Linear Collider Vision

The Linear Collider Facility (LCF) at CERN – Back-up Document –

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In this paper we outline a proposal for a Linear Collider Facility as the next flagship project for CERN. This proposal offers the opportunity for a timely, cost-effective and staged construction of a new collider that will be able to comprehensively map the Higgs boson's properties, including the Higgs field potential, thanks to a large span in centre-of-mass energies and polarised beams. A comprehensive programme to study the Higgs boson and its closest relatives with high precision requires data at centre-of-mass energies from the Z pole to at least 1 TeV. It should include measurements of the Higgs boson in both major production mechanisms, $e^+e^- \to ZH$ (Higgs strahlung) and $e^+e^- \to \nu\bar{\nu}H$ (WW fusion), precision measurements of gauge boson interactions as well as of the W boson, Higgs boson and top-quark masses, measurement of the top-quark Yukawa coupling through $e^+e^- \to t\bar{t}H$, measurement of the Higgs boson self-coupling through HH production, and precision measurements of the electroweak couplings of the top quark. In addition, e^+e^- collisions offer discovery potential for new particles complementary to HL-LHC. The facility we propose robustly satisfies these scientific goals. With a total length of 33.5 km, two interaction regions as well as additional R&D and fixed-target experiments, it offers significant flexibility to take into account scientific and strategic developments. From today's perspective, we propose to equip the Linear Collider Facility in a first stage with superconducting RF cavities for polarised e^+e^- collisions at a centre-of-mass energy of 250 GeV with a luminosity of $2.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which requires an investment of about 8.3 BCHF. With a preparatory phase of six years, followed by ten years of construction, this first stage could start data-taking by 2042. First upgrades comprise doubling of the luminosity for 0.8 BCHF and an increase of energy up to at least 550 GeV, which can be achieved with the same accelerator technology for about 5.5 BCHF. Later stages will involve further luminosity and energy upgrades and other new capabilities that will further enhance the Higgs programme and extend the discovery potential for new physics. These upgrades and new capabilities will primarily be accomplished by accelerator technology innovations rather than by additional civil construction.

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1 Stages and parameters

The main stages of the Linear Collider Project (LCF) and the key scientific goals of each are sketched in Fig. 1 for two scenarios A and B, which are defined as follows:

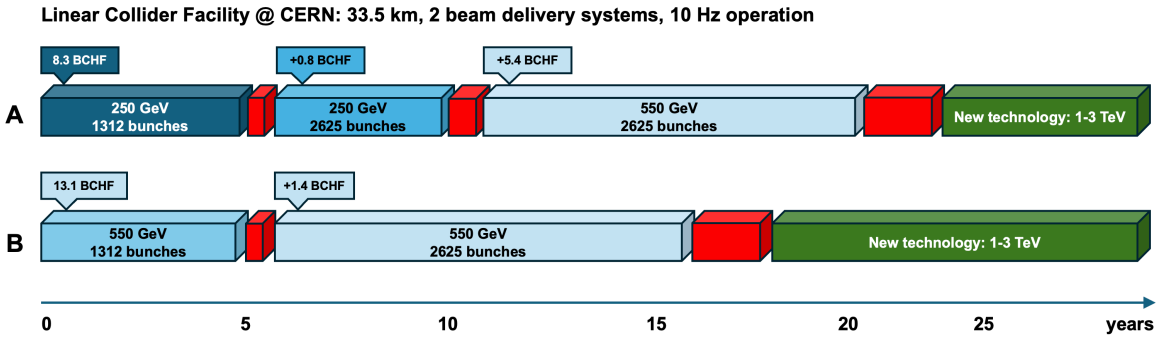


Figure 1: Visualisation of the timelines of scenarios A and B. The technical time zero would be around 2042. Note that the Linear Collider Facility offers significant flexibility to react to i) findings at or developments with other machines (HL-LHC, CEPC, ...) and to ii) the technical readiness of particular implementations.

- **Scenario A**, i.e. starting with 250 GeV, gives a large data set of $e^+e^- \to ZH$ events for measurements of Higgs branching ratios (to 1 %), the total ZH cross section (to 1 %), the absolute Higgs coupling normalisations and the Higgs boson mass (to 10^{-4} precision). It also enables searches for non-standard Higgs boson decays (to the 10^{-4} level of branching ratios), and it allows for a collection of a few 10^9 events at the Z pole.
  - The **power upgrade of scenario A** from 1312 ("low power", LP) to 2625 bunches ("full power", FP) will double the available luminosity.
  - The **energy upgrade of scenario A** to 550 GeV will give access to WW fusion events, with an independent setting for Higgs branching ratio measurements and exotic decay searches. Importantly, it will facilitate measurements of the top quark Yukawa coupling (through $e^+e^- \to t\bar{t}H$) and of the Higgs self-coupling (through $e^+e^- \to ZHH$). It will also

Quantity	Symbol	Unit	Initial-250	Upgrades		Initial-550	Upgrade
Name		LCF	250 LP	250 FP	550 FP	550 LP	550 FP
Centre-of-mass energy	$\sqrt{s}$	GeV	250	250	550	550	550
Inst. luminosity	$\mathscr{L}$ (10^{34}cm^{-2}s^{-1})		2.7	5.4	7.7	3.9	7.7
Polarisation	$\lvert P(e^-)\rvert$/ $\lvert P(e^+)\rvert$ (%)		80 / 30	80 / 30	80 / 60	80 / 30	80 / 60
Repetition frequency	f_{rep}	Hz	10	10	10	10	10
Bunches per pulse	n_{bunch}	1	1312	2625	2625	1312	2625
Bunch population	N_{e}	10^{10}	2	2	2	2	2
Linac bunch interval	Δt_{b}	ns	554	366	366	554	366
Beam current in pulse	I_{pulse}	mA	5.8	8.8	8.8	5.8	8.8
Beam pulse duration	t_{pulse}	μs	727	897	897	727	897
Average beam power	P_{ave}	MW	10.5	21	46	23	46
Norm. hor. emitt. at IP	$\gamma\varepsilon_{\text{x}}$	μm	5	5	10	10	10
Norm. vert. emitt. at IP	$\gamma\varepsilon_{\text{y}}$	nm	35	35	35	35	35
RMS hor. beam size at IP	σ^*_{x}	nm	516	516	452	452	452
RMS vert. beam size at IP	σ^*_{y}	nm	7.7	7.7	5.6	5.6	5.6
Site AC power	P_{site}	MW	143	182	322	250	322
Annual energy consumption		TWh	0.8	1.0	1.8	1.4	1.8
Site length	L_{site}	km	33.5	33.5	33.5	33.5	33.5
Average gradient	g	MV/m	31.5	31.5	31.5	31.5	31.5
Quality factor	Q_0	10^{10}	2	2	2	2	2
Construction cost		BCHF	8.29	+0.77	+5.46	13.13	+1.40
Construction labour		kFTEy	10.12		+3.65	13.77	
Operation and maintenance		MCHF/y	170	196	342	291	342
Electricity		MCHF/y	66	77	142	115	142
Operating personnel		FTE	640	640	850	850	850

Table 1: Summary table of the LCF accelerator parameters in the initial 250 GeV configuration and possible upgrades, as well as in an initial 550 GeV configuration and its luminosity upgrade.

enable measurements of top quark properties, not least the top mass in top-pair threshold measurements.

- **Scenario B**, i.e. starting with 550 GeV, gives immediate access to all mentioned measurements in the entire energy range from the Z pole to 550 GeV.
  - The **power upgrade of scenario B**, from 1312 to 2625 bunches, will double the available luminosity.
- A later **stage at 1** TeV or beyond provides access to WW fusion to HH and thus a complementary access to the Higgs self-coupling. There will be increased sensitivity to anomalies in the top quark couplings. Ample single-Higgs production will allow for further scrutiny of the Higgs couplings to SM particles.
- An potential ultimate **stage at 3** TeV might grant access to new particles discovered or hinted to at the HL-LHC, and will give access to the quartic Higgs coupling.

The ordering of stages is not fixed and allows for flexibility. The vision for a Linear Collider Facility at CERN has two alternative starting scenarios, one with 250 GeV and one with 550 GeV centre-of-mass energy, as sketched above. These scenarios are interchangeable, depending e.g. on the initially available funding. Note also that the Linear Collider Facility in general offers significant flexibility to react to i) findings at or developments with other machines (HL-LHC, CEPC, ...) and to ii) the technical readiness of particular implementations

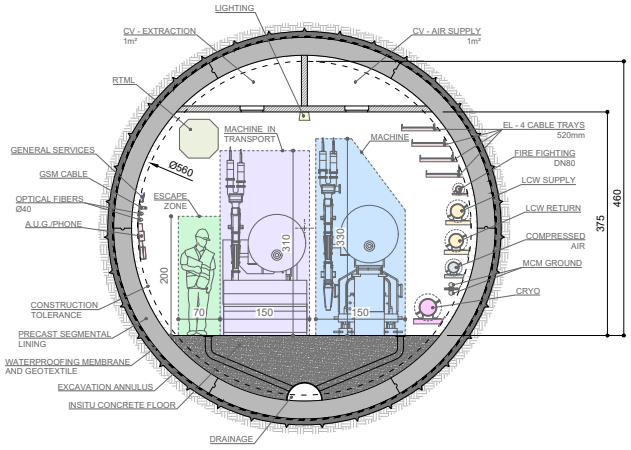


Figure 2: Cross section of the 5.6 m tunnel of a Linear Collider Facility at CERN.

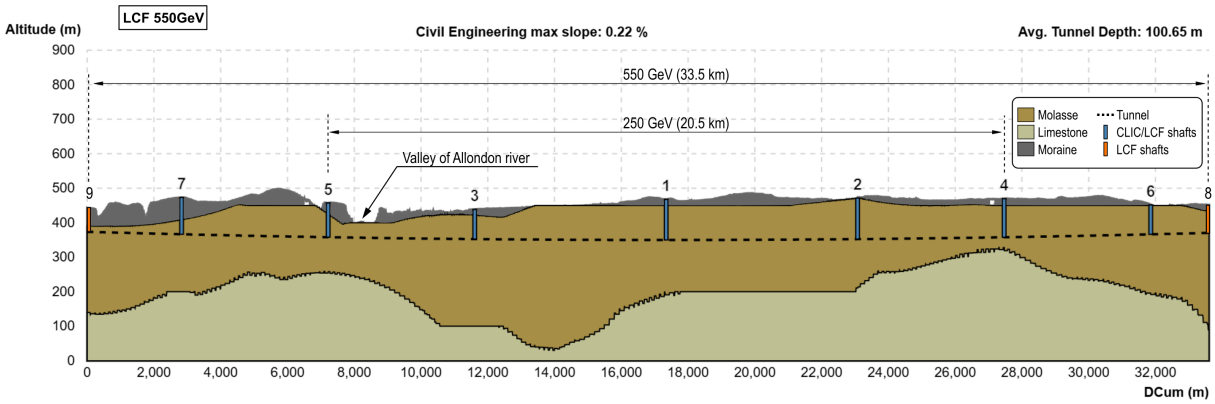


Figure 3: . Geological profile of the LCF tunnel and the location of its access shafts.

For each stage, in both scenarios, the main technical parameters are listed in Tab 1. As an important ingredient, Fig. 2 shows the tunnel cross-section of diameter 5.6 m for the Linear Collider Facility at CERN. Figure 3 shows the geological profile of the foreseen LCF tunnel location, together with the indicative shaft locations.

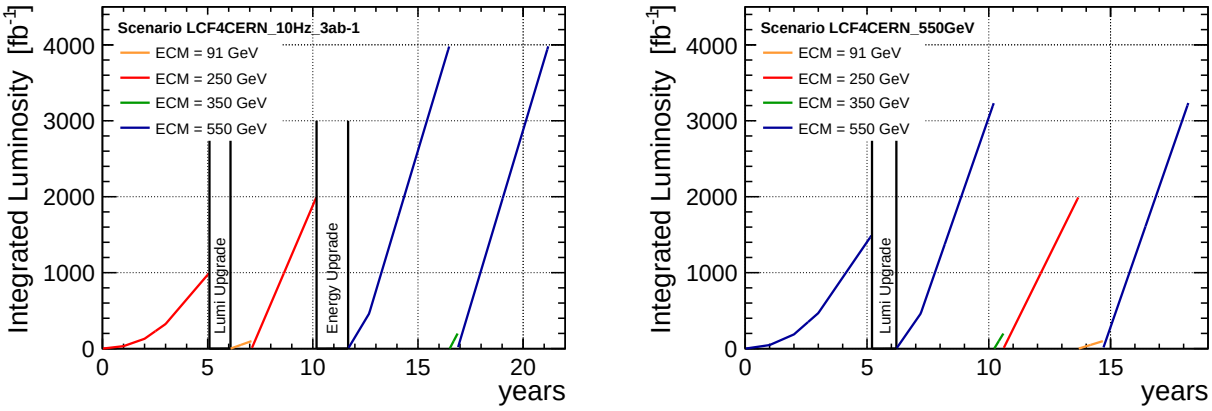
2 Timeline

Both scenarios A and B are essentially ready to be built (see the discussion of remaining R&D items in Sect. 5). The chosen technology – ILC-type super-conducing RF – is mature and has its industrialisation has been successfully completed in the context of the European XFEL at DESY, Hamburg. A construction and site preparation time of 9 years is assumed, irrespective of the scenario. Table 2 shows the anticipated timeline for the various steps of the project in years. The definition of project implementation phases is used as given in the main document of this submission.

The anticipated running times and envisaged integrated luminosities for scenarios A and B are indicated in Fig. 4. Note that these are tentative, and numerous other combinations of running periods are possible, depending on the physics landscape at the time. Not shown are **technology upgrades** to higher energies of 1 TeV and beyond. For these, a construction and installation phase of 3 years each is foreseen. The necessary R&D can be carried out in the shadow of running in scenario A or B.

	Year(s)
Technical design report (ILC)	2013
Project implementation Phase 1	
Definition of the placement scenario	2026
Preliminary implementation with the host states	2026 – 2028
Environmental evaluation	2026 – 2029
Design optimisation	2026 – 2029
Main technologies R&D completion	2029
Technical design report (LCF)	2029
Earliest project approval	2029
Project implementation Phase 2	
Site investigation and preparation	2029 – 2032
Engineering details and industrialisation studies	2029 – 2032
Engineering design completion	2032
Construction phase	
Civil engineering – surface installations	2032 – 2036
Civil engineering – injectors and collider	2032 – 2036
Installation	2036 – 2040
HW and beam commissioning	2037 – 2041
First data	2042

Table 2: Timeline of essential development and construction steps of the LCF project.



(a) (b)

Figure 4: Suggested run plans for an LCF at CERN (a) starting in the baseline configuration in scenario A, and (b) starting directly at 550 GeV. The technical time zero would be around 2042.

3 Resource requirements

3.1 Construction cost and costing methodology

The capital cost of all stages in the scenarios A and B sketched above as well as the annual costs of operation are given in Tab. 1. No cost estimates are given here for later stages of the project.

The human resources requirements for the construction of initial stage amount to 10 120 FTEy, and to around 13 770 FTEy for the 550 GeV, full-luminosity machine.

All cost estimates given here for scenario A or B stages are based on the ILC technical design report (TDR) [1] from 2012 and several cost updates performed since then:

- the cost estimate for a staged 20.5 km, 250 GeV configuration of the ILC as a Higgs factory in Japan from 2017 [2], which was based on the cost basis of the TDR estimate from 2012, but included the effect of a reduced length and centre-of-mass energy as well as a number of minor design updates;
- the 2024 updated cost estimate of the ILC in Japan performed by the International Development Team (IDT) [3, 4];
- a new cost evaluation of the construction costs for the CERN site from 2025 [5].

The ILC cost estimate for the TDR [1] is a full bottom-up cost estimate based on around 2000 line items, going down to the level of the cost of individual components such as cavities, couplers, or magnets for key cost drivers. The costs were evaluated and aggregated by an international team of experts and reviewed by an independent international expert panel in 2013. The updated 2024 cost estimate was again reviewed by an international expert panel in Dec. 2024.

The scope of the cost estimate encompasses the construction cost for the accelerator systems as detailed in the TDR, with applicable design changes. Detectors are excluded, but detector assembly buildings, underground experimental halls, and detector access shafts are included. Computing equipment for accelerator operation is included, while computing installations for detector operation, data taking and analysis are excluded. The cost estimate covers the 10 year construction time until start of commissioning, and therefore excludes costs for project engineering and design, and for R&D prior to construction authorization, as well as costs for commissioning, pre-operation, operation, and de-commissioning. Taxes, contingency, and escalation during project construction are not included. Costs for upgrading the machine beyond 550 GeV are not included, except the cost of those systems that would be very difficult to provide after construction of the 550 GeV machine, in particular the main beam dumps and the beam delivery system (BDS). Costs for land acquisition and site activation (external roads, water supplies, power lines) are not included.

The scope of the new civil engineering cost estimate [5] encompasses the construction costs for underground buildings (tunnels, caverns, shafts) based on a design for the CERN site (Figs. 2 and 3), with tunnels and a central cavern for two beam delivery systems, adapted from the ILC TDR design to accommodate a possible later installation of CLIC. It also encompasses costs for accelerator-related surface buildings for cryogenics, cooling and power infrastructure, and for surface infrastructure in support of the detectors.

As discussed above, costs for land acquisition and site activation (external roads, water supplies, power lines) are **not included**, nor are costs for spoil removal.

The estimated amount of **spoil**, including a bulk factor of 1.3, is $2.7 \times 10^6\,\mathrm{m}^3$ ($1.9 \times 10^6\,\mathrm{m}^3$) for the 33.5 km (20.5 km) long facility. The corresponding costs are estimated to be 200 and 140 MCHF, respectively.

The methodology adopted for the ILC cost estimate was chosen as deemed appropriate for the ILC as an international, in-kind contribution project, with no specific site or host country identified at the time of the TDR. Civil infrastructure (separated in costs for construction and for infrastructure such as electric power supply, water systems, heating, ventilation and air conditioning (HVAC) and several other systems) was evaluated for three potential sites, one in Japan, one in the United States,

and one at CERN. The costs were separated into “Labour” and “Value”, where “Labour” corresponds to the total work performed by staff of participating institutions, measured in full-time equivalent person years (FTEy), while “Value” corresponds to the monetary value of goods and services procured from commercial vendors, expressed in ILCU2012 (ILC Currency Unit). An ILCU2012 corresponds to the purchasing power of 1 USD in the United States in Jan 2012. Comparisons between prices obtained in different countries were made on the basis of PPP (purchasing power parity) conversion rates, as evaluated and publicised by the OECD and World Bank. Where price information from several vendors was available, in particular for SCRF components, prices were converted to ILCU2012 and the lowest reasonable price (where “reasonable” takes into account whether the offering company has been demonstrated the capability to meet the required specifications) was adopted as price estimate. The information of the country of origin and currency of the original offer was retained, so that all quotations can be traced back to the original prices.

The **estimate for institutional Labour** of the 550 GeV configuration was taken from the TDR estimate [1] and amounts to 13.77 kFTEy, the estimate for the 250 GeV configuration is taken from the 2017 staging report [2] and amounts to 10.12 kFTEy.

For the 2024 IDT cost update [3], approximately 75 % of the costs were re-evaluated based on new quotations for SCRF components and updated civil engineering prices for the Japanese site. The costs that were not re-evaluated covered the more conventional accelerator systems such as magnets, vacuum system, diagnostics, etc. Those costs were converted back to the original currency, escalated with the respective region’s inflation index for machinery and equipment, and converted to an updated ILCU2024, defined as purchasing power of a USD in January 2024 in the United States.

A cost estimate for the Linear Collider Facility at CERN was derived based on the described inputs, with a number of important differences:

- The Value estimate was converted to a procurement cost, expressed in 2024 Swiss Francs (CHF).
- The cost estimate was adjusted to take into account differences in the design of the facilities, such as different beam energies, the presence of a second BDS, and different RF configurations.
- The cost estimate for the construction costs of tunnels, caverns, shafts and surface buildings was based on a new study for the CERN site performed in early 2025.
- The cost estimate for the other civil engineering infrastructure (electric power, water, HVAC, etc.) was based on the costs evaluated in the 2012 TDR for the CERN site, escalated with the Swiss inflation index for machinery and equipment.

The conversion from Value to actual Cost in Swiss Francs takes into account a procurement model appropriate for a CERN-based project, different from the ILC approach to quantify the Value of goods: The ILC is a project based on international in-kind contributions, where the procurement is done separately by the contributing institutions, subject to price differences and possibly with a motivation to procure locally at potentially higher prices. This is a reason to consider the Value of contributed goods in lieu of the actual procurement cost in order to determine the monetary value of contributions to the overall project as laid out in a cost-book, which is not the same as the sum of all costs paid. In contrast, a CERN-based project would predominantly organise a central procurement

on the world market, and consider the cost of purchased goods, converted to CHF based on market currency exchange rates.

To convert the ILC Value numbers to **Cost expressed in CHF**, all item values were converted from ILCU2024 back to the local currency (i.e. US Dollars, Japanese Yen, Euros, or Swiss Francs) and then converted to CHF with exchange rates as of January 2024. For goods that are available from different vendors around the world this is a conservative estimate insofar as the lowest reasonable price assumed in the ILC cost estimate is based on a PPP comparison, which leaves the possibility that the goods may be acquired in a different region of the world where price levels are lower than estimated from PPP rates.

The total cost for the baseline configuration LCF 250 LP amounts to 8.29 BCHF, for the full configuration LCF 550 FP to 14.53 BCHF in 2024 prices. These values are also summarised in Tab. 1.

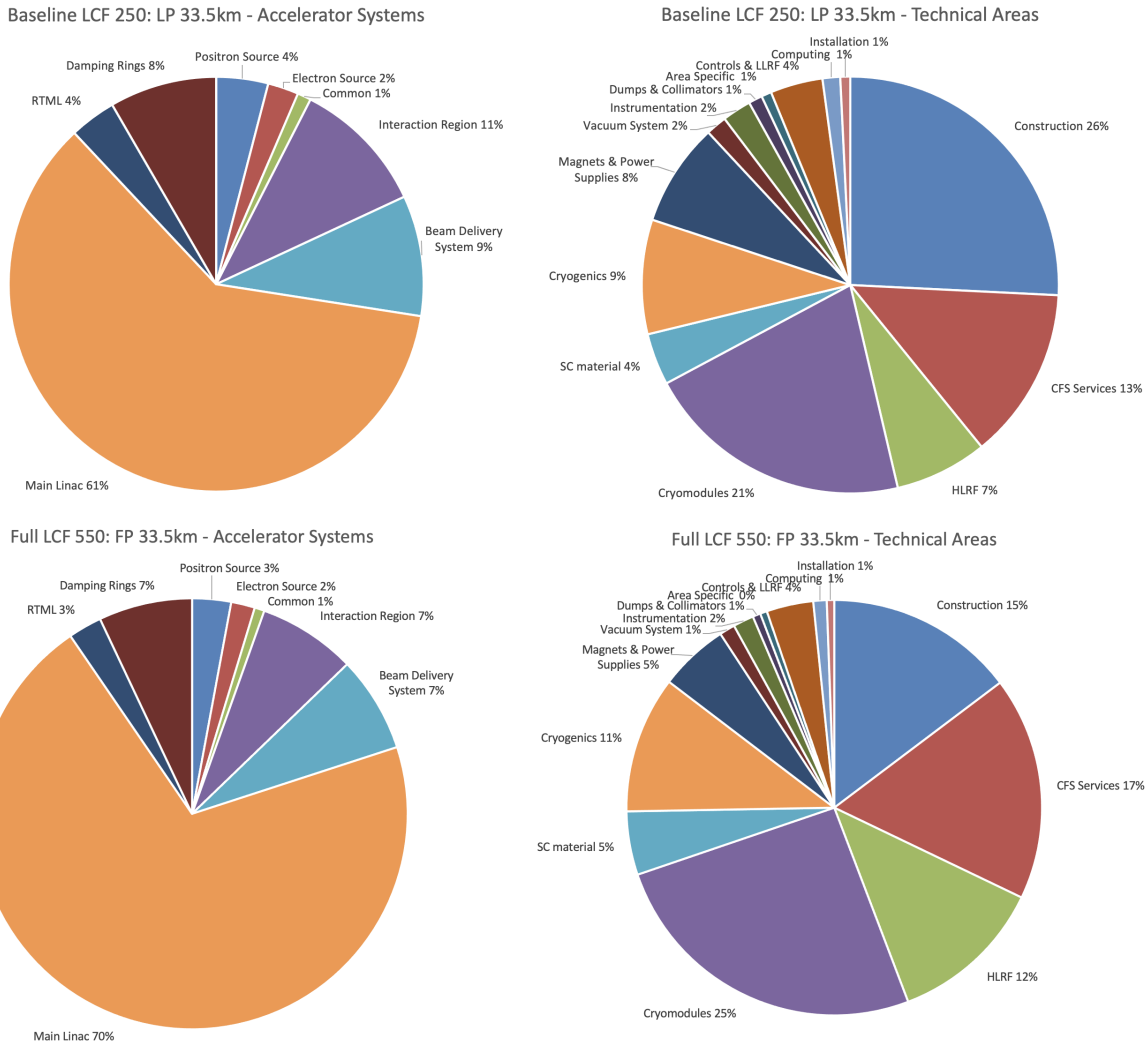


Figure 5: . Costs for a Linear Collider Facility at CERN in the baseline 250 GeV low-power (1312 bunches) configuration (top) and the final 550 GeV full-power (2625 bunches) configuration (bottom), broken down according to accelerator systems (left) and technical areas (right). The total cost for the baseline configuration LCF 250 LP amounts to 8.29 BCHF, for the full configuration LCF 550 FP to 14.53 BCHF in 2024 prices.

Design differences that were taken into account between the ILC design for Japan and the LCF design for CERN are:

- a second BDS: To account for the cost of a second BDS, all costs associated with the BDS and the interaction region were doubled, with the exception of the construction costs, because those were evaluated separately to include a design for the 2nd BDS;
- beam energy and main linac length;
- cryogenic power, arising from different repetition rate and different quality factor Q_0;
- CERN being not a greenfield site: The ILC cost estimate assumes a greenfield site and thus includes cost items that are already present at CERN, in particular investment for computing (computing centre and computing capacity for accelerator simulation and operation, without the computing capacity for the experiments). These items were removed from the cost estimate for CERN.

Some performance differences between ILC and LCF are considered to arise from successful R&D, with the assumption that these performance improvements will not affect component costs. These are in particular:

- an increase of the quality factor Q_0 of the superconducting cavities from 1×10^{10} to 2×10^{10}: This increase is achieved by a modification of the heat treatment recipe, which is not expected to have a sizeable cost impact, assuming that the overall yield stays the same;
- better klystron efficiency, increased from 65 % to 80 %: This improvement results from a change in the electron optics of the klystron, based on a better design [6]. While this makes the klystron larger and heavier, the cost increase is hard to quantify and it is assumed that any resulting cost increase is covered by the cost uncertainty assigned to this item.

The cost uncertainty, or cost premium, of the cost estimate is defined as the difference between cost estimate at 50 % (median) and 84 % confidence level, which for normally distributed data corresponds to a $1\,\sigma$ uncertainty.

The uncertainty associated with each cost element depends on the nature, quality and maturity of the basis of estimate for that element. In the TDR estimate, uncertainties were evaluated by cost estimators for each cost element, based on defined guidelines, taking into account:

- the maturity of the item's design (conceptual, preliminary, or detailed);
- the level of technical risk involved in the design and manufacture of the item;
- the impact of delays in this item on the project schedule (critical-path impact, non-critical-path impact, no schedule impact on any other item);
- the source of the cost information (engineering estimate based on minimal experience, engineering estimate based on extensive experience, vendor quote, industrial study, catalogue price);
- the extent, if any, of cost scaling to large quantities.

Uncertainties from the TDR were retained; for new estimates, uncertainties are determined according to the same guidelines.

For line items whose cost estimate has not been updated in 2024, but has been escalated from 2012 prices, the uncertainty of the regional escalation factor has been evaluated, and the resulting error has been added in quadrature to the original cost premium.

Cost premiums of line items are added linearly, which corresponds to treating all uncertainties as fully correlated and is a conservative approach [1].

The cost uncertainty reflects cost risk, i.e. uncertainties or errors in the cost basis (e.g. procurement of a similar item, quantity discount from a single unit price, engineering estimate, etc.) on which the cost of a specific item is based. This is to be distinguished from **technical risk** that is related to failure of a specific item to achieve the design performance, requiring a redesign which may result in schedule delays and increase the cost, and from **schedule risk** that is related to failure to supply a specific item on schedule, requiring delays which may increase the cost (typically by introducing inefficiencies and additional manpower requirements). **Market risk** is related to deviations in procurement costs from the estimate, due to changes in economic market conditions between when the estimate was made, and when the procurement is made. **Contingency** is a broader term, and includes not only cost uncertainties but also, for example, allowances for missing items.
The resulting cost premium for the overall cost has been determined to be 29 %.

3.2 Operating costs

Operational year and energy consumption The assumptions on the operational year are summarised in Tab. 3. The numbers correspond to an availability of 75 %, in accordance with ILC design parameters. The approach follows the one laid out in [7] for FCC-ee and CLIC.

The power consumption, relative to the power for data taking, has been calculated under the following assumptions: Four operating modes are assumed – data taking, standby, shutdown, and machine development. In standby mode, RF is switched off, but all other systems are assumed to be operational. This saves between 46 % and 56 % of power. Standby mode is assumed to correspond to the state during down time and technical stops. In shutdown mode, RF is switched off permanently, so that the cryogenic load is reduced to about 32 % of its nominal value (calculated from the ratio of static to total cryogenic load, see [1, Tab. 3.11]) as well as magnets and other accelerator systems are switched off. Remaining power loads are the civil infrastructure (lighting, cooling, ventilation, etc.), and cryo plants satisfying the static load. In this mode, between 25 % and 28 % of the nominal power are estimated to be consumed. These operating scenarios are the basis for the calculation of the total yearly energy consumption, as summarised in Tab. 5.

		Fraction of peak power			
Operational phase	days/year	LCF 250 LP	250 FP	550 LP	550 FP
Annual shutdown	120	28 %	18 %	28 %	25 %
Commissioning	30	77 %	72 %	75 %	72 %
Technical stops	10	54 %	45 %	50 %	44 %
Machine development	20	77 %	72 %	75 %	72 %
Downtime (faults)	46	54 %	45 %	50 %	44 %
Data taking	139	100 %	100 %	100 %	100 %

Table 3: Operational phase definition, with relative power consumption for each operation phase in relation to the nominal operating power assumed in the electricity consumption calculation.

Operating costs are summarised in Tab. 4. They were calculated taking into account the yearly electricity consumption, at a price of 80 CHF per MWh, and the costs for spares and maintenance.

[1] Treating them as uncorrelated would lead to an unrealistic reduction of the cost uncertainty when large cost items are split into smaller ones

Spare and maintenance costs were evaluated in relation to the construction costs as follows: Construction items are categorised into

- fixed accelerator installation, taken to be the total costs for cryomodules, magnets, vacuum system;
- consumables, taken to be the costs for HLRF equipment, magnet power supplies, dumps, and cryogenics[2];
- technical infrastructure, taken to be the costs for civil infrastructure such as water cooling, electric power infrastructure, air handling, installation equipment, computing, area-specific equipment such as source targets and guns, controls and LLRF, and instrumentation,

and assuming a replacement and maintenance cost per year of 1 % / 3 % / 5 %, respectively, of the corresponding capital expense. The operating costs for cryogenics includes the costs for liquid helium losses.

Human resource needs for operation have been estimated for the ILC [9] to be 850 FTE for the 500 GeV and 638 FTE for the 250 GeV machine. These numbers are consistent with estimates for CLIC [10] and the general experience at CERN.

Operating costs	LCF	250 LP	250 FP	550 LP	550 FP
Nominal operating Power	MW	143	182	250	322
Yearly electricity consumption	TWh	0.8	1.0	1.4	1.8
Electricity price	CHF/MWh		80		
Yearly electricity costs	MCHF	66	77	115	142
Fixed accelerator inst. (1 %)	BCHF	2.6	2.7	5.0	5.1
Consumables (3 %)	BCHF	1.7	2.0	2.9	3.7
Technical infrastructure (5 %)	BCHF	2.9	2.2	3.1	3.6
Operation & maintenance	MCHF/y	170	196	291	342
Total yearly operation costs	MCHF/y	236	273	406	484
Personnel	FTE	640	640	850	850

Table 4: Operating costs, for electricity and operation and maintenance (including helium, see text).

4 Sustainability and environmental impact

The construction and operation of large-scale accelerator infrastructures such as the planned LCF at CERN require considerable resources and therefore entail a significant impact on the environment throughout the lifecycle of the project. As scientists and citizens, we acknowledge our obligation to future generations to plan our projects in the most sustainable way possible. Optimisation requires quantitative knowledge of the burdens imposed by the construction, operation and demolition of the entire facility. To this end, the ILC and CLIC projects have commissioned two lifecycle assessment (LCA) studies with ARUP, a consultancy company [11, 12]. These lifecycle assessments form the basis for the greenhouse gas (GHG) emission numbers summarised in Tab. 5.

[2] For cryogenics, experience from LHC indicates that the yearly operating and maintenance costs are 2.8 % of the original invest, which includes the costs for replenishing liquid helium losses [8].

A first study [11] quantified the environmental impact of the civil construction of the underground tunnels, caverns and shafts of the ILC and CLIC in several configurations, as it was assumed that this would constitute the largest contribution to the overall emissions. The study was based on the detailed available designs of the underground installations and considered the relevant construction methods. In particular the tunnelling methods chosen are different: the ILC in Japan will use the New Austrian Tunnelling Method (NATM), a drill–and–blast method, in a solid granite geology, while at CERN a tunnel boring machine would be used in molasse rock. These resulting tunnel cross sections differ substantially in shape and in the amounts of material used for grouting, linign, rock bolts, and reinforcement steel. This is reflected in the LCA. The numbers quoted for the LCF at CERN are based on these analyses, which is possible as the LCF's tunnel design closely follows the CLIC design.

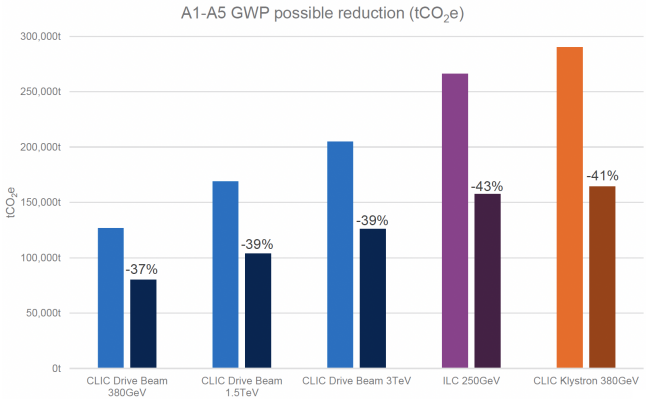


Figure 6: CO_2 emission reduction opportunities for the ILC and CLIC underground facilities identified in an LCA study of underground civil construction [11].

The purpose of this and other life cycle assessment studies is not so much to produce a set of numbers that quantify the environmental impact, in particular the global warming potential (GWP) as a measure of effective greenhouse gas emissions, as to provide quantitative data early in the project to reduce the impact as far as possible. Important conclusions that can be drawn from the LCA study of underground facilities are:

- Given the low carbon intensity of French electricity, for a project at CERN the embodied carbon in civil construction by far surpasses that arising from electricity consumption.
- The GHG impact of underground structures is by far dominated by the embodied carbon in the materials used for construction, in particular cement (around 85 %) and steel (around 15 %).
- The GHG impact of concrete and steel can be substantially (more than 40 %) reduced by optimising the design (e.g. by a reduced lining thickness) and by usage of carbon-reduced materials, in particular as cement[3]. The overall reduction opportunities are shown in Fig. 6.

A second, more comprehensive study [12] also quantified the environmental impact of the accelerator and detector construction for the CLIC and ILC designs. Owing to the enormous complexity of an entire particle accelerator and the detectors, with a multitude of different components and materials, an LCA of a complete accelerator project is extremely challenging. Nonetheless, an attempt was made to quantify the overall impact by focussing on the most abundant and

[3] For instance, usage of cement with 50 % addition of GGBS (ground granulated blast-furnace slag) would provide a 22 % overall CO_2 reduction.

material-intensive systems and components, in particular the magnets and accelerating RF structures. Because some materials, in particular very pure niobium used in superconducting cavities, are specific to accelerators, so that no lifecycle data have been available in the usual databases, detailed studies of these materials were necessary as part of the overall effort. The same applies to specific production methods such as electropolishing used in the cavity fabrication. This study also made an attempt, for the first time, to quantify the environmental impact of the operation phase beyond the electricity consumption (e.g. the impact of spare part production) and of the demolition stage with the recycling or disposal of materials.

	ILC 250	**ILC 500**	**LCF 250 LP**	**LCF 550 FP**
CoM energy [GeV]	250	500	250	550
Luminosity/IP [10^{34} cm^{-2}s^{-1}]	1.35 / 2.7	3.6	2.7	7.7
Number of IPs	1		2	
Operation time for physics/yr [10^7s/yr]	1.6		1.2	
Integrated luminosity/ yr [1/fb/ yr]	215 / 430	580	320	920
Host countries	Japan		France / Switzerland	
GHG emissions from construction, stages A1-A5				
Subsurface tunnels, caverns, shafts [kt CO_2e]	282	402	305	411
Accelerator (coll.) [kt CO_2e]	151	273	166	313
Accelerator (inj.) [kt CO_2e]	82	82	59	82
Detectors [kt CO_2e]	94		94	
Total [kt CO_2e]	609	851	624	900
Collider tunnel length [km]	21.5	33.5	33.5	
Collider tunnel diameter [m]	9.5		5.6	
Collider tunnel GHG / m [t CO_2e/ m]	8.6		8.5	
Concrete GHG [kg CO_2e/ kg] / [kg CO_2e/ m^3]	0.16 / 400 (C25/30)		0.16 / 400 (C25/30)	
Main Linac accelerator GHG / m [t CO_2e/ m]	5.3		5.3	
GHG emissions from operation				
Maximum power in operation [MW]	111 / 138	164	143	322
Annual electricity consumption [TWh/ yr]	0.7 / 0.9	1.1	0.8	1.8
Reference year of operation	2040	2040	2050	2050
Carbon intensity of electricity [g CO_2e/ kWh]	81	81	16	16
Average Scope 2 emissions / yr [kt CO_2e]	59 / 74	87	13	28

Table 5: Data on GHG emissions for the ILC project in Japan and the Linear Collider Facility proposal for CERN. These are baseline numbers, before application of possible CO_2 reduction measures.

Some important conclusions from this study:

- The GHG impact of the accelerator and detector installations together is as big as or even bigger than the impact of civil construction.
- The impact is dominated by the embodied carbon in the materials used; material processing (e.g. refinement by electron beam melting) for specific material qualities required for accelerators (ultra pure niobium, oxygen free copper) plays an important role and cannot be neglected in the analysis.
- Again, significant reduction opportunities exist, but owing to the multitude of components and materials these are more diverse than in the civil construction case and require careful individual assessment.
- The GHG impact of electricity consumption depends on the location of the project and on the time of (first) operation owing to envisaged carbon reduction measures in the electricity sector. Assumptions about these parameters have ramifications for the overall system optimisation (embodied carbon versus operation).

- Detectors contribute a sizeable amount to the GWP impact, dominated by the iron required for the magnet return yokes.

The data gathered in this study were also used to estimate the CO_2 impact of an LCF at CERN, based on ILC technology, as summarised in table 5. The ILC data were adjusted, to the extent possible, for design differences, in particular a second BDS, a third damping ring for full power (2625 bunches) operation, longer tunnel lengths, and different centre-of-mass energies, to estimate the LCF numbers.

The peak and annually integrated energy consumption during each stage of operation is given in Tab. 5, together with the integrated carbon-equivalent energy costs for the construction of the various stages. The required site AC power ranges between 143 MW and and 322 MW for the initial 250 GeV and the final 550 GeV machine.

Further environmental impacts are expected to be small in comparison. In particular it is assumed that direct emissions from detectors of green house gases with very high weighting factors such as chlorofluorocarbons (CFC) or SF_6, which currently dominate CERN's GHG emissions [13], will be fully curtailed in a future project by adequate protection measures. As additional information, Tab. 6 gives the estimated land use of the LCF project at CERN.

	20.5 km machine	33.5 km machine
Number of new access shafts	7	11
Number of new surface sites	6	10
Area of land permanently occupied [km^2]	0.248375	0.343575
Area of land temporarily occupied during construction [km^2]	-	-
Area of surface buildings	0.054601	0.072601

Table 6: Area of land occupied by the LCF project at CERN.

5 Technology and delivery

In principle, all **key technologies** for the 250 and 550 GeV machines **are mature and construction-ready**. In particular, the superconducting radio-frequency technology is extremely well understood and at the heart of well-established and excellently performing machines like the European XFEL in Hamburg, Germany, or the LCLS II at SLAC. Still, compared to e.g. the ILC TDR from 2013 [1], significant R&D progress has been achieved in terms of, e.g., gradients, quality factors (Q_0), energy efficiencies, and repetition rates (see Sect. 3.1 "Some performance differences"). A discussion of the R&D progress and Eurooean XFEL operation experience on which the LCF capitalizes can be found in [14].

The overall technological readiness of the project is reflected in the timeline discussed in Sect. 2 and shown in Tab. 2. The necessary steps are given separately for the two three-years phases 1 and 2 defined in the main document of this submission. The following subsections 5.1 and 5.2 discuss the most important remaining R&D topics and necessary technology choices and the TRL levels of individual sub-systems of the machine, respectively.

5.1 Overview, R&D requirements and next steps

Despite the overall technological readiness of the project, some R&D needs to be carried for certain aspects of an LCF machine, and important studies for siting etc. are required, each with

significant durations. The most time-critical aspect is the exact siting – i.e. a detailed placement study, which might even be technology-independent. Furthermore, also definite parameter choices (e.g. gradient versus number of cryomodules) need to be made.

This work is split up into two phases of three years each, for a construction start in 2032:

Phase 1, ideally starting directly in mid-2026 after the finalisation of the EPPSU, builds on and integrates the on-going work of the ILC Technology Network (ITN) on the key technologies [3, 15], complementing it with siting and implementation studies, in parallel with design and technical studies to determine and confirm the final LCF parameters. This phase is required to prepare a project decision by CERN Council, which is not expected before 2028, and should deliver:

- **Final placement of the collider complex** and its infrastructure after assessment of their territorial compatibility, both for its initial phase and potential upgrades. This is followed by an initial review of the placement scenario with the relevant regional and local stakeholders as a part of engaging in wider implementation studies with the host regions / states.
- **Optimisation of LCF design:** Review of the accelerator design along with updated cost, power and risk assessments, including in particular:
  - a detailed design of the Interaction Region for two experiments – including re-optimised Beam Delivery Systems – that is suitable for an initial SCRF-based accelerator as well as for future technology upgrades like CLIC, C^3, ERLs or PWA;
  - studies of the implications for Civil Engineering and the equipment used in the initial SCRF based facility, in order to allow collider upgrades in the future, and to accommodate the "beyond colliders" physics programme described in the main document;
  - design and parameter optimisation of the entire machine including further nanobeam studies. This comprises an R&D programme to develop prototypes of key components with regard to performance and cost risks and opportunities, or with ramifications for the CFS design, in particular cavities, cryomodules, klystrons, RF input couplers, main dumps, and the positron source target and capture device.

The estimated resources needed for Phase 1 are 35 MCHF material and 180 FTEy of personnel effort. These resources are backed up by the ITN efforts that, over 5 years, amount to around 30 MCHF and about 250 FTEy.

Phase 2 would require a decision to go ahead with the project preparation as needed to start construction. It targets the final engineering design, larger industrial pre-series and an extensive site preparation, in particular:

- SCRF industrialisation for a design based on more ambitious goals for cavity quality factors (Q_0) and power (klystron) efficiency, with higher repetition rate and hence cryogenic needs than foreseen in the ILC TDR design. This task builds on the work of the ITN [15];
- detailed studies of the Cryogenics system and Infrastructure Systems (e.g. cooling and ventilation, electrical, access and safety systems, transport and installation) adapting them to standard solutions used by CERN and industry;
- final site preparation including documentation and specifications for the time-critical civil engineering contracts.

These steps of Phase 2 will lead up to a full CFS planning and an engineering design.

The estimated resource needs for Phase 2 are 120 MCHF for pre-series and 420 FTEy of personnel effort for the technical studies, pre-series, engineering design and laboratory infrastructure. With the widespread expertise built up worldwide for SCRF based free-electron lasers (e.g. the European XFEL or LCLS-II) as well as for the ILC, a significant part of this work can be done outside CERN for an LCF starting with SCRF technology. In parallel, civil engineering preparation including continued environmental studies will require significant resources, typically 5% of the civil engineering budget.

Also during the preparation period, detector collaborations need to be prepared and set up, building on the experience of the numerous detector concepts for Higgs factories, but also embracing new ideas.

5.2 Assessment of technology readiness

The technological readiness of the ILC has been scrutinised by the Implementation Task Force in the context of the Snowmass process in 2021 [16], with the result that all areas considered were given the highest mark, corresponding to a Technology Readiness Level (TRL) of 7 to 8, except the positron source, which was assigned the second highest category, corresponding to TRL of 5 to 6. Parallel to that, the IDT formulated a plan for a preparatory lab [17], identifying the most important R&D topics, based on considerations of technical risk, but also cost risks and opportunities. Based on a revised version of this plan [15], the International Technology Network (ITN) has been formed that now actively pursues these issues.

In the following, we discuss the most important R&D topics and give our own assessment of technology readiness. We follow the TRL definitions given in [16, Appendix A.7], which are closely aligned with the definitions in the DOE Technology Readiness Assessment Guide [18].

Cryomodules and cavities Cryomodules with a design that is almost identical to the design foreseen for the LCF have been successfully produced in series for the European XFEL, and very similar ones for LCLS-II, and have been in operation at the European XFEL since more than 8 years without problems. Industrial production of cavities with more than 800 cavities produced for the European XFEL alone has been demonstrated [19, 20], with many cavities surpassing ILC specifications. For ILC specifications, the remaining risk is not any more of technological nature, but predominantly concerning the production yield. The resulting cost risk is small, as a 90 % production yield is already factored into the cost calculation, and a further yield reduction of e.g. 10 % would lead to only a few percent overall project cost increase.

The operating gradient of 31.5 MV/m required for the LCF has also been demonstrated for complete cryo modules [21]. All key components (couplers, cavities, tuners, cold mass and vessel) have been successfully produced in industry (**TRL 9**). LCF assumes improved performance in cavity quality factor ($Q_0 = 2\times^{10}$ instead of $1\times^{10}$) at an average operational gradient of 31.5 MV/m. Successful industrial series production of cavities with these performance parameters has to be demonstrated; with regard to the quality factor, we rate the cavities **TRL 7** (prototype demonstration in operational environment).

The main parameter to be improved is the quality factor Q_0 at the operational gradient of 31.5 MV/m.

Overall, superconducting TESLA-type cavities and cryomodules for the main linac have been fully industrialised and thus do not constitute a technological risk for the construction of a superconducting linear collider facility as proposed, which is a main strength of the proposal. As cavity and cryomodule production (including costs for superconducting material) constitutes 25 % of the overall cost of the proposed LCF, successful R&D offers large benefits in terms of performance and construction cost, which is why this is considered a high priority item.

The time-critical work packages WP'1 (cavity production) and WP'2 (cryomodule assembly) of the

ITN [15] have been created to conduct this R&D. In the context of a preparatory study for an LCF at CERN, these activities should be further intensified.

Positron source The baseline source design for the ILC as well as the LCF is the helical undulator positron source, which provides polarised positrons at a rotating target from polarised photons created in a helical undulator operated with the accelerated electron beam. The basic principle (production of polarised positrons from photons generated in a helical undulator) has been demonstrated in a successful experiment (E166) at SLAC [22, 23].

The status of the ILC positron source has been summarised by the positron working group [24]. Since then, significant progress has been made on several fronts [25]. This system has a number of critical key components:

The superconducting helical undulator comprises a number of modules that form a 230 m long undulator section, creating a highly collimated, narrow beam of photons. Helical undulators have been successfully produced, a prototype design for a cryostat as required for the ILC has been successfully built and tested [26]. The operation of long undulator sections in high-energy beams is state of the art, e.g. at LCLS, PAL-XFEL and European XFEL [27–29]. A fully operational undulator module with the required parameters (k-value) would be the next step.

The positron target design foresees a rotating wheel made of titanium alloy, cooled either by radiation or heat conduction via friction [30]. The engineering challenges are vacuum tightness of the rotating assembly, sufficient cooling and damage from shock waves created by the pulsating photon beam. Due to the large activation of the materials, a remotely operated target exchange mechanism is required. First engineering prototypes of a rotating target have been built. Target materials have been characterised in test beams, demonstrating the required radiation hardness [31]. Overall, we consider the target design **TRL 5** (component validation), consistent with the evaluation of the ITF. A next step will entail a fully operational target, operating at the required parameters (vacuum, rotational speed, cooling, operation in presence of pulsating magnetic field of capture device), which would raise the TRL to 6.

For the positron capturing device, several design ideas exist. The most promising design is based on a pulsed solenoid design [32]. Pulsed solenoids have been successfully operated in other accelerator applications. An engineering study of a pulsed solenoid is under way. We consider the pulsed solenoid **TRL 5** (component validation). A next step will entail a fully operational pulsed solenoid, operating at the required parameters (field strength, pulse shape, flat top length, aperture), which would raise the TRL to 6.

The photon dump, in particular its entrance window,is also challenging owing to the fact that changing the entrance point by moving the beam spot (“painting”) is not possible.

The time-critical work packages WP’6 (rotating target), WP’7 (magnetic focusing system) and WP’11 (target maintenance) of the ITN [15] have been created to conduct the necessary R&D.

In the context of a preparatory study for an LCF at CERN, these activities should be further intensified.

As a risk mitigation strategy, an alternative positron source concept based on a separate electron beam impinging on a slowly rotating target (electron-driven source) has been developed over the last decade [33, 34]. Such a source concept has important advantages in terms of ease of operation, as it decouples positron production from the electron main linac; however, it does not provide positron polarisation. Should an undulator driven, polarised positron source turn out to be too risky, a decision to build an electron-driven source would ensure that the project can proceed, albeit without positron polarisation. The time-critical work packages WP’8 (rotating target), WP’9 (magnetic focusing system) and WP’10 (capture cavity and linac) of the ITN [15] have been created to conduct further R&D on this concept.

Electron source photo injector gun High voltage photo guns with the characteristics required for the LCF have been built and successfully operated in accelerators, thus this system does not pose a technological risk. In order to take advantage of experience accumulated over the last decade, and to preserve the existing know-how, the time-critical work packages WP'4 (higher voltage ILC photo-gun R&D) of the ITN [15] has been created to conduct the necessary work.

IP spot size / stability Focussing the beams to the required nanometre size and bringing them to stable collision is the core challenge of the nanobeam technology that makes any linear collider possible. This has been the topic of extensive R&D over the last decades, with dedicated test facilities where the necessary technologies can be tested and verified. The Accelerator Test Facility ATF2 [35, 36] is the main workhorse for this R&D. At ATF2, the final focus concept of the ILC, based on local chromatic correction, has been verified [37], together with the necessary beam stabilisation with the FONT feedback system [38, 39].

Based on the extensive testing at the ATF2, we rate the issue of IP spot size and stability to be **TRL 7** (prototype demonstration in operational environment), in agreement with the assessment by the ITF.

The time-critical work packages WP'15 (final focus) and WP'16 (final doublet) of the ITN [15] have been created to conduct further R&D.

Crab cavity A number of competing designs for the crab cavities around the interaction point have been put forward and assessed in a dedicated workshop [40], with a down-select of the two most promising designs for further R&D.

The time-critical work packages WP'3 (crab cavity) has been created to conduct the necessary R&D.

Damping rings The ILC damping ring design is similar to planned and existing storage rings for synchrotron radiation production. Key parameters are the same as those of operating facilities: with a 3.2 km circumference at 5 GeV beam energy, it is similar to PETRA III, and the normalised emittance $\gamma\varepsilon_{x/y} = 4\,\mu$m/20 nm has been achieved in operating light sources. Important challenges are the 400/800 mA beam current for electrons/positrons, which were tested at the CESR-TA test facility [41], the large dynamical aperture required for positron injection, and the small transverse (longitudinal) damping time of 13 (7) ms, to be provided by radiation damping from superconducting undulators. Lattices that fulfil the design requirements have been developed. Overall, we consider the damping ring system design to be **TRL 7** (prototype demonstration in operational environment), in agreement with the assessment by the ITF.

Further R&D concerning the overall damping ring system design is being conducted as ITN time-critical work package WP'12 [15].

Injection and extraction kickers Injection into and extraction from the damping rings requires kickers that are capable of kicking individual bunches at a minimal bunch separation of 3.2 ns. The damping ring bunch pattern consists of mini trains of about 25 consecutive bunches, followed by a gap of about 10 empty bunches. Bunches are extracted from the tail of these mini trains, therefore the rise time is the bigger concern. A prototype kicker has been tested successfully at ATF2 [42]. Therefore, we rate the kicker system to be **TRL 7** (prototype demonstration in operational environment), in agreement with the assessment by the ITF.

Further R&D into the design of the kickers is being conducted as ITN time-critical work package WP'14 [15].

Emittance preservation Preserving the very small emittance of the beam exiting the damping rings along the low energy (5 GeV) transport line [43, 44], the bunch compressors [45] and the main linac [46, 47] is a central element to achieving the required small beam spot sizes and thus the target luminosity, and has been extensively studied. An intrinsic advantage for emittance preservation are the large apertures of the accelerating L-band cavities, which lead to modest wakefield effects compared to accelerators operating at higher frequencies.

Therefore, we rate the emittance preservation to be **TRL 8** (system completed and qualified through test and demonstration), in agreement with the assessment by the ITF.

Main dump The ILC main dump is designed for up to 17 MW of beam power (for a single beam), which is more than sufficient for the full LCF 550 configuration, where the maximum 23 MW beam power would be shared by two beam delivery systems and main dumps. The main dump design is based on a water dump, which follows the design of the SLAC 2 MW water beam dump that has been successfully operated in the past. An engineering design is required for a detailed planning of the enclosing cavern, including cooling, ventilation and treatment of generated isotopes, in particular tritium. The entry window of the dump is another important challenge.

The design of main dump, including prototyping of the entry window, is the topic of the ITN time-critical work package WP'17 [15].

RF systems The RF systems (modulators, klystrons, power distribution system) required to operate the accelerator have parameters that are mostly identical to those of the corresponding systems of operational accelerators, in particular the European XFEL.

Klystrons with the required parameters (pulse length and output power) are commercially available and are in use in comparable facilities (TRL 9). The LCF proposal assumes that the efficiency can be raised from 65 % (commercially available) to 80 % , based on a design study for 1.3 GHz and experience from similar developments [6]. We consider this as **TRL 7** (prototype demonstration in operational environment), in agreement with the assessment by the ITF. It is worthwhile to note that the klystron efficiency does not pose a technical risk to the LCF. If the expected efficiency improvement would fail to fully materialise, this would be know early enough to install more powerful modulators[4] and cooling systems. The resulting impact on construction and operation costs is in the few percent range.

A prototype of a design suitable for installation and operation in the accelerator tunnel with the required availability parameters would be beneficial. The modulator foreseen for the ILC (semiconductor-based Marx modulator design) is different from the modulator employed in the European XFEL (bouncer modulator and pulse transformer), operating at the full high voltage of the klystron without the need for a transformer. Prototype Marx modulators exist and have been tested, and we consider this **TRL 7** (prototype demonstration in operational environment), in agreement with the assessment by the ITF.

The waveguide power distribution system, although different in design from the European XFEL one, is comprised of commercially available components, i.e. **TRL 9** (proven through successful operations).

The main parameter to be improved is the klystron efficiency (65 % to 80 %).

HOM detuning / damping Absorption of higher order modes in SRF cavities of Tesla design uses the same design employed at the European XFEL. The components are commercially available from

[4] Cost savings from reduced modulator capacity are not taken into account in the LCF cost estimate, which assumes 65 % in the costing, thus an 80 % is a cost reduction opportunity.

industry, the design has been proven at the European XFEL. We rate this topic to be **TRL 9** (proven through successful operations).

Component/Sub-system	TRL	Main parameter to be improved or demonstrated	Improvement factor
RF systems	7	Klystron efficiency	65 % to 80 %
Cryomodules / cavities	7	Quality factor Q_0	2
Positron source	5 5	Target cooling Pulsed solenoid peak field	
Inj./extr. kickers	7	Rise time	
Damping rings	7	Dynamic acceptance Damping time	
IP spot size/stability	7	Vertical beam size	

Table 7: Technical readiness and R&D requirements for the LCF at CERN.

All further stages, i.e. going to 1 TeV or beyond, require significant R&D. However, since these stages will enter any construction phase at the earliest in the middle of the 2050s, no critical paths or R&D needs can be discussed here in a meaningful way.

6 Dependencies

The described scenarios assume **CERN as a host site** for the Linear Collider Facility. However, the construction of an ILC-like machine has also been studied, naturally, for Japan, and other locations.

With modest power needs and operation costs compared to other projects, the Linear Collider Facility in the stages up to 550 GeV centre-of-mass energy would not interfere negatively with other activities on the CERN site. In particular, a **rich scientific diversity programme** and a broad portfolio of advanced accelerator R&D activities (e.g. magnet developments, plasma, ...) could be maintained as an important complement to CERN's portfolio, as postulated also by the 2020 European strategy update.

The LCF realisation and operation at CERN does, in particular, not depend on the LHC injector chain and could thus be developed independently of the ongoing (HL-)LHC programme.

Furthermore, the realisation of the LCF programme at CERN does not entail the premature definition of the precise technology for a future 10 TeV parton-parton centre-of-mass energy collider.

7 Commentary on current project status

The ILC project has, since decades, assembled a **large community** supporting it and bringing it to the level of maturity that is observed today. This is also documented in the project TDR [48, 49], in the ILC staging report from 2017 [2], and e.g. in the report to the Snowmass process 2021 [50]. The ILC has been, in fact a **global project** for 20 years, with accompanying technology collaborations like the Tesla Technology Collaboration, TTC, for the advancement of SRF technology.

The **size of the community** of scientists who directly work on the project can be estimated from the number of institutions supporting the TDR (rougly 400) or the number of individuals that signed the Snowmass report (rougly 500). The relevant community event – the International Linear Collider Workshops (LCWS) – typically attract between 300 and 800 participants.

Another measure for the potential size of potential community is the expected **number of collaborators** for a facility with two large collider experiments and an ample and diverse "beyond colliders" programme attached. Assuming the typical size of an experimental collaboration of 3,000 members, and 1,000 members for the diversity programme, the Linear Collider Facility might be foreseen to hold a community of around 7,000 members.

The project in both scenarios A and B lends itself easily to the realisation of significant **in-kind contributions**. In particular the mass production of cryomodules – as already exercised in an industrialised fashion e.g. for the European XFEL – allows for distributed the production of attractive technology in different world regions. Several cavity vendors take a keen interest in the project, and the highly modularised production possibilities allow for a high added economic value.

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