PRESENT STATUS OF THE ILC PROJECT AND DEVELOPMENTS*

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Abstract

The Technical Design of the International Linear Collider (ILC) Project will be finished in late 2012. The Technical Design Report (TDR) will include a description of the updated design, with a cost estimate and a project plan, and the results of research and development (R & D) done in support of the ILC. Results from directed ILC R & D are used to reduce the cost and risk associated with the ILC design. We present a summary of key challenges and show how the global R & D effort has addressed them. The most important activity has been in pursuit of very high gradient superconducting RF linac technology. There has been excellent progress toward the goal of practical industrial production of niobium sheet-metal cavities with gradient performance in excess of 35 MV/m. In addition, three purpose-built beam test facilities have been constructed and used to study and demonstrate high current linac performance, electron-cloud beam dynamics and precision beam control. The report also includes a summary of component design studies and conventional facilities cost optimization design studies.

INTRODUCTION

In 2001 high energy physicists in Europe, America and Asia outlined the need for an e+ e- collider to complement the Large Hadron Collider [1]. Their input was interpreted and summarized in 2006 in a Parameters document that has been used to define performance specifications for the International Linear Collider (ILC) [2]. The ILC Reference Design Report (RDR) detailed the design with a cost estimate and outlined critical R & D [3].

The ILC Global Design Effort (GDE) was created by International Committee for Future Accelerators (ICFA) to coordinate and provide a focus to multi-laboratory contributions to the design. The task of the GDE in the years since the publication of the RDR is to develop the reference design and coordinate the R & D so that the project is ready to submit to agencies worldwide. (This project phase is called the Technical Design Phase - TDP). The work includes evaluation and optimization of the collider design with a primary aim of containing cost through by achieving a better balance between cost, risk and performance. Four major changes to the reference design, discussed below and summarized in Table 1, have been presented to the community for discussion and have been approved. The new TDR baseline parameters are listed in Table 2.

To help enable the formidable communication task, the GDE published and updated an R & D plan which explains the strategy and shows expected resources [4]. A complementary report that describes TDP R & D progress was published in June 2011[5].

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Table 1: Top-Level Changes (TLC) to Reference Design

Number	TLC	Key element
TLC-1	Gradient Spread (Average Linac Gradient Retained)	<V>=31.5 ± 20% MV/m;
TLC-2	Single Main Linac tunnel	3 alternate HLRF schemes
TLC-3	Reduce bunch number (n_b);	n_b=1312 3.2 km DR
TLC-4	Relocation of positron source	Central region complex

DESIGN

Accelerator Design and Integration

After the publication of the RDR, the focus of the GDE shifted to R & D with the intention to use that to modify the design to reduce cost and risk. Lacking resources to apply 'value engineering' to the entire technical design, it was decided to focus on high-level, highly leveraged global value engineering. Superconducting RF (SCRF) linac high-technology and conventional facilities (civil construction and utilities) were targeted for study because the two together comprise 75% of the cost estimate developed for the RDR. Seven trade-off studies were identified, ranked and coalesced into the four top-level changes listed in Table 1 [6].

Baseline Changes

TLC-1: The decision to retain the average linac gradient specified in the RDR, but to allow up to a ±20% gradient spread, was taken both on the basis of technical performance and cost risk reduction. Excellent cavity performance has been achieved with performance in vertical test far in excess of the nominal 35 MV/m; up to 45 MV/m. Thus the *effective* gradient of an ensemble of cavities can exceed the specified per-cavity performance using the allowed gradient spread and a greater fraction of cavities can be accepted, thereby increasing the *production yield*. However, there is an associated penalty; to make optimum use of both high and low gradient cavities requires 10-15% additional high-level RF (HLRF) power.

TLC-2: A main linac configuration with deep underground twin tunnels was adopted for the reference design primarily because of safety (egress) and availability considerations. Further studies focused on evaluating different site topographies and construction techniques were foreseen as part of the TDP. Two alternate HLRF schemes with quite different component arrangements, 'Klystron Cluster Scheme' (KCS) and 'Distributed RF Scheme' (DRFS) were proposed as part of the study to provide flexibility in the design and allow a workable single tunnel configuration.

Table 2: ILC TDR Baseline Beam Parameters

Center of-mass collision energy	E_{cm}	GeV	200	230	250	350	500	1000*
Luminosity	L	10^{34} cm^{-2}s^{-2}	0.5	0.5	0.7	0.8	1.5	2.8
Luminosity (Travelling Focus)	L_{TF}	10^{34} cm^{-2}s^{-2}	0.5		0.8	1.0	2.0	
Number of bunches	n_b		1312	1312	1312	1312	1312	2625
Collision rate	f_{rep}	Hz	5	5	5	5	5	4
Electron linac rate	f_{rep}	Hz	10	10	10	5	5	4
Positron bunch population	N+	10^{10}	2	2	2	2	2	2

* tentative: under review

Since both schemes require R & D, a third backup alternate based on the original TESLA scheme is also considered.

TLC-3: Reducing the beam power (halving n_b) and the damping ring (DR) circumference has the largest estimated cost-reduction of the four TLC.

This change also meant a large estimated change in luminosity performance, as reflected in Table 2, with L reduced to 1.5x10^{34} compared to 2x10^{34} in the RDR. Performance may be restored using the 'travelling focus' scheme [7] which introduces a correlation between the waist location and particle position along the bunch.

TLC-4: The last of the four baseline changes is the relocation of the positron source system to the end of the electron linac, placing it within the central region complex. This change is motivated by the integration of sources into the central region, resulting in reduced conventional construction and accelerator component count. The proposal, together with ongoing physics and detector group studies of collider performance, prompted a look at L at lower energies (Table 2). Below 300 GeV E_{cm}, the baseline undulator does not provide an adequate photon flux for positron production so an electron linac operation scheme with twice the pulse repetition rate (to 10 Hz) has been adopted for E_{cm} <300GeV. In the scheme, the linac delivers a beam of variable energy as requested for a given E_{cm} with half of its pulses and a positron production beam of at least 150 GeV with the other half.

Accelerator Systems R & D

The ILC is made up of six accelerator subsystems: 1) electron source, 2) positron source, 3) damping rings, 4) ring-to-main linac, 5) main linac, and 6) beam delivery. R & D activities for 1, 2, 3, 5 and 6 are described here.

Sources

Electron source R & D has been focused on the tunable high-power drive laser, semiconductor cathode and gun electrode performance, all of which are key components of the photo-cathode gun [8]. Polarized beam strained gallium-arsenide-phosphide photocathode performance (~85% polarization) has been deemed adequate and it is assumed this technology will be used.

The key aspects of positron source target R & D are: 1) simulation of beam-impact thermal performance, 2) rotating target eddy current heating measurement, 3) rotating high vacuum seal performance and 4) integration with the proximity-focus tapered-solenoid flux concentrator lens. A 1m diameter cold-test prototype 2000 rpm (30Hz) rotating target wheel was built and used to provide experimental measurements of eddy current heating in a 25kG magnetic field [9]. The observed heating appears to be quite manageable and tests of rotating vacuum seals are underway. A full power lab-model (no-beam) prototype flux concentrator has been designed, is under construction and will be used with the prototype target wheel for system tests [10].

The production gamma beam is created when the primary high energy electron beam traverses ~200 m of high-field, low-pitch (11mm) superconducting helical undulator. Two 4m full-field modules were constructed and tested successfully [11]. Development of smaller-pitch undulators based on Nb_3Sn conductor has started. This would allow production full intensity positrons at lower, (100 GeV rather than 150 GeV), electron beam energy and remove the need for the 10Hz scheme foreseen as part of TLC-4.

Damping Rings

The most serious concern for the DR is the electron-cloud generated positron beam instability which can lead to coherent instability and incoherent emittance growth. A comprehensive study [12] that includes 1) vacuum chamber surface chemistry testing, 2) development of specialized diagnostics for high-speed and precision-profile cloud density measurements, and 3) simulations of cloud generation and cloud-beam interaction was done at the Cornell e+/e- storage ring CesrTA. The program culminated in characterization, in each magnetic field region, of various cloud suppression techniques.

Ultra-low emittance beam tuning was also identified as critical R & D. The Accelerator Test Facility at KEK (ATF) was built to study the production and manipulation of beams with vertical emittance ε_y of ≤ 4 pm-rad, below that needed at the interaction point. Acceptable emittances have been achieved at ATF and have been surpassed at several third generation light sources.

The third DR critical R & D item is the study of fast pulse injection/extraction kicker magnet systems. A kicker rise/fall time of at most 3.1 ns is required in order to fit the full n_b in the 3.2 km ring without disturbing neighboring bunches during the injection and extraction process. In addition, the system must pulse at a rate of

2.7 MHz with a kick stability of better than 0.07% rms for the duration of the 1 ms linac pulse. A prototype pair of stripline kicker magnets powered by a solid-state pulser has been used to extract a sequence of 30 bunches from the ATF damping ring [13]. The system achieved the required rise and fall time with excellent pulse-to-pulse and bunch-to-bunch stability.

Main Linac

The superconducting linac is the cornerstone of the ILC. ILC–like SCRF accelerator performance was first demonstrated at DESY in 2001 [14] at the TESLA Test Facility (TTF) linac. TTF, now a VUV FEL renamed 'FLASH', remains the primary beam test facility for ILC SCRF.

Demonstrating high gradient and stability at full current are the main R & D goals for the linac. Under these conditions, all cavities should be capable of operating within 3% (~ 1 MV/m) of their limiting gradient. Table 3 summarizes present experimental status [15].

Table 3: High Beam Power Studies at FLASH (DESY)

Metric	ILC goal	Flash (achieved)
Macro-pulse beam current	9 mA	9 mA
Bunches / pulse	2625 x 3nC	1800 x 3nC 2400 x 2nC
Pulse length	970 µs	800 µs
Gradient	31.5 MV/m	> 30 MV/m (4 each)
Gradient spread	± 20%	± 25%
Gradient flatness	2%ΔV/V	2.5%ΔV/V (400 µs, 4.5 mA)
Gradient margin	within 3% of quench limit	To be studied (2012)
Energy stability	0.1 % at 250 GeV	<0.15% p-p (0.4ms) <0.02% rms (5Hz)

Low-level RF (LLRF) feedback and active electromechanical controls are required to stabilize and flatten the vector sum accelerating gradient of an ensemble of cavities, (26 in the reference design), to ±1% maximum deviation during the beam pulse. Two additional constraints demand constant gradient in individual cavities. 1) Each cavity should operate quite close to its gradient limit. Systematic slopes will effectively reduce the available gradient since the peak must remain below the quench limit. To achieve the required flat-top at nominal current with a given cavity input power from the klystron, the loaded Q (*Q_l*) must be adjusted appropriately [16]. *Q_l* must also be adjusted to compensate for current variations. 2) Each cavity has a systematic transverse kick associated with its misalignment from the nominal trajectory. A small difference between the kick given to the first and the last bunch in the train will result in an increased projected emittance which is difficult to correct.

Beam Delivery System

The optics of the beam delivery system consists of a sequence of demagnification sections with chromatic and non-linear correction elements. The basic principles of the system have been demonstrated [17] but the convergence of the tuning strategy, including optimization feedback integration, is important to test and validate. The ATF2 extraction line, fed from the ATF low-emittance damping ring, was constructed for this purpose [18]. There are no beam-beam collisions at ATF so the ultimate measure of performance is made using a laser interference-fringe Compton profile monitor [19]. The extraction line is a scaled-down version of the ILC design and consists of dispersion, coupling and chromatic sections and a final focus which is designed to produce 35 nm σ_y beams at the pseudo-interaction point. Innovative beam instrumentation, feedback systems and tuning algorithms are required to maintain control of nanometer beams and ATF2 is a critical integration test of this equipment. Although both ATF and ATF2 were damaged in the great eastern Japan earthquake, on 11 March 2011, recovery is now underway and seems to be going well [20].

Conventional Facilities and Siting

Even though the ILC design is mature, siting studies have been done only with generic sample sites. To date, sample - site design studies have been done for 1) semi-urban, 2) mountain - region and 3) flat-land topography. Geotechnical studies of specific Japanese mountain region sites, (one in the Tohoku area in the northeast and one in the Kyushu area in the far west), were started [21] in 2010. General site studies have been done using geological data from the CERN, Fermilab and Dubna areas [22].

SUPERCONDUCTING RF

Superconducting Linac System

The ILC Superconducting linac system is made up of

- high gradient 9-cell, 1.3 GHz niobium sheet metal standing wave resonator cavities, each 1 m long
- fast and slow electromechanical cavity tuners (stepping motors and piezo-electric movers)
- coaxial power couplers with adjustable *Q_l*
- directly inter-connected cryomodules, without intervening warm sections, each ~12 m long with 8 (or 9) cavities
- superconducting focusing and steering magnets
- beam instrumentation
- HLRF sources with waveguide power distribution system
- high-performance 2 degree K cryogenic system.

This paper describes cavity and cryomodule R & D and preparations for mass-production.

Cavity

Superconducting niobium cavity peak achievable gradient is the key cost-driver for ILC construction. Several hundred cavities have been built and tested in the roughly 20 years since the TESLA collaboration set basic parameters [23]. Roughly 800 are now in fabrication for the European XFEL project (EU-XFEL) [24]. Capturing the best R & D cavity performance with a reliable fabrication, processing and testing recipe and understanding practical limits to performance is a critical goal of the ILC TDP [25].

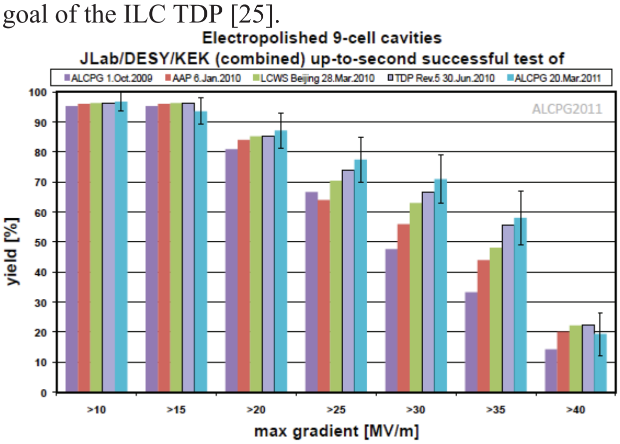

Figure 1: 2009-2011 global integrated cavity production yield vs. gradient. Acceptance criteria have been defined: $\langle V\rangle=35 \pm 20\%$ MV/m. The data (until 03.2011) show the standard recipe cavity yield is >70%.

The ILC baseline resonator cavity is a monolithic welded niobium/niobium-titanium component that can be easily carried by two people. Typically cavities are produced by industry and tested at partner institutions. All cavities are tested in a simple vertical dewar with CW RF and many are tested in a single-cavity horizontal test stand before string assembly and installation into an accelerator cryomodule cryostat.

To provide guidance for the TDR cost estimate, cavity production yield is assessed by scoring performance of all cavities fabricated and processed according to the baseline recipe by qualified companies and institutions. Figure 1 shows the global three-region, (Asia, Europe, and Americas), integrated cavity yield in the period 2008-early 2011.

The challenge of SCRF is to control both thermal-runaway quench caused by impurity or surface deformation in the high-current region (equator) of each cell and control field emission from contaminants or scratches in the high-field region (iris) of the cell. Progress has been made during the TDP on 1) understanding quench with the development of specialized instrumentation for mapping cavity surfaces [26] and on 2) reducing field emission with the development of chemical rinsing [27].

Cryomodule

The ILC cryomodule assembly process requires extensive ultra-high (ISO-4/class 10) clean room activity in order to connect cavity assemblies via their beam flanges and to insert the center conductor of the power coupler. In practice inconsistencies in this process can lead to gradient performance degradation caused by field emission. Prototype EU-XFEL cryomodules, the ILC 'S1 Global' cryomodule and CM-1 at Fermilab each have one or two cavities with ~ 20% performance reduction compared with the individual cavity's vertical dewar test [29]. A challenge for the next year or two is to develop diagnostic tools and perfect assembly procedures to reduce this problem. More than 120 cryomodules are to be constructed during this period, (mostly for the EU-XFEL project), and we expect the assembly tooling and related procedures to be improved.

Industrial Mass-Production of Cavities

Preparing a plan for the mass production of cavities is an important deliverable for the TDR. By working with institutional and industrial expertise in each global region, the GDE is assured of having competent partners and a robust and credible cost estimate. Furthermore, negotiations on in-kind contribution share may be facilitated through the prior sharing of knowledge and the qualification of vendors.

Roughly 1/3 of the cavity cost is the raw material (see for example [30]), namely the ultra- pure 'RRR' 3mm thick niobium sheet used for the high field cells themselves. In contrast, the complex end-groups are costly to fabricate and include lower grade niobium and niobium titanium in addition to the RRR metal.

The ILC will require a small but not negligible fraction of global niobium production, roughly equal to that used for the LHC superconducting magnets. It will, however, require a large fraction of the world's electron beam refining capacity as the required purity may require 6 to 10 electron beam vacuum melting cycles. The large, high-power refining systems have a long fabrication lead time and are best deployed in places where electricity is plentiful. The cost of 1) the pure niobium ingots, 2) the forging/rolling process and 3) the finishing, (grinding and pickling), are roughly equal [31].

Cavity assembly requires deep drawing, trimming, pre-weld etching and high-vacuum electron beam welding. Because each weld has complicated geometry, (with tight tolerances), and requires clean conditions welding is a critical cost-driver technology. Fortunately, welding equipment has seen steady development and proliferation in the last few years so that high quality clean-environment welding systems are readily available.

GDE cavity industrialization studies are aimed at understanding tradeoffs between the capital cost of fabrication equipment and direct production costs and duration. The ILC main linac will require the production of 16,000 cavities in 6 years. Assuming production is divided between five plants, with >500 cavities/plant/year, the required production rate is only 3 to 4 times greater than that required for the EU-XFEL. The scale of such a plant is similar enough to existing facilities that the process of cost estimation will have a practical basis and cost-saving innovations can be included in the plan.

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