Linear colliders
@ CERN

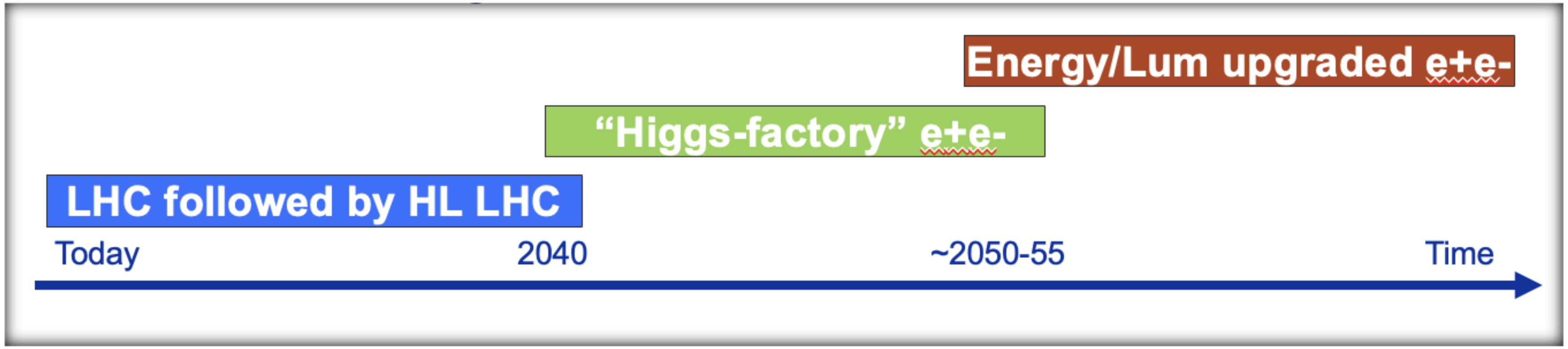
Outline

- LC general considerations
- ILC - in Japan
- CLIC - at CERN
- Brief: C^3 and HALHF, energy recovery options
- LC options at CERN, consider ILC technology as starting point, ESPP inputs

Steinar Stapnes – CERN

Jan 23th - 2025

LC general considerations - reminder



Energy/Lum upgraded e+e-

“Higgs-factory” e+e-

LHC followed by HL LHC

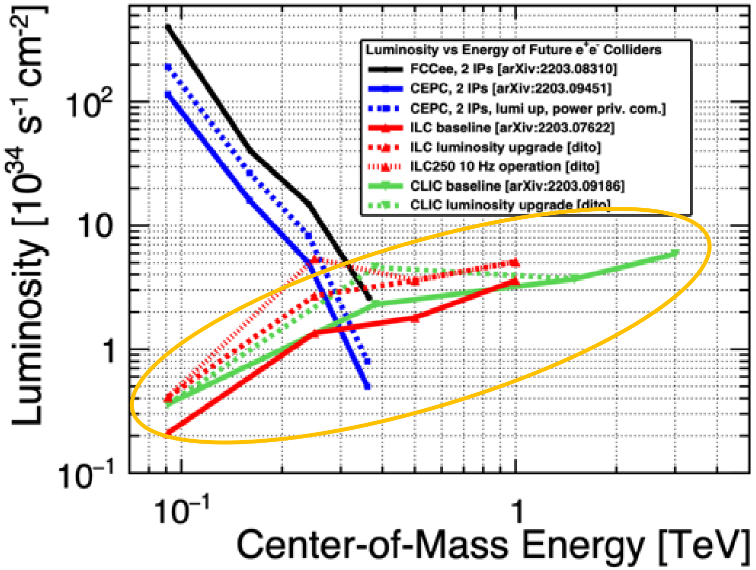
Today

2040

~2050-55

Time

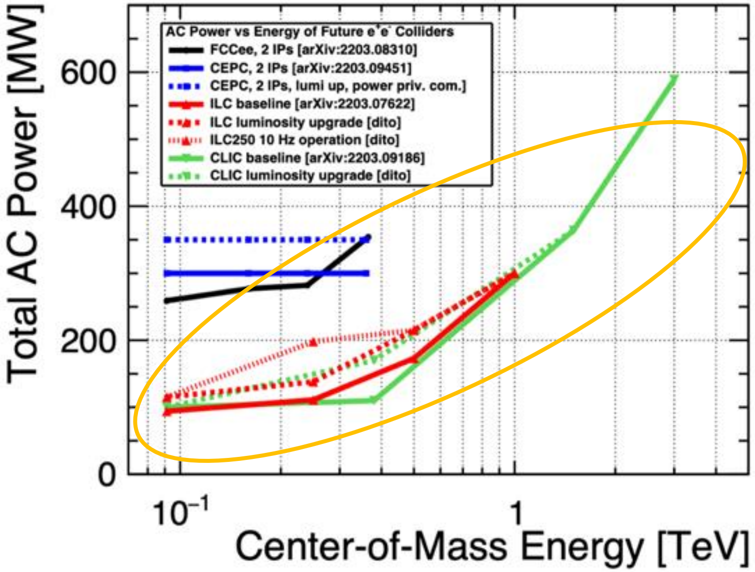
Start with mature technology, can expand in length and/or technology



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

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.



General goals for LCs:

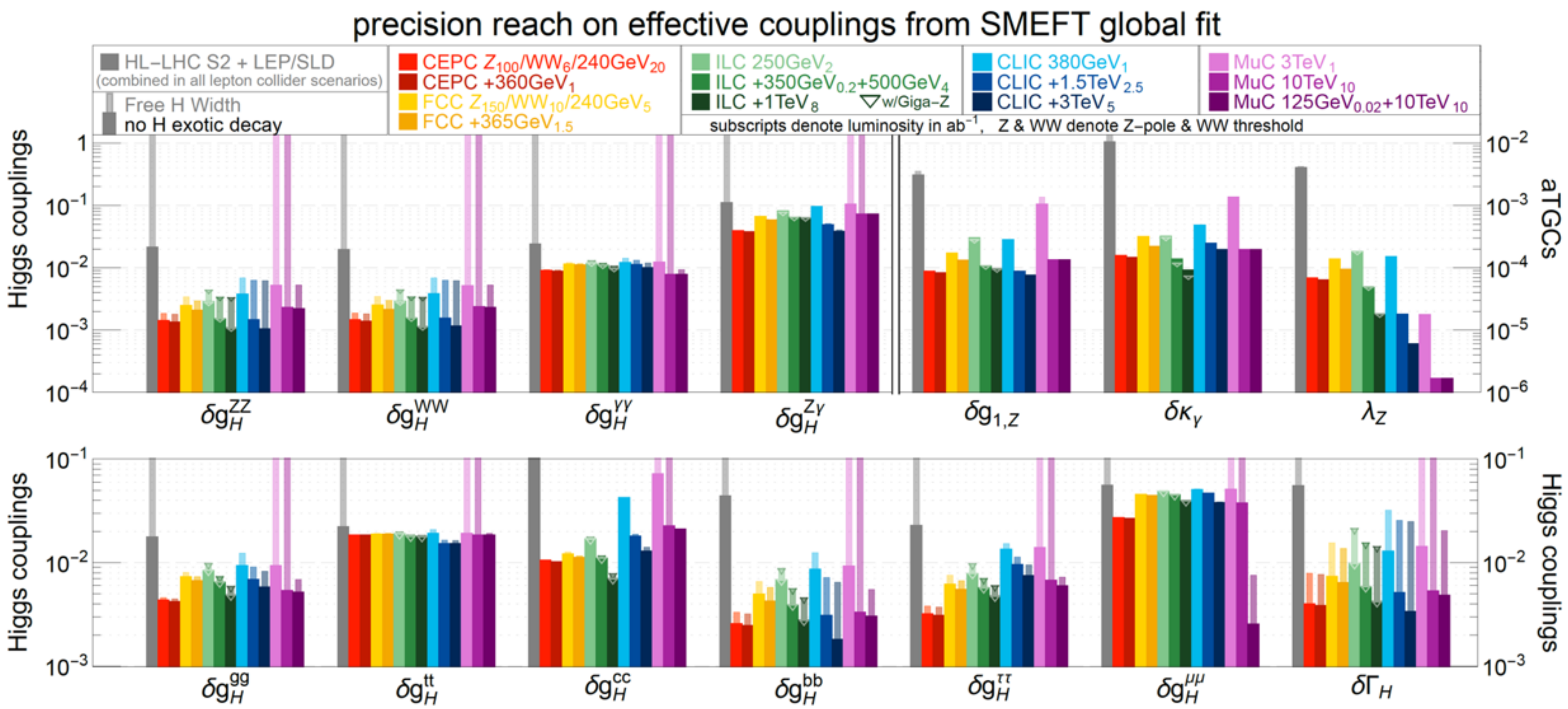
Energy reach and flexibility:
- Physics opportunities from Z-pole to 1-2 TeV (maybe more later on)
- One can adapt – with limitations – cost, power versus E and L
- Allows to adapt to development in physics

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



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

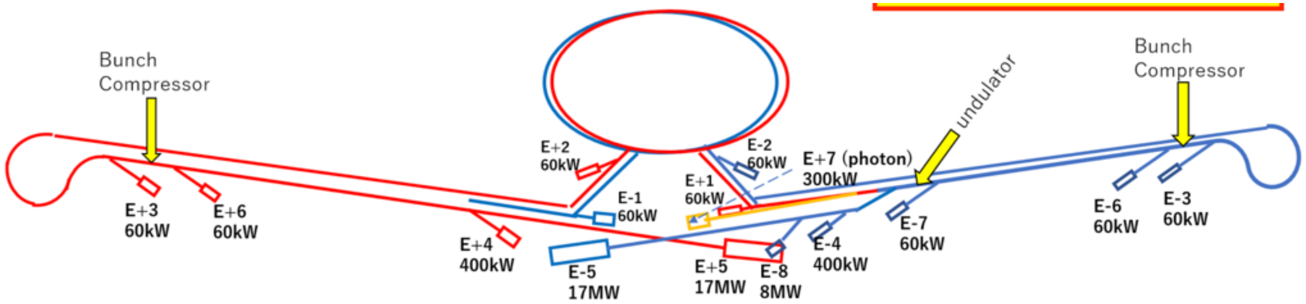
- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c

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:

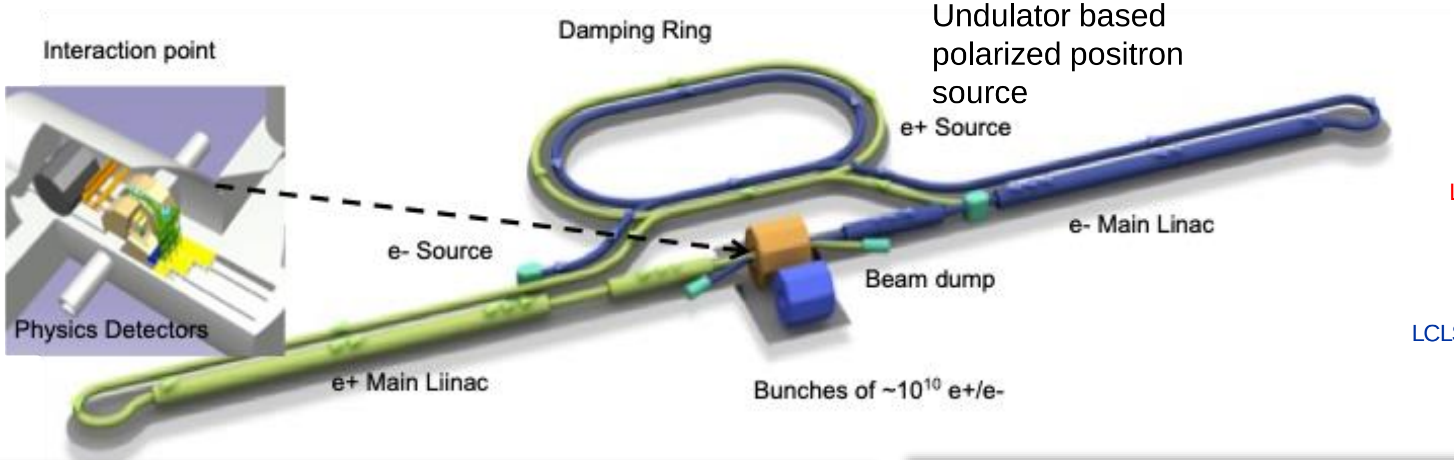
- ILCX – e.g. beam-dump experiments, dark sector physics, light dark matter, strong QED (ILCX workshop)
- Test and R&D beams for detector and accelerator studies



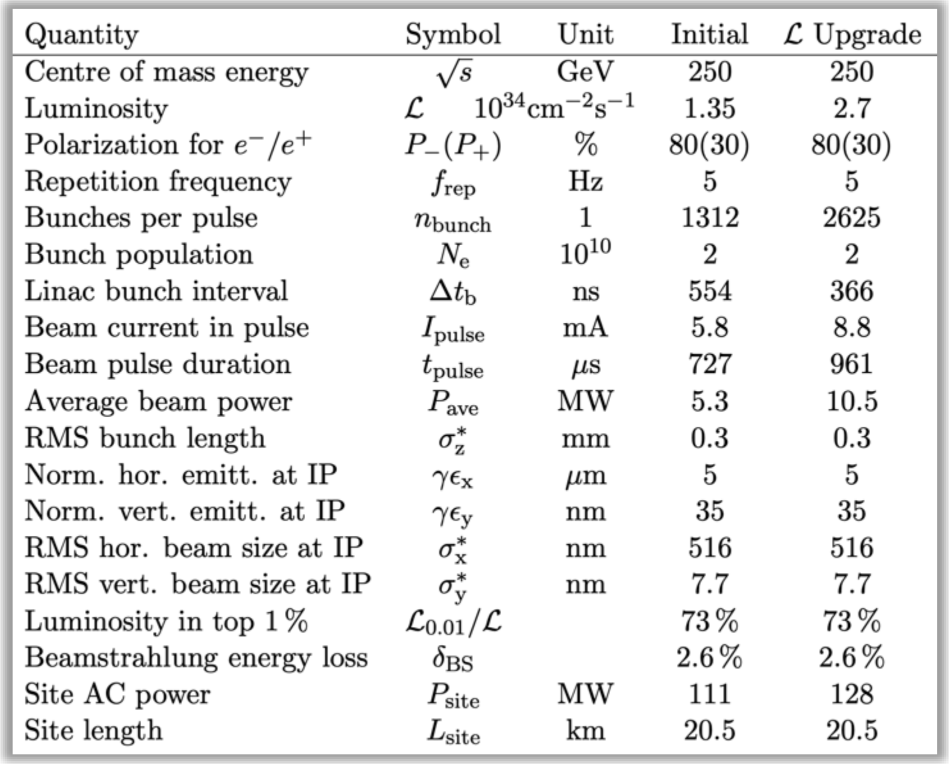
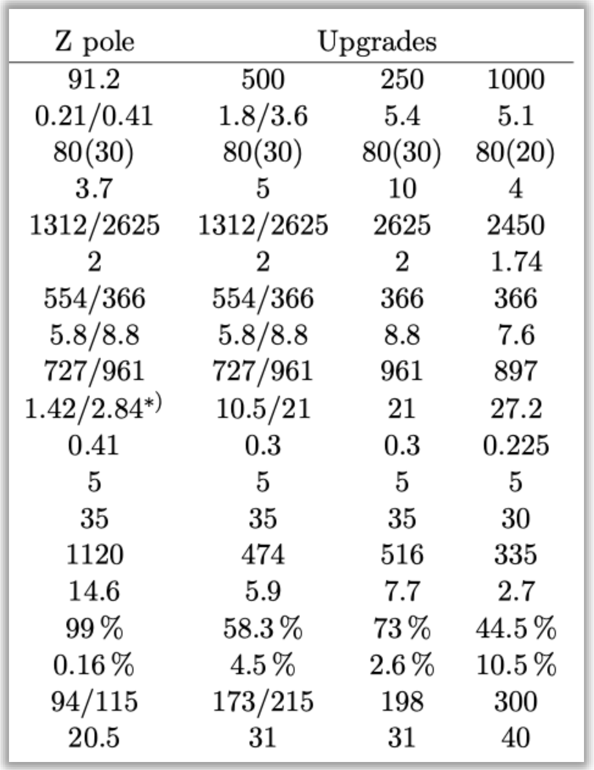
From J.List/M.Peskin

ILC – general updates and implementation in Japan, with some considerations for a CERN implementation (more later)

The ILC250 accelerator facility



Undulator based polarized positron source

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

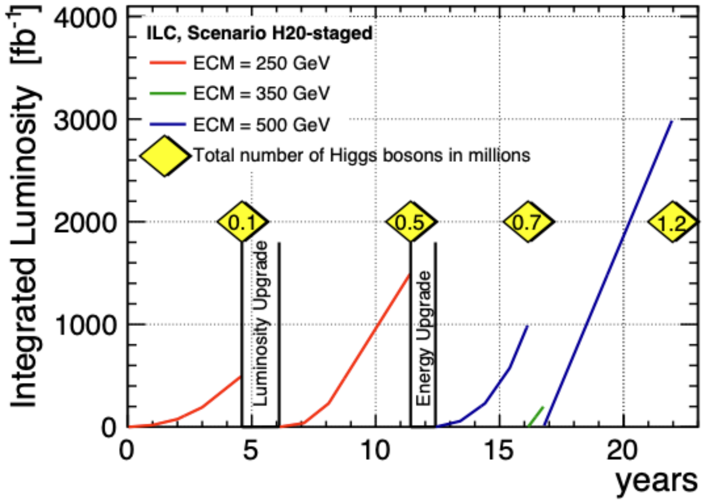
Parameters and plans for luminosity and energy upgrades are available, including information about relevant SCRF R&D for such upgrades at (Snowmass input)

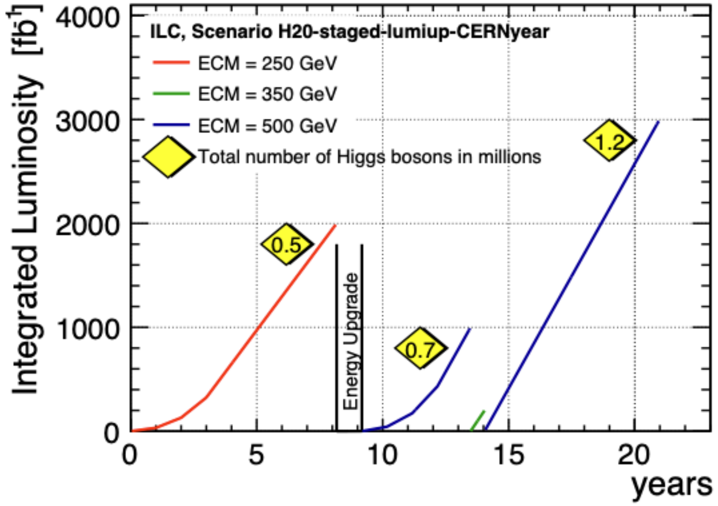
ILC in Japan has a certain run-plan, but one can easily consider higher luminosities and higher energies earlier.

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

From J.List (link)

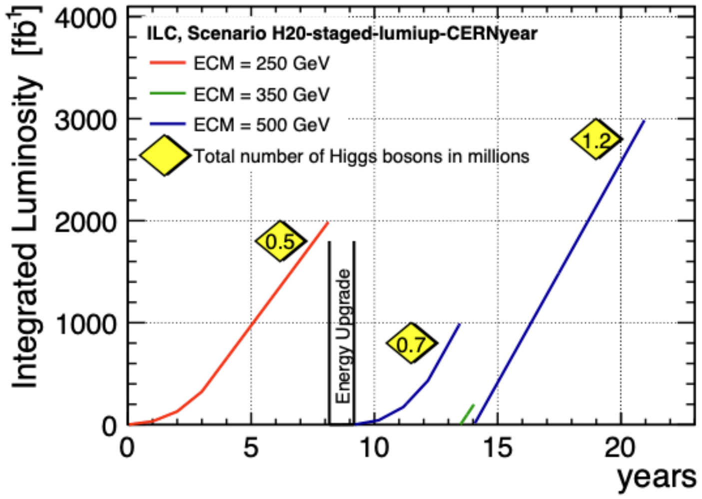
Increasing the number of bunches in a train, and adjusting to a CERN running year

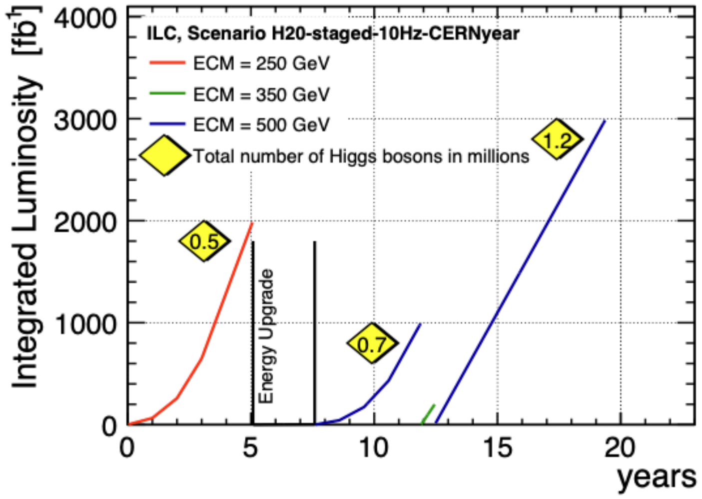




Higgs run ~8 years

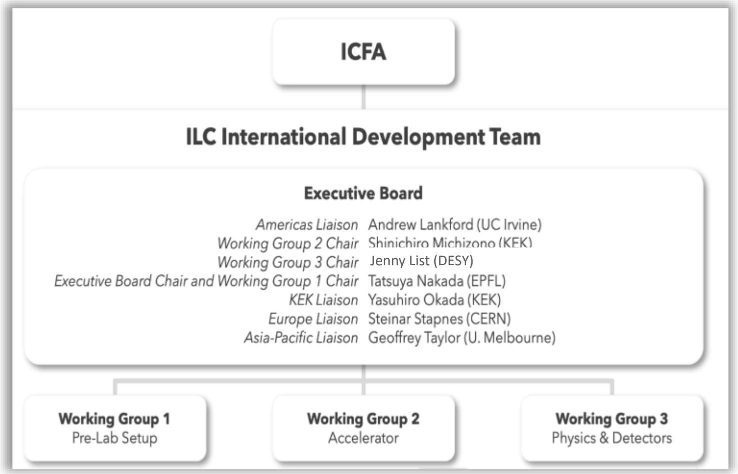
Doubling the frequence to 10 Hz (~200 MW). Note that in all cases a luminosity ramp up is foreseen





Higgs run 5 years

Some recent ILC developments - I



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)

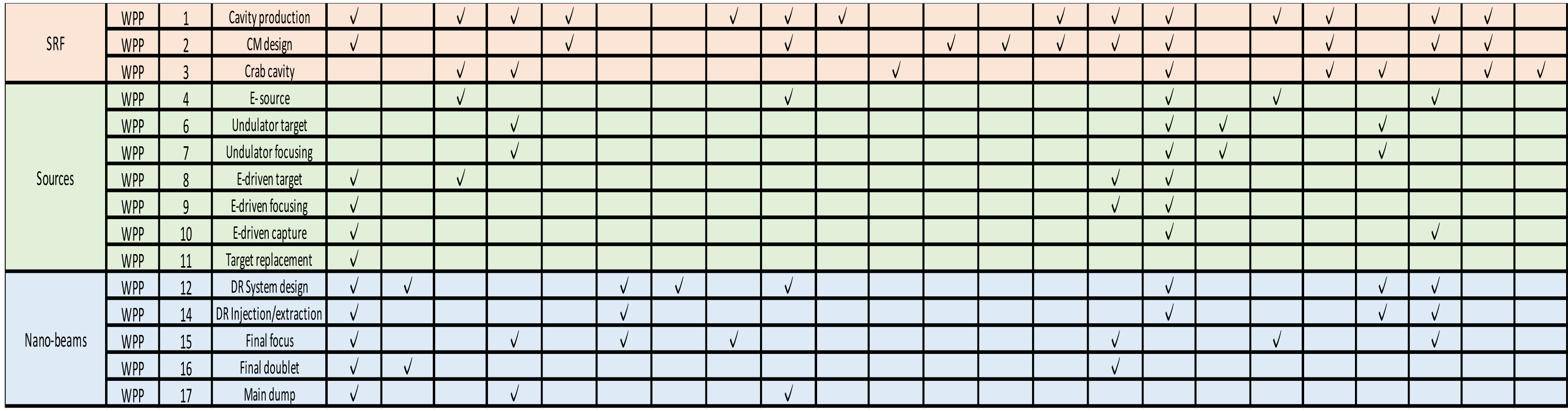
Working Group 1
Pre-Lab Setup

Working Group 2
Accelerator

Working Group 3
Physics & Detectors

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

2023/11/16



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

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)

INFN in ITN

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

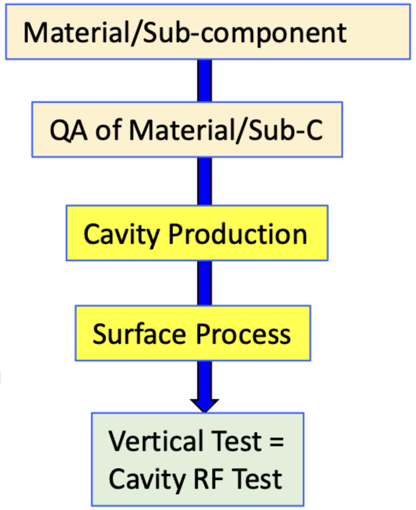
ML related tasks

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

Plus key industrial suppliers, R1, ZAMON, Thales, more

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)



Production process

	# of cavities to be produced		
	Americas	Europe	JP/Asia
single-cell	2	2	2
nine-cell	8	8	8

Some recent ILC developments - II

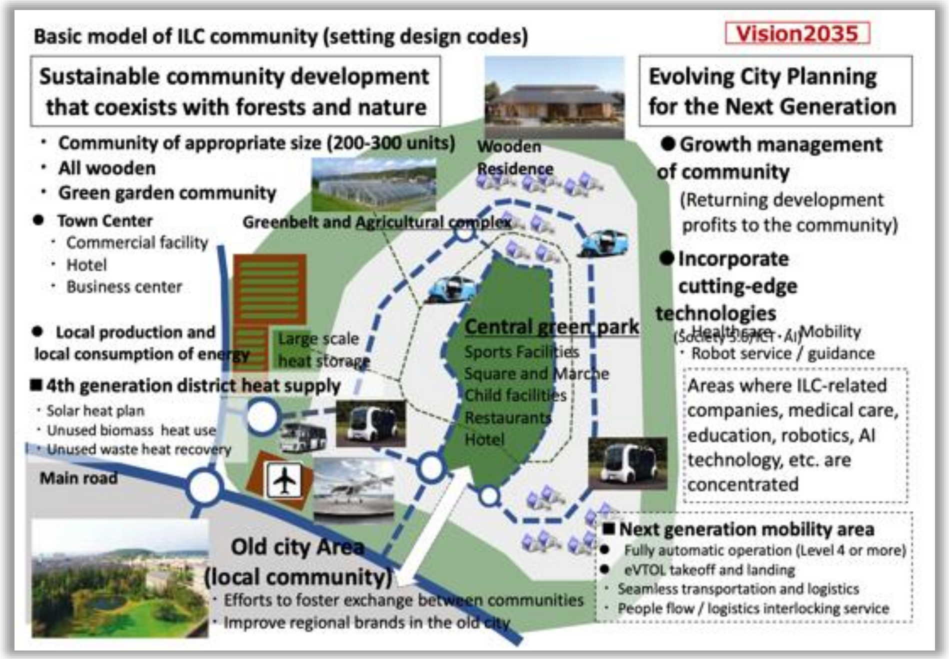
Re-evaluate CFS costs for ILC in Japan

- 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



Basic model of ILC community (setting design codes)

Vision2035

Sustainable community development that coexists with forests and nature

- **Community of appropriate size (200-300 units)**
- **All wooden**
- **Green garden community**

● **Town Center**

- Commercial facility
- Hotel
- Business center

● **Local production and local consumption of energy**

■ **4th generation district heat supply**

- Solar heat plan
- Unused biomass heat use
- Unused waste heat recovery

Wooden Residence

Greenbelt and Agricultural complex

Large scale heat storage

Main road

Central green park

Sports Facilities
Square and Marche
Child facilities
Restaurants
Hotel

Old city Area (local community)

- Efforts to foster exchange between communities
- Improve regional brands in the old city

Evolving City Planning for the Next Generation

● **Growth management of community**

(Returning development profits to the community)

● **Incorporate cutting-edge technologies**

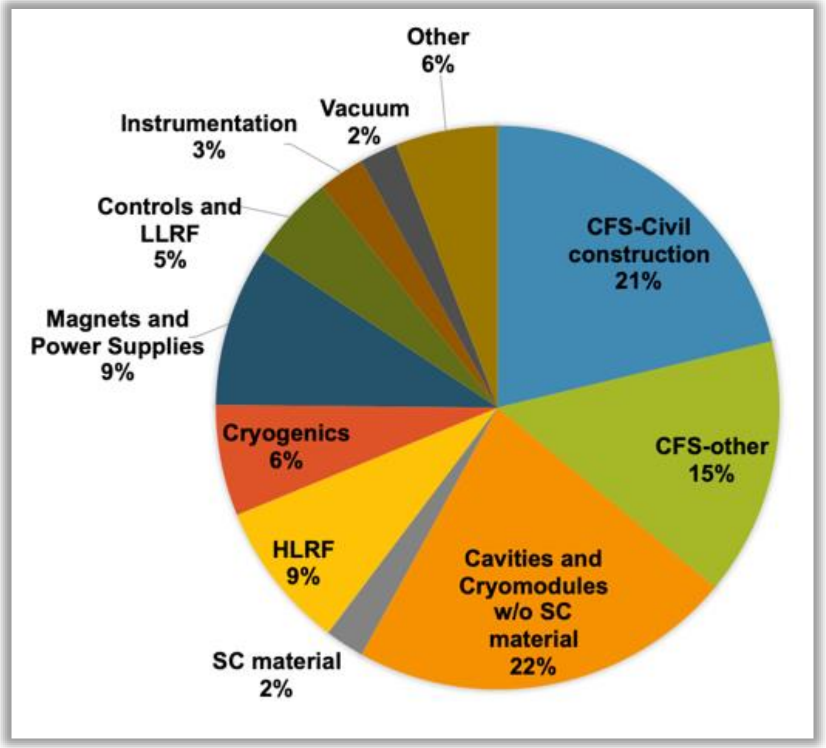
(Society 5.0/ICT · AI)

- Healthcare · AI Mobility
- Robot service / guidance

Areas where ILC-related companies, medical care, education, robotics, AI technology, etc. are concentrated

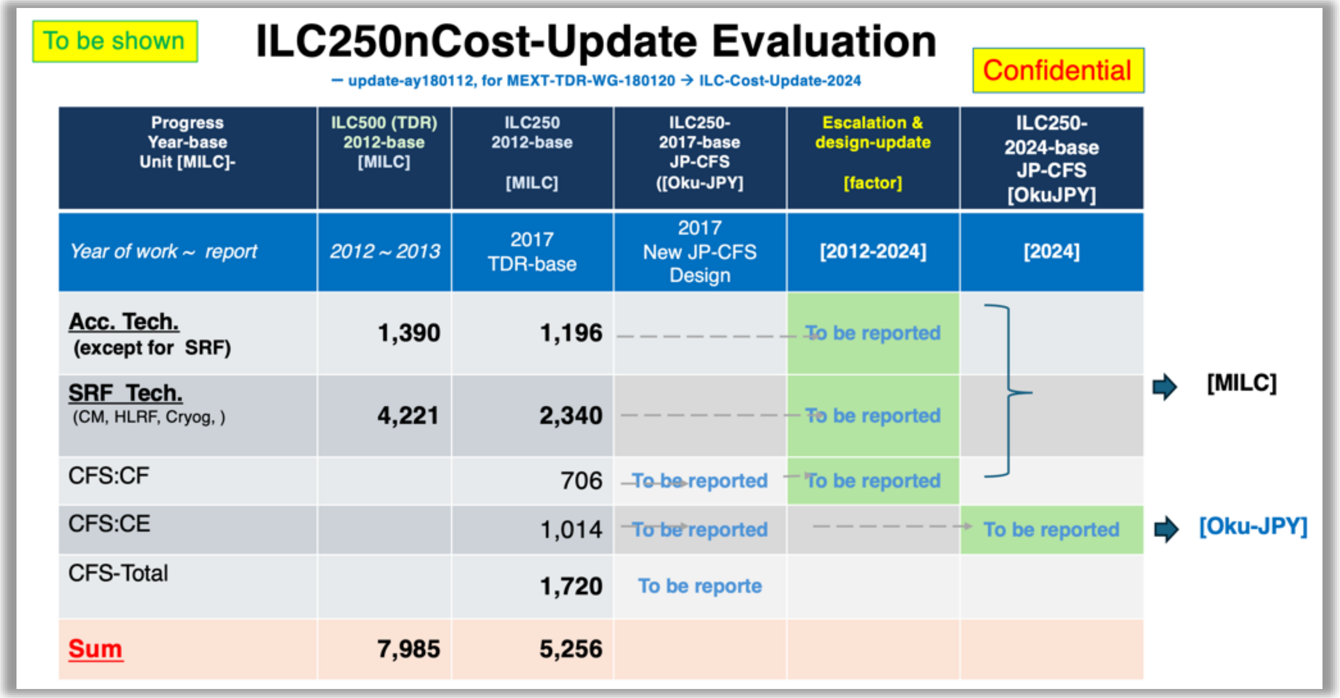
■ **Next generation mobility area**

- ● Fully automatic operation (Level 4 or more)
- ● eVTOL takeoff and landing
- Seamless transportation and logistics
- People flow / logistics interlocking service



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



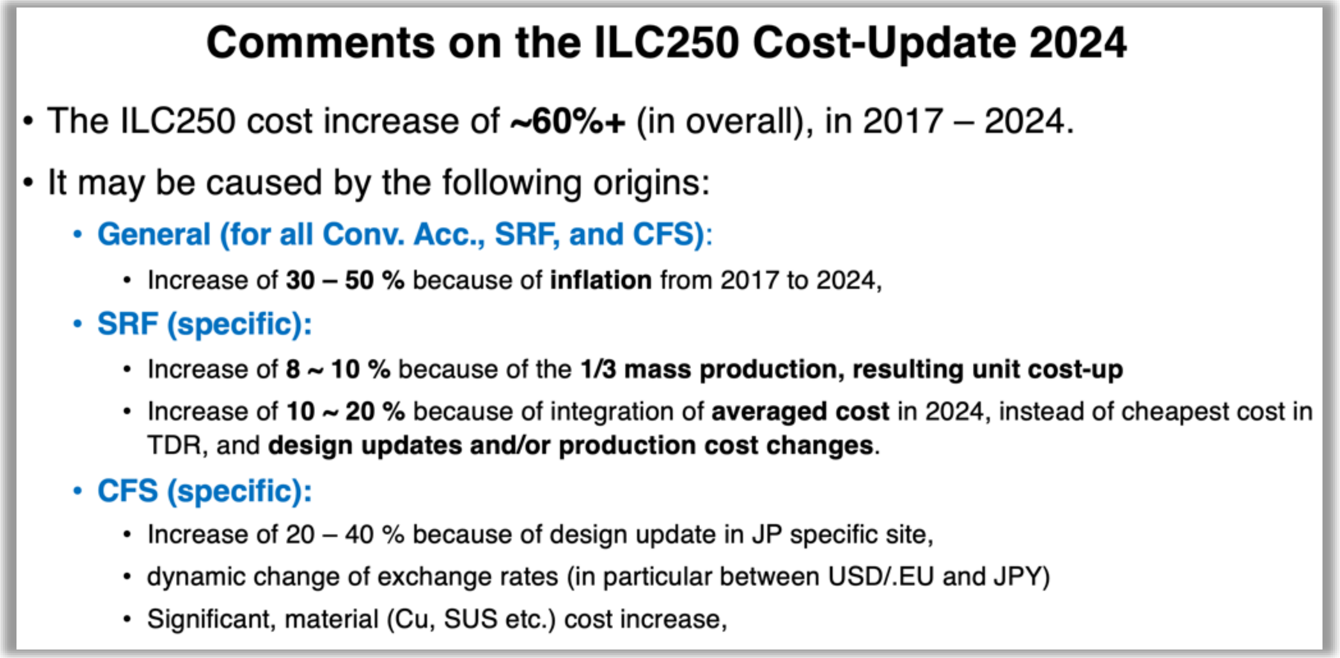
To be shown

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		
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				



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,

From report by A.Yamamoto (LINK)

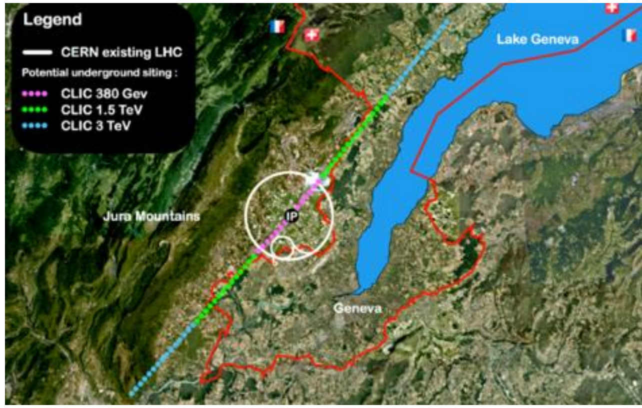
For CERN (in progress):

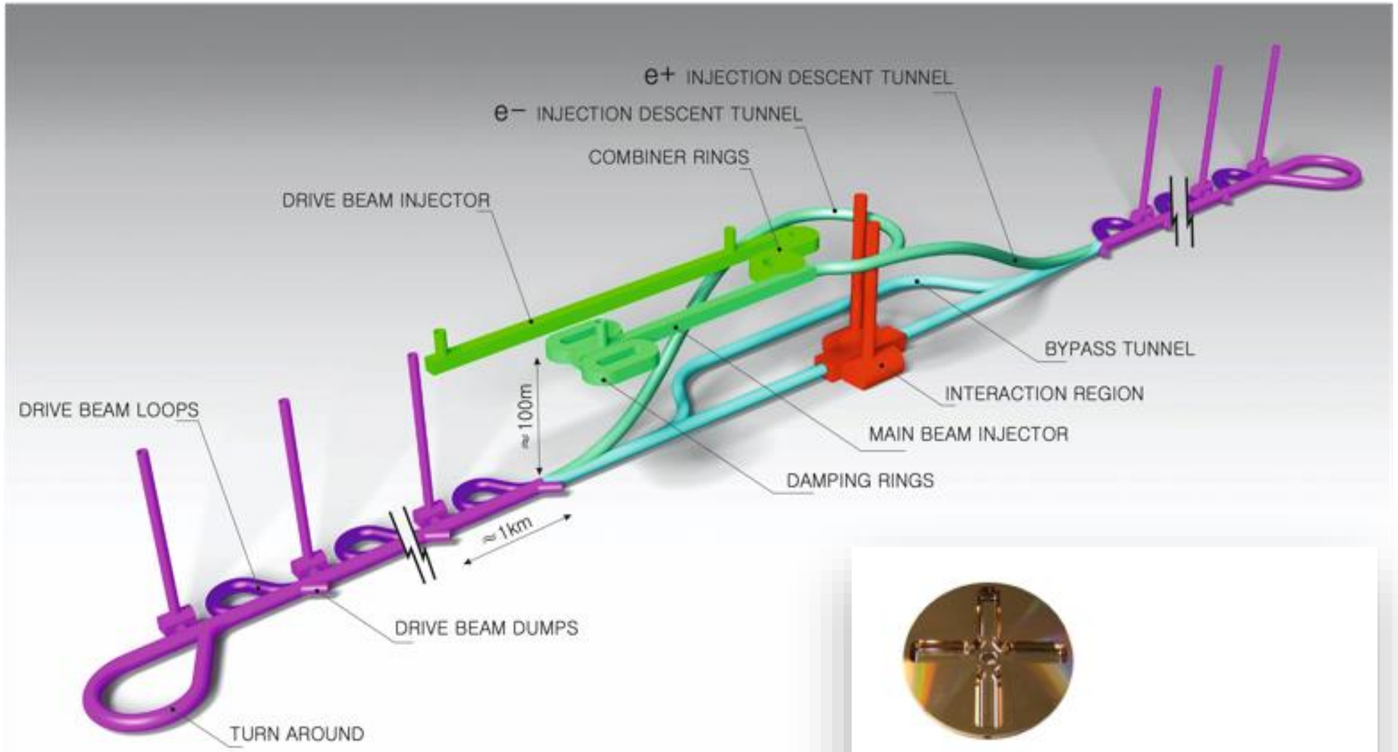
- Redo CE costing (see later)
- Redo CF costing (EL, CV, etc)
- Use 2024 costing for all components in their respective currencies, and change to CHF with exchange rate (not PPP)
- Cost second IP

1 CHF = 1.10 $

CLIC at CERN

The Compact Linear Collider (CLIC)





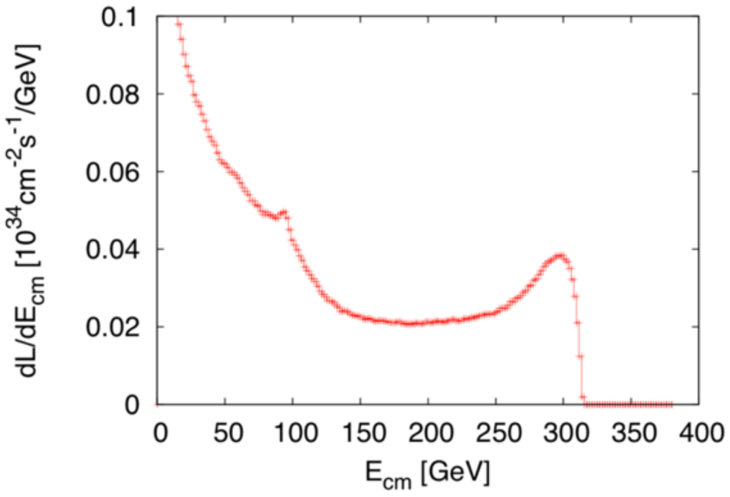
Accelerating structure prototype for CLIC: 12 GHz (L~25 cm), 100 MV/m

- **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[a], P. N. Burrows[b], S. Calatroni[a], N. Catalan Lasheras[a], R. Corsini[a], G. D'Auria[c], S. Doebert[a], A. Faus-Golfe[d], A. Grudiev[a], A. Latina[a], T. Lefevre[a], G. Mcmonagle[a], J. Osborne[a], Y. Papaphilippou[a], A. Robson[e], C. Rossi[a], R. Ruber[f], D. Schulte[a], S. Stapnes[a]*, I. Syratchev[a], W. Wuensch[a]

[a]CERN, Geneva, Switzerland, [b]John Adams Institute, University of Oxford, United Kingdom, [c]Elettra Sincrotrone Trieste, Italy, [d]IJCLab, Orsay, France, [e]University of Glasgow, United Kingdom, [f]Uppsala University, Sweden

April 4, 2022

Abstract

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

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

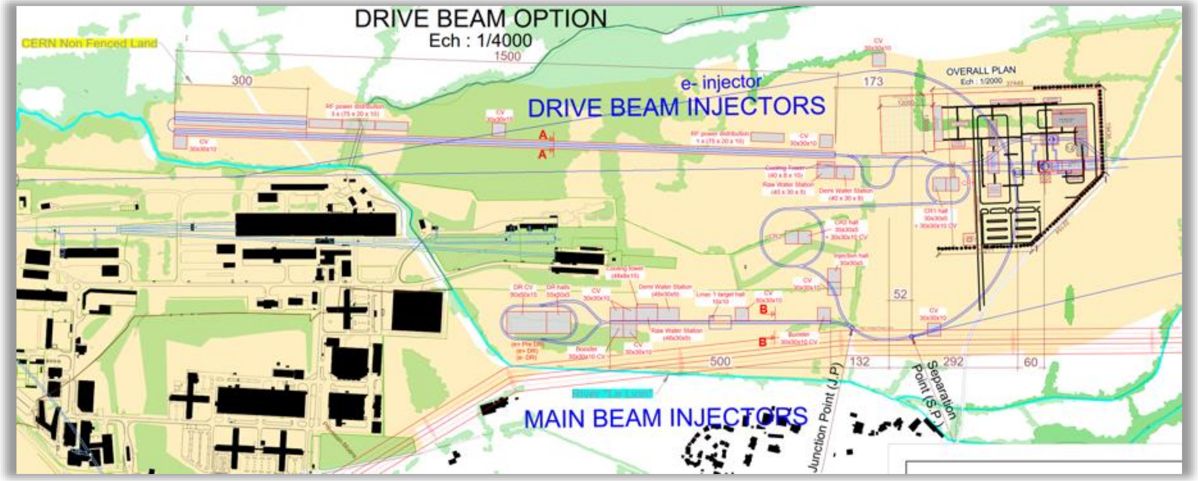
GENEVA
2024

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

The CLIC ESPP update - II



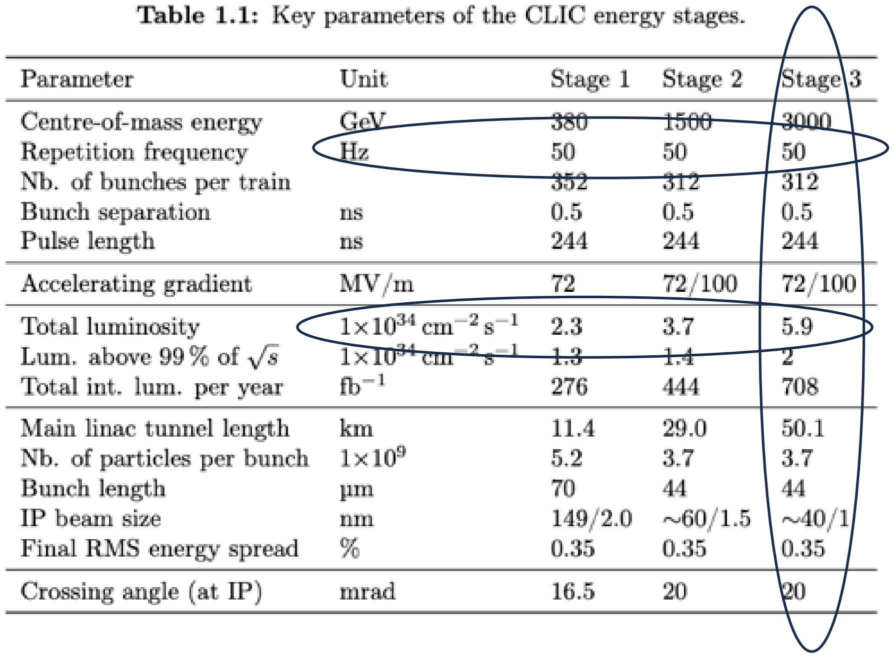
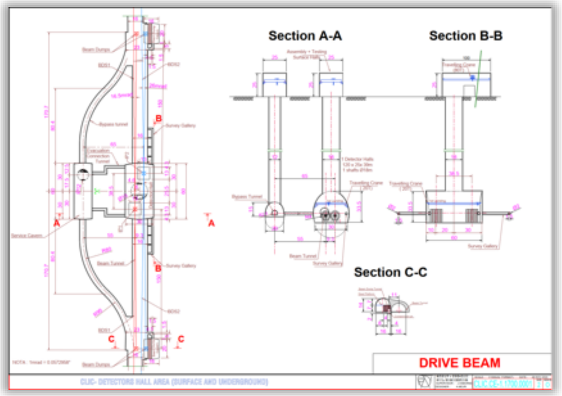


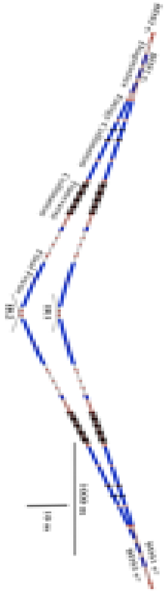
Table 1.1: Key parameters of the CLIC energy stages.

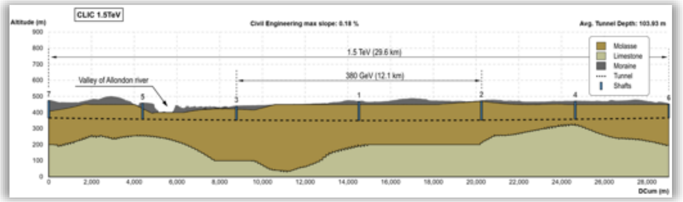
Parameter	Unit	Stage 1	Stage 2	Stage 3
Centre-of-mass energy	GeV	380	1500	3000
Repetition frequency	Hz	50	50	50
Nb. of bunches per train		352	312	312
Bunch separation	ns	0.5	0.5	0.5
Pulse length	ns	244	244	244
Accelerating gradient	MV/m	72	72/100	72/100
Total luminosity	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	2.3	3.7	5.9
Lum. above 99 % of $\sqrt{s}$	$1\times10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$	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

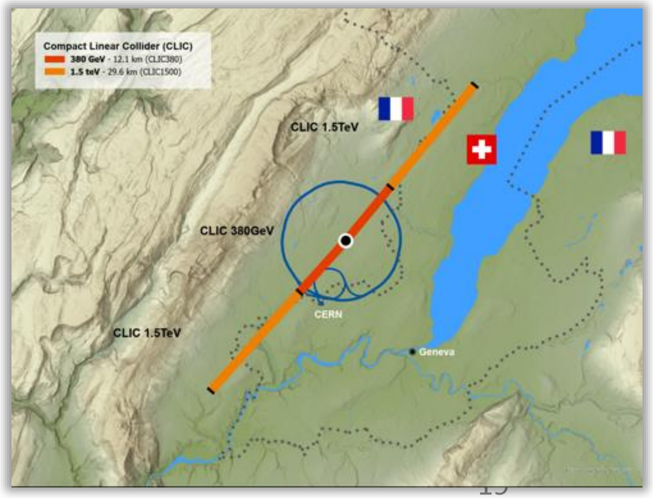
Add:
- 250 GeV parameters
- 100 Hz running for both 250 and 380 GeV

3 TeV: refer to earlier reports



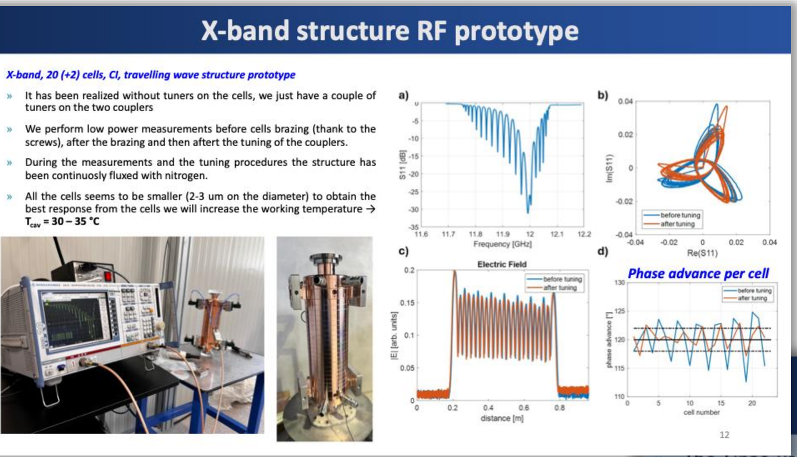






INFN and X-band

Talk of F. Cardelli July 2024 – LCWS 2024 in Tokyo (LINK)

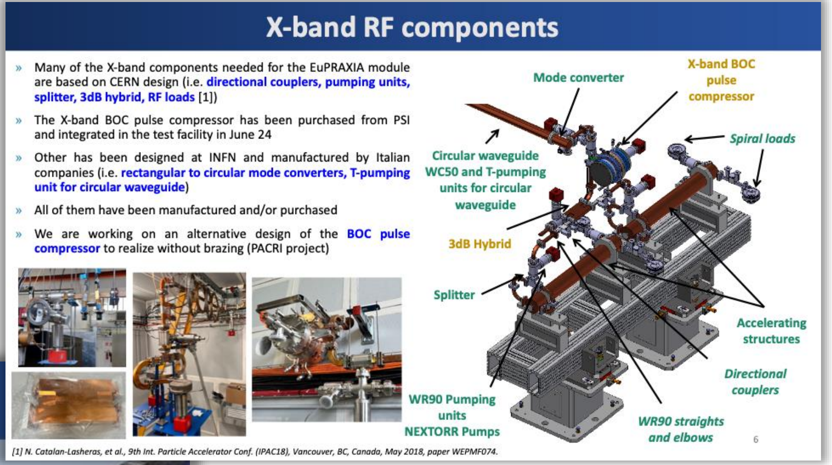


X-band structure RF prototype

X-band, 20 (+2) cells, CI, travelling wave structure prototype

- It has been realized without tuners on the cells, we just have a couple of tuners on the two couplers
- We perform low power measurements before cells brazing (thank to the screws), after the brazing and then aftert the tuning of the couplers.
- During the measurements and the tuning procedures the structure has been continuosly fluxed with nitrogen.
- All the cells seems to be smaller (2-3 um on the diameter) to obtain the best response from the cells we will increase the working temperature → T_{cav} = 30 – 35 °C

12



X-band RF components

- Many of the X-band components needed for the EuPRAXIA module are based on CERN design (i.e. **directional couplers, pumping units, splitter, 3dB hybrid, RF loads** [1])
- The X-band BOC pulse compressor has been purchased from PSI and integrated in the test facility in June 24
- Other has been designed at INFN and manufactured by Italian companies (i.e. **rectangular to circular mode converters, T-pumping unit for circular waveguide**)
- All of them have been manufactured and/or purchased
- We are working on an alternative design of the **BOC pulse compressor** to realize without brazing (PACRI project)

[1] N. Catalan-Lasheras, et al., 9th Int. Particle Accelerator Conf. (IPAC18), Vancouver, BC, Canada, May 2018, paper WEPMF074.

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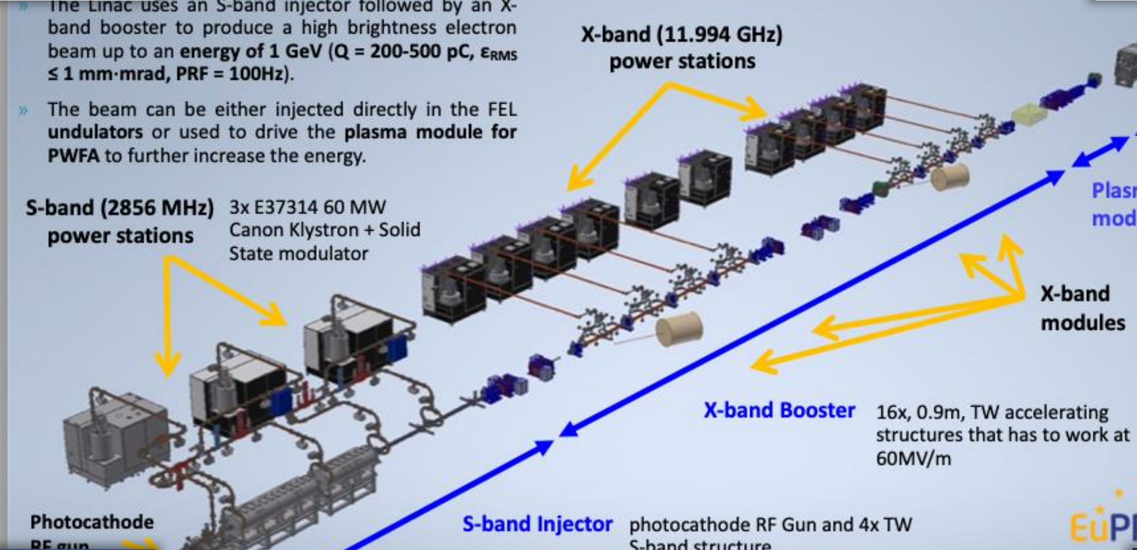
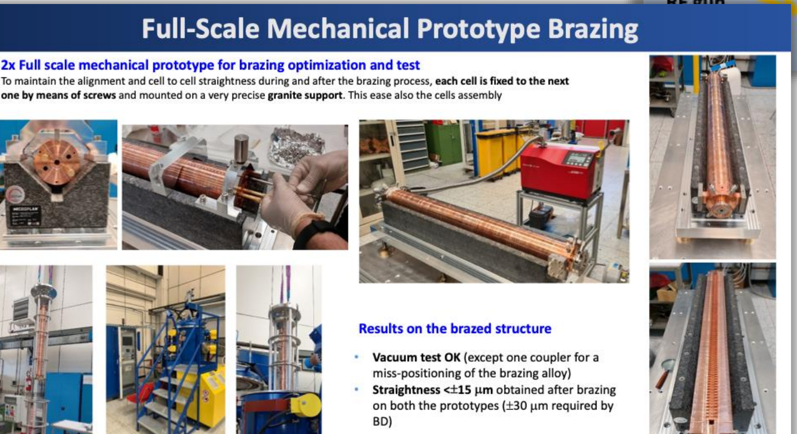


Overview of the LINAC

- The Linac uses an S-band injector followed by an X-band booster to produce a high brightness electron beam up to an **energy of 1 GeV (Q = 200-500 pC, ε_{RMS} ≤ 1 mm·mrad, PRF = 100Hz)**.
- The beam can be either injected directly in the FEL **undulators** or used to drive the **plasma module for PWFA** to further increase the energy.



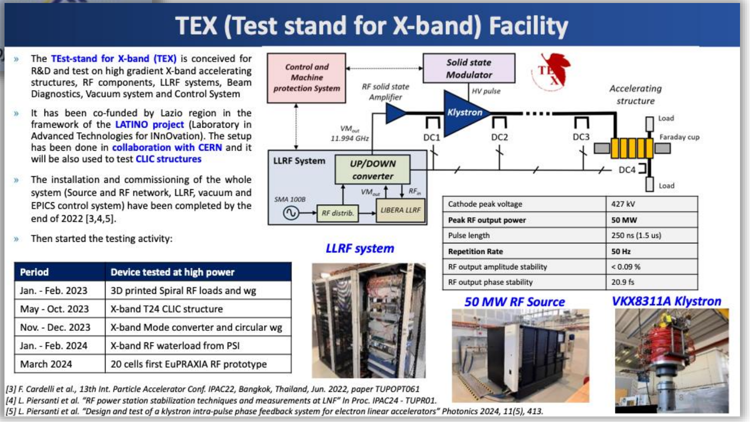
Full-Scale Mechanical Prototype Brazing

2x Full scale mechanical prototype for brazing optimization and test

To maintain the alignment and cell to cell straightness during and after the brazing process, **each cell is fixed to the next one by means of screws** and mounted on a very precise **granite support**. This ease also the cells assembly

Results on the brazed structure

- **Vacuum test OK** (except one coupler for a miss-positioning of the brazing alloy)
- **Straightness <±15 µm** obtained after brazing on both the prototypes (±30 µm required by BD)



TEX (Test stand for X-band) Facility

- The **TEst-stand for X-band (TEX)** is conceived for R&D and test on high gradient X-band accelerating structures, RF components, LLRF systems, Beam Diagnostics, Vacuum system and Control System
- It has been co-funded by Lazio region in the framework of the **LATINO project** (Laboratory in Advanced Technologies for INnOvation). The setup has been done in **collaboration with CERN** and it will be also used to test **CLIC structures**
- The installation and commissioning of the whole system (Source and RF network, LLRF, vacuum and EPICS control system) have been completed by the end of 2022 [3,4,5].
- Then started the testing activity:

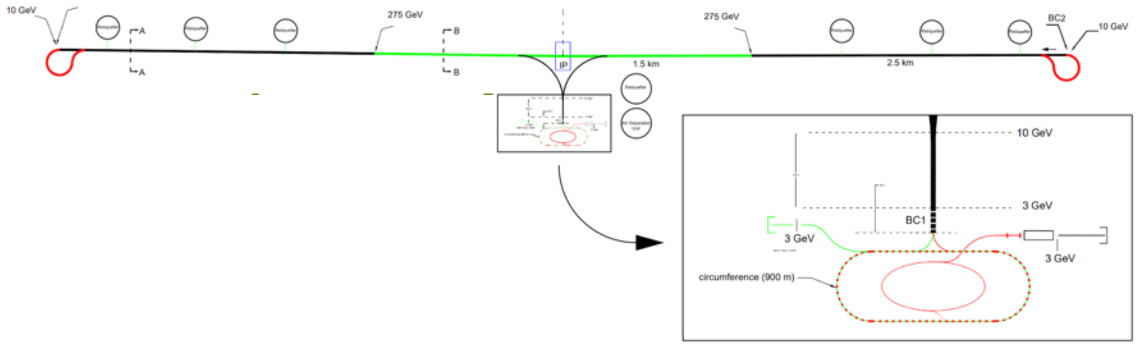
Period	Device tested at high power
Jan. - Feb. 2023	3D printed Spiral RF loads and wg
May - Oct. 2023	X-band T24 CLIC structure
Nov. - Dec. 2023	X-band Mode converter and circular wg
Jan. - Feb. 2024	X-band RF waterload from PSI
March 2024	20 cells first EuPRAXIA RF prototype

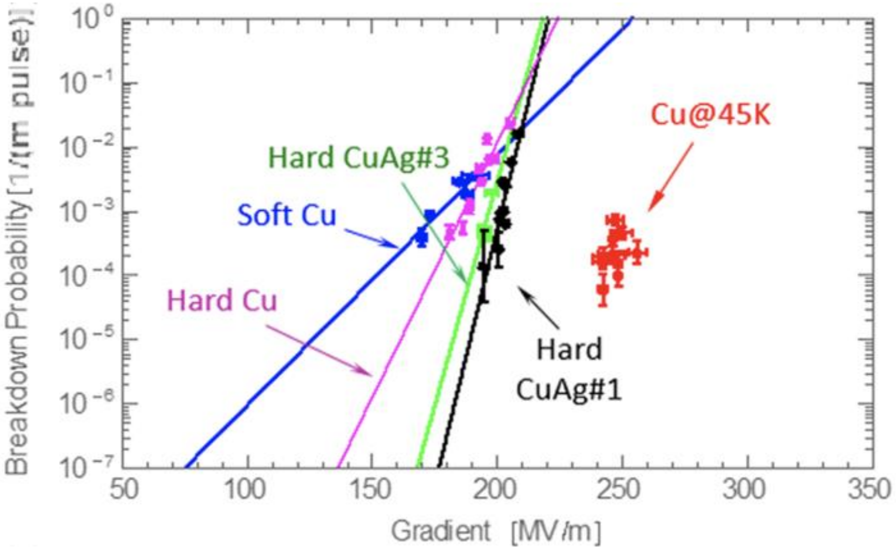
Cathode peak voltage	427 kV
Peak RF output power	**50 MW**
Pulse length	250 ns (1.5 us)
Repetition Rate	**50 Hz**
RF output amplitude stability	< 0.09 %
RF output phase stability	20.9 fs

[3] F. Cardelli et al., 13th Int. Particle Accelerator Conf. IPAC22, Bangkok, Thailand, Jun. 2022, paper TUPOPT061
[4] L. Piersanti et al. "RF power station stabilization techniques and measurements at LNF" In Proc. IPAC24 - TUPR01.
[5] L. Piersanti et al. "Design and test of a klystron intra-pulse phase feedback system for electron linear accelerators" Photonics 2024, 11(5), 413.

C3 and other options, stand-alone but currently not site specific, or now also being considered as upgrades of initial facility

C^3 Accelerator Complex





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

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

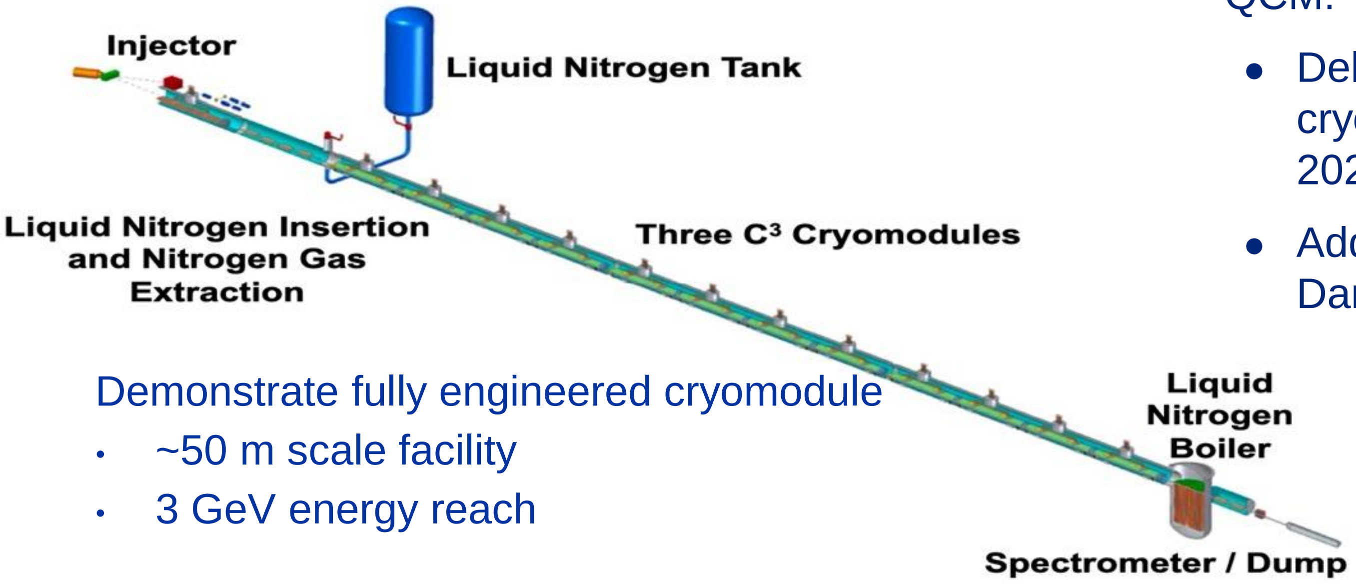
Large portions of accelerator complex compatible between LC technologies

- 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

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

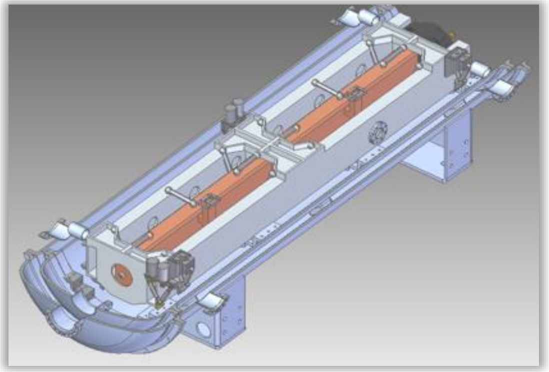


Demonstrate fully engineered cryomodule

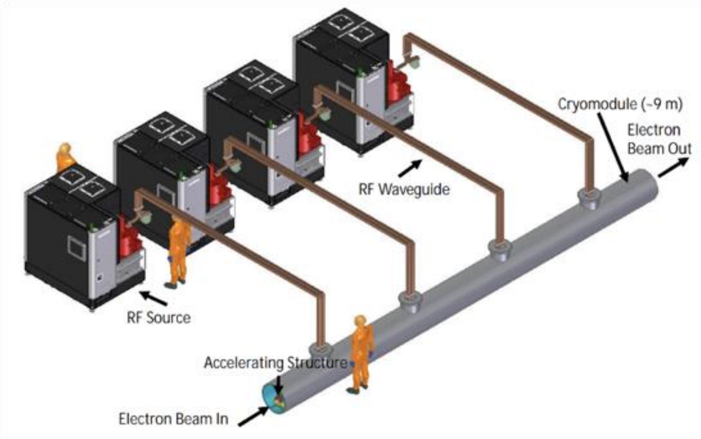
- ~50 m scale facility
- 3 GeV energy reach

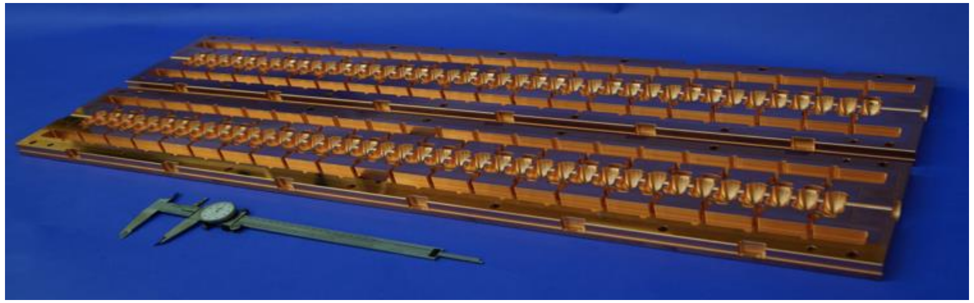
QCM:

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



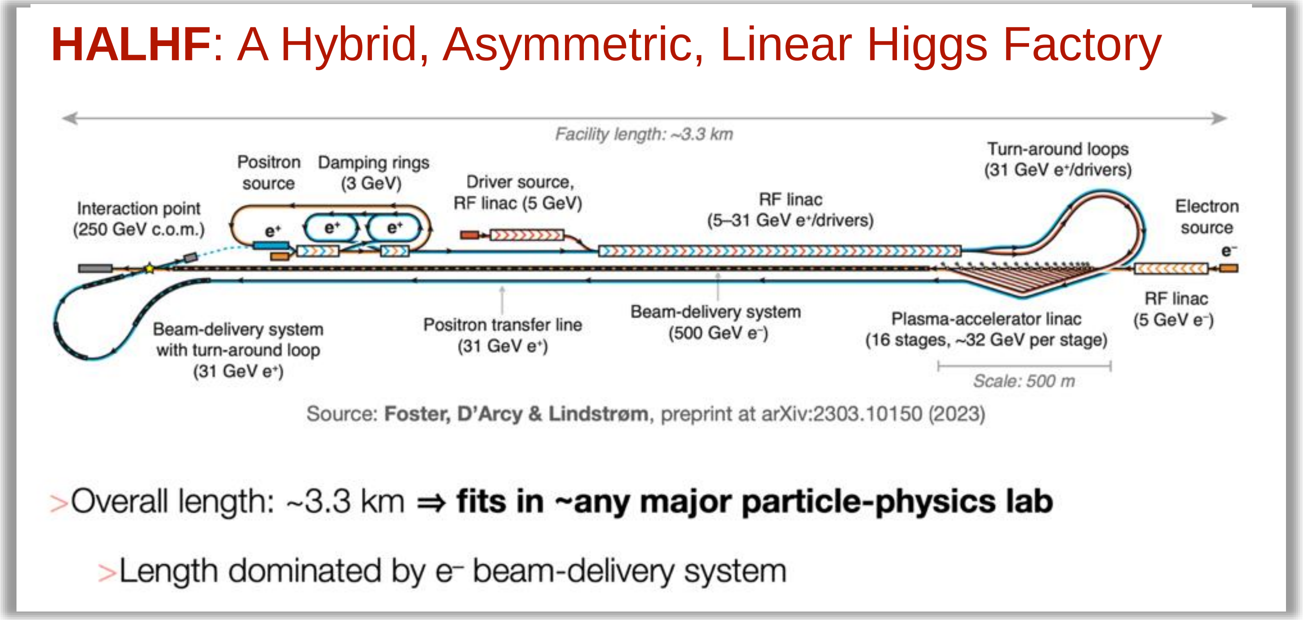
C^3 Main Linac Cryomodule
9 m (600 MeV/ 1 GeV)





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

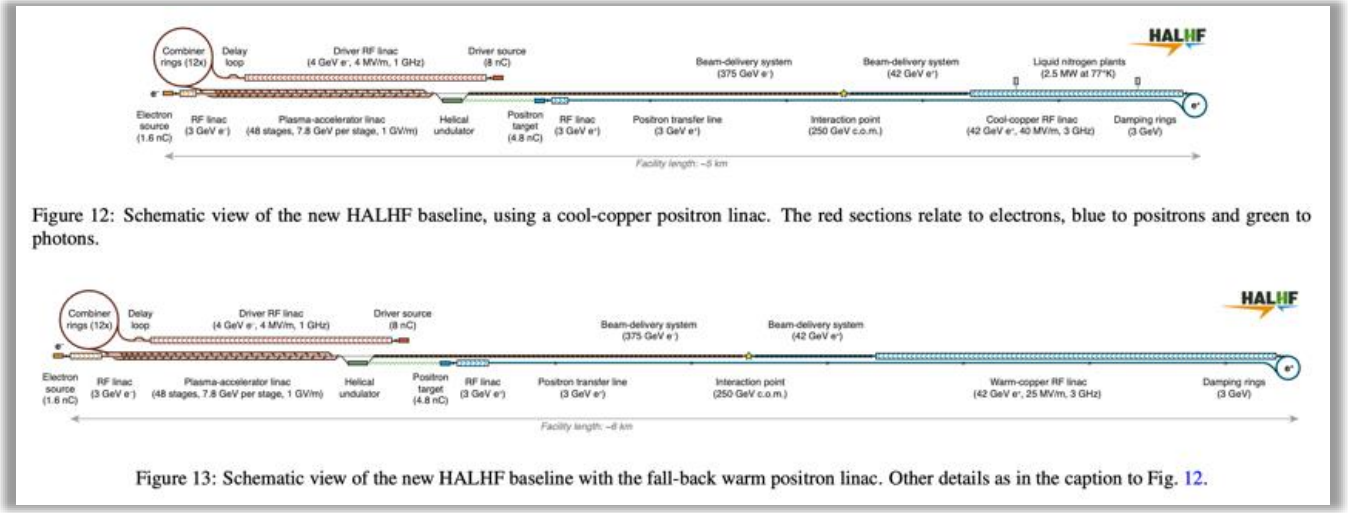


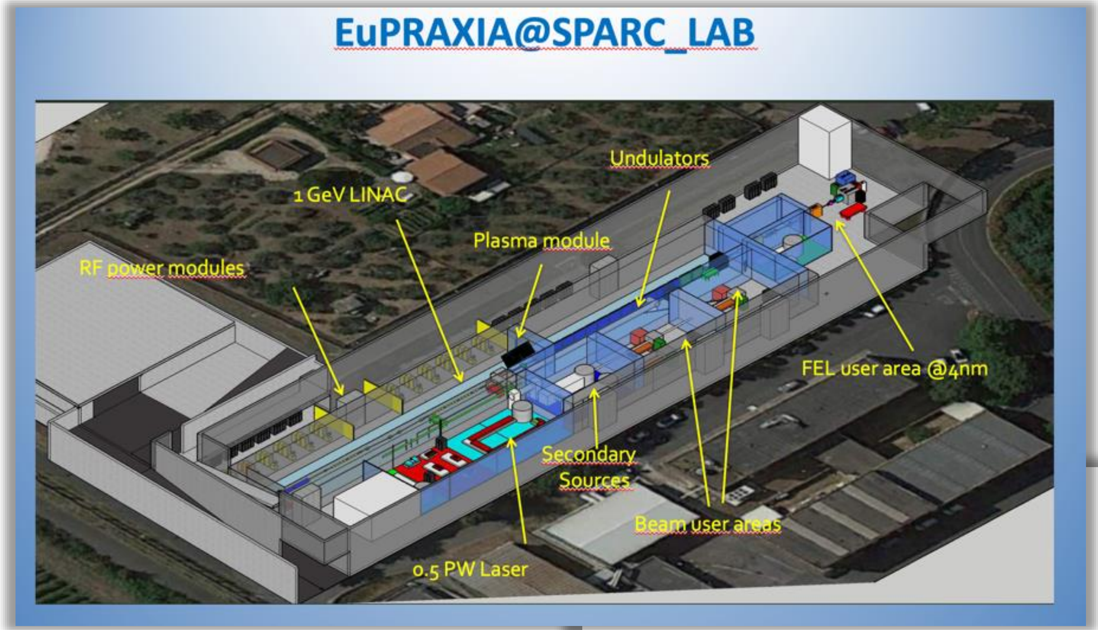
Figure 12: Schematic view of the new HALHF baseline, using a cool-copper positron linac. The red sections relate to electrons, blue to positrons and green to photons.

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

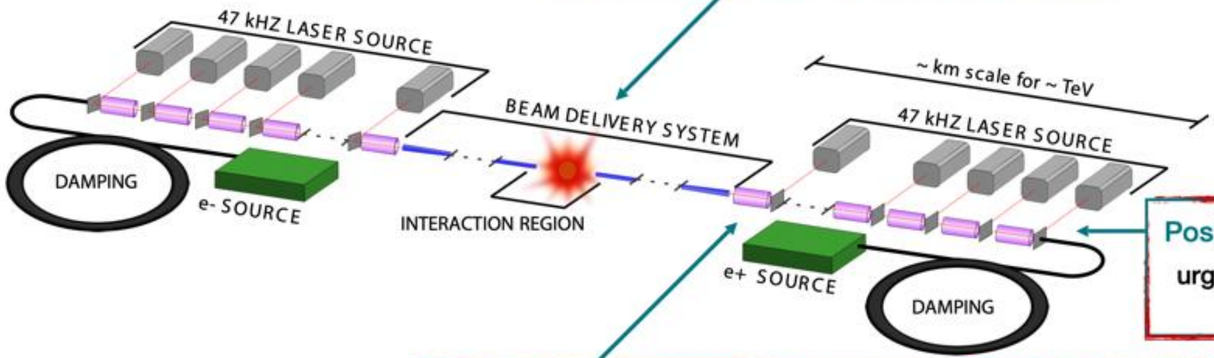
EUPRAXIA workshop September 2024:
Massimo Ferrario (LINK)
Jens Osterhoff (LINK)

EuPRAXIA@SPARC_LAB



Interaction region

- *10 TeV collider:* nonlinear QED studies
  to verify codes for beam/beam interaction



Positron acceleration

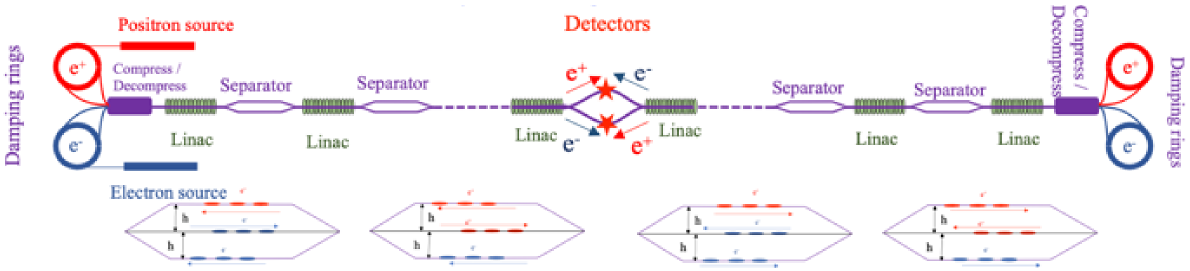
urgent need for positron test facility capabilities
→ new concepts under active R&D

Plasma stages + coupling

- Focus and key charge for our field, no roadblocks known
  critical - beam quality (incl. polarization), efficiency, stability, longevity, resilience to jitter (in time, space, and momentum), resilience to catastrophic errors (one bad shot)
- *Plasma stage:* requires demonstration of collider parameters
- *Staging:* requires detailed concepts, additional test facilities
  + critical - driver in-/out-coupling, geometric gradient

BERKELEY LAB

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



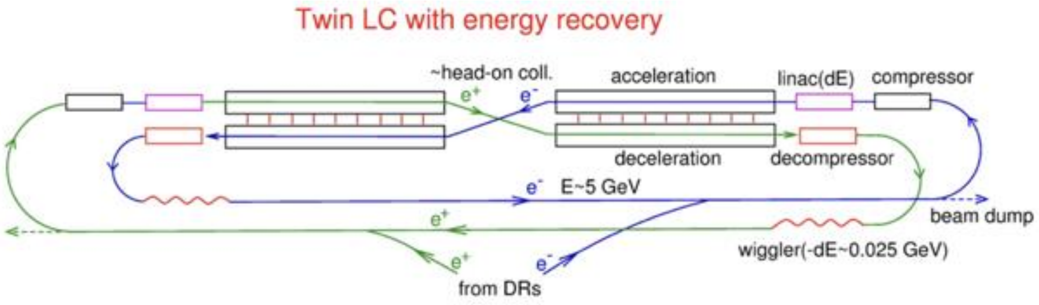


Figure 3-10. *Conceptual layout of the ERLC.*

ESPP inputs – I

Higgs factory focussed studies	**Project input (the traditional way)** **See earlier slides**
ILC	ILC in Japan (JAHEP/ILC-Japan and IDT)
CLIC	CLIC at CERN
C3	Project study, focus on next phase
HALHF	Project concept, pre-CDR
Energy recovery	Project concepts and plans (tbd)

LC “vision”

Also as option at CERN

An adaptable e+e- LC facility at CERN

Energy/Lum upgraded e+e-

“Higgs-factory” e+e-

LHC followed by HL LHC

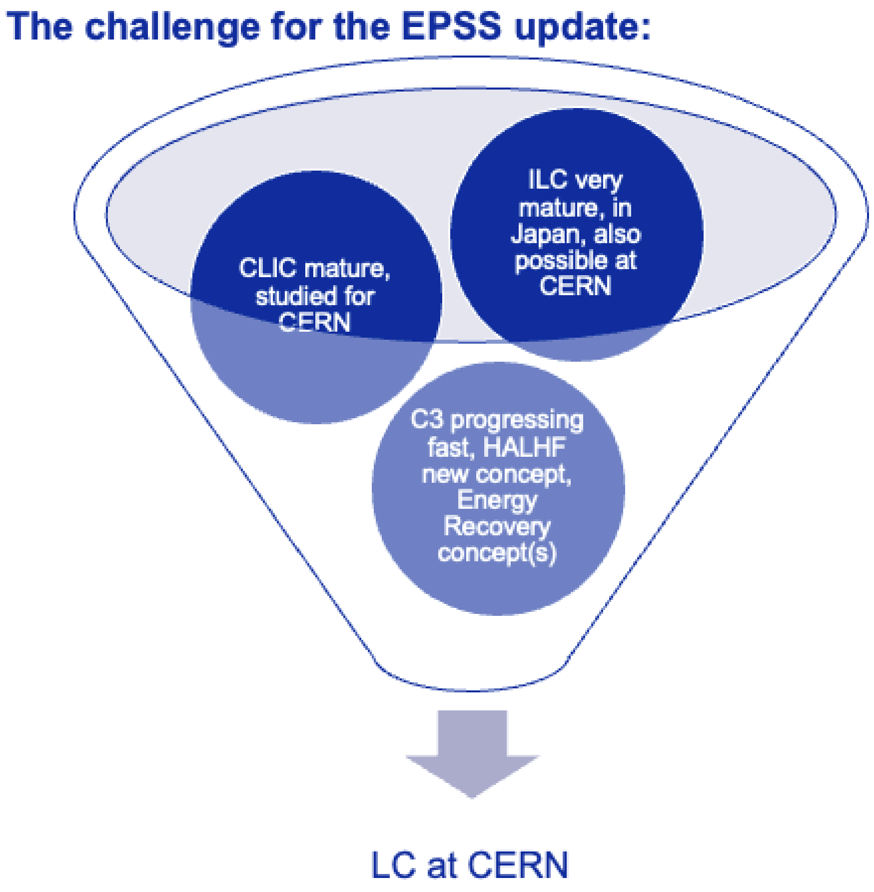
Today 2040 ~2050-55 Time

A LC facility can be extended in length for higher energies, using the same or improved versions of the same technology, e.g. as suggested for ILC, CLIC, C3 and HALHF.

- It is also possible and realistic to change to more performant (usually higher gradient) technologies in an upgrade, e.g. from ILC to CLIC or C3, maybe even plasma and energy recovery based solutions
- The physics at higher energies – Higgs sector and extended models with increased reach and precision, top in detail well above threshold, searches and hopefully new physics – will open for a very exciting long term e+e- programme
- Such a programme can run in parallel with future hadron and/or muon colliders that can be developed, optimised and implemented as their key technologies mature
- It keep options open, provides flexibility, encourages and motivates R&D across a broad range of technologies and potential future colliders/accelerator/detector technologies

ESPP inputs – II

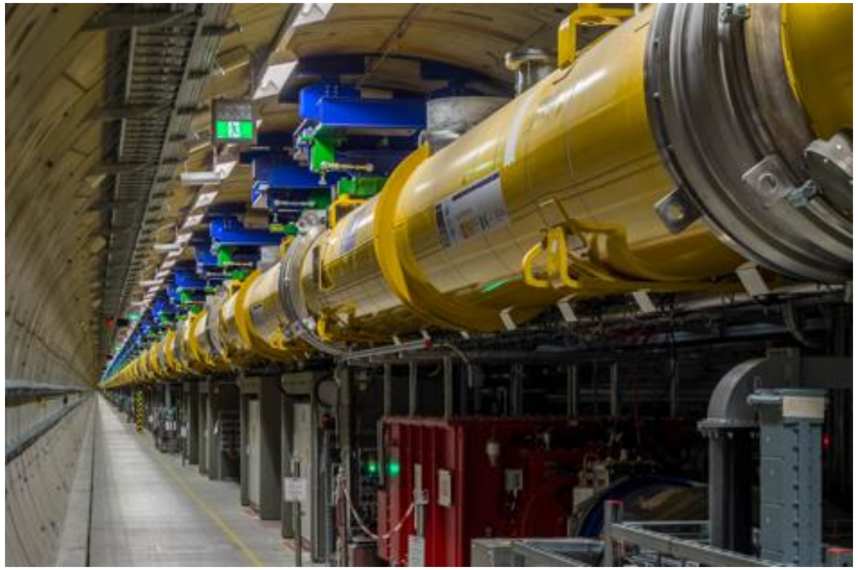
For a LC at CERN, what would be the possible options to start with – keeping in mind technology changes can be envisaged ?



New approach for this ESPP (facility and community approach) – with three key inputs to the ESPP
Common LC physics paper covering from 90 GeV to 1000 GeV or even above. Include also non collider programme (see slide 5). Serves also the projects on previous page.
Starting with ILC technology, look at energy and luminosity extension options with improved SFR, or CLIC, C3, plasma and Energy Recovery technologies
Implementation of the above at CERN in footprint studied for CLIC (and ILC back in the TDR days), with two BDS, and experimental area at Prevessin, and considerations of upgrade options.

ESPP inputs – III

Why consider SRF 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) ?
  - Can this be turned into schedule advancement ?

Cost and Personnel estimates – Higgs factories

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						

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.

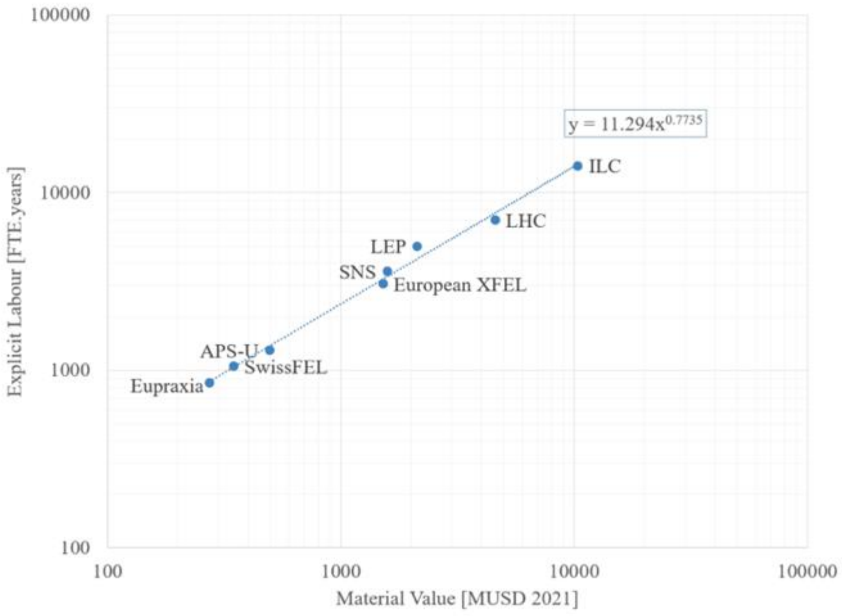


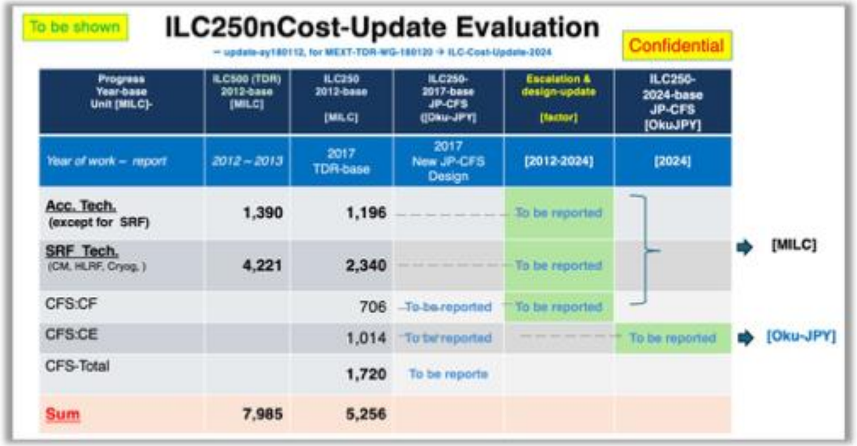
Figure 5: Explicit labor for several large accelerator projects vs. project value.

One FTEy estimated to 200kUS$.

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)



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		
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				

Comments on the ILC250 Cost-Update 2024

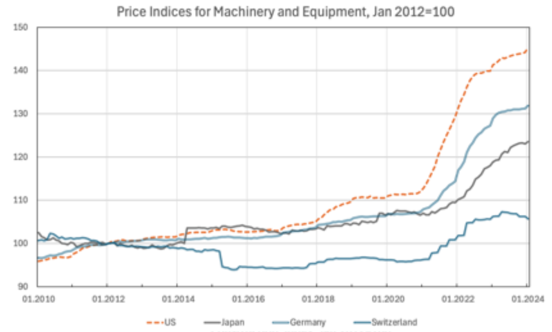
- The ILC250 cost increase of **~60%+** (in overall), in 2017 – 2024.
- It may be caused by the following origins:
  - **General (for all Conv. Acc., SRF, and CFS):**
    - Increase of **30 – 50 %** because of **inflation** from 2017 to 2024,
  - **SRF (specific):**
    - Increase of **8 ~ 10 %** because 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,

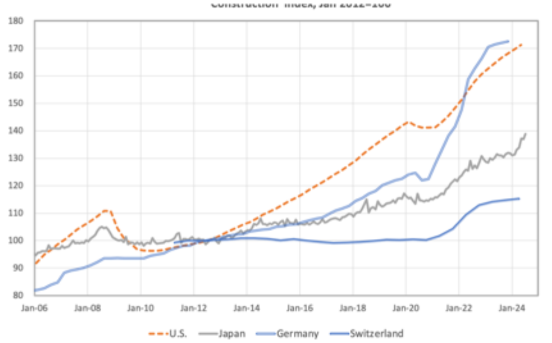
From report by A.Yamamoto (LINK)

For CERN (in progress):

- Redo CE costing (see later)
- Redo CF costing (EL, CV, etc)
- Use 2024 costing for all components in their respective currencies, and change to CHF with exchange rate (not PPP)
- Cost second IP

1 CHF = 1.10 $





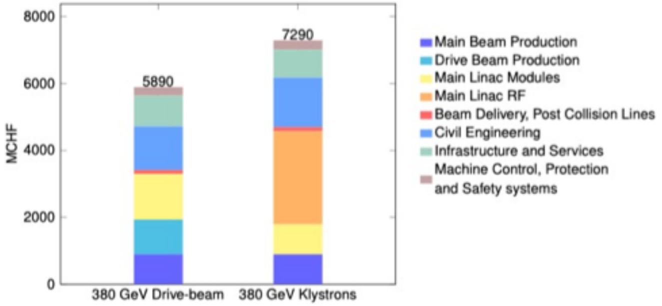
Cost – I (currently being updated)

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;

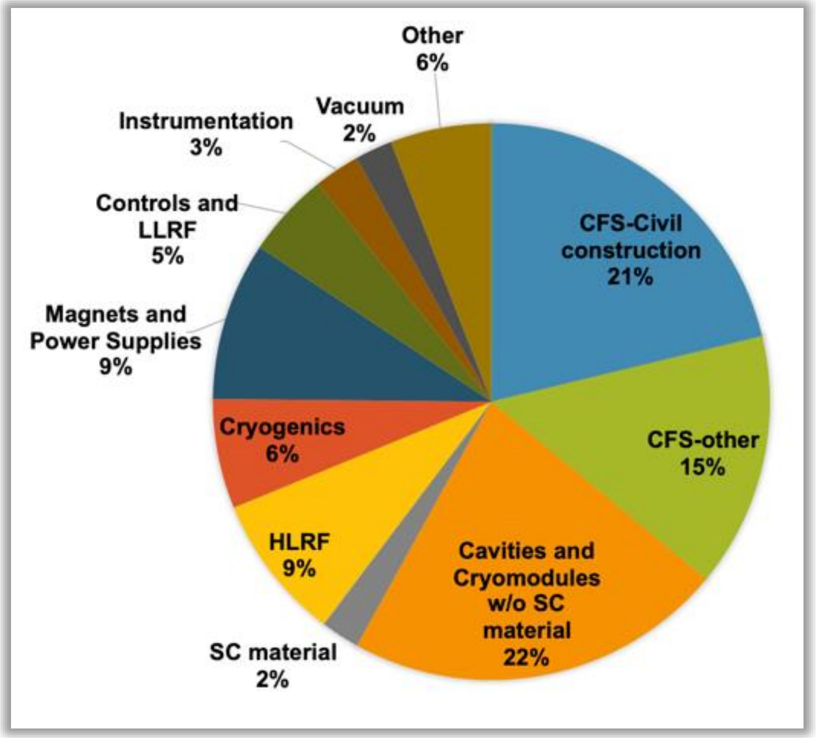
CLIC 380 GeV Klystron based: 7290^{+1800}_{-1540} MCHF.

Costs

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 12-13)



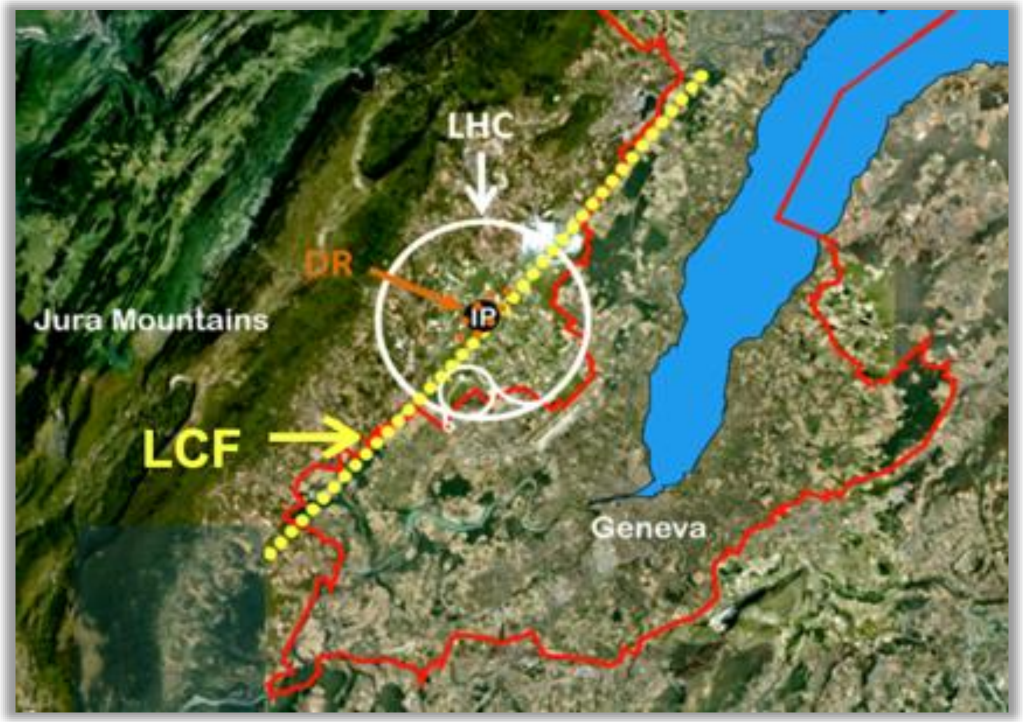
For the ESPP – concerning starting with ILC technology at CERN:

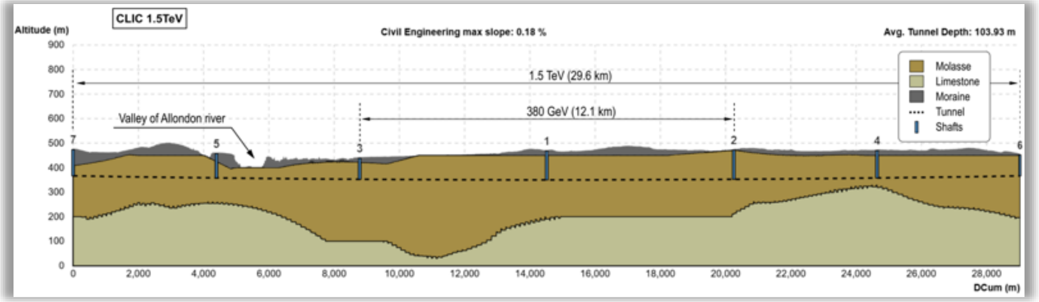
- Updated: ILC in Japan with updated technology results, updated CFS (CE and conv. systems, SRF) – discussed on slide 12-13
- CERN implementation: CE costs based on CLIC and other CERN projects, same main linac footprint, change in number of shafts, add larger underground DR, remove drivebeam CE and turn arounds, slightly different BDS dimensions and cavern sizes

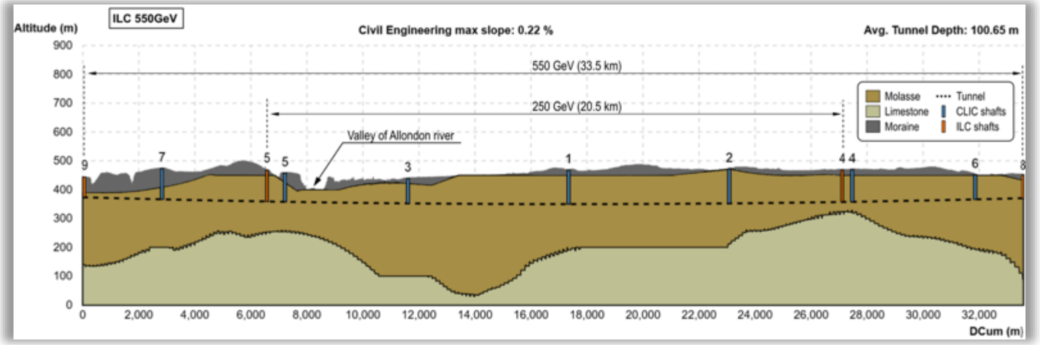
Civil Engineering

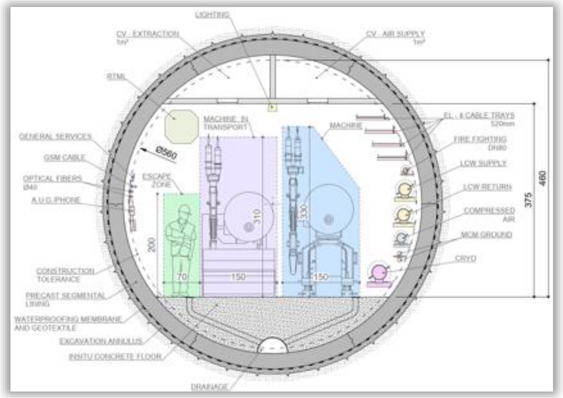
CE studies for LC at CERN:

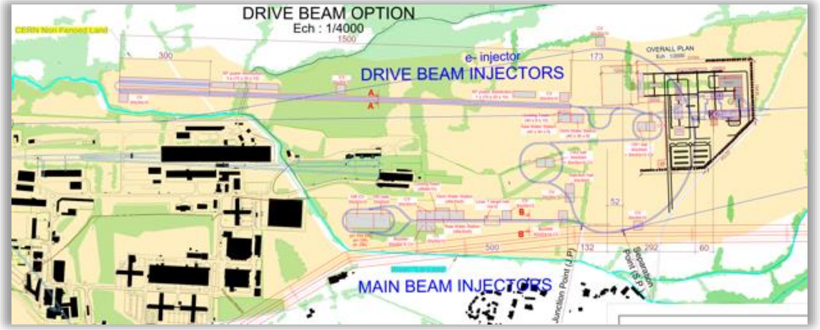
- CLIC, up to 3 TeV. Contract with Amberg Engineering for CDR in 2012-2013.
- ILC up 1 TeV. Contract with Amberg for the TDR in 2012-13.
- CLIC up to 3 TeV, TOT (layout tool) with ARUP, for Project Implementation Report 2018
- Update on-going, ILC up to 500 GeV, CLIC to 1.5 TeV, in both cases ~30km,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



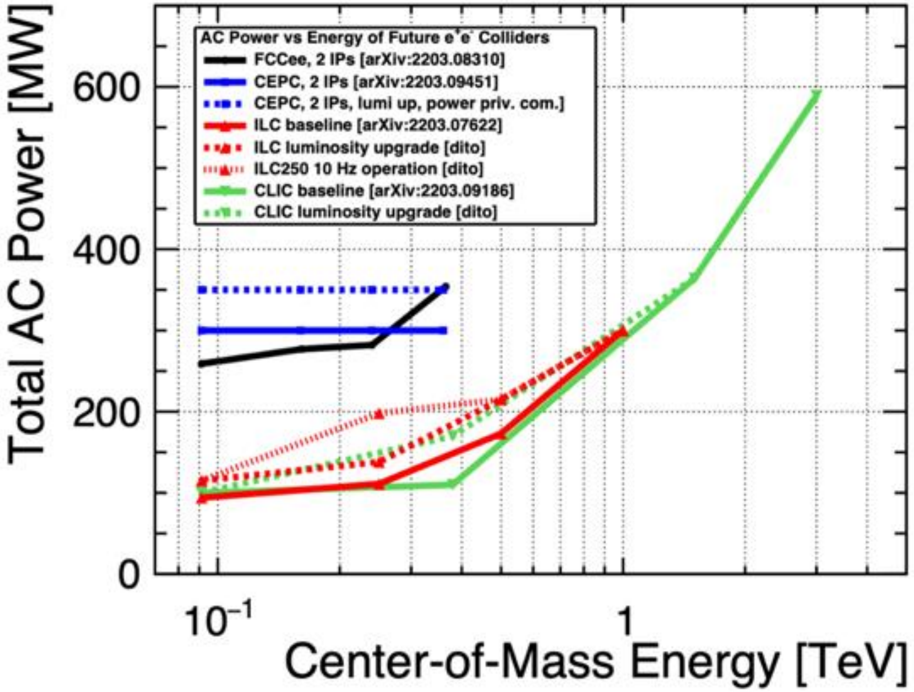








Power and energy

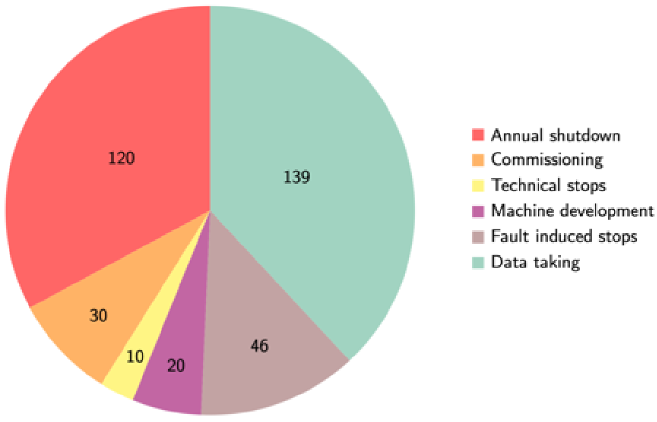


Power at 250-380 GeV in the 100-200 MW range for the projects above

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

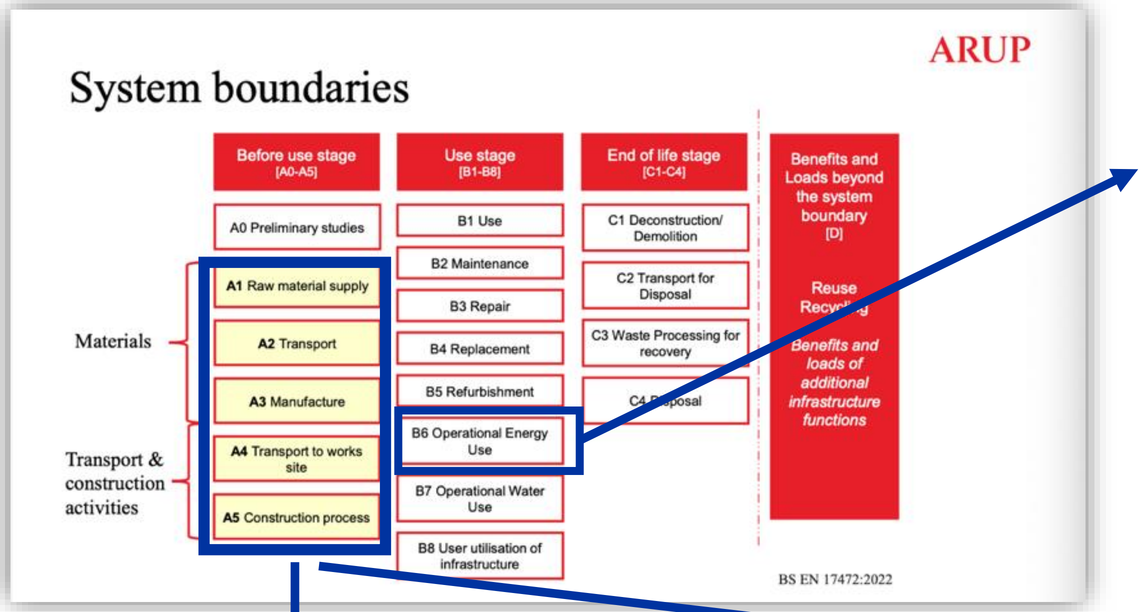
CERN is currently consuming 1.2 – 1.3 TWh annually

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)



ARUP

System boundaries

Before use stage [A0-A5]	Use stage [B1-B8]	End of life stage [C1-C4]	Benefits and Loads beyond the system boundary [D]
A0 Preliminary studies	B1 Use	C1 Deconstruction/ Demolition	Reuse Recycling
A1 Raw material supply	B2 Maintenance	C2 Transport for Disposal	*Benefits and loads of additional infrastructure functions*
A2 Transport	B3 Repair	C3 Waste Processing for recovery	
A3 Manufacture	B4 Replacement	C4 Disposal	
A4 Transport to works site	B5 Refurbishment		
A5 Construction process	B6 Operational Energy Use		
	B7 Operational Water Use		
	B8 User utilisation of infrastructure		

Materials

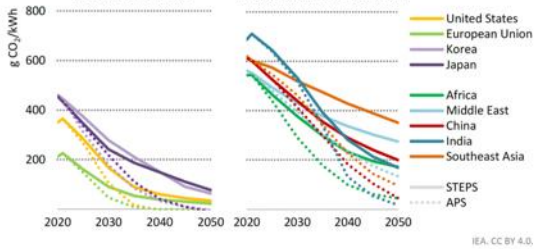
Transport & construction activities

BS EN 17472:2022

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)

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



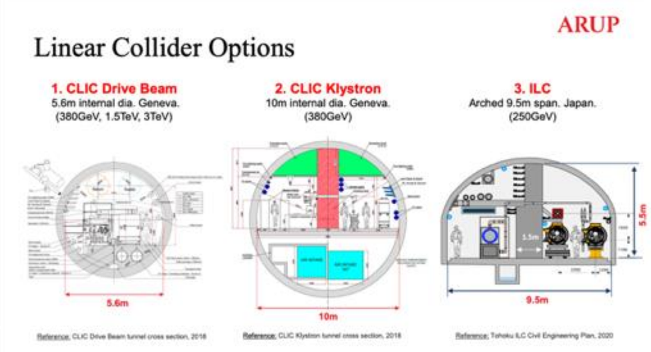
IEA. CC BY 4.0.

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

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

LCA report for **Civil Engineering**: LINK

Addressing the Civil Engineering impact



ARUP

Linear Collider Options

1. CLIC Drive Beam
5.6m internal dia. Geneva.
(380GeV, 1.5TeV, 3TeV)

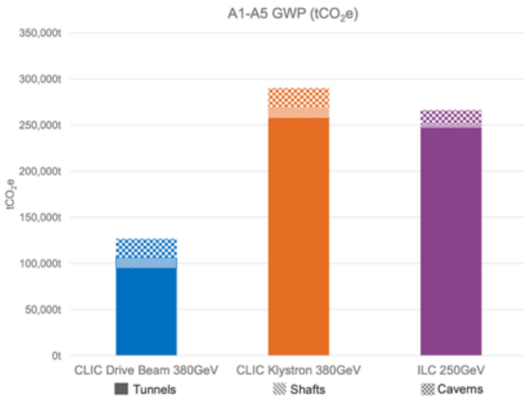
2. CLIC Klystron
10m internal dia. Geneva.
(380GeV)

3. ILC
Arched 9.5m span. Japan.
(250GeV)

Reference: CLIC Drive Beam tunnel cross section, 2018

Reference: CLIC Klystron tunnel cross section, 2018

Reference: Tohoku ILC Civil Engineering Plan, 2020



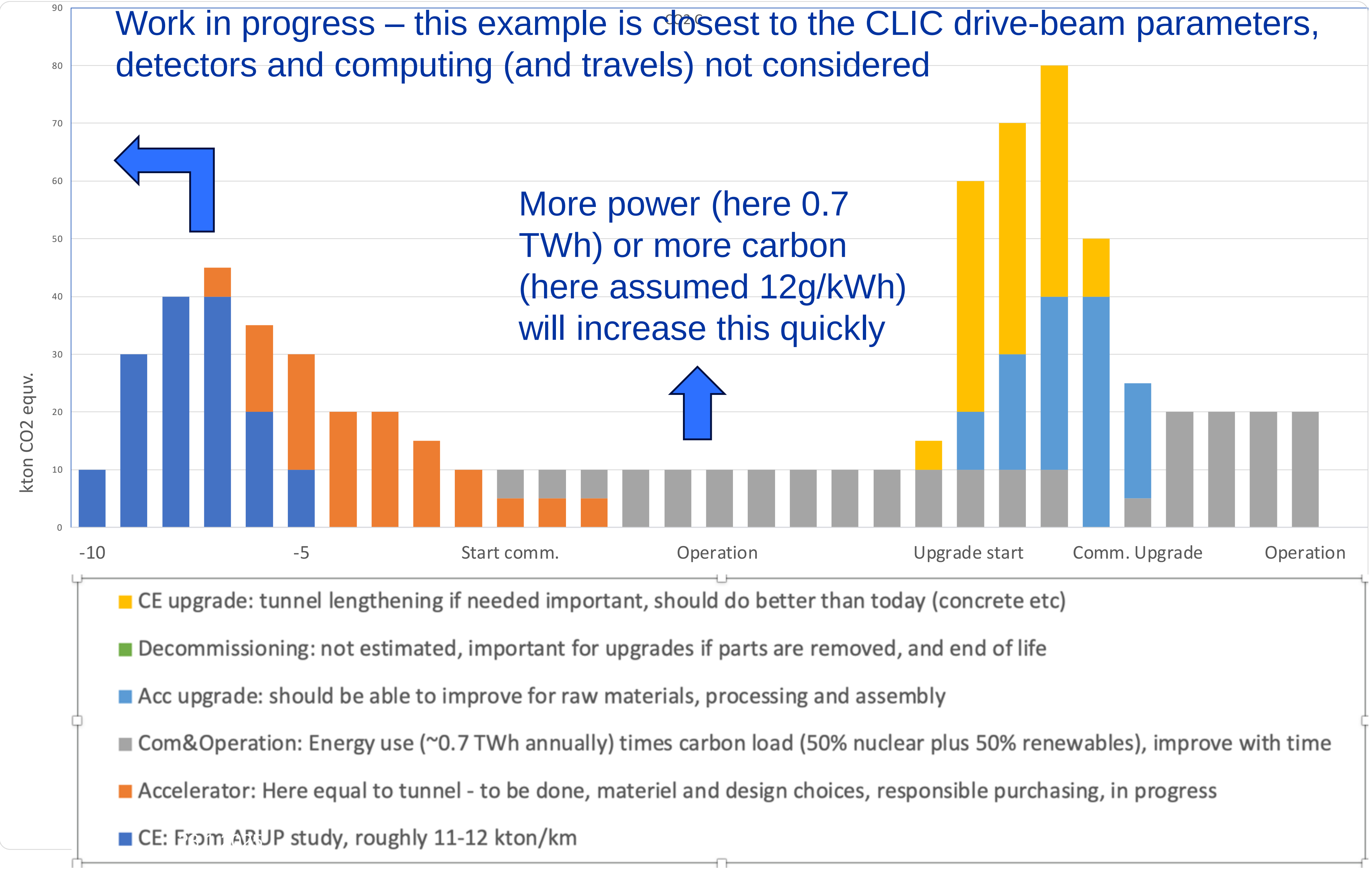
Towards Carbon Accounting with LCA

- 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



Work in progress – this example is closest to the CLIC drive-beam parameters, detectors and computing (and travels) not considered

More power (here 0.7 TWh) or more carbon (here assumed 12g/kWh) will increase this quickly

- 🟨 CE upgrade: tunnel lengthening if needed important, should do better than today (concrete etc)
- 🟩 Decommissioning: not estimated, important for upgrades if parts are removed, and end of life
- 🟦 Acc upgrade: should be able to improve for raw materials, processing and assembly
- ◼ Com&Operation: Energy use (~0.7 TWh annually) times carbon load (50% nuclear plus 50% renewables), improve with time
- 🟧 Accelerator: Here equal to tunnel - to be done, materiel and design choices, responsible purchasing, in progress
- 🟦 CE: From ARUP study, roughly 11-12 kton/km

Some key points

- 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)
- CLIC will be proposed with several changes wrt to 2018 (X-band also an upgrade option) (Improved wrt 2018, 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 making use of improved technologies

- In the LC vision framework further R&D on all LC technologies highly encouraged (both for initial implementation with SRF and upgrades). LC vision (extended meeting at CERN 8-10.1.2025 to prepare ESPP inputs: https://indico.cern.ch/event/1471891/overview)

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), M.Ferrari, L.Monaco, F. Cardelli, many more home.cern