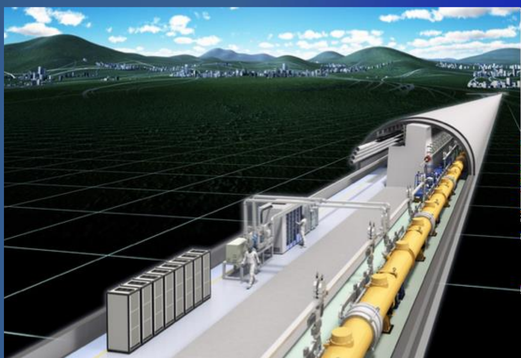
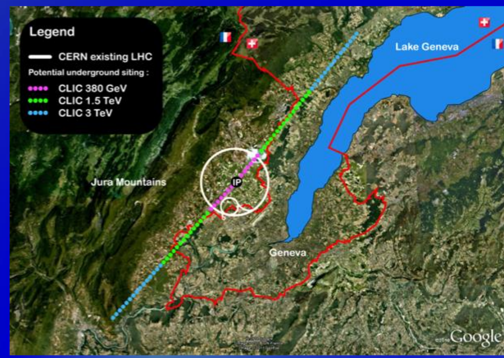
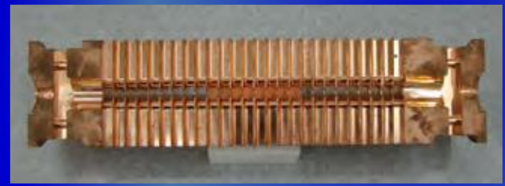
# Linear Colliders – The Path to the Energy Frontier

Linear colliders (LC): ***ILC, CLIC***
(technical extendability to TeV)


**Maxim Titov,**
**CEA Saclay, France**



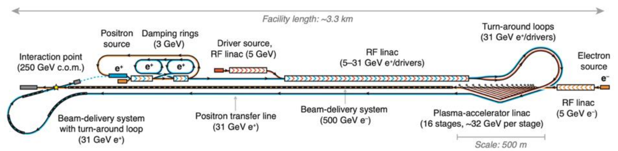



## *Outline*

- LC general considerations
- ILC - in Japan
- CLIC - at CERN
- Other: $C^3$ and HALHF
- LCF at CERN, ESPP inputs

More LC concepts emerging: **C3 & HALHF**

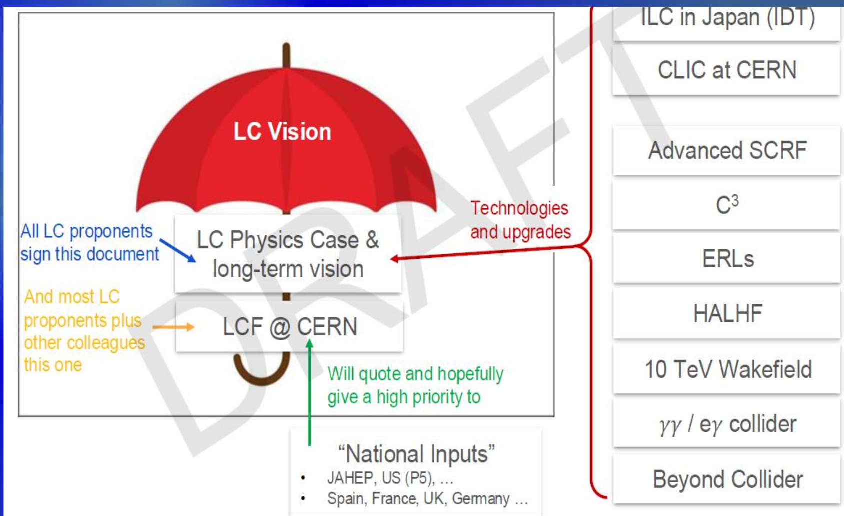
**Schematic layout** of HALHF




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

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

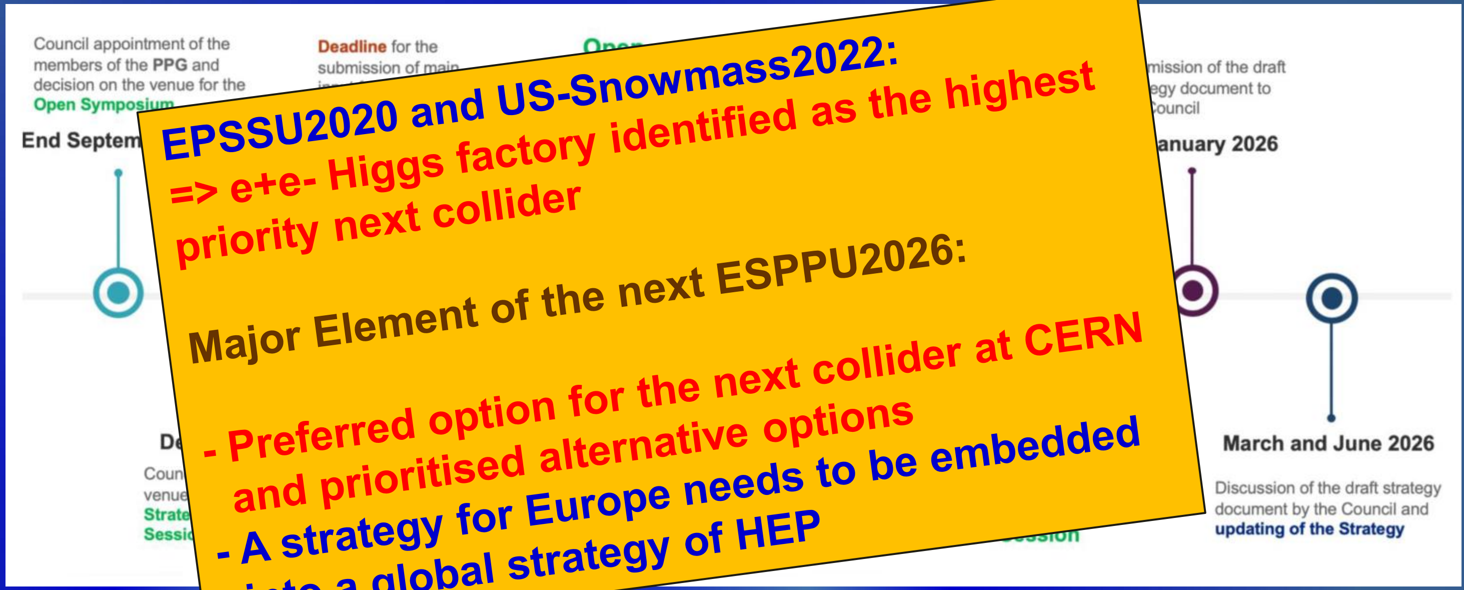
> Length dominated by e⁻ beam-delivery system




*Belgian National ESPP Meeting,*
*Antwerpen, Belgium, February 5, 2025*

# Charting the Future of Particle Physics – EPSSU 2026

- ✓ Mar. 2025: deadline for submission of community input
- ✓ June 23-27 2025: Open Symposium
- ✓ Dec 2025: Strategy Drafting Session
- ✓ June 2026: approval of the Strategy update by CERN Council




**EPSSU2020 and US-Snowmass2022:**
**=> e+e- Higgs factory identified as the highest priority next collider**

**Major Element of the next ESPPU2026:**

**- Preferred option for the next collider at CERN and prioritised alternative options**
**- A strategy for Europe needs to be embedded into a global strategy of HEP**

**https://europeanstrategyupdate.web.cern.ch/**

- ✓ Strategy update should include the ***preferred option for the next collider at CERN*** and ***prioritised alternative options*** to be pursued ***if the chosen preferred plan turns out not to be feasible or competitive (due to cost, timing, international developments, etc…)***

- ✓ Strategy update should also indicate areas of priority for exploration complementary to colliders and for other experiments to be considered at CERN and at other laboratories:
  - National Inputs: physics, role in accelerator R&D, detector R&D, interaction with CERN, …

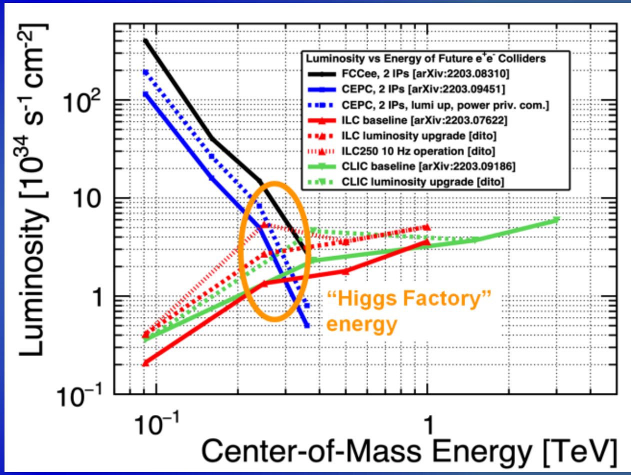
  **E.g. French National ESPPU Symposium: https://indico.in2p3.fr/e/esppu-symposium-fr**

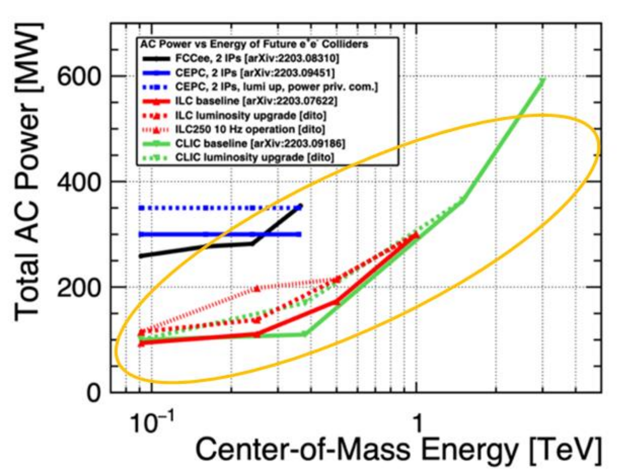
  - European LDG: accelerator R&D roadmap – which topics (e.g. high-field magnet, RF technology, alternative8 accelerators/colliders) should be pursued; LDG Sustainability WG

# Linear Colliders – General Considerations:


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

- Expandable – make them longer for more beam energy
  - Cost of initial configuration can be kept reasonable (staging)
  - Upgrade with future, improved accelerator technologies
- Flexible
  - Project can be adjusted to changes in physics knowledge, competition, or funding
- Highly modular
  - Much of project value is in acceleration modules with industrial production basis in several regions
- Higher energies "natural" – 3 TeV studied (for CLIC):
  - Power increases with energy and luminosity; reach up to 50km; Higher energy means smaller beams and increasingly important beam-beam effects



# General Goals for Linear Colliders:

*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

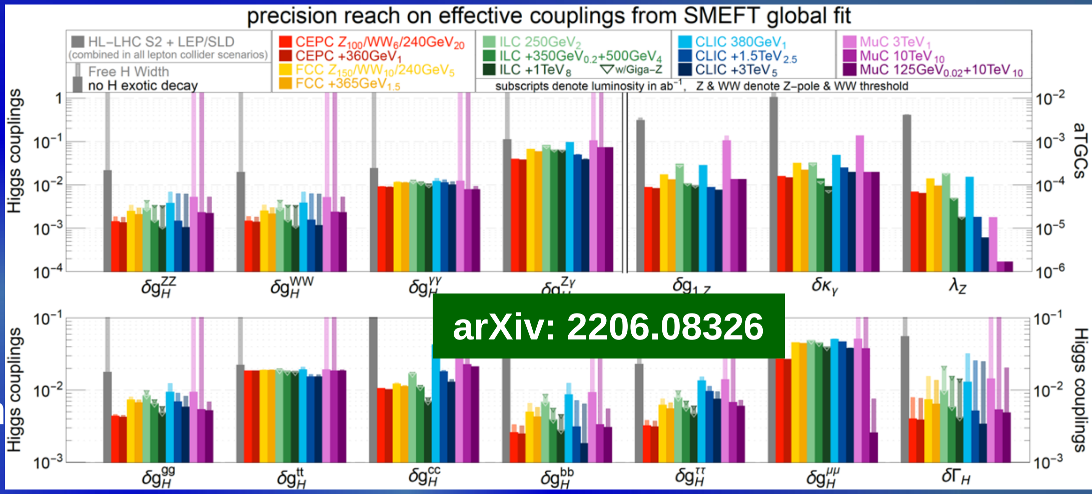
*Provide many opportunities and increased flexibility for the future:*

- *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

# Linear Collider – Physics-Driven, Polarised Operating Scenario

- ✓ **250 GeV, ~2 ab-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 HNLup 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…

## *Higgs Couplings: The Snowmass SMEFT fit*




***all e+e- colliders show very comparable performance for standard Higgs program***
despite quite different assumed integrated luminosities
***=> beam polarisation!***

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

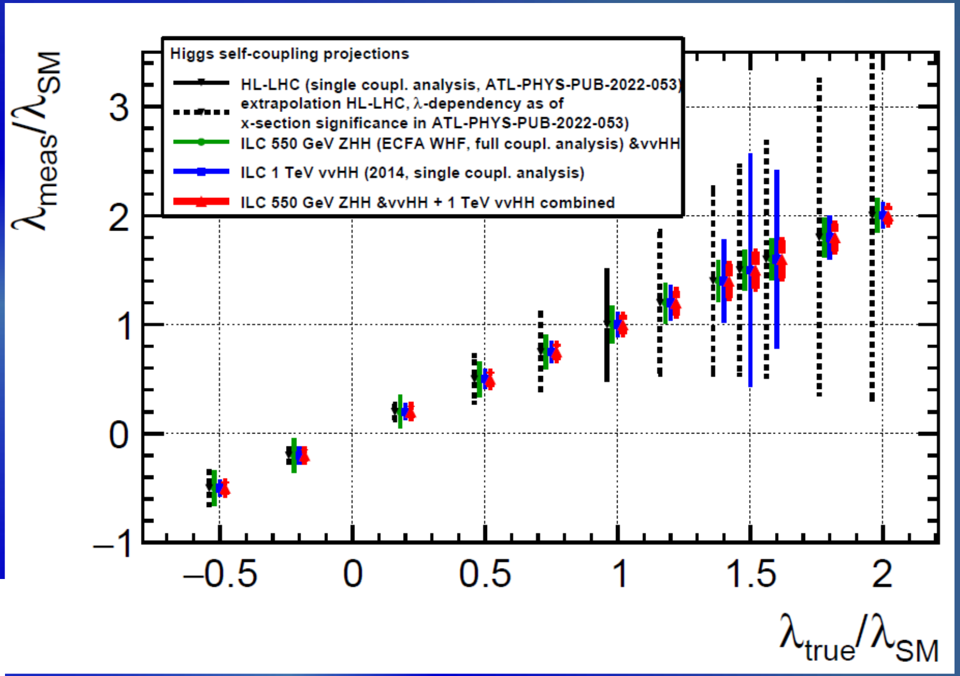
***Gain wrt to HL-LHC:***

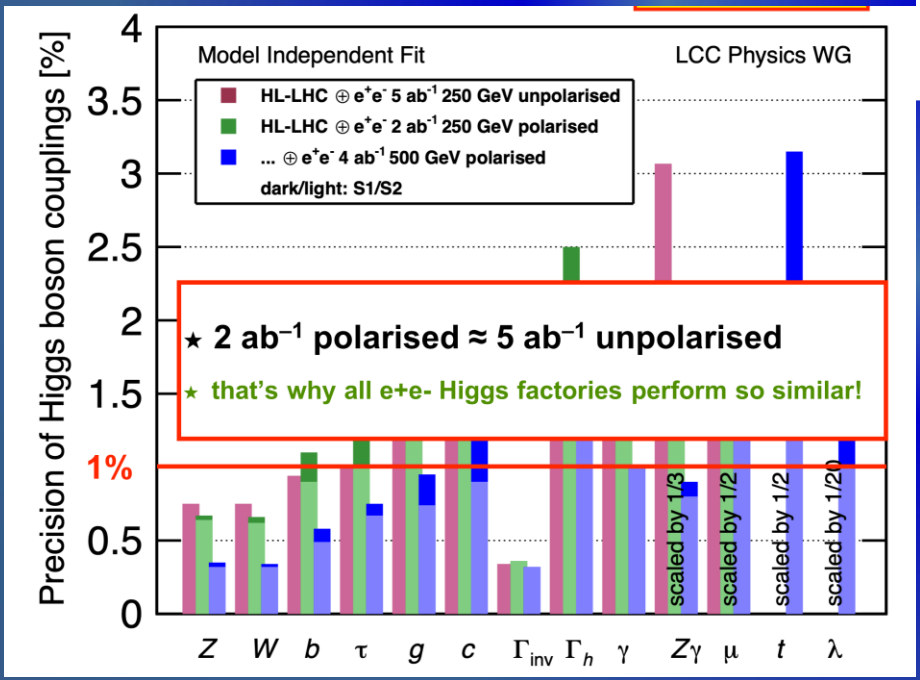
- assuming **no exotic Higgs decays** exist:
  => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays**:
  **=> qualitative jump since no absolute couplings from HL-LHC *at all***

# Polarization and Higgs Self-Coupling

A relationship only appreciated a few years ago:

- ***THE key process*** at a Higgs factory: Higgsstrahlung e+e–→Zh
- $A_{LR}$ of Higgsstrahlung: very important to ***disentangle*** different ***SMEFT operators!***




- $\lambda > \lambda_{SM}$:
  pp cross section drops
  ee cross section rises
- ***Combination*** of e+e- -> ZHH and e+e- -> ννHH ensures at least ***10-15% precision for all λ***

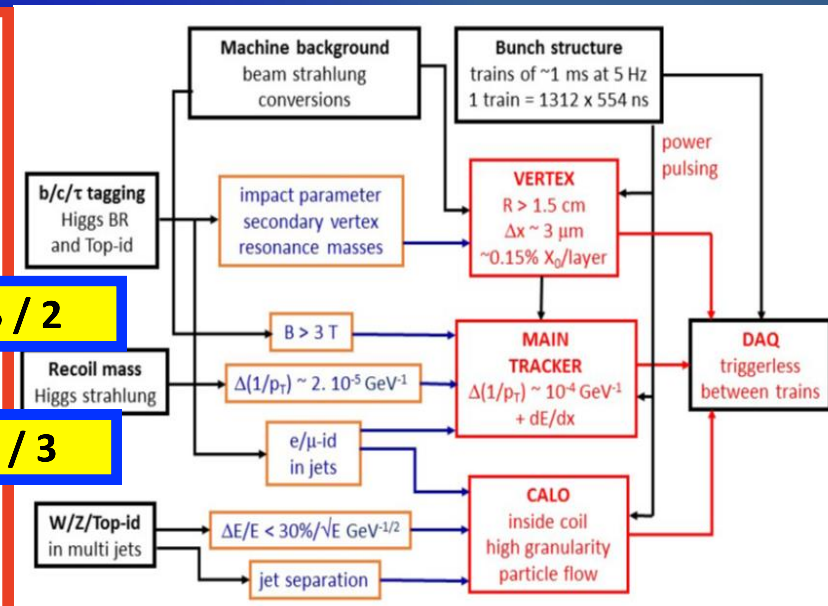
# Higgs Factory Detector Concepts

Key requirements from Higgs physics:

- **$p_t$ resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$
  **≈ CMS / 40**
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$
  **≈ CMS / 4**
- **jet energy resolution** ($H \rightarrow$ invisible) 3-4%
  **≈ ATLAS / 2**
- **hermeticity** ($H \rightarrow$ invis, BSM) $\theta_{min}$ = 5 mrad
  (FCCee: ~50mrad)
  **≈ ATLAS / 3**

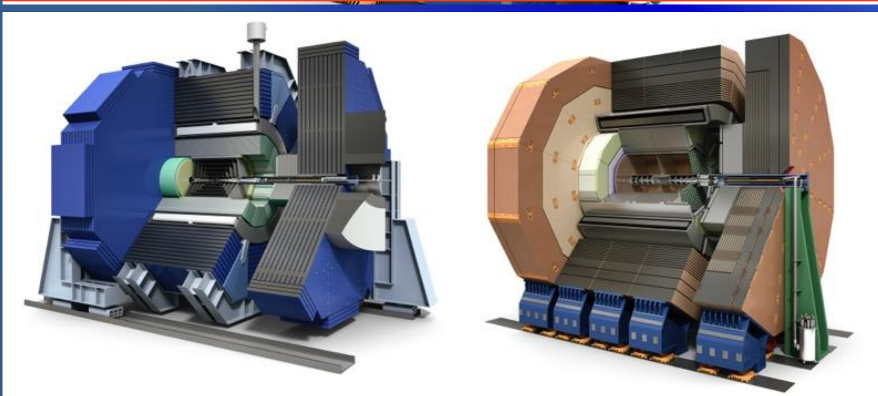
Determine to key features of the **detector**:

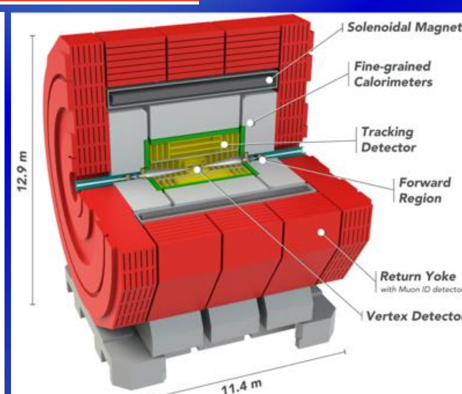
- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **calorimeters**
  - **highly granular,** optimised for particle flow
  - or dual readout, LAr, …




For LCs, bunches inside trains

- at ILC: $\Delta t_b$ = 554 ns; $f_{rep}$ = 5 -10 Hz
- at CLIC: $\Delta t_b$ = 0.5 ns; $f_{rep}$ = 50-100 Hz






The lower collision rate enables

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

# Two e+e- linear collider designs, starting as a Higgs factory

## International Linear Collider (ILC):

- 250 GeV CME, upgradeable to 500, 1000 GeV
- L = 1.35E34 $cm^{-2}s^{-1}$, 20km length, in Tohoku / Japan

- SRF Cavities, 31.5 MV/m, 1.3 GHz

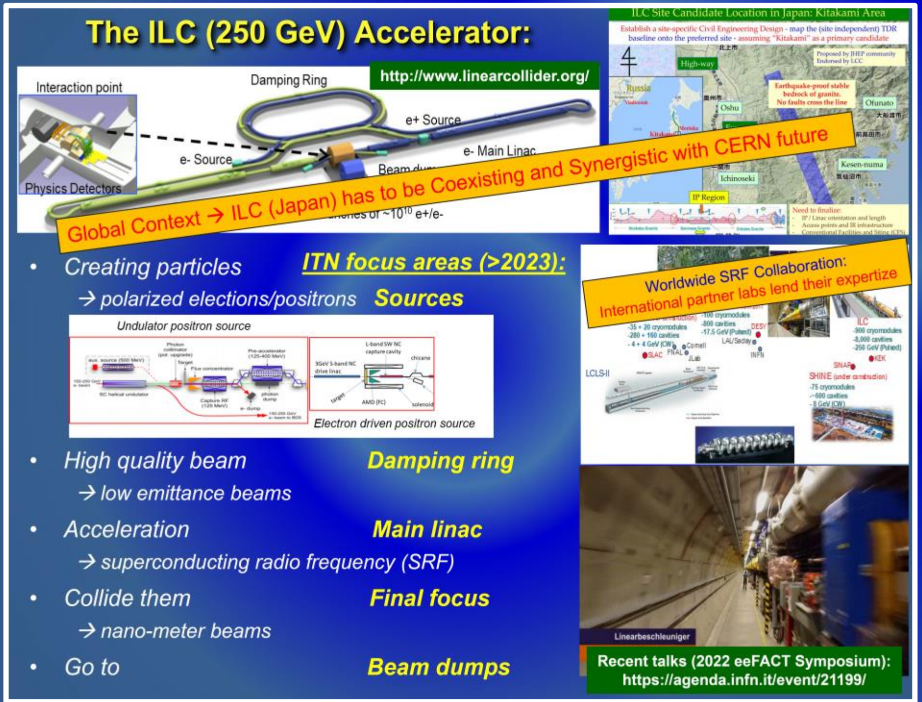
  → relaxed tolerances & smaller emittance dilution
- High-Q ($Q_0 = 10^{10}$):
- Larger aperture / better beam quality
- Long beam pulses (~ 1 ms or CW)
- Cryogenics

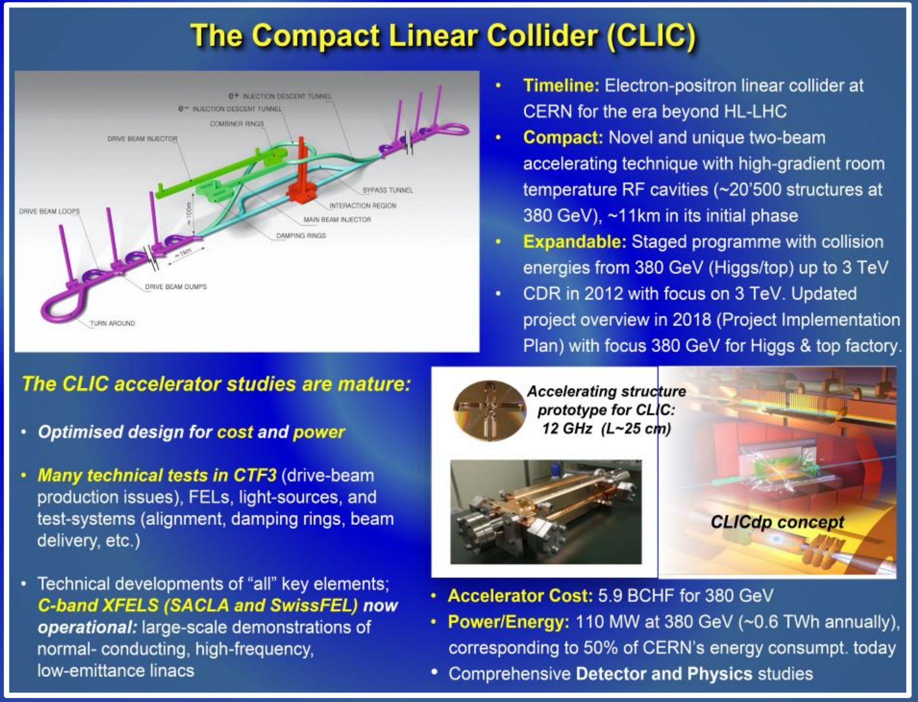
## Compact Linear Collider (CLIC):

Two-beam acceleration (or klystron driven initially)

- 380GeV CME, upgradeable to 1500, 3000 GeV
- L = 2.3E34 $cm^{-2}s^{-1}$ , 11.4km long, at CERN

- NC Copper Cavities, 72 MV/m, 11.4 GHz
- → more accuracy required
- Ordinary-$Q_0$
- Smaller aperture / better accuracy
- Ultra-short beam pulses ($\mu$s pulse)

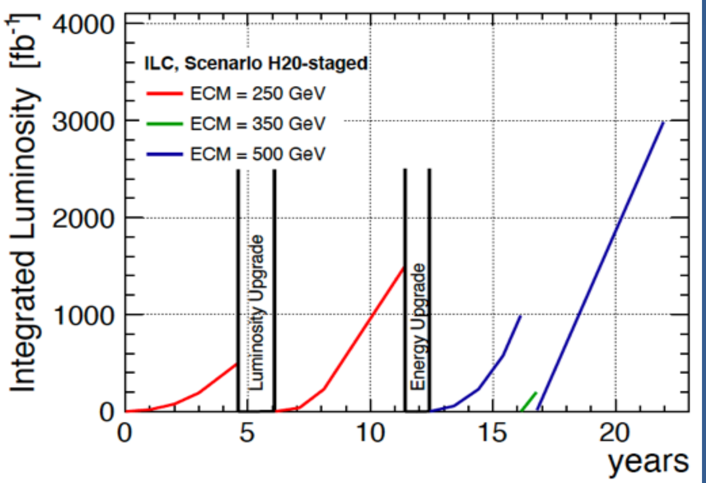


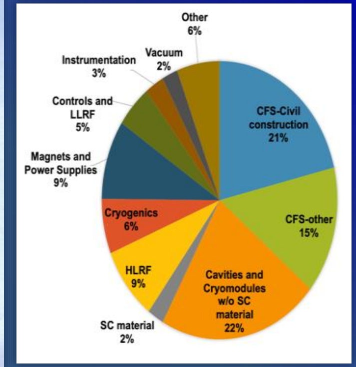
# ILC Baseline, Extensions and Upgrades

| Quantity | Symbol | Unit | Initial | $\mathcal{L}$ Upgrade | Z pole | E / $\mathcal{L}$ 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 | $\Delta t_b$ | 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 | $t_{pulse}$ | $\mu$s | 727 | 961 | 727/961 | 727/961 | 961 | 897 |
| Accelerating gradient | $G$ | MV/m | 31.5 | 31.5 | 31.5 | 31.5 | 31.5 | 45 |
| Average beam power | $P_{ave}$ | MW | 5.3 | 10.5 | 1.42/2.84*) | 10.5/21 | 21 | 27.2 |
| RMS bunch length | $\sigma^*_z$ | mm | 0.3 | 0.3 | 0.41 | 0.3 | 0.3 | 0.225 |
| Norm. hor. emitt. at IP | $\gamma\epsilon_x$ | $\mu$m | 5 | 5 | 5 | 5 | 5 | 5 |
| Norm. vert. emitt. at IP | $\gamma\epsilon_y$ | nm | 35 | 35 | 35 | 35 | 35 | 30 |
| RMS hor. beam size at IP | $\sigma^*_x$ | nm | 516 | 516 | 1120 | 474 | 516 | 335 |
| RMS vert. beam size at IP | $\sigma^*_y$ | 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 | $\delta_{BS}$ | | 2.6 % | 2.6 % | 0.16 % | 4.5 % | 2.6 % | 10.5 % |
| Site AC power | $P_{site}$ | MW | 111 | 138 | 94/115 | 173/215 | 198 | 300 |
| Site length | $L_{site}$ | km | 20.5 | 20.5 | 20.5 | 31 | 31 | 40 |

**Luminosity upgrades**:
- 2 x bunches, 1.5 x RF (1.35 -> 2.7x1034)
- Run 500GeV machine at 250GeV, 10Hz: factor 2 (2.7x1034 -> 5.4x1034)




- The ***limited intrinsic luminosity*** value of the baseline option follows from a deliberate choice to ***minimise the cost & power consumption.***
- There exists ***no technical limitation*** forbidding to achieve ***4x luminosity*** (or even more) if one accepts to operate the collider with ***200 MW*** (or more)


**Energy upgrades**:

- 500GeV (31.5 MV/m Q0=1 x 1010)
- 1 TeV (45 MV/m Q0=2 x 1010, 300 MW) more SCRF, tunnel extensionKitakami site: 50km long, sufficient for 1TeV

# International Development Team (IDT) to Prepare ILC Pre-Lab


*The original timescale to start the ILC Pre-lab in 2022 was too optimistic:*

- *→ there was no progress in the "top-down" political-governmental approach (> 2021)*
- *→ The IDT Pre-lab plan was reviewed by a MEXT appointed panel and deemed premature, referring to that the prospects for ILC international cost sharing are not clear.*
- *→ increased support for technical developments & accelerator R&D was recommended (these plans were included MEXT budget request and has been approved by the JP Finance Ministry in FY2023 → double KEK resources for ILC preparation for the ILC ITN)*

arXiv:2106.00602v1 [physics.acc-ph] 1 Jun 2021

Proposal for the ILC Preparatory Laboratory (Pre-lab)

International Linear Collider
International Development Team

1 June 2021

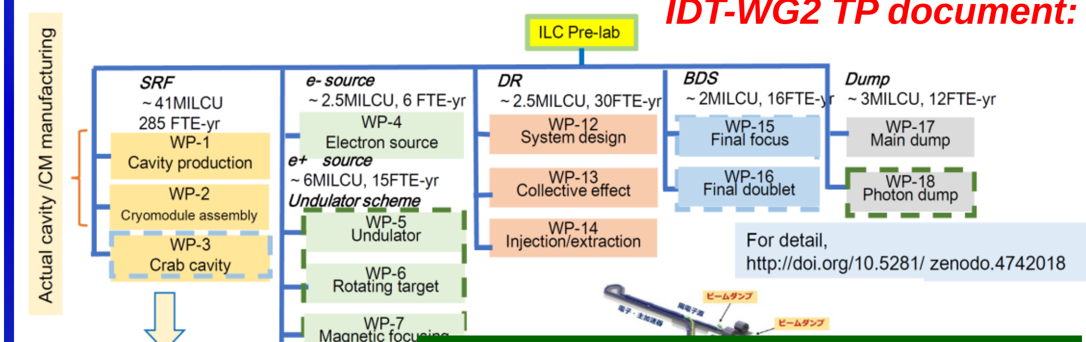
***ILC Pre-lab proposal developed by IDT-WG1 and submitted to MEXT on Jun. 2, 2021:***

Abstract

During the preparatory phase of the International Linear Collider (ILC) project, all technical development and engineering design needed for the start of ILC construction must be completed, in parallel with intergovernmental discussion of governance and sharing of responsibilities and cost. The ILC Preparatory Laboratory (Pre-lab) is conceived to execute the technical and engineering work and to assist the intergovernmental discussion by providing relevant information upon request. It will be based on a worldwide partnership among laboratories with a headquarters hosted in Japan. This proposal, prepared by the ILC International Development Team and endorsed by the International Committee for Future Accelerators, describes an organisational framework and work plan for the Pre-lab. Elaboration, modification and adjustment should be introduced for its implementation, in order to incorporate requirements arising from the physics community, laboratories, and governmental authorities interested in the ILC.

**arXiv: 2106.00602**

***IDT-WG2 TP document:***



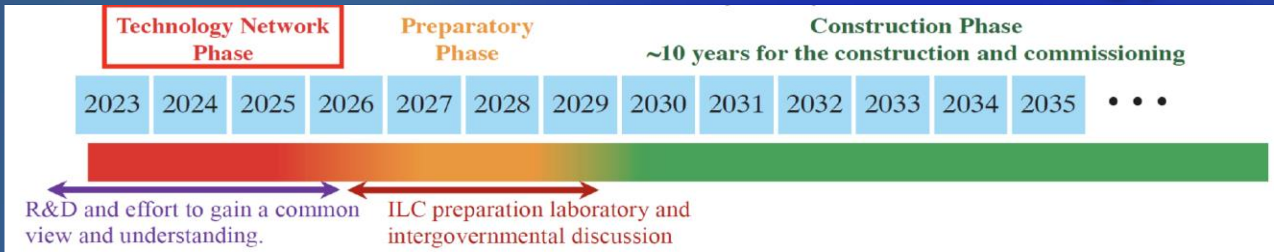

SRF technology is energy-efficient, and its applications are increasing around the world.
These WPs will contribute to the promotion of SRF accelerators in each region.

**http://doi.org/10.5281/ zenodo.4742018**

- The technical preparation document was reviewed by the international review committee (chair:Tor Raubenheimer (SLAC)).
- The total global cost of the project is about 60 MILCU and about 360 FTE-year. (This does not include the cost of the infrastructure for the WPs.)
- The cost will be shared internationally as in-kind contribution.

***IDT - WG2 summarized the technical preparation as Work Packages (WPs) for the Pre-Lab stage in the Technical Preparation (TP) Document***

# ILC ESPPU: ILC Technology Network (ITN)




4-Years preparation phase to produce an Engineering Design Report and Project implementation Plan

*Technical Progress in (ITN):* interest /capability matrix from 28 labs/ universities

| | | | | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 | C10 | C11 | C12 | C13 | C14 | C15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 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 | √ | | | √ | | | | | √ | | | | | | |

| | | |
|---|---|---|
| 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 |

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

# Topics

2023/11/16

**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)

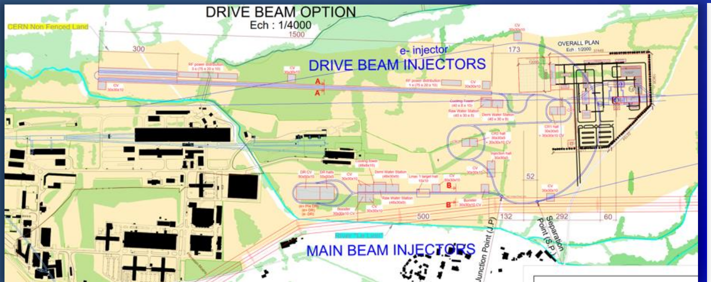
**Sources**
- Pulsed magnet and wheel/target (Uni.H, DESY, CERN)

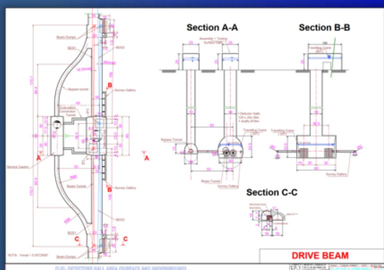
**Damping Ring including kickers**
- Low Emittance Rings (UK)

**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)

# CLIC ESPPU: Project Readiness Report as a Step towards TDR



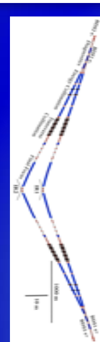



Table 1.1: Key parameters of the CLIC energy stages.

| 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 | $1\times10^{34}$ cm$^{-2}$s$^{-1}$ | 2.3 | 3.7 | 5.9 |
| Lum. above 99 % of $\sqrt{s}$ | $1\times10^{34}$ 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 | $1\times10^{9}$ | 5.2 | 3.7 | 3.7 |
| Bunch length | μm | 70 | 44 | 44 |
| IP beam size | nm | 149/2.0 | $\sim$60/1.5 | $\sim$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

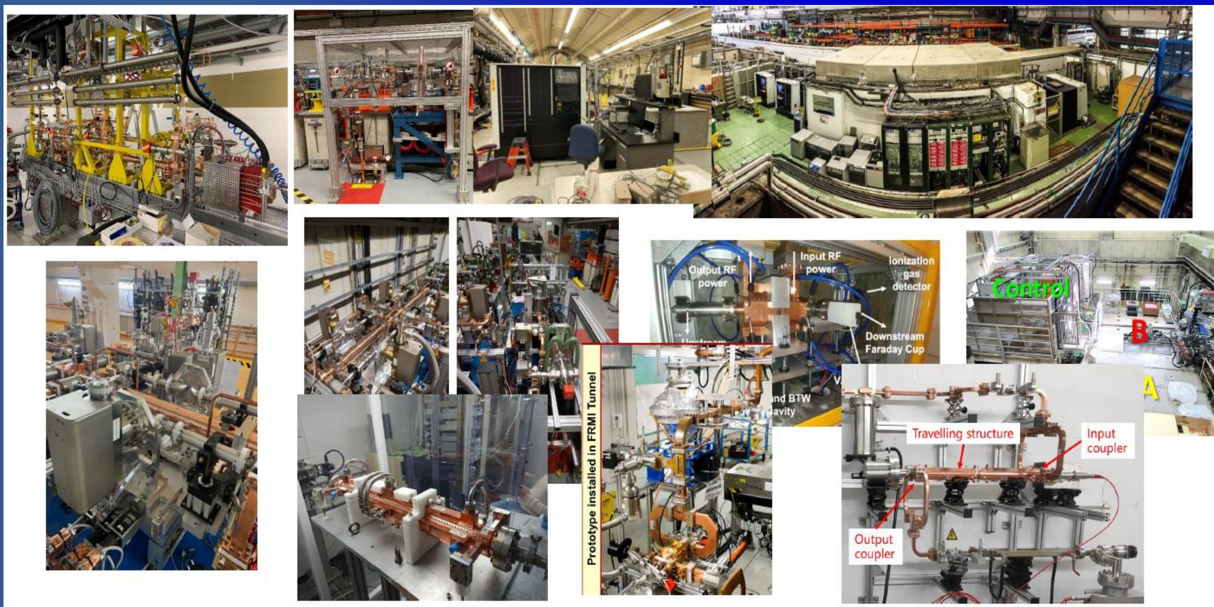
3 TeV: refer to earlier reports

*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)

# Industry Connection & Beyond CLIC: X-Band RF Technology

***Main benefits for CLIC:*** much strengthened industrial base and strong increase in research/experience on/with X-band technology and associated components




***Compact Linacs have many uses:***

- As part of research accelerators (e.g. in FELs as main technology or special elements), or in medical or industrial linacs
- Many/most of these developments are driven by CLIC collaborators, for their ”local” applications

***Global X-band and High-Gradient Deployment***

| | | | | | |
|---|---|---|---|---|---|
| Trieste, Fermi | Linearizer | KEK | NEXTEF | TU Eindhoven | Smart*Light, ICS |
| SwissFEL | Linearizer and Polarix deflector | CERN | XBox-2,3 and SBox | Tsinghua. | VIGAS, ICS |
| SARI: | Linearizer, deflectors | Tsinghua | TPot | CERN: | AWAKE electron injector |
| CERN: | Xbox-1 with CLEAR, accelerator | Valencia | IFIC VBox | INFN Frascati | EuPRAXIA@SPARC LAB, accelerator |
| DESY: | PolariX deflectors in FELs | Trieste | FERMI S-Band | DESY: | SINBAD/ARES, deflector |
| SLAC: | NLCTA, XTA | SLAC | Cryo-systems | CHUV/CERN. | DEFT, medical accelerator |
| Argonne | AWA | LANL | CERF-NM | Daresbury | CLARA, linearizer |
| Arizona | CXLS, ICS | INFN Frascati. | TEX | Trieste: | FERMI energy upgrade |
| | | Melbourne | AusBox | + more | |

***Non-exhaustive list***

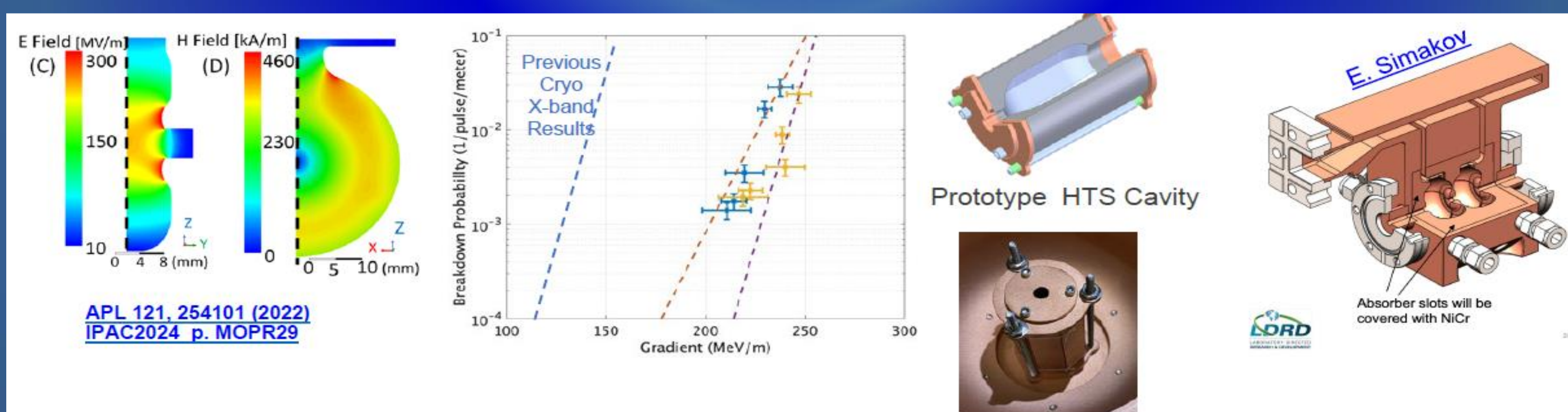
# C³ Accelerator: Recent Highlights

| Scenario | C³ -250 | C³ -550 | C³ -250 s.u. | C³ -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 |

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

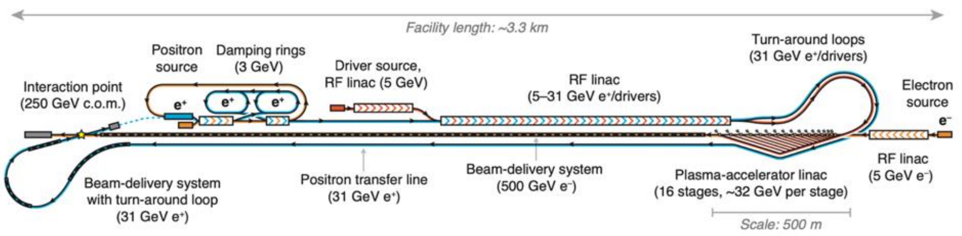
- Beam delivery / IP modified from ILC (1.5 km for 550 GeV CoM), compatible w/ ILC-like detector
- Damping rings and injectors to be optimized with CLIC as baseline

- Improved coupler design significantly reduced breakdown probability
- **C-band cavities were able to reach gradients over 250 MeV/m in cryogenic tests**
- Exploratory research to develop the basis for a HTS based RF cavity for pulse compression
- Multi-bunch simulation studies have been conducted to identify required damping and detuning to mitigate long-range HOMs
- Ni-Cr coatings for two-cells structures have been tested



# Hybrid Asymmetric Linear Higgs Factory (HALHF)

**Schematic layout** of HALHF




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

- Exploit high gradient of e- acceleration in PWFA and avoid difficulty of e+ acceleration by using conventional RF linac, reducing cost by low E(e+) (31 GeV)=> high E(e-) (500 GeV), boost g ~ 2.7 => ECM ~ 250 GeV.
- Reduce running costs by increasing current I(e+) and reducing I(e-); this & asymmetric emittance (increased for e-) ease PWFA req.
- ~ 400m length PWFA stage ( PWFA gradient~ 6.4 GV/m; <gradient>~ 1.2 GV/m) => facility length ~ 3.3 km and cost ~ ¼ of ILC/CLIC - $1.9B (2022 $).

**Several key plasma acc. challenges:**
Multi-staging, emittances, energy spread, stabilities, spin polarisation preservation, efficiencies, rep rate, plasma cell cooling, reduced plasma density (increased beam length, reduced gradient), etc…

**Conventional beam(s) challenges:**
Polarized positron source, damping rings, RF linac, beam delivery system

**Experimental challenges** with asymmetric beams

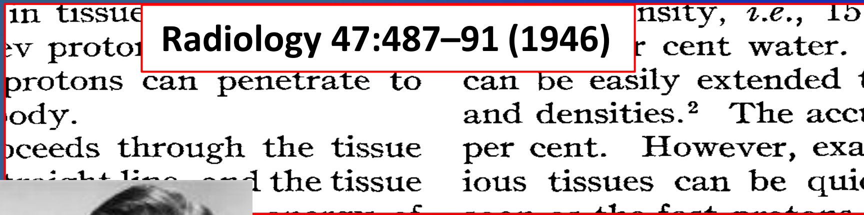
*New concept aiming for: "pre-CDR" input to European Strategy and to LC Facility/Vision. Longer term – CDR by early 2026.*

**B. Foster**

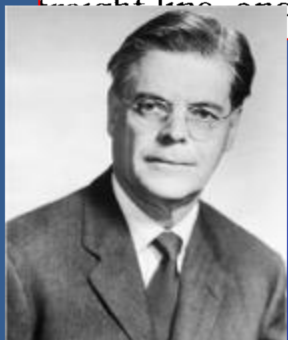
Erice workshop (Oct. 3-8, 2024)

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

# Advanced Accelerator Technologies: Past, Present, Future


Radiology 47:487–91 (1946)

in tissue ... nsity, *i.e.*, 15
ev proton ... r cent water.
protons can penetrate to ... can be easily extended t
ody. ... and densities.² The accu
ceeds through the tissue ... per cent. However, exa
... d the tissue ... ious tissues can be quic

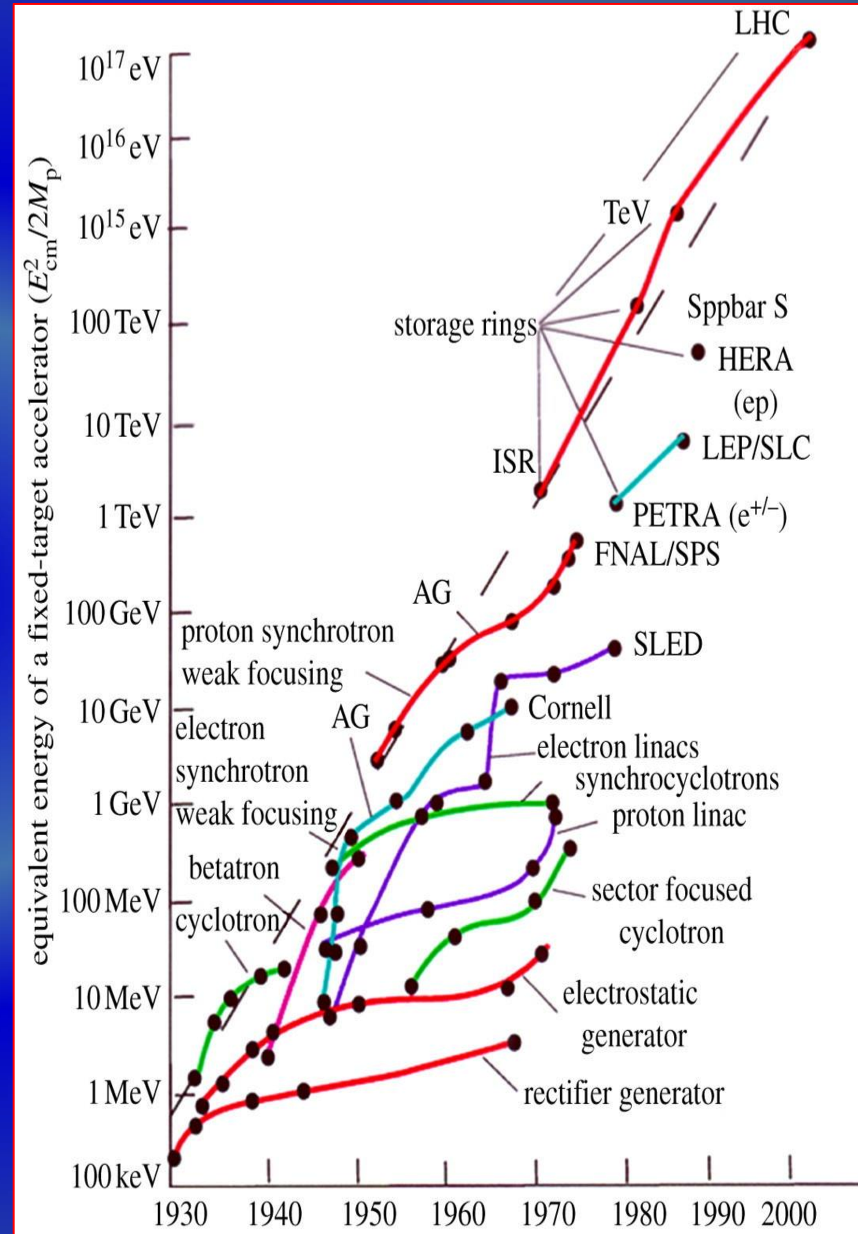


*Wilson, at Harvard designing 150 MeV cyclotron:*

- Identified benefits and properties of proton beams for RT
- Pointed out potential of ions (carbon) and electrons

*Promote industrial base and application of advanced accelerator technologies as part of the R&D strategy (innovate through applications):*

- *Compact and robust accelerators with different parameters requiring different RF and design solutions*
- *Focus on low cost and energy efficient accelerator technologies*
- *Maintain and Strengthen industrial base and capabilities*
- *Recruitment & retention, education, and training of accelerator physicists*
- *Future Plasma acceleration platforms: synergies between HEP (HALHF) & applications (EUPRAXIA, LhARA)*

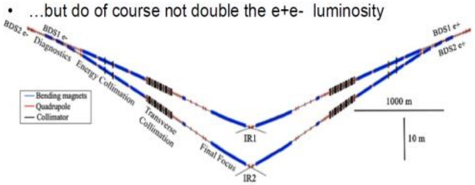


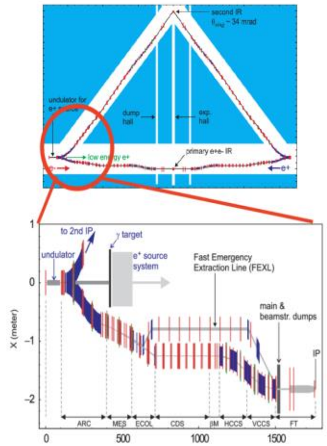
# Linear Colliders: 2 BDS and Upgrade Options

## 2nd Interaction Region — for 2nd e+e- detector — or γγ / eγ / e-e- ?

**2 different interaction regions for additional physics opportunities**

- 2nd Beam Delivery System (BDS) to 2nd Interaction Region, served "quasi-concurrently", by switching on train-by-train basis have been designed for ILC & CLIC
- eliminating it from ILC baseline "saved" O(0.250) BILCU — has been reinstantiated for a Linear Collider Facility
- 2 IRs are important for
  - 2 detectors for redundancy, technological complementarity, systematic cross-checks, competition
  - special collision modes: e-e- / $\gamma e$ / $\gamma\gamma$ , each adding specialized, unique physics opportunities
  - …but do of course not double the e+e- luminosity





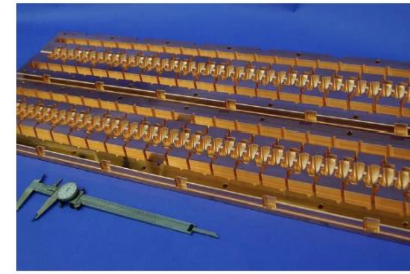

## Upgrade option: Higher Energy

**Increasing the energy by conventional accelerator technology**

- ILC TDR: upgrade of SCRF machine up to ~1 TeV
  - extend tunnel to ~50 km, upgrade power to 300 MW => huge but unsexy? Still: guaranteed fall-back…
- Advanced SCRF
  - higher gradient cavities exist in the lab (> 60 MV/m vs 31.5 MV/m ILC design), though ~10..20 years until industrialisation => upgrade to ~ 1 TeV or less new tunnel
- rip out SCRF and replace by X-band copper cavities (à la CLIC or C[3])
  - Raise gradient to 70-150 MV / m => double (3x, 4x …?) energy without tunnel extension
  - sell / donate SCRF modules to build XFELs, irradiation facilities, … all around the world

| | ECM [GeV] | Gradient [MV/m] | Length [km] | #of cavities | AC power [MW] *5 |
|---|---|---|---|---|---|
| TDR | 250 | 31.5 | 20.5 | ~8,000 | ~110 |
| TDR | 500 | 31.5 | 33.5 | ~16,000 | ~170 |
| TDR | 1,000 | 45 | 44.5 | ~23,000 | ~300 |
| Nb3Sn/multilayer or TW | 500 | 63 | 20.5 | ~8,000 *2 | ~180 *6 |
| NB3Sn/multilayer & TW | 1,000 | 126 *3 | 20.5 | ~8,000 *4 | ~260 *7 |

Ref: Chap 15 of arXiv:2203.07622



**LC Vision Baseline: higher energy by advanced technology, tunnel extension fall-back**



## Upgrade Options - Double $E_{CM}$ by "HALHFing" LCF

**Employing novel accelerator technologies**

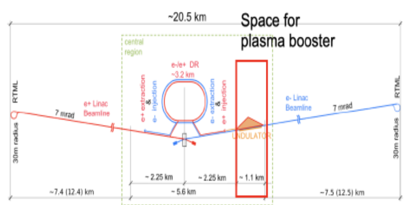
- **Apply HALHF concept to eg 250 GeV ILC:**
  - plasma-accelerate e- to 550 GeV
  - keep e+ linac (small upgrade 125 -> 137.5 GeV)

⇒ 137.5 GeV × 550GeV ⇒ $E_{CM}$ = 550 GeV

⇒ upgrade Higgs Factory to tt / tth / Zhh factory

- How?
  - Reduce e- linac energy by 4 to 34.4GeV
  - Drive 16 stage plasma accelerator
  - Use space between electron ML and BDS to install plasma booster
  - Feed boosted electrons into existing BDS (already laid out for $E_{beam}$ ≈ 500 GeV)

| | | E- (drive) | E- (Collide) | E+ |
|---|---|---|---|---|
| Beam energy | GeV | 34.4 | 34.4 → 550 | 137.5 |
| Linac Gradient | MV/m | 8.7 | | 35 |
| CoM energy | GeV | | 550 | |
| Bunch charge | nC | 4.3 | 1.6 | 6.4 |
| Bunches/pulse | | 10496 | 656 | 656 |
| Rep rate | Hz | | 5 | |
| Beam power | MW | 8.0 | 0.18 → 2.9 | 2.9 |
| Lumi (approx.) | $cm^{-2}s^{-1}$ | | ~ 1 · $10^{34}$ | |




Ref: BL, HALHF workshop Erice



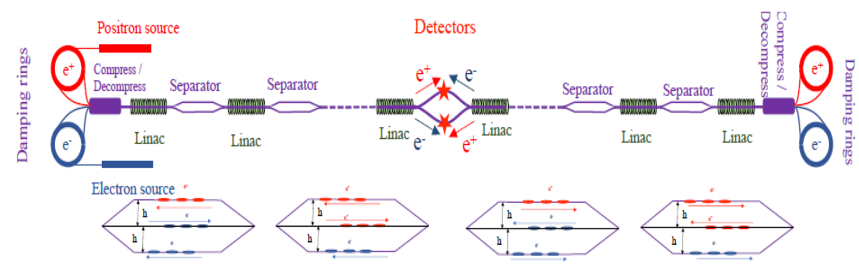
## Upgrade Options - Higher Luminosity à la "ReLiC"

**Energy recovery: gateway to the highest luminosities**

- Energy and particle recovery by de-celaration and re-cooling
- Conceptual study indicates up to O(100) higher luminosity than ILC / CLIC conceivable
- Effectively no beamstrahlung => even Higgs resonance operation not fundamentally excluded (conceptual idea exists but needs verification by beam optics study)

**Integrate R&D and demonstrator into initial LCF, upgrade option if successful?**

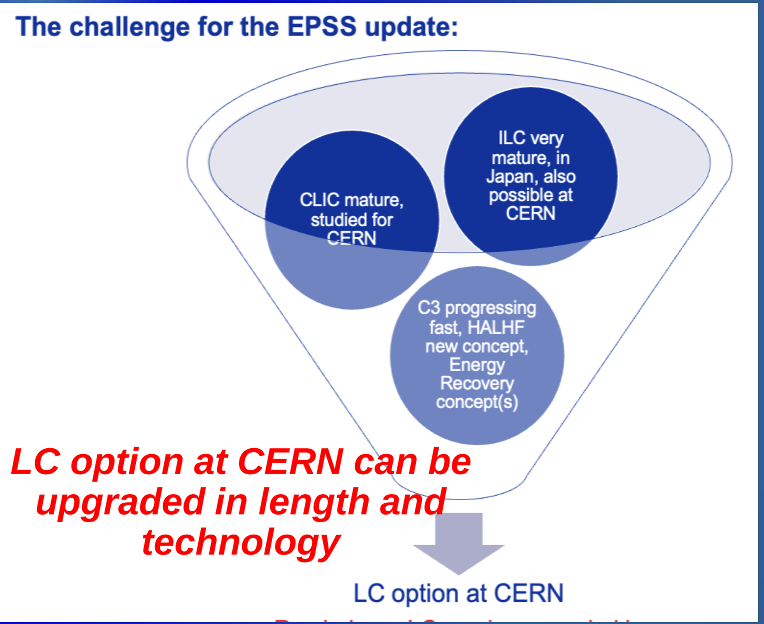
arXiv:2203.06476 [hep-ex]



# An Adaptable (ILC + CLIC) Linear Collider Facility @ CERN


**LC** facility @ CERN can be upgraded in energy & luminosity, using the same or improved versions of the same technology (ILC, CLIC, C3, HALHF):

- ***Starting with ILC (EUXFEL) technology*** – very mature technical design and industrialization - can be upgraded in energy and luminosity to more performant technologies, e.g. plasma or ERL
- ***Implementation at CERN*** in footprint studied for CLIC (and ILC back in the TDR days), with two BDS, and experimental area at Prevessin
- 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

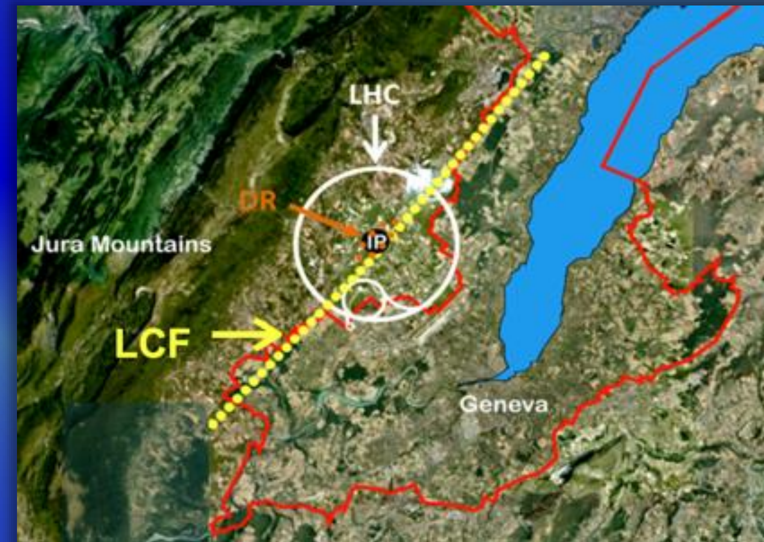



"ILC model" could be exploited to reduce load on CERN during the HL-LHC period (lab support from outside for cryomodules)

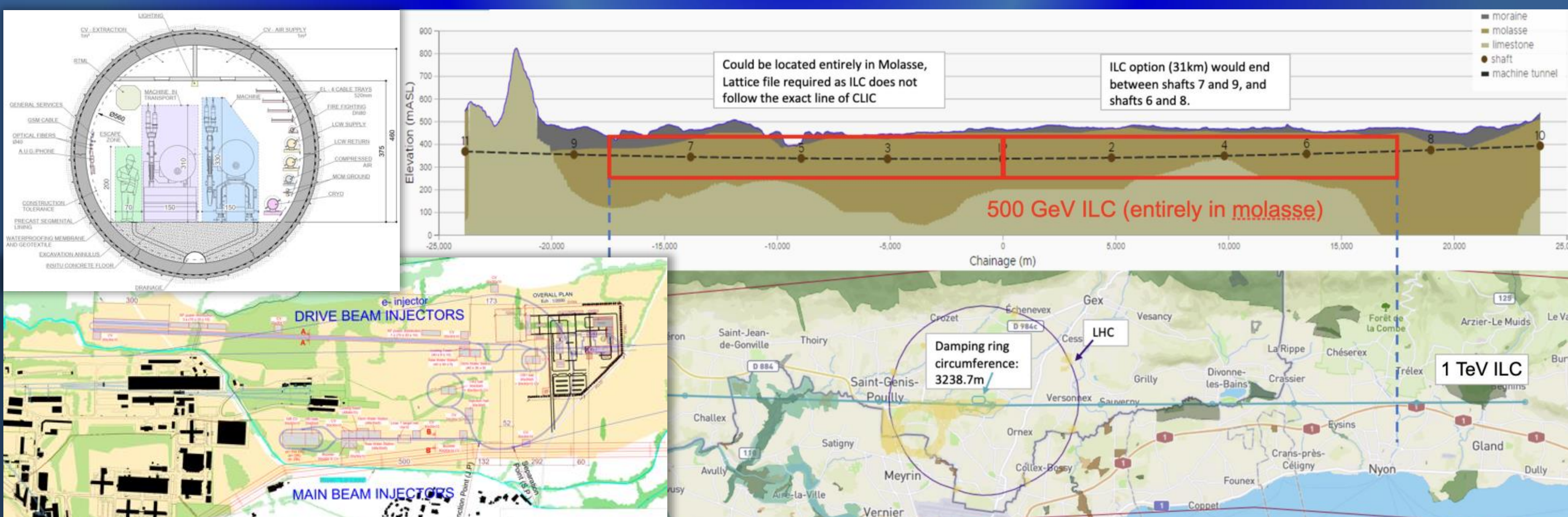
# Linear Collider: Civil Engineering @ CERN

***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 /CLIC up to 500 (1500) GeV, in both cases ~ 30km, using Geoprofiler layout tool
- *Injectors and experimental areas on Prevessin site ("CERN land")*




***Siting study (including cost estimate) for CERN in preparation, based on CLIC siting***



# Linear Collider: Costing

### *Cost exercises and international reviews:*

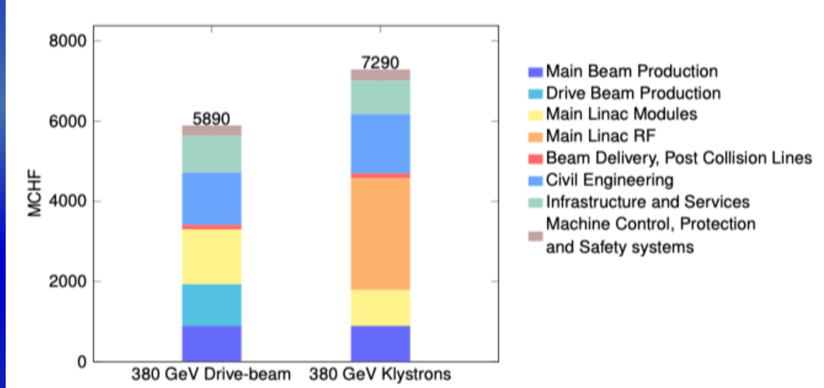
- *ILC TDR* 2012-13, 500 GeV primarily (LINK)
- *CLIC CDR* 2012-13, 3 TeV primarily and 500 GeV (LINK)
- *ILC in Japan* 2017-18, 250 GeV, reviewed within LCC (LINK)
- *CLIC PiP* 2018, 380 GeV primarily (LINK)
- *Costs for ILC and CLIC* (and others) are currently being re-costed and *updated in 2024*, including currency changes and price escalations.

### *CLIC Costing (2018):*

- Machine has been re-costed bottom-up in 2017-18
- Technical uncertainty and commercial uncertainty estimated
- From 380 GeV to 1.5 TeV, add 5.1 BCHF (drive-beam RF upgrade and lengthening of ML)
- From 1.5 TeV to 3 TeV, add 7.3 BCHF (second drive-beam complex and lengthening of ML)
- Labour estimate: ~11500 FTE for the 380 GeV construction

### *CLIC Costing (2018):*

| 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.

# IDT Framework: ILC Costing in Japan

Cost estimates for ILC in 2012 US$ (US$ ≃ CHF) (ILC Currency Unit ILCU), for the Japanese site TDR:

- **500 GeV, 31.5km tunnel: 7.98 BILCU**
  + 13.5 kFTE-y,operation 390 MILCU/y + 850 FTE
- Higgs factory: **250 GeV, 20.5km tunnel**: **5.26 BILCU**
  + 10.1 kFTE-y,operation 316 MILCU + 638 FTE
- + 2 detectors: 0.71 BILCU + 2.1 kFTE-y
- Costs include accelerator & CE construction, exclude site activation (roads, power lines) & land acquisition
- ***Substantial inflation since 2021***

**APPENDIX A: ILC250 PROJECT COSTS**

| | TDR: ILC500 [B ILCU] (Estimated by GDE) | ILC250 [B ILCU] (Estimated by LCC) | Conversion to: [B JPY] (Reported to MEXT/SCJ) |
|---|---|---|---|
| **Accelerator Construction: sum** | **n/a** | **n/a** | **635.0 ~ 702.8** |
| Value: sub-sum | 7.98 | 4.78 ~ 5.26 | 515.2 ~ 583.0 |
| Tunnel & building | 1.46 | 1.01 | 111.0 ~ 129.0 |
| Accelerator & utility | 6.52 | 3.77 ~ 4.24 | 404.2 ~ 454.0 |
| Labor: Human Resource | 22.9 M person-hours (13.5 K person-years) | 17.2 M person-hours (10.1 K person-years) | 119.8 |
| **Detector Construction: sum** | **n/a** | **n/a** | **100.5** |
| Value: Detectors (SiD+ILD) | 0.315+0.392 | 0.315+0.392 | 76.6 |
| Labor: Human Resource (SiD + ILD) | 748+1,400 person-years | 748+1,400 person-years | 23.9 |
| **Operation/year (Acc.) : sum** | **n/a** | **n/a** | **36.6 ~ 39.2** |
| Value: Utilities/Maintenance | 0.390 | 0.290 ~ 0.316 | 29.0 ~ 31.6 |
| Labor: Human Resource | 850 FTE | 638 FTE | 7.6 |
| **Others (Acc. Preparation)** | **n/a** | **n/a** | **23.3** |
| **Uncertainty** | **25%** | **25%** | **25%** |
| **Contingency** | **10%** | **10%** | **10%** |
| **Decommission** | **n/a** | **n/a** | **Equiv. to 2-year op. cost** |

http://www.mext.go.jp/component/b_menu/shingi/toushin/__icsFiles/afieldfile/2018/09/20/1409220_2_1.pdf

FIG. 7. Costs of the ILC250 project in ILCU as evaluated by the Linear Collider Collaboration (LCC), converted to JPY and re-evaluated by KEK, and summarised in the MEXT ILC Advisory Panel report, in July, 2018.

**Updated cost estimate prepared for input to European Strategy update (cost review completed in Feb. 2025)**

- New estimates for main cost drivers (75% of cost):civil construction and SRF
- Other items scaled up for inflation

- ***ILC (250 Gev) with 2 BDL cost***
  ***6.8 ILCU + 2.0 JPY + < 1 ILCU (2 BDL)***

- ***ILC TDR (500 GeV) cost:***
  ***6.8 ILCU + 2.0 Yen + < 6.0 ILCU***

2024 cost estimate for ILC@250 GeV in a model Japanese site

| Item | Cost in $10^9$ ILCU | Cost in $10^{11}$ JPY |
|---|---|---|
| Accelerator | | |
| Conventional part | 1.7 | |
| SRF related part | 3.7 | |
| Facilities | | |
| Conventional components | 1.4 | |
| Civil construction | | 2.0 |
| Total | 6.8 | 2.0 |

- ILCU is 2024 USD where prices are converted by Purchasing Price Parities of the OECD from different currencies
- The civil construction cost remains in JPY since its cost highly depends on the site

# A Linear Collider Facility (LCF) @ CERN

***Initial LCF facility:***

- Based on superconducting (ILC) technology
- Higgs factory with **250 GeV (length: 20.5km) &** alternative 550 GeV (33.5km)
- Luminosity 2.7·1034 at 250GeV, alternative 5.4·1034
- Two interaction points (sharing luminosity)
- Single tunnel, TBM (tunnel boring machine),5.6m diameter -> suitable for Geneva area
- Space for extracted beam facilities for non-colliding experiments and R&D
- Compatible with upgrades to 1 … 1.5TeV

- ***Upgrade path:***
- Luminosity (more power, energy/particle recovery)
- Energy (new technology or extended tunnel)
- Possible technologies: CLIC, C3, plasma, ERL…

| 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) |

***LCF Vision Team Concept for a CERN (LCF at CERN is NOT "ILC at CERN"):***

- ***Transfer / adapt to CERN (important technical differences:):***

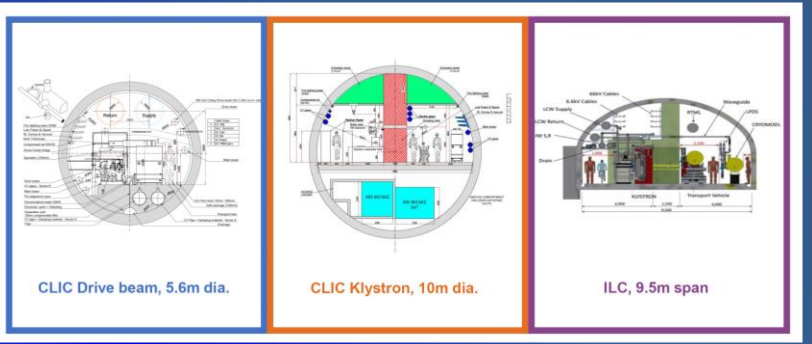
  - Different site (different tunnel & building costs)
    → cost addressed by separate study, in prog.;
    same main linac footprint, larger underground DR, remove drive-beam CE, slightly different BDS, etc…
  - Different baseline
    Build full 33km tunnel (for 550 GeV) from start?
    Second interaction region, crossing angle
    Different energy and luminosity stages
    Laser straight
  - Different time line
    different tunnel and building costs

- ***Input to the European Strategy: Linear***
  - Collider physics case (site independent)
  - Linear Collider Facility at CERN proposal

- ***Will be based on :***
  - Updated 2024 ILC costs
  - CLIC project implementation plan
  - CERN site study, updated and costed
  - Design adaptions for CERN site

# Sustainability: ILC & CLIC Life-Cycle Assessment (LCA) Studies

***CERN commissioned a study with ARUP to perform a Lifecycle Assessment for the CLIC and ILC civil infrastructure (tunnels, shafts, caverns)***




**Full ARUP report: https://edms.cern.ch/document/2917948/1**

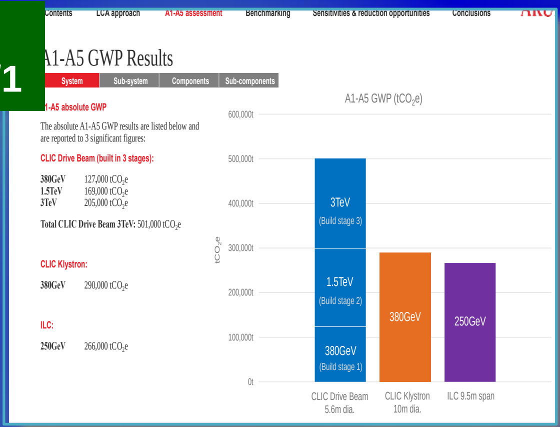
- *Study provided results on:*

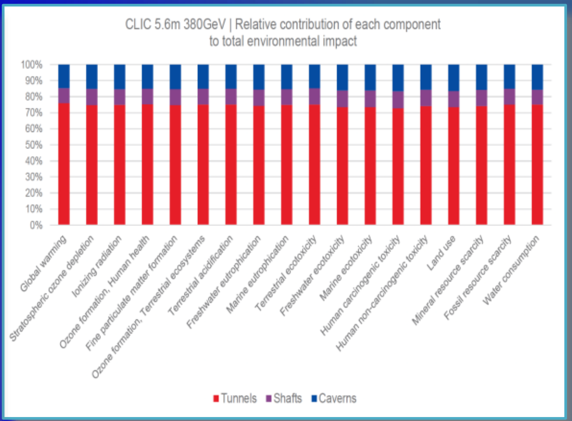
  - Greenhouse gas emissions from construction

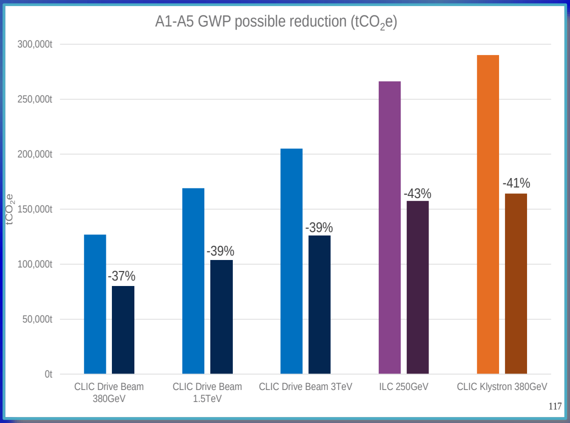
  - Full set of ReCiPe 2016 impact categories
  ***Reduction potential (40%) from optimized design and use of lower carbon material***

- New LCA study on accelerator construction is being prepared:

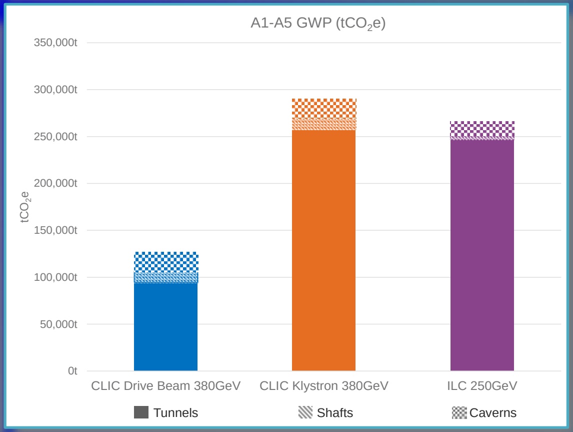
  - Quantify LCA impact of the full project (data inventory for ILC and CLIC accelerator & detector components)




Reduction potential: 40% reduction through use of low-CO2 materials (steel, concrete) and reduction of tunnel wall thickness)




CO2-eq from underground civil engineering and electricity for operation

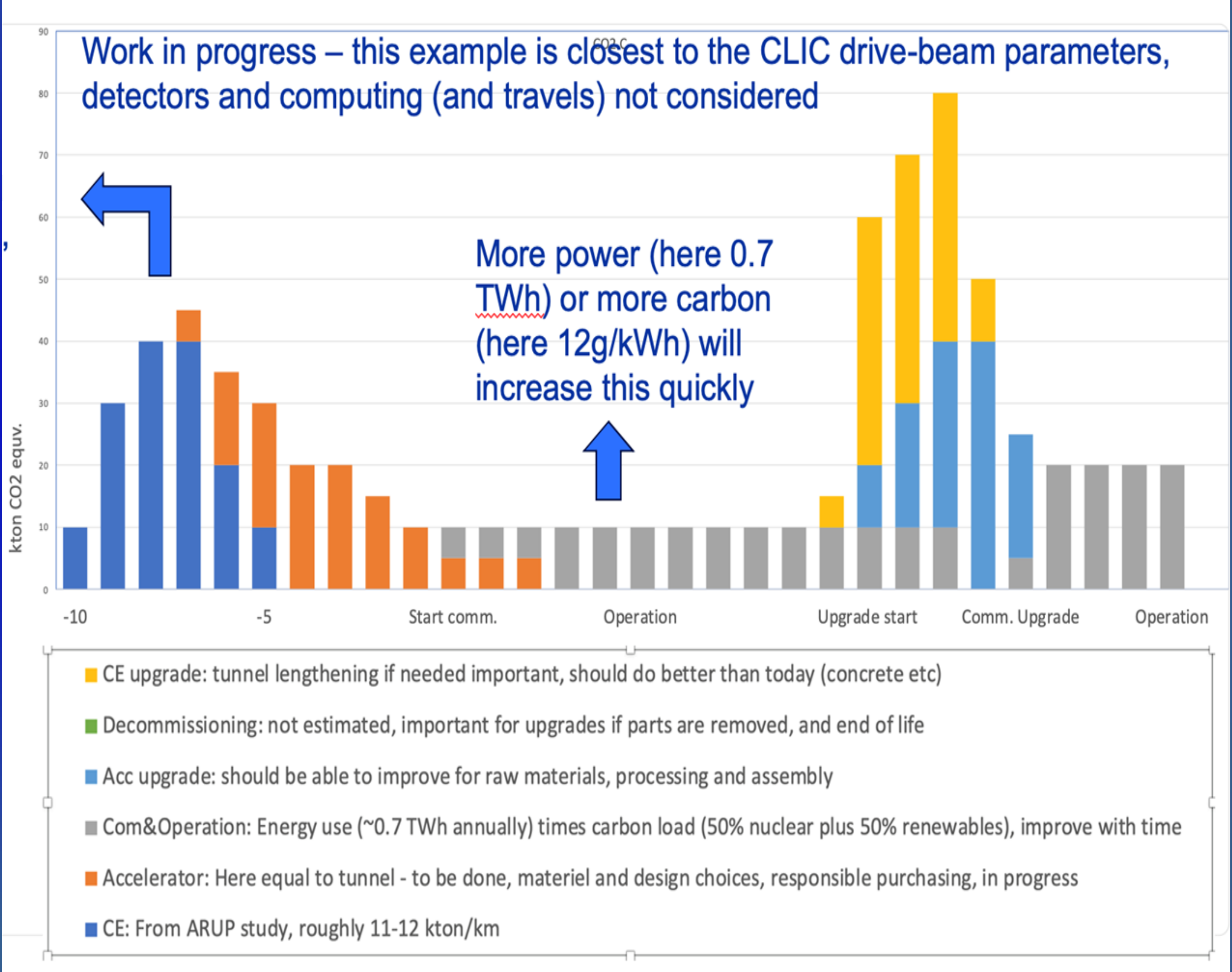
# Example: Towards Carbon Accounting with LCA

## CLIC, also (being) done for ILC, C3, HALHF

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

*NEXT: working on machine parts* here, orange graph assumes accelerator hardware & infrastructure = equal civil engineering impact

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



Laboratory Directors Group

# Sustainability Working Group

## LDG Sustainability WG Mandate and Composition

*Development of guidelines and a minimum set of key Indicators for the sustainability assessment of future accelerators*

*Panel consisting of 15 members with technical expertize in evaluation of accelerator sustainability and future collider project representatives*

***Ensuring broad community representation:***

- Sustainability Lab. Panels established at CERN, DESY, ESS, NIKHEF, STFC
- ICFA Sustainability Panel
- EU- Horizon Programs
- Future accelerator projects: FCC, ILC, CePC, CLIC/Muon, LHeC, C3
- Invited experts on specific topics

- Walib Kaabi - PERLE, EU-iSAS
- Mats Lindroos - ESS (deceased May 2, 2024)
- Roberto Losito - CERN Sust. Panel
- Ben Shepherd - STFC Sust. Task Force
- Andrea Klumpp - DESY Sust. Panel, EU-iFAST
- Hannah Wakeling - ISIS-II Neutron & Muon Source
- Patrick Koppenburg - NIKHEF Sust. Panel

- Johannes Gutleber - FCC
- Yuhui Li - CePC
- Benno List - ILC
- Emilio Nanni - ICFA Sust. Panel & C3
- Vladimir Shiltsev - LHeC
- Steinar Stapnes - CLIC & Muon collider

- Caterina Bloise - Co-Chair
- Maxim Titov - Co-Chair, EU-EAJADE

in the Editorial Board also
- Enrico Cennini (CERN), Luisa Ulric (CERN).
- Beatrice Mandelli (CERN), Niko Neufeld (CERN)
- Thomas Schoerner (DESY)

✓ *Draft is expected for the LDG review early 2025*

✓ ***Executive summary as an input to the ESPPU due by March 2025*** *→ some tables with parameter numbers might be complemented at a later stage*

*Caveat:*
- *not all of these topics can be addressed in details in a limited time*
- ***A homogeneous evaluations of all issues will probably need more time to develop and deserves a strategy to be pursued***

## *Report Structure and Sustainability Assessment Guidelines:*

**Sustainability WG report is advancing, the bulk of issues elaborated pertain to:**
- *socio-economic benefits of accelerators-based research infrastructures*
- *basis of sustainability assessment*
- *methodology and reporting of LCA for future HEP accelerators*
- *evaluation of Greenhouse gas (GHG) emissions in construction, operation, decommissioning*
- *mitigation & compensation strategies*

**Content for each chapter will contain:**
- *description of landscape & highlights*
- *recommendations (major and more technical ones)*
- *the list of open questions*

**Sustainability assessment for future large-scale accelerator infrastructures is quite complex:**
- *assessment criteria needs to be properly tuned to the maturity of the project (stage)*
- *differently developed for Researchers, Management and Society*





UKRI Science and Technology Facilities Council

# Summary and Some Key Points

- *Strong scientific consensus that an e+e- Higgs Factory is the highest-priority next collider → CLIC and ILC are two mature designs for an e+e- Higgs Factory*

- *Particular attention has to be devoted to find a baseline ("affordable") scenario to start with, which costs less than 10 GEUR, assuming that increases of energy and luminosity would follow from successive upgrades, exploiting the outcome of R&D on advanced accelerator technologies, while operating the infrastructure*

- *LC vision Concept: extended meeting at CERN 8-10.1.2025 to prepare ESPP inputs: https://indico.cern.ch/event/1471891/overview)*

*Special thanks to – most information from:*

S.Michizono, S. Stapnes, T, Nakada, B. List, IDT and ILC colleagues, CLIC team, J.List, A.Robson, E.Nanni, C, Vernieri, the HALHF team, ARUP, and all the colleagues from CLIC, ILC, C3 and HALHF collaborations

# OUTLOOK

**Our HEP field will need:**

- ✓ Flexibility & Coordination
- ✓ Preparedness
- ✓ Visionary Global Policies
- ✓ Funding and

… a little bit of luck