Future colliders

Steinar Stapnes

Adapted from talk at Chamonix 26.01.2023

Outline

ESPP (2018-19), Snowmass (2021-23)

Mature Higgs factory studies (FCC-ee, CLIC, ILC, CEPC – mention also C3)

Beyond Higgs Factories:

- LCs towards 3 TeV
- FCC-hh/SPPC
- Muon collider

General points (will use Snowmass mostly)

- Cost
- Power and other environmental issues (carbon)
- Schedules

ESPP update 2018-19:

Higgs factory next – project studies
FCC feasibility study
R&D on technologies and projects

Report of the Snowmass'21 Collider Implementation Task Force

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August 15, 2022

Abstract

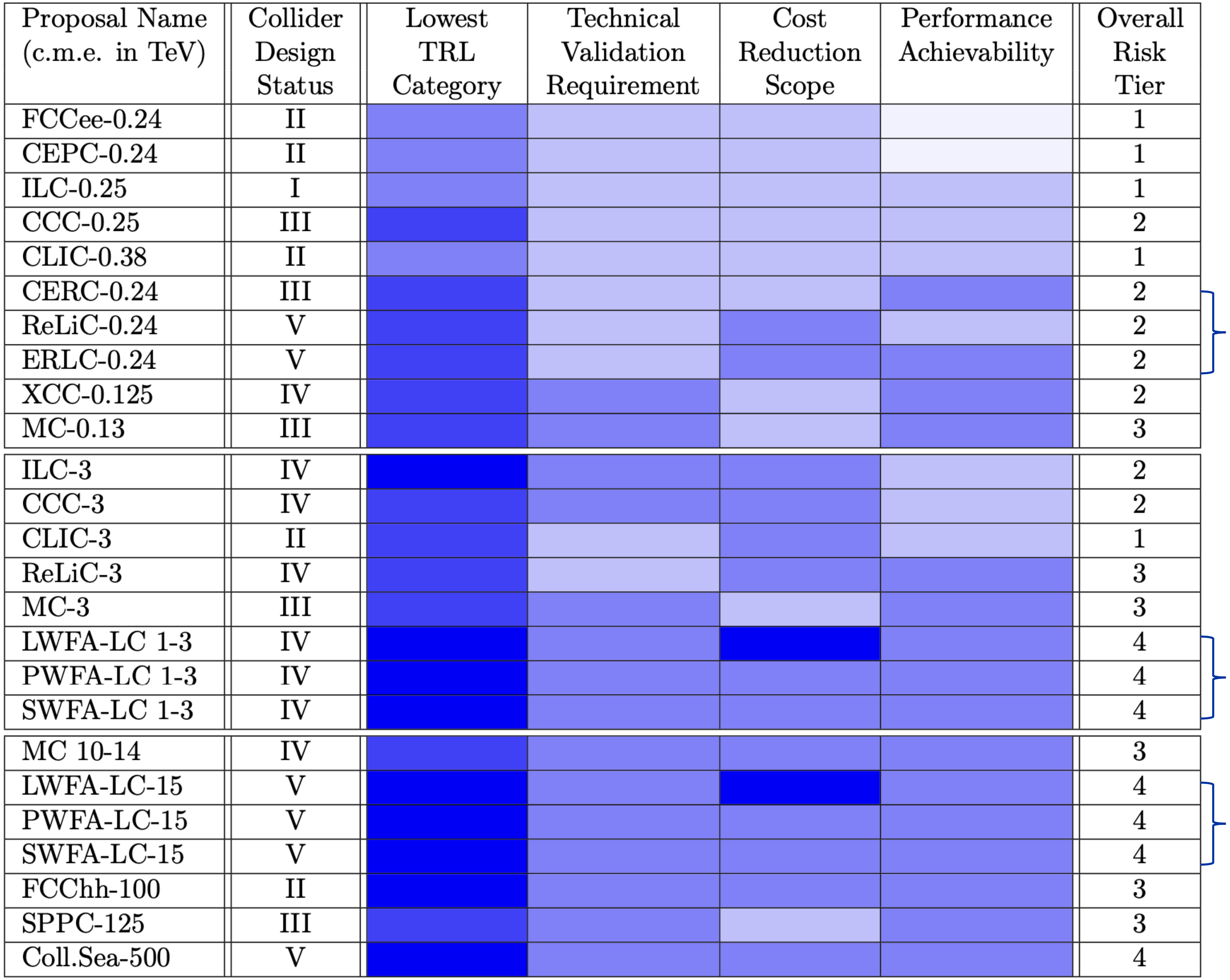
The Snowmass'21 Implementation Task Force has been established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics has been developed for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and *ep* collider facilities, based on traditional and advanced acceleration technologies. This report documents the metrics and processes, and presents evaluations of future colliders performed by Implementation Task Force.

Interesting Implementation Task Force Report:
https://arxiv.org/pdf/2208.06030.pdf

Snowmass provided(s) an opportunity for formulating new ideas, intermediate reports, overviews – for the US and worldwide

ESPP update 2025-26-27:

… to be written …



Consider only the most mature projects:

Proposal Name (c.m.e. in TeV)	Collider Design Status	Lowest TRL Category	Technical Validation Requirement	Cost Reduction Scope	Performance Achievability	Overall Risk Tier	
FCCee-0.24	II	▒	░	░	□	1	Included
CEPC-0.24	II	▒	░	░	□	1	Included
ILC-0.25	I	▒	░	░	░	1	Included
CCC-0.25	III	▓	░	░	░	2	Partly included
CLIC-0.38	II	▒	░	░	░	1	Included
CERC-0.24	III	▓	░	░	▒	2	Refer to R&D roadmap
ReLiC-0.24	V	▓	░	▒	░	2	
ERLC-0.24	V	▓	░	▒	▒	2	
XCC-0.125	IV	▓	▒	░	▒	2	A picture ?
MC-0.13	III	▓	▒	░	▒	3	
ILC-3	IV	█	▒	▒	░	2	Mentioned briefly as ILC upgrade to 1-3 TeV
CCC-3	IV	▓	▒	▒	░	2	
CLIC-3	II	▓	░	▒	░	1	Mentioned as CLIC upgrade to 3 TeV
ReLiC-3	IV	▓	░	▒	▒	3	
MC-3	III	▓	▒	░	▒	3	Included together with 10-14 TeV MC option
LWFA-LC 1-3	IV	█	▒	█	▒	4	Refer to R&D roadmap
PWFA-LC 1-3	IV	█	▒	▒	▒	4	
SWFA-LC 1-3	IV	█	▒	▒	▒	4	
MC 10-14	IV	▓	▒	▒	▒	3	Included together with 3 TeV MC option
LWFA-LC-15	V	█	▒	█	▒	4	Refer to R&D roadmap
PWFA-LC-15	V	█	▒	▒	▒	4	
SWFA-LC-15	V	█	▒	▒	▒	4	
FCChh-100	II	█	▒	▒	▒	3	Included
SPPC-125	III	▓	▒	░	▒	3	Included
Coll.Sea-500	V	█	▒	▒	▒	4	

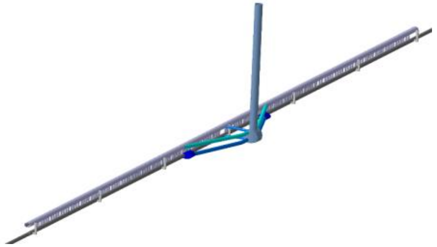
Light colour is good. Performance Achievability contentious/subjective. Will remove non red lines in the following tables.

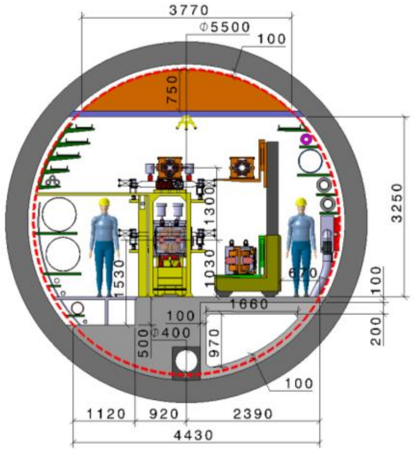
FCC

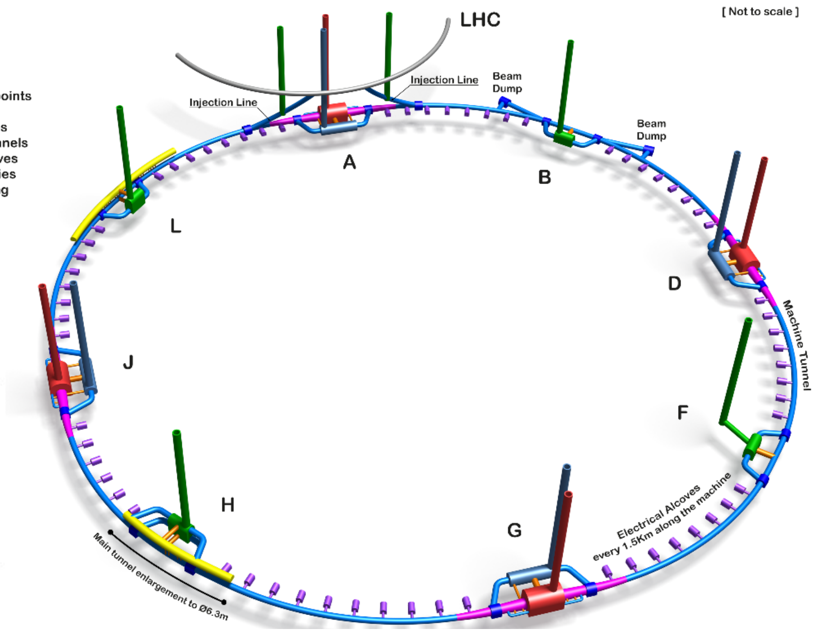
Main activities:

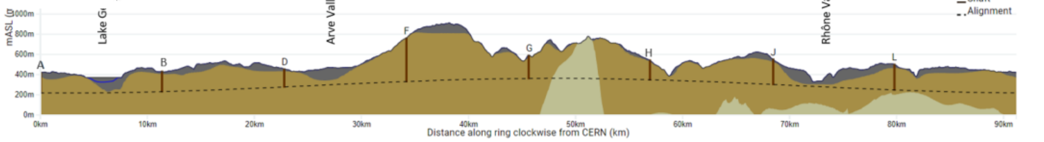
- Developing & confirming concrete implementation scenario, in collaboration with host state authorities, including environmental impact analysis
- Machine optimization and technology R&D (examples next slide)
- Physics studies
- Global collaboration, supported by the EC H2020 Design Study FCCIS and Swiss CHART.
- Goals:
  - Demonstrate feasibility by 2025/2
  - Next milestone is the mid-term review, October 2023
  - CE Cost & construction schedule underway

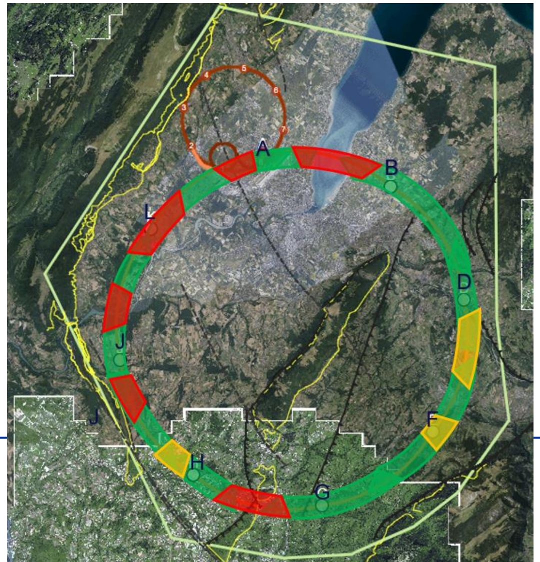
Material from: PECFA (Benedikt), SCE (Watson, Cunningham, Osborne) – slides, FCC week (Peauger) 2022



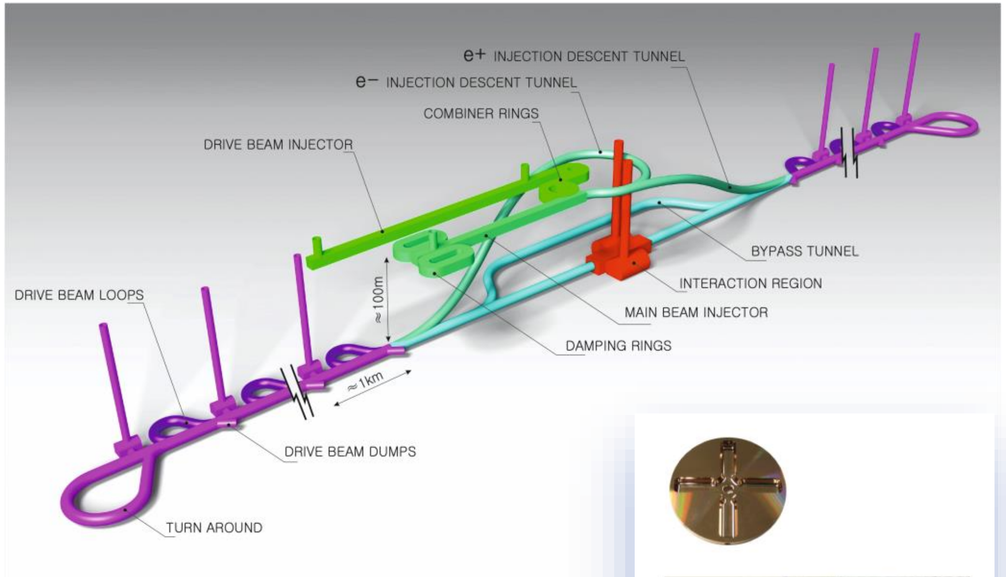


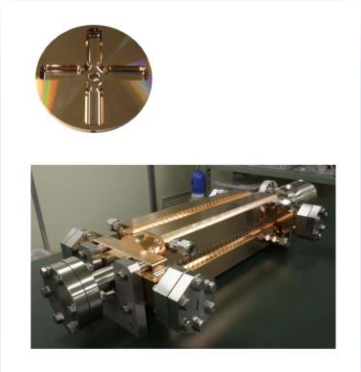






The Compact Linear Collider (CLIC)





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

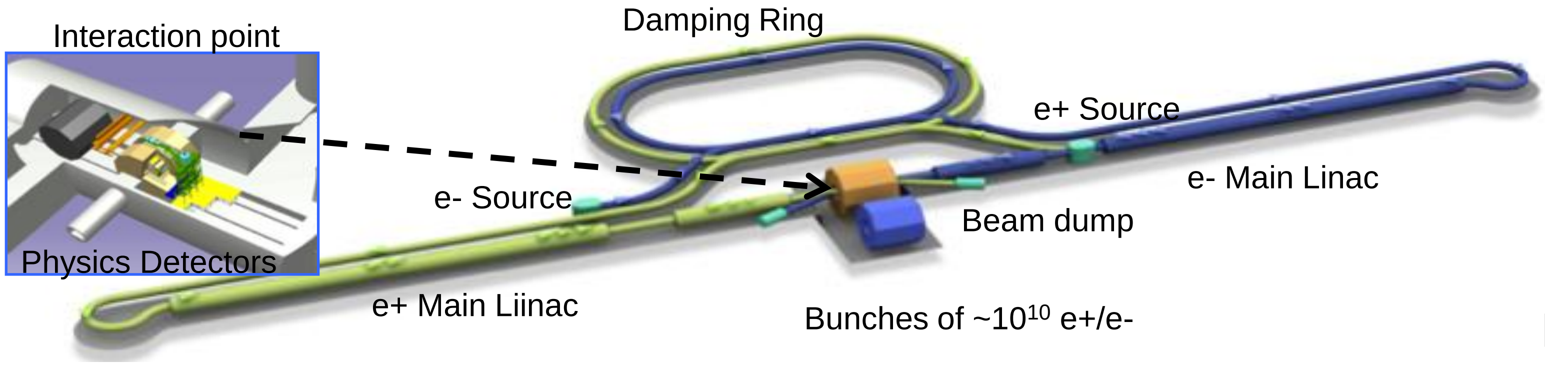
The CLIC accelerator studies are mature:
- Optimised design for cost and power
- Many tests in CTF3, FELs, light-sources and test-stands
- Technical developments of “all” key elements

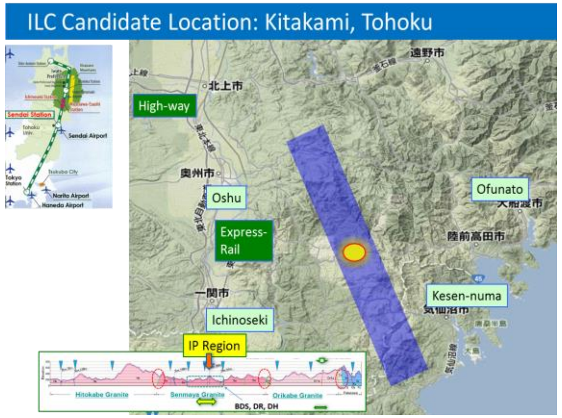
- **Timeline:** Electron-positron linear collider at CERN for the era beyond HL-LHC
- **Compact:** Novel and unique two-beam accelerating technique with high-gradient room temperature RF cavities (~20’500 structures at 380 GeV), ~11km in its initial phase
- **Expandable:** Staged programme with collision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

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

Recent talks (with more references): eeFACT1 and eeFACT2

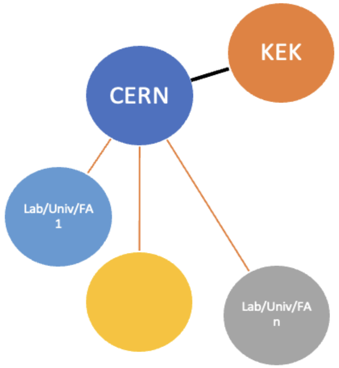
The ILC250 accelerator facility

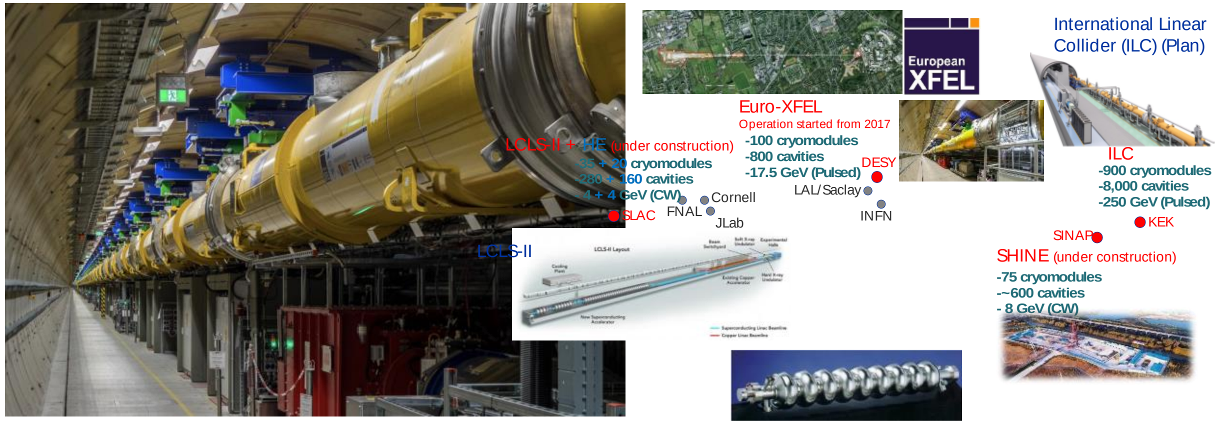




- Creating particles Sources
  - polarized elections/positrons
- High quality beam Damping ring
  - low emittance beams
- Acceleration Main linac
  - superconducting radio frequency (SRF)
- Collide them Final focus
  - nano-meter beams
- Go to Beam dumps

New funding for technology development, involving most European labs

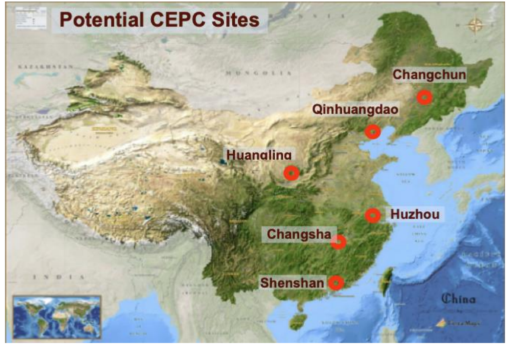


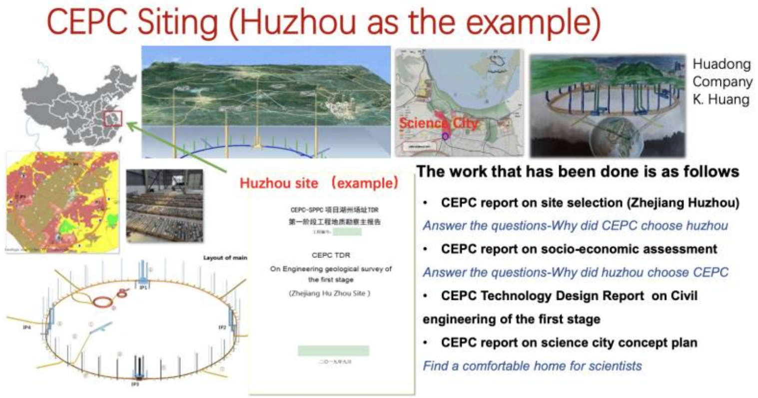


Recent talks (with more references): eeFACT-I1 and eeFACTI2

CEPC

- The CEPC CDR was released in 2018. Since then, extensive technology R&D has been carried out, as well as design and luminosity optimization
- CEPC-TDR is planned to be finished in early 2023
- A three-year EDR phase is planned after TDR
- The accelerator construction is scheduled to be started in the 15th five-year-plan (2026-30)





CEPC Siting (Huzhou as the example)

Huadong Company K. Huang

Huzhou site （example）

CEPC-SPPC 项目湖州场址TDR
第一阶段工程地质勘察主报告

CEPC TDR
On Engineering geological survey of the first stage
(Zhejiang Hu Zhou Site)

The work that has been done is as follows

- CEPC report on site selection (Zhejiang Huzhou)

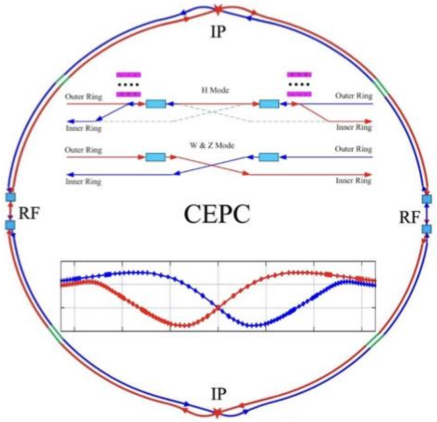
Answer the questions-Why did CEPC choose huzhou

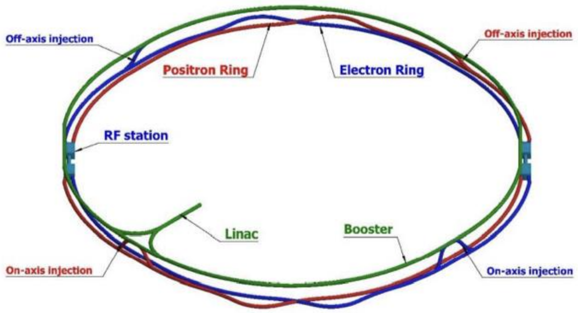
- CEPC report on socio-economic assessment

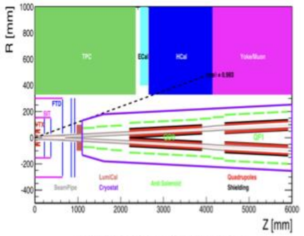
Answer the questions-Why did huzhou choose CEPC

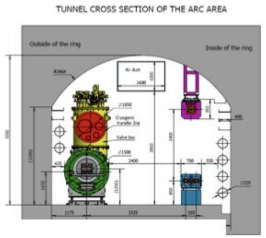
- CEPC Technology Design Report on Civil engineering of the first stage
- CEPC report on science city concept plan

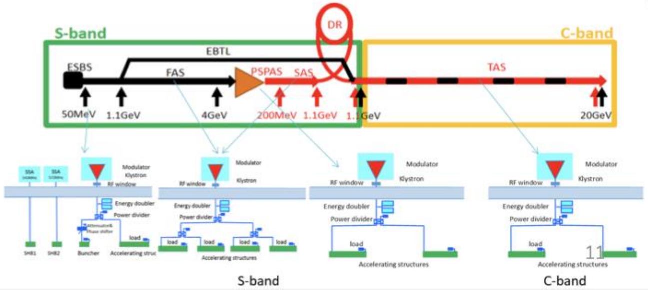
Find a comfortable home for scientists











- CEPC as a Higgs Factory
- Upgradable to 50 MW
- Upgradable to High Lumi. Z & ttbar
- Compatible to SPPC

Six sites studied.

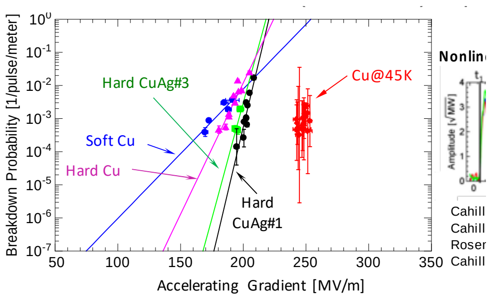
Funding model now considered is 2/3 from region, making regional interest more important, and 1/3 central government, which is more in line with other previous science projects in China

Information mostly from
Yuhui Li and Jie Gao

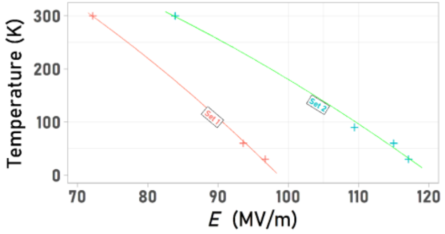
C3 Accelerator Complex

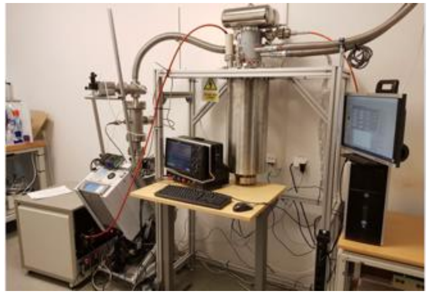
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m
- 7 km footprint at 155 MeV/m for 550 GeV CoM – present Fermilab site

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
- Reliant on work done by CLIC and ILC to make progress

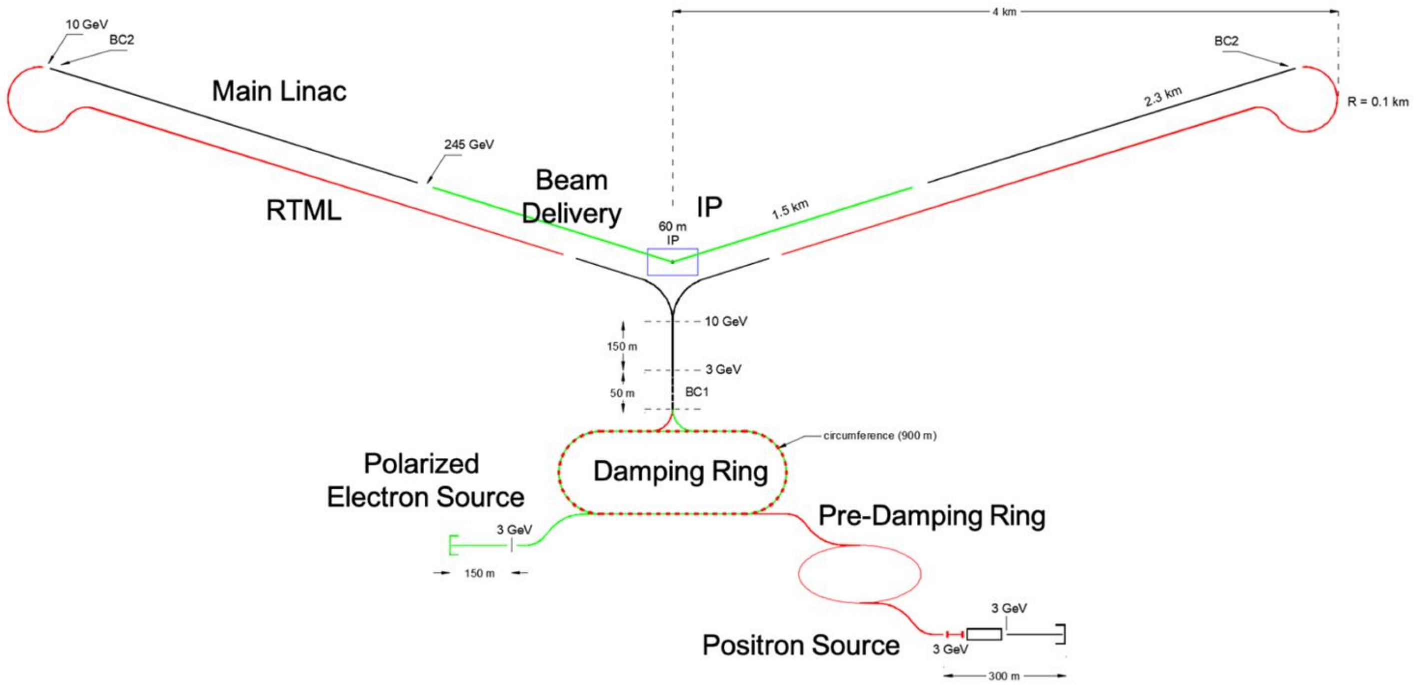


Cryo-cooled copper cavity, SLAC

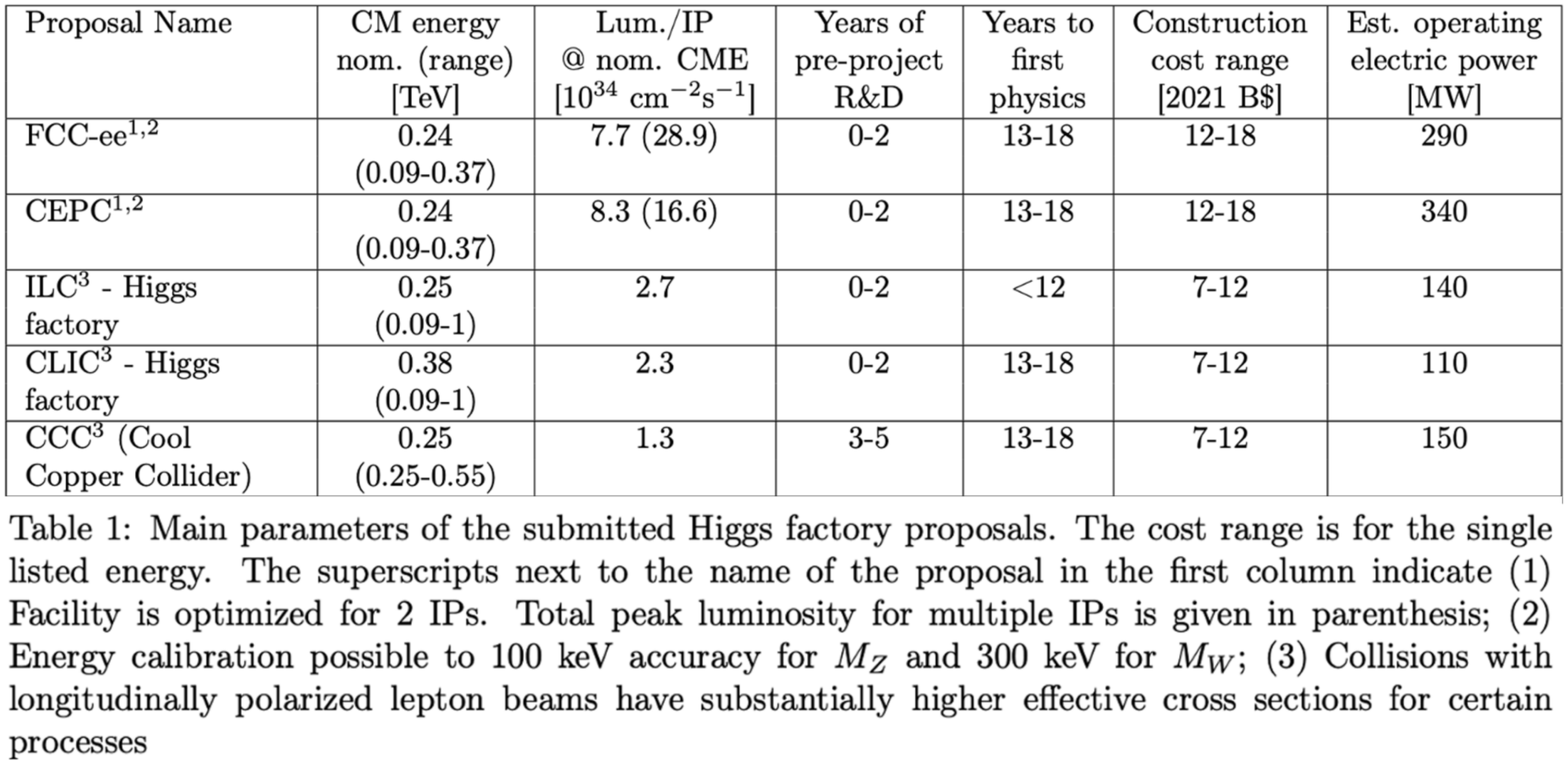




Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN

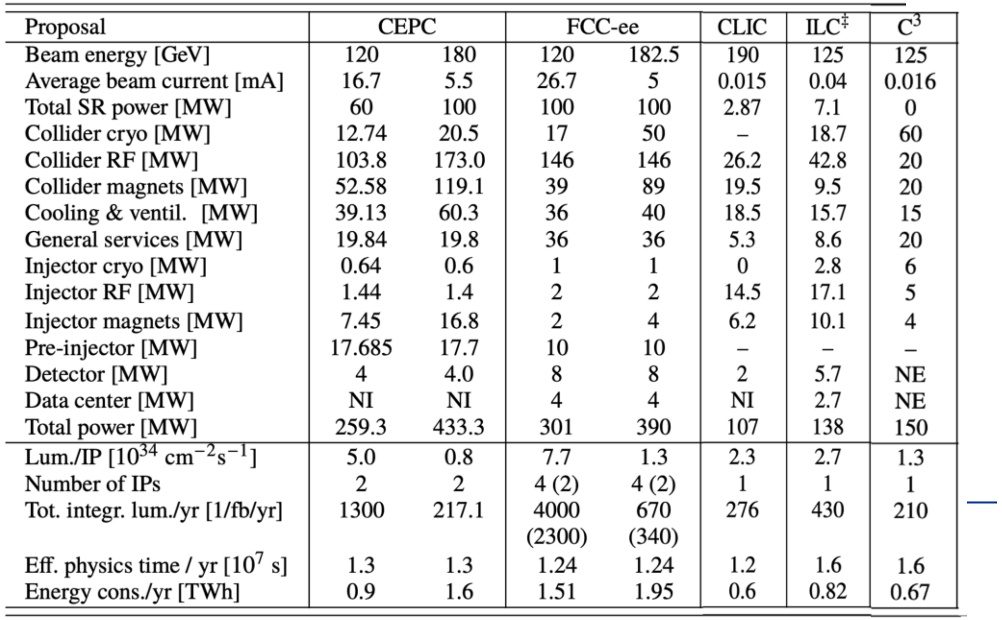


Higgs factories

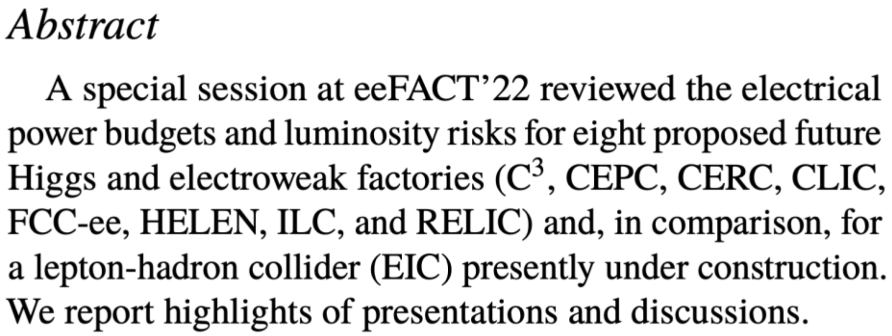


Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee[1,2]	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC[1,2]	0.24 (0.09-0.37)	8.3 (16.6)	0-2	13-18	12-18	340
ILC[3] - Higgs factory	0.25 (0.09-1)	2.7	0-2	<12	7-12	140
CLIC[3] - Higgs factory	0.38 (0.09-1)	2.3	0-2	13-18	7-12	110
CCC[3] (Cool Copper Collider)	0.25 (0.25-0.55)	1.3	3-5	13-18	7-12	150

Table 1: Main parameters of the submitted Higgs factory proposals. The cost range is for the single listed energy. The superscripts next to the name of the proposal in the first column indicate (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis; (2) Energy calibration possible to 100 keV accuracy for M_Z and 300 keV for M_W; (3) Collisions with longitudinally polarized lepton beams have substantially higher effective cross sections for certain processes



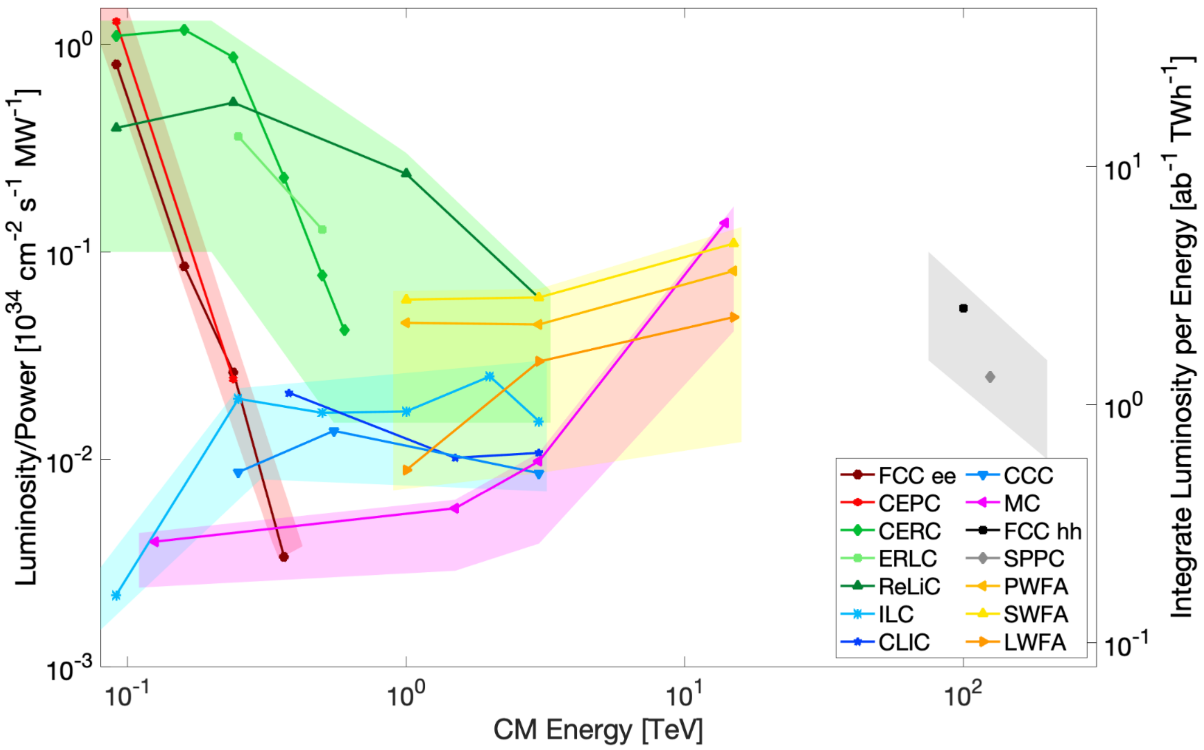
Proposal	CEPC		FCC-ee		CLIC	ILC[‡]	C^3
Beam energy [GeV]	120	180	120	182.5	190	125	125
Average beam current [mA]	16.7	5.5	26.7	5	0.015	0.04	0.016
Total SR power [MW]	60	100	100	100	2.87	7.1	0
Collider cryo [MW]	12.74	20.5	17	50	–	18.7	60
Collider RF [MW]	103.8	173.0	146	146	26.2	42.8	20
Collider magnets [MW]	52.58	119.1	39	89	19.5	9.5	20
Cooling & ventil. [MW]	39.13	60.3	36	40	18.5	15.7	15
General services [MW]	19.84	19.8	36	36	5.3	8.6	20
Injector cryo [MW]	0.64	0.6	1	1	0	2.8	6
Injector RF [MW]	1.44	1.4	2	2	14.5	17.1	5
Injector magnets [MW]	7.45	16.8	2	4	6.2	10.1	4
Pre-injector [MW]	17.685	17.7	10	10	–	–	–
Detector [MW]	4	4.0	8	8	2	5.7	NE
Data center [MW]	NI	NI	4	4	NI	2.7	NE
Total power [MW]	259.3	433.3	301	390	107	138	150
Lum./IP [10^{34} cm^{-2}s^{-1}]	5.0	0.8	7.7	1.3	2.3	2.7	1.3
Number of IPs	2	2	4 (2)	4 (2)	1	1	1
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	276	430	210
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.2	1.6	1.6
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.6	0.82	0.67

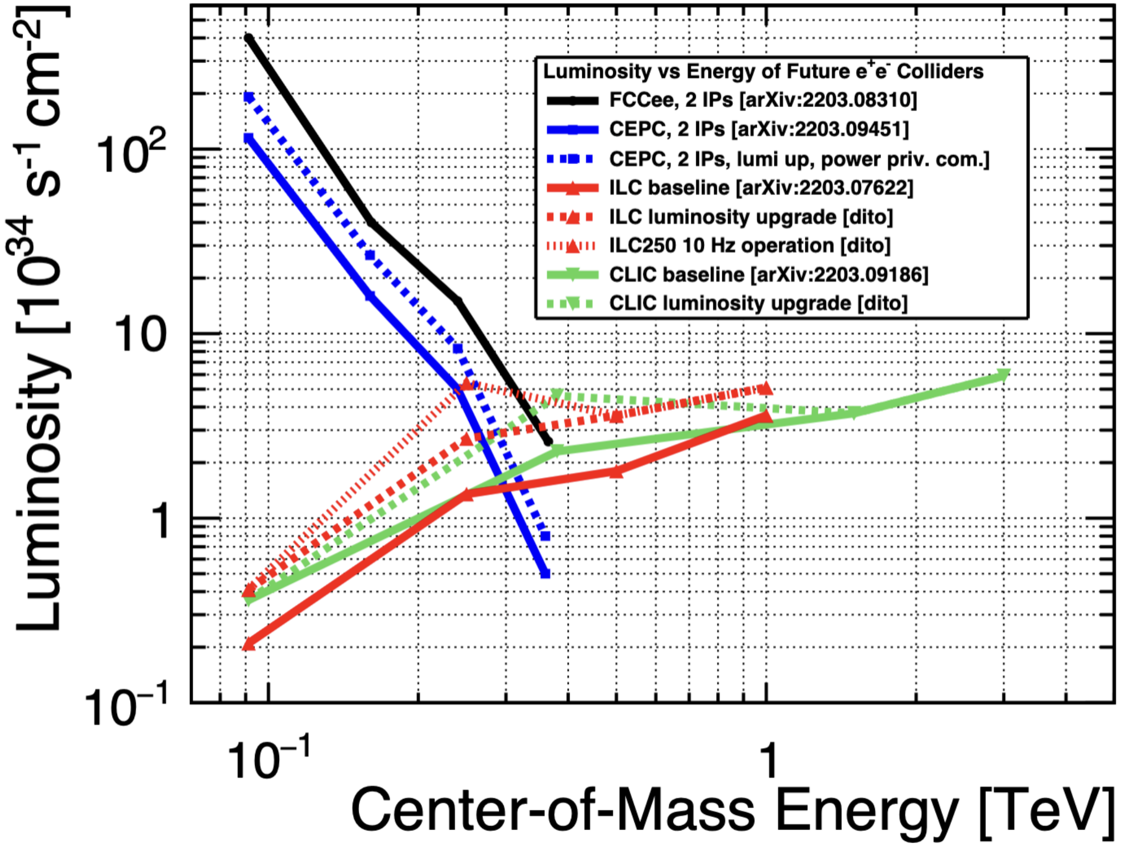


Abstract

A special session at eeFACT'22 reviewed the electrical power budgets and luminosity risks for eight proposed future Higgs and electroweak factories (C^3, CEPC, CERC, CLIC, FCC-ee, HELEN, ILC, and RELIC) and, in comparison, for a lepton-hadron collider (EIC) presently under construction. We report highlights of presentations and discussions.

Luminosities

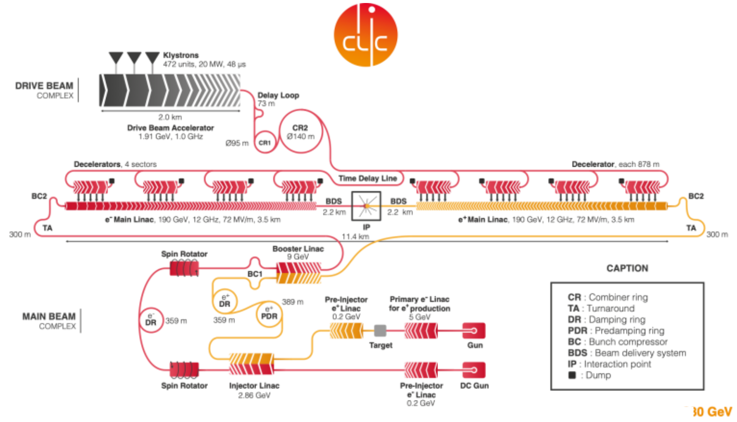


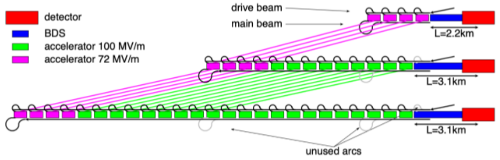


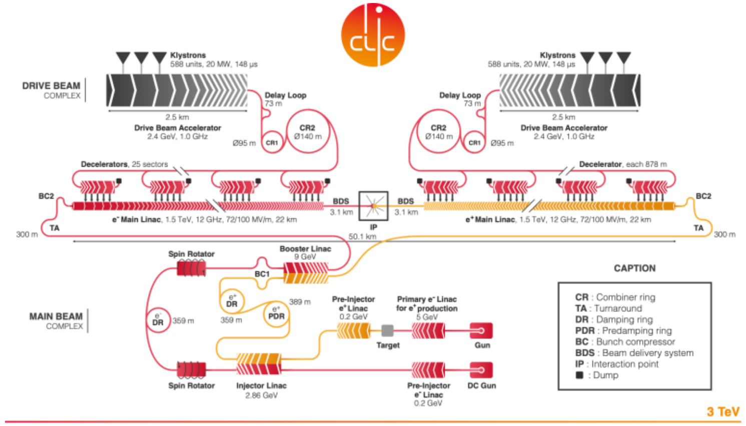
Per IP, from Snowmass

CLIC, ILC, C3 energy upgrades

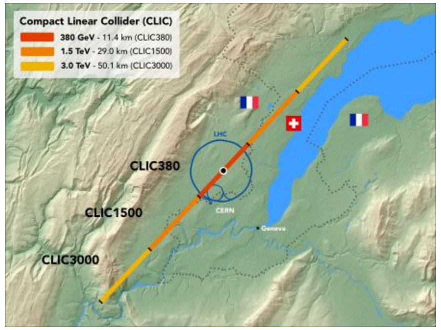
CLIC can easily be extended into the multi-TeV region (3 TeV studied in detail)







CLIC - Scheme of the Compact Linear Collider (CLIC)



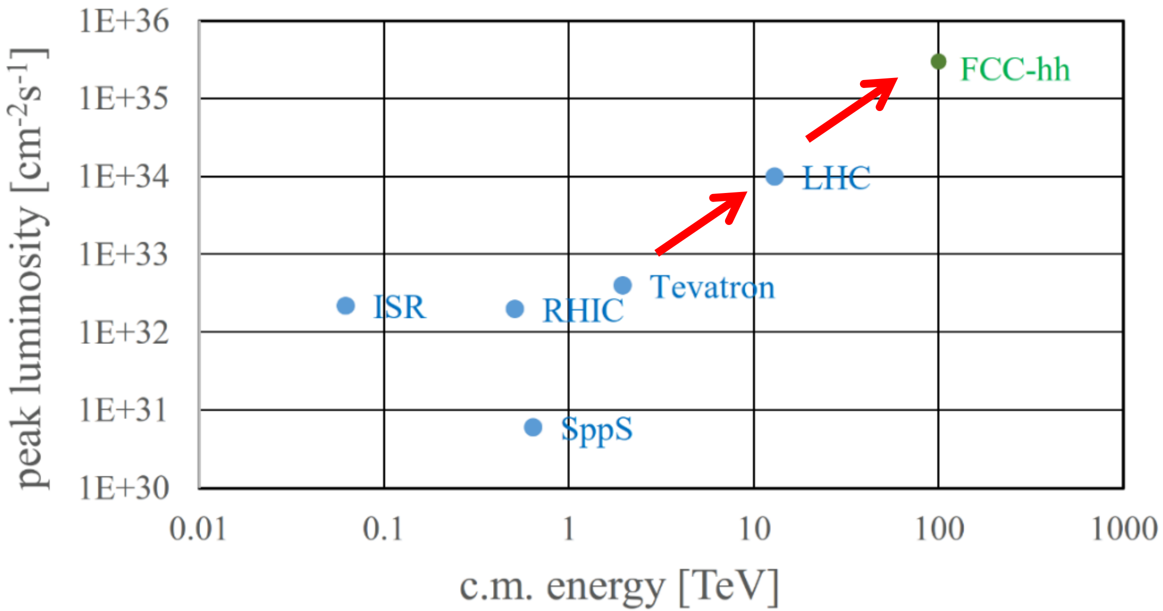
Extend by extending main linacs, increase drivebeam pulse-length and power, and a second drivebeam to get to 3 TeV

ILC has foreseen extensions to ~ 1TeV with existing or modestly improved SCRF technology.
However, improvements in gradients with for example travelling wave structures or Nb_3Sn coating have motivated ideas of reaching ~3 TeV in 50km (gradients well above 50 MeV/m needed)

C3 is similar to CLIC in gradient and a 3 TeV C3 concept have been formulated.
C3 would also fit into an ILC tunnel with its suitable klystron gallery, as a potential upgrade.

No convincing study of improving lum/P ratio for LCs at multi-TeV energies well above 3 TeV, even maintaining it is hard. Going beyond 3 TeV (with other RF methods) would require very small beams, extreme requirements for stability, improved wall-plug to beam efficiency, etc.
It is not only a question of gradient.

FCC-hh: highest collision energies



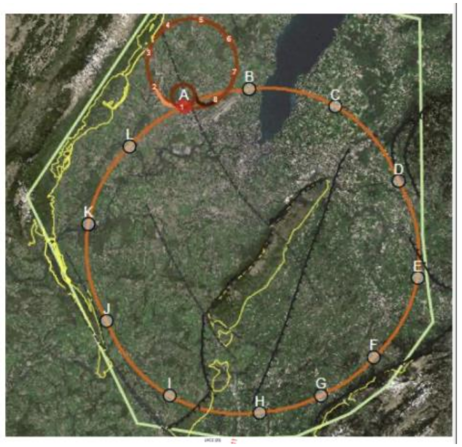
Order of magnitude performance increase in energy & luminosity

100 TeV cm collision energy
(vs 14 TeV for LHC)

20 ab^{-1} per experiment collected over 25 years of operation (vs 3 ab^{-1} for LHC)

similar performance increase as from Tevatron to LHC

Key technology: high-field magnets



parameter	FCC-hh		HL-LHC	LHC
collision energy cms [TeV]	100		14	14
dipole field [T]	16		8.33	8.33
circumference [km]	97.75		26.7	26.7
beam current [A]	0.5		1.1	0.58
bunch intensity [10^{11}]	1	1	2.2	1.15
bunch spacing [ns]	25	25	25	25
synchr. rad. power / ring [kW]	2400		7.3	3.6
SR power / length [W/m/ap.]	28.4		0.33	0.17
long. emit. damping time [h]	0.54		12.9	12.9
beta* [m]	1.1	0.3	0.15 (min.)	0.55
normalized emittance [mm]	2.2		2.5	3.75
peak luminosity [10^{34} cm^{-2}s^{-1}]	5	30	5 (lev.)	1
events/bunch crossing	170	1000	132	27
stored energy/beam [GJ]	8.4		0.7	0.36

Detailed documentation from the ESPP: http://fcc-cdr.web.cern.ch, and more recent talk in the 2022 FCC week: LINK (Giovannozzi)

Magnets

Primary goal of HFM is to open for high energy hadron colliders

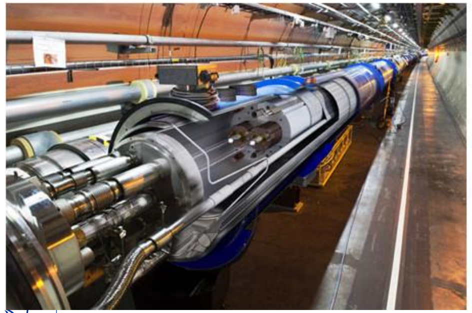
Also important for muon collider (solenoid fields for cooling system probably ok, performance increases with achievable dipole fields in collider ring)

Increased interest for HTS not only for high field, but for power reduction (also for Higgs factories). In some cases permanent magnets can also be used.

Three linked challenges of machines depending on HFM at very large scale as hadron colliders: fields, costs and power

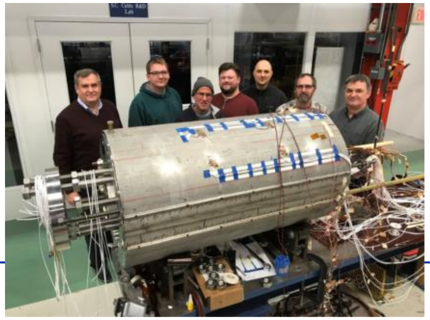
- Even with cost targets a factor 2-3 lower than today (a much larger factor for HTS) the costs are very high (see later)
- FCC-hh estimated roughly at 560 MW and ~4TWh annually from CDR, for Nb_3Sn and at 1.9K. Do not have estimate for SPPC. Combined with increased energy price this is a "challenge".
- A fourth challenge is the industrial interests for HF and long dipole magnets (and Nb_3Sn generally). Contrary to RF systems such magnets are generally not needed for small accelerators or industry.

8.3 T Nb-Ti



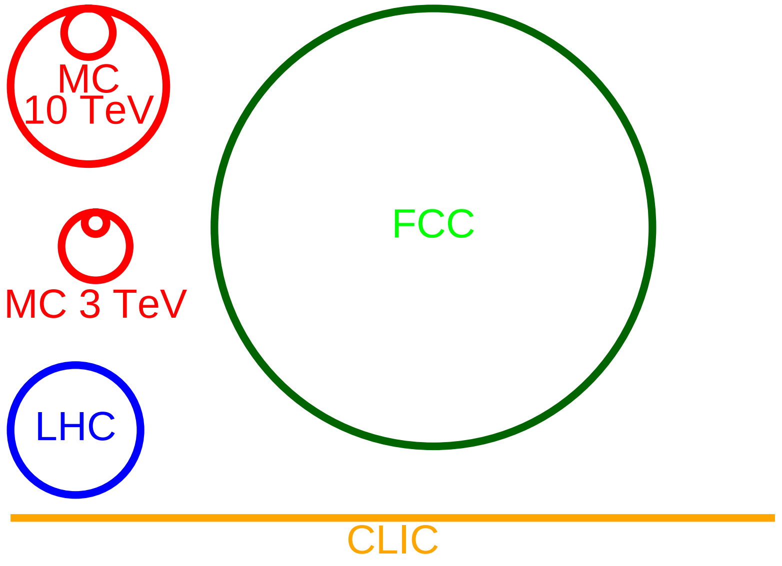
12 T Nb_3Sn quadrupole

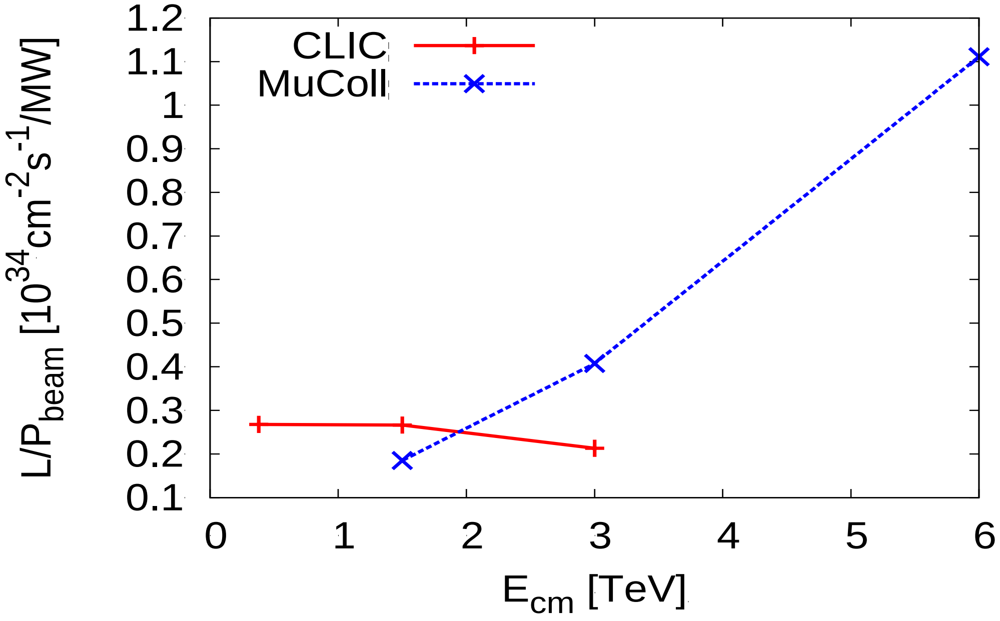
14.5 T Nb_3Sn



HTS …. and more … work in progress

Addressing size, lumi, cost, power - a Muon Collider





CLIC is highest energy proposal with CDR:

- No obvious way to further improve linear colliders (decades of R&D)
- Cost 18 GCHF, power approx. 500 MW

Rough rule of thumb:

- cost proportional to energy
- power proportional to luminosity

Muon Collider goals (10 TeV), challenging but reasonable**:**

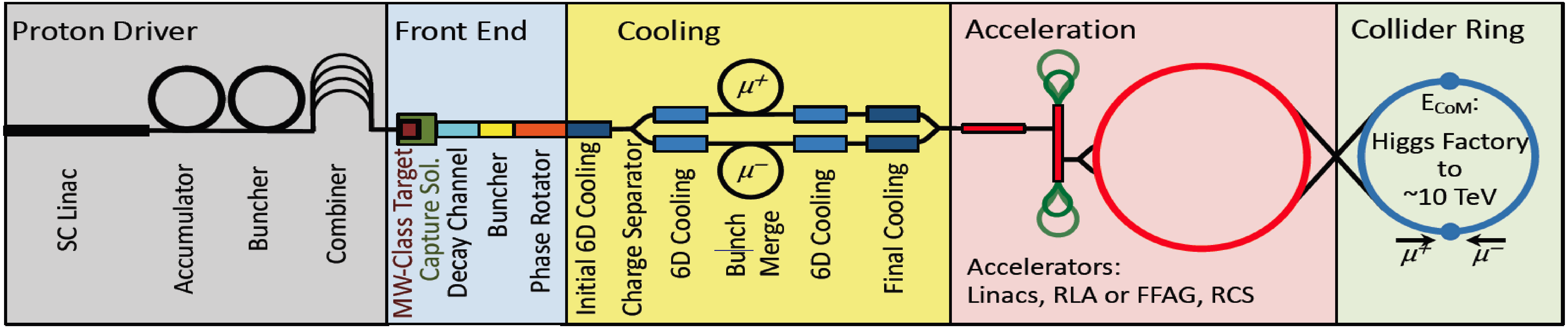
- Much **more luminosity** than CLIC at 3 TeV **(L=20x10^{34}, CLIC: L=6x10^{34})**
- **Lower power consumption** than CLIC at 3 TeV ($P_{beam,MC}$=0.5$P_{beam,CLIC}$)
- **Lower cost**

Staging is possible

Synergies exist (neutrino/higgs)

– Unique opportunity for a **high-energy, high-luminosity lepton collider**

Key Challenges and possible solutions



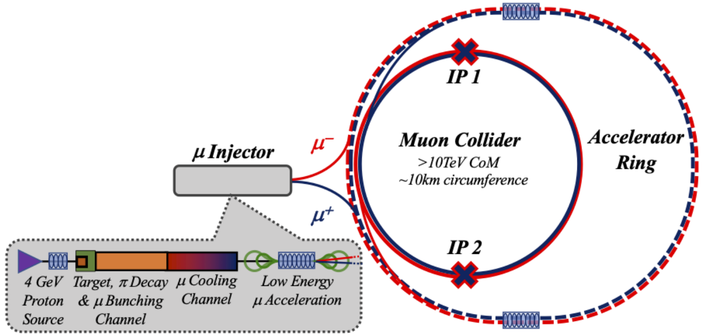
Proton complex
- Compressing proton to few bunches

Target
- Target
- Solenoid

Cooling channel
- Channel design
- Solenoids
- RF in magnetic field
- Absorbers
- Integration

RCS
- Beam dynamics
- Ramping magnets
- Power converter
- RF system

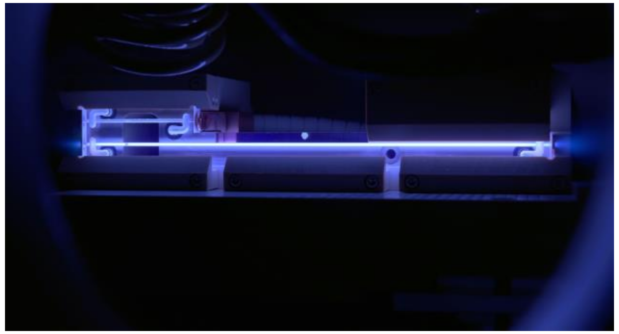
Collider ring
- Optics
- Magnets
- Neutrino flux
- Detector background background

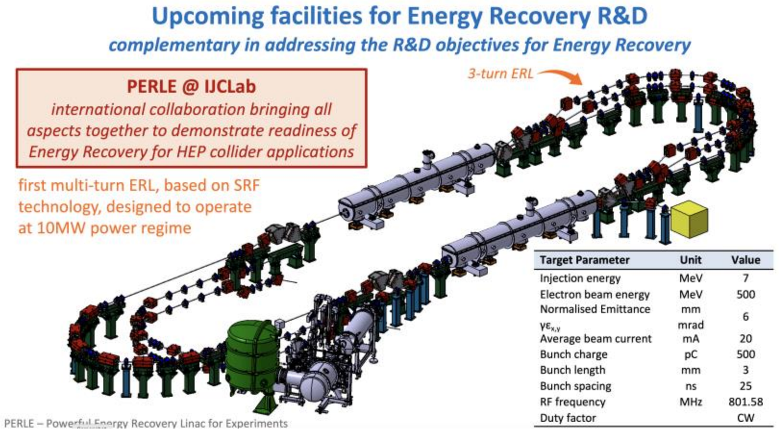


Solutions studied – linked to progress in many areas (not complete):
Progress on **high** power proton drivers and targets, cooling studies/demonstrations in MICE and RF in magnetic fields, progress in high field solenoids as needed for target and cooling channel, RCS technologies as RF (similar to ILC) and fast ramping magnets (normal or HTS), use of NbTi or HTS in collider ring, studies of mover system to reduce environmental neutrino flux and it results, detector background studies and experiences from HL-LHC detector studies … more information at link to EPP2024 (Schulte)

Energy recovery and Plasma

Project concepts exists and need to be further checked and developed. Practical work concentrated on smaller facilities (e.g. PEARL, bERLinPro, EUPRAXIA and many others (Flashforward, CLARA, AWAKE ……), use of plasma acc. for injectors, in many cases outside particle physics). LHeC still the most “worked through” collider concept making use of energy recovery ?





Upcoming facilities for Energy Recovery R&D

complementary in addressing the R&D objectives for Energy Recovery

PERLE @ IJCLab

international collaboration bringing all aspects together to demonstrate readiness of Energy Recovery for HEP collider applications

first multi-turn ERL, based on SRF technology, designed to operate at 10MW power regime

Target Parameter	Unit	Value
Injection energy	MeV	7
Electron beam energy	MeV	500
Normalised Emittance $\gamma\varepsilon_{x,y}$	mm mrad	6
Average beam current	mA	20
Bunch charge	pC	500
Bunch length	mm	3
Bunch spacing	ns	25
RF frequency	MHz	801.58
Duty factor		CW

PERLE – Powerful Energy Recovery Linac for Experiments

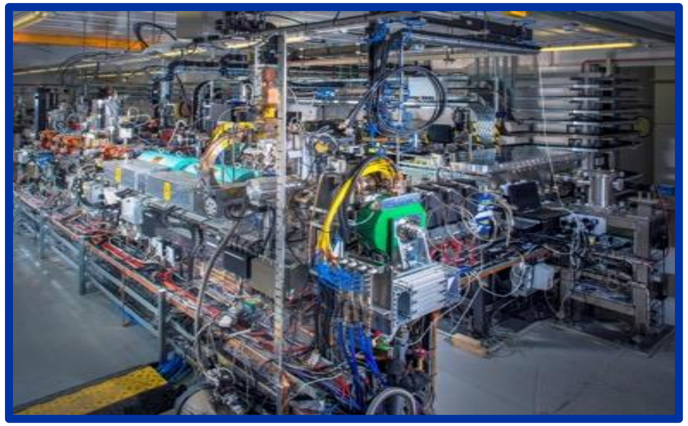
ALEGRO 2023

22-24 MARCH

Location: DESY Hamburg, Germany
Organisation: Brigitte Cros, Richard D'Arcy, Patric Muggli, Jens Osterhoff
Administration: Daniela Koch

ALEGRO2023 Workshop

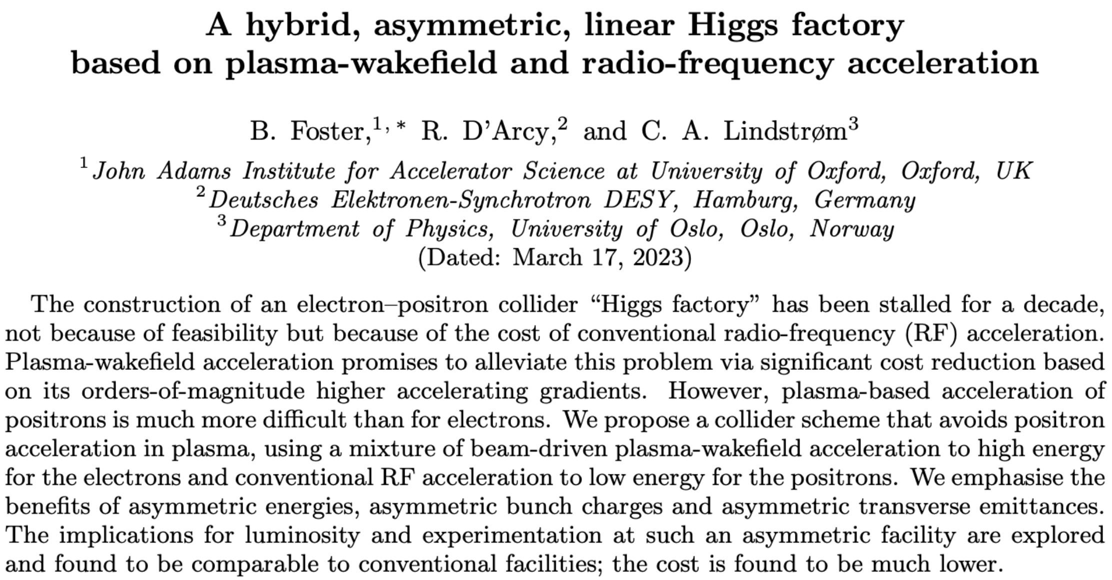
22–24 Mar 2023
DESY
Europe/Zurich timezone



From PECFA reports on Plasma and Energy Recovery

HALHF

https://arxiv.org/abs/2303.10150



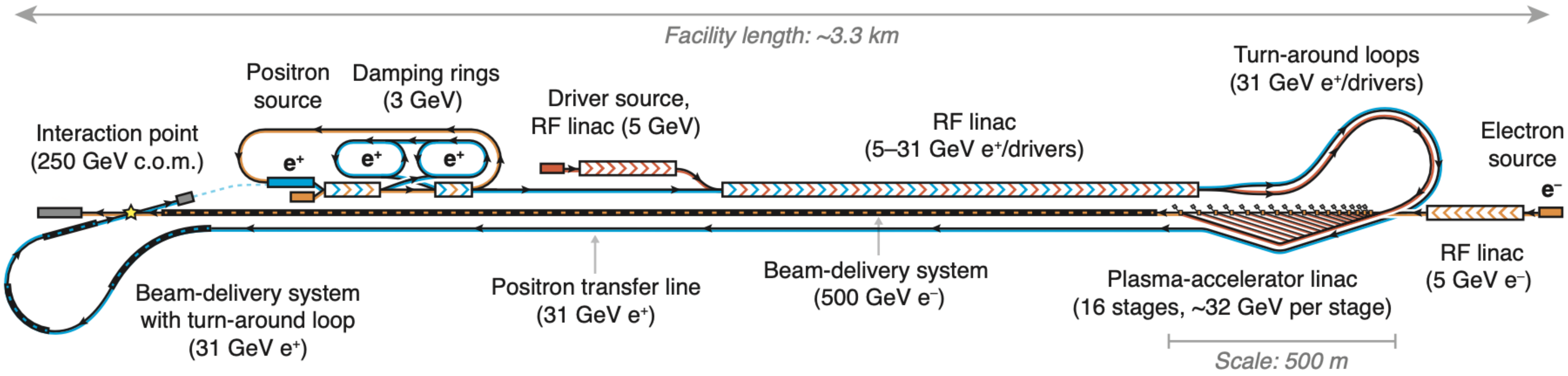
A hybrid, asymmetric, linear Higgs factory based on plasma-wakefield and radio-frequency acceleration

B. Foster,[1,*] R. D'Arcy,[2] and C. A. Lindstrøm[3]

[1] *John Adams Institute for Accelerator Science at University of Oxford, Oxford, UK*
[2] *Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany*
[3] *Department of Physics, University of Oslo, Oslo, Norway*

(Dated: March 17, 2023)

The construction of an electron–positron collider "Higgs factory" has been stalled for a decade, not because of feasibility but because of the cost of conventional radio-frequency (RF) acceleration. Plasma-wakefield acceleration promises to alleviate this problem via significant cost reduction based on its orders-of-magnitude higher accelerating gradients. However, plasma-based acceleration of positrons is much more difficult than for electrons. We propose a collider scheme that avoids positron acceleration in plasma, using a mixture of beam-driven plasma-wakefield acceleration to high energy for the electrons and conventional RF acceleration to low energy for the positrons. We emphasise the benefits of asymmetric energies, asymmetric bunch charges and asymmetric transverse emittances. The implications for luminosity and experimentation at such an asymmetric facility are explored and found to be comparable to conventional facilities; the cost is found to be much lower.



Some key parameters across projects …

All proposals can provide excellent physics – no doubt – but the projects (the subset discussed above) have some common challenges and/or differ in many aspects. In the following four are discussed:

- Costs
- Schedules
- Power/energy/operation costs and other environmental issues (one obvious is carbon)

Many of the considerations below are taken from the Snowmass implementation report mentioned initially.

Cost

EPPS 2019:

- FCC-ee (~11-12 BCHF), FCC-hh (~+17-18 BCHF) – FCC-hh standalone (~24 BCHF)
- CLIC 380 and CEPC (both ~6 BCHF)
- ILC 250 (~5 BCHF)
- CLIC 3TeV (~+11 BCHF) if extended from 380 GeV, or standalone (~18 BCHF)
- ILC 1 TeV and luminosity increase (+ depends on SRF technology advances ..)
- Muons not estimated

Material costs (value) estimated in a traditional way (ala LHC), prices in 2018 CHF

Snowmass ("30 Parameter Cost Model") – main elements in report (link on page 2 of this talk):

- 2021 US$
- Green field (in reality some machines will be extension of others)
- Add personnel estimate (see next slide)
- In most cases use estimates from recent machines (e.g. injectors, RF, CE, …)
- Use learning curves
- For HF magnets use “aspirational costing”, a factor ~2 lower than current Nb_3Sn pricing and a higher factor for HTS
- Special considerations made for Novel Technologies (will not show these estimates)

Personnel estimate and cost – and Higgs factories

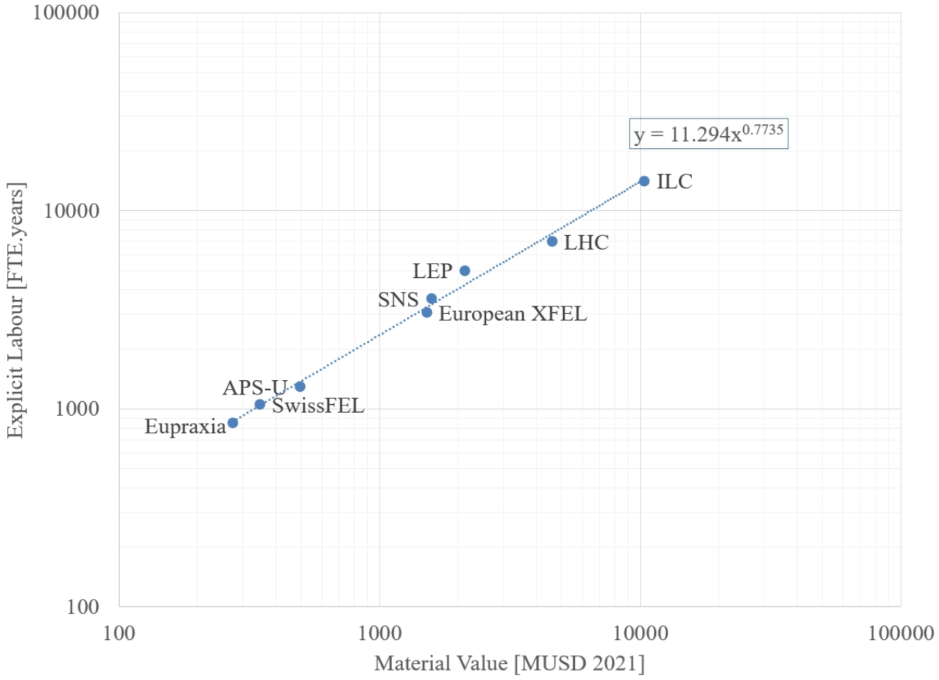
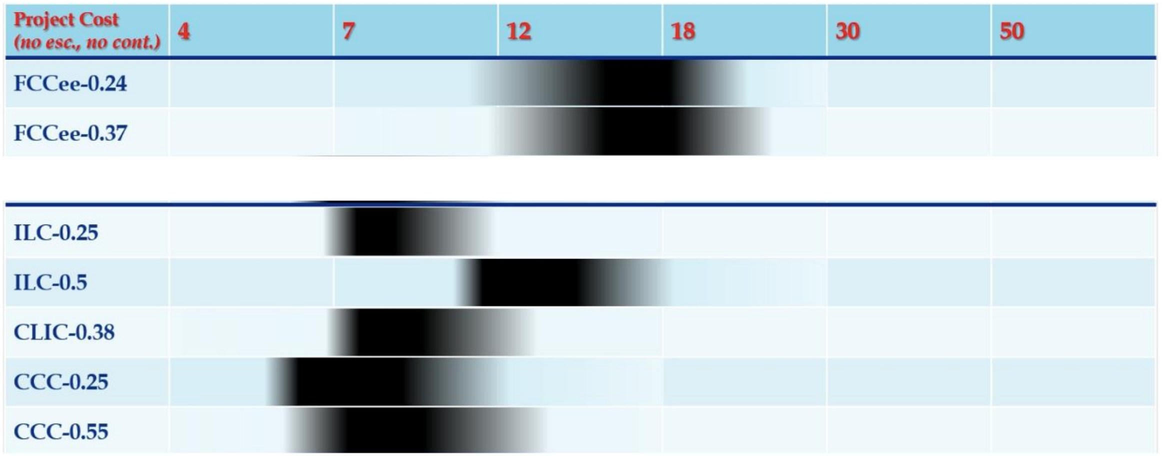


Figure 5: Explicit labor for several large accelerator projects vs. project value.

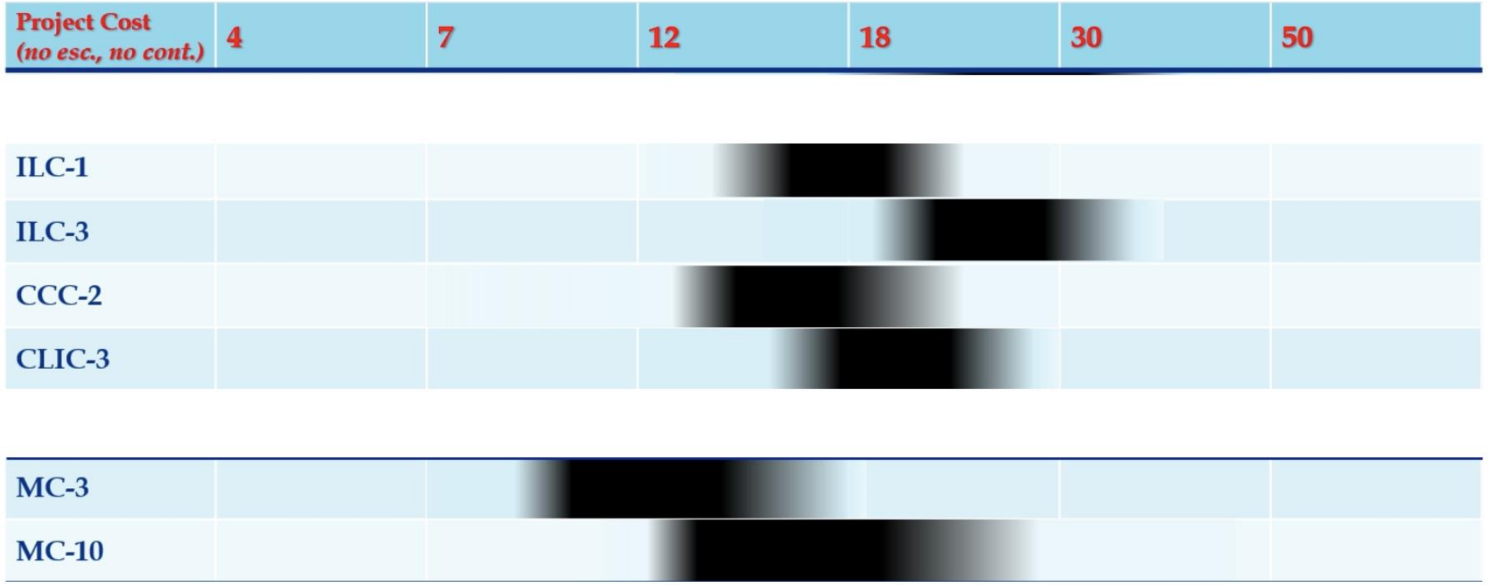
One FTEy estimated to 200kUS$



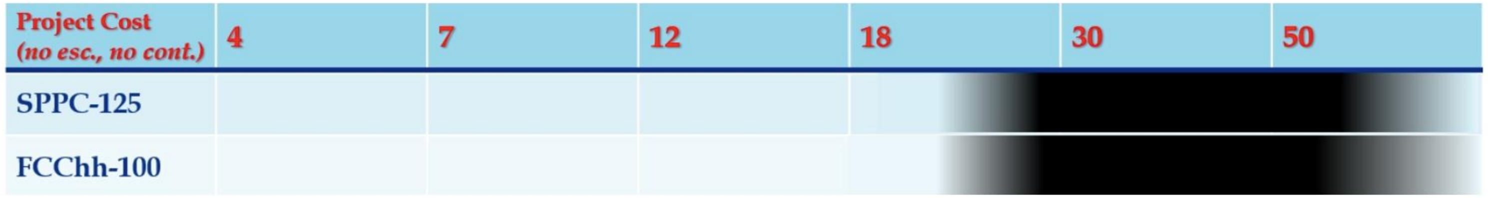
Project Cost (no esc., no cont.)	4	7	12	18	30	50
FCCee-0.24						
FCCee-0.37						
ILC-0.25						
ILC-0.5						
CLIC-0.38						
CCC-0.25						
CCC-0.55						

Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

Higher energy projects – and costs

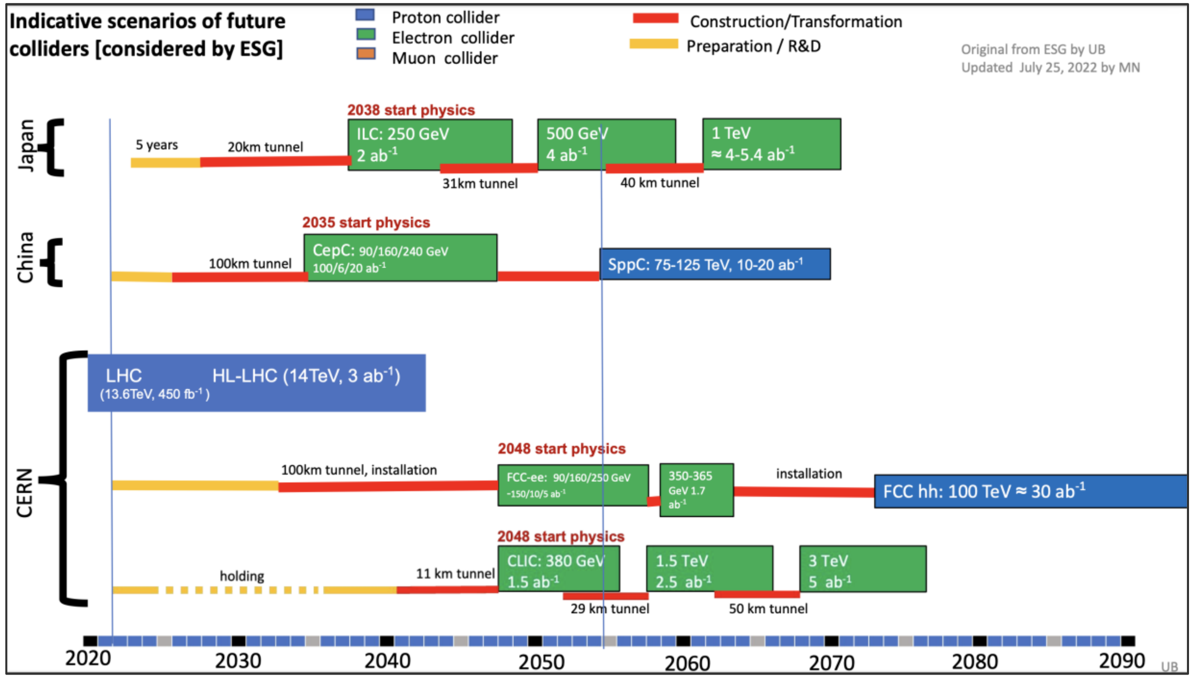


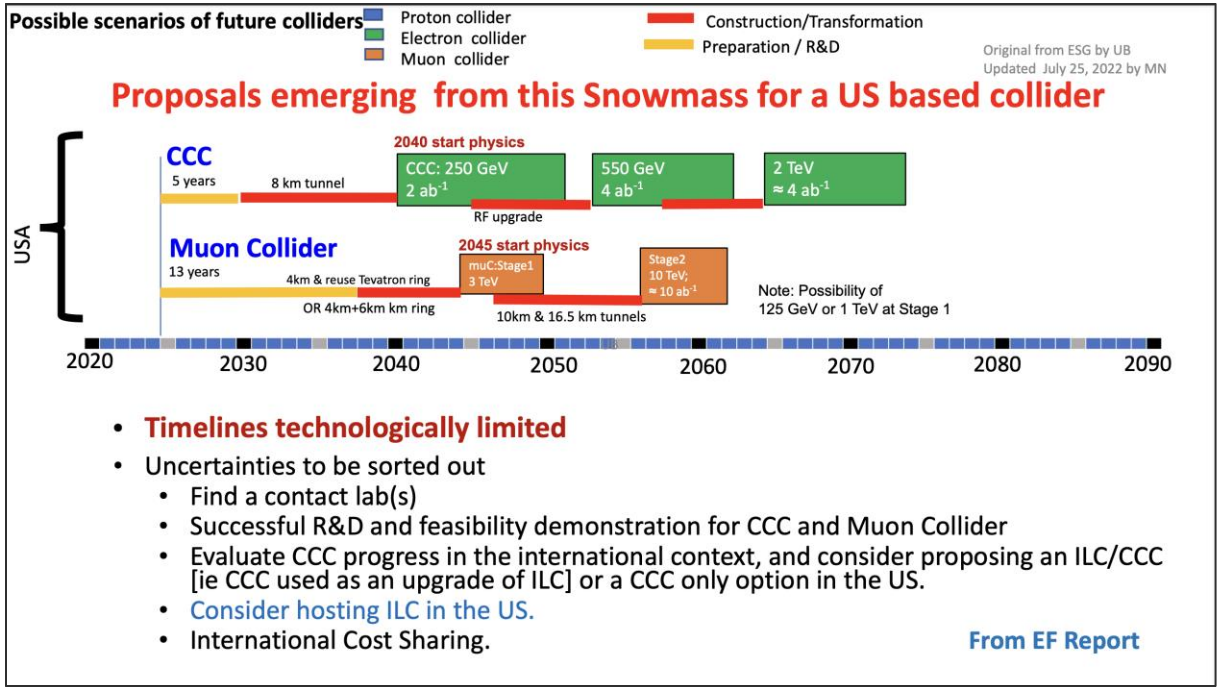
Project Cost *(no esc., no cont.)*	4	7	12	18	30	50
ILC-1			▨	▨		
ILC-3				▨	▨	
CCC-2			▨	▨		
CLIC-3			▨	▨		
MC-3		▨	▨			
MC-10			▨	▨		



Project Cost *(no esc., no cont.)*	4	7	12	18	30	50
SPPC-125				▨	▨	▨
FCChh-100				▨	▨	▨

Timelines in Snowmass Energy Frontier summary





- **Timelines technologically limited**
- Uncertainties to be sorted out
  - Find a contact lab(s)
  - Successful R&D and feasibility demonstration for CCC and Muon Collider
  - Evaluate CCC progress in the international context, and consider proposing an ILC/CCC [ie CCC used as an upgrade of ILC] or a CCC only option in the US.
  - Consider hosting ILC in the US.
  - International Cost Sharing.

From EF Report

Comments:

- Timelines are technologically limited – except the CERN projects that are linked to completion of the HL-LHC
- CEPC and ILC schedules are mature, but the projects need to pass approval processes in the near future to maintain these schedules
- CCC and MC are less well defined but R&D and project development on the shown timescales is reasonable, CCC can also upgrade ILC
- A clear wish to develop options for future US sited EF colliders
- US put emphasis on “fast” access to a Higgs factory
- From Meenakshi Narain EF summary Snowmass

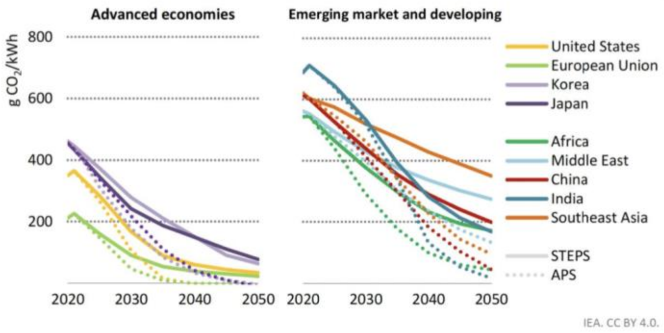
Sustainability – proactivity

- **Operation costs dominated by energy (and personnel)**
  - Reducing power use, and costs of power, will be crucial
  - Carbon footprint related to energy source, relatively low already for CERN (helped by nuclear powe expected to become significantly lower towards 2050 when future accelerators are foreseen to become operational (in Europe, US and Japan).
  - Align to future energy markets, green and more renewables, make sure we can be flexible customer and deal with grid stability/quality
  - Other consumables (gas, liquids, travels, computing …) during operation need to be justified (and estimated)

- **For carbon the construction impact might be (more) significant (also rare earths etc)**
  - Construction: CE, materials, processing and assembly – not easy to calculate, very likely a/the dominating carbon source
  - Markets will push for reduced carbon, “responsible purchasing” crucial – construction costs likely to increase
  - Many other factors than a carbon life cycle assessment, rare earths, toxicity, acidity ..
  - Environmental studies, integration in local environment/power grids, very important (FCC, CERN generally, Green ILC)

- **Decommissioning – how do we estimate impacts ?**

Figure 6.14 ▷ Average CO_2 intensity of electricity generation for selected regions by scenario, 2020-2050



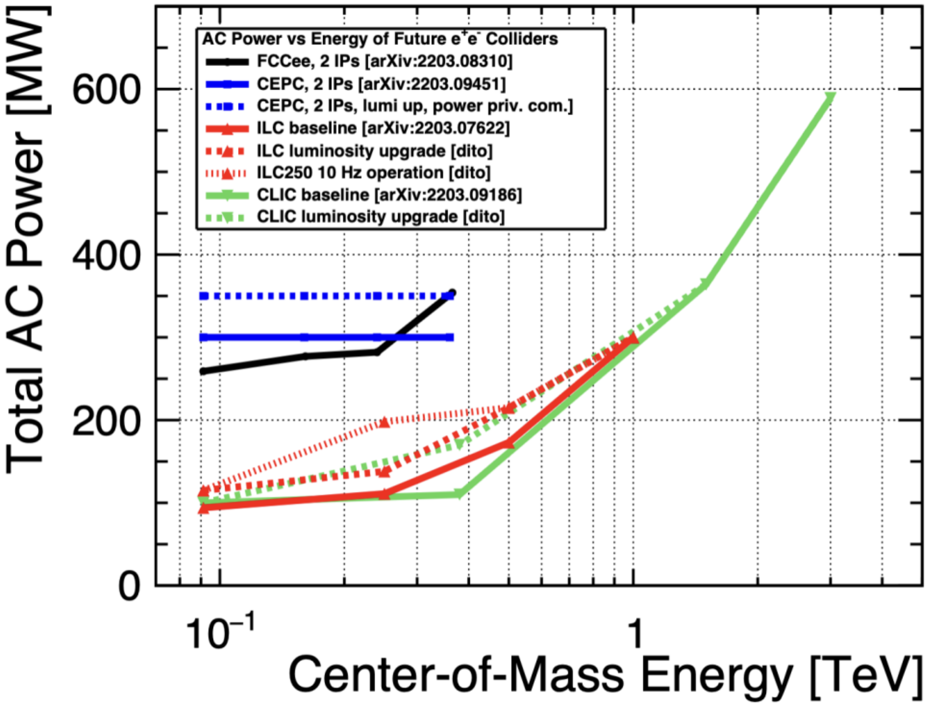
IEA. CC BY 4.0.

CO_2 intensity of electricity generation varies widely today, but all regions see a decline in future years and many have declared net zero emissions ambitions by around 2050

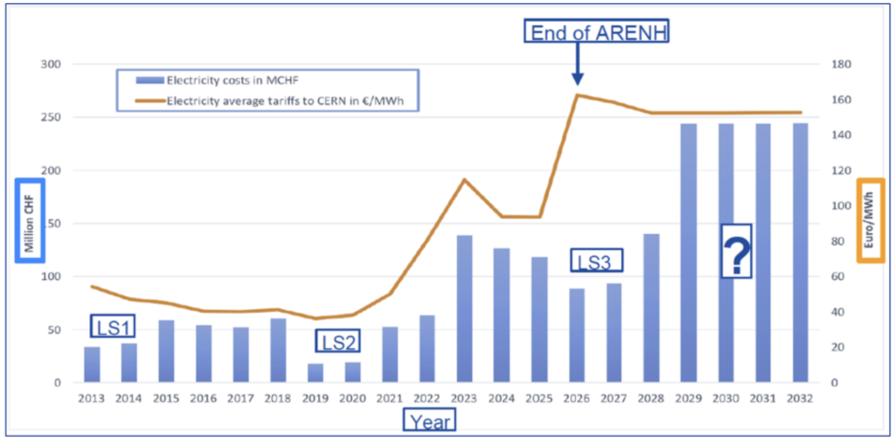
Power and energy

Typical power numbers for Higgs factories on the right – see also table on page above.

The CERN “standard” running scenario is shown below, used to convert to annual energy needs.

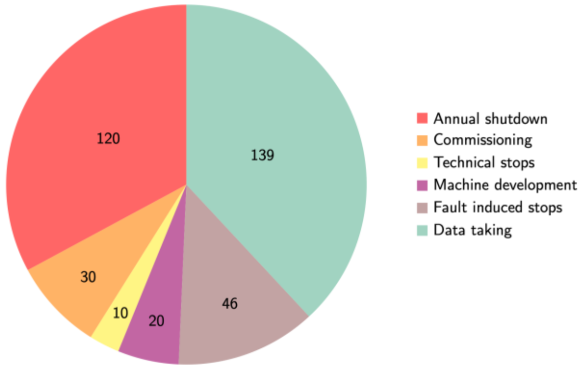


Extrapolating out to 2032 assuming: No ARENH and ”high” future electricity prices



Very uncertain but MTP assumes 140 MCHF/TWh beyond 2026.

With “standard” running scenario (on the right) every 100 MW corresponds to ~0.6 TWh annually, corresponding to ~85 MCHF annually.



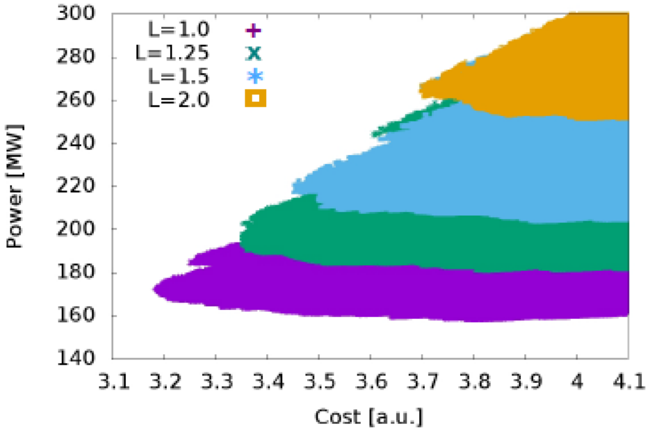
Optimisations – examples

Design Optimisation:
All projects aim to optimize – most often energy reach, luminosities and cost. Examples from all Higgs factories mentioned above.
Power is becoming at least as important, maybe even compromising ultimate performance for power saving.

Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, and super conducting (traditional SC, and HTS in particular) including cryo, and permanents magnets.

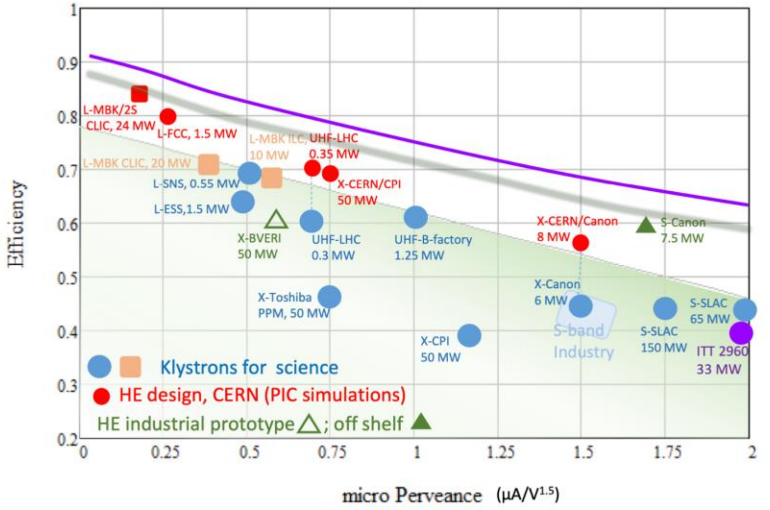
Heat recovery:
Already implemented in point 8 for LHC

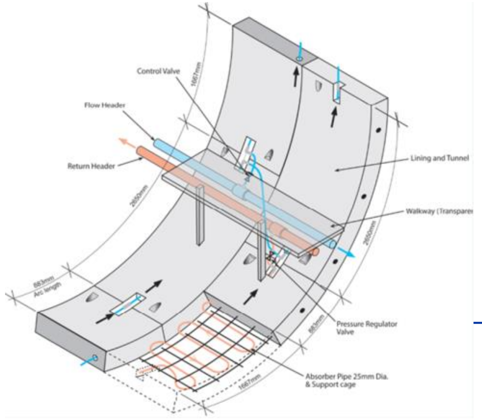
Tunnel heat recovery study by ARUP in 2022, results interesting but …

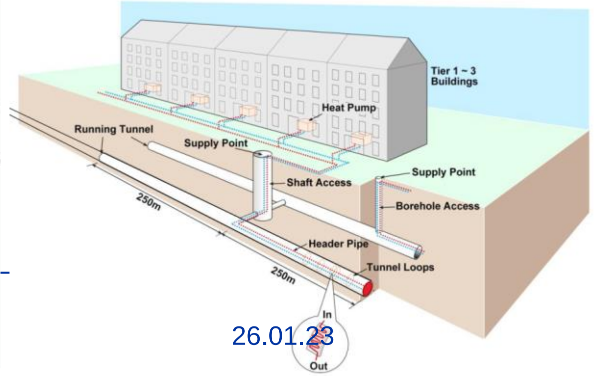


Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

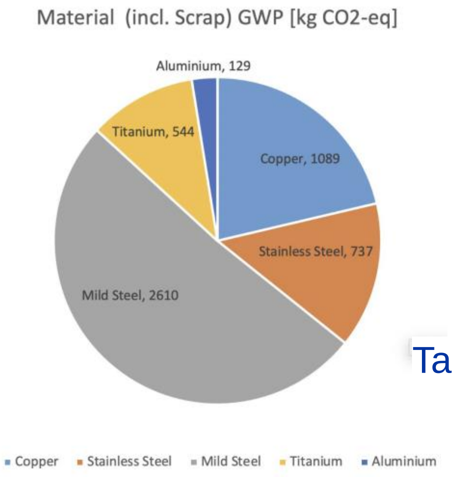
The designs of CLIC, including key performance parameters as accelerating gradients, pulse lengths, bunch-charges and luminosities, have been optimised for cost and power

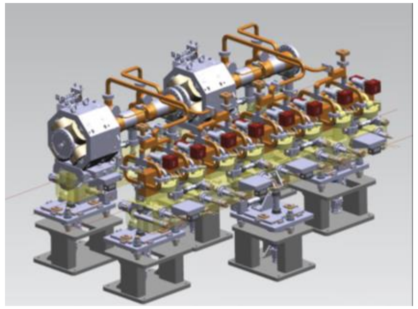




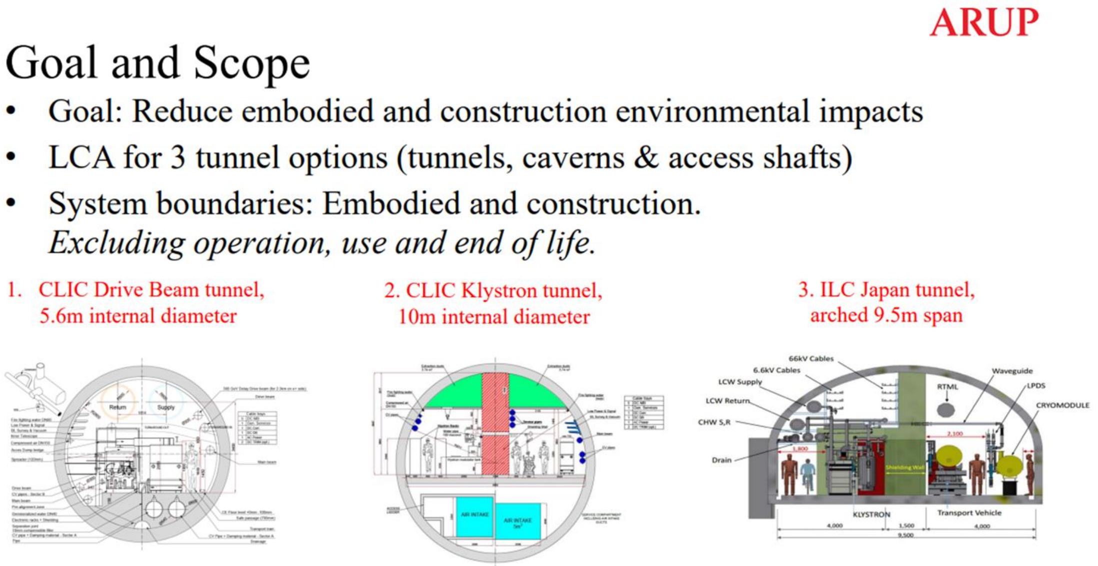


Sustainable Construction – some elements





Talk by B.List (link)



ARUP

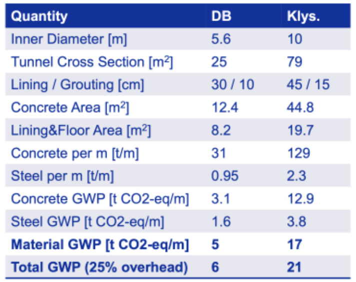
Goal and Scope

- Goal: Reduce embodied and construction environmental impacts
- LCA for 3 tunnel options (tunnels, caverns & access shafts)
- System boundaries: Embodied and construction.
  Excluding operation, use and end of life.

1. CLIC Drive Beam tunnel, 5.6m internal diameter
2. CLIC Klystron tunnel, 10m internal diameter
3. ILC Japan tunnel, arched 9.5m span

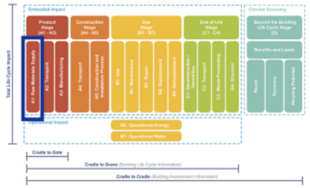
Carbon Cost/Life Cycle Assessment LCA study 2023

Tunnel GWP (CO2 Impact) from Materials



Quantity	DB	Klys.
Inner Diameter [m]	5.6	10
Tunnel Cross Section [m^2]	25	79
Lining / Grouting [cm]	30 / 10	45 / 15
Concrete Area [m^2]	12.4	44.8
Lining&Floor Area [m^2]	8.2	19.7
Concrete per m [t/m]	31	129
Steel per m [t/m]	0.95	2.3
Concrete GWP [t CO2-eq/m]	3.1	12.9
Steel GWP [t CO2-eq/m]	1.6	3.8
Material GWP [t CO2-eq/m]	**5**	**17**
Total GWP (25% overhead)	**6**	**21**

Lifecycle stages according to EN 15978



Only A1 considered here!

Similar CO2 estimates made for the FCC tunnel in the framework of Snowmass.

Assume a small tunnel (~5.6m diameter) and that the equipment in the tunnel has the same carbon footprint as the tunnel itself, 20km acc. incl. tunnel corresponds to 240 kton. This is equivalent to 50-60 TWh of nuclear power.

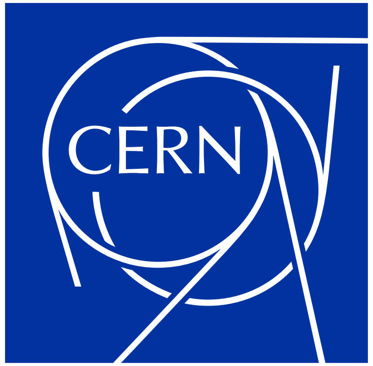
Two final comments:

- The work on-going for the FCC to "integrate" into the areas near CERN, including getting rid of spoil, is obviously also a crucial element on the way to a environmentally integrated collider.
- Responsible purchasing – and understanding the impact on our supply chain, costs and potential for changes – will be essentials for future projects (information from E.Cennini)

No conclusions but
thanks – most of the slides/information from:

The Snowmass Implementation Task Force (names on page 2, chair T.Roser)
The eeFACT summary team (F.Zimmermann et al. – linked to Snowmass AF3 WG)
M.Benedikt, F.Peauger
T.Watson, R.Cunningham and J.Osborne
S.Michizono, B.List
W.Wuensch, I.Syratchev, S.Calatroni
D.Schulte
E.Nanni
M.Giovannozzi
Y.Li, J.Gao
N.Bellegarde, E.Cennini
M.Narain
more
….

Some other talks: Chamonix and CERN seminar on future colliders



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