PROGRESS TOWARDS THE INTERNATIONAL LINEAR COLLIDER

N. Walker, DESY, Hamburg, Germany.
M. Ross#, Fermilab, Batavia, IL 60510, U.S.A
A. Yamamoto, KEK, Tsukuba, Japan
For the ILC Global Design Effort.

Abstract

With a now extended plan to 2012, the ILC Global Design Effort Technical Design Phase focuses on key R&D to verify performance goals and to reduce both technical risk and cost. This paper will review the progress during the last two years, and plans for the future.

INTRODUCTION

With the publication by of the ILC Reference Design Report in 2007 [1], the GDE achieved its most important and significant milestone to-date. The consolidation and re-structuring that followed – aimed at producing an "Engineering Design Report" in 2010, needed to be re-evaluated at the beginning of 2008 due to the reduction of available resources in the U.S. and U.K, resulting in an extended two-year plan (the Technical Design Phase, TDP). Notwithstanding these unfortunate events, the GDE TD Phase Project Management remains focused on delivering a design report in 2012 suitable for submission for approval to the world funding agencies. A shift in emphasis to risk-mitigating R&D – focused on the superconducting RF technology (SCRF) and existing Test Beam Facilities has lead to a comprehensive R&D Plan over the next years. In this report, The Technical Design Phase Project Managers will give an overview of plans and progress on the main identified priority R&D items.

TECHNICAL DESIGN PHASE

The TDP project structure is divided into three separate "Technical Areas" reflecting the three identified RDR design cost-drivers: SCRF Main Linac technology; Conventional Facilities & Siting (CFS) and Global Systems; Accelerator Systems, which included the accelerator design of the more conventional accelerator systems (sources, damping rings, bunch compressors and beam delivery system). These three Technical Areas are each associated with one of the three GDE project managers, and are themselves subdivided into several Technical Area Groups. Table 1 shows the current project structure.

PRIMARY GOALS FOR THE TECHNICAL DESIGN PHASE

At the conclusion of the Technical Design Phase in 2012, the GDE intends to produce documents which should be sufficient to support a proposal to the world funding agencies for the ILC as a global project. It is expected that the TDR will consist of documents which specifically address the following four deliverables:

Table 1: ILC Technical Design Phase Project Structure, indicating the three Technical Areas, divided into fifteen Technical Area Groups.

GDE Director (Barish)		
SCRF Main Linac Tech (Yamamoto)	**CFS & Global Systems** (Ross)	**Accelerator Systems** (Walker)
Cavity Preparation	Civil Engineering & Services	Electron Source
Cavity Integration	Conventional Facilities Process Management	Positron Source
Cryomodules	Controls	Damping Rings
Cryogenics		Ring to Main Linac
HLRF		Beam Delivery System
Main Linac Integration		Simulations

- An updated and detailed technical design for the ILC, which will include modifications to the original RDR design based on the results of the on-going TDP activities.
- An associated and updated cost estimate.
- The results of all risk-mitigating R&D, in support of the design decisions reflected in the updated machine design and cost estimate.
- A Project Implementation Plan, which will outline a possible model for an international project, including governance, finance models, concepts of "in-kind" contributions, mass-production models *etc*.

Given the expected global resources and the current focus on R&D, the GDE does not expect to produce a fully-engineered solution for the ILC. Part of the TDR documentation, therefore, will be to quantify the scope of the remaining engineering and R&D that needs to be done before project construction – but not necessarily before project approval.

TECHNICAL DESIGN PHASE R&D PLAN

With an effective two-year extended programme and reduced resources, the GDE shifted the emphasis of the initial work to focus on priority risk mitigating R&D. The TDP Project Management has produced and published a TDP R&D Plan [2] which contains top-level milestones and deliverables, as well as a description of the scope of the priority activities and their justification. The document is reviewed and updated every six-months.

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The R&D Plan specifically outlines the technical priorities for TD Phase:

- Development of SCRF technology in all three regions: specifically a globally coordinated effort on achieving the required high-gradient yield in 1.3 GHz nine-cell niobium cavities; development of cost-effective cryomodule design; systems testing ("string tests").
- Support for accelerator Test Beam Facilities: specifically for work on electron-cloud mitigation (CesrTA at Cornell, DAΦNE at INFN, ATF at KEK); and final focus optics and instrumentation (ATF2 at KEK); SCRF linac "string test" at TTF2/FLASH at DESY.
- Accelerator design and integration studies aimed at cost-containment and/or reduction.

The priority R&D themes are based on an analysis of the RDR design, representing a consensus prioritisation of the remaining technical performance risks in that design. The emphasis is placed on the identified cost-drivers, namely SCRF technology and CFS. For the latter, a better analysis of the use of underground volume, water cooling and power requirements is expected to yield a more cost-effective design.

PROGRESS AND PLANS FOR THE SCRF MAIN LINAC TECHNOLOGY

An important but implicit goal of the GDE is to promote the establishment of SCRF infrastructure and expertise in all three regions (Americas, Asia and Europe). The GDE believes this is mandatory, as all three regions are expected to contribute to the construction of the main linacs, irrespective of where the machine will be built. In addition, the technology has wide applicability beyond ILC which makes it highly-attractive to national funding agencies.

Infrastructure for both manufacture and R&D has been constructed and is as of writing beginning to yield results. In the U.S.A, facilities primarily at FNAL in association with ANL, JLab, and SLAC are now beginning to construct full ILC-like cryomodules (primarily but not exclusively in support of Project-X [3]). In Europe, existing infrastructure at DESY, together with new production facilities at CEA Saclay and IN2P3 LAL, Orsay are being constructed and commissioned for production of ~100 cryomodules for the European XFEL [4]. In KEK, work on the Superconducting Test Facility (STF) continues [5]: the STF1 programme now complete, STF2 is now underway. In addition, plans to construct a mass-production R&D facilities at KEK together with industry is currently being discussed.

With the continued investment in the necessary infrastructure world-wide, the GDE priorities are still focused primarily on the identified risk-mitigating R&D:

High-Gradient Nine-Cell Cavities

The RDR design is based on an average operational accelerating gradient of 31.5 MV/m. As part of cavity production, cavities should achieve ≥35 MV/m in a single vertical low-power acceptance test. While several tens of cavities have achieved these (and higher) gradients, the *yield* still remains significantly below the 90% goal for ILC production.

The GDE has instigated a global R&D plan to address the gradient yield. The intermediate and final goals of the programme are:

- Demonstrate by the end of TD Phase 1 (2010) a *process yield* of 50% at 35 MV/m;
- Demonstrate by the end of TD Phase 2 (2012) a *production yield* of 90% at 35 MV/m.

The initial focus on "process yield" reflects the emphasis on surface preparation. Problems due to identified (and curable) mechanical defects or non-qualified vendors are excluded from the statistics. Yield in this sense is defined in terms of 'treatment cycles' rather than number of cavities. Production yield, by comparison, refers to individual cavity production (material preparation, fabrication, surface treatment), and is more in-line with the true mass-production definition.

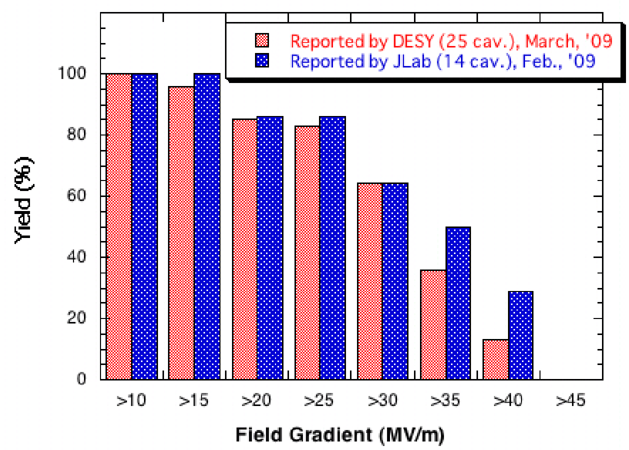

Figure 1: Recent status of global cavity yield (DESY 25 cavities [6], and JLab 14 cavities [7]). Datasets represent cavities from more than one vendor. Majority of results represent first vertical test (second test in a few cases).

In the last ~2 years there has been significant progress on the gradient yield [7], although due to the budget crisis in 2008 in the U.S.A., less cavities and testing was achieved as previously hoped. Specifically, the application of so-called "de-greasing" techniques after electro-polishing have significantly reduced gradient limitations due to field-emission (a primary identified limitation during the RDR phase) [7]. With the success of the de-greasing techniques, focus has now shifted to consolidating mechanical fabrication – in particular the electro-beam welding (EBW) of the cavity dumbbells. Novel high-resolution optical inspection techniques developed jointly by KEK and Kyoto University have revolutionised the analysis of the equator weld and 'heat-effected' zone [8]. Further development of the high-resolution camera is on-going, with a goal to establishing the technique as part of industrial production. In particular, ILC work at DESY (together with KEK and

Kyoto University) is aimed at developing the technology for the European XFEL mass-production [9].

Complimentary to the optical inspection techniques, extensive use of thermometry (thermal-mapping) and novel techniques such as "second-sound" [10] for localising quenches are being developed with a view to mass production.

An important element in the current plans is close cooperation with industrial fabricators in all three regions. The goal is to 'qualify' at least two industrial vendors in each region.

Figure 1 shows recent promising results from the latest cavity productions at both DESY and JLab, using cavities from the European companies Research Instruments[1] and ZANON. The majority of the data represent the results of the first vertical cold test, and as such are comparable to the current mass-production models. (In a few cases, the result of a second test are used.)

Cryomodule Development

The second identified R&D priority for the main linac technology is the production of an ILC-like cryomodule with an average accelerating gradient of 31.5 MV/m. A GDE-driven international collaboration, hosted by KEK, will attempt to construct a single cryomodule with eight high-gradient cavities supplied by KEK (4 cavities), DESY (2 cavities) and FNAL (2 cavities) [11]. The programme (designated S1-Global) is considered complimentary to regional-based activities to produce high-gradient cryomodules. The cavities from DESY, FNAL and KEK are of different design, and KEK's responsibility is to provide the mechanical integration into a single unit. This integration exercise in itself is important with respect to the concept of mechanical interface definition, which is the corner stone of the concept of mechanical "plug compatibility", an important part of the TD Phase design philosophy (see later). The S1-global programme is due to be complete by end of 2010.

String Test

Ultimately a full string test consisting of several cryomodules driven by an ILC-like beam is consider mandatory before final prototypes for mass-production are established. Plans are well underway for main linac beam test facilities at both FNAL and KEK. The TTF2/FLASH facility at DESY represents a currently unique facility in the world. Construction of the European XFEL (~100 cryomodules) also represents a major deployment of this technology which will provide significant relevant systems test information for ILC.

Within the 2012 time-frame for the GDE Technical Design Phase, no one test facility will achieve simultaneously all the required (current) design parameters for the ILC:

- TTF2/FLASH – the most mature facility currently operating at ~1 GeV primarily as a VUV SASE user facility. This facility represents the primary focus of the TD Phase string test activities. A GDE-driven experiment to demonstrate reproducible 800 µs 9 mA beam-loading is planned for September 2009. Although this programme will demonstrate many of the critical design features (low-level RF beam control, required RF overhead, HOM heating *etc*.), it will do so at lower average gradients (~25 MV/m) than the foreseen ILC gradient of 31.5 MV/m [12].
- At FNAL a test linac containing 1 RDR ILC-like RF units (three cryomodules in total) will be constructed in the recently converted New Muon Lab (NML) building. Although primarily driven by plans for Project-X, it is still currently planned to achieve the required ILC high-gradients for this linac. The currently foreseen electron gun will not provide the full 9mA ILC-specified beam, although this is under review. The current phase will see the RF unit installed by the end of 2012. The possibility of a second RF unit constructed by industry is currently under discussion.
- The current STF plans at KEK have a full ILC-like RDR RF unit (three cryomodules) constructed and installed by 2014/15. Within the TDP time-frame (end 2012) one of the three cryomodules is expected to have been installed and ready to run with beam.

The above foreseen facilities – although all relevant for ILC – are constrained by the desire to support national projects. Nonetheless, all existing and foreseen facilities acknowledge the relevance and support the need for ILC development. With respect to project approval, the GDE believes that there will be enough relevant results from these facilities (particularly TTF2/FLASH), that extrapolation to ILC specifications is possible with a reasonable and minimum remaining risk at the end of 2012.

Towards Industrialisation and Mass-Production

An important and critical aspect of the on-going R&D is to prepare for cost-effective mass-production in all three regions. Cost-reduction via innovative design and mass-production techniques is a mandatory pre-requisite for the ILC as an affordable international project.

At the current stage, it is important to allow the flexibility necessary for innovative R&D in each of the regions, both to encourage the development of local expertise, and – via *competitive collaboration* – to help the local industrial base to become cost-effective (competitive) on the world-market. This flexibility must be counterbalanced by the need to rapidly transition to a construction project after 2012. With these apparently contradictory requirements in mind, the Project Management has developed the concept of "Plug Compatibility" for the current R&D phase [13]. The concept is to establish by international agreement a set of well-defined interface definitions for the various sub-systems of a cryomodule. These interface specifications will allow flexibility in design of the individual components, while guaranteeing that these components can be easily combined (or replaced) by alternative designs. The plug compatibility concept thus allows a focused cryomodule design and development which can be regionally based, and supports future R&D developments in a seamless fashion. The development of the interface specifications is a top-level TD Phase 1 deliverable, and development of the final specifications is well-underway. The S1-global cryomodule programme at KEK (see above) is an important practical exercise in this respect.

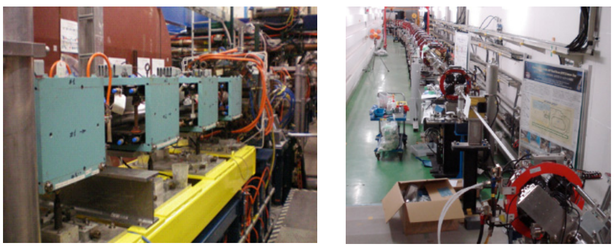

Figure 2: Examples of Beam Test Facilities. Left: the PEP-II chicane installed in CesrTA at Cornell. Right: the newly installed ATF2 facility at KEK

(NON-SCRF) TEST BEAM FACILITIES

The RDR design has identified other technical areas, which, while not primary cost-drivers, are of relatively high *performance* risk. The associated risk-mitigating R&D for these areas is focused on the Beam Test Facilities. The highest-priority Damping Ring R&D is covered at the following facilities:

- The R&D for electron cloud suppression for the positron damping ring is primarily focused at the dedicated CesrTA facility at Cornell [14], with support from SLAC and KEK. Additional R&D is supplied by DAΦNE (INFN), ATF (KEK) as well as the B-Factories (SLAC, KEK).
- Demonstration and subsequent stabilisation of the required low vertical emittance (2 pm) tuning is being addressed specifically at the ATF in KEK.
- Beam tests for the fast kicker development for the damping ring injection and extraction is being addressed at ATF (KEK) and DAΦNE (INFN).

For the Beam Delivery System, the focus is on the dedicated ATF2 facility, currently being commissioned at KEK [15]. The ATF2 is an example of an international collaboration, based on "in-kind" contributions and a governance structure not unlike that currently being considered for ILC. The primary goals of ATF2 are:

- Demonstration of the required final-focus demagnification using the ILC-like compact optics, including the development of sophisticated beam-based tuning algorithms.
- Demonstration of beam stabilisation at the required component vibration levels.
- A test-bed Prototype Final Doublet magnet technologies.

Due to the beam quality and parameters, the ATF2 also offers a unique facility for testing instrumentation, including laser-based beam size monitors, high-precision BPMs and fast intra-train feedback systems.

ACCELERATOR DESIGN & INTEGRATION ACTIVITIES

An important component of the TD Phase R&D Plan is the re-evaluation of the RDR design with a view to simplification and – where appropriate – cost reduction. While currently in an R&D focused phase, the Project Management remains aware of the primary TDR deliverables already described above: namely an updated design for the ILC an associated updated cost-estimate.

A fundamental premise of the TD Phase cost-driven design activities is that – while the RDR design is "sound" and represents a machine we can build – it is a conservative design. With the addition of two-years to the GDE plan, it is considered prudent to critical review the RDR design with a view to producing a more cost-driven design (the RDR design is generally considered to be *performance-driven*). A critical review and consolidation of the design with cost as the primary factor will i) further establish the defensibility of the design and its cost estimate, ii) provide for up-front design-driven cost savings which will allow for potential future increases in unit (i.e. component) costs.

With the CFS – and in particular the underground volume – being the primary cost-driver, a review of the CFS requirements and in particular alternative machine layouts and solutions was considered prudent. The initial part of this process began in June 2008 at the JINR Dubna GDE workshop, and concluded at the end of the 2008 with an agreed set of 'design strategies' which could potentially lead to cost-savings at the level of 10-15% TPC, albeit at the potential of some additional risk [16]:

- Removal of the service tunnel (single linac tunnel scheme). See "Alternative High-Level RF Solutions" below.
- Reducing the beam power by (for example) a factor of two, by reducing the number of bunches in the pulse by the same factor. This would allow a reduction in the number of klystrons and the use of a 3.2 km damping ring (together with a reduction in the associated conventional facilities). The luminosity can in principle be regained by squeezing the beam parameters at the interaction point.
- Further underground housing integration: a general approach to "tunnel sharing" for sub-systems current in separate housings in the RDR design. Specifically making use of the central region injector complex, placing both the positron and electron sources in the same tunnel as Beam Delivery System. Such a scheme, if feasible, could save several kilometres of additional tunnel.

Other modifications (such as the adoption of a single-stage bunch compressor, and more general "value engineering" activities for the conventional facilities) are also being considered.

Alternative High-Level RF (HLRF) Solutions

As part of the studies aimed at removing the linac service tunnel, two novel proposals for the HLRF have been made.

The "Klystron Cluster" scheme has been proposed by SLAC [17]. The modulators/klystrons are removed from the underground volume by placing them in localised surface buildings ("clusters"). Each surface building would contain two groups of ~30 klystrons, feeding RF power into ±1 km of linac. The power from the 30 klystrons will be combined into a single over-moded waveguide which will transport the ~300 MW of power into the linac tunnel, where the power will be tapped-off to drive individual RDR-like RF units (three cryomodules). The primary foreseen R&D will address the power-handing capabilities of the RF components. Additional considerations of RF control and feedback etc. are also required. In addition to supporting a single underground tunnel, the approach is made further attractive by the (surface) localisation of processed cooling water.

An alternative has been proposed by KEK [18] where the 10MW klystrons are replaced by 13 smaller ~700 kW klystrons, each one directly driving two cavities. The so-called Distributed RF Source (DRFS) concept is predicated to have several advantages in reliability and conventional facilities requirements over the reference RDR design. This solution may also prove more attractive to certain possible sites where the surface buildings associated with the klystron cluster scheme are not easily achievable.

Both schemes are considered applicable to a single-tunnel solution. The GDE will support both R&D activities over the remainder of the TD Phase.

SUMMARY

The now restructured GDE plans for the Technical Design Phase (ending in 2012) are now complete and are underway. Despite the unfortunate reduction in U.S. and U.K. resources in 2008, significant world-wide progress has still been made. Development of consolidation of SCRF expertise in all three regions (including industry) remains the highest priority. Global collaboration on achieving the required high-gradient yield has shown significant and promising progress. The concepts of "plug-compatibility" for the cryomodule design is now well-established, and work on cost-effective mass-production is beginning.

Risk-mitigating R&D is directly supported by Beam Test Facilities in the U.S. (CesrTA in Cornell), Europe (TTF2/FLASH at DESY, DAϕNE at INFN) and Asia (ATF, ATF2 at KEK).

With a view to the ultimate TDP deliverables, design and integration work continues with an emphasis on reduction of the underground volume and a cost-driven review of the CFS requirements. Two novel HLRF approaches have been identified as promising alternatives in support of a single-tunnel configuration for the main linac. These (and other design studies) will continue through the TDP. A review of the RDR design resulting in a baseline update for subsequent costing is planned for the beginning of 2010.

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