7.2 ILC-specific R&D programme

7.2.1 ILC international collaboration

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) [1] was published by the Global Design Effort (GDE) international team in 2013. More than 2 400 researchers have contributed to the TDR. After publication, 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 as the ILC Machine Staging Report 2017 [2]. The International Development Team (IDT) was established [3] by the International Committee for Future Accelerators (ICFA) in August 2020 to prepare to establish the ILC preparatory laboratory (Pre-lab) [4] as the first step towards the construction of the ILC in Japan. The principal accelerator activities of the ILC Pre-lab are technical preparations and engineering design and documentation, and the former is summarised in "Technical Preparation and Work Packages (WPs) during ILC Pre-lab" [5]. The ILC Pre-lab activities are expected to continue for approximately four years, and the ILC accelerator construction will require nine years.

7.2.2 The ILC accelerator

A linear accelerator has an important advantage with natural extendability for accelerating electron and positron beams to higher energies towards the 1 TeV energy level/scale. The spins of the electron and/or positron beams can be maintained during acceleration and collision (polarised sources). This can help significantly improve the precision of measurements. 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 (to compress the beam bunch length) to accelerate the e^-/e^+ beams using superconducting RF technology, (5) beam delivery, and a final focusing system (BDS) 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 (DUMP). Two key technologies are required, one of which is nano-beam technology applied at DRs and the BDS. Here, the beam is focused vertically at 7.7 nm at the interaction point. The other is SRF technology applied at the MLs. Approximately 8000 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 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 inputted into the cavities through the input couplers to generate 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 the accelerator will be 111 MW [6]. The ILC parameters are summarised in Table 7.1. The AC plug power is minimised due to the small surface resistance of the SRF accelerating structure (cavity). Further improvements in energy efficiency are anticipated as part of the Green ILC concept, which aims to establish a sustainable laboratory [7].

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7.2.3 Recent status of the ILC accelerator

7.2.3.1 Positron source

There are two options for ILC positron sources: undulator and electron driven. The undulator scheme provides polarisation (30%), but is a new method. The electron-driven scheme is conventional and technically more proven. Considering the physical potential of the polarised 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 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.

7.2.3.2 BDS and interaction point

Nanobeam technology has been demonstrated at the ATF-2 hosted at KEK as an international collaboration, and it has nearly satisfied 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 we have achieved 41 nm. 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 the prospect of suppressing the wakefield effect at the ILC. In the ATF international review, the achievements of the ATF till now were evaluated critically, and the importance of continuing the research for the detailed design of the ILC final focus was highlighted.

7.2.3.3 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. International consistency and quality control have also been 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 through international cooperation.

7.2.4 Remaining technical preparation at 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 any update (including SRF cost reduction R&D) is necessary. The MEXT advisory panel and the Science Council of Japan also pointed out some remaining technical issues that need to be resolved during the ILC preparation period. The technical preparations, 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) over five accelerator domains have been proposed.

Pre-lab technical preparations for the SRF include cavity industrial production readiness (WP-1), demonstration of cryomodule 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 (40%) 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 described in Section 3 ("High-gradient RF structures and systems").

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 during ground transport of CMs. 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.

7.2.5 Future upgrade

The ILC can be upgraded energy wise by extending the tunnel or increasing the acceleration gradient. The advantage of a linear collider is that the energy can be increased without being affected (limited) by synchrotron radiation. The beam delivery system (BDS) and beam dump of the ILC can handle collision energies up to 1 TeV. Another upgrade scenario is 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.

Recently, the energy recovery linear collider (ERLC) concept was proposed by Valery Telnov as a hyper-high-luminosity alternative for the ILC. It is based on twin-axis superconducting cavities for enabling energy recovery from one axis to another. It would also enable the re-use of the beam by re-circulation back to the linac through low-energy beam transport loops. The ERLC concept has outstanding potential to exceed the luminosity performance projections of the ILC by over an order of magnitude. However, it requires fundamental R&D efforts for the design of fully coupled SRF systems requiring a high Q_0 cavity operating at a higher temperature ($\sim$ 4.5 K), as well as for very efficient higher-order mode (HOM) loss absorption at higher temperatures with CW operation. If the ERLC is envisioned as an ILC upgrade, careful investigation and R&D will be required for the ILC to accommodate the upgrade in luminosity in future.

Table 7.1: Parameters for ILC250 GeV and future 500 GeV and 1 TeV upgrade.

Parameter	Symbol	Unit	Option					
			Higgs			500 GeV		TeV
			Baseline	Lum. up	L up, 10Hz	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} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$	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

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