

# LINEAR COLLIDER STUDIES AND PROSPECTS

S. Stapnes, University of Oslo, Norway

## Abstract

Linear  $e^+e^-$  colliders can provide a broad physics programme spanning centre-of-mass energies from the Z pole to the TeV scale, enabling precision measurements of the Higgs boson, top quark, and the electroweak sector with polarised beams. Two mature accelerator technologies are under development for a possible linear collider facility (LCF) at CERN beyond the HL-LHC: the superconducting RF (SCRf) approach embodied by the ILC as developed for hosting in Japan, and the proposed normal-conducting high gradient RF (NCRF) two-beam scheme of CLIC. Both options are described in detailed documents contributed to the European Strategy for Particle Physics Update (ES-PPU) process. Beyond an initial implementation in the 250-380 GeV range, upgrades in energy and/or luminosity enabled by R&D on cool copper structures, higher gradient SCRf, energy recovery and plasma wakefield options can be considered. This paper summarises the status of the studies and associated technology developments, potential long-term upgrade paths, and key implementation parameters including cost, power, and sustainability assessments.

## 1. INTRODUCTION

Linear  $e^+e^-$  colliders are the preferred technology for a precision lepton collider spanning a broad range of centre-of-mass energies up to one to a few TeV. Their defining advantages beyond the energy range include the availability of longitudinally polarised beams for both electrons and positrons, a clean experimental environment free of synchrotron radiation backgrounds at the interaction point, and inherent upgradability in energy and luminosity without or with limited additional civil construction. A linear collider is uniquely able to realise a true multi-stage Higgs factory while providing a natural path to the multi-TeV energy frontier.

At 250–380 GeV,  $e^+e^- \rightarrow ZH$ , also called Higgs-strahlung, yields model-independent Higgs coupling measurements to the percent level or better. An optional Z-pole run and W-mass threshold scan, both polarised, complement the programme with precision electroweak measurements.

While the top mass can be measured at the  $t\bar{t}$  threshold (expected precision: 40 MeV), a centre of mass energy of 550 GeV enables measurements of the top Yukawa coupling (2.8%) and the trilinear Higgs self-coupling (11%). Beam polarisation aids the analyses at every stage [1]. The multi-stage design is a key asset: anomalies at one energy can be verified at the next, providing the robustness needed to establish genuine discoveries from precision measurements [1,2].

Two RF technologies have reached the level equivalent of a Technical Design Report (TDR). The International Linear Collider (ILC) is based on 1.3 GHz niobium SCRf cavities at 31.5 MV/m and has been studied for possible construction in Japan since 2012. The Compact Linear

Collider (CLIC) uses a novel two-beam acceleration scheme with normal-conducting X-band cavities reaching 72-100 MV/m, targeting an initial stage at 380 GeV expanding to 1.5 TeV later. At CERN a 550 GeV version of an SCRf based collider has been studied, with a choice of higher luminosities and hence power consumption compared to parameters chosen for the ILC in Japan. Both are compatible with a civil-engineering footprint of approximately 30-34 km length near CERN. Advanced upgrade technologies - C<sup>3</sup>, HELEN, Nb<sub>3</sub>Sn coated or travelling wave SCRf, plasma wakefield acceleration, energy-recovery linac concepts, and more - are under active R&D as upgrade candidates towards higher energies and/or luminosities [1, 2].

## 2. SCRf TECHNOLOGY: LCF-SCRf AT CERN AND THE ITN

The ILC TDR, published in 2013, describes a 500 GeV linear collider based on 1.3 GHz nine-cell niobium SCRf cavities at 31.5 MV/m. The design has since been reviewed repeatedly by ICFA and Japanese government committees. A comprehensive cost update was completed in December 2024 by an international expert committee, confirming the technical maturity and establishing updated cost estimates consistent with the original TDR. Key technical advances since 2013 include the two-step baking surface treatment (sequential heat treatment at 75°C followed by 120°C), which reliably achieves  $Q_0 \geq 1.0 \times 10^{10}$  at 35 MV/m. Large-scale SCRf-based free-electron laser facilities (EuXFEL, LCLS-II, SHINE) are in operation worldwide, demonstrating the full industrial maturity and reproducibility of the technology [3].

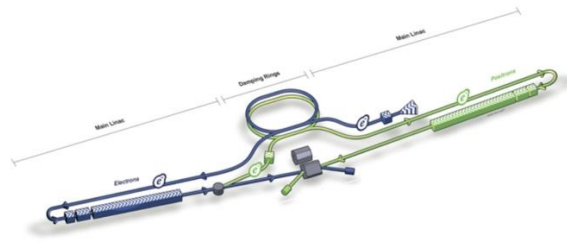


Figure 1: ILC in Japan. When adapted to a CERN facility two beam-delivery systems are foreseen providing two collision points.

The proposed Linear Collider Facility (LCF) at CERN adapts the ILC SCRf linac design for the CERN environment (Fig.1), combining it with the civil-engineering footprint and infrastructure standards developed over many years for CLIC. The baseline LCF configuration uses a 33.5 km tunnel that includes a 4-5 km beam-delivery region (BDS), with two interaction regions sharing the luminosity. The SCRf main linacs suggested for

implementation at CERN operate at 31.5 MV/m with quality factor  $Q_0 = 2 \times 10^{10}$ , trains of 1312 bunches ( $2 \times 10^{10}$  electrons per bunch) at a repetition rate of 10 Hz. The resulting instantaneous luminosity at 250 GeV is  $2.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . Both beams are polarised with  $P(e^-, e^+) = 80\%/30\%$ . The total construction cost is 8.3 BCHF and the site AC power 143 MW. An immediate luminosity upgrade doubles the bunch count per train to 2625, reaching  $5.4 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  for an additional 0.77 BCHF and 39 MW. Filling the remaining tunnel length with further SCRF modules achieves 550 GeV at an incremental cost of  $\approx 5.5$  BCHF, with a luminosity of  $7.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  at 322 MW [1].

The ILC Technology Network (ITN) was established in 2022 by the ILC International Development Team (IDT) under ICFA auspices to advance the engineering studies required for construction readiness. KEK acts as lead laboratory with dedicated budget; CERN serves as European hub under a formal KEK–CERN agreement, facilitating participation by European institutes. Fifteen work packages across three technical areas are under active development by laboratories in Asia, Europe, and beyond [3].

In the Superconducting Technology area, work-package WPP-1 (cavity production) targets nine-cell ILC-specification cavities with two-step baking surface treatment. Six single-cell and three nine-cell cavities have been completed in Japan as of early 2026, including the world's first nine-cell cavity in medium-grain (MG) niobium. Single-cell cavities are also produced in Europe (CERN, CEA, INFN) and South Korea. All completed single-cell cavities have met or exceeded the ILC specification. WPP-2 (cryomodule design) develops the assembly procedures, alignment and RF interconnects for full cryomodules. WPP-3 addresses crab cavities, the transverse RF deflectors essential for the crab-crossing luminosity scheme [3].

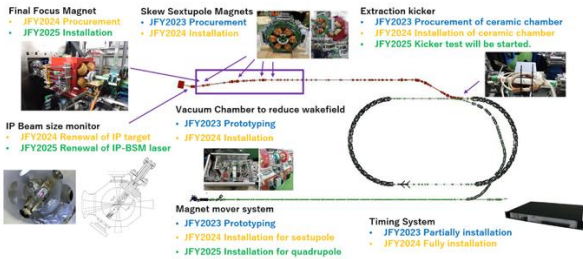


Figure 2: The ATF2 facility for nano-beam and final-focus beam physics and instrumentation.

In the Particle Sources domain, WPP-6/7 study the undulator-based polarised positron source - photon collimation, capture section, and pulsed wheel target - while WPP-8–11 develop the electron-driven positron source as an alternative that avoids high-power beam through the undulator. WPP-4 focuses on high-brightness polarised electron sources. In the Nano-beam area, WPP-12 and WPP-14 address the damping ring design and injection/extraction kicker systems needed to achieve the ultra-low vertical emittance at the interaction point. WPP-15 and WPP-16 study the final-focus quadrupole design and magnetic vibration mitigation, while WPP-17 covers the main beam

dump. ATF2 at KEK (Fig.2) is the central experimental facility for final-focus beam physics, with an ATF3 upgrade planned to directly demonstrate the ILC nanobeam. European ITN contributions span CERN, DESY, CEA, INFN, and universities in the UK, Germany, France, Italy and Spain, partly supported through the EAJADE Marie Skłodowska-Curie training network.

### 3. CLIC TECHNOLOGY AND KEY R&D

CLIC is a mature proposal for a multi-TeV linear  $e^+e^-$  collider based on a unique two-beam acceleration scheme (Fig.3). This technology could also serve as a starting point for a linear collider facility at CERN and its implementation at CERN has been studied in detail. A dedicated high-current drive beam, produced in a separate linac at low RF frequency, is transported alongside the main linac in decelerating sectors. In Power Extraction and Transfer Structures (PETS) the drive beam releases its stored RF energy, which is transferred via waveguides into 12 GHz normal-conducting accelerating structures of the main beam, reaching gradients of 72-100 MV/m. This avoids the large number of conventional high-power klystrons otherwise needed and gives a significant cost and power advantage, particularly at multi-TeV energies [2].

The 2025 CLIC baseline for the initial stage is 380 GeV centre-of-mass energy with a 100 Hz repetition rate and a dual beam-delivery system (BDS) serving two interaction regions simultaneously. The total luminosity is  $4.5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  ( $2.2 \times 10^{34}$  per detector on average), the site length 11.4 km, and the AC power 166 MW. Compared with earlier designs, a factor-of-three improvement in luminosity per unit power has been achieved through optimisation of injectors, damping ring RF systems, and accelerating structure parameters; higher-efficiency drive beam L-band klystrons are a key contributor. The construction cost is approximately 7.2 BCHF. A second stage at 1.5 TeV extends the main linacs to a 29 km site length using a single drive beam at 50 Hz, reaching  $3.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  at 287 MW and an incremental cost of  $\approx 7.1$  BCHF [2].

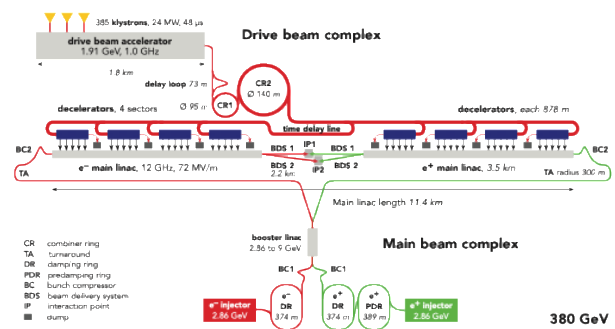


Figure 3: Schematic layout of the CLIC complex at 380 GeV, with a double beam-delivery system operating with two detectors.

The CLIC footprint near CERN has been optimised for both the 380 GeV and 1.5 TeV stages, placing the main-beam and drive-beam production complexes on the CERN

site avoiding existing infrastructures as much as possible [2]. An energy option at 250 GeV is obtained by removing 35% of two-beam modules; a 550 GeV option with 100 Hz and two IPs is achievable with a modest 5 km tunnel extension. The dual BDS design provides two IPs with a transverse separation of  $\approx 10$  m and a 40 m longitudinal offset, each with its own optimised beam crossing angle.

Extensive technology demonstrations validate the CLIC performance goals. The CLIC Test Facility CTF3 at CERN confirmed the complete two-beam acceleration scheme, including RF power transfer, drive-beam stability, and two-beam acceleration up to 145 MV/m. Modern C-band and X-band free-electron lasers - SACLA, SwissFEL (particularly relevant), and the ongoing EUPRAXIA 1 GeV X-band linac at LNF - provide large-scale demonstrations of normal-conducting, high-frequency, low-emittance linac technology. Precision pre-alignment using active remote alignment systems, nm-level vibration stabilisation of final-focus quadrupoles with inertial sensors and actuators, and CLIC-level vertical emittances at modern light sources have all been experimentally demonstrated. Beam-based alignment algorithms have been tested at FACET and FERMI to be within CLIC requirements. Integrated start-to-end luminosity simulations confirm that 90% of machine realisations achieve  $\geq 4.5 \times 10^{34}$  cm<sup>-2</sup>s<sup>-1</sup>, with an average of luminosity of  $5.6 \times 10^{34}$  [2].

#### 4. LONG-TERM UPGRADE SCENARIOS

A core design principle of a Linear Collider Facility is that energy upgrades beyond the initial stage can be achieved by replacing or supplementing the linac technology within the existing tunnel, and/or if needed adding new civil construction. The common civil-engineering footprint - a 33–34 km tunnel with a 4–5 km BDS sized for multi-TeV operation - can be designed from the outset to accommodate future technologies (Fig.4). Four technologies targeting accelerating gradients of 70–155 MV/m and centre-of-mass energies of 1–3 TeV are under active R&D, with all expected to reach maturity during the next decade [1,2].

The C<sup>3</sup> (Cool Copper Collider) concept operates cryogenically cooled (77 K) copper cavities at C-band frequency (5.7 GHz) with a distributed-coupling design that enables gradients of 70–150 MV/m with excellent RF-to-beam efficiency. First bench tests have confirmed the gradient principle. Depending on the achievable gradient and the efficiency of high-power RF sources, centre-of-mass energies of 1.5–3 TeV are projected for the LCF tunnel. C<sup>3</sup> represents one of the most promising paths to a compact TeV-scale collider.

The HELEN proposal (High-Energy Linac with Enhanced performance) uses travelling-wave niobium SCRF cavities at 60 MV/m, enabling  $\geq 1$  TeV while leveraging the SCRF industrialisation ecosystem developed for the initial stage.

Advanced Nb<sub>3</sub>Sn superconducting cavities targeting 90–100 MV/m are under development at Cornell, DESY, and Jefferson Lab and would enable  $\geq 1.5$  TeV once application-ready [1].

Energy-Recovery Linac (ERL) schemes such as ReLiC, ERLC or similar concepts recirculate the spent beam, recovering its kinetic energy and the beam particles themselves. The resulting near-continuous beam power enables luminosities approaching  $10^{36}$  cm<sup>-2</sup>s<sup>-1</sup>, orders of magnitude above standard designs, opening access to rare processes at high statistics.

Plasma wakefield acceleration (PWA) offers GV/m-scale gradients; the hybrid asymmetric linear Higgs factory (HALHF) deploys plasma cells in the electron arm to reach high asymmetric collision energies in a compact footprint.

The ALEGRO R&D programme targets all-plasma e<sup>+</sup>e<sup>-</sup> or  $\gamma\gamma$  colliders at 10 TeV and above.

A photon-collider interaction region uses either X-ray free-electron (XCC scheme) or optical laser back-scattering on the main beam to access  $\gamma\gamma \rightarrow HH$  for an independent Higgs self-coupling measurement at lower centre-of-mass energy.

All these upgrade options need to be considered carefully for compatibility with the initial civil-engineering footprint and can be developed in parallel with the initial stage implementation [1].

#### 5. KEY IMPLEMENTATION PARAMETERS

Table 1 summarises construction costs, site power, and annual energy consumption for the main LC configurations studied for CERN, based on detailed work-breakdown-structure exercises reviewed by international expert committees. LCF civil-engineering costs are derived from CLIC and other CERN projects using CERN unit prices; CLIC costs were updated in 2024–25 from the 2018 Project Implementation Plan. Both SCRF and NCRF options have been analysed in a comparative report commissioned by the European Strategy Preparatory Group [4].

Table 1: Key Parameters for the Main LC Configurations [1, 2]

Parameter	LCF 250 LP	LCF 550 FP	CLIC 380	CLIC 1500
$\sqrt{s}$ (GeV)	250	550	380	1500
Lumi. ( $10^{34}$ cm <sup>-2</sup> s <sup>-1</sup> )	2.7	7.7	4.5	3.7†
Power (MW)	143	322	166	287
Energy/yr (TWh)	0.8	1.8	0.8	1.4
Const. cost (BCHF)	8.3	+5.5	7.2	+7.1
Operation (MCHF/yr)	170	342	137	$\approx 250$

† Not yet updated for latest alignment studies; may reach  $5.6 \times 10^{34}$ . LP/FP = Low/Full Power (1312/2625 number of bunches/train). LCF 550 and CLIC 1500 costs are incremental above the initial stage.

A decade of systematic effort has reduced the power consumption of both projects. For a SCRF based collider this includes optimisation of SCRF cavity gradients and Q-values, cryogenic system efficiency, klystron and modulator performance, RF-to-beam efficiency through improved fill factors, heat recovery schemes, and nanobeam optimisation to reduce required beam power. For a NCRF collider the key gains come from reduced injector power, re-designed damping ring RF with higher-efficiency, and L-band klystrons allowing more efficient drive-beam generation.

Life Cycle Assessments (LCAs) carried out in collaboration with engineering consultancy ARUP quantify CO<sub>2</sub>-equivalent embodied carbon and operational emissions across the full life cycle (A1-A5 phases for materials and construction, plus operational energy) [5]. For LCF 250 (LP), the total embodied carbon in underground civil engineering is approximately 380 kton CO<sub>2</sub>eq, and machine elements (including injectors) contribute a further 236 kton. For CLIC 380, underground civil engineering accounts for 286 kton and machine hardware for 140 kton. Surface buildings (primarily injector and service buildings on the Prévessin site) add 118 kton for CLIC. Two detectors contribute approximately 94 kton (a preliminary estimate). Assuming the projected 2050 carbon intensity of the French grid at 14–18 g CO<sub>2</sub>/kWh, annual operational emissions are ≈13 kton CO<sub>2</sub>eq for the initial stage of either project, rising to 22 kton (CLIC 1500) and 28 kton (LCF 550) for higher-energy stages. LCA results are increasingly used as design optimisation tools — informing choices of materials, suppliers, and construction methods — and hardware remains the dominant contribution to embodied carbon in both cases [5].

Operation costs cover personnel, electricity, and maintenance and component replacement. For LCF 250 these are estimated at 170 MCHF/yr for 640 FTE at full luminosity, rising to 342 MCHF/yr at 550 GeV. For CLIC 380 the estimate is 137 MCHF/yr for 650 FTE, using the standard CERN electricity price assumption of 80 EUR/MWh. Construction personnel for the initial implementation are estimated in the 10 000–11 000 FTE-year range for both projects, using the standard CERN scaling formula. A detailed schedule towards construction foresees preparation Phase 1 (2026–2028) and Phase 2 (2028–2034), followed by construction, allowing commissioning and first physics a decade later [1,2,4].

## 6. NEXT STEPS AND CONCLUSIONS

The path to a construction decision for a linear collider at CERN is structured in two preparation phases following ESPPU finalisation in 2026 [1,2]. Phase 1 (2026-2028) integrates and extends the ongoing programmes. Five work packages have been identified: WP1 - accelerator design and parameters (start-to-end simulations, machine layouts, performance margins, and upgrade scenarios); WP2 - civil engineering and conventional systems (tunnel and shaft layouts, services adapted to CERN standards, siting optimisation); WP3 - technology development targeting TRL 6–7 for key RF systems, positron source, cryogenic

infrastructure, and beam instrumentation; WP4 - beyond-collider and upgrade interface studies (plasma, energy recovery, and  $\gamma\gamma$  options, civil-engineering compatibility with baseline); and WP5 - management, integration, costing, power, and LCA estimates, with risk management and preparation for Phase 2 decision-making. It should be noted that the priority placed on HL-LHC operations and FCC-ee preparation in the current CERN planning means that the full scope of Phase 1 is still under discussion.

A key milestone in Phase 1 is a decision process to validate the project's progress and promise and authorise entry into Phase 2, also depending on decisions on a potential FCC-ee implementation on a similar timescale. Phase 2 would target final engineering design, large-scale industrial pre-series production, and site preparation, including environmental integration with host states. For SCRF technology, a significant fraction of Phase 2 activities can be distributed globally through the existing ILC industrialisation network: cryomodule assembly facilities at KEK, DESY, CERN and other laboratories; niobium cavity manufacturing and surface-treatment facilities; klystron and modulator manufacturers in Japan, Europe, and beyond. Construction start will be determined by a formal project approval by the CERN Council based on the Phase 2 preparation.

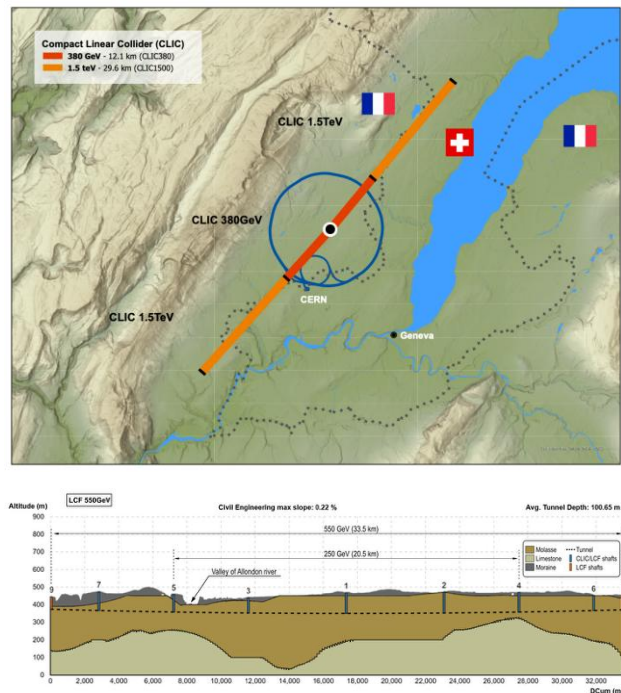


Figure 4a and 4b: The footprint and profile of CLIC and LCF-SCRF at CERN, using the same path with lengths adapted to the desired energy reach and RF technology.

In summary, two mature and complementary linear collider technologies - SCRF or NCRF based - are ready for detailed implementation studies at CERN. Both offer an initial construction cost of 7-9 BCHF, a comprehensive

physics programme from the Z pole to 550 GeV and beyond, polarised beams, two interaction regions, and well-defined upgrade paths extending to 1.5 TeV and beyond within the same civil-engineering footprint. The combined international R&D programme - the ITN for a SCRF based collider technology, implementation studies at CERN and partner laboratories, and advanced accelerator R&D spanning C<sup>3</sup>, HELEN, plasma concepts, and ERL designs - provides the technological foundation for a future Linear Collider Facility.

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