International Linear Collider: Accelerator

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Abstract

The International Linear Collider (ILC) is an electron–positron collider with an initial collision energy of 250 GeV (total length of approximately 20 km) for a Higgs factory [1, 2]. The scientific significance of the ILC has been clearly recognized since the discovery of the Higgs boson in 2012. The features of the ILC are polarized sources, superconducting RF (SRF) acceleration, nano beam, and future energy upgrade. International collaborations have been integrating the ILC's technical design and development [3]. The International Committee for Future Accelerators (ICFA) has announced a new phase towards the preparation of the ILC organized by the International Development Team (IDT), in August 2020 [4].

Accelerator overview

The ILC consists of polarized electron and positron sources (e^-/e^+ sources); damping rings (DR) to minimize the emittance of the e^-/e^+ beams, main linacs (ML) to accelerate the e^-/e^+ beams using SRF technology, and beam delivery systems (BDS) to focus and adjust the final beam to realize the luminosity required at the interaction point (IP) where physics detectors are installed. Subsequently, the beams move towards the main beam dumps. The accelerator system is operated at 5 Hz. A series of 1,312 beam bunches, each containing 2 $\times 10^{10}$ particles (from the electron and positron sources), are formed in one RF pulse duration of 0.73 ms, and they are accelerated in the ML. Two key technologies are required, one of which is SRF technology. Approximately 8,000 SRF cavities are installed in ML and operated at an average gradient of 31.5 MV/m. The other is nanobeam technology applied at DR, BDS, and IP. Here, the beam is focused vertically at 7.7 nm at the IP.

The TDR was published in 2013 for a 500 GeV center-of-mass energy [1]. More than 2,400 researchers have contributed to TDR. The 250 GeV ILC as the initial stage was proposed and published as the ILC Machine Staging Report 2017 [2]. The construction cost (value) of the accelerator and the tunnel, was approximately five billion ILC units (one ILC unit corresponds to one US dollar as of 2012). The AC power required to operate the accelerator will be 111 MW [5], and its operational cost (utility and maintenance), including electricity, is estimated to be approximately 0.3 billion ILC units [2,6].

Advantages of the ILC

The 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 with minimal background. 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 AC plug power may be minimized owing 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].

Technical Maturity

The SRF technology readiness has been proved by the successful operation of the European X-ray Free Electron Laser (Eu-XFEL) in Hamburg, where 800 superconducting cavities (one-tenth the scale of the ILC SRF cavities) have been installed. Following the Eu-XFEL, the LCLS-II at SLAC and the SHINE in Shanghai are under construction.

Nanobeam technology has been demonstrated at the ATF-2 hosted in KEK under 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. The other is to demonstrate precise position feedback. A feedback latency of 133 ns satisfied the ILC requirement of less than 366 ns.

The remaining technical preparation (such as cost-effective mass production of the SRF cavities, positron source, and beam dump) can be completed during the preparation phase before starting the construction of the ILC. These activities are well summarized in "Recommendations on ILC Project Implementation" [8].

Positron Source

The positron beam is produced by transporting the primary electron beam through a superconducting helical undulator string (the “undulator scheme”). This scheme produces polarized photons that are converted into positrons in a rotating target system with a longitudinal polarization of 30%, which can be enhanced to approximately 60% by introducing photon collimators (polarization upgrade). This scheme requires a rapidly rotating target whose technology is yet to be completed.

As a backup scheme, TDR also describes an alternative design of the positron source, namely the electron-driven source (the “e-driven scheme”) which utilizes a dedicated S-band electron linear accelerator to produce a 3 GeV beam that is used to generate positrons in pairs. This source does not provide positron polarization but would have advantages for operation at lower electron beam energies for the production and the independence of the source from the main electron beam.

The scheme is to be selected before commencing the detailed engineering design based on its relative evaluation for physics potential, costs, and technical maturity.

BDS and Interaction Point

The BDS is designed such that it can be upgraded to a maximum beam energy of 500 GeV for the center-of-mass energy of 1 TeV in collision. The components necessary for the 125 GeV beam operation are installed initially, and extra space is reserved for future upgrades. To enable the beams to collide with the necessary nanometer accuracy, a continuous compensation of drift and vibration effects is required, which can be carried out through precise position feedback. Finally, the 3.9 GHz crab cavities close to the interaction point are incorporated to kick and rotate the bunches to compensate for the 14 mrad beam-crossing angle. The baseline designed luminosity (updated) for ILC250 is 1.35×10^{34} /cm^2/s.

Advancement of SRF Technology

The US and Japan are collaborating on “cost-reduction R&D projects” [6,9,10]. One is a new surface treatment for high *Q* and gradient, and the other is the effort for the niobium (Nb) material process. The new cavity surface treatment developed at the Fermi National Accelerator Laboratory, including nitrogen infusion and low-temperature baking, improves both the accelerating gradients and *Q*. Such surface treatment enables the reduction of the SRF linac length and may reduce the cryogenic capacity and cost. The R&D project focusing on Nb material aims to reduce the material cost by optimizing the process used for production of the Nb ingots (raw material), disk/sheet production including direct-slice, and tube formation process. SRF accelerator technology is continuously advancing with promising future prospects. The R&D of the cavity material that can be used at higher temperatures and that has a higher critical magnetic field is progressing worldwide. Thin-film superconductors with a higher performance will be applicable for future energy upgrades.

Schedule and Future Upgrades

Currently, we are starting the pre-preparation phase that is aimed at the preparation phase (to be realized within one to two years). The IDT facilitates the transition into the preparatory phase of the ILC. After four years of the preparatory phase, the ILC accelerator construction will require nine years.

The ILC accelerator can be upgraded to a higher energy by extending ML and further implementing higher gradient operation. It is also included in the basic design concept to upgrade the luminosity by increasing the number of bunches [11, 12]. These upgrade plans are described in the TDR. Recently, the operation at the Z-pole has also been extensively investigated [13].

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