INDUSTRIALIZATION OF THE ILC PROJECT*

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Abstract

The International Linear Collider (ILC) Global Design Effort (GDE) team completed the Technical Design Report (TDR) in early 2013 [1]. The TDR consists of a description of the machine design, a summary of the R&D program carried out in support of the design, a cost estimate and a project plan. The number of high technology components to be fabricated for ILC is large, similar to that built for the Large Hadron Collider [2], and industrial partners have had an important role throughout the technical development and design period. It is widely recognized that transfer of new technology to industrial partners and its subsequent collaborative development can be difficult [3]. To try to counter this, the ILC Technical Design Phase (TDP) team carried out an industrialization program that consisted of two series of vendor visits, component development contracts, workshop satellite meetings and industrial production study contracts. The GDE collaboration provided the framework for development through an agreed-upon performance parameter set and project implementation scheme [4]. The latter includes a 'plug-compatibility' policy that enables innovation as long as specified interface conditions are met. In this paper we describe the evolution of ILC technology from the labs where it was developed to companies worldwide where high performance cavities are now routinely produced.

INTRODUCTION

The ILC, with a scale similar to the Large Hadron Collider (LHC) at CERN, is set to become the most complicated and ambitious high-technology particle physics project ever carried out. From the outset it was conceived to be of such scientific scope that no single institution or region would be able to provide the needed resources for construction [5]. This resulted in the formation of a thoroughly international team, known as the GDE, to prepare the design, technical R&D, industrialization scheme, cost estimates, and management planning for the project. ILC know-how and key responsibilities are therefore widely distributed.

The ILC is to be a 500 GeV center-of-mass energy electron / positron linear collider based on superconducting RF technology. This paper describes the industrialization approach applied to the two 11 km long linacs. The linacs are the highest cost subsystem of ILC. Table 1 shows the critical high technology superconducting RF (SRF) linac equipment to be fabricated by industrial mass-production techniques. The ILC project plan requires the linac SRF equipment to be fabricated in seven years (five year full production following a two-year ramp-up period).

The ILC design has been developed over the last twenty years. Critical SRF performance and cost improvements were carried out by the Tera-electron-volt-Energy Superconducting Linear Accelerator (TESLA) collaboration in the 1990s. Since 2005 the worldwide R&D has been coordinated by the GDE. The ILC Reference Design Report (RDR - 2007) [6] included a cost estimate, based largely on the TESLA studies, that was used to help identify and prioritize critical R&D. A key component of the new TDR cost estimate is the input from industrial partnerships developed during the Technical Design Phase.

Industrialization is the final step in technology development before beginning the production cycle. It includes aspects of technology transfer, especially: 1) developing the build-to-print strategy that delineates the responsibilities of industry, 2) evaluating and testing the production process to estimate the scale of the required production infrastructure and labor and, 3) developing the full cost model. Industrialization takes a different character if it is expected the technology has application beyond the project as the companies involved will naturally evaluate business opportunities based on the new technology [7]. It is not expected, for example, that LHC dipole magnets will be directly adapted for general-purpose application but it is likely that SRF cavities will eventually find use in small-scale accelerators, including industrial and medical accelerators or accelerator systems devoted to energy production[8].

With the successful completion of critical R&D and the publication of the TDR in 2013 the team is now ready to embark on the project. The next step is to prepare a "Proposal to Construct" for review and submission. In this paper we describe the steps taken from the final technical R&D stages done in institutions to the successful deployment of the technology in companies in each of the three ILC regions: Europe, Americas and Asia.

Table 1: ILC SRF Linac Summary

Linac Parameters	Value	Unit
Linac Energy	250	GeV
Linac length	11130	m
Average Cavity Gradient	31.5	MV/m
Allowed Gradient Spread	+/- 20	%
Component Total (both linacs)	**Number**	
Cavities	16024	each
Cryomodules	1855	each
Klystrons	426	each

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PROJECT COST ESTIMATION

The governance of a large international science project is a complex endeavour and there is no precedence for a truly global project of this scale. Without specific guidance, we developed an innovative yet practical strategy to prepare a project construction cost estimate based on close interaction with institutional and industrial regional partners. Each potential regional or national partner participated in discussions of international project strategy and each was asked to consider how they would industrialize high-technology mass-production and what range of contributions they might provide. Ultimately these discussions and the full cost estimate provide a necessary framework that enables industrialization to proceed efficiently.

As is appropriate for a project intended to be funded mainly by in-kind contributions, the Value cost-estimating methodology is used. The Value estimate for a component or subsystem is the lowest world-wide vendor cost for the item, which is practical, feasible, and reasonable, for the required specification and quantity, with a procurement time consistent with the project schedule [9].

The TDR value cost estimate for ILC is 7.8 billion ILC Units, (ILCU). (The ILCU is an artificial currency unit defined to be 1 US dollar on 1 January 2012.) Of the total (in billions), 2.2 (28%) is for cavities and cryomodules, 0.4 (5%) for niobium semi-finished material and 0.9 (12%) for high level RF generation and distribution systems.

The project construction cost estimate allows preparation of a “Proposal to Construct” to proceed because it shows the scope of the work and thus allows partners to consider sharing models in detail and subsequently evaluate their own potential contribution. As the cost estimate will strongly depend on industrial practice specifics, it is vital to develop the cost estimate in parallel to industrialization. The cost sharing model is most useful if the cost estimate is all-embracing and includes input from each major regional partner since it is unlikely that representatives from a given region can properly comprehend and develop an estimate for work carried out in another. Ultimately, of course, the estimate of the direct cost of the contribution made by a given region or country must be prepared and evaluated by the partners themselves and not by the global team alone.

INTEGRATION IN LARGE SCALE IN-KIND PROJECTS

Large scale projects based on in-kind contributions require a careful and very strictly applied integration protocol [10]. This ensures proper interface definition, functional specification development and, ultimately, that it all will fit together. For the International Thermonuclear Experimental Reactor (ITER) project this is quite important because of its intrinsic complexity and relative lack of modularity.

ILC by its extended linear design and mostly modular technology is very different. In a linac, generally, each accelerator section is not required to provide exactly the same accelerating voltage gradient. This means the large number of essentially equivalent cryomodules that are connected together to constitute the linac can have differences in many aspects of their internal design and their operation without adversely impacting other systems. To take advantage of this intrinsic characteristic during both the TDP R&D and the project construction phase, the GDE proposed a ‘plug-compatibility’ policy [11] that promotes component and process innovation and development. Since ILC SRF technology is expected to find application well beyond the project itself, this flexibility provides incentive for institutional and industrial partners to leverage their investment in ILC toward future projects.

PROCESS SPECIFICATION

Technical performance criteria that were set for SRF cavities at the outset of the TDP have been met [12]. Associated fabrication protocols and surface processing recipes have been standardized to the required level, codified, released and shared among institutional and industrial partners. This has been done in each of the three ILC regions. DESY, with the greatest practical experience with ILC-type cavities, is the lead partner in launching this process. The DESY-hosted European XFEL project, with roughly 1/15 the number of SRF components, has shared their industrialization and production strategies with the ILC team and this has proved enormously helpful.

As of late 2012, five companies (two in Europe, two in Asia and one in America) had successfully followed ILC process guidance and fabricated cavities with performance as required for ILC. A restricted build-to-print scheme was adopted wherein some fabrication aspects were allowed to vary according to the plug-compatibility policy. The surface processing final stage in cavity construction, typically done at institutions, is shown in figure 1. In all cases acceptance testing was carried out by laboratory-based institutional partners. The build-to-print scheme includes minimum acceptance criteria such as vacuum leak testing, room-temperature RF tuning, high-pressure test, etc., but does not include the final accelerating gradient performance guarantee.

In-kind schemes involving multiple contributors of a given component require parallel development of laboratory and industrial infrastructure. As this is a critical part of technology transfer and can take several years it is important to start the process during the R&D phase before the project construction process begins. [13], [14]. Accessible institutional infrastructure thereby serves to validate quality of industrial contributor’s efforts.

Potential industrial partners were called upon to participate in TDP R&D by 1) producing cavities for demonstration tests, 2) developing and proving their capabilities in order to allow a well-balanced set of in-kind contributors and 3) modeling various aspects of the construction project as part of the ILC value estimate effort.

PRODUCTION OF SUPERCONDUCTING RF TECHNOLOGY

Production Process

ILC SRF linac construction has three basic industrial steps: 1) niobium refining and semi-finished product manufacturing, 2) cavity forming, welding and surface processing, and 3) final cryomodule assembly. Testing is done following each of the three steps. ILC SRF industrialization efforts have focused on step 2), the basic 9-cell cavity fabrication and surface processing, as this was justified by the cavity value estimate cost-fraction of the total project. Table 2 shows cavity parameters. The most serious challenge of this technology, characteristic of high-tech in general, is that direct performance tests are not at all possible until the cavity fabrication and processing is completed.

Table 2: ILC Superconducting Cavity parameters

Parameter	Value
Fundamental	1.300 GHz
Average accelerating gradient	31.5 MV/m (±20%)
Quality factor	≥ 1 x 10 10
Active length	1.038 m
Total length	1.247 m
Numbers of cells	9
Cell construction	2.6 mm thick Niobium sheet metal
Niobium material	RRR > 300
Weight	35 kg

Mass production for each of the three steps involves substantial investment in infrastructure and substantial touch-labor. With an emerging technology such as SRF it is reasonable to expect innovation from better understanding of both the basics and improved tooling.

Industrial Studies for TESLA

The ILC design is the result of more than twenty years of R&D, including over a decade of pioneering work by the TESLA collaboration in the 1990s [15]. Their original goal was to reduce costs by increasing the operating accelerating gradient by a factor of five from 5 MV/m to 25 MV/m, and reducing the cost per meter of a complete accelerating module by a factor of four for large-scale production. In order to get a comprehensive overview and gauge progress the TESLA collaboration commissioned industrial mass-production studies from European industry assuming a single full-production strict build-to-print plant model [16]. The TESLA collaboration performed the first cost estimate for the production of 1.3GHz SRF that was broadly based on industrial mass-production techniques.

This groundbreaking study is taken as a starting point to analyze the scale of the technology and build a single-production-facility model. A single concentrated co-location of specialized equipment was believed to be the most economic approach to the project and would allow the greatest 'economy of scale'. In this arrangement the cost model 'unit-cost' depends explicitly on the number of items produced. This can be parameterized for purposes of comparison using the 'learning curve' formalism. It was assumed the plant would be purpose-built for ILC and would not lead to a viable commercial entity based on SRF after the completion of the project. A similar scheme was adapted for the fabrication of the LHC main ring superconducting dipoles and the plants used to build them are no longer outfitted for magnet production.

The ILC cost estimate retains this basic scheme with one critical difference: at least two vendors are assumed for all industrial procurements for which the cost model has an explicit dependence on the number of items. This potentially more costly scheme was chosen for two reasons. First, it is believed that two independent vendors provide a kind of security against one of them failing. Second, it is believed that multiple vendor parallel development is a necessary ingredient for a project scheme based on in-kind contribution and this is in fact enabled through the modularity of the technology. The latter point is quite important to explain to potential industrial partners as it makes clear the project expects their active engagement; i.e. they are not simply 'job-shops'. An avowedly single vendor model, although superficially more economical, would provide little reassurance to potential partners that their input would be seriously included.

Industrial Studies for ILC

Industrial studies for ILC were more broadly based than those done for TESLA and included 1) vendor visits, 2) component development contracts, 3) satellite meetings at major conferences and, 4) industrial production study contracts. Roughly 15 companies in the three regions received one-day visits on two occasions. The first such visit, near the start of the TDP, was to explain the ILC project preparation scheme and second, two years later near the end of the TDP, was to gauge their progress adapting the technology and to explain global progress in understanding basics and developing fundamental tools. It was considered important to make sure that each visited party received an equivalent presentation. Also, as it was not possible to meet with each interested party worldwide, each visit sequence was announced and the associated presentations were posted through the GDE website [15].

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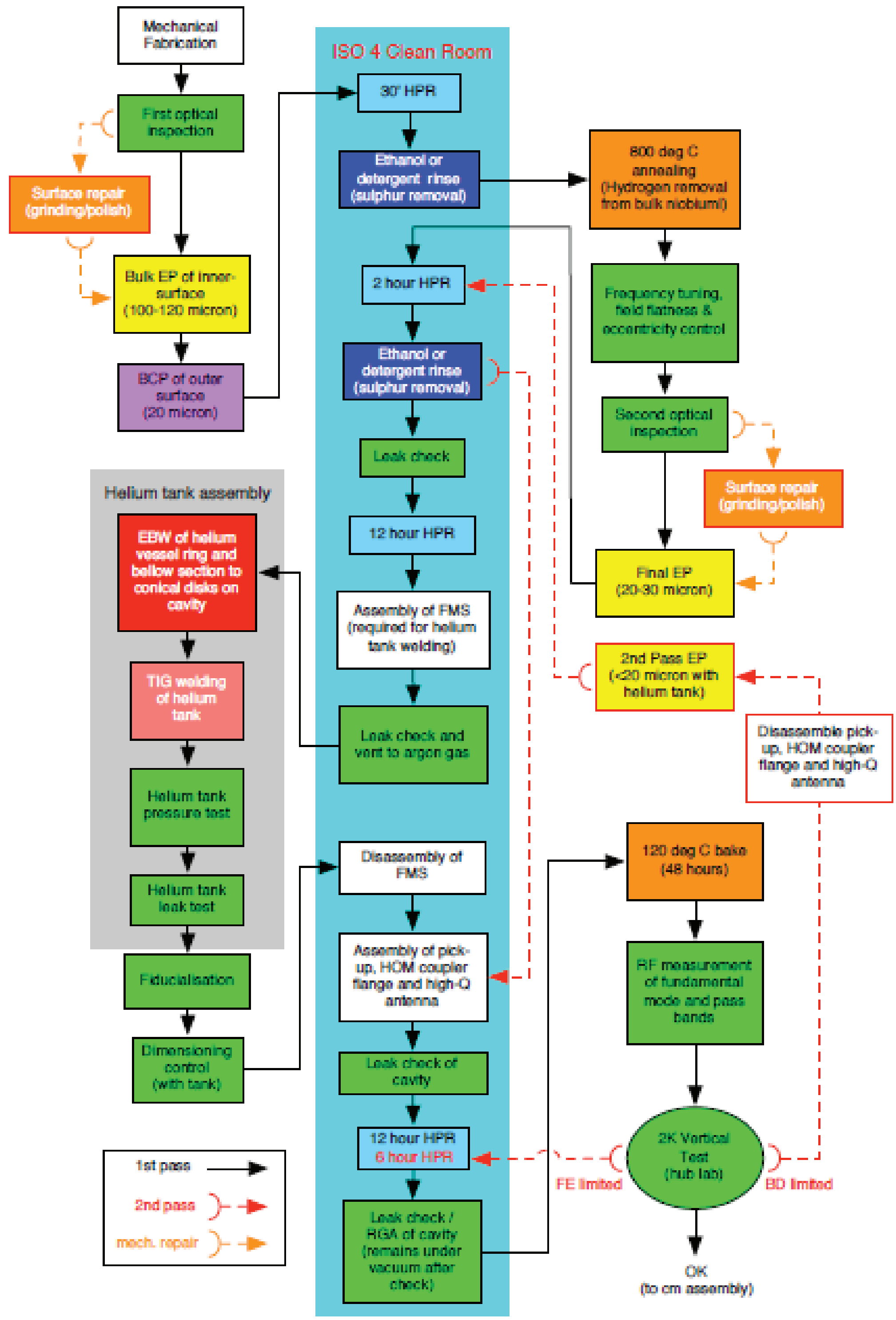

Figure 1: Cavity Processing and testing steps as adopted for the European XFEL [18].

In addition to the visits the GDE arranged two day-long workshops held as satellite meetings in conjunction with major conferences. The satellite meeting agenda included GDE, institutional partner and industrial reports in addition to retrospective reports from other similar-size projects such as LHC and ITER [19]. The workshops served the critical function of providing a discussion forum to explain and illustrate the direction to be taken in preparing and carrying out the ILC project.

As part of the second series of visits each interested party was requested to provide information and make cost comparisons between construction models with 20%, 50% or 100% of full-scale production in either a 3 or 6 year schedule. (The difference in proposed project schedule with respect to the expected five year full production allows a direct comparison with the earlier TESLA studies). Companies were also asked to comment on questions such as preferred factory site location,

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responsibility sharing for the cost-effective production and 'build-to-print' fabrication deliverable definition. Near the end of the TDP several companies were commissioned to provide more in-depth construction models, typically 50 and 100% with a 3 year production schedule.

SUMMARY

Industrial and institutional GDE partners advised a strong industrialization program for ILC from the outset of the TDP. A key ingredient was the development, within the GDE, of a project governance and Value cost-estimating strategy that was well-balanced regionally and took advantage of the intrinsic modularity and relative maturity of the SRF technology. The most costly and time-consuming part of the process is the construction and commissioning of heavy infrastructure, notably institutional test facilities. Long lead time high-power high-tech industrial equipment such as vacuum smelting furnaces and electron-beam welders are also critically important. In contrast securing the involvement with industry is not costly and is well worth the time and travel expense. A well-supported and realistic cost-estimate is the output of this process, so far, and promises to be a strong point in the project proposal going forward.

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