Linear colliders
@ CERN

Steinar Stapnes – CERN

Jan 30th - 2025

Outline

- LC general considerations
- CLIC - at CERN
- ILC - in Japan
- Using ILC technology for a LC at CERN
- Implementation studies on-going

LC general considerations - reminder

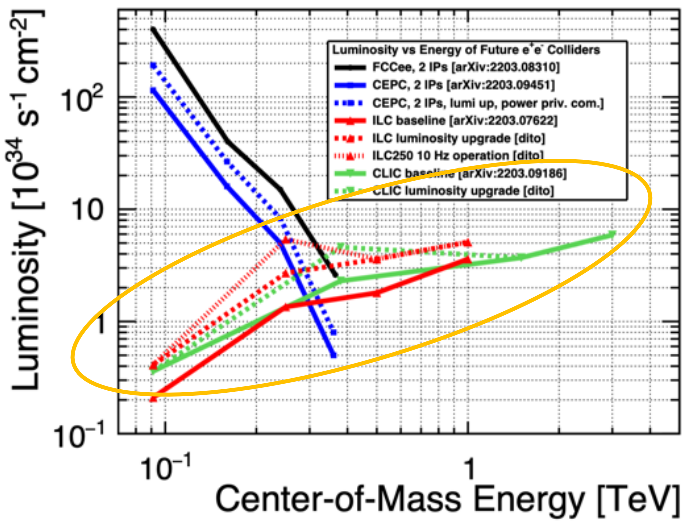
Increased luminosity with energy, e.g. 1-4 x 10^{34} $cm^{-2}s^{-1}$ for Higgs factories at 250-380 GeV, 6 x 10^{34} at 3 TeV.

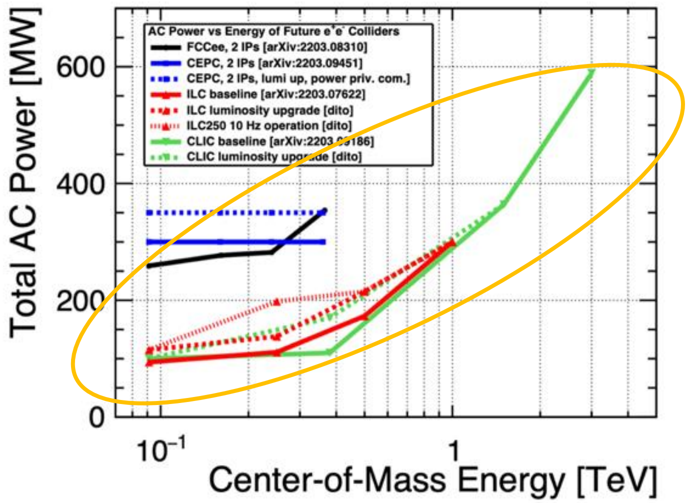
For a given energy, also higher luminosity with increased power, see more later.

Higher energies "natural" – 3 TeV studied (for CLIC), but many TeVs challenging:

- Power increases with energy and luminosity
- Reach up to 50km
- Higher energy means smaller beams and increasingly important beam-beam effects.

Start with mature technology, can expand in length and/or technology





General goals for LCs:

Energy reach and flexibility:

- Physics opportunities from Z-pole to 1-2 TeV (maybe more later on)
- One can choose – within limitations – cost, power versus E and L
- Allows to adapt to development in physics

Footprint, power and cost:

- Lower cost to get to Higgs and top than a circular machine
- Power similar to LHC, or lower, for initial configuration
- Footprint similar to LHC, CE cost risks therefore manageable

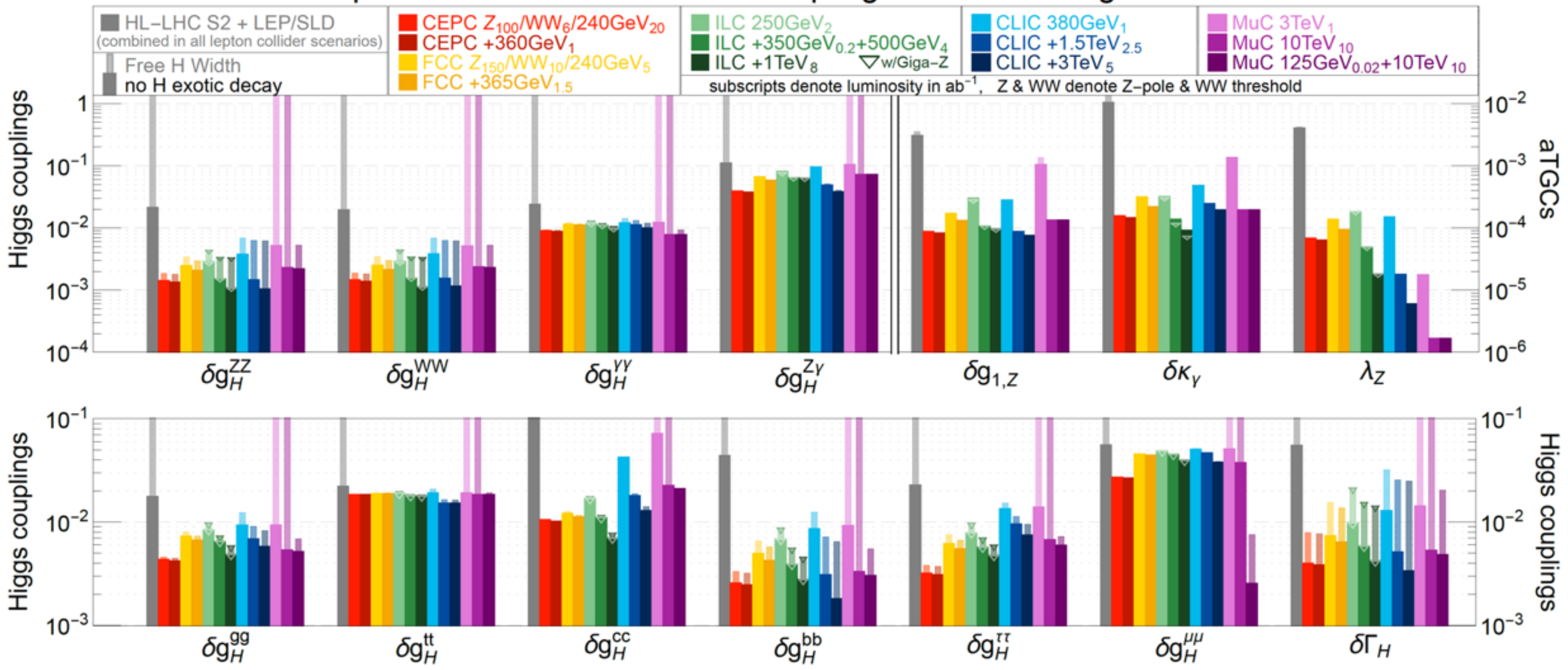
Provide many opportunities and increased flexibility for the future:

- Does not determine footprint of future energy frontier machines (hadrons and muon), and it has its own upgrade opportunities
- Encourage accelerator and detector R&D for all these options

LC physics opportunities - reminder

arXiv:2206.08326

precision reach on effective couplings from SMEFT global fit



e+e- colliders show very comparable performance for standard Higgs program, despite quite different assumed integrated luminosities => longitudinal beam polarization an important factor for LCs

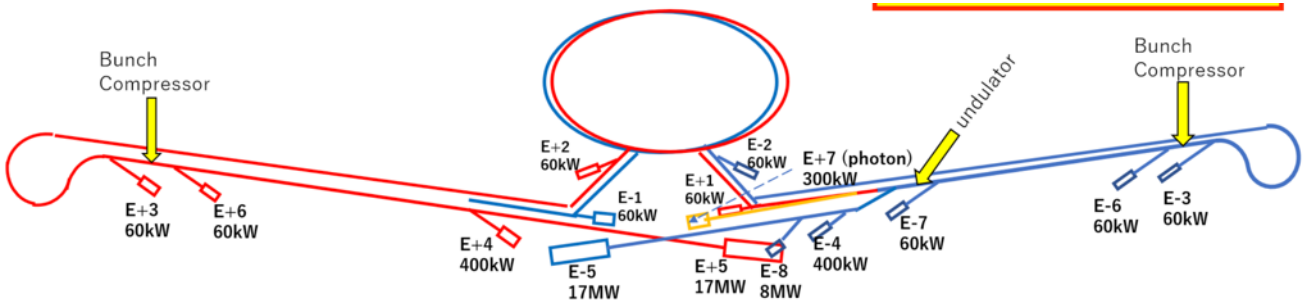
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

A physics-driven, polarised operating scenario for a Linear Collider

- **250 GeV, ~2ab-1:**
  - precision Higgs mass and total ZH cross-section
  - Higgs -> invisible (Dark Sector portal)
  - basic ffbar and WW program
  - optional: WW threshold scan
- **Z pole, few billion Z's: EWPOs 10-100x better than today**
- **350 GeV, 200 fb-1:**
  - precision top mass from threshold scan
- **500…600 GeV, 4 ab-1:**
  - Higgs self-coupling in ZHH
  - top quark ew couplings
  - top Yukawa coupling incl CP structure
  - improved Higgs, WW and ffbar
  - probe Higgsinos up to ~300 GeV
  - probe Heavy Neutral Leptons up to ~600 GeV
- **800…1000 GeV, 8 ab-1:**
  - Higgs self-coupling in VBF
  - further improvements in tt, ff, WW, ….
  - probe Higgsinos up to ~500 GeV
  - probe Heavy Neutral Leptons up to ~1000 GeV
  - searches, searches, searches, …

Beyond collider:

- ILCX – e.g. beam-dump experiments, dark sector physics, light dark matter, strong QED (ILCX workshop)
- Test and R&D beams for detector and accelerator studies



Longer paper being prepared for the ESPP update, serves any type of LC facility

From J.List/M.Peskin

Higgs Factory Detector Concepts

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
- **hermeticity** ($H \rightarrow$ invis, BSM) θ_{min} = 5 mrad
  (FCCee: ~50mrad)

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **calorimeters**
  - **highly granular,** optimised for particle flow
  - or dual readout, LAr, …

≈ CMS / 40

≈ CMS / 4

≈ ATLAS / 2

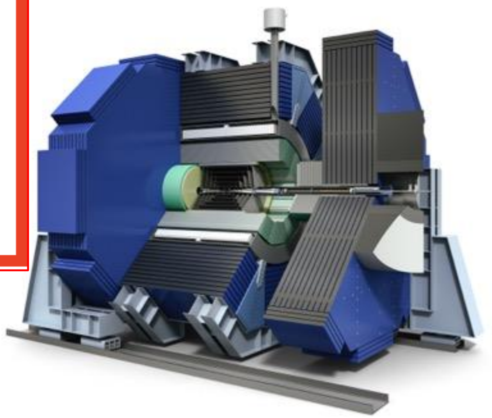
≈ ATLAS / 3

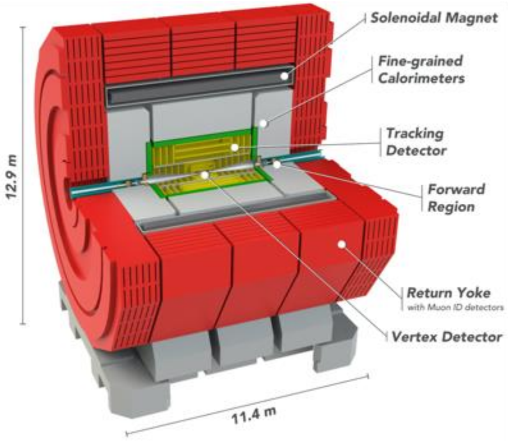
For LCs, bunches inside trains

- at ILC: Δt_b = 554 ns; f_{rep} = 5 -10 Hz
- at CLIC: Δt_b = 0.5 ns; f_{rep} = 50-100 Hz

The lower collision rate enables

- passive cooling only => low material budget
- triggerless operation

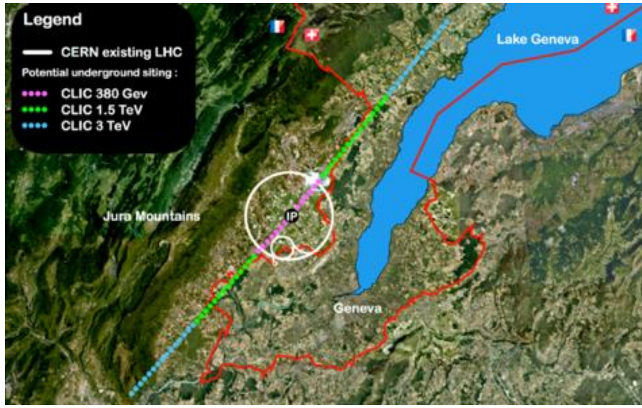


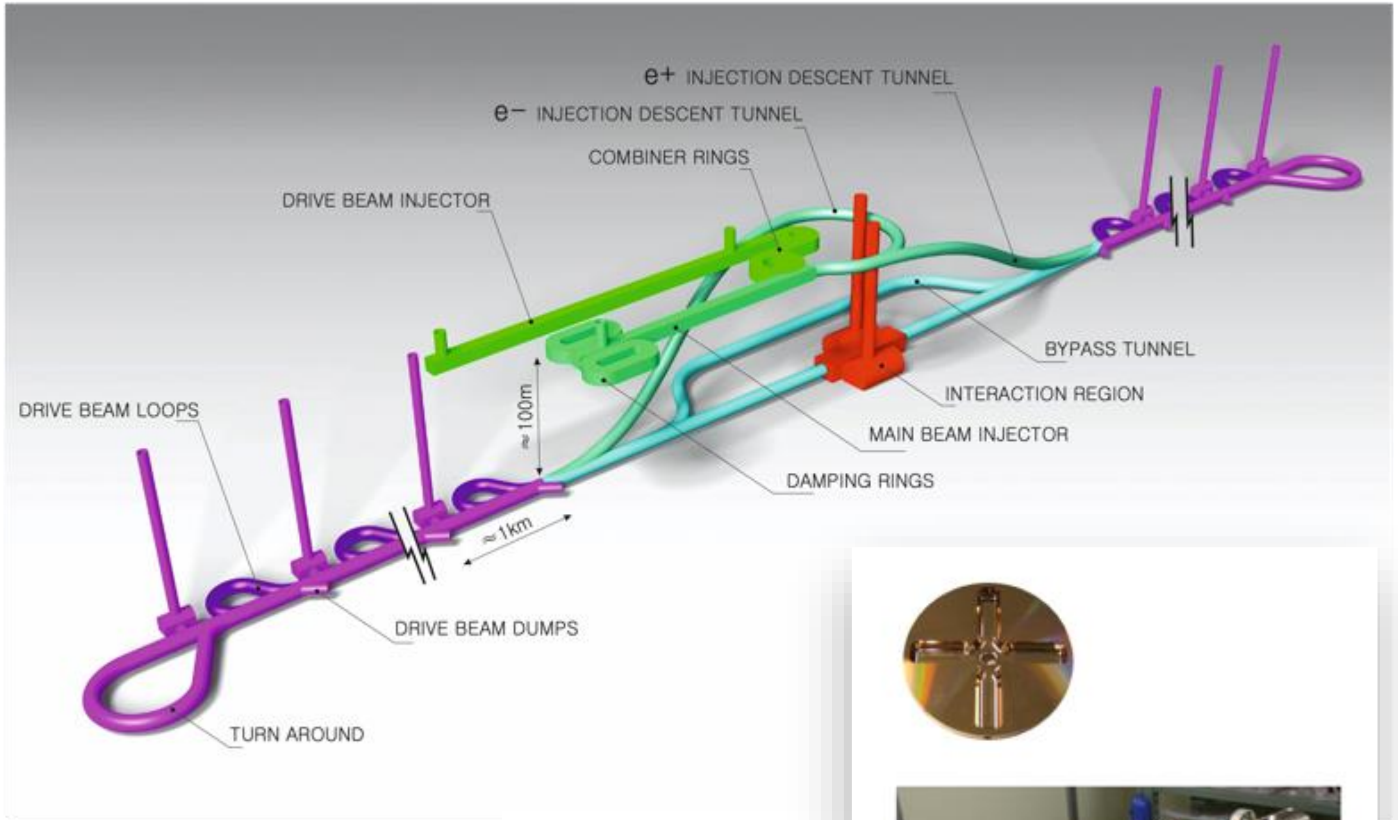


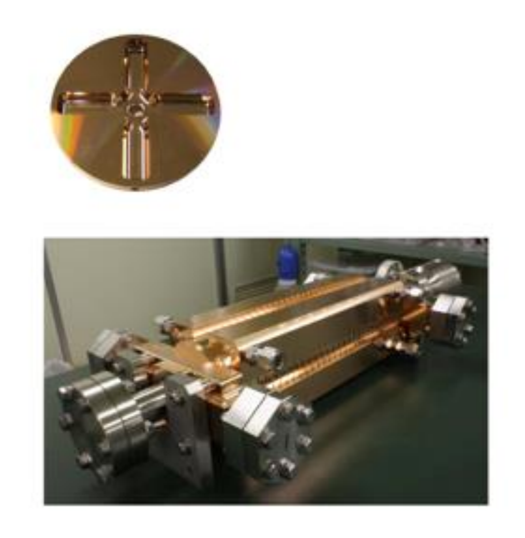
From J.List

CLIC at CERN

The Compact Linear Collider (CLIC)





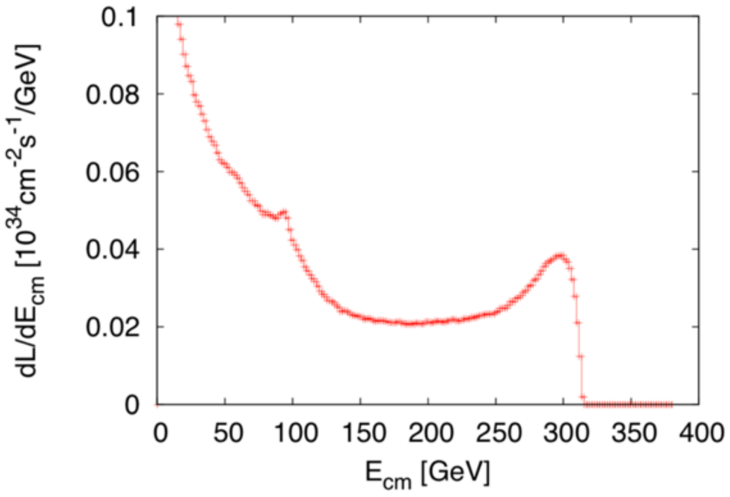


Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

- **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.
- **Project Implementation Plan in 2018** with focus on 380 GeV for Higgs and top.

Luminosities studies 2019-22, and continued

- 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 give 2.8 on average, and 90% of the machines above **2.3 x 10^{34} cm^{-2} s^{-1}**
  - A "perfect" machine will give : 4.3 x 10^{34} cm^{-2} s^{-1}
  - In addition: **doubling the frequency (50 Hz to 100 Hz) would double the luminosity**, at a cost of ~55% and ~5% power and cost increase
- Z pole performance, 2.3x10^{32} – 0.4x10^{34} cm^{-2} s^{-1}
  - The latter number when accelerator configured for Z running (e.g. early or end of first stage)
- Gamma – Gamma collision luminosity spectrum on the right (example with 190 GeV e-beams)



These numbers are already included (but 100 Hz only mentioned in passing, not in tables) in the Snowmass report 2021. See link of previous slides.


The CLIC project

O. Brunner, P. N. Burrows, S. Calatroni, N. Catalan Lasheras, R. Corsini, G. D'Auria, S. Doebert, A. Faus-Golfe, A. Grudiev, A. Latina, T. Lefevre, G. Mcmonagle, J. Osborne, Y. Papaphilippou, A. Robson, C. Rossi, R. Ruber, D. Schulte, S. Stapnes, I. Syratchev, W. Wuensch

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April 4, 2022

Abstract

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration, hosted by CERN. The CLIC accelerator has been optimised for three energy stages at centre-of-mass energies 380 GeV, 1.5 TeV and 3 TeV [21]. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70 MV/m to 100 MV/m.

The CLIC ESPP update – I

Guidelines:

Preparing “Project Readiness Report” as a step toward a TDR

Assuming ESPP in ~ 2025-6, Project Approval ~ 2028, Project (tunnel) construction can start in ~ 2030.


CERN-2024-nnn-M
31 December 2024

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

THE COMPACT LINEAR COLLIDER (CLIC)
READINESS REPORT

GENEVA
2024

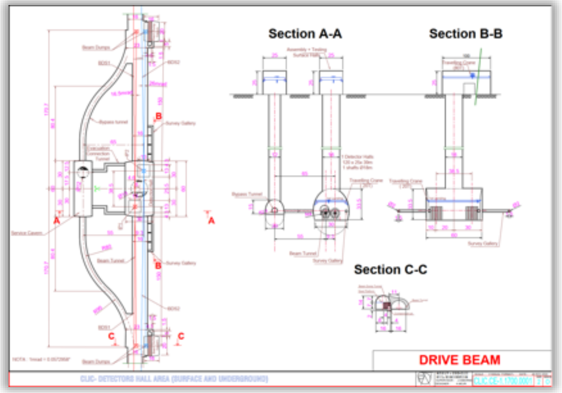
Several important changes:

- Energy scales: 380 GeV and 1.5 TeV with one drivebeam
- Present 100 Hz running at 250 GeV and 380 GeV (i.e. two parallel experiments, two BDSs) – some increased cost and increased power wrt to one IP
- New run plan, 10+10 year for two stages (380 -> 1500 GeV) – with ramp-ups
- Several updates on parameters (injectors, damping rings, drive-beam) based on new designs, results and prototyping (e.g. klystrons, magnets) - however no fundamental changes beyond staying at one drivebeam
- Technology use examples, including more on use of them in other projects (e.g. alignment, instrumentation, X-band RF is small linacs)
- Update costing and power – interplay between inflation and CHF
- Life Cycle Assessments
- More detailed prep phase planning (next 5-7 years)

Project summary for Snowmass already include some of these changes, i.e. luminosity improvements, 100 Hz study is mentioned, the power is updated for 380 GeV: LINK

Recent: Consider also 550 GeV

The CLIC ESPP update - II



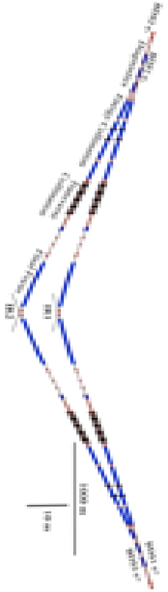
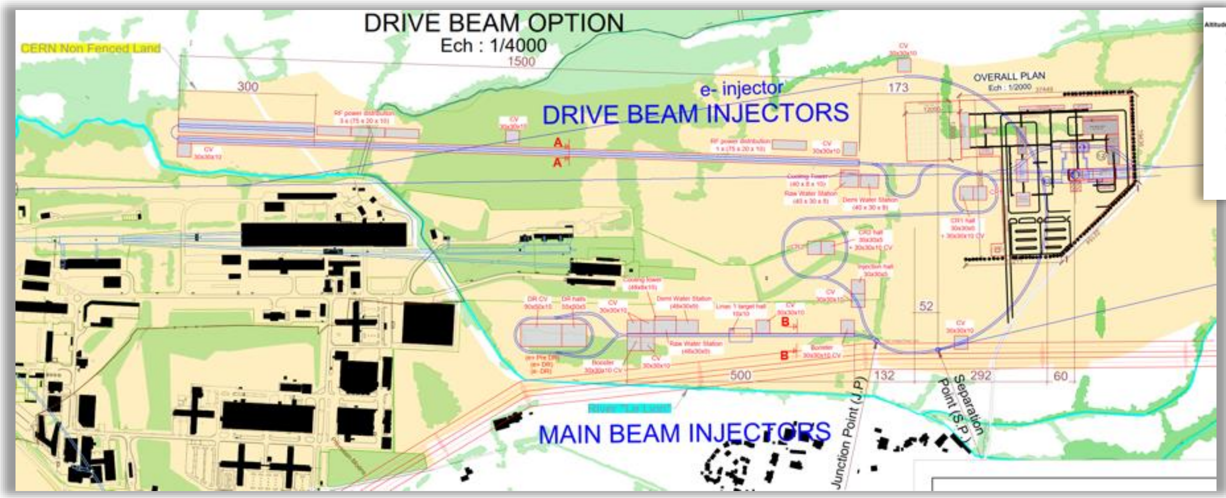


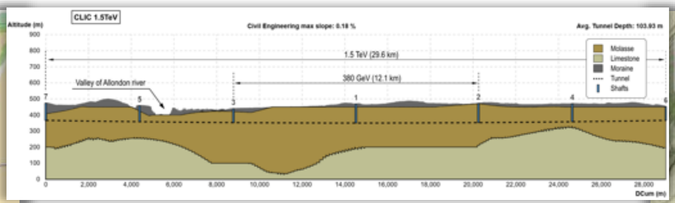
Table 1.1: Key parameters of the CLIC energy stages.

Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	1×10^{34} cm^{-2}s^{-1}	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	1×10^{34} cm^{-2}s^{-1}	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^{9}	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	~60/1.5	~40/1
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

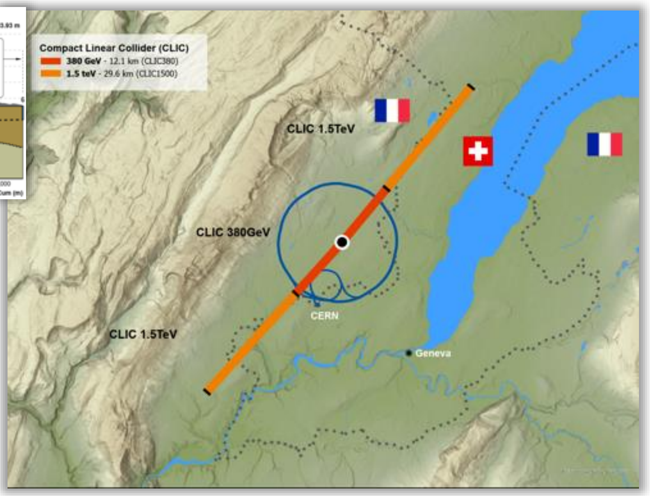
Add:
- 250 GeV parameters
- 100 Hz running for both 250 and 380 GeV

3 TeV: refer to earlier reports





More on CE later

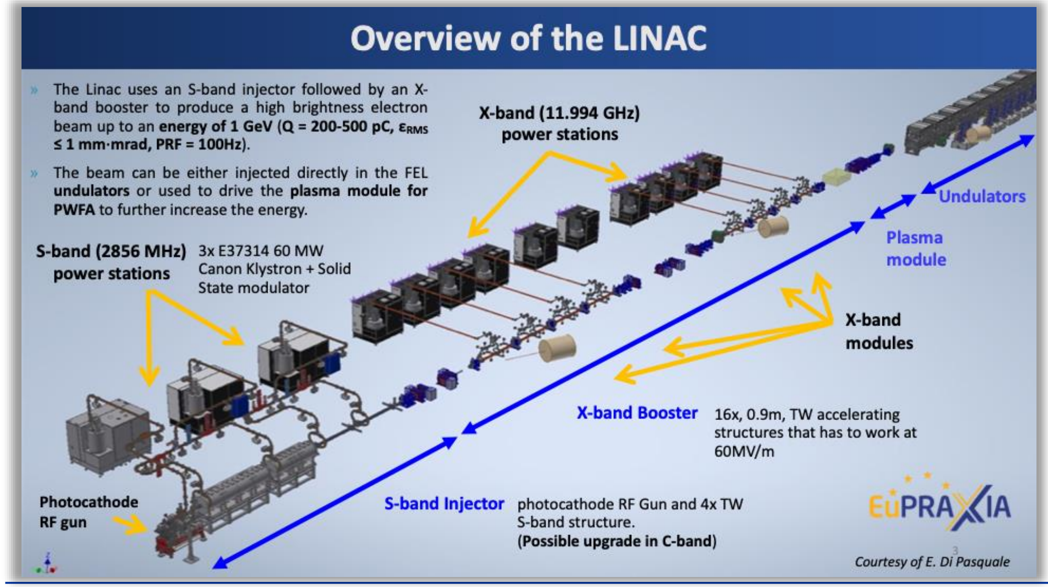


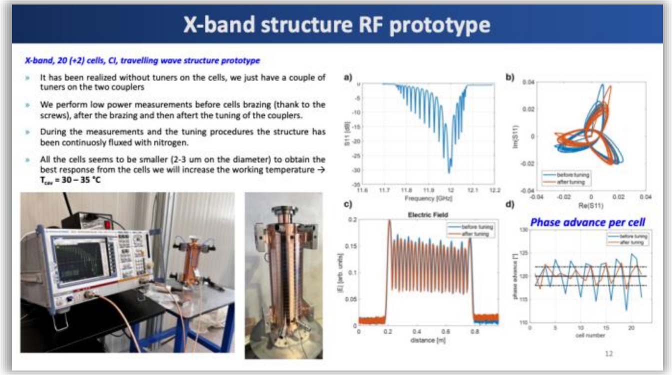
Larger NC linacs (most relevant operational ones are C-band based)

SwissFEL: C-band linac

- 104 x 2 m-long C-band (5.7 GHz) structures (beam up to 6 GeV at 100 Hz)
- Similar µm-level tolerance
- Length ~ 800 CLIC structures
- Being commissioned
- X-band structures from PSI perform well

Photo: SwissFEL/PSI



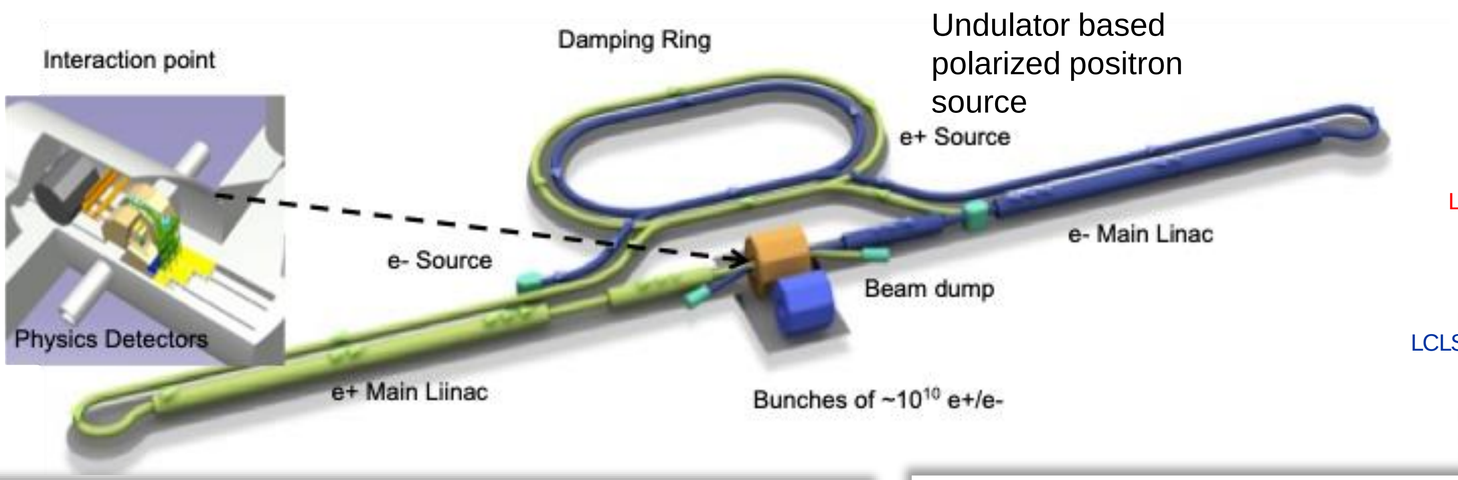


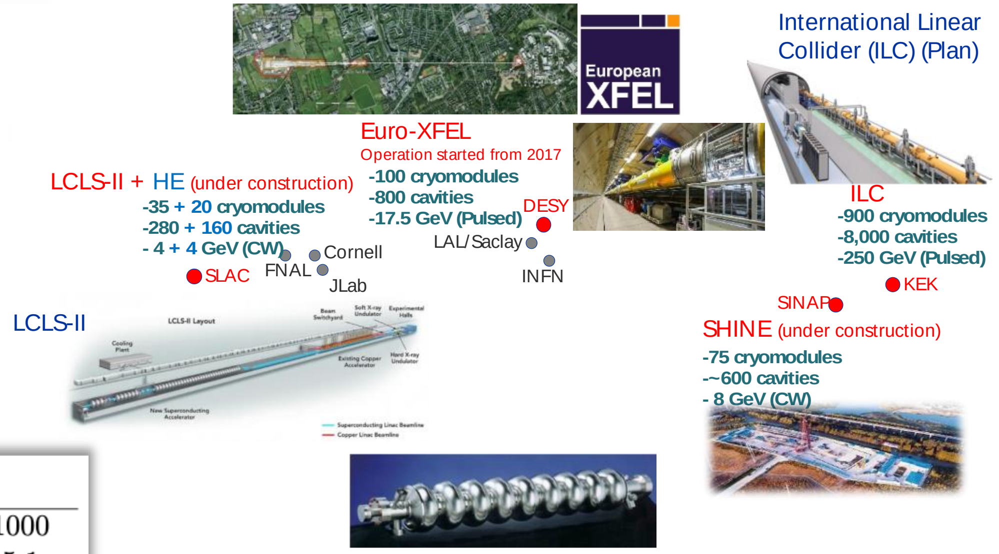
1GeV X-band linac at LNF
F.Cardelli (LCWS 2024): LINK

Examples from N.Catalan (IAS Fundamental Physics HK 2025 (LINK)

ILC – general updates and implementation in Japan (for CERN see later)

The ILC250 accelerator facility

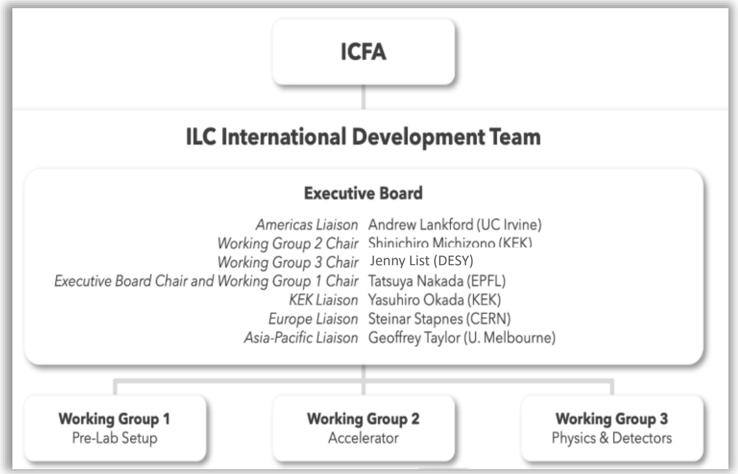




Quantity	Symbol	Unit	Initial	$\mathcal{L}$ Upgrade	Z pole	Upgrades		
Centre of mass energy	$\sqrt{s}$	GeV	250	250	91.2	500	250	1000
Luminosity	$\mathcal{L}$	$10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$	1.35	2.7	0.21/0.41	1.8/3.6	5.4	5.1
Polarization for e^-/e^+	$P_-(P_+)$	%	80(30)	80(30)	80(30)	80(30)	80(30)	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	$\gamma\epsilon_{\mathrm{x}}$	μm	5	5	5	5	5	5
Norm. vert. emitt. at IP	$\gamma\epsilon_{\mathrm{y}}$	nm	35	35	35	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

Parameters and plans for luminosity and energy upgrades are available, including information about relevant SCRF R&D for such upgrades at (Snowmass input)

Some recent ILC developments - I



SRF	WPP	1	Cavity production	√		√	√	√			√	√	√				√	√	√		√	√		√	√	
	WPP	2	CM design	√				√				√			√	√	√	√	√			√		√	√	
	WPP	3	Crab cavity			√	√							√					√			√	√		√	√
Sources	WPP	4	E- source			√						√							√		√			√		
	WPP	6	Undulator target				√												√	√			√			
	WPP	7	Undulator focusing				√												√	√			√			
	WPP	8	E-driven target	√		√												√	√							
	WPP	9	E-driven focusing	√														√	√							
	WPP	10	E-driven capture	√															√					√		
	WPP	11	Target replacement	√																						
Nano-beams	WPP	12	DR System design	√	√				√	√		√							√				√	√		
	WPP	14	DR Injection/extraction	√					√										√				√	√		
	WPP	15	Final focus	√			√		√		√							√			√			√		
	WPP	16	Final doublet	√	√													√								
	WPP	17	Main dump	√			√					√														

Above: ILC Technology Network (ITN), interest/capability matrix from 28 labs/universities

Promoting the technological development of the International Linear Collider: Twenty-eight research institutes participated in the ITN Information Meeting

Topics 2023/11/16

WPP	1	Cavity production
WPP	2	CM design
WPP	3	Crab cavity
WPP	4	E- source
WPP	6	Undulator target
WPP	7	Undulator focusing
WPP	8	E-driven target
WPP	9	E-driven focusing
WPP	10	E-driven capture
WPP	11	Target replacement
WPP	12	DR System design
WPP	14	DR Injection/extraction
WPP	15	Final focus
WPP	16	Final doublet
WPP	17	Main dump

European ITN studies are distributed over five main activity areas:

ML related tasks
- SRF and ML elements: Cavities and Cryo Module, Crab-cavities, ML quads and cold BPMs (INFN, CEA, DESY, CERN, IJCLAB, UK, CIEMAT, IFIC)

Sources
- Pulsed magnet and wheel/target (Uni.H, DESY, CERN)

Damping Ring including kickers
- Low Emittance Rings (UK)

ATF activities, final focus and nanobeams
- ATS and MDI (UK, DESY, IJCLAB, CERN, IFIC)

Implementation
- Dump, CE, Cryo – follow up efforts at CERN
- Sustainability, Life Cycle Assessment (CERN, DESY, CEA, UK groups)
- EAJADE started (EU funding) (DESY, UK, CEA, CNRS, IFIC, INFN, UHH, CERN)

Some recent ILC developments - II

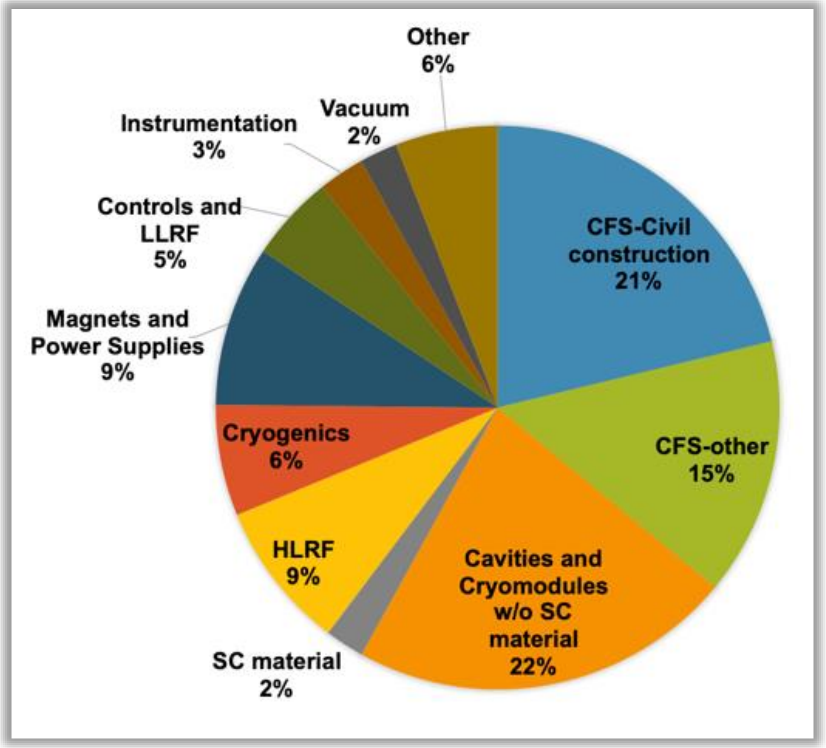
Re-evaluate CFS costs for ILC in Japan

- Mountainous site -> mostly sloped access tunnels
- CE based on NATM tunnelling method (blast and spayed concrete)

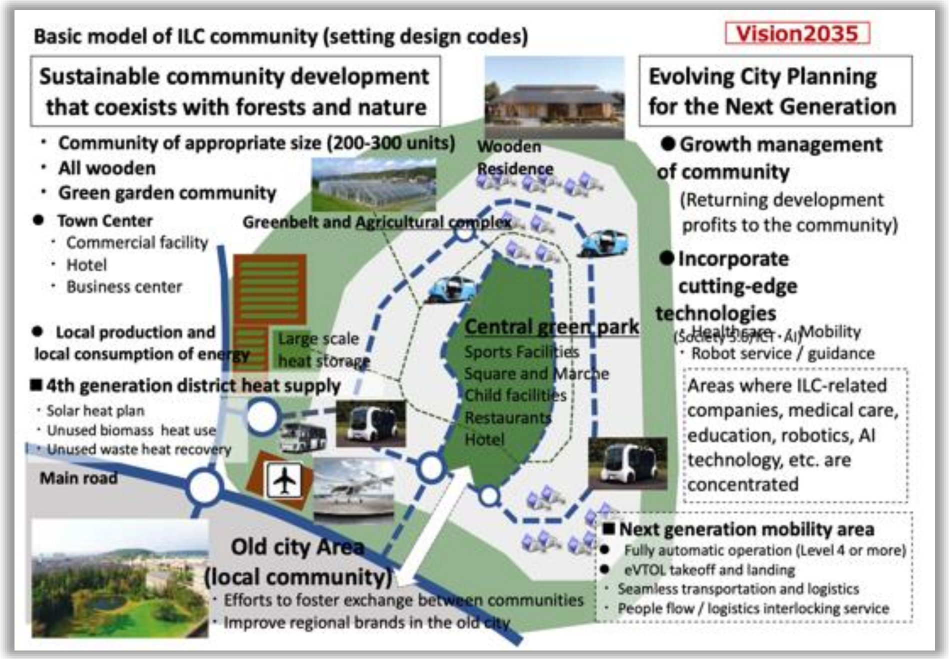
Includes design updates from TDR/ILC-250

- Some tunnel and cavern extensions for latest acc. and utility designs

Re-evaluated to 2024 National Cost Estimating Standards



Cost matrix, updating SCRF and CFS (~75%), escalation and currency updates for the rest (~25%)



The ILC implementation is extensively studies in Japan, civil engineering, integration locally, environmental impacts, etc

To be shown

ILC250nCost-Update Evaluation

— update-ay180112, for MEXT-TDR-WG-180120 → ILC-Cost-Update-2024

Confidential

Progress Year-base Unit [MILC]-	ILC500 (TDR) 2012-base [MILC]	ILC250 2012-base [MILC]	ILC250-2017-base JP-CFS ([Oku-JPY]	Escalation & design-update [factor]	ILC250-2024-base JP-CFS [OkuJPY]	
Year of work ~ report	*2012 ~ 2013*	2017 TDR-base	2017 New JP-CFS Design	[2012-2024]	[2024]	
Acc. Tech. (except for SRF)	**1,390**	**1,196**		To be reported		→ [MILC]
SRF Tech. (CM, HLRF, Cryog,)	**4,221**	**2,340**		To be reported		
CFS:CF		706	To be reported	To be reported		
CFS:CE		1,014	To be reported		To be reported	→ [Oku-JPY]
CFS-Total		**1,720**	To be reporte			
Sum	**7,985**	**5,256**				

From report by A.Yamamoto (LINK)

Comments on the ILC250 Cost-Update 2024

- The ILC250 cost increase of **~60%+** (in overall), in 2017 – 2024.
- It may be caused by the following origins:
  - **General (for all Conv. Acc., SRF, and CFS)**:
    - Increase of **30 – 50 %** because of **inflation** from 2017 to 2024,
  - **SRF (specific):**
    - Increase of **8 ~ 10 %** because of the **1/3 mass production, resulting unit cost-up**
    - Increase of **10 ~ 20 %** because of integration of **averaged cost** in 2024, instead of cheapest cost in TDR, and **design updates and/or production cost changes**.
  - **CFS (specific):**
    - Increase of 20 – 40 % because of design update in JP specific site,
    - dynamic change of exchange rates (in particular between USD/.EU and JPY)
    - Significant, material (Cu, SUS etc.) cost increase,

LC implementation at CERN

- CLIC already studied in detail at CERN - including CE, infrastructure, costs, power, etc. Some of this was shown earlier, more below on these points.

Reminders: ILC at CERN was studied for the ILC TDR in ~2012, CE including costing, infrastructure partly.
ILC CE and cryo has been actively supported the last decade and more.
Many common studies, e.g. positrons, BDS, damping rings, life cycle assessments, power reductions, etc.

- Starting with ILC technology, how would we implement a SCRF LC at CERN ?
  - Use CLIC footprint/studies as much as possible
  - Cost estimate as for CERN projects in CHF, with CE costs from CERN
  - Increase luminosity wrt to Japan parameters and share on two IPs, and consider implementation of energies above 250 GeV (even initially), more similar to the TDR
  - Consider if such a facility can use improved or other RF technologies in the future (a true LC facility) – stimulate wide R&D and open options for the future

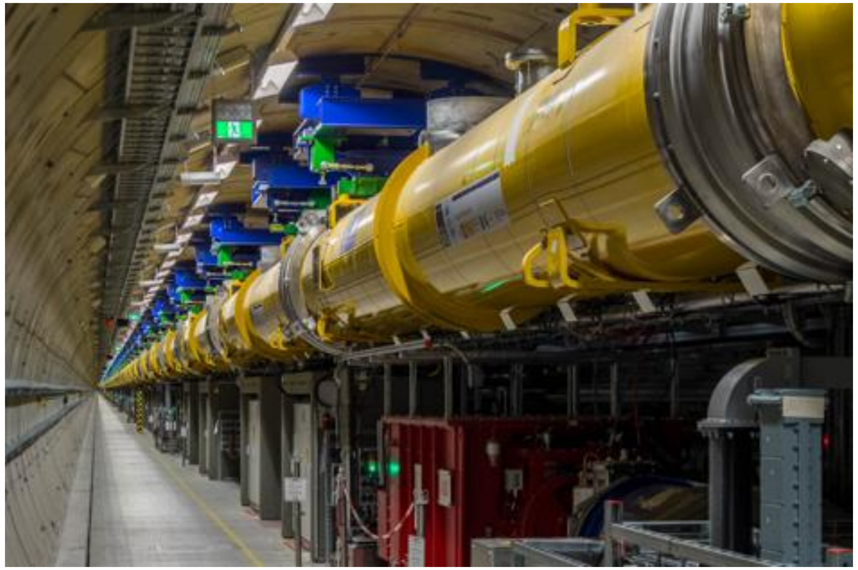
Why consider SCR as starting point ?

- Very detailed and mature technical design and industrialisation, several FEL linacs build and being operated

- Can be upgraded in Energy and Luminosity.

- Worldwide interest in technology.

- Large technology interest in Europe (EUXFEL and several other projects), and leading industries in Europe.
  - Could it be exploited to reduce load on CERN during the HL period (lab support outside for cryomodules for example as foreseen for ILC – and also in Europe) ?
  - Can this be turned into schedule advancement ?

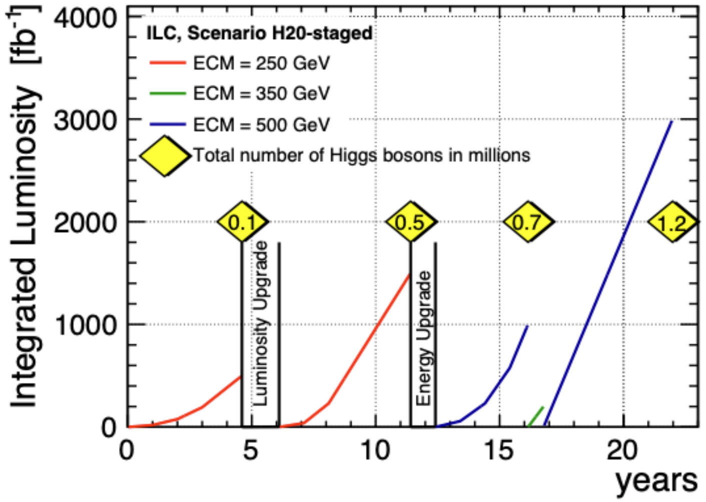


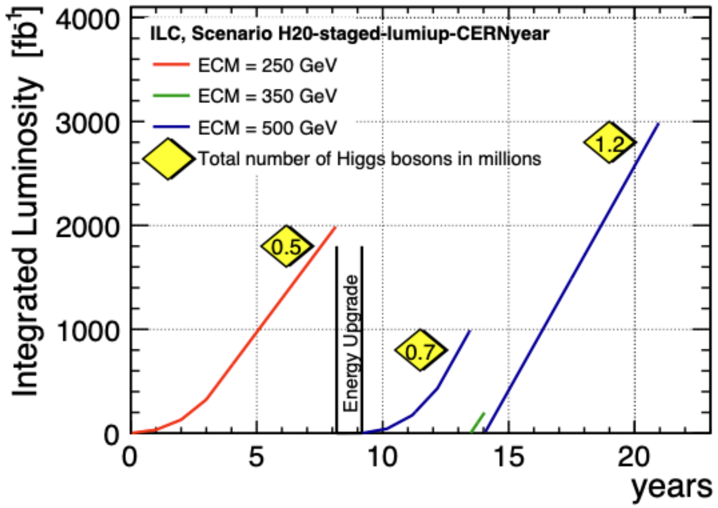
ILC in Japan has a certain run-plan, but one can easily consider higher luminosities and higher energies.

If starting with ILC technology at CERN for a LC this will certainly be considered.

From J.List (link)

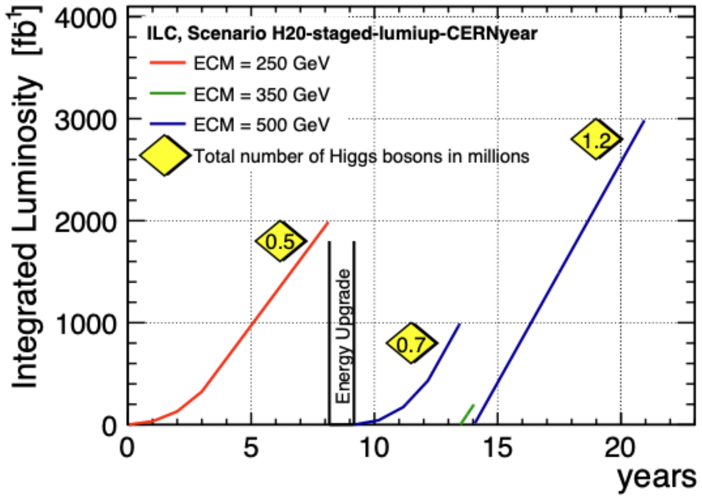
Increasing the number of bunches in a train (as in the TDR), and adjusting to a CERN running year

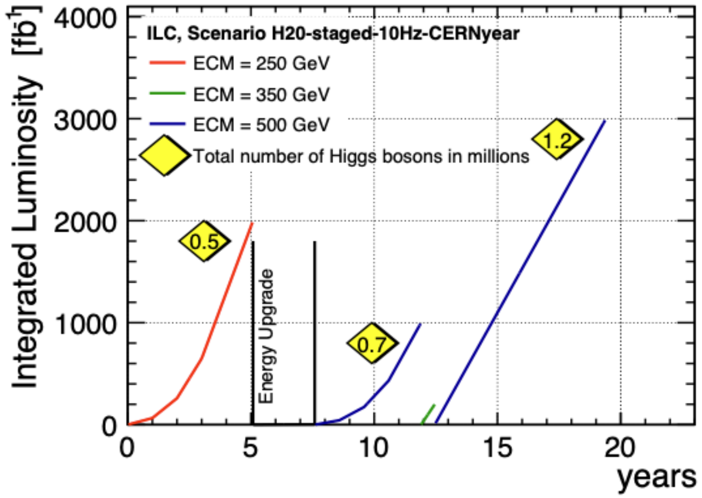




Higgs run ~8 years

Doubling the frequence to 10 Hz (~higher power impact). Note that in all cases a luminosity ramp up is foreseen

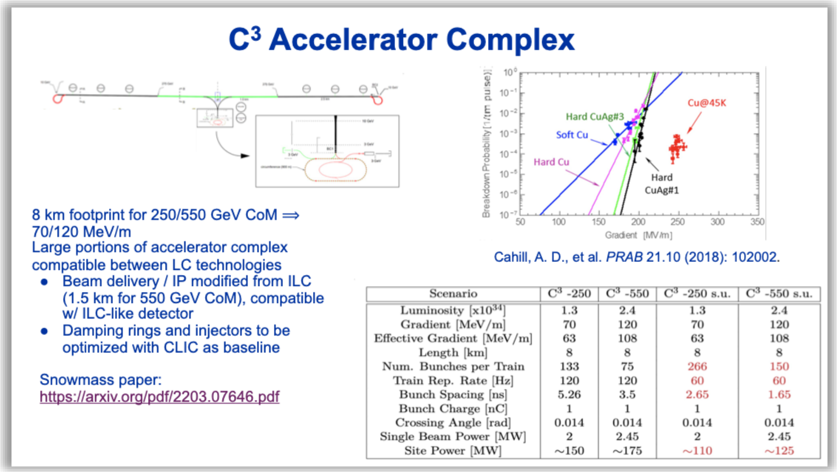




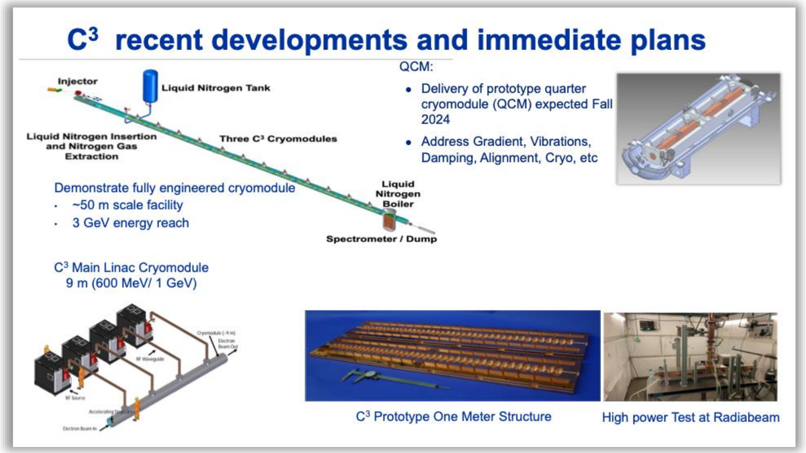
Higgs run 5 years

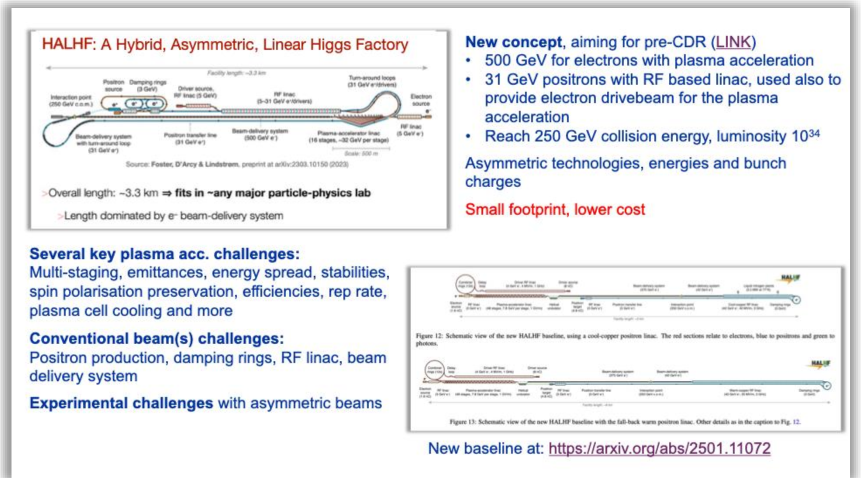
Longer term upgrades that can be studied

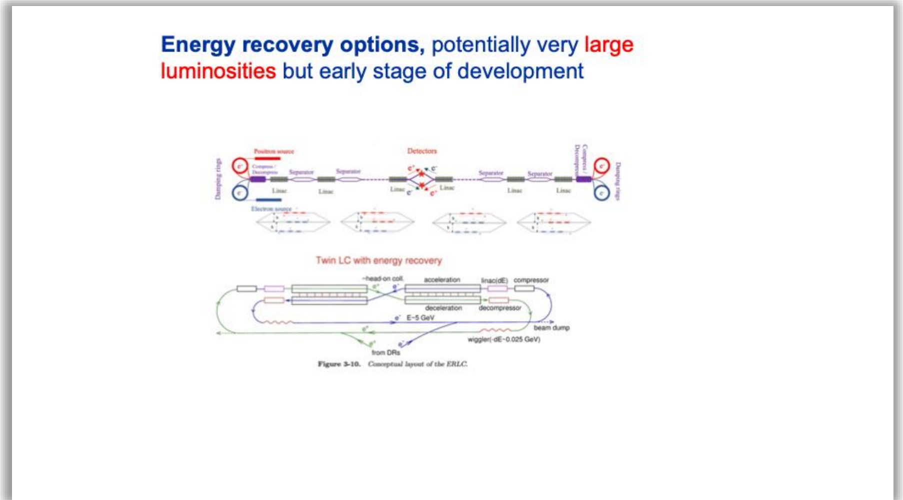
Improved SCRF (both gradient and Q values), CLIC or C3, plasma boosts, energy recovery options



Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125



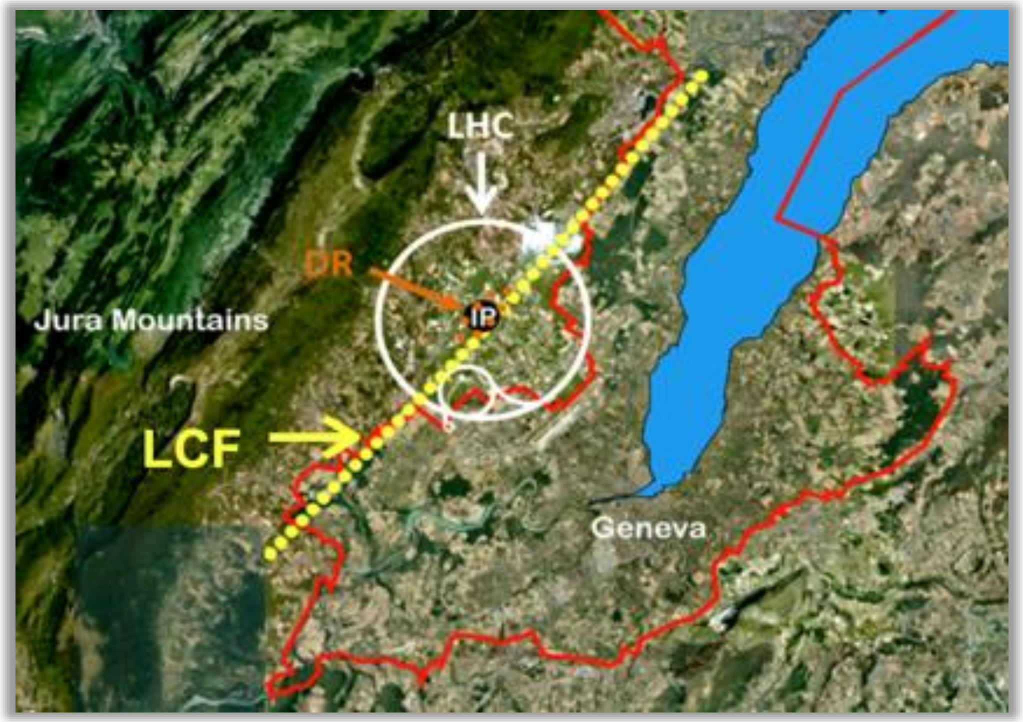


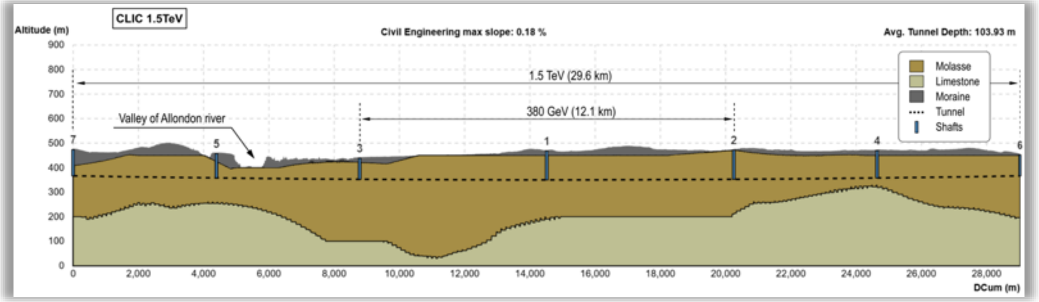


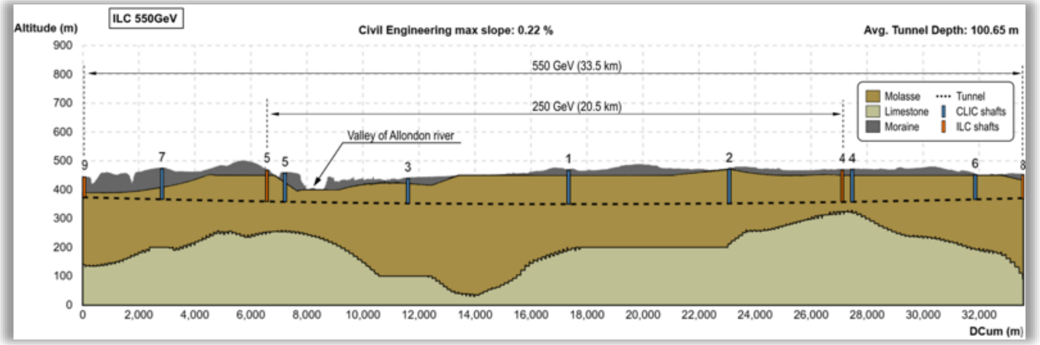
Civil Engineering

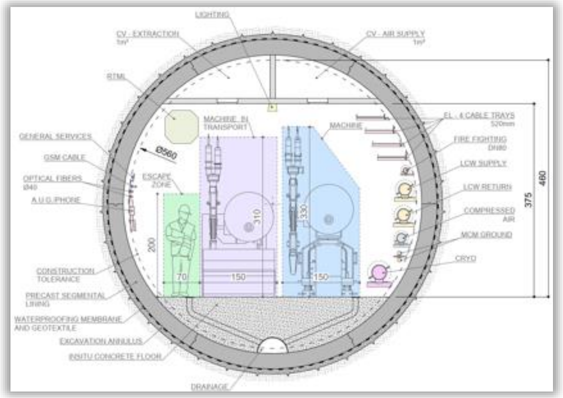
CE studies for LC at CERN:

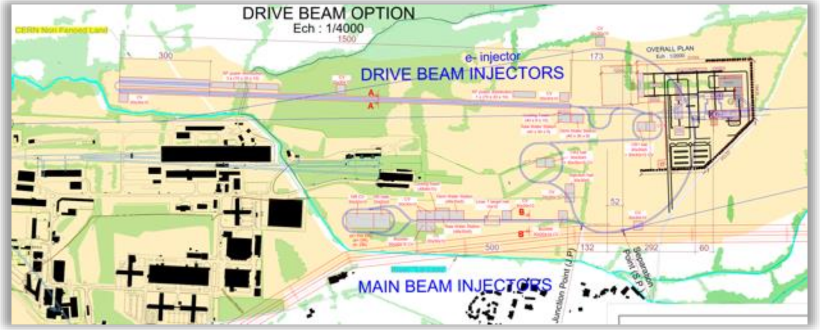
- CLIC, up to 3 TeV. Contract with Amberg Engineering for CDR in 2012-2013.
- ILC up 1 TeV. Contract with Amberg for the TDR in 2012-13.
- CLIC up to 3 TeV, TOT (layout tool) with ARUP, for Project Implementation Report 2018
- Update on-going, ILC up to 500 GeV, CLIC to 1.5 TeV, in both cases ~30km, using Geoprofiler layout tool
- Injectors and experimental areas on Prevessin site ("CERN land")









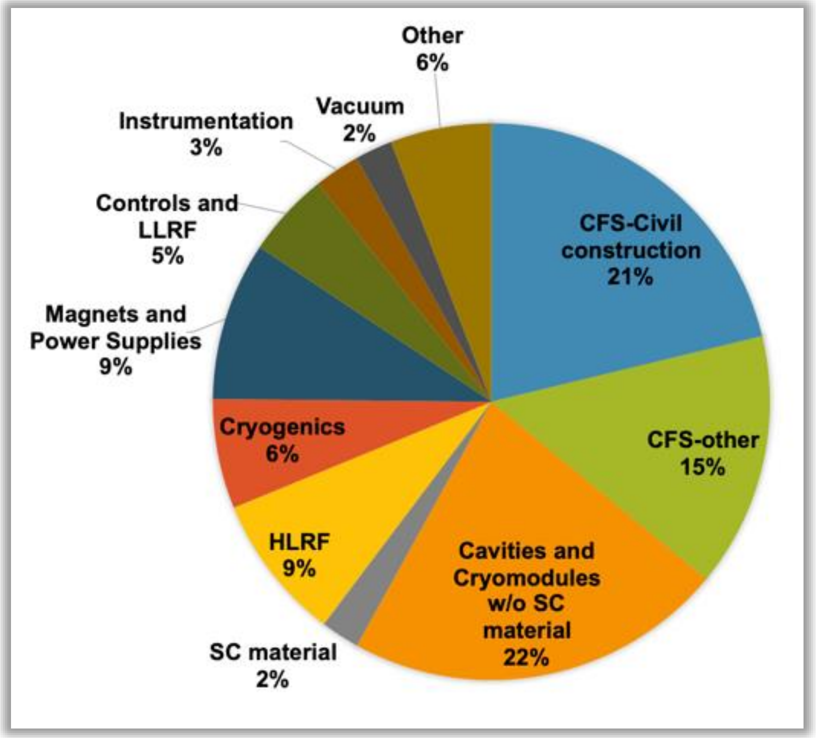


Costs – I

Cost exercises and international reviews:

- ILC TDR 2012-13, 500 GeV primarily (LINK)
- CLIC CDR 2012-13, 3 TeV primarily and 500 GeV (LINK)
- ILC in Japan 2017-18, 250 GeV, reviewed within LCC (LINK)
- CLIC PiP 2018, 380 GeV primarily (LINK)

Updates and review recently done for ILC 19-20.12.2024 (slides 17-18)



For the ESPP – for starting with ILC technology at CERN:

- Updated: ILC in Japan with updated technology results, updated CFS (CE and conv. systems, SRF) – discussed on slide 17-18
- CERN implementation: CE costs based on CLIC and other CERN projects, same main linac footprint,
- Add larger underground DR, remove drivebeam CE and turn arounds
- Slightly different BDS dimensions and cavern sizes (but as for CLIC cost for 2 IPs)

Costs - II

ILC250nCost-Update Evaluation

To be shown | Confidential

– update-ay180112, for MEXT-TDR-WG-180120 → ILC-Cost-Update-2024

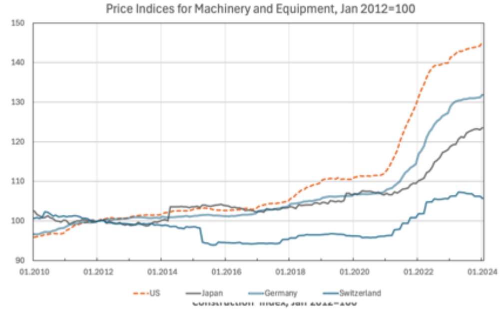
Progress Year-base Unit [MILC]-	ILC500 (TDR) 2012-base [MILC]	ILC250 2012-base [MILC]	ILC250- 2017-base JP-CFS ([Oku-JPY]	Escalation & design-update [factor]	ILC250- 2024-base JP-CFS [OkuJPY]
Year of work – report	*2012 – 2013*	2017 TDR-base	2017 New JP-CFS Design	[2012-2024]	[2024]
Acc. Tech. (except for SRF)	1,390	1,196		To be reported	
SRF Tech. (CM, HLRF, Cryog.)	4,221	2,340		To be reported	→ [MILC]
CFS:CF		706	To be reported	To be reported	
CFS:CE		1,014	To be reported		To be reported → [Oku-JPY]
CFS-Total		1,720	To be reporte		
Sum	7,985	5,256			

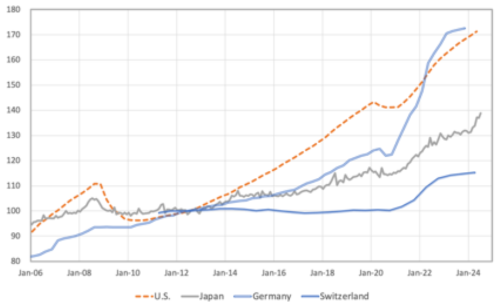
From report by A.Yamamoto (LINK)

Comments on the ILC250 Cost-Update 2024

- The ILC250 cost increase of **~60%+** (in overall), in 2017 – 2024.
- It may be caused by the following origins:
  - **General (for all Conv. Acc., SRF, and CFS):**
    - Increase of **30 – 50 %** because of **inflation** from 2017 to 2024,
  - **SRF (specific):**
    - Increase of **8 ~ 10 %** because of the **1/3 mass production, resulting unit cost-up**
    - Increase of **10 ~ 20 %** because of integration of **averaged cost** in 2024, instead of cheapest cost in TDR, and **design updates and/or production cost changes.**
  - **CFS (specific):**
    - Increase of 20 – 40 % because of design update in JP specific site,
    - dynamic change of exchange rates (in particular between USD/.EU and JPY)
    - Significant, material (Cu, SUS etc.) cost increase,

Re-costing, check also consistency with FCC (items, assumptions, costs if relevant)





For ILC like implementation at CERN (in progress):

- Redo CE costing (previous slide)
- Redo CF costing (EL, CV, etc)
- Use 2024 costing for all components in their respective currencies, and change to CHF with exchange rate

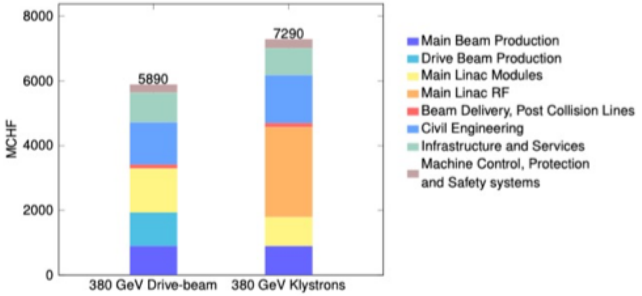
Cost – I (currently being updated)

Cost exercises and international reviews:

- CLIC CDR 2012-13, 3 TeV primarily and 500 GeV (LINK)
- CLIC PiP 2018, 380 GeV primarily (LINK)

Machine has been re-costed bottom-up in 2017-18

- Methods and costings validated at review on 7 November 2018 – similar to LHC, ILC, CLIC CDR
- Technical uncertainty and commercial uncertainty estimated



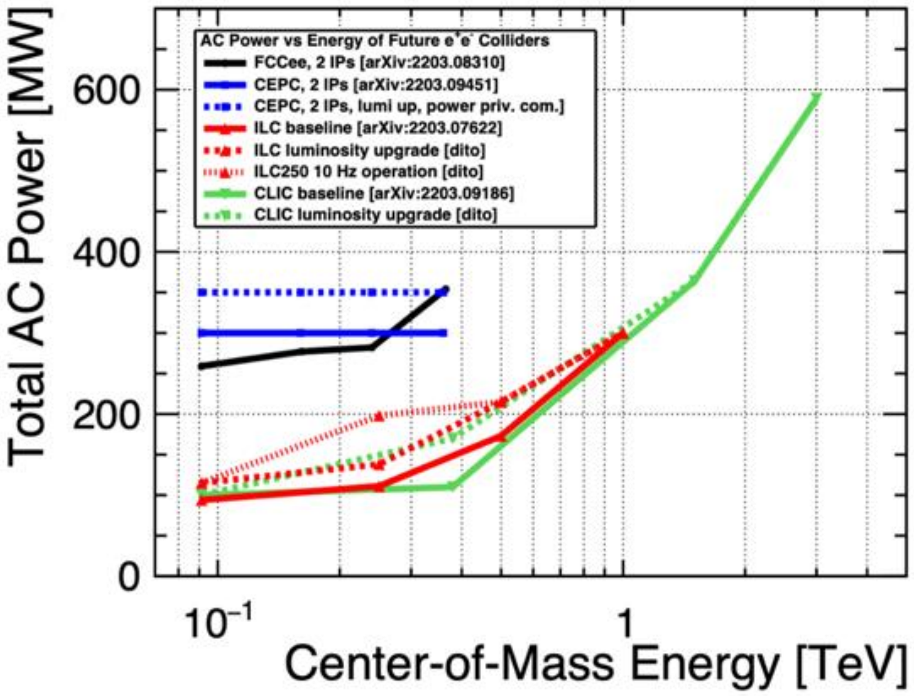
Domain	Sub-Domain	Cost [MCHF] Drive-Beam	Cost [MCHF] Klystron
Main Beam Production	Injectors	175	175
	Damping Rings	309	309
	Beam Transport	409	409
Drive Beam Production	Injectors	584	—
	Frequency Multiplication	379	—
	Beam Transport	76	—
Main Linac Modules	Main Linac Modules	1329	895
	Post decelerators	37	—
Main Linac RF	Main Linac Xband RF	—	2788
Beam Delivery and Post Collision Lines	Beam Delivery Systems	52	52
	Final focus, Exp. Area	22	22
	Post-collision lines/dumps	47	47
Civil Engineering	Civil Engineering	1300	1479
Infrastructure and Services	Electrical distribution	243	243
	Survey and Alignment	194	147
	Cooling and ventilation	443	410
	Transport / installation	38	36
Machine Control, Protection and Safety systems	Safety system	72	114
	Machine Control Infrastructure	146	131
	Machine Protection	14	8
	Access Safety & Control System	23	23
Total (rounded)		**5890**	**7290**

CLIC 380 GeV Drive-Beam based: 5890^{+1470}_{-1270} MCHF;

CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

17

Power and energy

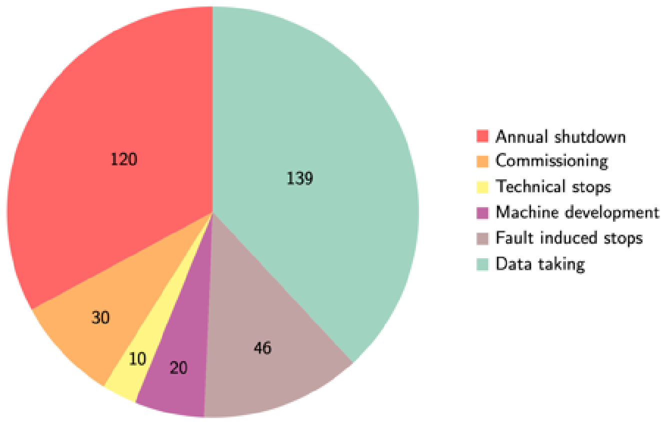


Power at 250-380 GeV in the 100-200 MW range for the LC projects above

With a running scenario on the right this corresponds to 0.6 - 1.2 TWh annually

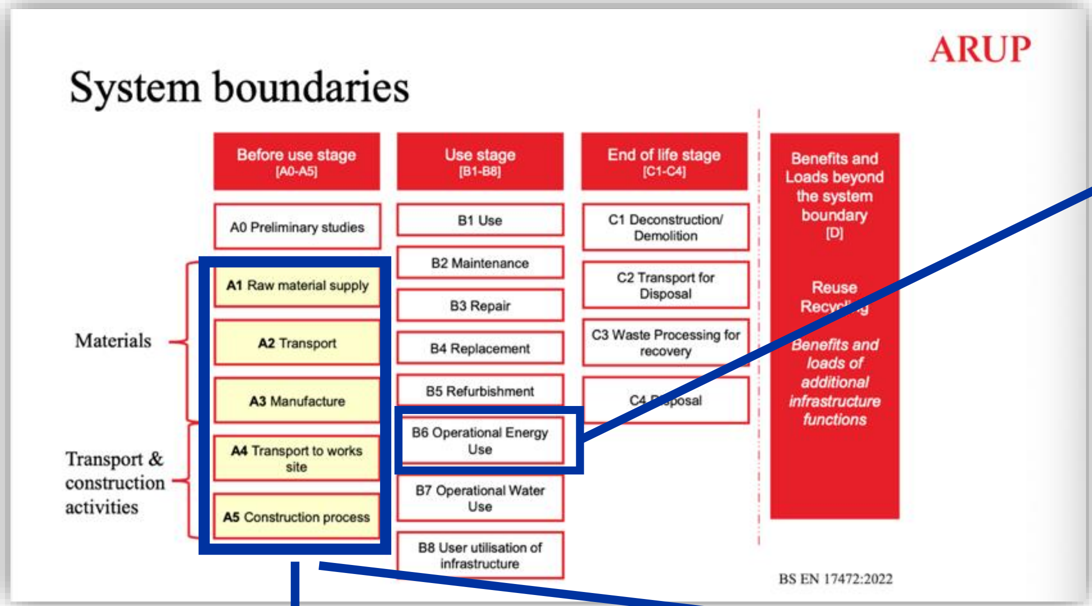
CERN is currently consuming 1.2 – 1.3 TWh annually

CERN “standard” running scenario used to convert to annual energy use



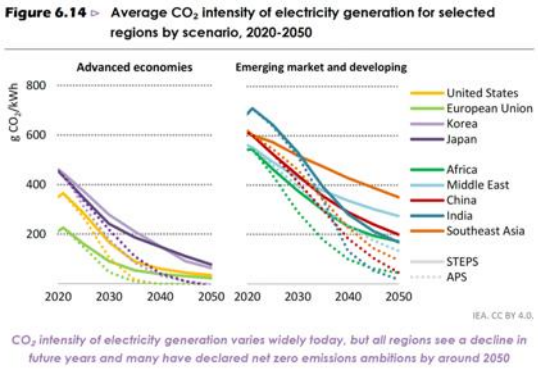
Includes studies of overall designs optimisation to reduce power, SRF cavities (grad,Q), cryo efficiency, RF power system (klystrons, modulators, components), RF to beam efficiencies, permanent magnets, operation when power is abundant, heat recovery, nanobeam and more.
Recent overview (LINK)

Sustainability: Life Cycle Assessment (LCA)



What is the carbon intensity of energy in ~2050 (operation):

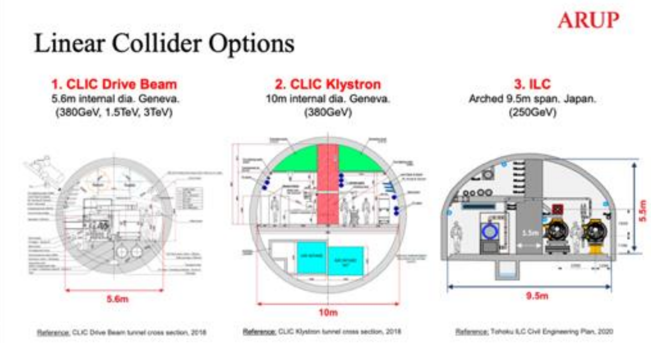
- 50% nuclear and 50% renewable give ~10-15g/kWh, to optimistic ?
- France summer-months are today ~40g/kWh
- Reductions predicted (LINK)

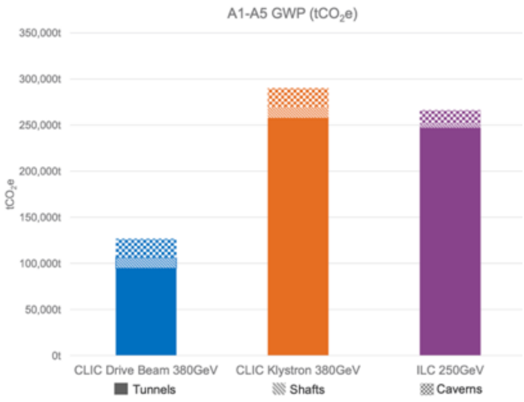


Next working on the machine parts, on top of the CE estimate

LCA report for **Civil Engineering**: LINK

Addressing the Civil Engineering impact





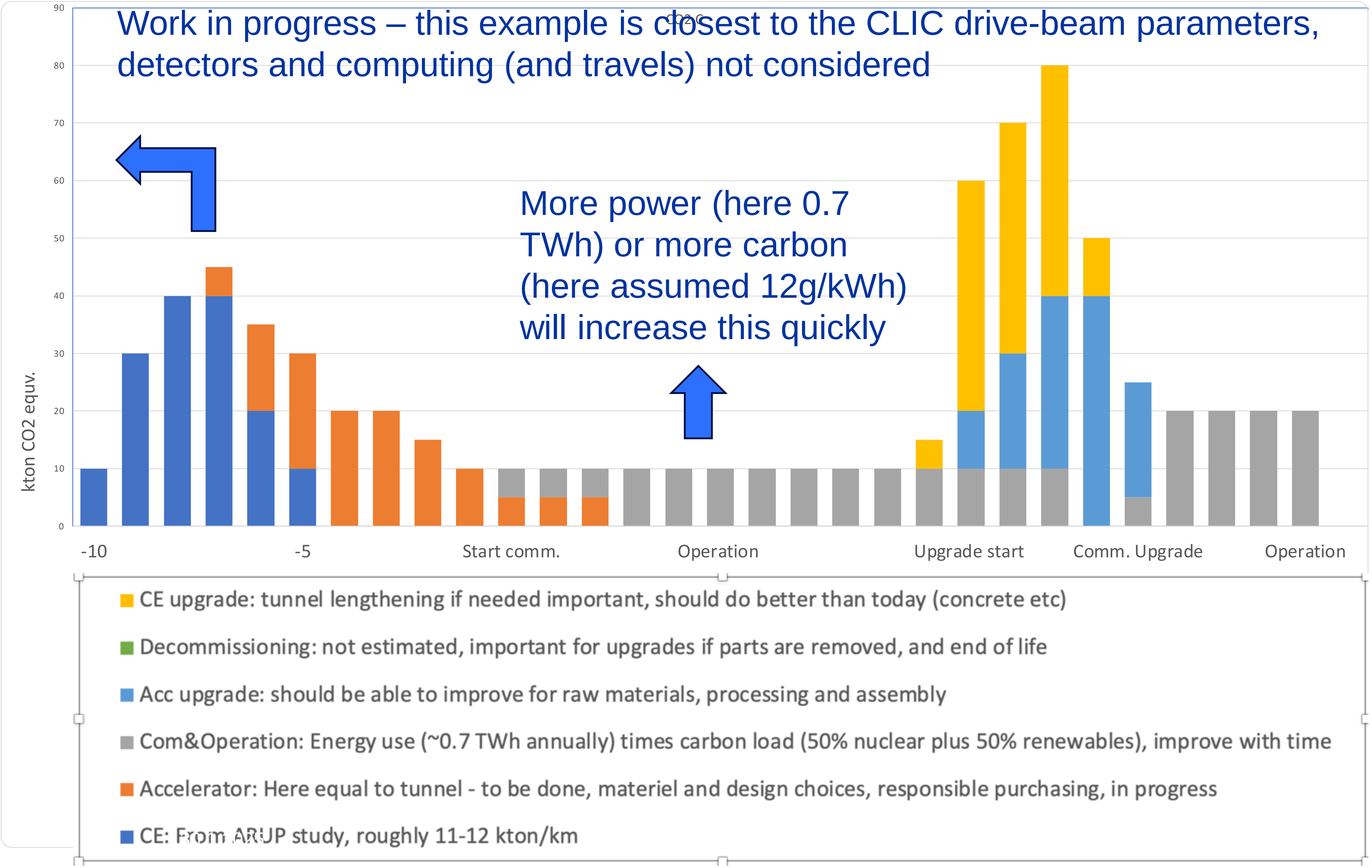
Towards Carbon Accounting with LCA

- example for CLIC, also (being) done for ILC, C3, HALHF, FCC -

This plot (blue part) is for 11 km of tunnel, scales with length, injectors will add to this

Next working on machine parts (orange), here assumed hardware and infrastructure = equal civil engineering impact.

Most likely this is optimistic, i.e. orange and light blue parts will be higher



Some key points

- CLIC will be proposed with several changes wrt to 2018 (X-band also an upgrade option) (Improved wrt 2018, hosted at CERN)

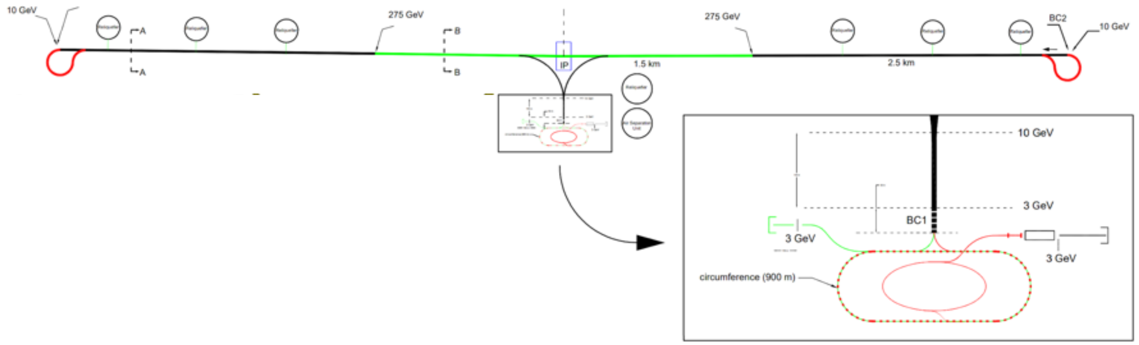
- A LC starting with SRF technology will be proposed for CERN, with upgrade considerations (E,L, length and technologies) (New concept considered for hosting at CERN)

- In both cases emphasis on initial ”affordable” and performant Higgs factories, emphasising the additional physics reach by going to at least 550 GeV, and possibly beyond, and provide parameters for higher energy ranges.
  → Aim to demonstrate the LC “parameter space” available with “baseline” examples, and variations of these (e.g. increased luminosities, empty tunnels preparing for upgrades, …)

Thanks – most of the slides/information from:
S.Michizono, B.List, IDT and ILC colleagues, CLIC team, J.List, A.Robson, E.Nanni and the C^3 team, the HALHF team, ARUP, the Snowmass Implementation Task Force (names on page 2 of the report, chair T.Roser), F.Cardelli, N.Catalan, many more

home.cern

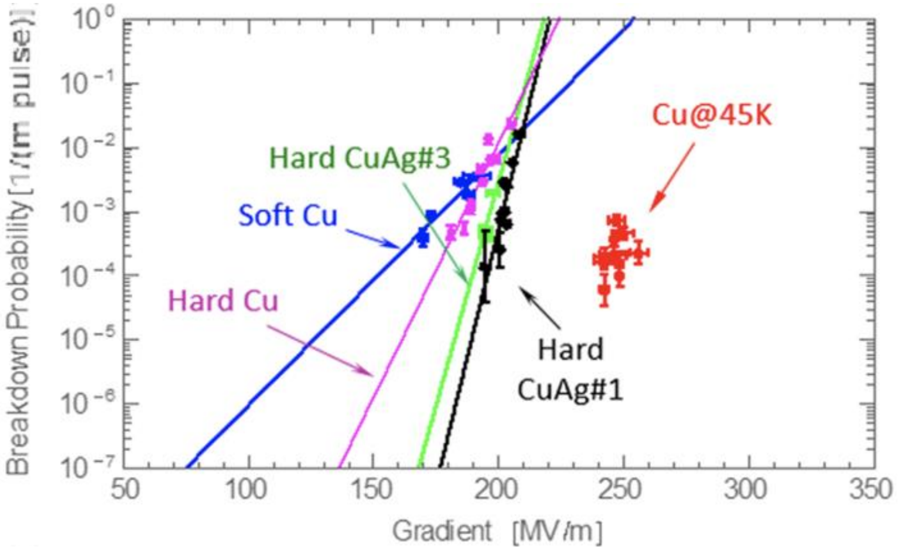
C3 Accelerator Complex



8 km footprint for 250/550 GeV CoM ⟹ 70/120 MeV/m
Large portions of accelerator complex compatible between LC technologies

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

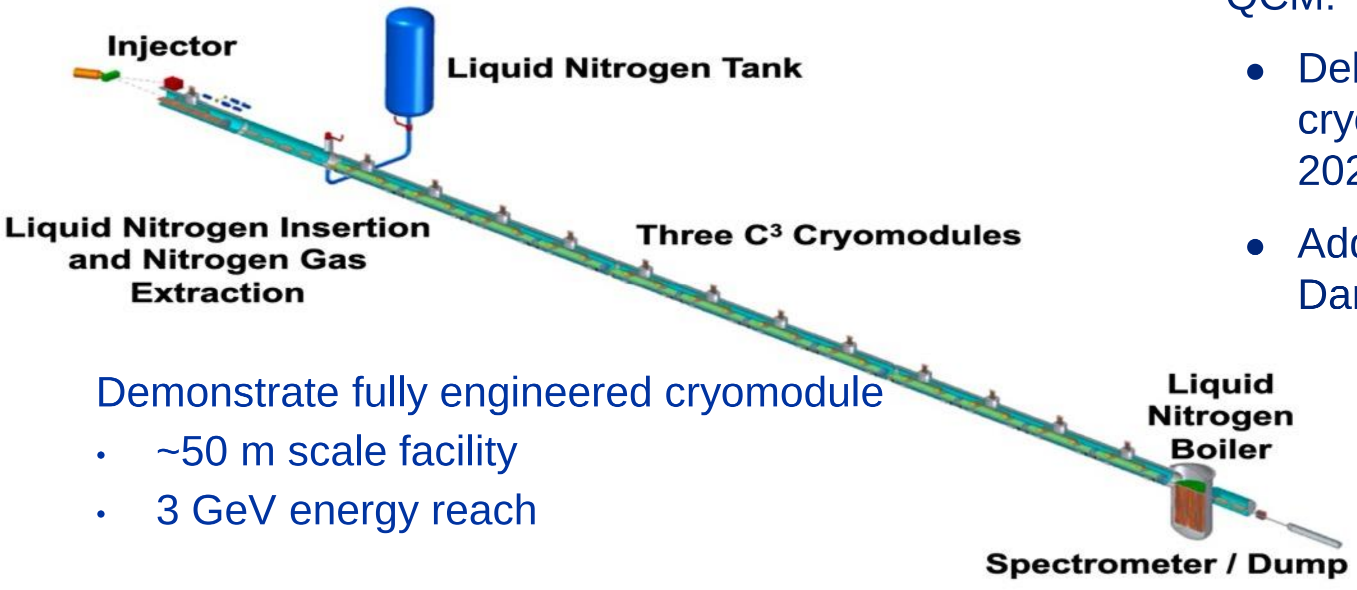
Snowmass paper: https://arxiv.org/pdf/2203.07646.pdf



Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

Scenario	C^3 -250	C^3 -550	C^3 -250 s.u.	C^3 -550 s.u.
Luminosity [x10^{34}]	1.3	2.4	1.3	2.4
Gradient [MeV/m]	70	120	70	120
Effective Gradient [MeV/m]	63	108	63	108
Length [km]	8	8	8	8
Num. Bunches per Train	133	75	266	150
Train Rep. Rate [Hz]	120	120	60	60
Bunch Spacing [ns]	5.26	3.5	2.65	1.65
Bunch Charge [nC]	1	1	1	1
Crossing Angle [rad]	0.014	0.014	0.014	0.014
Single Beam Power [MW]	2	2.45	2	2.45
Site Power [MW]	~150	~175	~110	~125

C^3 recent developments and immediate plans

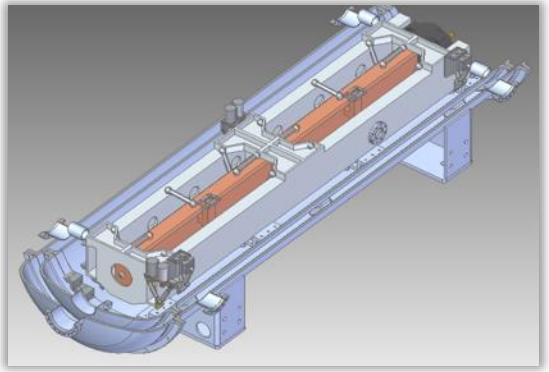


Demonstrate fully engineered cryomodule

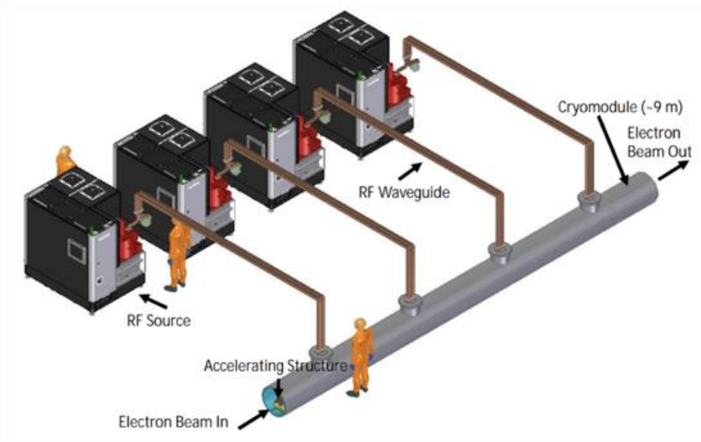
- ~50 m scale facility
- 3 GeV energy reach

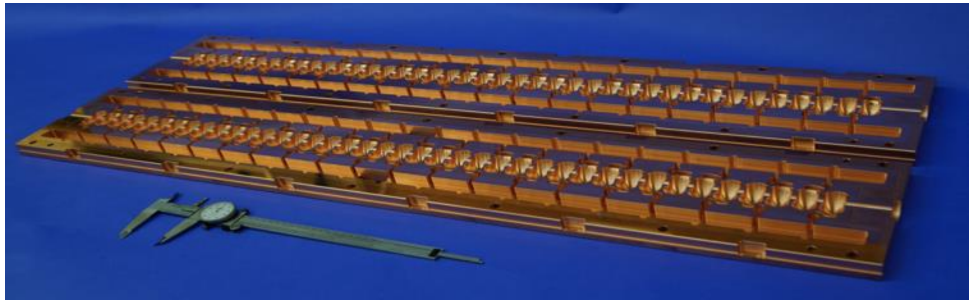
QCM:

- Delivery of prototype quarter cryomodule (QCM) expected Fall 2024
- Address Gradient, Vibrations, Damping, Alignment, Cryo, etc

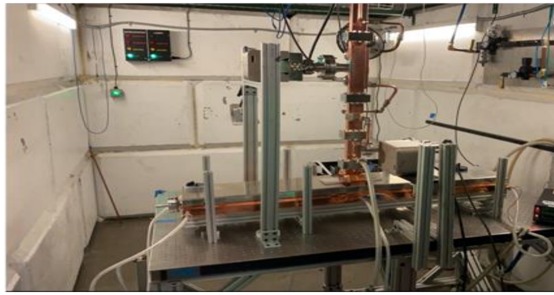


C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)



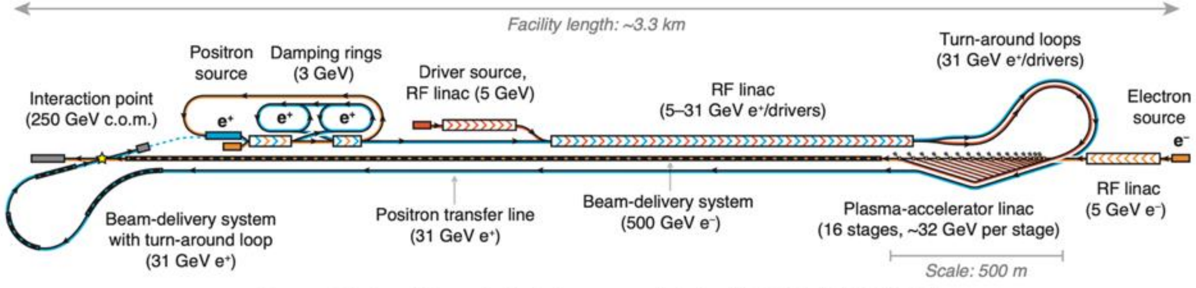


C^3 Prototype One Meter Structure



High power Test at Radiabeam

HALHF: A Hybrid, Asymmetric, Linear Higgs Factory



Source: **Foster, D'Arcy & Lindstrøm**, preprint at arXiv:2303.10150 (2023)

>Overall length: ~3.3 km ⇒ **fits in ~any major particle-physics lab**

>Length dominated by e⁻ beam-delivery system

New concept, aiming for pre-CDR (LINK)

- 500 GeV for electrons with plasma acceleration
- 31 GeV positrons with RF based linac, used also to provide electron drivebeam for the plasma acceleration
- Reach 250 GeV collision energy, luminosity 10^{34}

Asymmetric technologies, energies and bunch charges

Small footprint, lower cost

Several key plasma acc. challenges:
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling and more

Conventional beam(s) challenges:
Positron production, damping rings, RF linac, beam delivery system

Experimental challenges with asymmetric beams

Figure 12: Schematic view of the new HALHF baseline, using a cool-copper positron linac. The red sections relate to electrons, blue to positrons and green to photons.

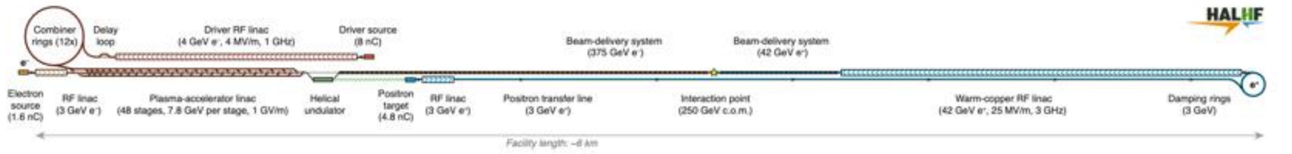
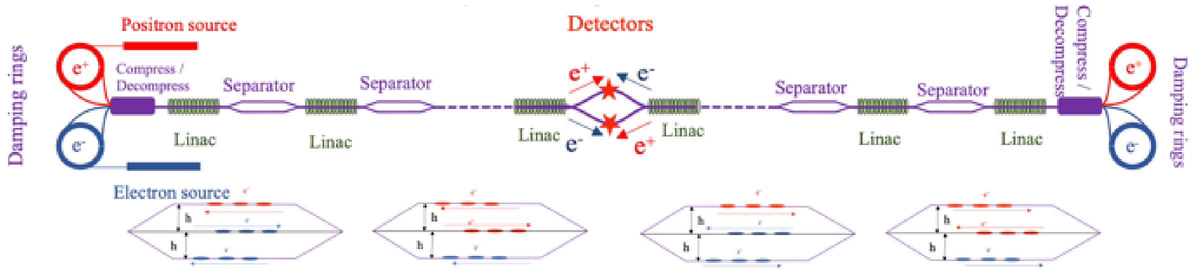


Figure 13: Schematic view of the new HALHF baseline with the fall-back warm positron linac. Other details as in the caption to Fig. 12.

New baseline at: https://arxiv.org/abs/2501.11072

Energy recovery options, potentially very large luminosities but early stage of development



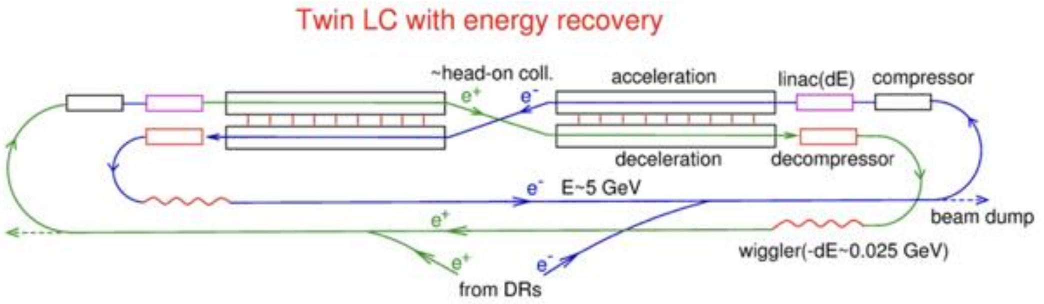


Figure 3-10. *Conceptual layout of the ERLC.*

Cost and Personnel estimates – Higgs factories

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.

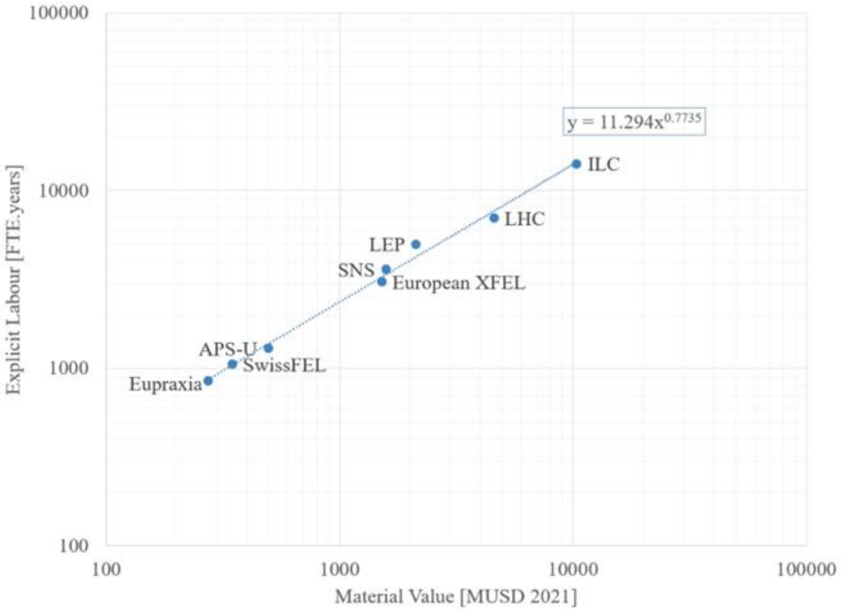


Figure 5: Explicit labor for several large accelerator projects vs. project value.

The estimates above from the Snowmass process includes personnel costs (usually kept separate in European project estimates, e.g. ILC and CLIC). Typically ~2 M$ on top.

Interesting to note that FCC-ee 250 estimated with this method at is 14-19 B$, in reasonably good agreement with FCC-ee mid term report.

Costs for ILC and CLIC (and others) are currently being re-costed and updated to 2023-24, including currency changes and price escalations. We will see if they also agree reasonably well with the Snowmass estimates shown above (so far reasonable)

One FTEy estimated to 200kUS$.