Linear colliders

Steinar Stapnes

CERN 14.03.2023

Outline

Introduction

Project specific:

- ✓ CLIC and ILC – status and on-going work
- ✓ Upgradability
- ✓ Very briefly about alternative LC ideas

Summaries and common issues:

- ✓ Parameters, cost and power, schedules, experimental conditions
- ✓ Sustainability studies (work in progress)

Very brief summary

Today: Snapshot early 2023

ESPP update 2018-19:

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

2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS

by the European Strategy Group

European Strategy Update

Report of the Snowmass'21 Collider Implementation Task Force

Thomas Roser (chair)[1], Reinhard Brinkmann[2], Sarah Cousineau[3], Dmitri Denisov[1], Spencer Gessner[4], Steve Gourlay[5], Philippe Lebrun[6], Meenakshi Narain[7], Katsunobu Oide[8], Tor Raubenheimer[4], John Seeman[4], Vladimir Shiltsev[9], Jim Strait[9], Marlene Turner[5], and Lian-Tao Wang[10]

[1]Brookhaven National Laboratory, Upton, NY 11973, USA
[2]DESY, 22607 Hamburg, Germany
[3]Oak Ridge National Laboratory, Oak Ridge, TN 37830, USA
[4]SLAC National Laboratory, Menlo Park, CA 94025, USA
[5]Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[6]ESI Archamps, 74160 Archamps, France
[7]Brown University, Providence, RI, 02912, USA
[8]KEK, Tsukuba, Ibaraki 305-0801, Japan
[9]Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
[10]University of Chicago, Chicago, IL 60637, USA

August 15, 2022

Abstract

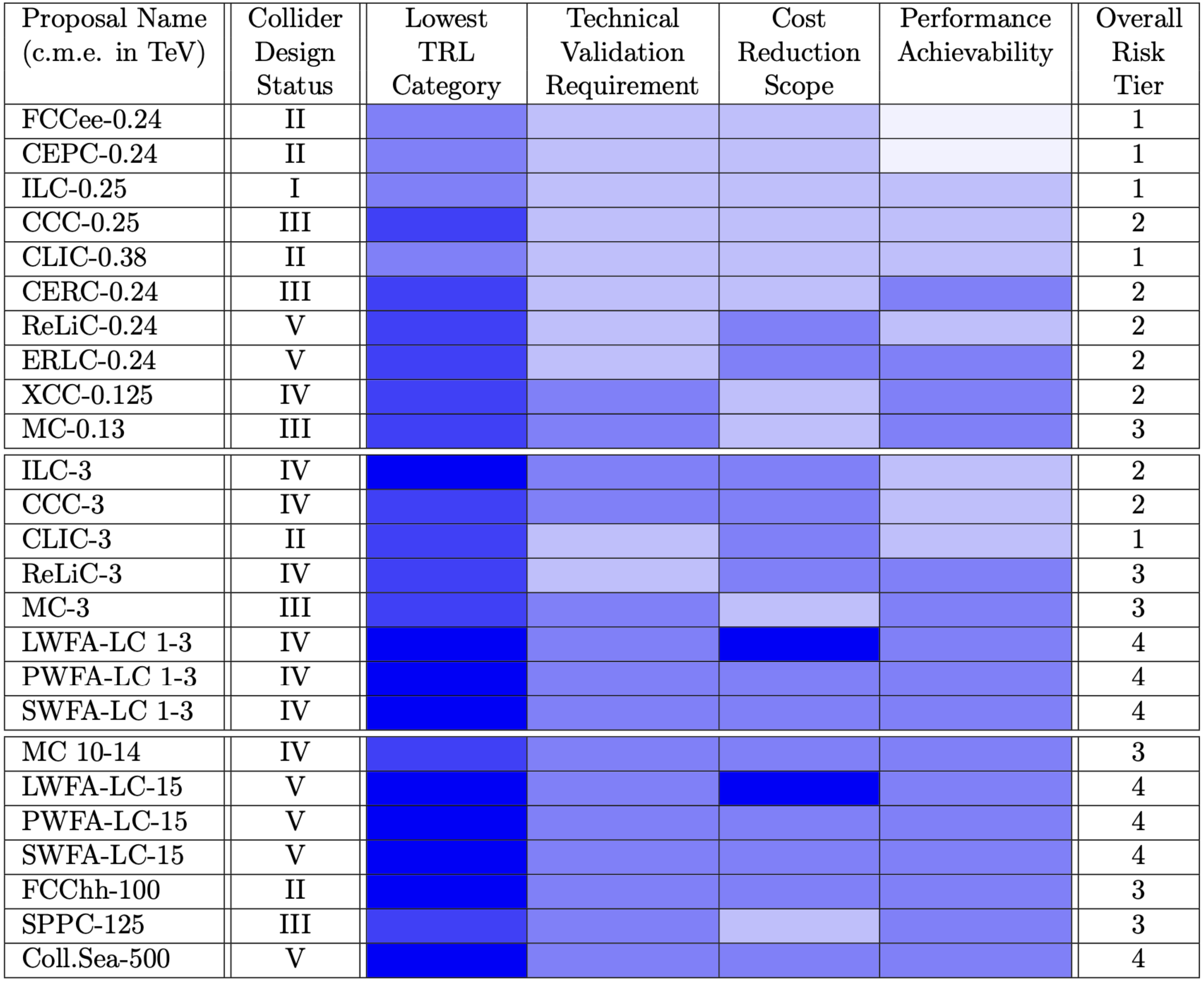
The Snowmass'21 Implementation Task Force has been established to evaluate the proposed future accelerator projects for performance, technology readiness, schedule, cost, and environmental impact. Corresponding metrics has been developed for uniform comparison of the proposals ranging from Higgs/EW factories 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 done …

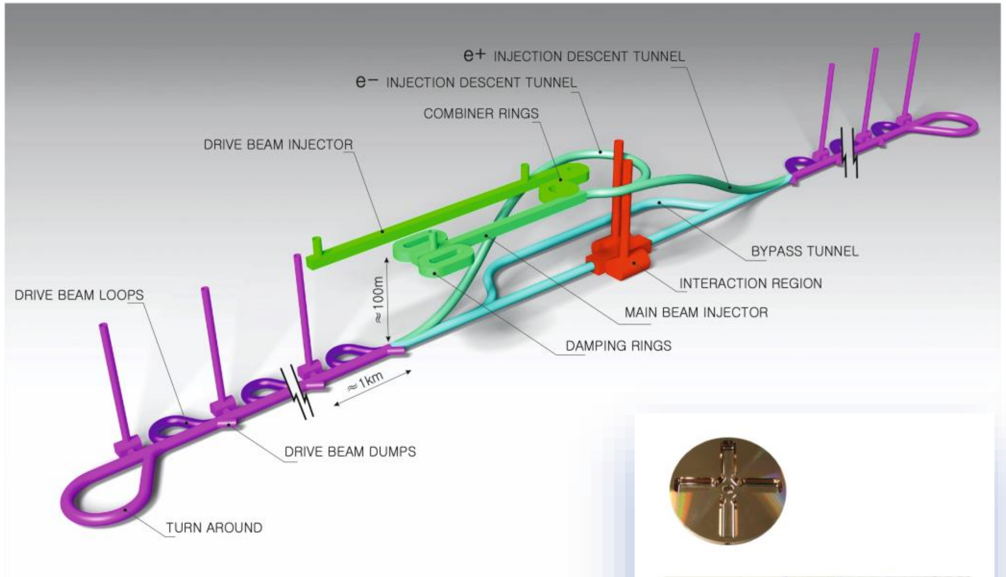


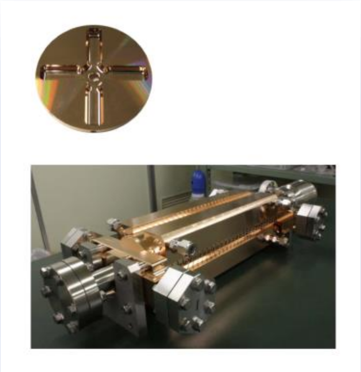
Focus on ILC and CLIC:

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	
CEPC-0.24	II	▒	░	░	□	1	
ILC-0.25	I	▒	░	░	░	1	Main topic
CCC-0.25	III	▓	░	░	░	2	Mention
CLIC-0.38	II	▒	░	░	░	1	Main topic
CERC-0.24	III	▓	░	░	▒	2	Mention
ReLiC-0.24	V	▓	░	▒	░	2	
ERLC-0.24	V	▓	░	▒	▒	2	
XCC-0.125	IV	▓	▒	░	▒	2	
MC-0.13	III	▓	▒	░	▒	3	
ILC-3	IV	█	▒	▒	░	2	Mentioned 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	
LWFA-LC 1-3	IV	█	▒	█	▒	4	LDG R&D roadmap, mention
PWFA-LC 1-3	IV	█	▒	▒	▒	4	
SWFA-LC 1-3	IV	█	▒	▒	▒	4	
MC 10-14	IV	▓	▒	▒	▒	3	
LWFA-LC-15	V	█	▒	█	▒	4	LDG R&D roadmap, mention
PWFA-LC-15	V	█	▒	▒	▒	4	
SWFA-LC-15	V	█	▒	▒	▒	4	
FCChh-100	II	█	▒	▒	▒	3	
SPPC-125	III	▓	▒	░	▒	3	
Coll.Sea-500	V	█	▒	▒	▒	4	

Light colour is good. Performance Achievability contentious/subjective in particular for new concepts.

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)

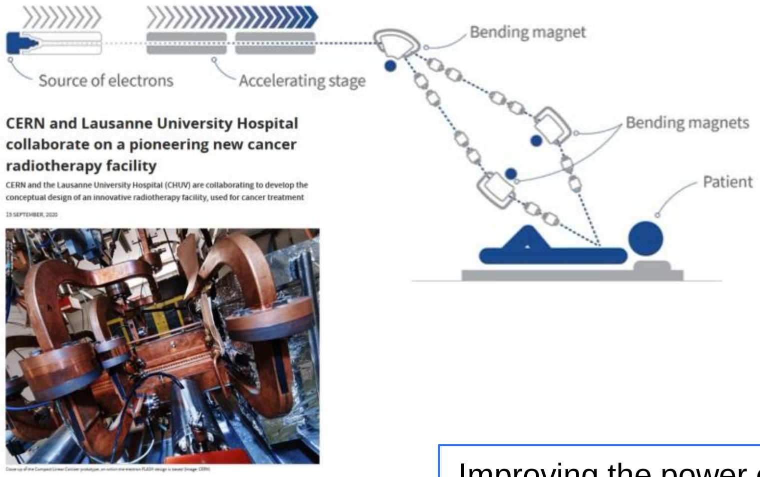
- CDR in 2012 with focus on 3 TeV. Updated project overview documents in 2018 (Project Implementation Plan) with focus 380 GeV for Higgs and top.

Recent talks (with more references): eeFACT1 and eeFACT2

On-going CLIC studies towards next ESPP update

Project Readiness Report as a step toward a TDR
Assuming ESPP in ~ 2026, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.

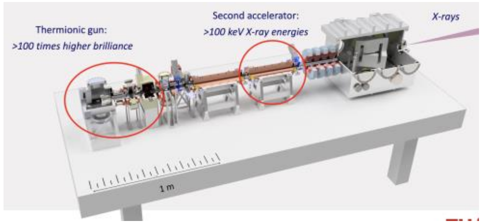
The X-band technology readiness for the 380 GeV CLIC initial phase - more and more driven by use in small compact accelerators

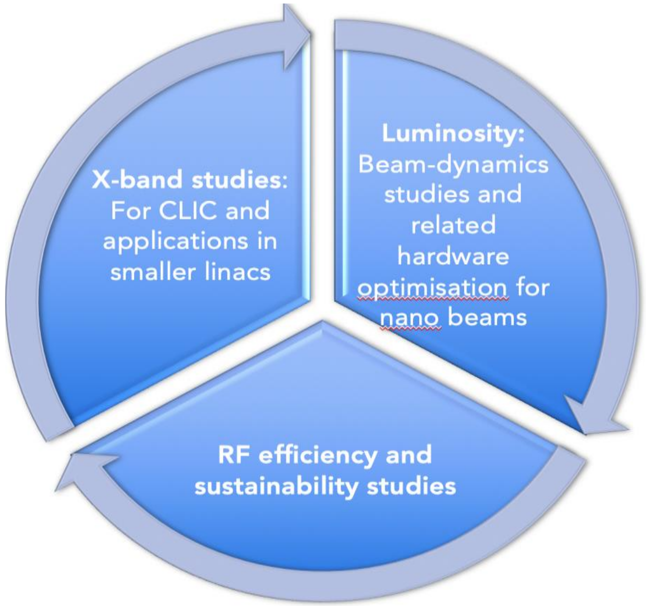


CERN and Lausanne University Hospital collaborate on a pioneering new cancer radiotherapy facility

CERN and the Lausanne University Hospital (CHUV) are collaborating to develop the conceptual design of an innovative radiotherapy facility, used for cancer treatment

15 SEPTEMBER, 2020





X-band studies: For CLIC and applications in smaller linacs

Luminosity: Beam-dynamics studies and related hardware optimisation for nano beams

RF efficiency and sustainability studies

Optimizing the luminosity at 380 GeV – already implemented for Snowmass paper, further work to provide margins will continue.

Luminosity margins and increases:

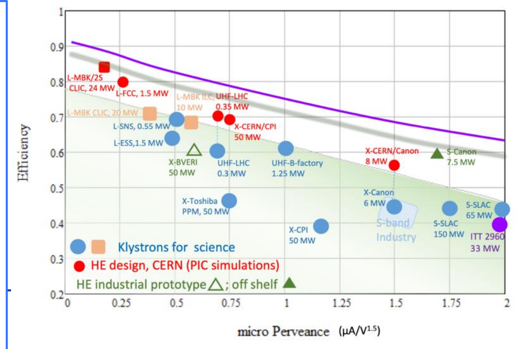
- Initial estimates of static and dynamic degradations from damping ring to IP gave: 1.5 x 10^{34} cm^{-2} s^{-1}
- Simulations taking into accord static and dynamic effects with corrective algorithms give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}** (this is the value currently used)

Improving the power efficiency for both the initial phase and at high energies, including more general sustainability studies

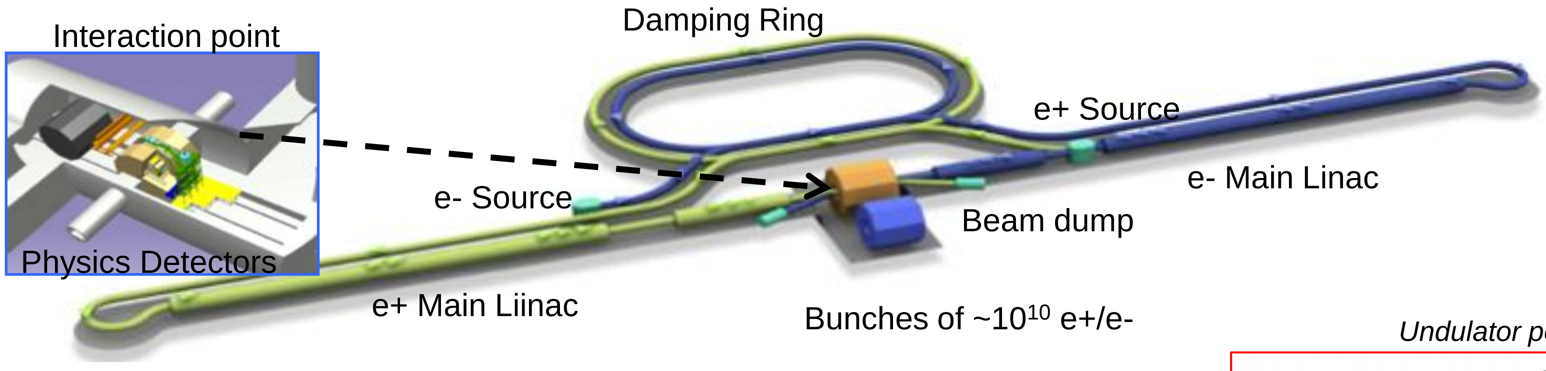
Power estimate bottom up (concentrating on 380 GeV systems)

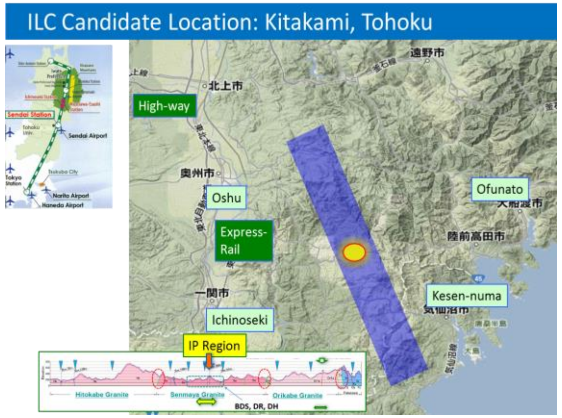
- Very large reductions since the CDR, better estimates of nominal settings, much more optimised drivebeam complex and more efficient klystrons, injectors more optimized, main target damping ring RF significantly reduced, recent L-band klystron studies

Energy consumption ~0.6 TWh yearly, CERN is currently (when running) at 1.2 TWh (~90% in accelerators)

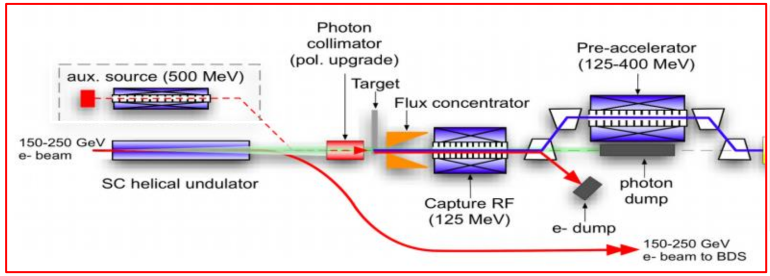


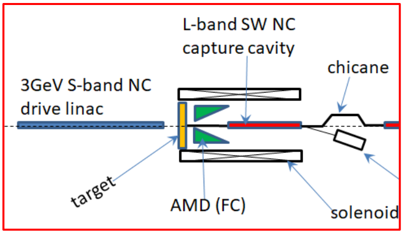
The ILC250 accelerator facility





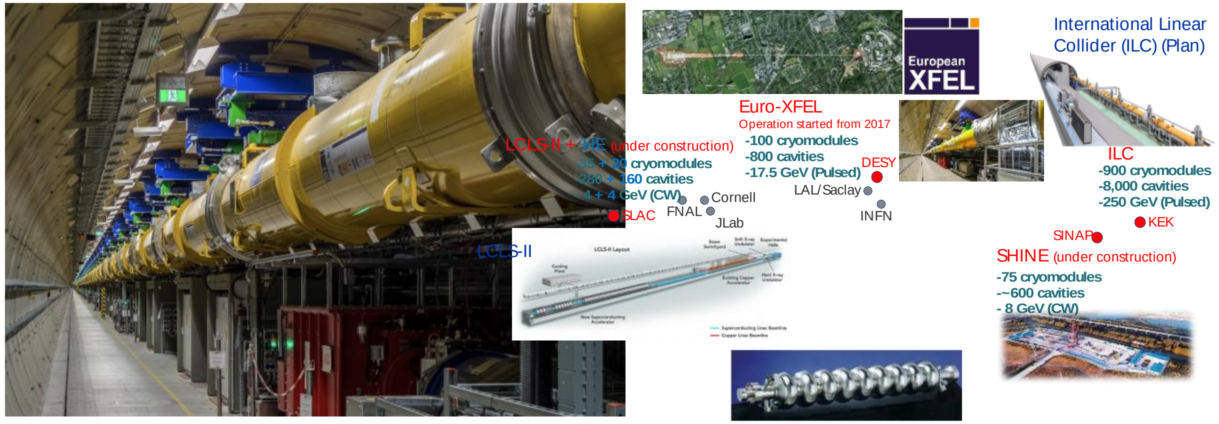
Undulator positron source





Electron driven positron source

- 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



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

Technical work in progress – European focus

Recent progress:
A subset of the technical activities of the full ILC preparation phase programme have been identified as critical. Moving forward with these is being supported by the MEXT (ministry) providing increased funding. European ILC studies, distributed on five main activity areas, is foreseen to concentrate (for the accelerator part) on these technical activities :

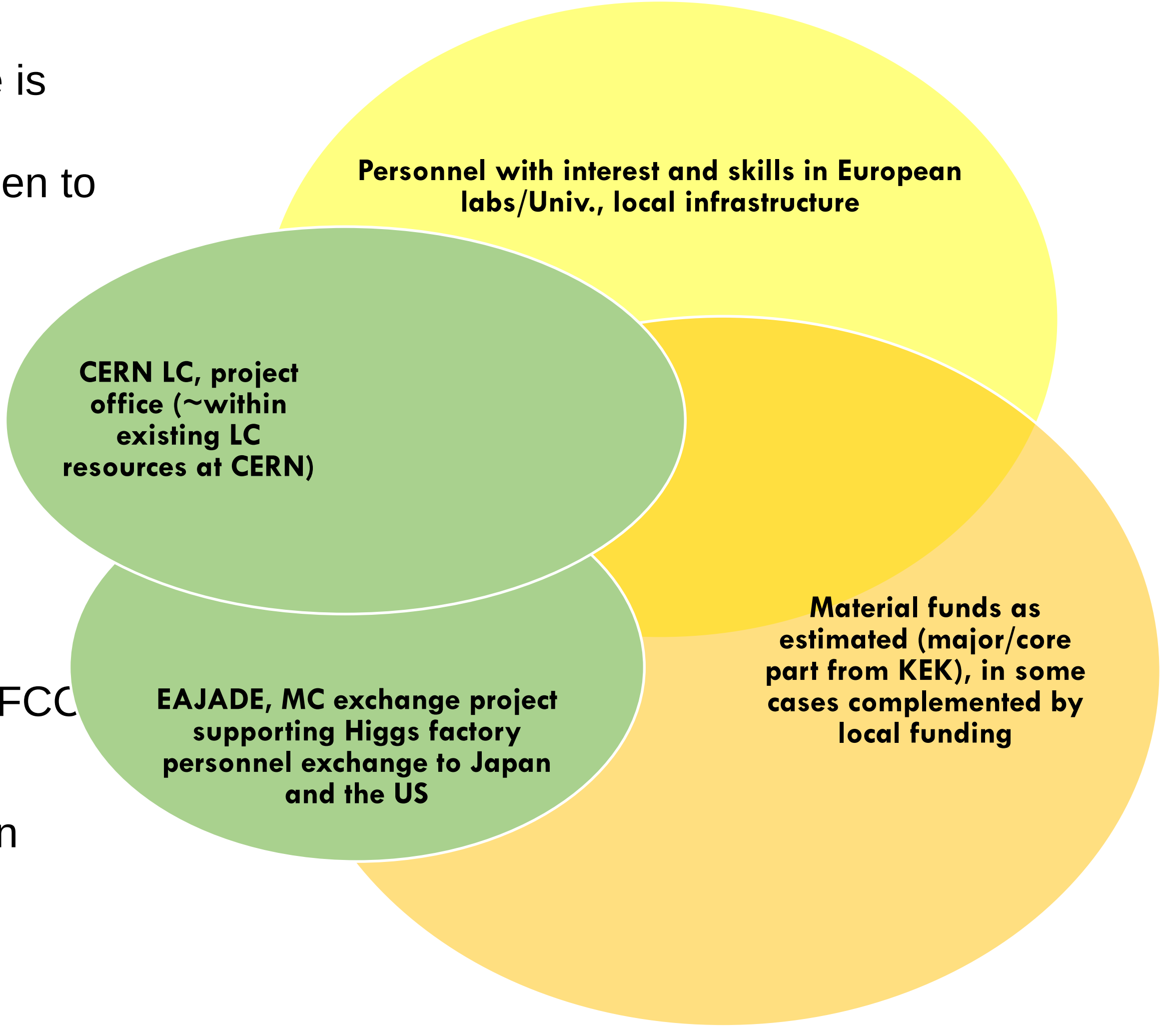
A1 with three SC RF related tasks
- SRF: Cavities, Module, Crab-cavities

A2 Sources
- Concentrate on undulator positron scheme – fast pulses magnet, consult on conventual one (used by CLIC and FCC-ee)

A3 Damping Ring including kickers
- Low Emittance Ring community, and also kicker work in CLIC and FCC

A4 ATF activities for final focus and nanobeams
- Many European groups active in ATF, more support for its operation expected using the fresh funding

A5 Implementation including Project Office
- Dump, CE, Cryo, Sustainability, MDI, others (many of these are continuations of on-going collaborative activities)



Personnel with interest and skills in European labs/Univ., local infrastructure

CERN LC, project office (~within existing LC resources at CERN)

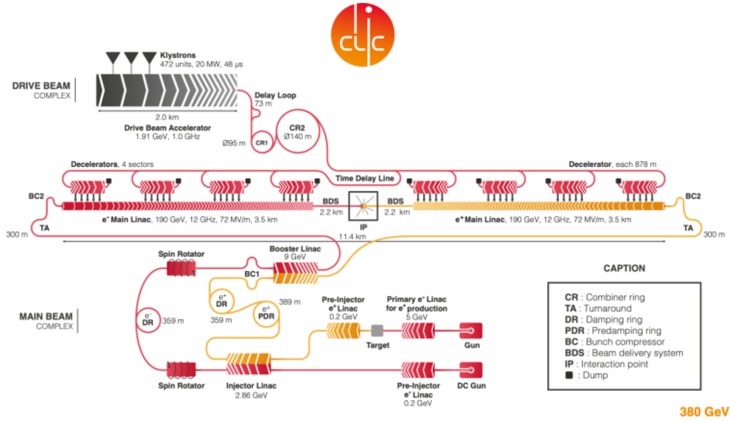
EAJADE, MC exchange project supporting Higgs factory personnel exchange to Japan and the US

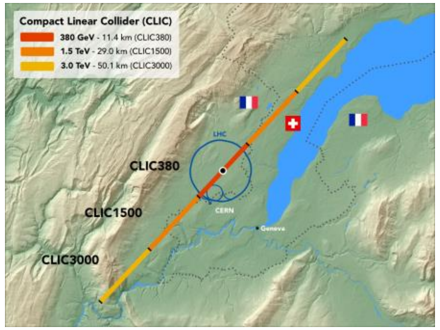
Material funds as estimated (major/core part from KEK), in some cases complemented by local funding

EAJADE MC: Information at LINK

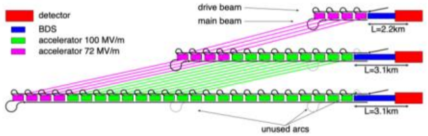
CLIC, ILC energy upgrades

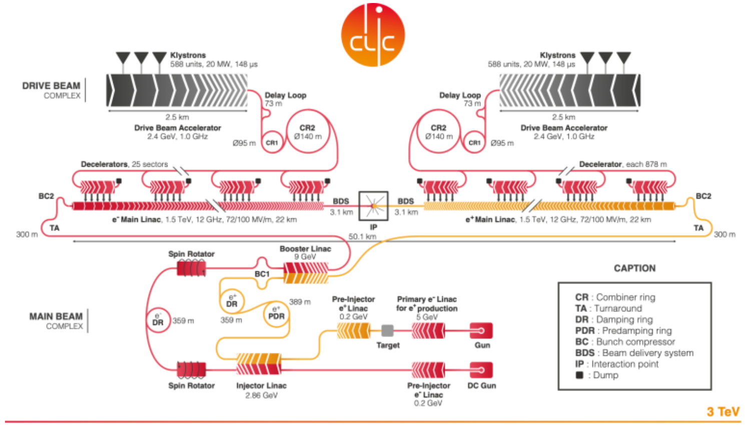
CLIC can easily be extended into the multi-TeV region (3 TeV studied in detail)





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

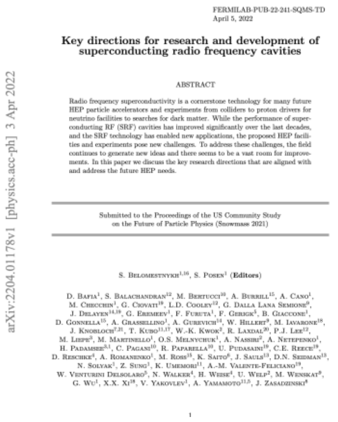




CLIC – Scheme of the Compact Linear Collider (CLIC)

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)
- https://arxiv.org/abs/2204.01178
  and
  https://www.frontiersin.org/articles/10 3
  3479/full



FERMILAB-PUB-22-241-SQMS-TD
April 5, 2022

Key directions for research and development of superconducting radio frequency cavities

arXiv:2204.01178v1 [physics.acc-ph] 3 Apr 2022

ABSTRACT

Radio frequency superconductivity is a cornerstone technology for many future HEP particle accelerators and experiments from colliders to proton drivers for neutrino facilities to searches for dark matter. While the performance of superconducting RF (SRF) cavities has improved significantly over the last decades, and the SRF technology has enabled new applications, the proposed HEP facilities and experiments pose new challenges. To address these challenges, the field continues to generate new ideas and there seems to be a vast room for improvements. In this paper we discuss the key research directions that are aligned with and address the future HEP needs.

Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

S. Belomestnykh[1,16], S. Posen[1] (**Editors**)

D. Bafia[1], S. Balachandran[12], M. Bertucci[10], A. Burrill[15], A. Cano[1], M. Checchin[1], G. Ciovati[19], L.D. Cooley[12], G. Dalla Lana Semione[9], J. Delayen[14,19], G. Eremeev[1], F. Furuta[1], F. Gerigk[5], B. Giaccone[1], D. Gonnella[15], A. Grassellino[1], A. Gurevich[14], W. Hillert[9], M. Iavarone[18], J. Knobloch[7,21], T. Kubo[11,17], W.-K. Kwok[2], R. Laxdal[20], P.J. Lee[12], M. Liepe[3], M. Martinello[1], O.S. Melnychuk[1], A. Nassiri[2], A. Netepenko[1], H. Padamsee[3,1], C. Pagani[10], R. Paparella[10], U. Pudasaini[19], C.E. Reece[19], D. Reschke[4], A. Romanenko[1], M. Ross[15], K. Saito[6], J. Sauls[13], D.N. Seidman[13], N. Solyak[1], Z. Sung[1], K. Umemori[11], A.-M. Valente-Feliciano[19], W. Venturini Delsolaro[5], N. Walker[4], H. Weise[4], U. Welp[2], M. Wenskat[9], G. Wu[1], X.X. Xi[18], V. Yakovlev[1], A. Yamamoto[11,5], J. Zasadzinski[8]

1

Will describe briefly later:
C3 (cool copper) is similar to CLIC in gradient and a 2 TeV C3 concept have been formulated. C3 would also fit into an ILC tunnel with its suitable klystron gallery, as a potential upgrade.

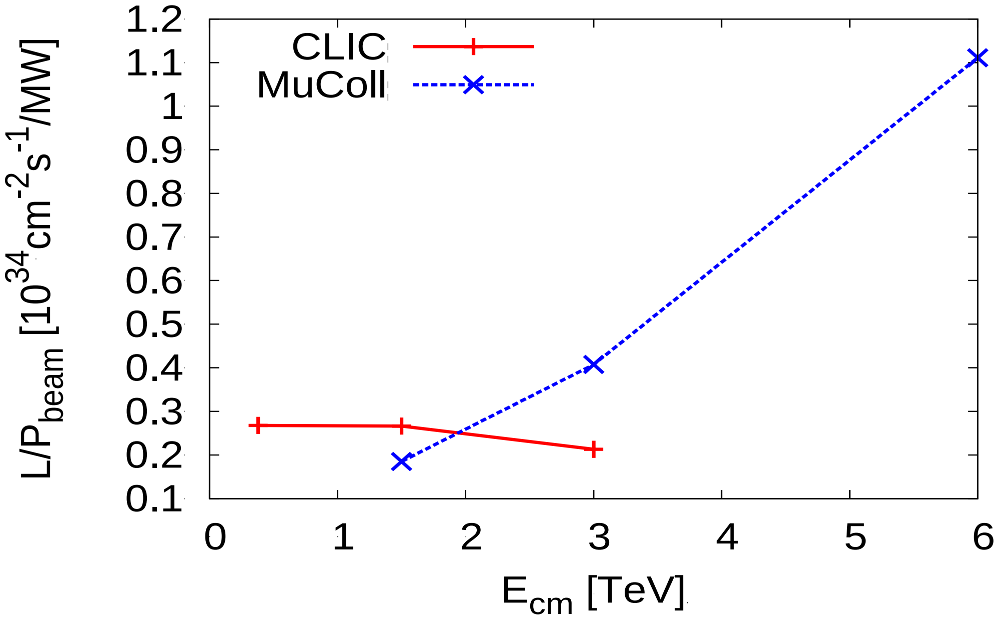
LCs towards much higher energies

CLIC is highest energy (3 TeV) detailed proposal with a CDR

Rough rule of thumb LCs:

- cost proportional to energy (need disruptive technologies for a LC going much beyond – much higher gradients)
- power proportional to luminosity - need higher power efficiency
- see talk by Daniel in a moment

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.



C3 studies

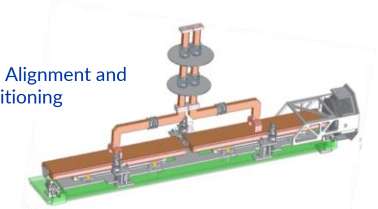
8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m

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

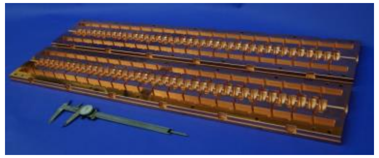
Large portions of accelerator complex are compatible between LC technologies

- 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

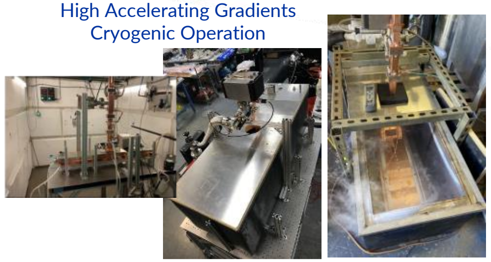
Preliminary Alignment and Positioning



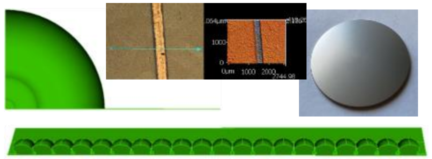
Modern Manufacturing Prototype One Meter Structure

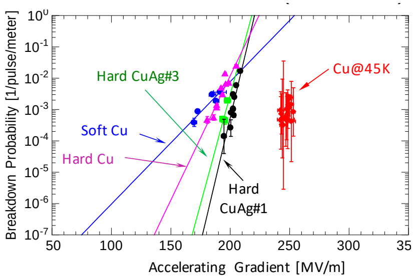


High Accelerating Gradients Cryogenic Operation

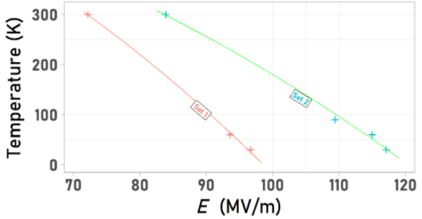


Integrated Damping Slot Damping with NiChrome Coating



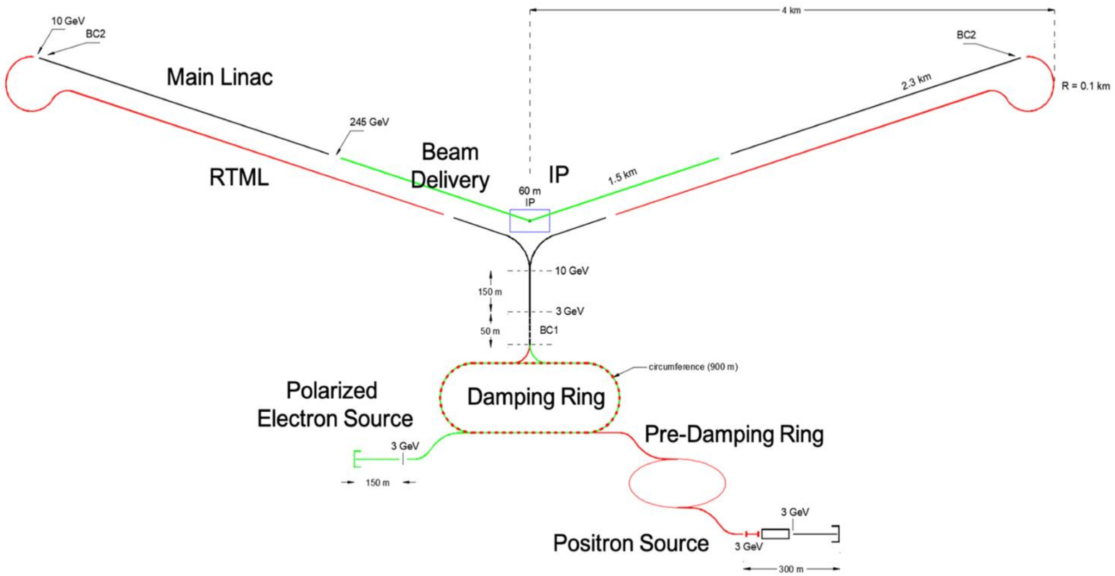


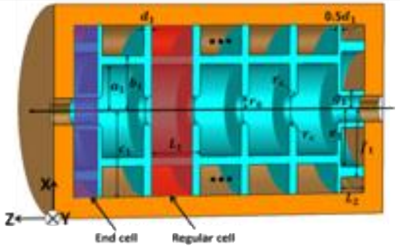
Cryo-cooled c



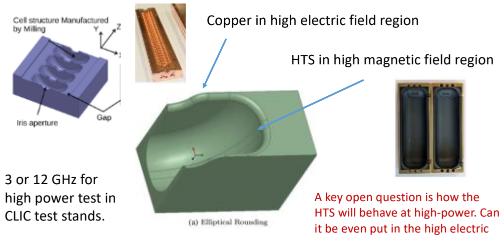
Cryo-cooled copper pulsed dc electrodes, Uppsala/CERN

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





Implementation



Copper in high electric field region

HTS in high magnetic field region

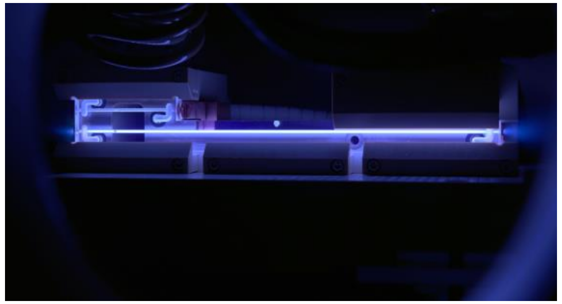
3 or 12 GHz for high power test in CLIC test stands.

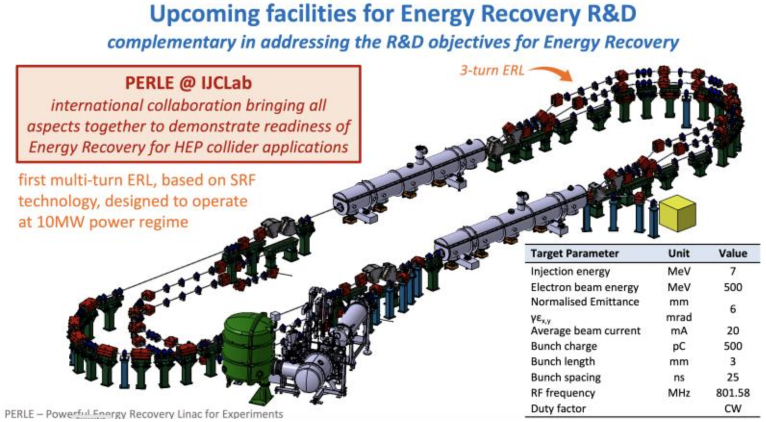
A key open question is how the HTS will behave at high-power. Can it be even put in the high electric field region?

Cryogenic systems extended: Combining high-gradients in cryo-copper and high-temperature superconductors for high-efficiency and reduced peak RF power requirements.

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, Flashforward, CLARA, AWAKE ……). In addition often motivated by use outside particle physics – however some plasma acc. ideas for injectors. Several energy recovery concepts were presented foe Snowmass.





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

ALEGRO 2023

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

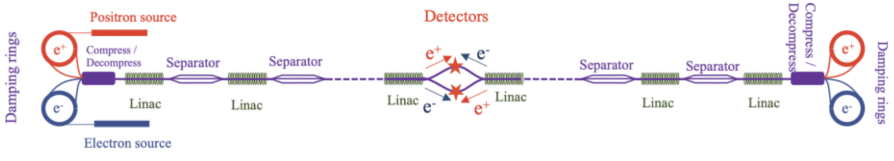


Figure 3-8. *Conceptual layout of ReLiC.*

Twin LC with energy recovery

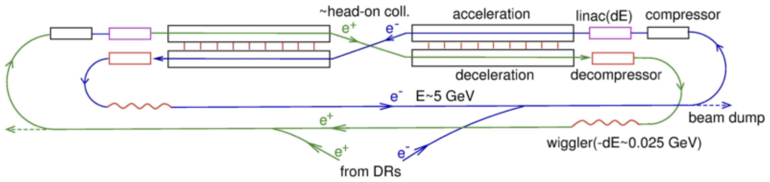
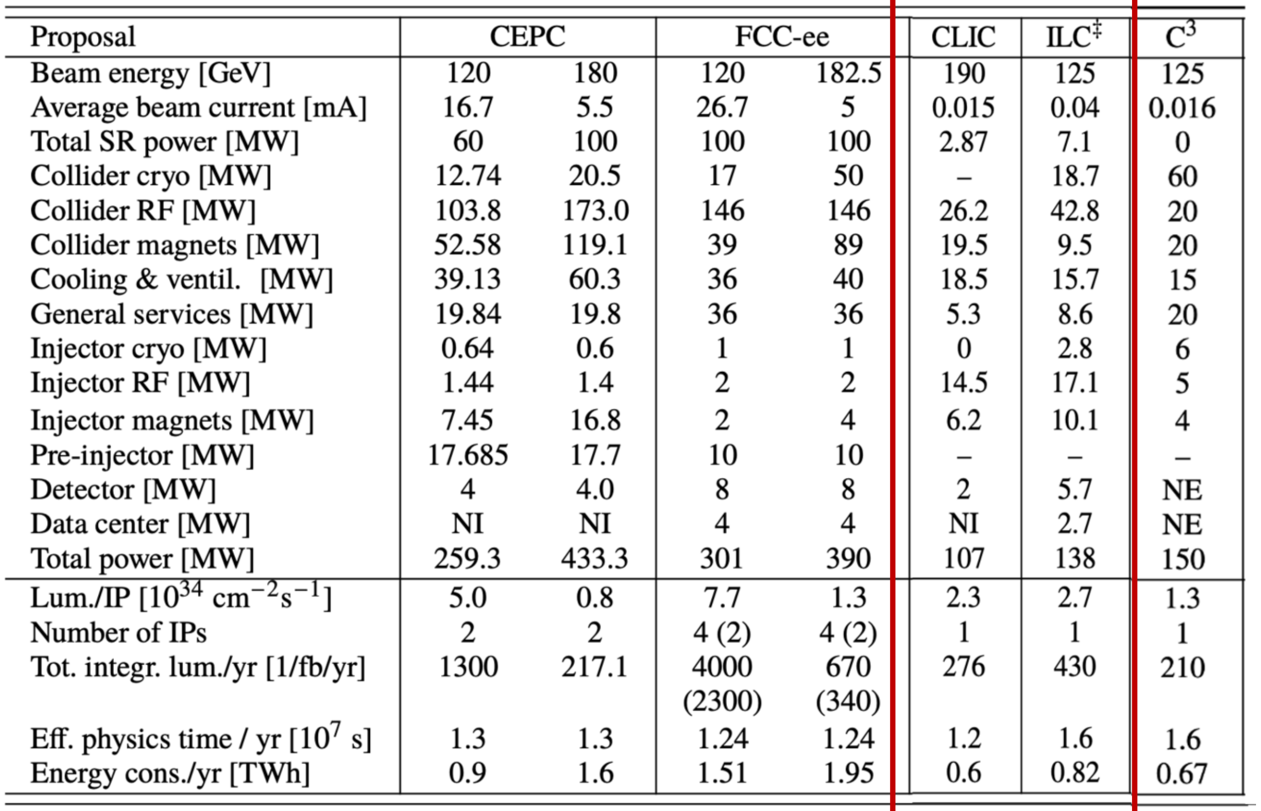


Figure 3-10. *Conceptual layout of the ERLC.*

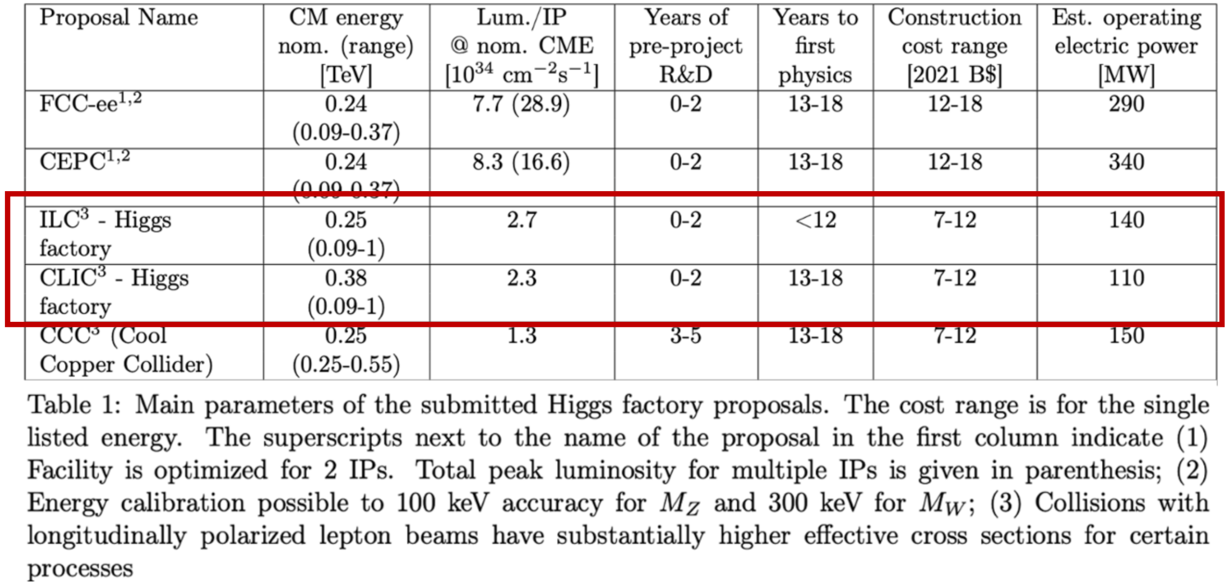
Both are part of the LDG acc. R&D roadmap, illustrations from PECFA reports on Plasma and Energy Recovery

Some key issues across projects … in many cases not limited to linear colliders

Higgs factories

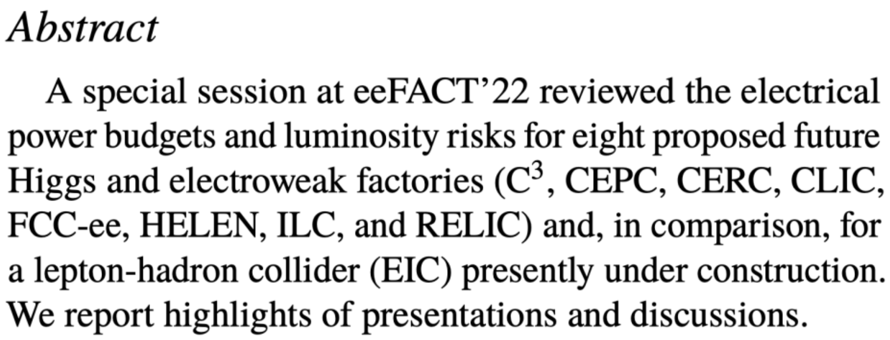


Proposal	CEPC		FCC-ee		CLIC	ILC‡	C^3
Beam energy [GeV]	120	180	120	182.5	190	125	125
Average beam current [mA]	16.7	5.5	26.7	5	0.015	0.04	0.016
Total SR power [MW]	60	100	100	100	2.87	7.1	0
Collider cryo [MW]	12.74	20.5	17	50	–	18.7	60
Collider RF [MW]	103.8	173.0	146	146	26.2	42.8	20
Collider magnets [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



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

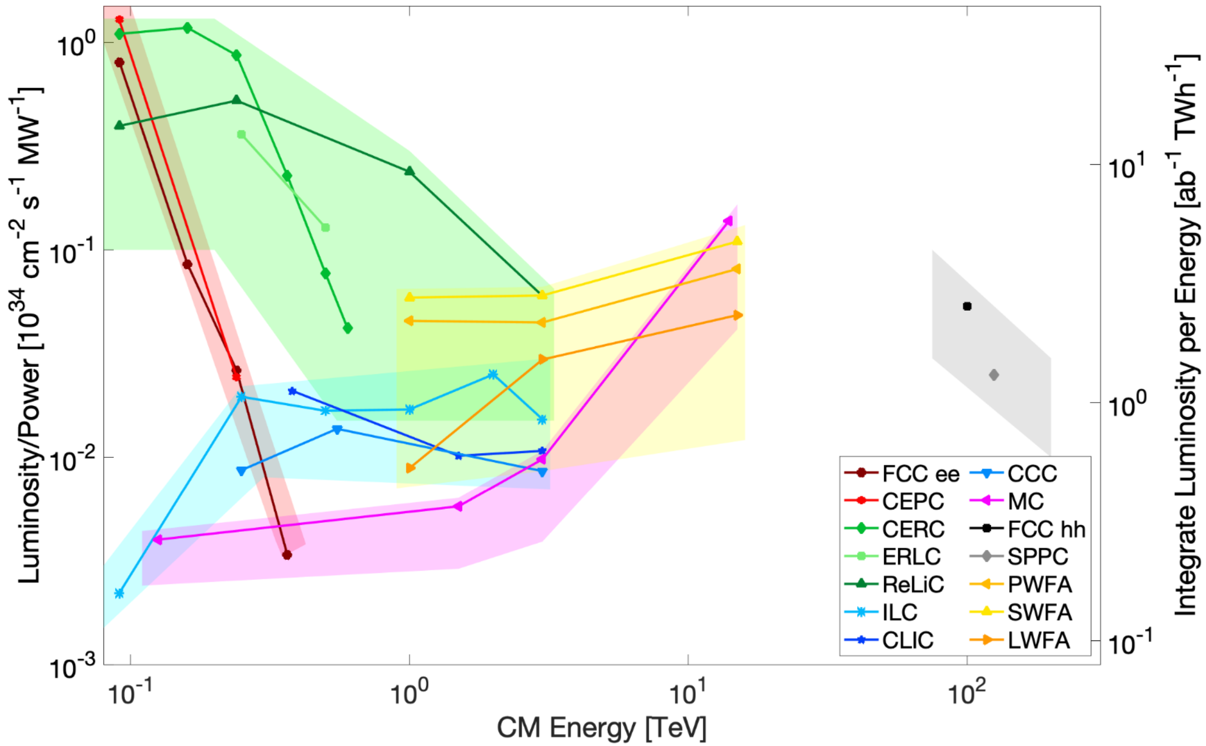
Table 1: Main parameters of the submitted Higgs factory proposals. The cost range is for the single listed energy. The superscripts next to the name of the proposal in the first column indicate (1) Facility is optimized for 2 IPs. Total peak luminosity for multiple IPs is given in parenthesis; (2) Energy 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

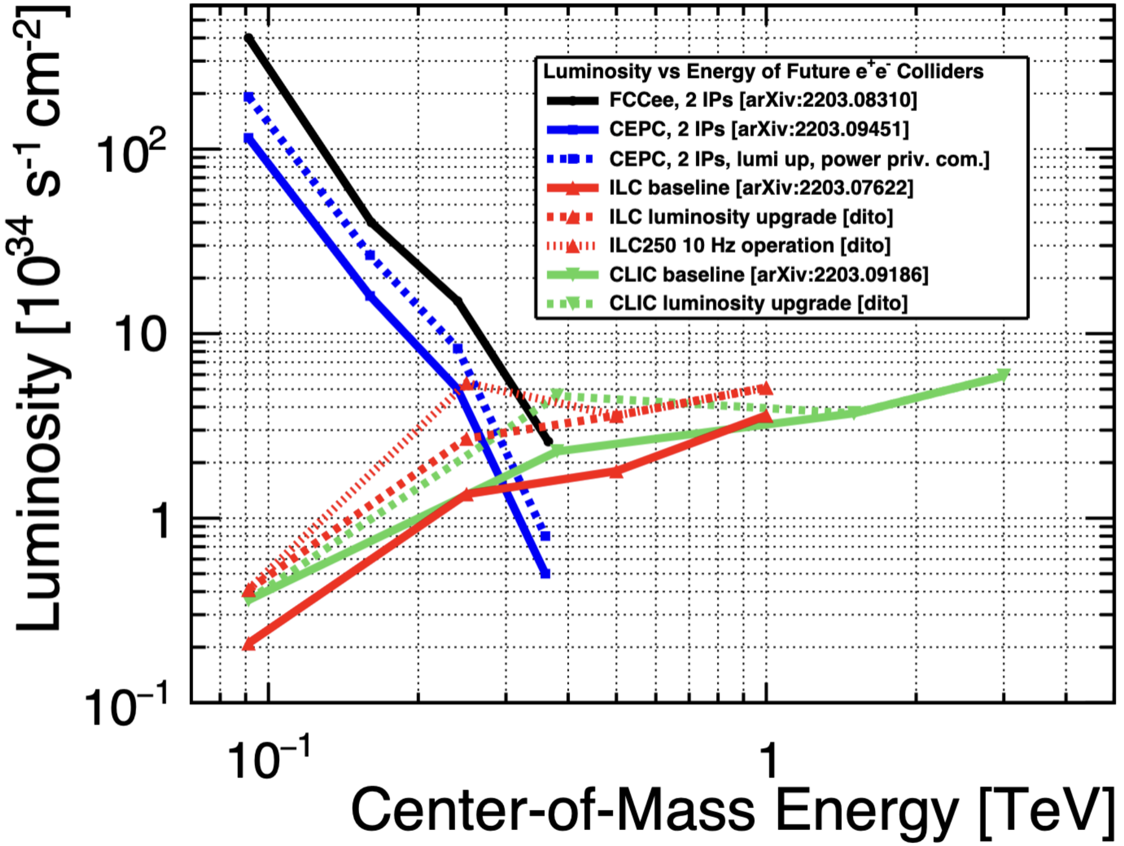


Abstract

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.

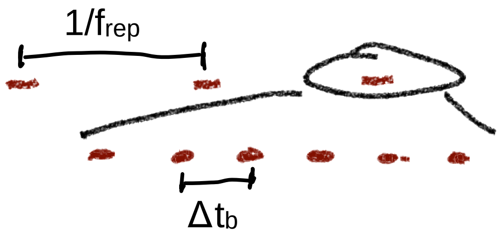
Luminosities





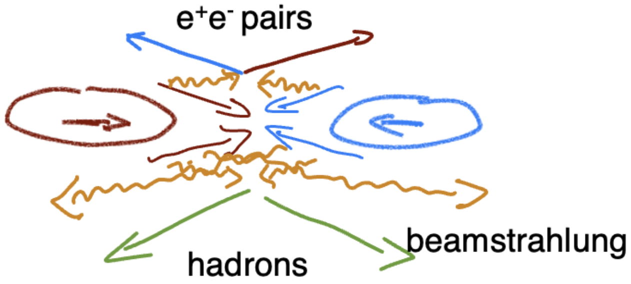
Per IP, from Snowmass

Detector interfaces



Bunches inside trains

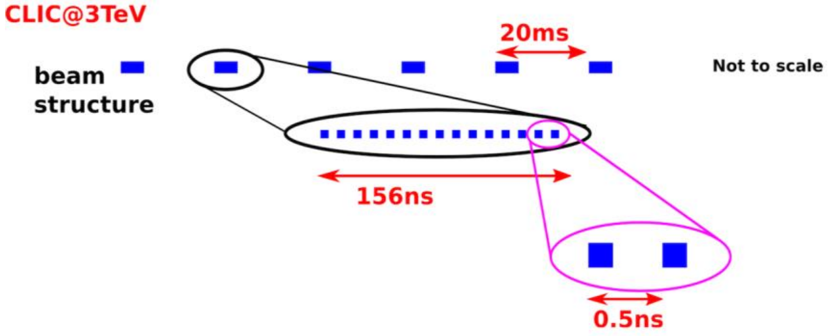
- at CLIC: Δt_b = 0.5 ns; f_{rep} = 50 Hz
- at ILC: Δt_b = 554 ns; f_{rep} = 5 -10 Hz



High *E*-fields of collisions bunch trains –> Beamstrahlung (flat beams)
Significant rates of beam-induced backgrounds in detector
(incoherent e+e- pairs, gg->hadrons)

Constrains layout, granularity, impacts physics

- In-time pile-up of hadronic background: **need sufficient granularity for topological rejection**
- At CLIC: small Δt_b also results in out-of-time pile-up: **ns-level timing** in many detector systems



CLIC bunch structure and consequences:

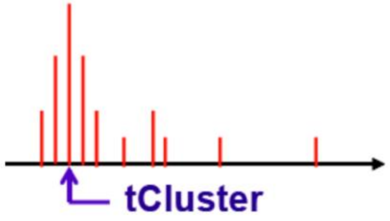
- CLIC: short luminous time (<200ns) & long gap between trains (20ms)
- Record data during collision times, read data out between trains
- Triggerless readout: all data are recorded

- When data is not being read out, switch off the detector –> power-pulsing concept developed for CLIC vertex detector (also done for ILC of course, easier)

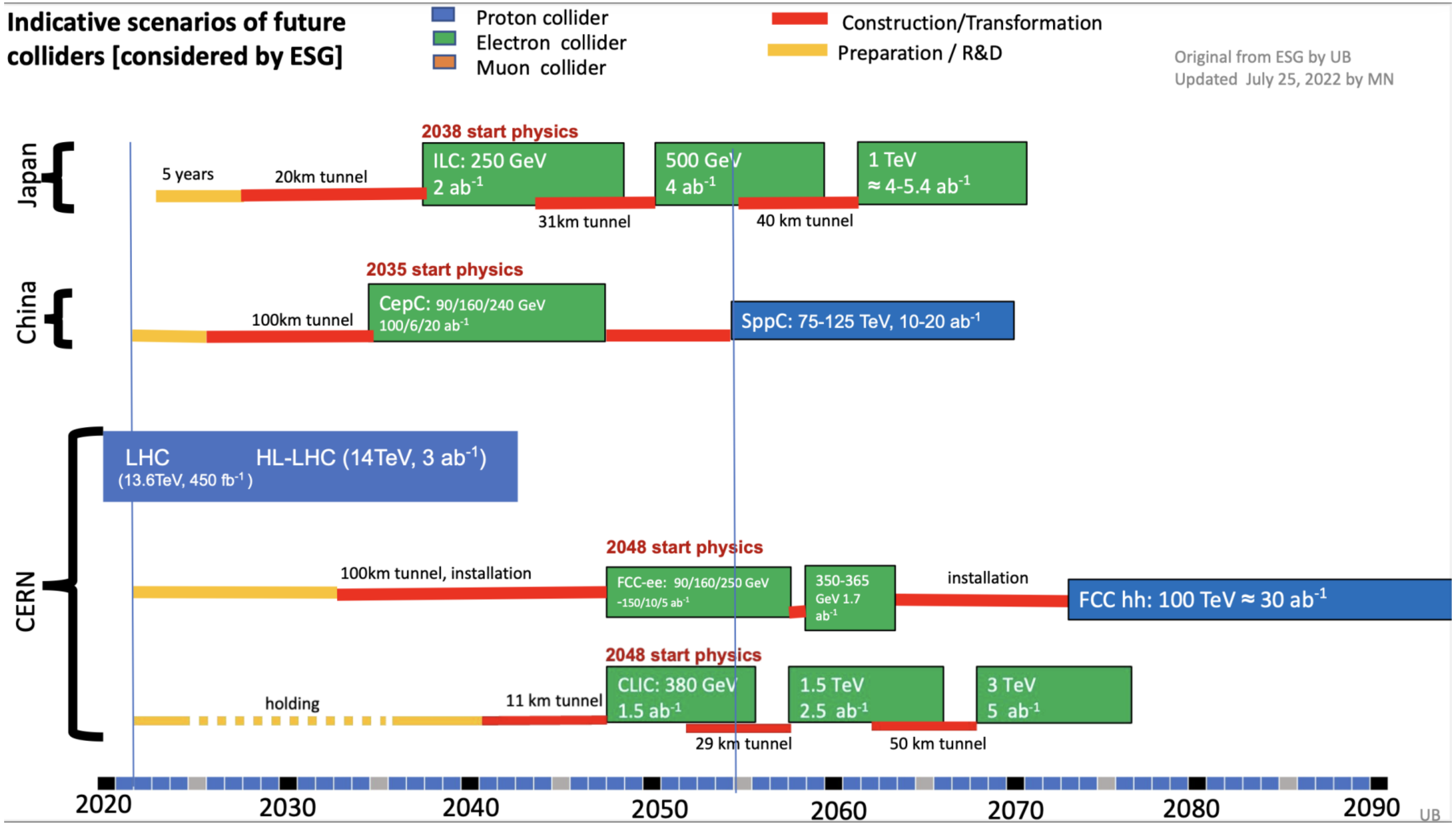
(Detector Technologies for CLIC: https://arxiv.org/abs/1905.02520)

- Read out full bunch train and identify time of physics event
- Select hits around the event using the time resolution of the sub-detectors
- Time-stamping: few ns @ 3 TeV CLIC (~1-10 μs @ ILC)

–> Fast detector signals / frontend



Timelines in Snowmass Energy Frontier summary



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
- A clear wish to develop options for future US sited EF colliders
- From Meenakshi Narain EF summary Snowmass

Cost

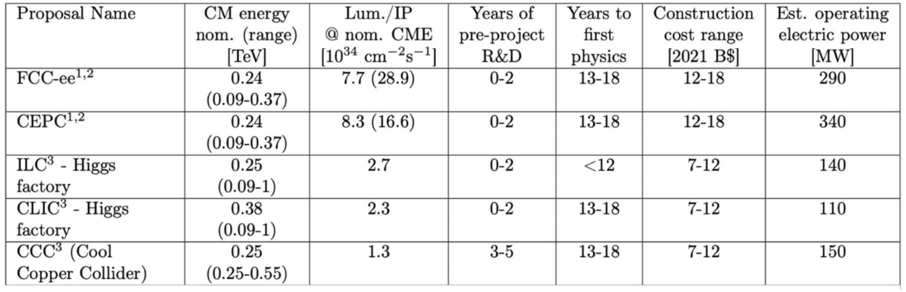
ESPP 2019:

- CLIC 380 (~6 BCHF) and 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 ..)

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)



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

Personnel estimate and cost – Higgs factories

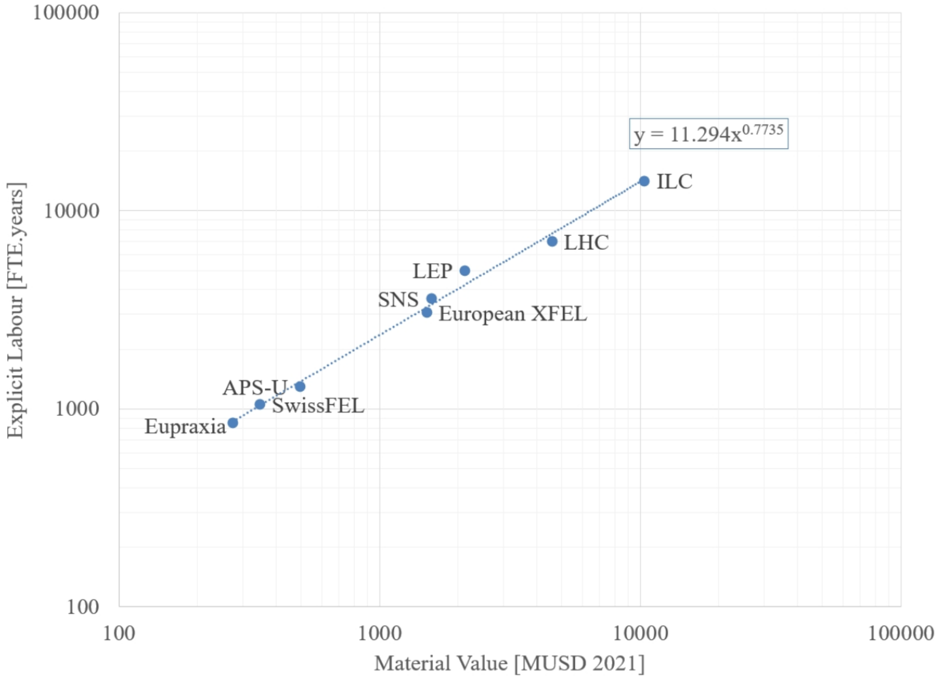


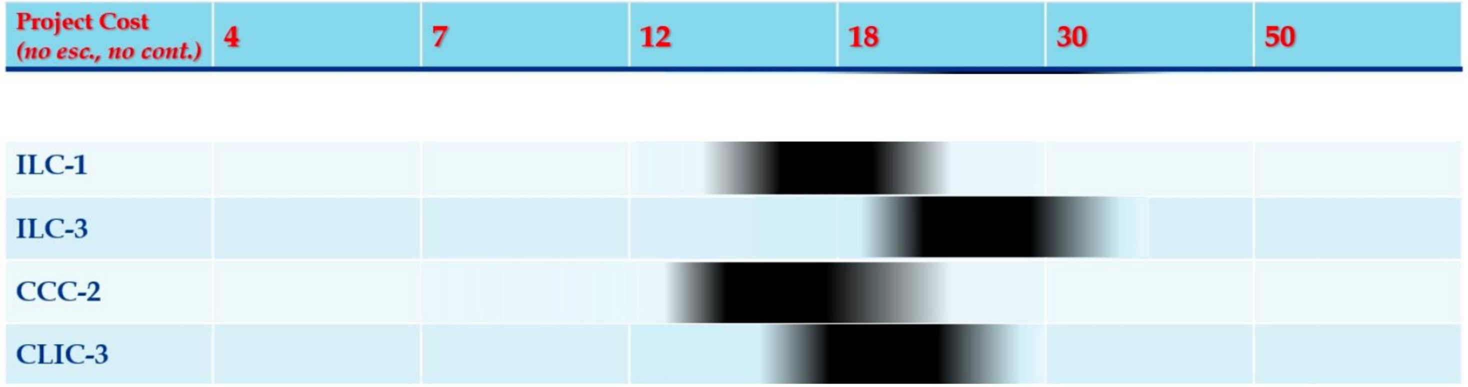
Figure 5: Explicit labor for several large accelerator projects vs. project value.

One FTEy estimated to 200kUS$

Good agreement between “bottom up” and Snowmass methodology

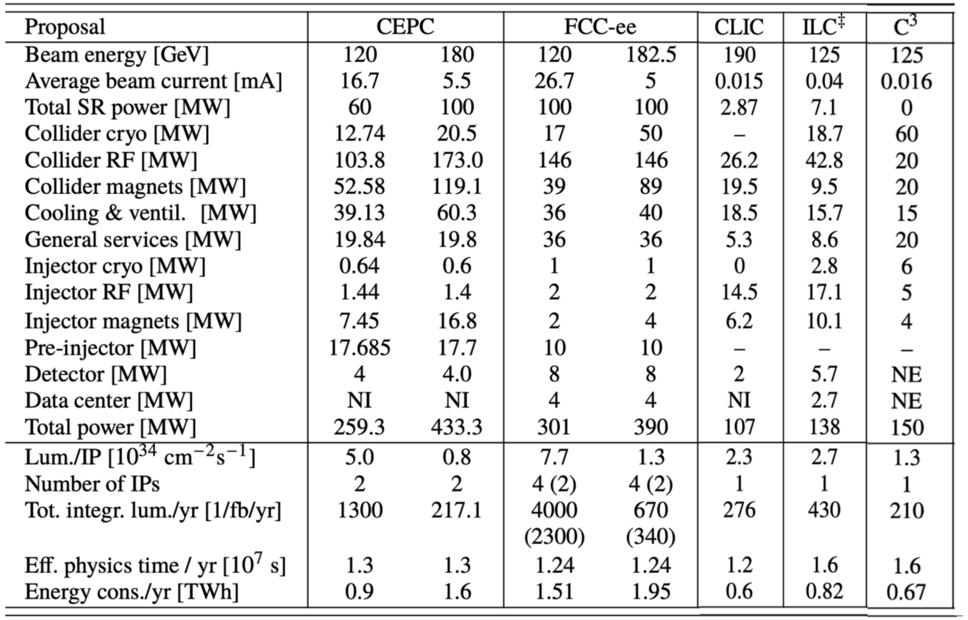
Figure 8: The ITF cost model for the EW/Higgs factory proposals. Horizontal scale is approximately logarithmic for the project total cost in 2021 B$ without contingency and escalation. Black horizontal bars with smeared ends indicate the cost estimate range for each machine.

Higher energy projects – and costs

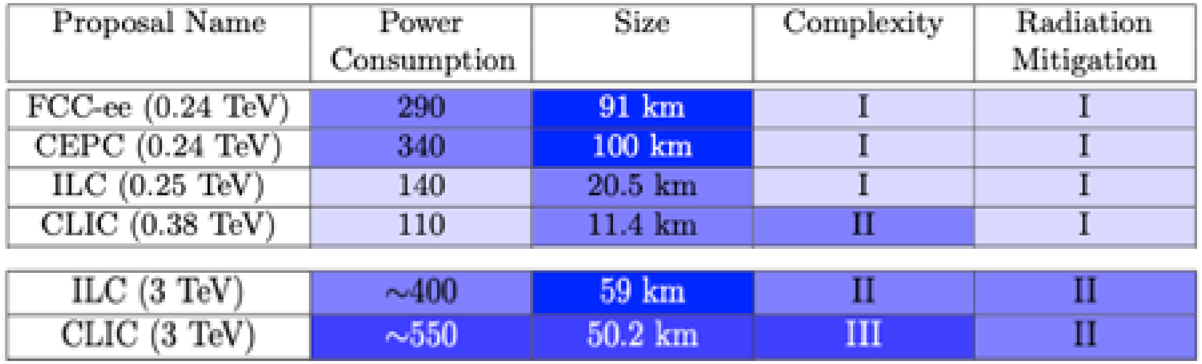


Project Cost *(no esc., no cont.)*	4	7	12	18	30	50
ILC-1			■	■		
ILC-3				■	■	
CCC-2			■	■		
CLIC-3			■	■		

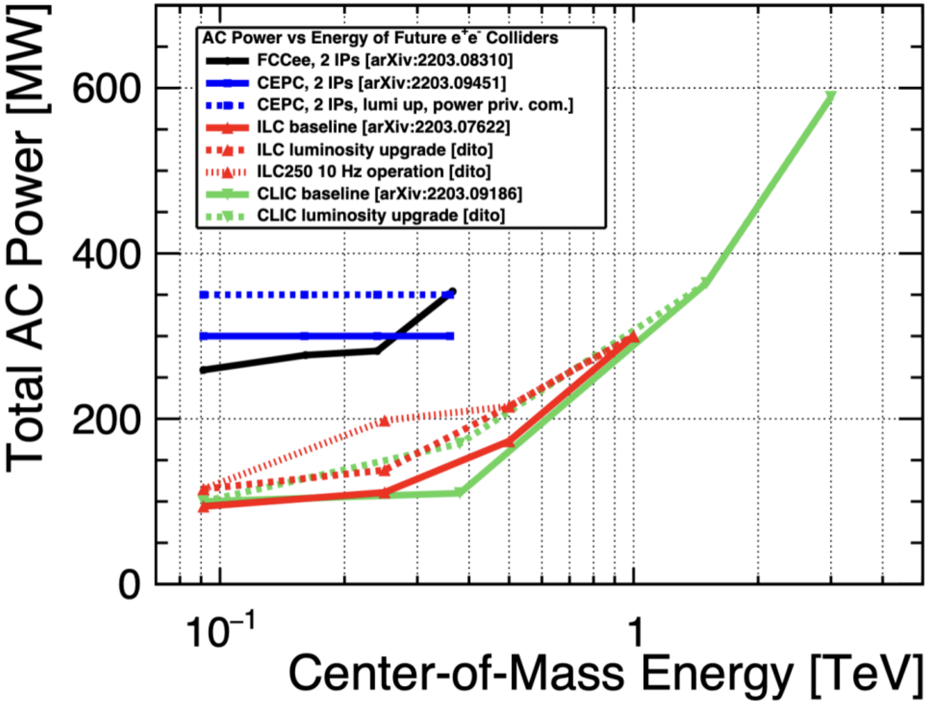
Power and energy



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



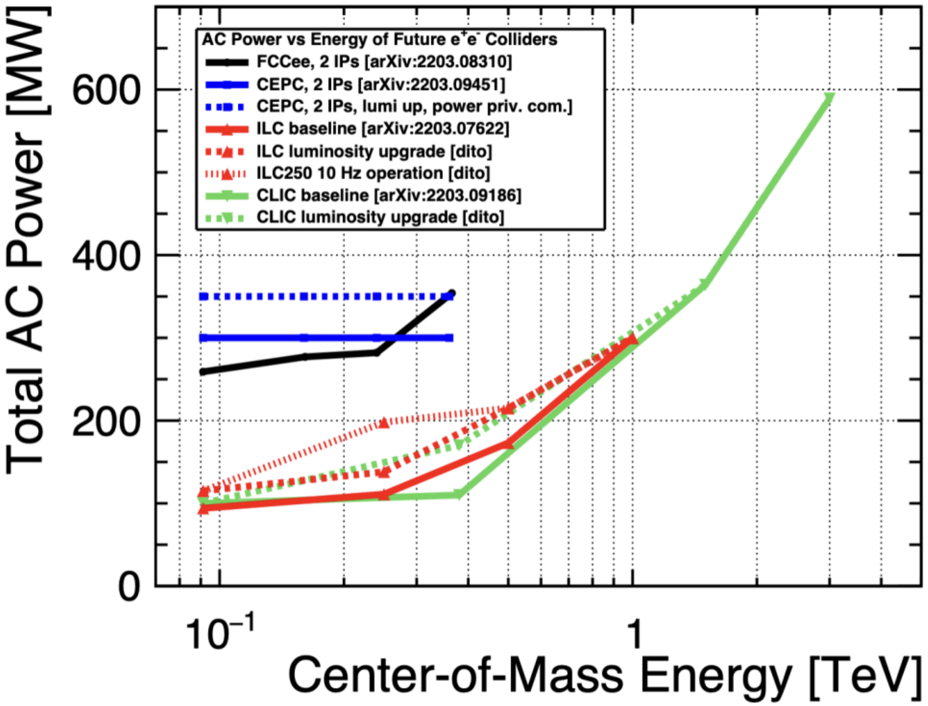
Proposal Name	Power Consumption	Size	Complexity	Radiation Mitigation
FCC-ee (0.24 TeV)	290	91 km	I	I
CEPC (0.24 TeV)	340	100 km	I	I
ILC (0.25 TeV)	140	20.5 km	I	I
CLIC (0.38 TeV)	110	11.4 km	II	I
ILC (3 TeV)	~400	59 km	II	II
CLIC (3 TeV)	~550	50.2 km	III	II



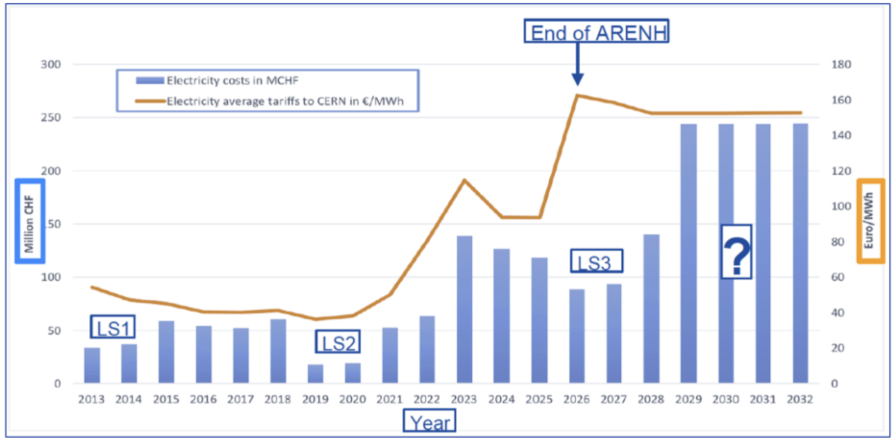
Power and energy

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.

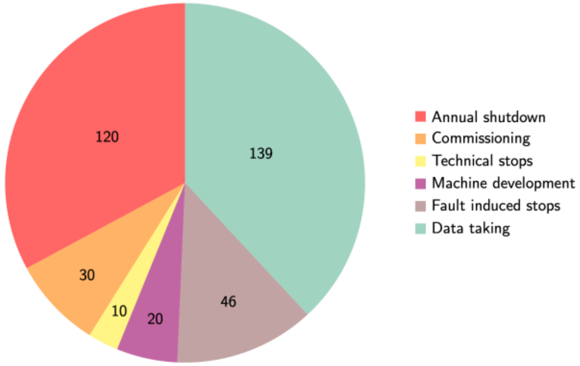


Extrapolating out to 2032 assuming: No ARENH and ”high” future electricity prices



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.



Power optimization – examples

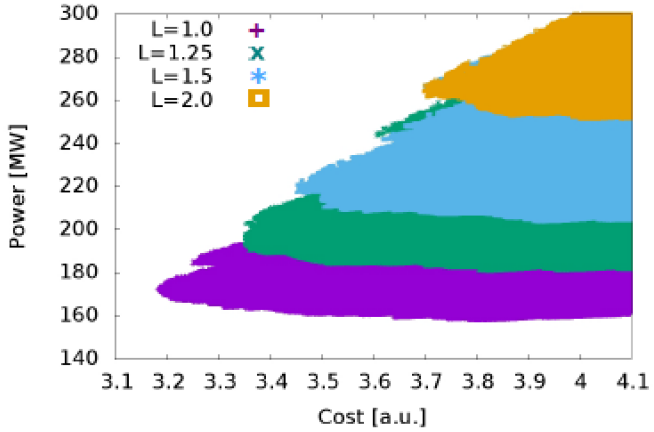
Design Optimisation:
All projects aim to optimize – most often energy reach, luminosities and cost. Power is becoming at least as important, maybe even compromising ultimate performance for power saving.

Technical Developments:
Technical developments targeting reduced power consumptions at system level high efficiency klystrons and RF systems generally, RF cavity design and optimisation, magnets (traditional SC and HTS including cryo, and also permanents magnets).

Heat recovery:

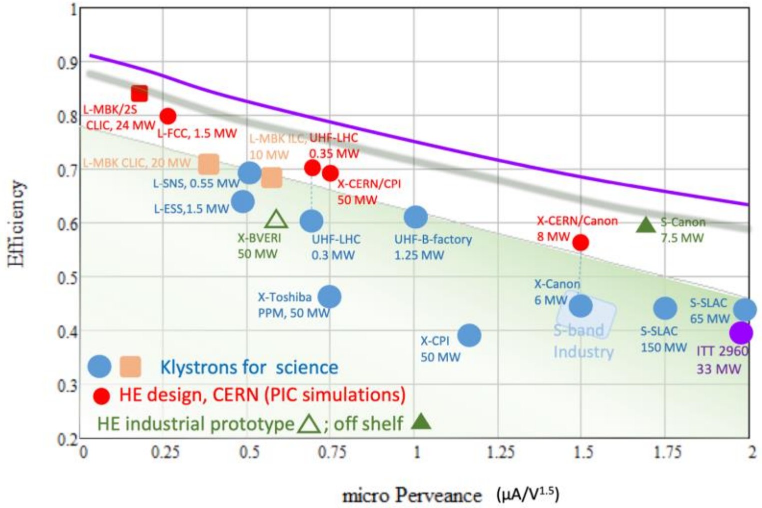
Already implemented in point 8 for LHC

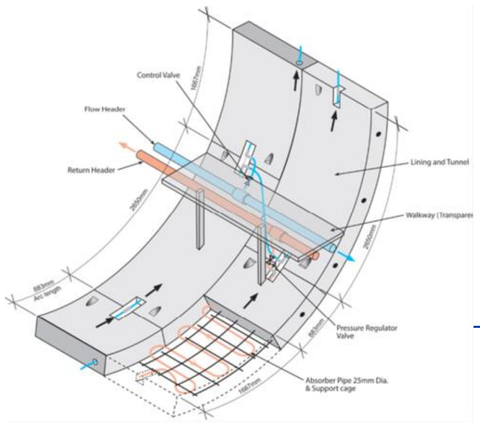
Tunnel heat recovery study by ARUP in 2022, results interesting but …

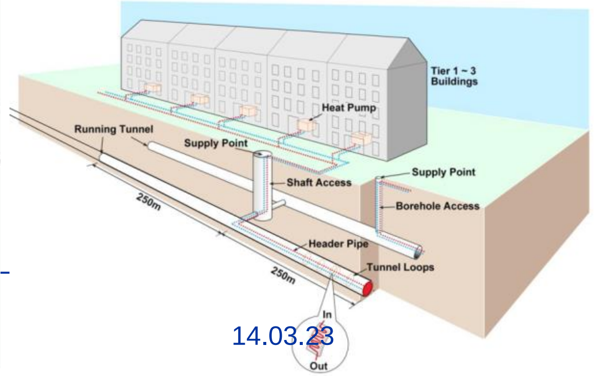


Parameter scans to find optimal parameter set, change acc. structure designs and gradients to find an optimum

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







Running on renewables and when electricity is cheap

Two studies in 2017:

- Supply the annual electricity demand of the CLIC-380 by installing local wind and PV generators (this could be e.g. achieved by 330 MW-peak PV and 220 MW-peak wind generators) at a cost of slightly more than 10% of the CLIC 380 GeV cost.
  - Study done for 200 MW, in reality only ~110 MW are needed
- Self-sufficiency during all times can not be reached but 54% of the time CLIC could run independently from public electricity supply with the portfolio simulated.

- Can one run an accelerator as CLIC in a mode where one turn “on” and “off” depending prices (fluctuating with weather, demand, availability etc) ?
- Specify transition times (relatively fast for a LC) and the annual luminosity goal
- Significant savings – but the largest saving is the obvious one, not running in the winter.
- Flexibility to adjust the power demand is expected to become increasingly important and in demand by energy companies.

More information (link)

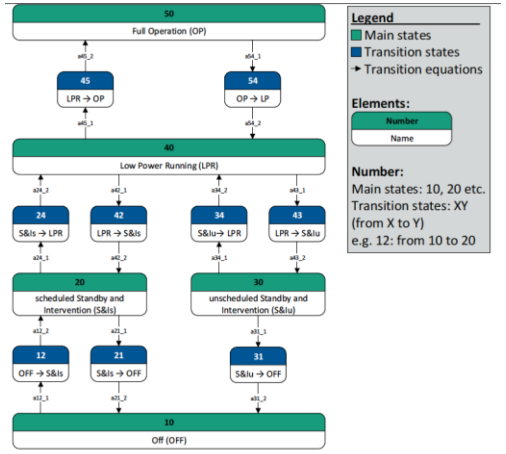
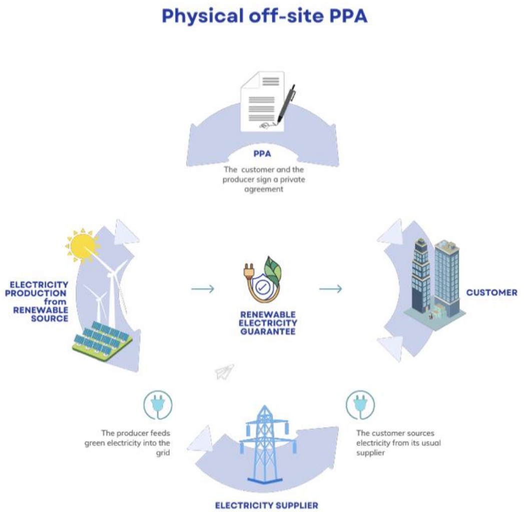


Figure 1-1: Schematic representation of the finite state machine



A real implementation of renewable energy supply:

A physical power purchase agreement (PPA) is a long-term contract for the supply of electricity at a defined, fixed price at the start and then indexed every year, negotiated between a producer of renewable electricity and a consumer for a defined period (generally 15 to 20 years).
Being considered for CERN, initially at limited scale.
Advantages: price, price stability, green, renewable.

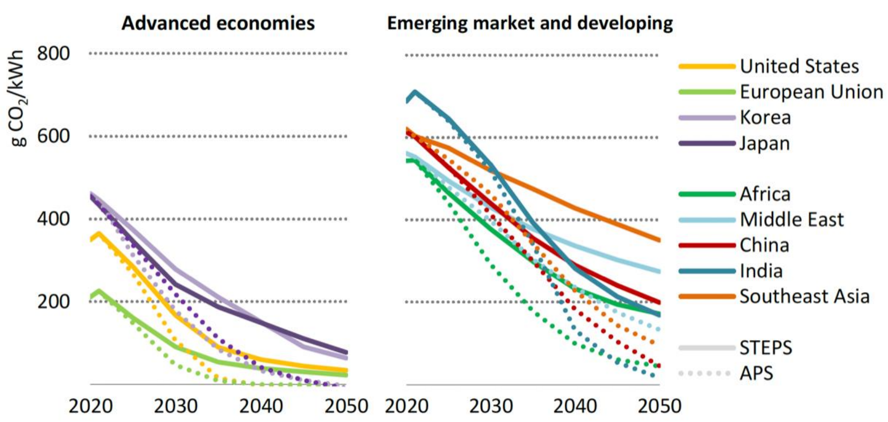
Nuclear energy remains very important, on the timescale of a future CERN facility maybe also: SMEs

Must be a goal to run future accelerator at CERN primarily on green and more renewable energy with very low carbon footprint. However, energy costs will remain a concern (two slides back).

Sustainability during operation – proactivity

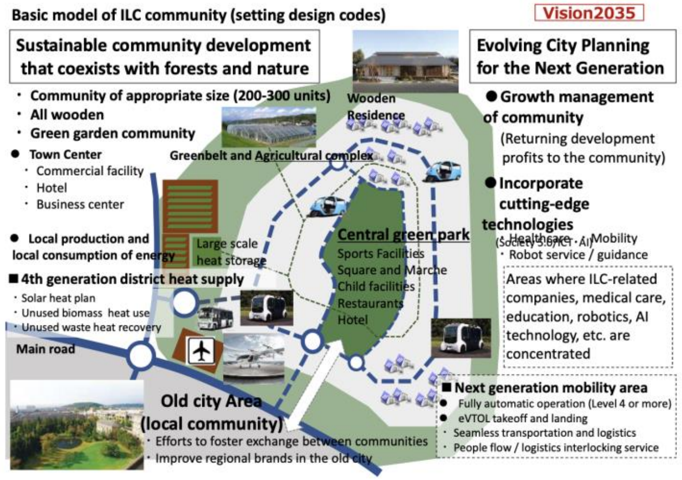
- Operation costs dominated by energy (and personnel, not discussed in the following)
- Reducing power use, and costs of power, will be crucial. Other consumables (gas, liquids, travels …) during operation need to be well justified. Align to future energy markets, green and more renewables, make sure we can be flexible customer and deal with grid stability/quality. Previous slide.
- Carbon footprint related to energy source, relatively low already for CERN (helped by nuclear power), expected to become significantly lower towards 2050 when future accelerators are foreseen to become operational (in Europe, US and Japan). Provided we can run on green mixtures (PPA example at CERN, also built fully into the green ILC concept) we can also contractually chose green options. LCs are very suited for this (variable power load).

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



For ILC: renewable energy available (Tohoku Electric Power) in local grid at ~23% level, need 0.5-1 % for ILC. Additionally considers increased CO2 absorption to be fully neutral.

A rough estimate, assuming ~50% nuclear and ~50% renewables (as wind/sun/hydro):

1 TWh annually equals ~12.5 ktons CO2 equiv. annually

(note: this is factor four below the current French summer month average)

Sustainable Construction – Life Cycle Assessment

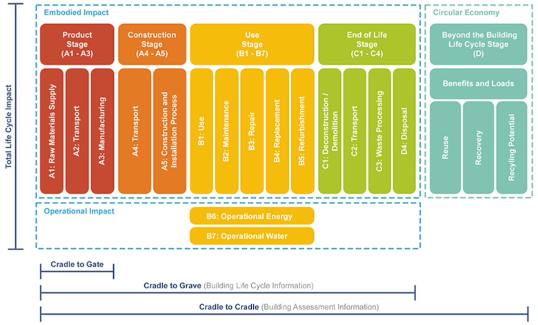
For carbon emission the construction impact will be much earlier and might be more significant (also rare earths and many other issues etc):

- Construction: CE, materials, processing and assembly – not easy to calculate
- Markets will push for reduced carbon, responsible purchasing crucial (see right) – construction costs likely to increase

Decommissioning – how do we estimate impacts ?

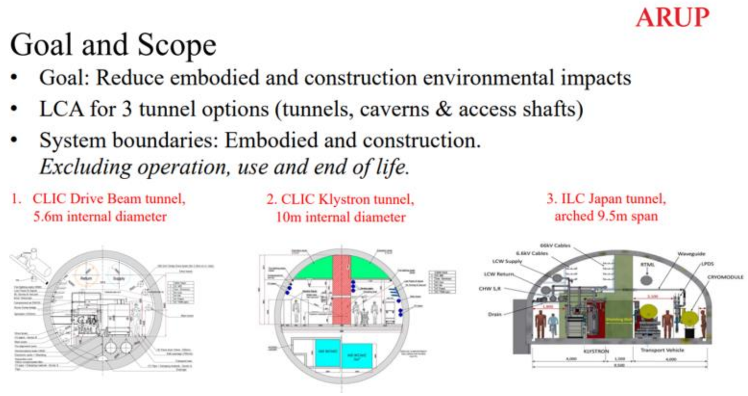
Responsible purchasing – and understanding the impact on our supply chain, costs and potential for changes – will be essentials for future projects (CERN implementation information from E.Cennini)

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**



Talk by B.List (link)

Carbon Cost/Life Cycle Assessment LCA study 2023

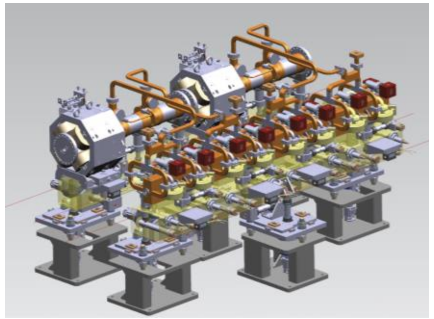


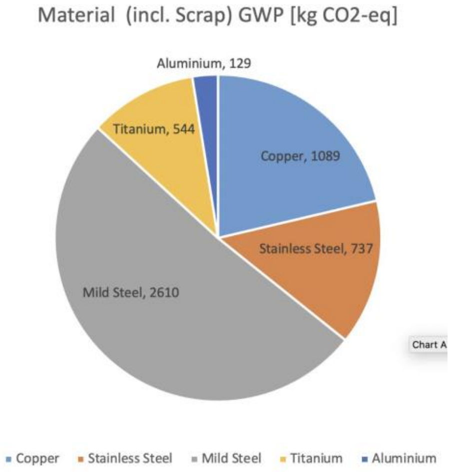
ARUP

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





Assume a small tunnel (~5.6m diameter) **and** that the equipment in the tunnel has the same carbon footprint as the tunnel itself, a 20km accelerator (tunnel plus components) corresponds to 240 kton CO2 equiv.

Many caveats, first of all this is a very first indication of the scale:

\+ many more components in tunnel (also infrastructure), injectors, shafts, detectors, construction work, spoils, etc etc

\+ upgrades and decommissioning, this is not only an initial important contribution

\- improvement and optimisations (e.g. less and/or better concrete mixes, support structures, less steel in tunnels, responsible purchasing, etc etc)

Summary

LCs as ILC and CLIC are mature options for a Higgs factory

Project risks:

- CE always a concern (tunnels however shorter than for LHC)
- Luminosity risk (nanobeams and sources) – many ways to mitigate

Flexibility with a LC:

- From initial Linear Collider: followed by energy increases and/or independent muon and/or hadron machines with radius and magnets to be determined. Can also overlap in time with the two latter.

User community:

- One of two main collider experiments
- ”Diversity programme” using injectors, single beams, “long range” effects, etc (ILCX workshop in 2021, much more to explore)

The LC “vision” is a balanced programme over the next 20-30 years for:

- a Higgs factory as soon as possible, upgradable
- R&D for the machine beyond, no constraints imposed by the LC
- a strong diversified programme using the LC complex and other small and large accelerators, or no accelerator

- and HL-LHC of course

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)
S.Michizono, B.List, M.Yoshioka
W.Wuensch, I.Syratchev, S.Calatroni
J.List, A.Robson
D.Schulte
E.Nanni
N.Bellegarde, E.Cennini
M.Narain
more

….

Collaborations

CLIC accelerator

- ~50 institutes from 28 countries*
- CLIC accelerator studies
- CLIC accelerator design and development
- Construction and operation of CLIC Test Facility, CTF3

CLIC detector and physics (CLICdp)

- 30 institutes from 18 countries
- Physics prospects & simulations studies
- Detector optimisation + R&D for CLIC

+ strong participation in the CALICE and FCAL Collaborations and in AIDA-2020/AIDAinnova

*Canada to be added

ILC organization

ICFA

ILC International Development Team

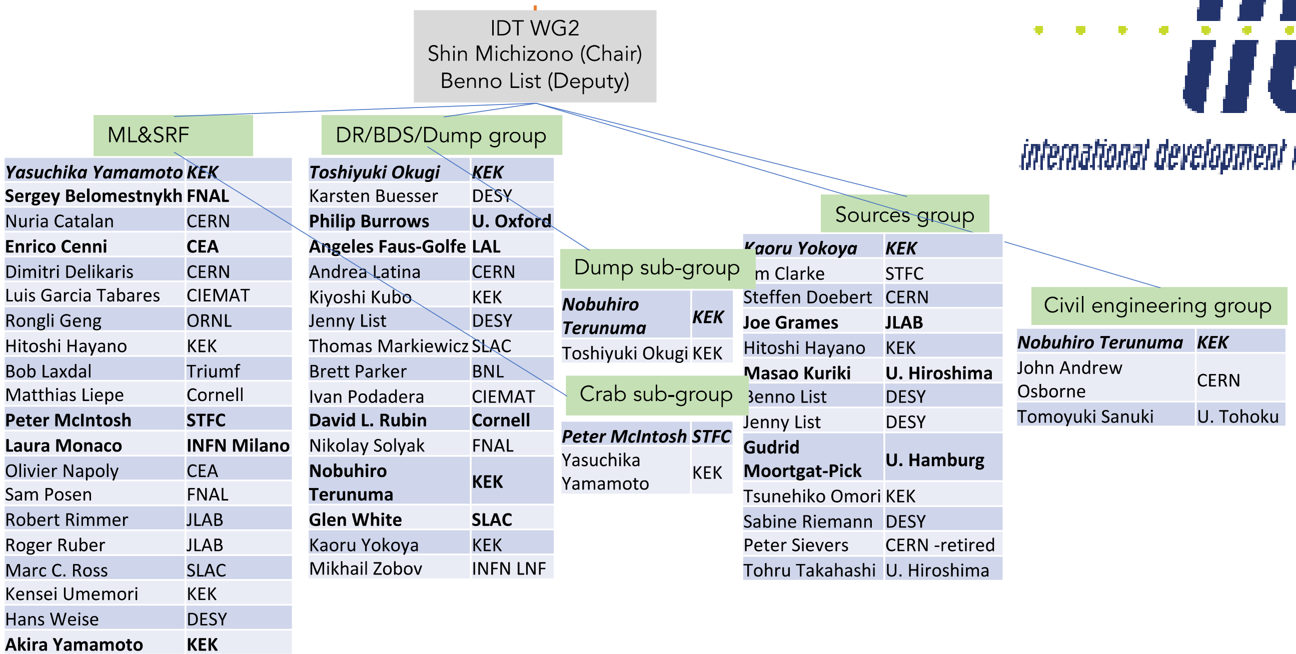
Executive Board

Americas Liaison Andrew Lankford (UC Irvine)
Working Group 2 Chair Shinichiro Michizono (KEK)
Working Group 3 Chair Jenny List (DESY)
Executive Board Chair and Working Group 1 Chair Tatsuya Nakada (EPFL)
KEK Liaison Yasuhiro Okada (KEK)
Europe Liaison Steinar Stapnes (CERN)
Asia-Pacific Liaison Geoffrey Taylor (U. Melbourne)

Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

Working Group 3
Physics & Detectors



IDT WG2
Shin Michizono (Chair)
Benno List (Deputy)

ML&SRF

Yasuchika Yamamoto	***KEK***
Sergey Belomestnykh	**FNAL**
Nuria Catalan	CERN
Enrico Cenni	**CEA**
Dimitri Delikaris	CERN
Luis Garcia Tabares	CIEMAT
Rongli Geng	ORNL
Hitoshi Hayano	KEK
Bob Laxdal	Triumf
Matthias Liepe	Cornell
Peter McIntosh	**STFC**
Laura Monaco	**INFN Milano**
Olivier Napoly	CEA
Sam Posen	FNAL
Robert Rimmer	JLAB
Roger Ruber	JLAB
Marc C. Ross	SLAC
Kensei Umemori	KEK
Hans Weise	DESY
Akira Yamamoto	**KEK**

DR/BDS/Dump group

Toshiyuki Okugi	***KEK***
Karsten Buesser	DESY
Philip Burrows	**U. Oxford**
Angeles Faus-Golfe	**LAL**
Andrea Latina	CERN
Kiyoshi Kubo	KEK
Jenny List	DESY
Thomas Markiewicz	SLAC
Brett Parker	BNL
Ivan Podadera	CIEMAT
David L. Rubin	**Cornell**
Nikolay Solyak	FNAL
Nobuhiro Terunuma	**KEK**
Glen White	**SLAC**
Kaoru Yokoya	KEK
Mikhail Zobov	INFN LNF

Dump sub-group

Nobuhiro Terunuma	***KEK***
Toshiyuki Okugi	KEK

Crab sub-group

Peter McIntosh	***STFC***
Yasuchika Yamamoto	KEK

Sources group

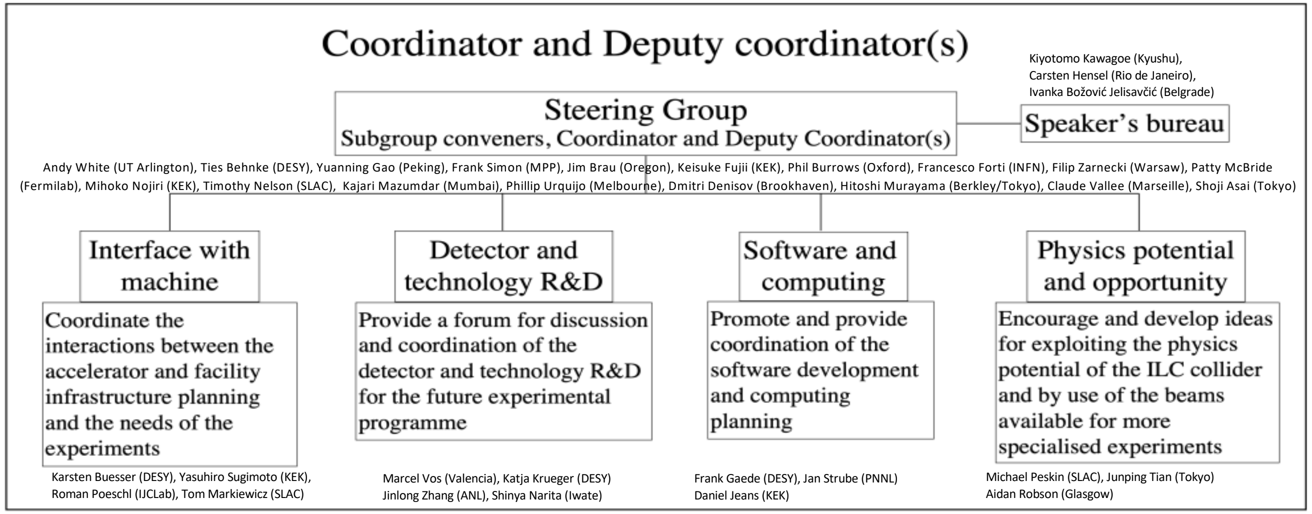
Kaoru Yokoya	***KEK***
m Clarke	STFC
Steffen Doebert	CERN
Joe Grames	**JLAB**
Hitoshi Hayano	KEK
Masao Kuriki	**U. Hiroshima**
Benno List	DESY
Jenny List	DESY
Gudrid Moortgat-Pick	**U. Hamburg**
Tsunehiko Omori	KEK
Sabine Riemann	DESY
Peter Sievers	CERN -retired
Tohru Takahashi	U. Hiroshima

Civil engineering group

Nobuhiro Terunuma	***KEK***
John Andrew Osborne	CERN
Tomoyuki Sanuki	U. Tohoku

WG3 Organisation and mandates

Chair: Jenny List (DESY/CERN) with Deputies: Roman Pöschl (IJCLab), Michael Peskin (SLAC), Daniel Jeans (KEK), Jinlong Zhang (ANL)



Coordinator and Deputy coordinator(s)

Steering Group
Subgroup conveners, Coordinator and Deputy Coordinator(s)

Andy White (UT Arlington), Ties Behnke (DESY), Yuanning Gao (Peking), Frank Simon (MPP), Jim Brau (Oregon), Keisuke Fujii (KEK), Phil Burrows (Oxford), Francesco Forti (INFN), Filip Zarnecki (Warsaw), Patty McBride (Fermilab), Mihoko Nojiri (KEK), Timothy Nelson (SLAC), Kajari Mazumdar (Mumbai), Phillip Urquijo (Melbourne), Dmitri Denisov (Brookhaven), Hitoshi Murayama (Berkley/Tokyo), Claude Vallee (Marseille), Shoji Asai (Tokyo)

Speaker's bureau

Kiyotomo Kawagoe (Kyushu),
Carsten Hensel (Rio de Janeiro),
Ivanka Božović Jelisavčić (Belgrade)

Interface with machine

Coordinate the interactions between the accelerator and facility infrastructure planning and the needs of the experiments

Karsten Buesser (DESY), Yasuhiro Sugimoto (KEK),
Roman Poeschl (IJCLab), Tom Markiewicz (SLAC)

Detector and technology R&D

Provide a forum for discussion and coordination of the detector and technology R&D for the future experimental programme

Marcel Vos (Valencia), Katja Krueger (DESY)
Jinlong Zhang (ANL), Shinya Narita (Iwate)

Software and computing

Promote and provide coordination of the software development and computing planning

Frank Gaede (DESY), Jan Strube (PNNL)
Daniel Jeans (KEK)

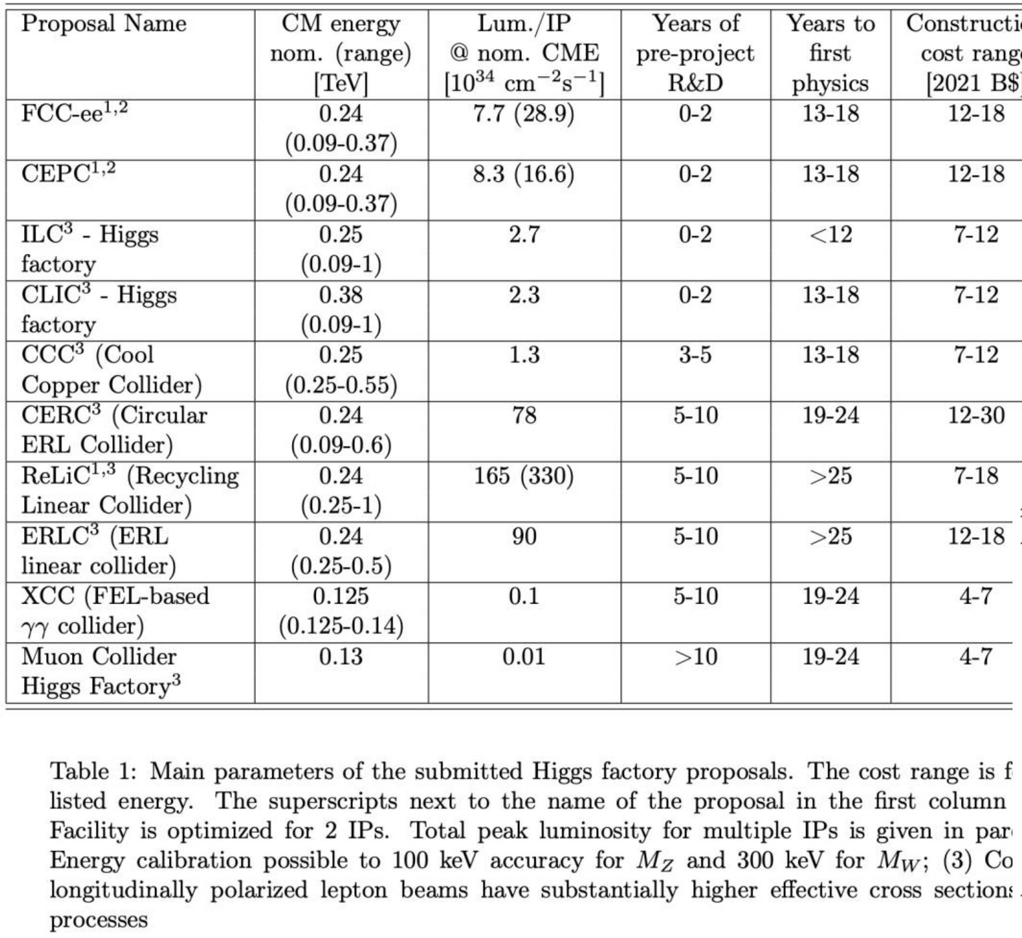
Physics potential and opportunity

Encourage and develop ideas for exploiting the physics potential of the ILC collider and by use of the beams available for more specialised experiments

Michael Peskin (SLAC), Junping Tian (Tokyo)
Aidan Robson (Glasgow)

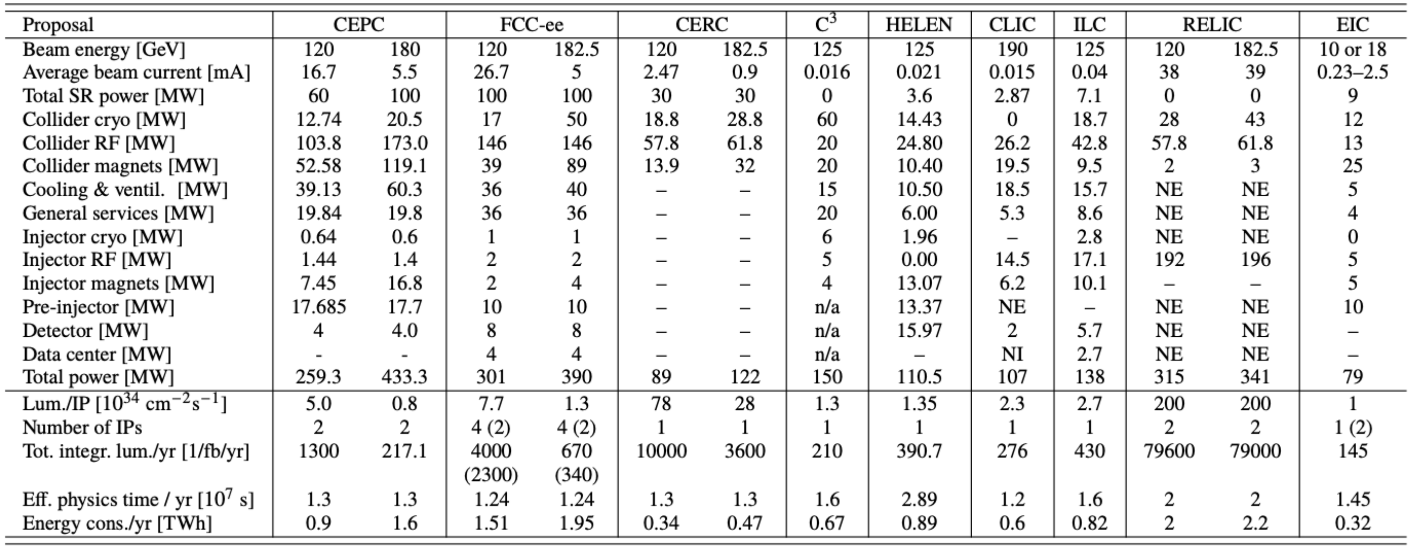
home.cern

Higgs factories



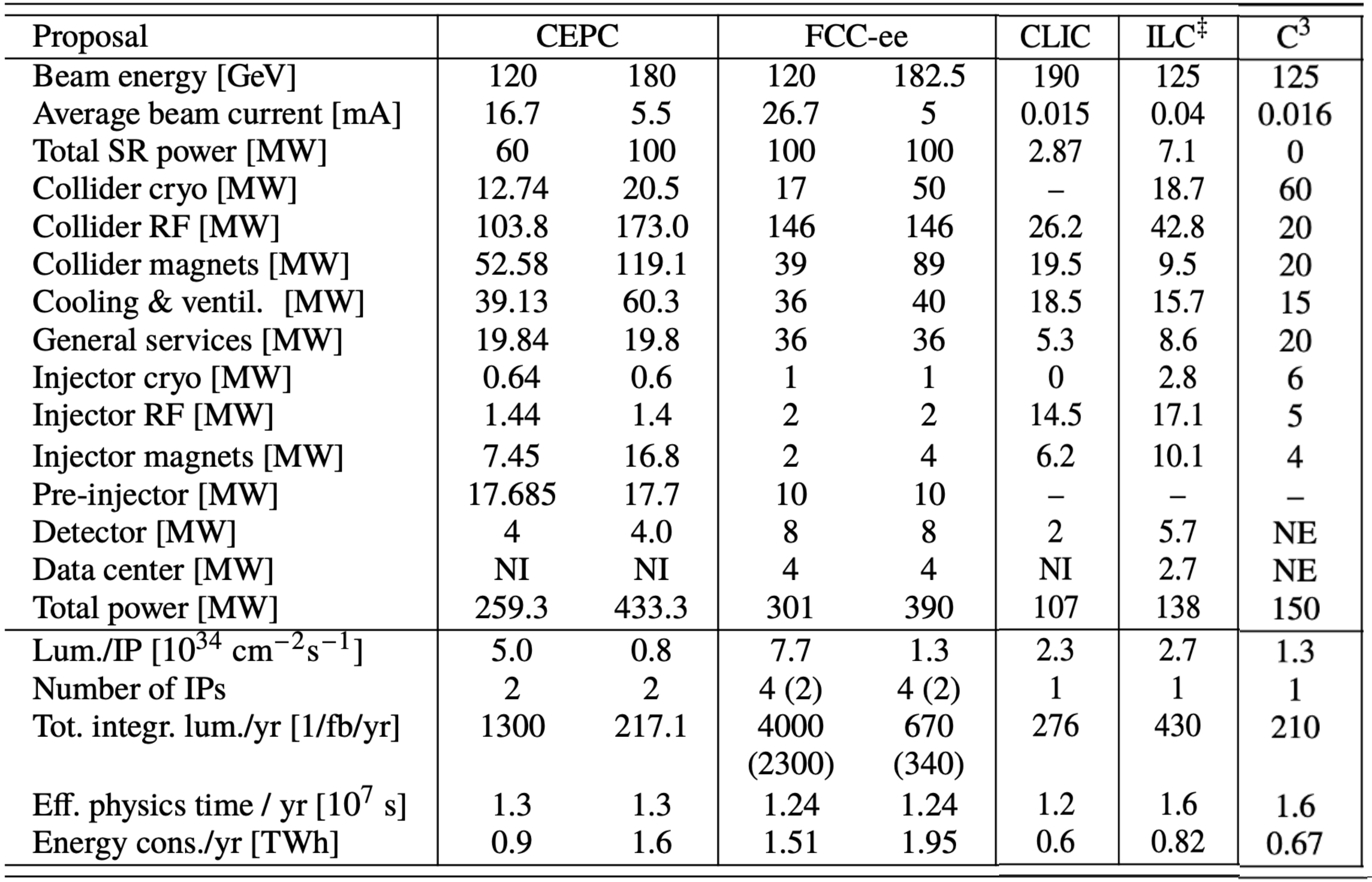
Proposal Name	CM energy nom. (range) [TeV]	Lum./IP @ nom. CME [10^{34} cm^{-2}s^{-1}]	Years of pre-project R&D	Years to first physics	Construction cost range [2021 B$]	Est. operating electric power [MW]
FCC-ee^{1,2}	0.24 (0.09-0.37)	7.7 (28.9)	0-2	13-18	12-18	290
CEPC^{1,2}	0.24 (0.09-0.37)	8.3 (16.6)	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
CERC^{3} (Circular ERL Collider)	0.24 (0.09-0.6)	78	5-10	19-24	12-30	90
ReLiC^{1,3} (Recycling Linear Collider)	0.24 (0.25-1)	165 (330)	5-10	>25	7-18	315
ERLC^{3} (ERL linear collider)	0.24 (0.25-0.5)	90	5-10	>25	12-18	
XCC (FEL-based $\gamma\gamma$ collider)	0.125 (0.125-0.14)	0.1	5-10	19-24	4-7	
Muon Collider Higgs Factory^{3}	0.13	0.01	>10	19-24	4-7	

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



Proposal	CEPC		FCC-ee		CERC		C^3	HELEN	CLIC	ILC	RELIC		EIC
Beam energy [GeV]	120	180	120	182.5	120	182.5	125	125	190	125	120	182.5	10 or 18
Average beam current [mA]	16.7	5.5	26.7	5	2.47	0.9	0.016	0.021	0.015	0.04	38	39	0.23–2.5
Total SR power [MW]	60	100	100	100	30	30	0	3.6	2.87	7.1	0	0	9
Collider cryo [MW]	12.74	20.5	17	50	18.8	28.8	60	14.43	0	18.7	28	43	12
Collider RF [MW]	103.8	173.0	146	146	57.8	61.8	20	24.80	26.2	42.8	57.8	61.8	13
Collider magnets [MW]	52.58	119.1	39	89	13.9	32	20	10.40	19.5	9.5	2	3	25
Cooling & ventil. [MW]	39.13	60.3	36	40	–	–	15	10.50	18.5	15.7	NE	NE	5
General services [MW]	19.84	19.8	36	36	–	–	20	6.00	5.3	8.6	NE	NE	4
Injector cryo [MW]	0.64	0.6	1	1	–	–	6	1.96	–	2.8	NE	NE	0
Injector RF [MW]	1.44	1.4	2	2	–	–	5	0.00	14.5	17.1	192	196	5
Injector magnets [MW]	7.45	16.8	2	4	–	–	4	13.07	6.2	10.1	–	–	5
Pre-injector [MW]	17.685	17.7	10	10	–	–	n/a	13.37	NE	–	NE	NE	10
Detector [MW]	4	4.0	8	8	–	–	n/a	15.97	2	5.7	NE	NE	–
Data center [MW]	-	-	4	4	–	–	n/a	–	NI	2.7	NE	NE	–
Total power [MW]	259.3	433.3	301	390	89	122	150	110.5	107	138	315	341	79
Lum./IP [10^{34} cm^{-2}s^{-1}]	5.0	0.8	7.7	1.3	78	28	1.3	1.35	2.3	2.7	200	200	1
Number of IPs	2	2	4 (2)	4 (2)	1	1	1	1	1	1	2	2	1 (2)
Tot. integr. lum./yr [1/fb/yr]	1300	217.1	4000 (2300)	670 (340)	10000	3600	210	390.7	276	430	79600	79000	145
Eff. physics time / yr [10^7 s]	1.3	1.3	1.24	1.24	1.3	1.3	1.6	2.89	1.2	1.6	2	2	1.45
Energy cons./yr [TWh]	0.9	1.6	1.51	1.95	0.34	0.47	0.67	0.89	0.6	0.82	2	2.2	0.32

Power and energy



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