

Chapter 22

Linear Colliders



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Abstract This article summarizes the studies for implementation of the Linear Collider projects, CLIC (the Compact Linear Collider) and ILC (the International Linear Collider). The accelerators aim to collide electrons and positrons at 380 and 250 GeV respectively, and both can be extended in length and/or with improved technologies to multi-TeV energies. CLIC is studied for construction at CERN, while ILC is being studied for implementation in Japan. The technical status, expected performances, recent progress and implementation parameters, as schedules, power and costs, are presented. The summary focuses on the accelerator studies for the colliders, but the accelerator studies are accompanied by comprehensive physics and detector studies referred to in the text and references. The future programs including the work for sustainable implementations are briefly summarized at the end. Many of the linear collider studies are common for the two projects and are presented as such. The projects are both implementable at costs similar to LHC and power/energy consumption similar or less than LHC.

22.1 Introduction

The Compact Linear Collider (CLIC) is a multi-TeV high-luminosity linear e^+e^- collider under development by the CLIC accelerator collaboration. The CLIC accelerator has been optimised for three energy stages at centre-of-mass energies 380 GeV, 1.5 and 3 TeV [1]. CLIC uses a novel two-beam acceleration technique, with normal-conducting accelerating structures operating in the range of 70–100 MV/m.

Detailed studies of the physics potential and detector for CLIC, and R&D on detector technologies, have been carried out by the CLIC detector and physics (CLICdp) collaboration. CLIC provides excellent sensitivity to Beyond Standard Model physics, through direct searches and via a broad set of precision measurements of Standard Model processes, particularly in the Higgs and top-quark sectors.

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The CLIC accelerator, detector studies and physics potential are documented in detail at: <http://clic.cern/european-strategy>. Information about the accelerator, physics and detector collaborations and the studies in general is available at: <http://clic.cern>. Since the publication of the reports above for the European Strategy Update in 2018–2019, the baseline luminosity at 380 GeV has been updated according to new studies, new power estimates show a significant reduction, and technical progress and improvements related to X-band technology and klystron design have been achieved. These developments are described in the CLIC input to the 2021 Snowmass process [2].

The International Linear Collider (ILC) is an electron-positron collider with a collision energy of 250 GeV (total length of approximately 20 km). The design study for the ILC for a collision energy of 500 GeV started in 2004, and the Technical Design Report (TDR) [3] was published by the Global Design Effort (GDE) international team in 2013. More than 2,400 researchers contributed to the TDR.

After publication of the TDR, R&D activities regarding linear colliders were organised by the Linear Collider Collaboration (LCC). The 250 GeV ILC for a Higgs factory was proposed and published in the ILC Machine Staging Report 2017 [4].

The International Development Team (IDT) was established [5] by the International Committee for Future Accelerators (ICFA) in August 2020 to prepare to establish the ILC preparatory laboratory (Pre-lab) [6] as the first step towards the construction of the ILC in Japan. The principal accelerator activities of the ILC Pre-lab are foreseen to cover technical preparations, engineering design and documentation for the ILC construction project. The former is summarised in “Technical Preparation and Work Packages (WPs) during ILC Pre-lab” [7]. The ILC Pre-lab activities are expected to continue for approximately four years, and the ILC accelerator construction will require nine years. Currently the Pre-lab activity planning is being revised to start more gradually with a subset of the highest priority technical WPs.

A recent updated and complete summary of the ILC project, including a detailed description of the physics potential, has been submitted to the 2021 Snowmass process. This document can be found at [8], and summarizes also the Pre-lab plans for next phase.

22.2 CLIC Layout

A schematic overview of the accelerator configuration for the first energy stage is shown in Fig. 22.1. To reach multi-TeV collision energies in an acceptable site length and at affordable cost, the main linacs use normal conducting X-band accelerating structures; these achieve a high accelerating gradient of 100 MV/m. For the first energy stage, a lower gradient of 72 MV/m is the optimum to achieve the luminosity goal, which requires a larger beam current than at higher energies.

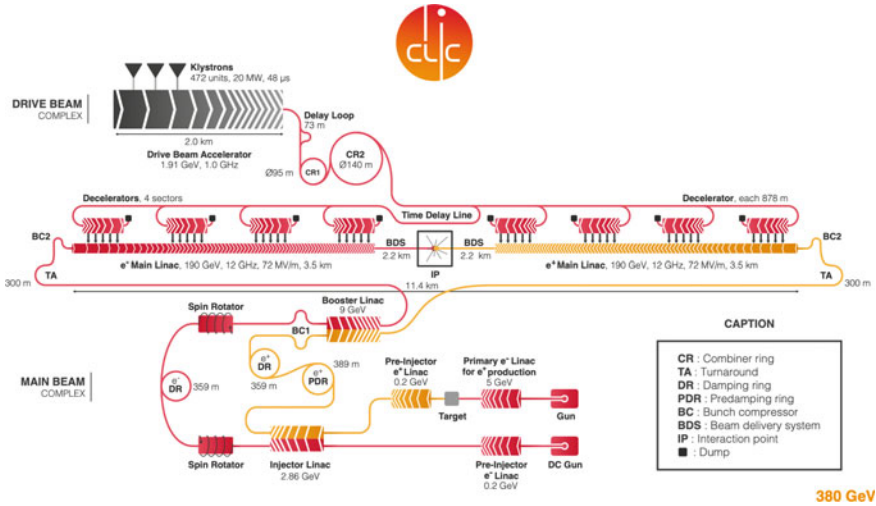


Fig. 22.1 Schematic layout of the CLIC complex at 380 GeV

In order to provide the necessary high peak power, the novel drive-beam scheme uses low-frequency high efficiency klystrons to efficiently generate long RF pulses and to store their energy in a long, high-current drive-beam pulse. This beam pulse is used to generate many short, even higher intensity pulses that are distributed alongside the main linac, where they release the stored energy in power extraction and transfer structures (PETS) in the form of short RF power pulses, transferred via waveguides into the accelerating structures. This concept strongly reduces the cost and power consumption compared with powering the structures directly by klystrons, especially for stages 2 and 3, and is very scalable to higher energies.

The upgrade to higher energies will require lengthening the main linacs. For the RF power the upgrade to 1.5 TeV can be done by increasing the energy and pulse length of the primary drive-beam, while a second drive-beam complex must be added for the upgrade to 3 TeV. An alternative design for the 380GeV stage has been studied, in which the main linac accelerating structures are directly powered by high efficiency klystrons. The further stages will also in this case be drive-beam based for the reasons mentioned above.

22.3 CLIC Parameter Overview

The parameters for the three energy stages of CLIC are given in Table 22.1. The baseline plan for operating CLIC results in an integrated luminosity per year equivalent to operating at full luminosity for 1.2×10^7 s [9]. Foreseeing 8, 7 and 8 years of running at 380, 1500 and 3000 GeV respectively, and a luminosity ramp up for the first years

Table 22.1 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	$1 \times 10^{34} \text{cm}^2 \text{s}^{-1}$	2.3	3.7	5.9
Lum. above 99% of \sqrt{s}	$1 \times 10^{34} \text{cm}^2 \text{s}^{-1}$	1.3	1.4	2
Total int. lum. per year	fb^{-1}	276	444	708
Main linac tunnel length	km	11.4	29.0	50.1
Nb. of particles per bunch	1×10^9	5.2	3.7	3.7
Bunch length	μm	70	44	44
IP beam size	nm	149/2.0	$\sim 60/1.5$	$\sim 40/1$
Final RMS energy spread	%	0.35	0.35	0.35
Crossing angle (at IP)	mrad	16.5	20	20

at each stage, integrated luminosities of 1.5, 2.5 and 5.0 ab^{-1} are reached for the three stages. CLIC provides $\pm 80\%$ longitudinal electron polarisation and proposes a sharing between the two polarisation states at each energy stage for optimal physics reach [10].

22.4 Luminosity Margins and Performance

In order to achieve high luminosity, CLIC requires very small beam sizes at the collision point, as listed in Table 22.1. Recent studies have explored the margins and possibilities for increasing the luminosity, operation at the Z-pole and gamma-gamma collisions [11].

The primary beamphysics and luminosity considerations for CLIC are presented in [12]. The impact of static and dynamic imperfections is studied in detail, being the determining factors for the luminosity performance. The dominant imperfections are the static misalignment of beamline elements and ground motion that degrades the initial emittances. Beam-based alignment is used to minimise the impact of static imperfections. For the expected alignment imperfections and with a conservative ground motion model, 90% of the machines achieve a luminosity of $2.3 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ or greater. This is the value used in Table 22.1. The average luminosity achieved is $2.8 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. Future improvements to the technologies used to mitigate imperfections, such as better pre-alignment, active stabilization systems and additional beam-based tuning, will also help further increase this luminosity. A start-to-

end simulation of a perfect machine without imperfections shows that a luminosity of $4.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ would be achieved.

At 380 GeV energy also the repetition rate of the facility, and consequently luminosity, could be doubled from 50 to 100 Hz without major changes but with increases in the overall power consumption and cost (at ~ 55 and $\sim 5\%$ levels, respectively).

The CLIC beam energy can be adjusted to meet different physics requirements. In particular, a period of operation around 350 GeV is foreseen to scan the top-quark pair-production threshold. Operation at much lower energies can also be considered. Running at the Z-pole results in an expected luminosity of about $2.3 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ for an unmodified collider. On the other hand, an initial installation of just the linac needed for Z-pole energy factory, and an appropriately adapted beam delivery system, would result in a luminosity of $0.36 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ for 50 Hz operation. Furthermore, gamma-gamma collisions at up to ~ 315 GeV are possible with a luminosity spectrum interesting for physics.

22.5 Brief Summary of the CLIC Technical Maturity

Accelerating gradients of up to 145 MV/m have been reached with the two-beam concept at the CLIC Test Facility (CTF3). Breakdown rates of the accelerating structures well below the limit of $3 \times 10^{-7} \text{ m}^{-1}$ per beam pulse are being stably achieved at X-band test platforms at the foreseen operational gradients of CLIC.

Substantial progress has been made towards realising the nanometre-sized beams required by CLIC for high luminosities: the low emittances needed for the CLIC damping rings are achieved by modern synchrotron light sources; special alignment procedures for the main linac are now available; and sub-nanometre stabilisation of the final focus quadrupoles has been demonstrated. In addition to the results from laboratory tests of components and the experimental studies in ATF2 at KEK, the advanced beam-based alignment of the CLIC main linac has successfully been tested in FACET at SLAC and FERMI in Trieste.

Other technology developments and prototypes include the main linac modules and their auxiliary sub-systems such as vacuum, stable supports, and instrumentation. Beam instrumentation and feedback systems, including sub-micron level resolution beam-position monitors with time accuracy better than 20 ns and bunch-length monitors with resolution better than 20 fs, have been developed and tested with beams in CTF3.

Recent developments, among others of high efficiency klystrons, have resulted in an improved energy efficiency for the 380 GeV stage, as well as a lower estimated cost. For an updated description of the technical developments please see [2].

22.6 CLIC Schedule, Cost Estimate, and Power Consumption

The technology and construction-driven timeline for the CLIC programme is shown in Fig. 22.2 [13]. This schedule has seven years of initial construction and commissioning. The 27 years of CLIC data-taking include two intervals of two years between the stages.

The cost estimate of the initial stage is approximately 5.9 billion CHF. The energy upgrade to 1.5 TeV has an estimated cost of approximately 5.1 billion CHF, including the upgrade of the drive-beam RF power. The cost of the further energy upgrade to 3 TeV has been estimated at approximately 7.3 billion CHF, including the construction of a second drive-beam complex.

The nominal power consumption at the 380 GeV stage is approximately 110 MW. Earlier estimates for the 1.5 and 3 TeV stages yield approximately 370 and 590 MW, respectively [14], however recent power savings applied to the 380 GeV design have not yet been implemented for these higher energy stages. The annual energy consumption for nominal running at the initial energy stage is estimated to be 0.6 TWh. For comparison, CERN's current energy consumption is approximately 1.2 TWh per year, of which the accelerator complex uses approximately 90%.

22.7 The CLIC Programme 2021–2025

The design and implementation studies for the CLIC e^+e^- multi-TeV linear collider are at an advanced stage. The main technical issues, cost and project timelines have been developed, demonstrated and documented.

The CLIC study will submit an updated project description for the next European Strategy Update 2026–2027. Key updates will be related to the luminosity performance at 380 GeV, the power/energy efficiency and consumption at stage 1, but also at multi-TeV energies, and further design, technical and industrial developments of the core-technologies, namely X-band systems, RF power systems, and nano-beams with associated hardware.

The X-band core technology development and dissemination, capitalizing on existing facilities (e.g. X-band test stands and the CLEAR beam facility at CERN), remain a primary focus. More broadly, the use of the CLIC core technologies—primarily X-band RF, associated components and nano-beams—in compact medical, industrial and research linacs has become an increasingly important development and test ground for CLIC, and is destined to grow further [15]. The adoption of CLIC technology for these applications is now providing a significant boost to CLIC related R&D, involving extensive and increasing collaborations with laboratories and universities using the technology, and an enlarging commercial supplier base.

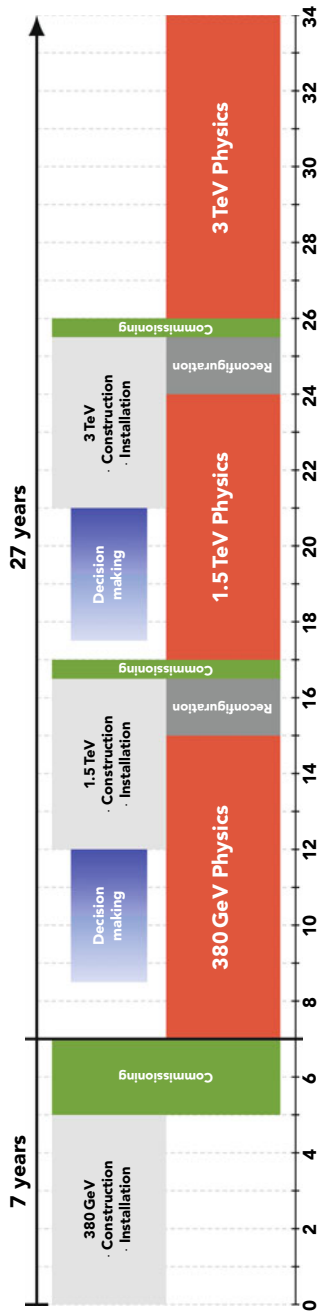


Fig. 22.2 Technology and construction-driven CLIC schedule. The time needed for reconfiguration (connection, hardware commissioning) between the stages is also indicated

On the design side the parameters for running at multi-TeV energies, with X-band or other RF technologies, will be studied further, in particular with energy efficiency guiding the designs.

Other key developments will be related to luminosity performance. On the parameter and hardware side these studies cover among others alignment/stability studies, thermo-mechanical engineering of modules and support systems for critical beam elements, instrumentation, positron production, damping ring and final focus system studies. These technology developments have clear synergies with what is needed for linear colliders using other RF-technologies, and also light sources. Many of the collaboration partners in CLIC involved in these developments are from laboratories with Synchrotron Sources or Free Electron Laser installations, and test components and units in their facilities in view of future use there.

In summary, the CLIC studies foreseen overlap in many areas with challenges for other Higgs-factories or other accelerators, especially with the R&D topics related to high gradient and high efficiency RF systems. CLIC and ILC have for many years had common working groups and workshop sessions on beam-dynamics, sources, damping rings, beam-delivery systems and more. Also the more recent sustainability studies fall into this category. There are also common challenges with the novel accelerator developments concerning linear collider beam-dynamics, drivebeams, nanobeams, polarization and alignment/stability solutions, and also with muon cooling RF systems.

22.8 The ILC Accelerator

The ILC consists of the following domains: (1) electron and positron sources, (2) damping rings (DRs) to reduce the emittance of the e^-/e^+ beams, (3) beam transportation from the damping rings to the main linear accelerators (RTML), (4) the main linear accelerators (MLs), including bunch compressors, that accelerate the e^-/e^+ beams using superconducting RF technology, (5) beam delivery system (BDS) and a final focusing system, to focus and adjust the final beam to increase the luminosity, and the beam interaction region for the machine and detector interface (MDI) where the detectors are installed. After passing through the interaction region, the beams go to the beam dumps. The ILC complex is shown in Fig. 22.3.

Two key technologies are required for ILC, one of which is nano-beam technology applied at DRs, ML and the BDS. The beam is focused vertically to 7.7 nm at the interaction point. The other is SRF technology applied in the MLs. Approximately 8,000 SRF cavities are installed in the MLs and operated at an average gradient of 31.5 MV/m. The accelerator is operated at 5 Hz. In total, 1,312 beam bunches are formed in one RF pulse with a duration of 0.73 ms, and 2×10^{10} electrons and positrons are generated per bunch from the electron source and the positron source, respectively. The high-power output from the klystrons is transferred to the cavities through input couplers generating an electric field of 31.5 MV/m. One klystron's RF power (up to 10 MW) is distributed to 39 cavities. The AC power required to operate

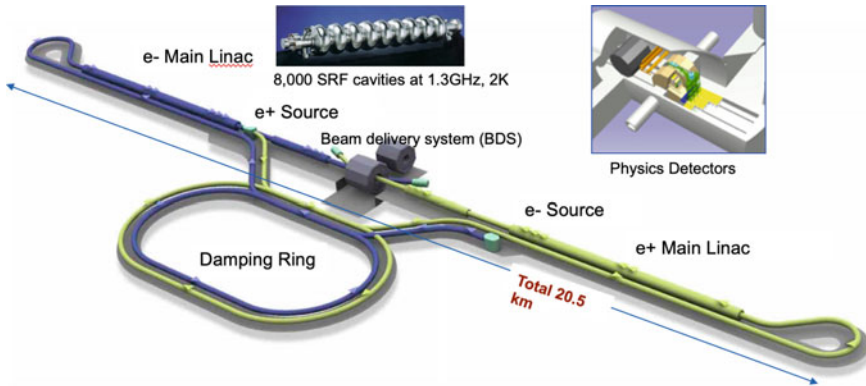


Fig. 22.3 Schematic layout of the ILC complex at 250 GeV

the accelerator will be 111 MW [16]. The spins of the electron and/or positron beams can be maintained during acceleration and collision (polarized sources). This can help significantly improve the precision of measurements. The ILC parameters are summarized in Table 22.2.

The ILC can be upgraded in energy by extending the tunnel or increasing the acceleration gradient. An important feature of linear colliders is that the energy can be increased without being affected (limited) by synchrotron radiation, allowing to adjust the facilities to emerging new physics. The beam delivery system (BDS) and beam dump of the ILC can handle collision energies up to 1 TeV. Another upgrade scenario is a luminosity upgrade. By increasing the high-power RF system, the luminosity can be doubled as compared to the current scenario discussed in the TDR. It might also be possible to re-use the tunnel, infrastructure and other facility resources for a future multi-TeV linear collider based on further improved or novel accelerator RF-technologies. Some of these options are described in [8].

22.9 Status of the ILC Accelerator Developments

22.9.1 Positron Source

There are two options for ILC positron sources: undulator and electron driven. The undulator scheme provides polarization (30%), but is a novel method for a collider. The electron-driven scheme is conventional and technically more proven. Considering the physical potential of the polarized positron, the undulator and electron-driven schemes are being developed in parallel. A superconducting helical undulator has been put into operation at APS (ANL, USA) and long undulators are also operated at European XFEL. Concerning the undulator scheme, the necessary techniques for

Table 22.2 Parameters for ILC250 GeV and future 500 GeV and 1 TeV upgrades. See [8] for detailed explanations

Parameter	Symbol	Unit	Option					
			Higgs			500 GeV		TeV
			Baseline	Lum. Up	L Up, 10 Hz	Baseline	Lum. Up	Case B
Center-of-Mass Energy	E_{CM}	GeV	250	250	250	500	500	1000
Beam Energy	E_{beam}	GeV	125	125	125	250	250	500
Collision rate	f_{col}	Hz	5	5	10	5	5	4
Pulse interval in electron main linac		ms	200	200	100	200	200	200
Number of bunches	n_b		1312	2625	2625	1312	2625	2450
Bunch population	N	10^{10}	2	2	2	2	2	1.737
Bunch separation	Δt_b	ns	554	366	366	554	366	366
Beam current		mA	5.79	8.75	8.75	5.79	8.75	7.6
Average power of 2 beams at IP	P_B	MW	5.26	10.5	21	10.5	21	27.3
RMS bunch length at ML & IP	σ_z	mm	0.3	0.3	0.3	0.3	0.3	0.225
Emittance at IP (x)	γe_x^*	mm	5	5	5	10	10	10
Emittance at IP (y)	γe_y^*	nm	35	35	35	35	35	30
Beam size at IP (x)	σ_x^*	mm	0.515	0.515	0.515	0.474	0.474	0.335
Beam size at IP (y)	σ_y^*	nm	7.66	7.66	7.66	5.86	5.86	2.66
Luminosity	L	$10^{34} \text{ cm}^{-2} \text{ s}^{-1}$	1.35	2.7	5.4	1.79	3.6	5.11
AC power	P_{site}	MW	111	138	198	173	215	300
Site length	L_{site}	km	20.5	20.5	20.5	31	31	40

undulator positron sources such as installation precision and orbit correction have been established. The durability test of the titanium alloy target was carried out and good results were obtained. For the electron drive system, the rotating target with magnetic fluid vacuum sealing was tested for degradation of the sealing part by irradiation and for long-term running of the simulated target, and the stable rotation and sufficient vacuum sealing performance were confirmed. For the magnetic convergence circuit, the electromagnetic design of the flux concentrator was completed based on the results at BINP, and the thermal design is now in progress.

22.9.2 BDS and Interaction Point

Nanobeam technology has been demonstrated at the ATF-2, hosted at KEK as an international collaboration, and is close to satisfying the requirements of the ILC. The ATF-2 has two goals. One is the generation of a small 37 nm beam, which is equivalent to 7.7 nm at the ILC-250 final focus at the IP. Until now 41 nm has been achieved. The other is to demonstrate precise position feedback. A feedback latency of 133 ns has satisfied the ILC requirement of less than 366 ns. Evaluation of the effect of the wakefield on the beam size at the ATF has led to studies aiming at suppressing wakefield effects at the ILC. The ATF programme, results, status and future opportunities, has recently been reviewed by an international committee, and the importance of continuing the research for detailed design and performance studies, of the ILC (and CLIC) final focus systems was highlighted.

22.9.3 SRF Technology

The SRF technology readiness has been proved by the successful operation of the European XFEL, where approximately 800 superconducting cavities (one-tenth the scale of the ILC SRF cavities) have been installed. A distributed and collaborative construction model was also successfully demonstrated. Following the European XFEL, the LCLS-II at SLAC and SHINE in Shanghai are under construction. Two major R&D programs are underway to improve the performance and reduce the cost of superconducting cavities. One is a new surface treatment for high Q and gradients, and the other is a new approach for niobium (Nb) material processes. New cavity surface treatments, such as two-step baking developed at FNAL, improve both the acceleration gradient and Q. Such surface treatments lead to a higher beam energy and/or cost reduction by shortening the length of the SRF linac and reducing the cryogenic heat load. Nb material R&D aims to reduce material costs during the production of Nb discs and sheets, including direct slicing and tube formation. Automation in a clean environment is important for the mass production of high-performance SRF cavities. The equipment for the automation of activities such as dust removal, is under development. Cryomodule assembly of a collection of 38 MV/m cavities significantly exceeding ILC specifications is in progress at FNAL in the USA with international cooperation.

22.10 Technical Preparation of ILC with a Pre-lab

Although significant work has already been done and described in the TDR and its addendum, it is necessary to revisit all the items to examine whether improvements or further developments are needed. The technical preparations during the Pre-lab

phase, i.e. accelerator work necessary for producing the final engineering design and documentation, are anticipated to be a starting point to discuss the international cooperation and technical efforts to be shared as in-kind contributions among the participating laboratories worldwide. A total of 18 work packages (WPs) have been proposed covering five accelerator domains.

A dominant part of the Pre-lab plans are related to SRF development, and three of the WPs are related to this topics. The technical preparations for the SRF include cavity industrial production readiness (WP-1), demonstration of cryomodule (CM) production readiness and global transfer while maintaining specified performance (WP-2), and crab cavity (WP-3). In WP-1, a total of 120 cavities will be produced (40 cavities per region, Europe, the Americas, and Asia), and successful production yields ($\geq 90\%$) are to be demonstrated in each region. Recent high-performance cavity preparation will be included. In WP-2, six CMs (two CMs per region) will be fabricated, and their performance will be qualified within each region. Thus, 48 of the 120 produced cavities will be used in the six CM assemblies. The compatibility of the CMs from different regions will be confirmed.

If the cavity is to be operated at a 10% higher gradient of 35 MV/m, it is necessary to confirm that the input coupler is compatible with the high gradient, and the introduction of a high-efficiency klystron is expected to reduce the electric power consumption. These are in line with the development of high-performance SRF cavities, input couplers, and high-efficiency klystrons.

WP-2 will also demonstrate readiness for the cost-effective production of other cryomodule components, such as couplers, tuners, and superconducting magnets. Overall CM testing after assembling these components into the CM is the last step for confirming the performance of the CM as a primary accelerator component unit.

The Americas and Europe have already developed significant expertise in cavity and CM production for their large SRF accelerators, including the formulation of countermeasures against performance degradation after cryomodule assembly, as well as degradation during ground transport of modules. As part of WP-2, the resilience of CMs to intercontinental transport will be established. In WP-3 (crab cavity), the first down-selection of the crab cavity will be carried out before Pre-lab to narrow down the choices from four to two, and then one of the two will be selected after the performance test during the Pre-lab.

The other WPs concerns the electron and positron sources, the damping rings, the beam-delivery and final focus system, and the dump. Overall their address the key elements needed for providing high luminosity with the ILC nano-beams. All the Pre-lab work-packages are described in detail in [6].

22.11 Sustainability of Linear Colliders

Power and energy efficiency studies will continue, covering accelerator structures and cavities, but also very importantly high efficiency RF power system with optimal system designs using high efficiency klystrons and modulators. It is expected that the

CLIC and ILC power consumptive can be further consolidated and possibly reduced. In particular for stages 2 and 3 of CLIC many technical developments affecting the power have not been included in the current power estimates. For ILC the wall-plug power is minimized making use of the small surface resistance of the SRF accelerating structures (cavities). Future SRF cavity studies can further improve the power efficiency, being particularly important for potential upgrades towards and into the TeV region. For ILC further improvements in energy efficiency are anticipated as part of the Green ILC concept, which aims to establish a sustainable laboratory [17] in a wide perspective, as part of the local region and economy.

Sustainability studies in general, e.g. power/energy efficiency, using power predominantly in low cost periods as is possible for a linear collider, use of renewable energy sources, and energy/heat recovery where possible, will therefore be a priority for further studies for both LC projects. Such studies were already made with initial parameters for the CLIC Implementation Plan (see Chap. 7 in [13]), but for example a complete carbon footprint analysis has not been made. Similar studies will be made for ILC. Both machines can benefit from use of permanent magnets and several studies and prototype have been successfully made. Future work in the area of sustainability will be synergetic with any future large accelerator study. In particular there are clear plans for future work common work between CLIC and ILC regarding sustainability and power/energy optimisation.

Acknowledgements This summary is made on behalf of the CLIC and ILC collaborations and communities. Many researchers work across and studies are carried out in common between the two collider concepts. The written resources used for this summary are primarily the CLIC and ILC sections being part of the European LDG roadmap report [18] and the CLIC and ILC input documents to the Snowmass 2021 process [2, 8]. The authors and editors of these reports are specially acknowledged.

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