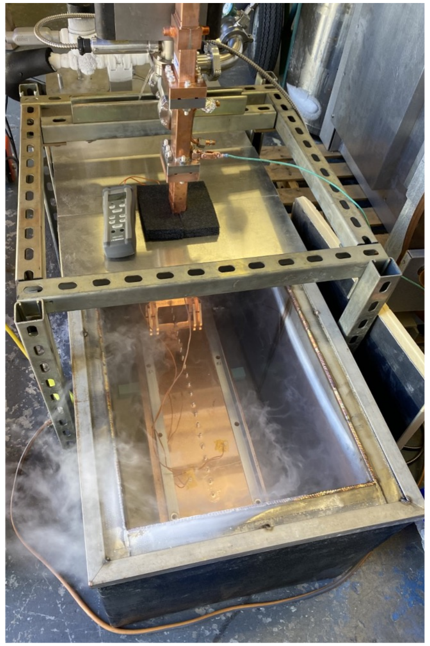
Modern Manufacturing
Prototype One Meter Structure



High Accelerating Gradients
Cryogenic Operation



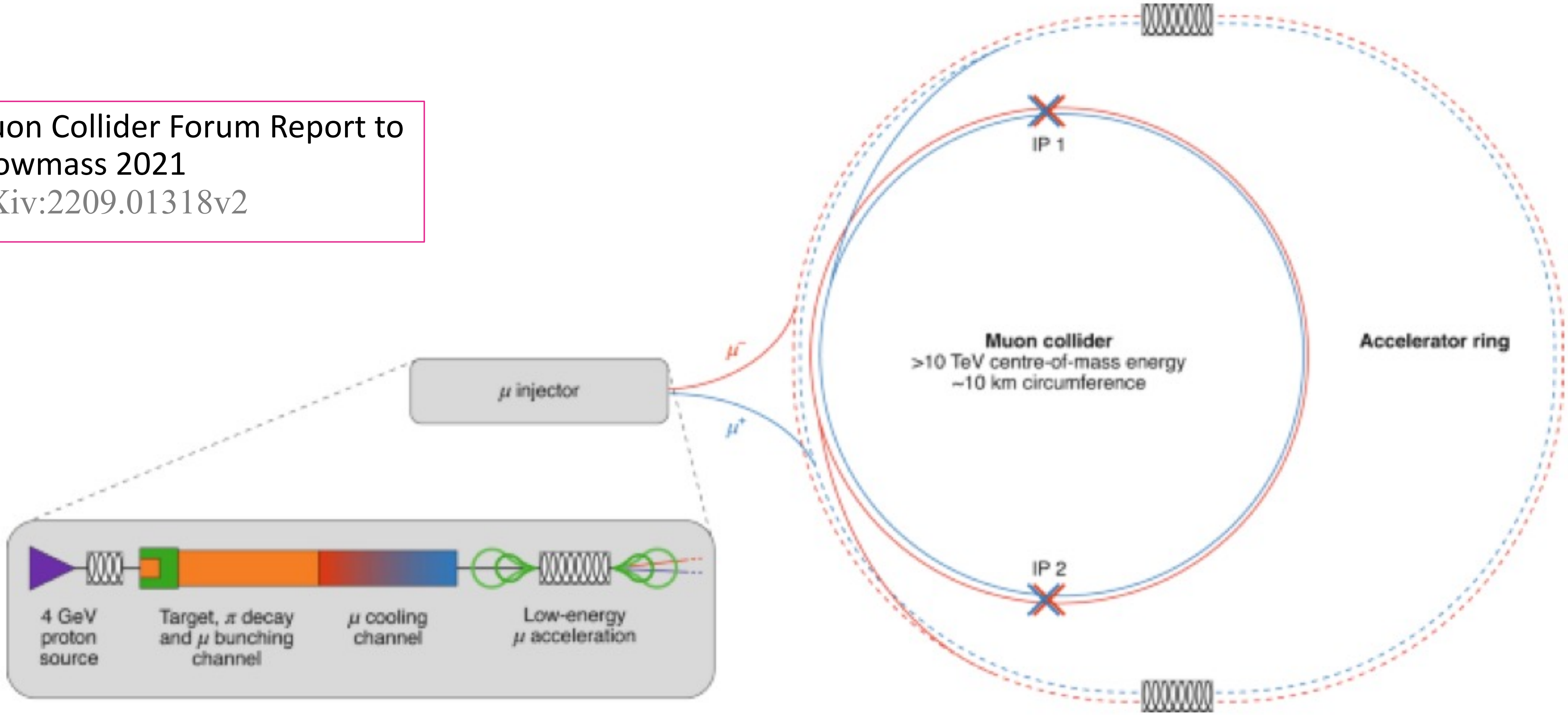
C^3 Cryo Test



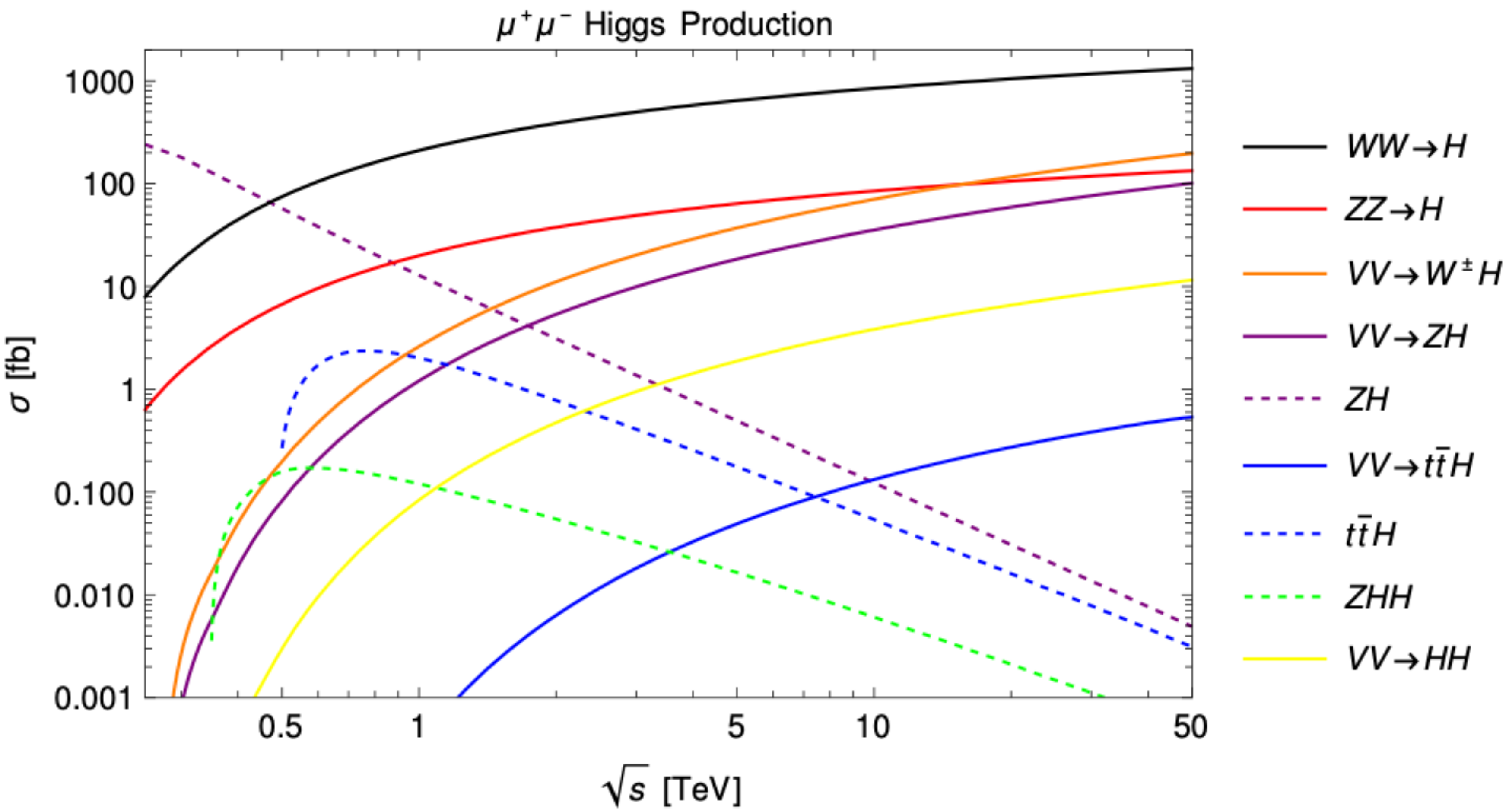
Integrated Damping
Slot Damping with NiChrome Coating

Muon Collider Higgs Factory?

Muon Collider Forum Report to Snowmass 2021
arXiv:2209.01318v2



Muon Collider as Higgs Factory



The Outlook for a Higgs Factory

- Are we at an existential moment for high energy colliders?
- Project timelines larger than single careers. eg. FCC(hh)
- Can China shorten the time-line with CEPC?
- Multiple projects - construction/operation in parallel:
  - But costs are staggering.
- In the longer-term need new techniques/technologies:
  - Magnet technology?
  - New accelerating technology?
    - Plasma wakefield? (perhaps as upgrade to ILC?)

ILC is lowest cost option (both capital and operations),
is most mature of current proposals,
can operate in parallel with HL-LHC.
Needs immediate support and approval!

ILC (and Upgrade) Parameters

Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	80(20)
Repetition frequency	f_{rep}	Hz	5	5	3.7	5	10	4
Bunches per pulse	n_{bunch}	1	1312	2625	1312/2625	1312/2625	2625	2450
Bunch population	N_e	10^{10}	2	2	2	2	2	1.74
Linac bunch interval	Δt_b	ns	554	366	554/366	554/366	366	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	5.8/8.8	5.8/8.8	8.8	7.6
Beam pulse duration	t_{pulse}	μs	727	961	727/961	727/961	961	897
Average beam power	P_{ave}	MW	5.3	10.5	1.42/2.84*)	10.5/21	21	27.2
RMS bunch length	σ_z^*	mm	0.3	0.3	0.41	0.3	0.3	0.225
Norm. hor. emitt. at IP	$\gamma\epsilon_x$	μm	5	5	6.2	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_y$	nm	35	35	48.5	35	35	30
RMS hor. beam size at IP	σ_x^*	nm	516	516	1120	474	516	335
RMS vert. beam size at IP	σ_y^*	nm	7.7	7.7	14.6	5.9	7.7	2.7
Luminosity in top 1%	$\mathcal{L}_{0.01}/\mathcal{L}$		73%	73%	99%	58.3%	73%	44.5%
Beamstrahlung energy loss	δ_{BS}		2.6%	2.6%	0.16%	4.5%	2.6%	10.5%
Site AC power	P_{site}	MW	111	128	94/115	173/215	198	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

Table 4.1: Summary table of the ILC accelerator parameters in the initial 250 GeV staged configuration and possible upgrades. A 500 GeV machine could also be operated at 250 GeV with 10 Hz repetition rate, bringing the maximum luminosity to $5.4 \cdot 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$ [30]. *): For operation at the Z-pole additional beam power of 1.94/3.88 MW is necessary for positron production.