ILC Research and Development Plan for the Technical Design Phase

Release 5

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ILC Global Design Effort

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Contents

1 Preamble

The current five-year ILC R&D program was initiated in 2007 after the technology choice to adopt superconducting radio frequency (SRF) cavities as the accelerating technology for the main linac and the subsequent Reference Design Report. The R&D program has the basic goals of project risk reduction and technology development, and at the mid-point of this program the results to date have been very encouraging.

One of the major technical aims is the demonstration of reproducible high-gradient (35 MV/m) SRF cavities. The gradient is an ambitious goal and in order to accomplish this a program of detailed fundamental understanding of physics involved in this technology was necessary. The results to date are very promising and it would appear that the end of the program will demonstrate the required production reproducibility with this design gradient in 2012. The R&D program will process in excess of 100 cavities during the 5-year program. The next step in the program involves using these high-gradient cavities to fabricate complete cryomodules in both the US and Japan. (The European programme is strongly linked to the construction of the European XFEL.) Other components of this system developed by the R&D program include a novel, tuneable high-power RF delivery system, and associated low-level RF controls. A next generation solid-state modulator is also presently under testing.

During the ILC reference design phase electron cloud issues were identified as the major technical risk to the design luminosity. On this basis a multi-year study was launched at the recently decommissioned CESR accelerator at Cornell. Using the well understood machine characteristics and highly-flexible operating parameters of this facility, the R&D program will soon conclude the definitive study of the physics of high intensity, positively charged beams. Many future projects will benefit from this work. The Accelerator Test Facilities (ATF, and ATF-2) at KEK have been successfully constructed and commissioned in preparation for the demonstrations needed to ensure stable collisions of very small beams. The FLASH FEL facility at DESY has recently successfully accelerated an ILC-like electron beam through a high-gradient cryomodule.

Other R&D which focus on specific critical components (for example: polarised electron source; undulator, target and capture device for the positron source; fast kicker systems for the damping rings; high-powered beam dumps for the BDS), have also made significant progress, and are for the most part on-going in TD Phase 2.

Design work aimed at cost-reduction / cost-containment – which is primarily focused on Conventional Facilities and Siting (CFS) – has significantly converged in TD Phase 1 with a proposal for a more cost-effective baseline configuration. This proposal will form the basis for future design work (and cost estimation) through to the completion of TD Phase 2.

The complete results of the ILC R&D program will be manifest in the production of the Technical Design Report (TDR) and associated cost estimate at the end of the R&D program in 2012. Since the original linear collider concept in 2007 the new machine baseline has seen several technical improvements which both minimise costs and improve the machine performance. The R&D program will provide the basis for a post-2012 strategy which emphasises systems tests, core technology and the feasibility of a linear collider as a global project.

2 Purpose of this Document

This document represents the 5th release of the R&D Plan for the GDE Technical Design Phase. The first release was in June 2008, and outlined the scope and top-level goals for the Technical Design Phase 1 and Phase 2. Release 2 through 4 followed at roughly six-month intervals. Release 5 comes at the midway point of the GDE's plans, and the end of TD Phase 1; as such it represents a review and re-structuring of the plans for TD Phase 2, which focus on consolidating the on-going R&D programmes and producing the Technical Design Report at the end of 2012.

The report is divided into 8 sections:

Section 1	**Preamble**
Section 2	**Purpose of this Document**: this section.
Section 3	**Overview of Technical Design Phase 2**: top-level management goals and milestones for the Technical Design Report.
Section 4	**SCRF RF Technology**: a comprehensive description of all aspects of the global development associated with the SCRF linac technology, including: high-gradient cavity R&D (yield); cryomodule design; development of beam test facilities and infrastructure; issues pertaining to mass-production and costs for ILC.
Section 5	**Accelerator Systems R&D**: primarily covers all other ILC-specific non-SCRF related R&D. Focus is on Beam Test Facilities (BTF: CesrTA, ATF2) and their associated risk-mitigating R&D programmes. Additional priority R&D not related to the BTFs is also included.
Section 6	**Accelerator Design & Integration (AD&I)**: Essentially covers evolving design goals for producing a robust cost-effective baseline for the ILC, upon which the updated VALUE estimate will be based (two key TDR deliverables). This section also includes the Conventional Facilities and Siting (CFS).
Section 7	**Cost & Schedule**: briefly outlines the challenges and strategy in producing an updated global VALUE estimate and construction schedule for the TDR.
Section 8	**Risk**: briefly outlines plans to develop a robust methodology for technical risk assessment for the TDR, and plans for its implementation.

Two appendices are structured as follows:

Appendix A:	Summarises the estimated global resources available for the Technical Design Phase 2 (2010-2012).
Appendix B:	Comprehensive list of participating institutes for TD Phase 2.

3 Overview of Technical Design Phase 2

The Technical Design (TD) Phase of the ILC Global Design Effort will produce a technical design of the ILC in sufficient detail that project approval from all involved governments can be sought. The TD phase will culminate with the publication of a Technical Design Report (TDR) at the end of 2012. The key elements of the TDR will be:

- An updated technical description of the ILC Technical Design in sufficient detail to justify the associated VALUE estimate.
- Results from critical R&D programmes and test facilities, which either demonstrate or support the choice of key parameters in the machine design.
- One or more models for a Project Implementation Plan, including scenarios for globally distributed mass-production of high-technology components as "in-kind" contributions.
- An updated and robust VALUE estimate and construction schedule consistent with the scope of the machine and the proposed Project Implementation Plan.

The report will also indicate the scope and associated risk of the remaining engineering work that must be done before project construction can begin.

Table 3-1: TD Phase Technical Areas

	Technical Area		
	1. Superconducting RF Technology	2. Conventional Facilities & Siting and Global Systems	3. Accelerator Systems
Technical Area Groups	1.1 Cavity	2.1 Civil Engineering and Services	3.1 Electron Source
	1.2 Cavity-Integration	2.2 Conventional Facilities Process Management	3.2 Positron Source
	1.3 Cryomodules	2.3 Controls	3.3 Damping Ring
	1.4 Cryogenics		3.4 Ring To Main Linac
	1.5 High Level RF		3.5 Beam Delivery Systems
	1.6 Main Linac Integration		3.6 Simulations

The TD project structure remains unchanged for Phase 2. The Project Management team leads and coordinates the international effort in the three regions (Americas, Asia, and Europe) needed to complete the TD Phase and deliver the TDR. The Project Management structure is summarised in Table 3-1. The project is divided into three Technical Areas subdivided into Technical Area Groups (TAG). Each Technical Area has an associated Project Manager. The fifteen TAG listed in Table 3-1 are each coordinated by a TAG leader, who reports to the respective Project Manager.

TD Phase 1 activities placed emphasis on high-priority risk-mitigating R&D – most notably the Superconducting RF linac technology – and quantifying the scope for potential cost reduction of the current Reference Design (Accelerator Design and Integration, or AD&I, activities)

A concise interim report will summarise the status of the critical R&D in TD Phase 1 (expected to be published at the end of 2010).

TD Phase 2 (2010-2012) will further consolidate the R&D, and finalise the updated baseline reference design on which the cost and design work for the TDR will be based. An additional critical component of TD Phase 2 will be the development of the Project Implementation Plan.

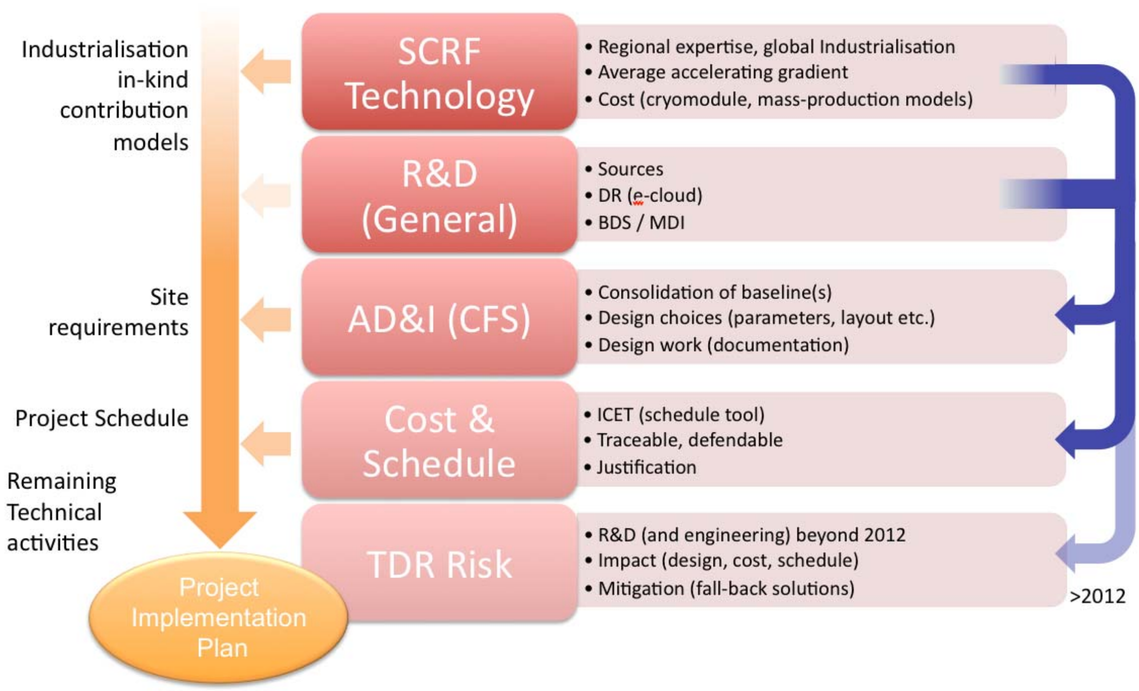

Figure 3.1: TD Phase 2 technical themes (scope of the Technical Design Report).

Figure 3.1 shows the five technical themes that reflect the scope of the Technical Design Report. How these five themes input into the Project Implementation Plan (PIP) is also indicated. It is these five technical themes (together with the PIP) than need to be successfully developed and brought to conclusion over the next two-years. The planning for these goals is the subject of this (updated) report.

4 Superconducting RF Technology

Superconducting RF (SCRF) Technology R&D is the primary global ILC technical activity during the Technical Design Phase. Underpinning the overall strategy of the R&D plan for the SCRF is the desire to produce the best possible cost-optimised solution for the Main Linac, consistent with the technology state-of-the-art. The 2007 Reference Design parameter choices for the accelerating gradient represented forward-looking goals which were felt could be demonstrated during the Technical Design Phase. Excellent progress has been made in TD Phase 1 towards these goals, and they remain fundamentally unchanged in TD Phase 2. TD Phase 2 also sees a shift in emphasis towards development of industrial mass-production models in support of the updated VALUE estimate, for which several parameters still require either specification or review, as part of an overall exercise is cost optimisation.

With Release 5 of the R&D Plan, several key changes to the Reference Design baseline (2007 RDR) are under consideration. These are intended to allow:

1. cost containment or cost reduction
2. development of a project plan for industrialisation of SCRF components and
3. adoption of different kinds of site topography.

Each of the above is an important strategic element for the GDE.

The most important baseline changes under study are:

- Accepting a *spread* of low-power test cavity gradients during production, and a subsequent spread in cryomodule operational cavity gradients, while maintaining the required average accelerating gradient.
    - The 2007 Reference Design baseline assumed that 80% of the manufactured cavities achieved a gradient ≥35 MV/m during the low-power vertical test, and that all cavities installed in the linacs operate at the same nominal gradient.
    - Supporting a distribution (spread) of accelerating gradients in the main linac is seen as cost effective as the choice of *average* accelerating gradient is the primary cost driver for the machine.
    - The benefit (cost effectiveness) of accepting cavity performance lower than 35 MV/m must be balanced against the need for high-performing cavities to maintain the average, and the increased cost and complexity of the RF power overhead, distribution system and LLRF controls, as well as the potential impact on operational gradient margin.
    - The specification of the cost-effective acceptable gradient spread is a TD Phase 2 deliverable.
- Specifying an *operational gradient margin* that would de-rate the effective gradient of an installed cryomodule in order to provide stable, controllable linac operation.
    - The 2007 Reference Designed assumed ~10% margin from vertical test (≥35 MV/m) to operational accelerating gradient (31.5 MV/m). This was intended to include some margin for cavity performance degradation during

cryomodule installation, and controls overhead for stable heavy beam-loaded operation. Both require review in TD Phase 2.

- Refining the definition of the *production yield* to allow a quantitative assessment of the cost-optimised accelerator gradient, ultimately supporting the adopted mass-production models and associated cost estimate.
- Redefining the baseline *RF unit* to reflect alternative HLRF schemes that may be better suited for a given site topography.
  - The 2007 Reference Design baseline RF unit (three cryomodules with 26 cavities and one focusing magnet-instrumentation package) remains a useful concept because it is half a linac FODO cell and because it is a manageable size for a beam test facility. In this section the term 'RDR RF unit' is refers to this subsystem.
- Allowing and promoting *plug compatibility* for key SCRF components within a cryomodule, potentially including the cryomodule itself.
  - This is a design, development and production concept that results in diverse technical approaches for these key components. A further development will be a consistent scheme for estimating the cost of a linac made from inter-changeable, plug-compatible components.

The primary R&D goals for SCRF include:

- **Cavity**: The primary R&D goal remains the demonstration of a field gradient of ≥35 MV/m at $Q_0 = 8\times10^9$ (operation at 31.5 MV/m at $Q_0 = 10^{10}$) with a production yield of ≥90%. (Designated as S0.) High-gradient R&D with single-cell and 9-cell cavities for R&D into: materials; mechanical forming; surface-preparation process; and vertical testing.
- **Cavity-integration**: Plug-compatible cavity-package design and integration including tuner, input-coupler, He-vessel and magnetic shield, and the cavity string test with an average field gradient of 31.5 MV/m in one cryomodule. Designated as S1 and S1-global program. In parallel to the on-going effort on field gradient improvement, studies will also be made during TD Phase 2 of the requirements for industrialisation and mass production technologies for a future construction project, as well as a basis for the TDR updated VALUE estimate.
- **Cryomodule**: Plug-compatible and thermally-optimised cryomodule design and integration for cost-effective fabrication and operation. The effect of microphonics during cryomodule operation will also be further studied.
- **SCRF-system with beam acceleration**: System integration and test of a string of cryomodules (more than one) with a suitable RF distribution system. Demonstration of an average accelerating gradient of 31.5 MV/m at $Q_0 = 10^{10}$ in the cryomodule operation with full beam-loading and beam acceleration. Designated as S2 program.
- **Cryogenics**: System-engineering to realise cost-effective construction and operation. Study the coordination required to satisfy high-pressure vessel code/regulation in each region.
- **High-Level RF**: Development of cost-effective modulator and power distribution systems capable of supporting a spread of cavity field gradients within a linac RF unit (average gradient operation). Specifically, the Klystron Cluster Scheme (KCS) and Distributed RF System (DRFS) solutions will be investigated as part of the on-going cost reduction studies, in support of a single Main Linac tunnel design.

- **Main Linac Integration**: Optimisation of layout and parameters of the Main Linac cryomodule string, including cavity, diagnostic, and quadrupole and alignment tolerances. Beam dynamics aspects including wakefield and HOM calculations.

The milestones for the TD Phase SCRF goals (notably the S0, S1 and S2 programs) are summarised in Table 4-1.

Table 4-1: Milestones for the SCRF R&D Programme

Stage	Subjects	Milestones to be achieved	Year
S0	9-cell cavity	35 MV/m, max., at $Q_0 \geq 8\times10^9$, with a production yield of 50% in TD PHASE 1, and 90% in TD PHASE 2 1), 2)	2010/ 2012
S1	Cavity-string	31.5 MV/m, on average, at $Q_0 \geq 10^{10}$, in one cryomodule, including a global effort	2010
S2	Cryomodule-string	31.5 MV/m, on average, with full-beam loading and acceleration	2012

1. The process yield of 50 % in TDP-1, in the R&D Plan (release 2), has been revised to be the production yield of 50 % in the TDP-1.
2. A quantitative evaluation of radiation emission is to be included in the milestone list in near future.

Table 4-2: Key cost-relevant ILC design parameters and their relationship to the R&D programmes. A review of the proposed specifications remains a TD Phase 2 deliverable.

Cost-relevant design parameter(s) for TDR	**Currently proposed specification**	**Relevant R&D programme**	***Comment***
Mass production distribution (models)		S0	*cost optimisation will require a model for the yield curves based on the S0 R&D results*
Average gradient	35 MV/m	S0	*primary cost driver*
Gradient spread	±20% (28-42 MV/m)	S0/S1/S2	*cost-optimisation and performance balance*
Average performance in a cryomodule (margin)	5% (33 MV/m average)	S1	*total of 10% specified in RDR, but distribution not given (assumed equally split here)*
Allowed operational gradient overhead for RF control (full beam-loading)	5% (31.5 MV/m average)	S2 (S1*)	
Required RF power overhead for control	10%	S2 (S1*)	

**) important input will also be gained from S1 programme*

While the R&D goals remain aggressive, the ILC baseline design parameters will be reviewed as part of the TD Phase 2 baseline assessment activities. These parameters – together with the cavity and cryomodule mass-production models adopted – will form the basis of the TDR cost estimate for the SCRF main linacs. The final choice of parameters for the TDR design (and cost) will be based on a critical review of the R&D results and an assessment of the perceived technical risk. Table 4-2 summarises the key ILC design parameters and their relationship to the R&D programmes described in the remainder of this section.

4.1 High-gradient cavity R&D

A tool for evaluating cavity performance statistics – the ILC cavity database – has been successfully implemented, and includes cavity test data from all presently participating labs (DESY, Fermilab, JLab, Cornell, and KEK) from the last few years. The current analysis has lead to two standardised yield plots, which comprehensively reflect the estimate of the production yield based on the available cavity data.

The implementation of the tool defines for the first time a common global basis for quantitative comparison of cavity processing and low-power vertical test performance. Through the definition of a common starting point, the cavity database provides a rough estimate of production yield, a critical deliverable of the Technical Design Phase. It includes cavity fabrication and processing information and test-result data from each of the participating labs. Key low-power test results are the maximum (limited) accelerating gradient, the intrinsic Q factor (Q_0) and the radiation emitted from the cavity. For emitted radiation, measurement techniques are not yet mature and no suitable calibrated monitor exists. This is an important goal for TD Phase 2.

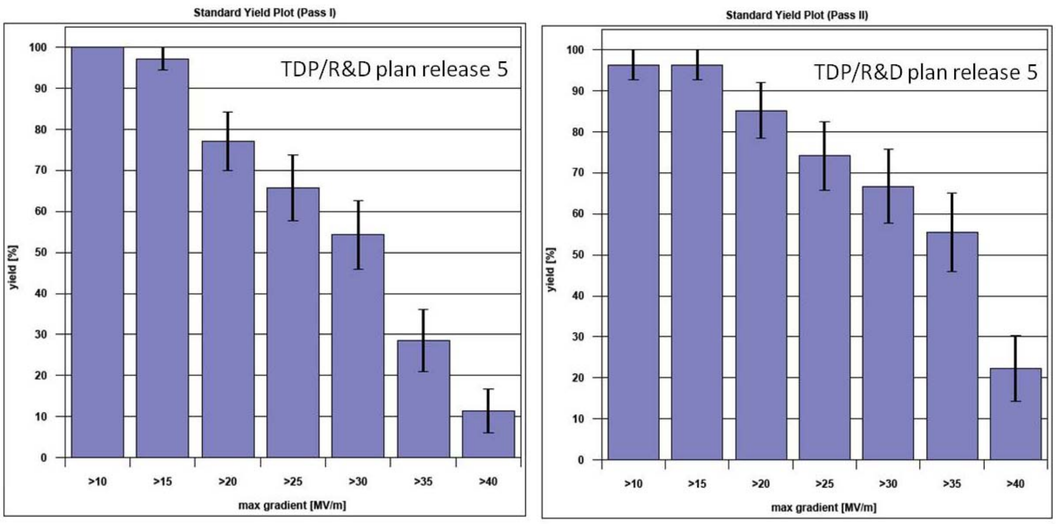

Figure 4.1: First-pass (left) and second-pass (right) yields as a function of maximum gradient. [updated data by June 30.]

To be included in the standard yield plots, cavities must be from established vendors (ACCEL/RI, ZANON, or AES 2nd batch or later, as of June 2010), and made from fine-grain material. The cavities must have undergone one standard electropolish etching (EP) process at either DESY or JLab for the 1st pass. If the cavity does not reach 35 MV/m, it is assumed to need a 2nd pass, the details of which may vary depending on the performance. If the cavity reaches 35 MV/m it is assumed not to need a 2nd pass. All cavities reaching the 35 MV/m gradient R&D goal also reached the Q_0 goal of 8×10^9, and no explicit Q_0 cuts are made on the data. Cavities in the 2nd pass plot are defined to be a subset of the 1st pass plot: if a cavity has not yet received a 2nd pass though it should, it is not included in the 2nd pass plot. Only cavity tests with cavity limitations (as opposed to test infrastructure limitations) are used. The cavity yield as a function of maximum gradient is shown in Figure 4.1, and the raw number of cavities as a function of maximum gradient is shown in Figure 4.2. The sample averages and standard deviations are shown as a function of the minimum accepted gradient in Figure 4.1. These data samples shall continue to be updated periodically as additional test data become available.

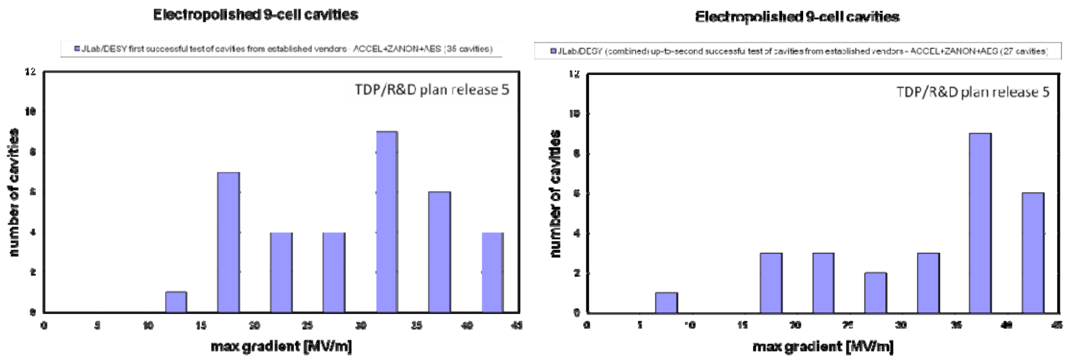

Figure 4.2: Number of cavities as a function of maximum gradient, for first-pass (left) and second-pass (right) data samples. [updated data by June 30.]

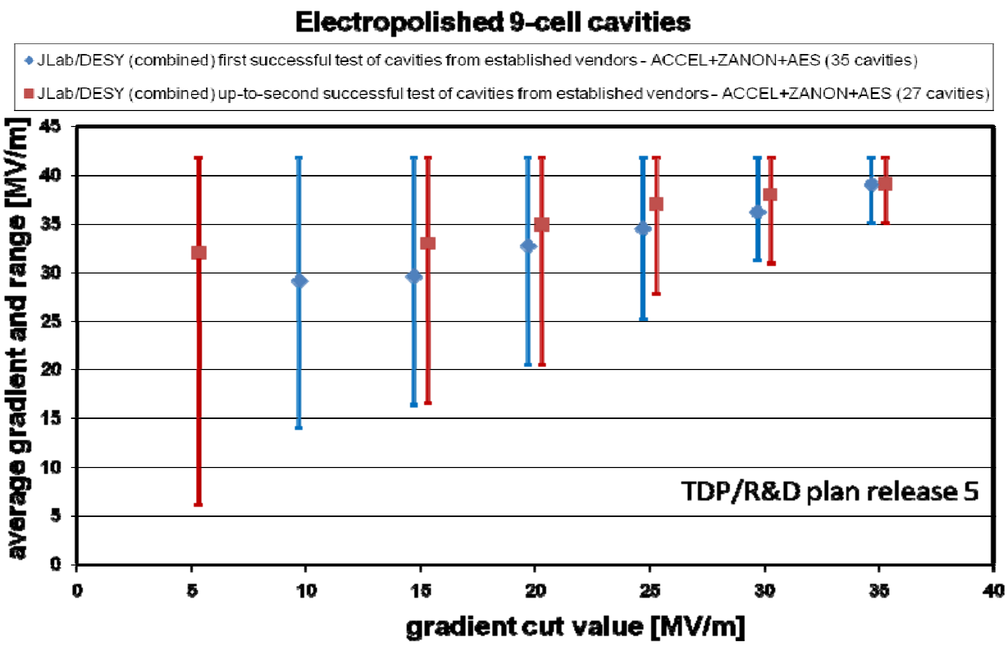

Figure 4.3: Average gradient (data points) and range (error bars) of the first-pass and second-pass data samples after excluding cavities which fail to meet the minimum gradient shown on the horizontal axis. The two data samples have been artificially offset from each other for clarity. [updated data by June 30.]

Figure 4.3 shows the 1st and 2nd pass 'average gradient yield' achieved if a spread in the gradient limit of individual cavities is supported operationally in the accelerator. The figure shows a 1st pass 25 MV/m production yield of (35-12)/35 = 66% and a 2nd pass yield of (27-4)/27=85%. The corresponding gradient in average (and range/spread) is 35 MV/m (b/w 25 – 42 MV/m) for 1st pass and 37 MV/m (b/w 27 – 42 MV/m) for 2nd pass. A finite operational gradient range/spread requires additional RF power overhead and sets additional requirements for both the high-level RF distribution system and the low-level RF controls performance. This will have a cost impact which remains to be determined. A reasonable operational cryomodule gradient range/spread might be within a level of ±20%

(corresponding to 31.5±7MV/m). The optimum allowable low-power test gradient limit spread will be specified by the end of 2010.

The key issues to address for the cavity performance evaluation are:

- Reduction in the horizontal bin size, if justified by the gradient measurement error.
- Cavity performance tracks/changes from vertical test to horizontal test to cryomodule test in current data samples.
- Cavity performance evaluation to be extended to 3rd pass process, if a sufficiently useful data set become available.
- Radiation emission to be added as further quantitative evaluation of the cavity performance.

The primary tasks planned for completion by September 2010[1] are:

- To create a standard plot tracking cavity performance for new vendors if there are new data available.
- To study Q_0 at the 31.5 MV/m operating gradient and Q_0 at the 35 MV/m vertical qualification gradient for data in the first- and second-pass data selections, for cavities which reach these gradients. This requires the adoption of a common algorithm to interpolate between measurements. As a later step, we will include this information in the ILC database.
- To evaluate annual progress of the maximum field gradient, at least for the first-pass evaluation, which can be widely and easily applied to cavity production in various projects (e.g. XFEL, Project-X) in a consistent fashion with the ILC R&D cavities.

The production yield plot will be a useful tool to track the cavity gradient progress, and will demonstrate manufacturing and industrialisation feasibility for the cavities. The current statistics of 35 cavities in the 1st pass and 27 cavities in the 2nd pass in the production yield is expected to be significantly improved by the end of TD Phase 2, based on the projected numbers of cavities procured from industries. More than 50 ILC type cavities in the Americas, and about 10 cavities in Asia are expected. The mass-production of ~660 cavities in Europe for the European XFEL (end of 2011 until early 2014) – about half of which will undergo the ILC-like process – will provide a very large statistical sample directly applicable to the 1st pass statistics without any bias. The ~330 EP cavities that will be used for the construction of the XFEL linac will only undergo one EP cycle (the acceptance criteria for XFEL is lower than ILC), but ~20 of the cavities (purchased via the ILC-HiGrade programme) will be available for a 2nd pass treatment and further R&D.

Table 3-2 summarise the projected numbers of cavities procured by the end of TD Phase 2.

[1] By the 1st Baseline Assessment Workshop – see section 6.1.1.

Table 3-2 Number of ILC-like (1.3 GHz) SCRF cavities manufactured, ordered and projected by the end of TD Phase 2.

		Before TDP	FY2008	FY2009	FY2010	Sum by Fy2010	TD PHASE -2 FY2011-2012
Americas		36	0	12	30+10	88	(TBD)
Asia	JP	15	3	13		31	~10 + (TBD)
	CN			1	1	2	
Europe (XFEL)		68	-		26* (640**)	94 (640)	(TBD)
Total		119	4	26	67	215 (+640)	~ 10 + (TBD)

*) High-gradient program (ILC-HiGrade),

**) number of order under discussion (for XFEL).

4.1.1 Superconducting cavity R&D to improve the gradient yield

The main effort of the ILC cavity gradient R&D is to improve gradient yield and reduce gradient scatter toward the TD Phase-2 goal of reaching 90% production yield.

Surface process and reduction of field emission

In R&D efforts on surface processing in the last several years, two post-EP rinsing methods, namely ethanol rinsing and ultrasonic cleaning with detergent, have been used in all major SRF facilities in all three regions, based on a recommendation given by the TTC collaboration[2]. The optimal detergent concentration has been found through trial cavity cleaning followed by cavity RF testing as well as sample cleaning studies. Alternative detergents are also found and are now in routine use. EP processing procedures and cavity handling and assembly procedures at various SRF facilities have been improved. Simplicity and repeatability in optimal 9-cell cavity EP processing have been demonstrated. Focused surface R&D has revealed that the key contaminants on the electropolished niobium surface are sulphur and niobium oxide granules. These efforts have resulted in a significant reduction of field emission in 9-cell cavities, a major success of the globally coordinated S0 program. A gradient yield of 50% at 35 MV/m with a $Q_0 \geq 8\times10^9$ has been realised for a second-pass processing.

The success of field emission reduction has allowed us to reveal remaining performance limitations due to quench limits. A fraction of 9-cell cavities turn out to be quench limited at a rather low gradient of 15-25 MV/m. This causes the gradient yield to drop to 65% at 25 MV/m for the first-pass processing (see Figure 4.1). A top priority of ILC gradient R&D for TD Phase 2, therefore, is to raise the gradient yield and reduce scatter by overcoming quench limits below 25 MV/m in 9-cell cavities.

Identifying defect to determine quench limit at lower gradient

Temperature mapping and optical RF surface inspection have been routinely used in all major labs since 2008 in association with RF testing of 9-cell cavities. These efforts

[2] H. Weise *et al.*, TTC Report 2008-2, 2008.

have provided new insights into the nature of the quench limit at 15-25 MV/m in 9-cell cavities. It is clearly shown that in most cases a local defect in only one cavity cell is the source of the quench limit. Other cavity cells when preferentially excited by pass-band modes show far superior capability equivalent to a gradient of 30-40 MV/m. Most defects responsible for quench limit around 20 MV/m are found to be sub-millimetre size geometrical defects, such as pits or bumps as revealed by optical inspection. Initial SEM studies of samples cut out from 9-cell cavities have shown complex 3D structure as well as foreign elements at quench locations. It is also fairly well established that re-processing for a second-pass electropolishing is not effective in raising the quench limit at 15-20 MV/m in 9-cell cavities. By comparison, local defect removal results in significant gradient improvement, as shown by recent successful experience with targeted grinding of 9-cell cavities. It has been even shown that it is possible to predict whether an initially observed feature will ultimately evolve into a gradient limiting defect in a 9-cell cavity. All the known facts about the quench limit between 15-20 MV/m in 9-cell cavities strongly imply that responsible defects have an origin from cavity fabrication and/or starting niobium material.

Gradient improvement with multiple surface process

An increasing number of 9-cell cavities quench limited above 30 MV/m have been also studied recently using T-mapping followed by optical inspection. In this case, no defect (down to the spatial resolution of the optical inspection tools) is observable at the quench location predicted by T-mapping. And a second-pass electropolishing is often effective in raising the quench limit up to 40 MV/m. This implies that re-electropolishing remains a viable method for raising gradient performance from 25-30 MV/m to above 35 MV/m. Repeatability and reliability of electropolishing process is necessary for reliable gradient improvement by using a second-pass electropolishing. (It is noted that sometimes the cavity gradient degradation occurs when a second-pass electropolishing is applied.)

The cavity gradient R&D during TD Phase 2 towards achieving a cavity yield of 90% at 35 MV/m will based on the three observations described above.

4.1.2 Fabrication QA/QC and fabrication improvement and optimisation

Fabrication QA/QC is expected to result in improved gradient yield. Production cavities for the XFEL project are unique opportunities in this direction, particularly in the context of cavity mass production. QA/QC tools such as optical inspection for production control should be improved and implemented. Despite that the gradient goal for XFEL is lower than that of ILC, overcoming the quench limit for 15-20 MV/m in the mass production context is a shared challenge. The European ILC-HiGrade cavities will be an integral portion of the XFEL cavity production and will be available for further surface treatment and additional R&D.

The established fabrication technology such as forming, machining and electron beam welding have room for improvement and optimisation. New vendors have particular motivation and opportunities to pursue. An industrial R&D pilot plant currently under construction at KEK is expected to play a unique role in this direction. Here, R&D cavities will be built in collaboration with industry, but in a purpose-built lab-based facility where expertise and facilities exist to allow inspection at intermediate stages during the fabrication.

The R&D cavities can also be sectioned (after RF tests) for microscopic studies of cut-out samples from the known defect locations.

Alternative fabrication technology such as hydroforming should be pursued. Such seamless cavity technologies eliminate/minimise weld preparation machining and electron beam welding and hence offers a potential for reduced cavity fabrication cost. Recent seamless cavity experience at DESY in collaboration with JLab has shown very good 9-cell cavity results.

4.1.3 Material improvement and optimisation

Improvement in the gradient yield is also expected from material improvement and optimisation. Niobium of different Tantalum concentration as well as different RRR should be pursued through single-cell cavity testing and basic material characterisation.

Large-grain niobium material directly sliced from ingots eliminates intermediate handling steps as compared to the standard sheet material. This alternative material offers opportunities for reduced defects introduced by rolling and forging steps. Excellent single-cell cavity results have been demonstrated in all three regions. The level of effort for 9-cell large-grain cavities will be maintained. Existing 9-cell large-grain cavities at DESY and JLab should be tested timely and new 9-cell large-grain cavities should be fabricated, in particular using the multi-wire slicing technique successfully demonstrated at KEK.

4.1.4 Post-fabrication improvement, optimisation and remediation

Post-fabrication improvement and optimisation are expected to provide expeditious improvement in the cavity gradient yield because this path offers improvement opportunities for cavities fabricated with the present standard fabrication technology and standard material.

Mechanical polishing prior to heavy EP eliminates weld irregularities. It reduces or may even eliminate the need of surface removal by heavy EP. A significant fraction of the near future 9-cell cavities could be mechanically polished prior to main electropolishing.

Post-fabrication heat treatment provides important material property improvements such as hydrogen removal and metallurgical recovery. There are presently three main recipes for cavity heat treatment in a vacuum furnace. Optimal heat treatment parameters should be investigated with cavity testing as well as material characterisation.

Effort for cavity remediation such as targeted repair should be continued. This path not only offers the potential for a cost-effective solution for gradient recovery of under-performing 9-cell cavities but also provides knowledge about the nature of localised defects. Success of 9-cell tumbling repair at Cornell and the more recent success of 9-cell local grinding at KEK clearly show the value of cavity remediation. Success of single-cell cavity local re-melting with a laser beam and an electron beam at FNAL and JLab respectively should be extended to 9-cell cavities.

The proposed new ILC Main Linac baseline design will facilitate operation of individual cavities close to their limits with some spread in cavity performance. In order to maintain the required average acceleration, some cavities are assumed to operate at very high gradients (~38 MV/m). This increases the field emission risk for these high-performance cavities. Effort should continue for further suppression of field emission in 9-cell cavities. From the linac operation point of view, dark current is an important issue. Efforts should start to quantify field emission during cavity vertical test and correlate field emission in cavity vertical test with dark current in cavity/cavity string horizontal tests. Field emission measurement techniques need to be developed to allow direct comparison across SCRF facilities.

The Cavity basic R&D to improve gradient and to improve QA/QC in the period of TD Phase 2 is summarised in Table 4-3.

Table 4-3: Basic R&D effort to improve field gradient with the cost effective cavity fabrication in TD Phase 2 (Categorised).

Priority	Subjects	R&D themes	Actions planned
Highest	Fabrication	Forming/machining EBW, improve tools for QC in mass production.	Cost effective fabrication R&D with Pilot Plant (KEK) Destructible bare 9-cell cavities, (FNAL/JLAB/Cornell) Bare 9-cell cavities w/ in-house welder (JLAB) XFEL and ILC-HiGrade Project (DESY)
High.	Mechanical polishing prior to heavy EP	Eliminate weld irregularities, reduce surface removal by heavy EP.	Raw 9-cell mechanical polishing before chemistry (FNAL) 9-cell tumbling for cavity recover (Cornell)
Mid,	Large-grain and direct slicing	Eliminate rolling and contamination.	Large-grain cavities and multi-wire slicing (KEK), Processing and evaluation of existing 9-cell large grain cavities,
High	Seamless cavity	Eliminate/minimise weld preparation, machining and EBW.	Hydroform and test multi-cell cavities, (DESY-JLab, KEK) Hydroform and test multi-cell cavities (FNAL/Industry)
Mid.	Material improvement	Nb with low Ta concentration.	Material characterisation and 1-cell cavity testing (FNAL) Material characterisation and 1-cell testing (JLab)
High	Post vertical test local treatment	Rapid quench limit improvement with small incremental cost.	Local grinding (KEK) Local re-melting with laser beam (FNAL) Local treatment/re-melting with electron beam (JLab)
Highest	Field emission quantified	Additional information than unloaded quality factor.	Correlation of vertical test FE with horizontal test FE as well as dark current in linac beam operation, Comparison across facilities world-wide,

4.2 Cryomodule assembly and test

4.2.1 Cavity integration

"Cavity Integration" refers to R&D associated with the following cavity auxiliary sub-systems:

- Tuner including integration with Helium jacket
- RF input-couplers
- Cavity assembly with plug-compatibility
- Preparation for industrialisation

There are currently three kinds of tuner design: lever-arm tuner, blade tuner, and slide-jack tuner. The FLASH and XFEL cryomodules use the lever-arm tuner, with which there is a lot of experience and performance demonstration around 35MV/m operation. It is installed into the inter-cavity beam pipe location, and the current design requires more length than ILC cavity design requirement. The blade tuner is designed to fit in the middle of the helium jacket, and has been designed for mechanical simplicity and cost reduction. The slide-jack tuner design has focused on achieving a stiff structure to reduce piezo stroke for long life and reducing risk of failure. Performance experience will be accumulated in FLASH and XFEL pre-series cryomodules for the lever-arm tuner, in the Project-X cryomodules for the blade tuner, and in STF phase 2 cryomodules for the slide-jack tuner. In 2010, the S1-Global cryomodule experiment at KEK-STF provides a good R&D opportunity to make a direct comparison of the three tuner designs in the same cryomodule and under the same conditions. During the S1-Global tests, frequency tuneablity including sensitivity, backlash, and stability, heat-load and maintainability will be tested and compared. For the piezo actuators, performance of Lorentz Force Detuning compensation will also be directly compared, together with frequency control sensitivity, and the ability to stabilise cavity frequency in response to repetitive linac pulsing.

The R&D for the high-power input-coupler will focus on achieving a compatible design between tuneability, ease of mechanical installation, and low heat load. The loaded-Q control for each cavity is essential for supporting a range of individual cavity gradients under varying beam-loading conditions. R&D on the ceramic windows will focus on achieving less stress due to thermal contraction, more stable brazing and a shorter RF processing time. In the S1-Global cryomodule, four TTF-III couplers and four KEK disk window couplers are operated and directly compared.

4.2.2 Cryomodule assembly (S1) and the global cryomodule test collaboration (S1-Global)

Studies intended to advance understanding of the cavity string assembly process and to improve cryomodule performance are underway in each of the three regions. Results reported in 2009 from DESY indicated that the prototype European XFEL prototype cryomodule 'PXFEL 1' achieved the ILC goal performance of 31.5 MV/m on average, with all cavities having $Q_0 \geq 10^{10}$. The cavities used in PXFEL 1 were fabricated and tested in Europe and the cryomodule was assembled and tested at DESY using a cold-mass fabricated in China.

The primary goal of the 'S1' activity is to demonstrate nominal cryomodule performance, including tests of integrated gradient, thermal heat load, mechanical alignment, operability with a high-power RF source and maintainability. A key issue is the ability for the cryomodule to retain, on a cavity-by-cavity basis, the gradient and Q_0 performance achieved in low power vertical test. This is one of the two main components that define *operational gradient margin*. A typical problem is the reduction of the onset-gradient for strong field emission, potentially due to contaminants introduced during the string assembly process. Development of radiation emission monitoring techniques is included in TD Phase 2 plans.

In addition to the above component performance characteristics, many linac systems operational studies can be made with a single cryomodule without beam and therefore can be considered part of the 'S1' program. The cryomodule string test program ('S2' – see Section 4.6) is the next step towards a complete understanding of linac performance, namely, a test of multiple cryomodules with beam. Whereas the generation of a beam with nominal current, energy gain, energy spread and stability is a paramount goal, indicating a good understanding of key aspects of linac operation, single cryomodule testing requires less testing infrastructure and is therefore more flexible and easier to accomplish. Many of the tests foreseen in the 'S1' and 'S2' programmes are quite similar.

The 'S1-Global' project is currently in progress, with an aim to demonstrate the ILC accelerating field gradient with an internationally constructed cryomodule (eight 9-cell cavities). It has been successfully assembled at KEK, and cold tests in progress during a period of June 2010 through December 2010 at KEK-STF. The cryomodule consists of the two half-length cryostats which house 4 cavities each. Table 4-4 indicates the configuration of cavities, tuners and high-power input couplers used.

Table 4-4: The S1-Global cryomodule configuration.

Cryostat	Cavities	Tuner	Coupler
A	4 × KEK	Slide-Jack (KEK)	KEK with double disk window
B	2 × DESY	Lever-Arm (Saclay)	TTF-III
	2 × FNAL	Blade (INFN)	TTF-III

One-half of the cryostat and cold mass has been developed in cooperation with INFN and KEK and another half has been provided entirely by KEK. From the assembly experience gained from these different components, the assembly processes and man-hours can be compared and reviewed. The data provide important input to the estimate of the assembly cost for the ILC cryomodule.

The experimental plan for the cryomodule is summarised in Table 4-5. The S1-Global programme will run until the end of December 2010, after which the STF phase-2 accelerator construction will begin (January 2011). It is therefore important to keep the S1-Global programme on schedule.

Table 4-5: R&D issues which are evaluated in S1-Global

Subject	Contents	Contributed by
Cool-down and cryogenic performance	Alignment and Frequency deviation Heat load	KEK, IHEP, DESY
Low-power RF	Tuner (motor and Piezo) test and frequency tuning Qt calibration HOM property Single pulse response to Piezo Tuner	KEK, FNAL, INFN
High-power RF Dynamic Heat Load	High gradient test with high-power RF	KEK, FNAL, DESY
LLRF Dynamic Heat Load	High gradient operation with high-power RF, control. and feedback	KEK, FNAL
Distributed RF	DRFS functioning with LLRF control/feedback	KEK, FNAL

4.2.3 Cavity-string test with the S1-Global cryomodule

As of writing, the cavity-string test is in progress at KEK with the institute participation summarised in Table 3.5. In the first stage of the RF test after the cool-down and cryogenic performance test, low-power RF test is carried out to check individual performance of each cavity and tuner. In the second stage after coupler conditioning during the cryogenics shut-down in the summer time, the cavity-string average gradient will be studied with high-power RF operation, followed by thermal load test as described below.

In the third stage before completing the S1-global cryomodule test, the high-level RF power source and distribution system is to be converted to the 'Distributed RF System' (DRFS) by using two compact klystrons locally placed just next to the cryomodule, to investigate technical feasibility of the DRFS system, also described below.

4.2.4 Thermal test of the S1-Global cryomodule

During the cold test of the S1-G cryomodule, scheduled for the remainder of 2010, thermal measurements of the static and dynamic heat loads will be made.

Heat load measurements

The dynamic heat load of three types of cavities at their maximum gradients will be measured. Heat load of each cavity in the detuned condition will also be measured at the same time. After the measurements of the individual cavities, the measurements of two sets of 4 cavities and then all 8 cavities at the average field gradient of 31.5 MV/m will be made.

Measurement of temperature profile in the two 6-m modules

Temperature profiles of the components will be measured and compared with thermal calculations.

Position deviation of cavities and Gas Return Pipe (GRP) during the cold test

Positions and deformations of the gas return pipes will be measured with 10 Wire Position Monitors (WPMs), 4 laser position sensors and 24 strain gauges.

Eight WPMs are assembled on the four KEK cavities, and the measured positions of cavities will be compared with the motion of the gas return pipe.

4.2.5 Distributed RF System (DRFS) test at S1-Global

For the RF power source in the third stage, S1-Global will use a prototype DRFS system. This system consists of the HV-DC power supply and the modulation anode power supply that are connected to the two modulated-anode klystrons (MAKs), together with a LLRF control system. Each klystron will be connected to two cavities in a half-cryomodule, so-called cryomodule A, consisting of 4 KEK cavities with a simple waveguide system eliminating the circulators.

4.3 Main Linac Cryomodule design

The goal of the cryomodule design effort is to develop a plug-compatible, thermally (and mechanically) optimised cryomodule. During TD Phase 1, cryomodule design adaptations (as required for the S1-Global programme, for example), were developed and tested and this is expected to be continued during TD Phase 2 and after completion of the TDR. Specific design improvements target reduction in material cost and operational heat-load and easing of the assembly process. The 'plug-compatibility' policy ensures that participating institutions and individuals can contribute effectively by making sure that their innovations fit within the internal, (between cavities and cavity assembly components), and external, (between cryomodules), interface definitions set by the GDE design team.

4.3.1 Thermal shield design

The proposed design of the ILC cryomodule in the RDR has two sets of thermal shields at 5 K and 70 K, the same as the TTF-Type-III and XFEL cryomodules. In previous GDE meetings, the heat load by thermal radiation to 2 K region without the 5 K shield and the total cost including the operation cost of 10 years were studied; the total cost without the 5K shield by optimising the cooling scheme can be less than that with 5 K shield. For the ILC cryomodule design, the cryomodule components need to be designed to make possible a study of this thermal concept. The cryomodule without 5 K shield is to be examined with a 12 m cryomodule for the STF-2 (corresponding to S2) at KEK, and the cryomodule cost will be re-evaluated, based on this experience, in comparison to the cost of the current TTF type III cryomodule.

4.3.2 Magnetic shield design

The magnetic shield design itself is part of the Cavity Integration Technical Area Group (Section 4.2.1). However, the shield inside or outside of the cavity jacket has a large impact on the cryomodule assembly and the required person-hours outside of the clean room. The performances of two types of shield will be compared in the S1-G cryomodule cold test. The overall cost including manufacturing shield components, assembly time and person-hours needs to be studied.

4.3.3 Design to limit vibration

Vibration of the cavities (microphonics) causes detuning of the cavities and requires additional RF power overhead to compensate (via LLRF feedback). Operational data from TTF / FLASH operations (for example) show that microphonics driven from preceding RF pulses, and/or from external environmental sources can be significant. Effects of predictable vibrations arising from well-controlled external sources can be minimised using piezo-tuner actuators, but this technique will have natural limitations. It is therefore important to design the cryomodule to minimise resonances and damp mechanical vibrations as far as possible.

In addition to the cavities, mechanical stability of the mid-mounted superconducting quadrupole must also be carefully considered. The quads should not vibrate vertically by more than ~100 nm RMS.

4.3.4 Plug-compatibility

The next-generation ILC prototype cryomodule should be designed to accommodate the "Plug-compatible" concept. The connection flange of the vacuum vessel, the size and position of cooling pipes, thermal shield shape and input coupler flange on the vacuum vessel should be standardised as far as possible, but still be flexible enough to support differing component designs. Although expected to be eliminated in the ILC cryomodule design, the 5 K shield *envelope* is to be retained to accommodate the possibility of accommodating cryomodules which include a 5 K shield in a plug-compatible way.

In addition, the alignment process and the fiducial targets for the cavities and cryomodule should be also discussed from the "Plug-compatible" design point of view.

4.4 Preparation for industrialisation

The cavity and cryomodule industrialisation will take complementary approaches in the three regions of Europe, Asia and Americas. In Europe, the European XFEL project will provide a major step for industrialisation with the mass-production of 80 cryomodules constructed from 640 cavities. In Asia, KEK is planning to develop a cavity fabrication facility as a pilot plant to prepare the industrialisation with a series of programmes hosted by KEK. In the Americas, multiple vendors are contributing to fabrication of a numbers of cavities, and a hydroforming technology will be intensively investigated as a possible alternative for cost-effective cavity production in a longer term scope.

Most of the current cavity vendors are not of the scale required for ILC type production, but they do have experience in SCRF cavity / resonator fabrication, and therefore have expertise that will help to optimise the overall process. As the ILC project becomes closer to a reality, our goal is to have experienced, successful vendors and a well-understood cavity fabrication methodology that can either be used to scale-up the production at one of the existing vendors or can be transferred to an alternative production factory. Our initial starting point has been with the vendors providing manufacturing and welding skills, with laboratories supplying processing, inspection, and test facilities, and providing feedback to the vendors. As vendors gain experience, we are pushing more of the standard processing to the vendors and away from the laboratories, and will continue to do so as the processes become better understood.

4.4.1 European Approach

The cavity production for the European XFEL project is to be carried out with European industries over the next 4 years (completing in early 2014). Approximately 680 cavities will be manufactured by two manufacturing companies in close collaboration with DESY and INFN, and will be vertically tested at DESY. The peak production rate is expected to be ~one cavity per day total. The ~80 cryomodule assembly will be performed at a purpose-built facility at CEA/Saclay with industry participating to the assembly work. The peak production rate is expected to be ~one cryomodule per week, approximately 5% of the required production rate foreseen for the ILC. Construction of the XFEL offers by far the largest single mass-production series of the three regions and will provide important feedback for the ILC mass-production.

4.4.2 Asian Approach

KEK will construct the KEK cavity fabrication facility (KEK-CFF), to function as a ‘pilot plant’ where cost-effective production methods and technology will be investigated. The electron beam welder (EBW), press machine and trimming machine as well as chemical treatment room and various inspection tools will be facilitated during 2010-2011. The first production of 9-cell cavities without HOM couplers partly using this facility will be made in 2010 (before delivery of the EBW machine) as an initial start-up. The next production series from 2011 on is planned to supply cavities for the STF cryomodule. The production technology development will be done in parallel with the cavity production during the TD Phase. The KEK-CFF is willing to be open to all interested industrial partners to study cost-effective manufacturing, in cooperation with KEK and other laboratories.

4.4.3 Americas Approach

In the Americas, the focus during TD Phase 2 will be to continue the current efforts of increasing industrial expertise across multiple (Americas-based) vendors. This will be done in conjunction with the cavity R&D plan, by increasing use of inspection and test facilities at the laboratories and improved feedback to the vendors. The expected number of cavities in the system has been almost doubled through the use of ARRA[3] funds, and these will provide the majority of the cavities to be tested in the Americas up through 2012.

As of this date the Americas region has one vendor and two laboratories that have manufactured and processed standard 9-cell cavities reaching or surpassing the ILC vertical test goal of 35MV/m with an acceptable Q_0. Two additional vendors have successfully manufactured single cell cavities that tested well, and are in process of manufacturing their initial 9-cell cavities. Over the course of the next 2 years these 3 vendors, in conjunction with the laboratories, will manufacture, process, and test approximately 50 more 9-cell cavities. The majority of these cavities have been recently purchased through ARRA funds, and maintenance of industrial expertise at a sufficient rate after the ARRA cavities have been completed will have to be addressed. ARRA funds have also allowed for the introduction of an EP facility at one of the manufacturers. This, in conjunction with the development of an integrated, scalable processing system at JLab, may help speed up the industrial understanding of the processing steps. The goal at the end of the TD Phase 2 period remains for the Americas region to have minimised the technical risk to the ILC in cavity production by developing multiple vendors and a known process that can deliver the ILC cavities. In addition to technical risk, the Americas region is working with vendors to understand cost and production scale-up issues. This is being done through targeted set of studies done under contract by vendors, looking at optimised production facilities, and design changes that would improve manufacturability when producing cavities in ILC quantities. To date these studies have focused on optimisations of the production / welding operations and a redesign of the helium vessel system, but in the future will continue with studies of optimised processing facilities and other improvements.

Alternative manufacturing and processing methods, such as hydroforming of cavities, tumbling and eco-friendly processing will be pursued in a longer-term R&D plan because of the potential cost savings to the ILC project.

4.4.4 Industrialisation models and the TDR VALUE estimate

The cavity industrialisation model is also under review, starting with an international workshop on the cavity technology and industrialisation carried out as a satellite meeting of the 1st International Particle Accelerator Conference, held in Kyoto[4]. Based on this workshop, the following observations, findings and subjects for further study have been identified.

Production of ~18000 cavities is more than likely not going to occur at a single vendor, but split across the 3 regions. One plausible model would have at least 2 vendors in each region, such that each vendor produced on order of 3000 cavities. Even so, such a scale of manufacturing is beyond the capacity of the current vendors, and is larger than any of the

[3] American Recovery and Reinvestment Act

[4] see: http://ilcagenda.linearcollider.org/conferenceDisplay.py?confId=4530

vendors can see as a sustainable business level after the ILC. This scale issue has several effects, first and foremost that the learning curve assumed in the VALUE estimate should be revisited, and second as stated by the vendors that the ILC project could largely assume that infrastructure and ramp-up associated with the project needs will have to be born by the project, as opposed to being amortised by the project and future business beyond the project.

One resulting fact from the lack of follow-on business as seen in the LHC, however, was that parallel industries were willing to share information on process and design improvements after the contracts were fixed, since the long term competitive needs were effectively removed.

One of the benefits of multiple vendors is a reduction in the business risk (at a cost) of cavity production, but this also tends to align the firm size more with the needs of the project, where the technical complexity and scope of work would favour the use of flexible workshops and flexible cells of manual work.

Development of a production model (or *models*) on which to base a robust and defendable VALUE estimate is a primary TDR deliverable. During TD Phase 2 the ILC management will review the existing RDR VALUE estimate, taking into account the XFEL experience and costs, and the information gained at the Kyoto and future industrial workshops.

4.5 High-Level RF Development

The main focus of the TD Phase High-Level RF R&D program is to develop and test a Main Linac section or RF Unit which meets ILC requirements and has an estimated cost significantly lower than that of the RDR RF unit. Specific targets for cost reductions are the modulator, the klystron and RF power distribution systems.

4.5.1 Modulator

The RDR baseline modulator is the Fermilab “Bouncer Modulator”. A transformer-less design based on Marx-generator circuits is an attractive alternative. The Marx-based design is being pursued because of potential cost savings and reliability improvements over the Bouncer design. The projected cost savings assume a lower component cost and a significantly less labour-intensive manufacturing process. A full-scale prototype has been designed and fabricated at SLAC. It is currently undergoing lifetime testing, driving a 10 MW Multi-Beam Klystron (MBK) at full power and with full droop compensation (as of this release for about 2000 hours). A second-generation Marx is currently under development and will be constructed and tested during TD Phase 2. It will include simplified droop compensation and an improved solid-state switch protection scheme. These two proof-of-principle devices provide good initial understanding of the new solid-state technology and allow a credible cost estimate.

4.5.2 Power Distribution System

The RDR baseline is a linear distribution system with individual tap-offs, circulators, and 3-stub tuners for each cavity. An alternative design using a semi-branched system (two cavities per tap-off) with variable tap-offs is under development and may make it possible to eliminate costly circulators. A critical aspect of the power distribution system activities is to develop low-cost implementations of key RF components such as the variable tap-offs, phase shifters, and loads. An additional focus for the power distribution system is to provide sufficient flexibility and adjustability to compensate for variations in cavity gradient, allowing the total gradient for each linac RF unit to be optimised. Recently, two proposals have been under investigation as alternative design configuration: a Klystron Cluster Scheme (KCS) and a Distributed RF Source (DRFS) scheme. Further investigation and R&D are under discussion in combination with a single tunnel CFS design, as discussed in Section 6.2.

TD Phase-1 Milestones:

- Demonstrate operation of Marx modulator powering a baseline multi-beam klystron
- Demonstrate performance of key distribution system components – variable tap-offs, phase shifters and loads

TD Phase-2 Milestones (and beyond)

- Perform a demonstration within an integrated RF system (modulator, MB klystron, power distribution, cryomodules, LLRF, controls). The goal is to perform initial tests at NML (Fermilab) and at STF (KEK) within TD Phase 2, with extended tests beyond 2012. Related testing of critical aspects will also be done at TTF/FLASH (DESY). Beam operation is required to demonstrate regulation and control.

4.5.3 Klystron Cluster Scheme R&D

The single-tunnel RF distribution option referred to as the Klystron Cluster Scheme (KCS) involves combining power from roughly 30 baseline 10 MW klystrons clustered in a surface building and transporting it down to and along the main linac in an oversized TE_{01}-mode circular waveguide. The power is then tapped off periodically in 10 MW portions that are distributed locally among 26 cavities. Two such clusters sharing a surface building can feed roughly 2.5 km of linac through a single shaft, one sending power upstream and other sending it downstream. While a full scale demonstration system would not be practical, there are a number of steps which can be taken during the TD Phase toward establishing the feasibility of this scheme.

Thus far, ten meters of 0.480 m diameter circular aluminium waveguide (WC1890), such as might be used for the KCS main artery, have been fabricated. Also in hand are two prototype 3 dB versions of a novel RF component, dubbed a Coaxial Tap-Off (CTO), designed to couple power into and out of this waveguide. Minor mechanical variations in its design allow the full range of coupling needed in a KCS.

The test plan underway at SLAC aims at verifying the component designs, testing vacuum high-power operation of aluminium waveguides, and demonstrating the sustainability in WC1890 of RF fields equivalent to those envisioned in the main linac KCS systems, where up to 350 MW would flow. The latter test will be done with the system pressurised with dry nitrogen as well as under vacuum; it should more RF robust under vacuum, but it would be less expensive to operate it under pressure for the ILC. Steps of our current (2010) plan are detailed below.

Current program:

- High-power vacuum test the aluminium spool with indium seals by which the vacuum windows will be attached to the CTO WR650 ports.
- Pump down with in-situ bake and leak check of a 10 m run of 0.480 m diameter aluminium circular waveguide (WC1890) with perforated pump-out spool in centre and closed with end plates.
- Cold test the shorted CTO TE_{01} mode launchers back-to-back with and without ¼-wave spacer. Tune their shorting caps, by shimming and then final machining, for optimal transmission, and then another for the small coupling needed for the resonant test.
- Measure and adjust if necessary via inter-flange spacers the phases to the input CTO WR650 ports through the magic-T and input arm assemblies (including directional couplers and windows). Connect the input assembly to the input CTO and cold-test from the magic-T to the output CTO, with the WC1890 tapers inserted. Insert WC1890 tapers and connect output assemblies (including windows, directional couplers, and loads) to the output CTO.
- Pump down with in-situ bake and leak check CTO assembly.
- Insert 10 m WC1890 run between tapers, pump down, connect to input waveguide from test-stand Thales klystron and high-power test for transmission at ~4 MW.
- Remove the output CTO and short-line at taper. Change the input CTO shorting cap for small line coupling. Cold test and adjust the line length for resonance by using ¼-wave spacer if necessary, and final machining of the end cap. Measure coupling and quality factor.
- Pump down, reconnect to klystron, and perform resonant test up to standing wave field levels equivalent to those of ~ 350 MW travelling waves.
- Pressurise line to 2 bar absolute (14.5 psig) dry nitrogen and repeat resonant test.

If these are successful, further development and tests will be done to more fully evaluate the KCS concept. They include solving the problem of bending the main waveguide by 90˚, which will need to be done 2 to 4 times at full power to bring it from the surface cluster building into the linac tunnel. Power-handling is more of a concern in the bend design than mode preservation and will have to be tested. The matched tap-off function of the CTO (used only as a launcher above) will be demonstrated, as well as its use in combining two sources. Finally, it is desirable to transport the power over longer distances in a travelling wave configuration to better simulate the ILC operating conditions; in particular, to approach the level of stored energy in the ILC system before it could be shut off (e.g. in the event of RF breakdown). The plan is to build a 160 m resonant ring that would operate at the 350 MW level. The follow-up R&D program will likely proceed as follows:

Follow-up plans (2011):

- Design and build bends for very high-power TE_{01}-mode WC1890.
- Cold test and high-power test (4 MW) bend between CTOs.
- Obtain 70 m more WC1890 waveguide and add to assembly.

- Incorporate bends into long waveguide run between CTOs and repeat high-power transmission and resonant tests. Insert ¼-wave spacer and repeat resonant test.
- Make third CTO (with different coupling) to test tap-off and combining function.

Further plans (2012):

- Design and build CTO-based directional coupler that would power a resonant ring.
- Acquire additional waveguide to construct a 160 m resonant ring.
- Include a tap-off/tap-in assembly that would provide a short 10 MW bypass.
- Test at full travelling wave power.

4.5.4 Distributed RF System R&D

Near-term R&D program

- 2 units of DRFS are planed to be used in the S1-Global project in the end of 2010. The test will comprise of: a prototype DC power supply; a modulating-anode (MA) modulator; 2 prototype MA klystrons (MAK); A circulator-less power distribution system; High-availability power supply system; and LLRF control system.
- The prototype DRFS klystron outputting a medium power of 750 kW has been designed and manufactured in 2009 and completed in 2010. A second tube is currently being manufactured. Various evaluations will be performed after the S1-Global tests (end 2010, beginning 2011).
- The power distribution system performance using high-isolation magic-tee without a circulator will be investigated under LLRF feedback control. Crosstalk and diagnosis of cavity parameters at the pulsed tail are part of the S1-Global test programme.
- For the RF power source, S1-Global cryostat 'A' will use the prototype DRFS system. This system consists of the HV-DC power supply and the MA power supply that are connected to the two MAKs, together with the LLRF control. Each MAK will be connected to two cavities with a simple waveguide system eliminating the circulators.

Follow-up plans (toward the "Quantum beam project" and STF-II)

Two successive programmes are currently planned at KEK after the completion of S1-Global: the "quantum beam project" in 2012, and STF-II planned for 2013. DRFS will be adapted to and further developed for these projects:

In the "quantum beam project", one klystron of DRFS is used and LLRF feedback is performed with the beam. In the first stage of STF-II, 5 klystrons driven by a DC-power supply and a modulator feed power to 8 cavities in an ILC-type cryomodule and a further 2 cavities in a "quantum beam" cryomodule (10 total), again with beam operation. LLRF digital feedback studies are also included.

For the DC power supply and MA modulator, important R&D items are the development of reliable and cost-effective:

- HV relays
- Gap switches for the crowbar circuit

- Large diameter current transformers or optically sensed current monitors.

A minimum R&D effort on these items will be performed through STF-II in three years. A prototype of the HV charger system and the switching regulator units will be evaluated.

For the klystron development, the study of permanent focusing magnets is important to achieve the high-availability, and prototype R&D will proceed in JFY2010. Studies for cost-effective manufacturing of the DRFS klystrons will be pursued through the series production for STF-II.

A layout of the DRFS that accommodates a tunnel floor mounted cryomodule will be developed for various tunnel diameters. DRFS in 5.75 m tunnel diameter has a 0.5 m emergency egress (during maintenance) and it is proposed to adopt this scheme as the standard DRFS tunnel configuration. Value engineering of this scheme will be pursued in parallel.

A critical concern is the effect of radiation damage for the systems installed in the beam tunnel. The LLRF systems require the critical evaluation (e.g. shielding requirements, a common problem for DRFS and the KCS). Much more will be learnt from the European X-FEL experience at DESY and the LHC at CERN, both of which face similar issues. Initial studies from LHC indicate that the greatest concern is the radiation sensitivity of the power converters. Additional (and independent) experimental plans to study the radiation shielding need to be made. Some operational experience may be available from the LHC, and also from XFEL project.

Detailed studies of single-tunnel installation scenarios will be studied in JFY2011.

Feasibility of maintenance and upgrade scenarios will be studied in JFY2011. This design work will be performed using simulation and 3D CAD, and also by fabricating a real size tunnel model (mock-up).

Detailed MTBF evaluation will be further studied. For the klystron, the data of KEKB injector linac and the newly manufactured DRFS klystron will be evaluated. For other equipment, studies of the individual component life-times using available published data will be made.

4.6 Linac System Tests including beam

4.6.1 Motivation for System Test

Full performance of multiple cryomodules will be demonstrated as part of the main linac SCRF system test, referred to as the ‘cryomodule-string test’ or ‘S2’ (ILC-EDMS ID D*860505). The test includes beam acceleration and beam handling. Most linac systems operational studies can be made with a single cryomodule without beam and therefore can be considered part of the ‘S1’ program. The key aspect of ‘S2’ is beam operation which provides a proper check of accelerator *energy gain and stabilisation systems*. It is important to note that ‘S2’ systems studies without beam are also quite important and useful.

The motivations of the cryomodule-string test are:

- Demonstration of ILC linac performance and evaluation of realistic cavity performance with beam acceleration.

- Demonstration of a number of cavities in accelerator operation showing repeatability of the performance and providing an estimate of reliability.

It is important that each region implement a full superconducting linac system, including the cryomodules, the beam generation and handling and the RF power source and distribution systems to integrate the accelerator technology and gain sufficient experience in that region. However, even with the planned three-fold regional string test infrastructure redundancy, no one of the test linacs will match the RDR RF unit, (or similar-scale cryomodule string) within the TD Phase timescale. This is partly due to institutional commitments to support parallel projects as well as more fundamental conventional facilities infrastructure limitations. In addition, the baseline design itself is expected to evolve as R&D results become available. It is foreseen, however, to address the essential technical aspects of the technology by globally developing suitably complementary programmes to obtain sufficient R&D results in preparation for the Technical Design Report.

Preparation for such tests are planned or underway at facilities built at DESY (TTF / FLASH), KEK (STF2), and Fermilab (ILCTA-NML).

4.6.2 Goals of the System Tests

Specific string test goals, listed in order of importance, include:

- **Demonstrate stable acceleration at nominal parameters**. The nominal accelerating gradient specification for the RDR RF Unit is 31.5 MV/m, average, with 0.5% pulse to pulse RF amplitude stability / 0.5° pulse to pulse phase stability at any point during the ~1 ms RF pulse.
    - The demonstration should include feedback and related controls to achieve stable phase and amplitude at nominal ILC beam intensity
    - Evaluation and demonstration of operational gradient margin budget and
    - Demonstration of operation with a spread in cavity limiting gradients.
- **Tests of basic system parameters**
    - demonstrate operation of a RDR RF-unit or similar linac segment
    - determine the required power overhead under practical operating conditions
    - to measure dark current and x-ray emission, (this is to be used to establish precise radiation dose-rate limit vertical test acceptance criteria), and
    - to check for heating from higher-order modes in order to determine the dynamic cryogenic heat load with full beam current operation
- **Tests and optimisation of operational and logistical strategies**
    - developing RF fault recognition and recovery procedures
    - evaluating cavity quench rates and coupler breakdowns
    - testing component reliability
    - performing long-term testing of cryomodules, (including thermal cycling between beam operations), and

- assembling the string an actual tunnel to explore installation, maintenance, and repair issues.

The-ILC main linac performance requirement is 9 mA peak beam current with 2625 bunches and 0.1% rms energy stability (at 250 GeV), with 5 Hz pulse repetition rate. The TTF/FLASH group very nearly achieved the specified ILC performance during a two-week dedicated experiment in September 2009. Current studies, underway at the DESY (TTF / FLASH) 750 – 1200 MeV linac, have demonstrated 7 mA peak beam current operation with 0.13% rms pulse to pulse beam energy stability and 0.5% peak to peak energy deviation within a 2400 bunch train. Current study results were done with cryomodules operating with a limiting average gradient of 23-27 MV/m.

Feedback and feed-forward control of the RF unit accelerating-field vector sum over many cavities is the most challenging aspect of full power, full gradient linac system tests. If the vector sum control is properly optimised, then the required operational gradient and HLRF power overheads will be minimised and the main linac baseline can be established accordingly. Three elements dominate controls development: 1) Lorentz Force detuning (LDF); 2) cavity input power and coupling (P_k, and Q_ext respectively) under nominal beam loading conditions; and 3) pulse-driven vibration or microphonics. These effects are strongly dependent on beam current and peak gradient.

Our strategy for accomplishing the goals depends on the infrastructure limitations and schedule constraints at each of the three main linac test facilities (see Section 4.6.3, below). It is important to note that the strategy relies heavily on experience gained at: 1) injector test facilities, such as PITZ (DESY/Zeuthen), FNPL (Fermilab/A0) and Quantum Beam (KEK); 2) high-power cavity 'horizontal test facilities', such as Checchia (DESY) and HTS (Fermilab/Meson); and 3) cryomodule test facilities, such as CMTF (DESY) and STF (KEK). This critical test infrastructure has allowed development of the technology required to produce ILC-like beam and to control and stabilise the superconducting linac accelerating RF. In many cases, equipment developed in these smaller test facilities is subsequently directly deployed in the full systems tests.

4.6.3 Main Linac SCRF Technology Test Facilities

TTF / FLASH (DESY)

Background and Goals for operations

The 'TESLA Test Facility / FLASH' linac at DESY is a 1.2 GeV linac based on the same technology planned for ILC. TTF is by far the oldest and best-established facility based on that technology, having started operation in its present configuration in 2005. FLASH operates as a VUV-FEL user facility for roughly 6000 hours each year. Time available to develop key technologies needed to demonstrate the above includes nominally allocated FEL machine development time since that program has several key goals which are the same as those of the string test. Extended FEL operations using long bunch trains (1 MHz bunch rate with 0.5 nC bunches at 10 Hz linac repetition rate) will begin in 2010. The European XFEL also requires long bunch train operations with similar parameters.

Anticipated Beam Parameters

The TTF/FLASH linac:

- Can support nominal ILC beam current with 2400 bunches (90% of nominal)

- Has seven cryomodules with 56 cavities powered by 4 klystrons (3×5 MW and 1.3 MW nominal forward power). The accelerating gradient for one of the seven meets the ILC goal. The gradient is limited to 30 MV/m average for two of the 7 cryomodules (95% of the ILC nominal). The spread in limiting gradients for these two highest average gradient cryomodules is 21-39 MV/m, about 2 times larger than the limiting gradient spread under consideration for the updated ILC baseline.
- Has RF units consisting of two cryomodules and ~6 MW power sources.
- Has cryogenic and power infrastructure capable of 10 Hz operation.

Development plans

The cryomodule string test at TTF/FLASH is referred to as the '9 mA' experiment. The objectives of the 9 mA experiment are closely aligned with the goals listed above. Studies and development activities in support of 9 mA experiment include:

- Modelling of the cavity / HLRF/ power distribution / LLRF control system, including 'Lorentz Force detuning' and microphonics.
- Development of LLRF controls.
- Integration of high-power linac machine protection systems.
- Studies of needed RF power and cavity gradient overhead.
- Studies of long-term RF stability.
- Studies and demonstrations of ILC bunch compressor RF stability.

Work on each of the above is proceeding in parallel and success so far can be attributed largely to DESY / FLASH expertise. Initial modelling results have provided very preliminary phase and amplitude stability tolerance budget estimates that can be used to guide technical strategy and prioritisation. As noted above, three elements are dominant: 1) Lorentz Force detuning (LFD) control; 2) cavity input power and coupling (P_k, and Q_ext) under nominal beam loading conditions; and 3) pulse-driven cavity vibration effects or microphonics. Item 2), above, refers to several effects, each of which is important: 1) the agility of the linac system to transition smoothly from low (or no) current to high current; and 2) the ability of the linac stabilisation control to isolate beam fluctuations cleanly so that the beam energy on each pulse is stable. However, there are other effects which are to be characterised through the '9mA' studies. These include component-level items such as LLRF front-end noise, linearity, and calibration accuracy and LLRF system long-term drifts, and residual errors.

In order of priority, the TTF/FLASH 9 mA program implementation will be based on:

- Improvements to the injector systems (laser, gun and related infrastructure) to provide control of the bunch-to-bunch energy and RF phase differences. Each bunch in the long multi-bunch train will then be 'aligned' so that the total phase space volume occupied by the train is not much larger than that of a single bunch.
- Improvements to the machine protection system that minimise the impact of beam off/on and RF off/on transients. These allow the steady high-power beam operation, a pre-requisite for controls studies. The most important transient is beam off / on in the SCRF cavities that are tuned for nominal high-current operation. The successful completion of the study requires adjustment of P_k and Q_ext for each cavity to match the 9 mA beam current.
- Adoption of a cavity frequency tuning and Q_ext adjustment procedure that provides 'flat' cavity amplitude and phase during the beam pulse and maximum

Sustainable (below quench) gradient. The procedure must include feed-forward compensation for LFD using piezo-electric cavity tuners. In preparation for the 9 mA studies, LFD control will be further developed and evaluated using the S1-Global cryomodule (KEK) and HTS (Fermilab).

- Adoption of nominal-gain vector sum feedback with the integral gain required to flatten the accelerating gradient during the beam pulse. The feedback primarily compensates for variations in beam current.

Issues with operation and schedule

Dedicated ILC 'cryomodule string test' operation of TTF/FLASH is expected to be around 250 hours per year. Since performance achieved in late 2009 was quite close to the goal performance for the 9 mA experiment, we are optimistic that the ILC intensity and stability goals will be achieved in 2011, after taking full advantage of the planned long-pulse FEL operation, together with the system improvements outlined above.

Superconducting Test Facility: STF2 (KEK)

Background and Goals for operations

STF development during TD Phase 2 will be on the injector construction and operation, and on the first ILC-type cryomodule construction and operation. The injector, which includes an L-band copper-cavity RF gun and two 9-cell cavities in a capture cryostat driven by one DRFS klystron will be operated for the "quantum beam experiment" for one-year from October 2011 to July 2012. It will then become the injector for the STF2 accelerator. At the end of 2012, the first ILC-type cryomodule will be assembled and installed in the tunnel. STF2 RF and beam operation will begin in 2013.

Anticipated beam parameters

Beam parameters of the "quantum beam experiment" are 162.5 MHz bunch repetition rate within a 1 ms RF pulse with 62 pC bunch charge. The beam loading (10 mA) is slightly higher than that required for ILC. For STF2 operation, the injector beam parameters will be changed to 3 MHz bunch repetition and 3.2 nC bunch charge within the nominal 1 ms RF pulse by changing the laser system.

Development plans

The photo-cathode RF gun is now under development by a collaboration of FNAL for the cavity part, and the Institute of Applied Physics (Russian Academy of Science, Nishni-Novgorod) for the ILC-type laser part. As of writing RF processing is underway and the laser system is ready for use. For the "quantum beam project", the laser system will be replaced by a 162.5 MHz one which has already been purchased and tested. Two 9-cell cavities and the capture cryomodule have already been ordered and will be delivered in early 2011. Nine 9-cell cavities, intended for the first ILC cryomodule are now in fabrication as part of a three-year fabrication plan. The design of the first ILC cryomodule will begin later this year. For the second ILC cryomodule, the plan is to include cavities from additional Japanese vendors and cavities produced in the KEK industrial R&D pilot plant (see section 4.4.2). Procurement for these cavities and for the cryomodule will start in 2011 and be completed by the end of 2013.

The ILC-type cryomodule will be driven by DRFS klystrons in the tunnel. The klystrons and the power supplies will be constructed in 2011- 2012. The LLRF system will also be installed in the tunnel.

Issues with operation – including system limitations and schedule

The “quantum beam project” assignment must finish by the end of JFY2012. The beam operation and its X-ray generation experiment should finish by the summer of 2012, after about one-year of operation, starting in October 2011. Due to budget constraints, the ILC cryomodule will be assembled in-situ in the STF tunnel, without the construction of a new vertical shaft large enough for full length ILC cryomodules at the very end of STF tunnel. For this construction scheme, the cavity-string cold-mass assembly is divided in two parts, i.e. two 4 cavity strings. Each string is brought into the STF tunnel separately and once there joined as part of the final cryomodule assembly.

Within the TD Phase 2 timeframe, the STF contribution to the cryomodule string test (‘S2’) task operation will be limited to one cryomodule with ILC beam-loading.

New Muon Lab (Fermilab)

Background and goals for operations

The Fermilab-based ‘New Muon Lab’ facility is under construction in two stages. The facility will produce 450 MeV ILC-like beams by the end of TD Phase 2 with 2 cryomodules. In 2013-2015 the facility will expand to 6 cryomodules and a beam energy over 1 GeV. To facilitate development of the needed technology and expertise, the injector single-cavity cryomodule is operational and under test for stabilisation and cryogenic system testing.

Anticipated beam parameters

The NML injector has been developed in collaboration with KEK and DESY and is based on more than a decade of experience at FNPL (A0). It uses a 1½-cell copper L-band RF gun with a capture cavity. FNPL equipment will be re-deployed at NML in 2011 and full ILC beam parameter operations with two cryomodules will begin in USFY 2012.

Development plans

As part of the general lab expansion funded through the ‘American Recovery and Reinvestment Act of 2009’, the New Muon Lab building is being extended to accommodate the installation of 6 nominal-length cryomodules. Construction is expected to be complete in late 2010. The Fermilab group has developed specialised controls for controlling and minimising the impact of Lorentz force detuning. This system will be applied to control pulse-driven microphonics and will be tested at NML, HTS (Fermilab), TTF/FLASH and S1 Global.

Issues with operation – including system limitations and schedule

In 2013 and 2014, approximately half of the scheduled linac operation (2000 hours/year) will be dedicated to demonstration of the cryomodule string test objectives. The system will be complete and operational for RF unit testing during USFY 2014.

5 Accelerator Systems Beam Test Facilities and R&D

5.1 Beam Test Facilities

Beam Test Facilities are required for critical technical demonstrations, including accelerating gradient, precision beam handling and beam dynamics. In each case, the test facility is used to mitigate critical technical risks as assessed during the development of the RDR. Beam test facilities for the SCRF accelerator have already been described in Section 4.6.3. The remaining (non-SCRF related) tests can be grouped into two categories:

1. Studies of instabilities, such as electron cloud, and mitigation techniques.
2. Demonstrations of the generation and handling of low-emittance beams using precision optics and stabilisation tools.

Test facilities also serve to train scientific and engineering staff and regional industry. In each case, design and construction of the test facility has been done by a collaboration of several institutes. Table 5-1 summarises the facilities which have been built in each region along with the their operation start date.

Table 5-1: Beam Test Facilities

Test Facility	Acronym	Purpose	Host lab	Operation start	Organised by
Accelerator Test Facility	ATF	Damping Ring	KEK	1997	ATF Collaboration
Cornell Test Accelerator	Cesr-TA	Damping Ring	Cornell	2008	Cornell
Beam Delivery Test Facility	ATF-2	Beam Delivery System	KEK	2008	ATF Collaboration
SCRF related beam test facilities (included for completeness; see Section 4.6.3).					
SCRF Test Facility	STF	Main Linac	KEK	2008	KEK
TESLA Test Facility/ Free Electron Laser Hamburg	TTF/FLASH	Main Linac	DESY	1997	TESLA Collaboration, DESY
ILC Test Accelerator	ILCTA-NML	Main Linac	FNAL	2009	FNAL

5.2 Cesr-TA - electron cloud mitigation

In early 2008 work began to reconfigure the Cornell Electron Storage Ring (CESR) as a test accelerator (CesrTA) for ILC Damping Ring R&D. With its 12 superconducting wigglers relocated to zero-dispersion regions, CESR provides a unique facility to study electron cloud (EC) effects in a parameter regime approaching that of the ILC Damping Ring. Table 5-2 shows the low-emittance operating parameters that are presently being implemented for CesrTA experimental program.

Table 5-2: Parameters for the 2.0 GeV CesrTA low-emittance lattice presently in use.

Parameter	**Value***
Number of Wigglers	12
Wiggler Field	1.9T
Beam Energy†	2.085 GeV
Energy Spread ($\Delta E/E$)	8.1×10^{-4}
Horizontal Emittance (geometric)	2.6 nm-rad
Vertical Emittance (geometric) Target	< 20 pm-rad
Transverse Damping Time	56 ms
Q_x	14.57
Q_y	9.62
Q_z	0.055
Total RF Voltage	8.5 MV
Bunch Length	9 mm
Momentum Compaction	6.76×10^{-3}
Species	Positrons and Electrons

* zero-current

† CESR can operate from 1.5 GeV to 5.5 GeV

There are three major components of the CesrTA R&D program:

- **Low-Emittance Tuning**
  - Development of optics correction and tuning tools needed to attain low-emittance beams (~20 pm-rad vertical).
  - Demonstration of low-emittance operation of a positron ring.
- **Instrumentation and Diagnostics**
  - Development of instrumentation and diagnostics to support low emittance correction and tuning as well as real-time characterisation of low-emittance beams.
  - Development of diagnostics and techniques to characterise the EC build-up and its impact on the stored beams.
- **Electron Cloud Characterisation and Mitigation**
  - Characterisation of the EC build-up in drift, dipole, quadrupole and wiggler regions and validation of techniques to mitigate it.
  - Characterisation of the beam dynamics effects of the EC (including incoherent emittance growth and the onset of instabilities) in a low-emittance parameter regime approaching that of the ILC DR.

- Validation of EC simulation codes in a parameter regime approaching that of the ILC DR to ensure that projections to the operating conditions of the ILC DR are reliable.

In order to accomplish these tasks, approximately 240 days of experimental operation over a two-and-a-half-year period were budgeted for the project. A central component of the program is participation by collaborators from within the ILC DR design team and from the broader community involved in electron cloud effects and low-emittance machine operation.

Through TD Phase 1, the CesrTA R&D program:

- Implemented and corrected the low-emittance 2.0 GeV baseline lattice to achieve a horizontal emittance of 2.6 nm-rad and a vertical emittance of 40 pm-rad (5 GeV).
- Deployed and commissioned the instrumentation needed for low-emittance correction and tuning – in particular x-ray beam size monitors for both positron and electron beams that are capable of single-pass measurements of individual bunches in the ILC DR.
- Deployed a range of vacuum chambers and experimental stations for measuring EC build-up and the effectiveness of mitigation techniques that can be applied to the ILC DR and other accelerators where performance is sensitive to or impaired by the EC (Table 5-3).
- Developed a combined simulation and experimental program to evaluate EC build-up in each of the magnet types in the ILC DR design as well as instability thresholds and emittance growth issues for low-emittance beams.

By the end of TD Phase 1, in late 2010, the CesrTA program will provide the information necessary to formulate a recommended scheme for mitigation of electron cloud effects to the ILC-GDE, a major milestone.

Table 5-3: Instrumented Vacuum Chambers (VC) deployed (or planned) in CesrTA showing local magnetic configuration and contributing institutions. Over 30 multi-channel Retarding Field Analyzers (RFA) have been installed in CesrTA.

	Drift	Quad	Dipole	Wiggler	VC Fabrication
Al	✓	✓	✓		CU, SLAC
Cu	✓			✓	CU, KEK, LBNL, SLAC
TiN on Al	✓	✓	✓		CU, SLAC
TiN on Cu	✓			✓	CU, KEK, LBNL, SLAC
Amorphous C on Al	✓				CERN, CU
NEG on SS	✓				CU
Solenoid Windings	✓				CU
Fins w/TiN on Al	✓				SLAC
Triangular Grooves on Cu				✓	CU, KEK, LBNL, SLAC
Triangular Grooves w/TiN on Al			✓		CU, SLAC

Triangular Grooves w/TiN on Cu				✓ (planned)	CU, KEK, LBNL, SLAC
Clearing Electrode				✓	CU, KEK, LBNL, SLAC

Major R&D milestones planned, or already completed, for 2010 include:

- Low-emittance optics tuning to achieve ~20 pm-rad vertical emittance.
- High-resolution bunch-by-bunch x-ray beam size measurements of both electron and positron beams to support incoherent EC-driven emittance growth studies.
- Studies of EC-driven coherent instabilities using bunch-by-bunch position monitors and feedback systems.
- Installation and characterisation of EC experimental hardware including chambers with diagnostics and mitigation methods (see Table 5-3).
- Report on studies conducted to characterise the EC build-up in wiggler, dipole, quadrupole and drift sections using RFA, shielded pickups and TE wave transmission methods.
- Report on EC dynamics studies of incoherent beam size growth and beam instabilities the low-emittance configuration
- Hosting of a workshop on CesrTA activities during late 2010 to evaluate progress in the experimental program and to help refine the design and experimental plans for the final phase of the program.
- Preparation of an evaluation of positron damping ring design criteria based on the CesrTA experimental results, including a provisory recommendation on the baseline DR design and mitigation features (due end 2010).
- Final comprehensive report in mid-2011, containing final detailed analysis of the CesrTA results, and their application to modelling of EC beam dynamics effects in the DR baseline design.

Beyond 2010, the focus of the CesrTA program will shift from instrumentation upgrades and instrumented VC deployment to beam studies. Discussions are currently underway to explore continuation of the CesrTA program beyond mid-2010 at the level of approximately 1 month of experimental operations per year. This extension would provide time for completing long-term durability tests of coatings under consideration for the ILC DR as well as continuing studies in low-emittance tuning targeting data in the <10pm vertical emittance regime, EC mitigation, and EC dynamics. This would also support the efforts of the CesrTA team to transfer the results of the R&D program to the ILC DR design.

5.3 ATF2 - Final Focus optics and stabilisation

An important technical challenge of ILC is the collision of extremely small beams of a few nanometres in size. The challenge has three distinct issues: creating small emittance beams; preserving the emittance during acceleration; transporting, and then focusing the beams to nanometres and colliding them. The Accelerator Test Facility (ATF) at KEK was built to create small emittance beams, and succeeded in obtaining an emittance that almost satisfies the ILC requirements. The ATF2 facility, which use the beam extracted from ATF damping ring, was constructed to address two major challenges of ILC: focusing the beams to nanometre scales using an ILC-like final focus, and providing nanometre-level stability. ATF2 is effectively a scaled version of the ILC final focus design.

The two primary ATF2 goals are:

1. Achieving a vertical beam size of 37 nm at the focal point.
2. Stabilising of that beam to nanometre levels (over various time scales).

Both goals will be pursued in 2011 and 2012 (through JFY2012) respectively, but are not expected to be fully demonstrated until 2013, after publication of the TDR.

During TD Phase 1, the following milestones have been successfully completed:

- Installation and initial beam commissioning of the ATF2 beamline.
- Development and successful commissioning of nanometre-precision laser-interferometer Beam Size Monitor at the interaction point (BSM, so-called Shintake monitor), to measure the achieved focal spot size.
- Commissioning of the sub-micron resolution cavity BPM system and associated beam-based feedback systems (trajectory correction).
- Development and commissioning of nanometre-scale BPMs and the FONT (Feedback On Nanosecond Timescale) fast feedback system (including development of nanosecond rise-time kickers).
- Development and initial commissioning (experience) with beam-based tuning algorithms.

As of writing, the precision ATF2 IP beam size monitor had been commissioned and a 300 nm beam size had been observed.

ATF2 provides an ideal test infrastructure that in many ways is as close as practical to the ILC low-emittance transport. A key technology under study is that associated with the interaction region final focus magnet or 'Final-Doublet' (FD). Two technologies are under development: 1) superconducting (SC FD); and permanent magnet (PM FD).

The technical objective of SC FD development is to demonstrate and, if needed, develop a way to ensure that the design approach and technology is suitable for achieving the necessary characteristics of the SC FD as required by ILC, in terms of field quality, quench performance, compactness of the design, heat-load characteristics, vibration stability of the cold-mass and cryogenic system, and stability of the position of magnetic field. The GDE-ATF2 team is pursuing discussion and preparations for a possible development of an ILC-like SC FD, built with the same technology as the ILC prototype, which can be installed and tested at the ATF2 final focus test facility. The ATF SC FD would feature a warm bore, which will allow direct observation of the stability of the magnetic centre either with coils or ultimately with the electron beam. The discussed benefits of the ATF2 SC FD will include a system-wide test of the SC FD use in the beamline, and in particular mastering the use of dipole, sextupole and higher-order correctors embedded in the SC FD for beam tuning. The expected higher field quality of the SC FD will facilitate reaching smaller beta functions at the IP, which is of importance for the low-power parameter set under consideration. The system-wide test will also allow complete integration of the SC FD with other beamline components, such as BPMs, fast feedback, etc, all of which will need to operate in unison.

The ATF collaboration (together with the GDE) will continue to evaluate the possibility and rationale of performing the ATF2 SC FD development in the near future, and finalise its plans by mid-2011.

The technical objective of the PM FD is to evaluate the feasibility of an adjustable PM for the ILC final doublet. At present, a prototype of an adjustable PM quadrupole has been produced and is being studied. The particular features of the prototype that require further studies include the field quality, motion of the magnetic centre during change of the quadrupole strength, and temperature effects. While these issues are being studied, it is also planned to make a beam test of this quadrupole at ATF2, in order to obtain operational experience. It is foreseen that the PM quad will be installed in a location in the ATF2 beamline where it could be quickly inserted or removed, to minimise interference with the ongoing research program.

Given the realities of available funding, the ATF2 team has rearranged and shifted project milestones to balance between:

1) developments of tools and instrumentation for linear collider;
2) Demonstration of optics and stabilisation; and
3) education of accelerator scientists.

Point 2 above is now expected to be achieved in early 2013, at the end of JFY2012.

ATF2 is considered a possible model for a future ILC collaboration, constructed by in-kind contributions, and commissioned and operated by international team of researchers from many institutions. Planning and coordination of the commissioning activity is of crucial importance. A key component is good advance planning which needs to take into account the diverse and complementary skills of the large accelerator laboratories and smaller university groups alike, as well as the availability of collaborators.

5.4 Other Accelerator Systems R&D

In addition to the focus activities on SCRF technology and Beam Test Facilities, there are several key R&D activities focused primarily on demonstrating accelerator sub-system performance. For completeness we briefly catalogue them in the following subsections.

5.4.1 Electron source R&D

Primary on-going R&D for the electron source is the construction and demonstration of a prototype polarised electron source to ILC specifications. In particular, such a facility would enable polarised cathode charge limit investigations in this regime to be quantified.

R&D Milestones:

mid 2010 Procurement of a coherent V18 laser

end 2010 Inverted DC gun prototype 2 at 120kV

end 2011 Inverted DC gun prototype 3 at 200kV

	Final laser demonstration
	ILC beam demonstration (time structure) using 100kV SLAC SLC gun and cathodes
mid 2012	Installation of final ILC test facility (gun and laser) at JLab
end 2012	Final beam tests

5.4.2 Positron source R&D

The positron source R&D programme can be separated into two categories:

1) R&D on critical components for the baseline source (undulator-driven).
2) R&D on alternative source technology (or for the auxiliary source).

R&D Milestones

Baseline R&D (Undulator-driven source)

end 2010	Completion of rotating target magnetic eddy-current tests
	Conceptual design study (feasibility) for magnetic flux concentrator
	Conceptual design study (feasibility) for liquid lithium lens
	Source parameters based on possible Nb_3Sn undulator design
mid 2011	Demonstration of target rotating vacuum seal using 'surrogate target'
	Horizontal cold-tests of 4m undulator prototype
	Conceptual design study (feasibility) for magnetic flux concentrator
end 2011	Analyse (simulation) of target shock-wave survivability
	Target radiation damage estimates (lifetime modelling)
	Radiation tests of ferrofluid (rotating seal)
end 2012	Prototype module of Flux Concentrator (funding permitting)
end 2013	Feasibility of Nb_3Sn undulator

Alternative / Auxiliary source R&D

end 2011	Boron-nitride window beam tests at KEK
	Liquid lead target beam tests at KEK

5.4.3 Damping Ring R&D

Beyond the CesrTA programme on e-cloud mitigation (section 5.2), the primary critical R&D item is the demonstration of the fast injection / extraction kicker, and the 2 pm vertical emittance. As of writing, the latter (2 pm vertical emittance) has been achieved and even surpassed in several light sources around the world. However, a key goal remains to demonstrate 2 pm or less in the extracted beam; this goal is considered a lower priority however.

R&D Milestones:

Remaining R&D on fast kickers

mid 2011 Demonstrate kick-angle stability with multibunch 3MHz extraction at ATF

mid 2011 Evaluate kicker impedance

end 2011 Complete and test SLAC fast pulser prototype

Low emittance tuning

end 2012 Demonstration of extracted 2 pm vertical emittance at ATF/ATF2 (multi-bunch)

5.4.4 RTML R&D

The ring-to-main-linac (RTML) comprises the following sections: the long return line; the turn-around; and the bunch compressor. Emphasis is placed on overall AD&I activities (Section 6), and in particular the preservation of transverse emittance in the bunch compressor systems, where the long bunch emerging from the damping ring and large energy spread resulting from the compressor RF makes the beam particularly sensitive to wakefield and coupler kicks. A further key R&D goal is the demonstration of the required bunch compressor RF phase stability (the tightest in the machine).

R&D Milestones:

end 2010 Complete design of lattice, and evaluation of beam dynamics

end 2012 Demonstration of required phase stability at TTF2/FLASH

5.4.5 BDS/MDI

The primary R&D goals for the BDS are associated with the ATF2 Beam Test Facility (Section 5.3). However, there are several other key R&D programmes not directly related to this programme. The GDE team is pursuing design and prototyping of the ILC superconducting final doublet, with most of the relevant ILC features reproduced. This prototype is not intended for a beam test but rather for laboratory studies with various instruments. An additional focus for TD Phase 2 is the engineering design work associated with the machine-detector interface, in support of the detector push-pull option.

Accelerator-related R&D

end 2012 Comprehensive design of the high-power main beam dumps

end 2012 SC final doublet prototype design and test

Machine detector interface R&D (engineering)

mid 2010	Finalisation of work plan and resources
end 2011	First draft of engineering requirements documents
mid 2012	Final draft of engineering requirements document

6 Accelerator Design & Integration (AD&I)

The primary deliverable for the AD&I effort is the establishment of the baseline layout configurations upon which the TDR updated VALUE estimate will be based. This includes:

- Top-level machine (and physics) parameters, consistent with the design assumptions, operational modes and level of identified (and acceptable) risk.
- Inclusion of the results and recommendations of the on-going risk-mitigating R&D into the machine design.
- Complete geometric footprint of the machine, based on lattice designs for all the accelerator systems.
- Operational modes of the machine under various physics running scenarios (centre of mass energy)
- Generation of requirements for technical systems, and most important for CFS.
- Development of cost-effective CFS solutions (an identified primary cost driver), including site-dependent configurations (variants).
- Documentation of the design and performance, providing support and traceability for the updated VALUE estimate.

As the name infers, this integrating effort spans all three Technical Areas of the project (SCRF Main Linac Technology, CFS and Global Systems, Accelerator Systems). A team of approximately 40 GDE members spanning the Technical Areas is responsible for the work. The AD&I team is made up of the Technical Area Group leaders, key work-package coordinators and additional identified experts.

For TD Phase 2, the AD&I work will essentially consolidate the accelerator design work and cost-reduction studies that have been made during TD Phase 1, which culminated in the Straw-man Baseline 2009 (SB2009) proposal submitted to the GDE Director in December 2009 (a TD Phase 1 milestone). Subsequent review of the proposal indicated areas of further work that needed to be made before adoption as the formal baseline. This has lead to the development of further study plans and the introduction of a more formal Change Control mechanism (Top-Level Change Control, TLCC). The primary goal for TLCC is to provide a mechanism for broader participation by the identified stakeholders (and in particular the Physics and Detector Community) in the AD&I process, leading to a final consensus on the baseline design and associated performance parameters.

A high-priority for the AD&I effort continues to be a better cost-performance design for the machine (as compared to the published 2007 Reference Design). As in TD Phase 1, the focus is on reduction of the scope of the CFS solutions, and in particular the underground volume requirements (civil construction).

6.1 General AD&I Schedule

The overall schedule for the design effort (and therefore the scope) is constrained by the requirement to publish the TDR at the end of 2012. Allowing for time to develop the updated VALUE estimate and documentation, as well as further iterations to the design itself, it is highly desirable to agree on the supported baseline configurations (including variants) as early as possible, to allow the more detail work (and in particular development of the CFS solutions) to go forward without fear of major changes to that baseline.

The AD&I activities can be loosely separated into four overlapping phases:

1. Top-Level Change Control (TLCC) process, concluding in March 2011 with the consensus agreement on the baseline configurations and associated parameters for the TDR.
2. Detailed design and documentation phase, including development and consolidation of CFS solutions (3rd Quarter 2011)
3. Development of the associated (preliminary) VALUE estimate (4th Quarter 2011)
4. Cost-driven design iteration, leading to final TDR design and VALUE estimate (2nd Quarter 2012).

6.1.1 Short term plans: Top-Level Change Control Phase

The development and inclusion of the TLCC process represents a new element of the TD Phase 2 plans original published in earlier releases (1-4). It has been developed as a direct response to the TD Phase 1 design work and (after review) the identified need for further design studies on key SB2009 elements, together with the need for a better dialogue with the Physics and Detector Community.

In keeping with the timescales outlined above, it is currently planned to conclude the TLCC process by the March 2011. A key component of the TLCC process will be the Baseline Assessment Workshops (BAW), four of which are planned, each focusing on critically identified aspects of SB2009:

Baw 1	Average operational accelerating gradient	8-9.09.10	KEK
Baw 2	Main Linac single-tunnel solutions including HLRF options	10-11.09.10	KEK
Baw 3	Re-location of the baseline positron source to the end of the electron Main Linac	18-19.01.11	SLAC
Baw 4	Reduced beam-power option and luminosity parameters	20-21.01.11	SLAC

The primary deliverable of each of these two-day workshops is a proposal (recommendation) document, to be submitted to the GDE Director for consideration.

Final and complete consolidation of the new baseline layout and parameters (including variants) is planned for the GDE Workshop in Oregon (ALCPG, March 2011). The deliverables for this process are expected to be:

- A consensus agreement on the overall layout and implementation of the machine (including CFS).
- A consolidated set of performance parameters (physics relevant), for centre-of-mass energies of 200 GeV, 250 GeV, 350 GeV and 500 GeV.
- An agreed-upon set of machine specific parameters and operation modes, consistent with the published physics parameters.
- Complete (as possible) set of top-level documents in ILC-EDMS in support of the new baseline layouts and parameters.

The updated and documented baseline will form the basis of the subsequent AD&I design phases and in particular the generation of the VALUE estimate (see section 7). Further development and iteration of the design is expected, and will be carried out under document-level Technical Change Control (to be established).

6.2 Conventional Facilities and Siting (CFS)

6.2.1 Scope and Deliverables for CFS

Conventional Facilities and Siting (CFS) is responsible for the civil engineering of the underground and surface construction, site electrical and cooling systems.

TD Phase 2 efforts will focus on the development and completion of the new ILC baseline design and cost estimate and the preparation of the Technical Design Report. The TD Phase CFS baseline design activities are broadly subdivided into five stages:

1. A preparatory stage, during which the design criteria used to develop the Reference Design are revisited and analyzed. Development of design criteria depends critically on input from the Accelerator Systems Technical Groups.
2. A Value Engineering review stage, where the functional requirements are compared one at a time with their respective cost and a small set of prospective improvements are proposed.
3. An evaluation and design update stage during which the design is improved through adoption and analysis of the suggestions.
4. Development of the new CFS baseline design and cost estimate
5. Completion of the Technical Design Report

In conjunction with the above, the CFS Group actively fosters and coordinates preliminary site-specific investigation efforts. The TDR CFS baseline design will include adaptations that are needed to promote the siting process. While the RDR utilised three deep-tunnel ‘sample’ sites, the TD Phase effort includes examination of different kinds of site topography in order to develop the needed adaptations. The scope of the CFS siting effort includes:

1. A description of the design and analysis done for different site topographies.

2. An evaluation showing each proposed scheme is a satisfactory and straightforward CFS solution for a given site.
3. References to the relevant technical R&D.
4. Cost estimate for each site done in sufficient detail to give confidence in (2), above.

Work on CFS design and siting is tightly coupled to the Accelerator Systems and Main Linac HLRF and cryogenic system development.

The CFS Deliverables are:

- A full description of the baseline design best suited to the most understood site and a full set of 2D drawings and cost tables for that site.
- Descriptions for each alternate site configuration with 2D drawings and associated reference cost material.
- A full set of 3D design files for at least one of the sites.
- A description of the CFS value engineering analysis of key cost drivers:
    - Tunnel configuration
    - Cooling Systems
    - Electrical Systems
    - Surface Buildings.
- An analysis of life-safety requirements for underground enclosures.

6.2.2 Specific CFS Goals

Specific CFS goals include:

- Develop and analyze functional requirements as specified by Accelerator Systems and Superconducting RF Technology Technical Area Groups, including functional requirements from the Physics and Detector Groups 'Machine Detector Interface' input.
- Create and validate the detailed design using the functional requirements provided by the Technical Area Groups.
- Execute a 'Value Engineering' review process, with special focus on the most costly aspects of the design:
    - Underground construction
    - Process water cooling and air handling
    - Surface construction.
- Evaluate results of the review process and recommend updates to the baseline.
- Complete TD Phase effort with an updated and improved baseline design and cost estimate.

6.2.3 Milestones

In order to highlight the interaction with other Technical Groups, TD Phase 1 milestones were grouped into two categories: 1) Value Engineering and 2) Developing. With one exception, the listed milestones were completed and documented on schedule. The activity toward the milestone: 'Improved Surface Building Facilities Criteria' is underway and the milestone will be achieved by the end of 2010. As noted above, work on developing and analysing criteria is tightly coupled to the Accelerator Systems and Main Linac HLRF and cryogenic system development, so the milestones must also be coupled.

Milestone for the CFS Group: Value Engineering

Improved Surface Building Facilities Criteria	01.2011

Milestones for the CFS Group: Development of Criteria

Accelerator Central Region Criteria Complete	01.2011
Central Region Design and 2D drawings Complete	06.2011
Main Linac – both alternative HLRF schemes Design and Drawings complete, each region	01.2012
Interaction Region Criteria Complete	01.2012

Baseline Design Complete	06.2012
Full 3D drawing set complete	06.2012
CFS cost estimates complete, each region	01.2012
Life-Safety analysis complete	01.2011
Review of CFS Design	03.2011

6.2.4 Siting

The development of a specific, particular site is the responsibility of the locally-based ILC teams who typically work independently and are not performing this function as part of the ILC Global Design Effort. The CFS Group, through the support of the ILC GDE, must work with the local teams to provide the technical information required for the development of a scheme which best adapts the ILC baseline design to the site. For example, if surface access in a given sample site is extremely limited, shafts, access tunnels and utilities must be configured appropriately. As part of the process, the CFS Group evaluates and advises the local team on the scheme.

Goals and Milestones for the siting effort are:

Site Specific Design Preliminary Evaluation	01.2011
Site Specific Design Final Evaluation	01.2012

Site Specific Design Cost Analysis	01.2012
Review of Site Specific Design Activity	06.2011

7 Cost & Schedule

An updated VALUE estimate for the ILC is a primary TDR deliverable. The TDR VALUE estimate will be fundamentally based on the original work done for the 2007 RDR, but will reflect the results of the TD Phase R&D:

- Extensive R&D on SCRF world-wide, including the development of regional competence and (qualified) industrial capability for the production of high-performance nine-cell SCRF cavities, as well as a better understanding of the cavity production process and expected gradient yield.
- Extensive cost-driven design modifications to the published 2007 Reference Design (e.g. single-tunnel design for the Main Linac). This in part will reflect the results and recommendations for the TD Phase risk mitigating R&D (e.g. electron cloud).
- Updated CFS solutions for the new baseline, including the results of targeted *value engineering*.

The exact scope of the cost and schedule activities will be significantly constrained by the available resources. In keeping with the TD Phase overall philosophy, emphasis will be placed on the key cost drivers, namely SCRF and CFS (approximately 70% of the published VALUE estimate).

7.1 SCRF Main Linac Technology

7.1.1 Cavity/Cryomodule costs

There are many factors which can affect the unit cost of a cryomodule:

- Basic fabrication approach and materials costs (especially for cavities).
- Availability of qualified vendors and their projected capacity.
- Global mass-production models, including the (political) constraints imposed by in-kind contribution scenarios.
- Overall approach to risk mitigation, including expected performance yields (cavities), QA/QC, mass-production testing rates etc.
- Production schedules.

In 2007 the RDR estimate was based on the European estimates, in turn scaled from the original industrial studies made by the TESLA Collaboration and subsequently scaled for the European XFEL project. These estimates were considered the most mature at that time. In keeping with the definition of the RDR VALUE estimate (see Section 7.5.1), they were based on single-vendor models for mass-production.

For the TDR, a new estimate is expected to be made which will take into account (as far as possible) the above constraints and new information. In addition, the actual costs for the

European XFEL mass-production (5% of the ILC) will be known, and will provide an important data point for the ILC estimates.

Before a defendable cost estimate can be made, it is first necessary to identify the mass-production models on which that estimate is based. The TESLA single-vendor model represents one extreme (single fabrication plant) and was assumed to give the lowest-cost solution (cost reduction via the maximum large volume fabrication). Other models being considered (e.g. multiple vendors in each of the three regions) are potentially more expensive, but may prove more realistic given the constraints listed above.

An early milestone will be the definition of one (preferable two) such models on which further studies can be based (end of CY 2010).

An initial comprehensive estimate for the cryomodule should be made available by the end of 2011.

7.1.2 High-Level RF (variants)

The on-going design work for the TDR has produced two new concepts for the High-Level RF (HLRF) in addition to the RDR solution (KCS and DRFS, see Section 4.5). The new concepts represent significantly different approaches, and have large impact on the CFS solutions (Section 7.2.2). Separate cost estimates will be required for both technical solutions. In addition, both solutions introduce components for which cost estimates will have to be made (novel power distribution system components for KCS; modulated anode modulator and klystron for DRFS).

A consolidated cost estimate for the HLRF variants (hardware) consistent with the final design parameters of the machine should also be made available by end of 2011.

7.2 Conventional Facilities and Siting

7.2.1 General considerations

A major part of the TD Phase design activities (see Section 5.4.5) is cost-reduction primarily via the reduction in the scope of the underground construction. Further CFS-related cost reductions either have been or will be identified via targeted value engineering of key CFS cost drivers (e.g. water cooling requirements).

The updated estimates will primarily reflect the change in requirements from the accelerator design team. While the estimates are expected to be predominantly based on unit costs developed for the RDR, specific new estimates will be made where possible, or where no estimate exists in the RDR.

7.2.2 Site specific issues

The RDR cost estimate was based on three similar sample sites (one per region), using an almost generic design for the machine, and with identical technical components for each of the sites. During the TD Phase, the development of these sites has progressed significantly, and the designs have diverged as the precise nature of the site-specific constraints have immerged. This has been in-part driven by the desire for a single-tunnel solution for the Main Linac, and the related proposals for two novel HLRF solutions (see Section 4.5). Although the progress in understanding realistic site constraints is considered a major step beyond the RDR, the challenge of producing cost estimates for these *variants* and possible options is not insignificant. A further (policy) issue is the inclusion of these potentially different estimates into a single VALUE estimate for the TDR. The approach here is to:

- Make an early decision on the number of *variants* to be studied for the CFS solutions (end 2010).
- Continued technical, cost and schedule work on these agreed-upon variants to an equivalent level of detail (resource permitting). Internal cost estimates for the CFS solutions should be available by the end of 2011.
- In parallel, develop a strategy for presenting the final TDR VALUE estimate, which can then be consolidated in early 2012.

A primary goal will be the definition of a single baseline machine with an associated VALUE estimate, with additional costs for the supported variants.

7.3 Conventional Accelerator Systems

The remaining ~30% of the RDR cost is associated with the more conventional accelerator technical components (e.g. magnets, power supplies, vacuum systems, instrumentation and controls). Due to resource constraints, it is not expected to produce new bottom-up estimates for these technical components for the TDR. Instead, the RDR numbers will be scaled appropriately to match the required component counts (quantities) for the updated baseline design. Where resources allow, updates to the existing unit costs will be made.

In principle therefore, the cost for the conventional accelerator systems should be relatively straightforward, once the lattices, requirements and component counts are known. The goal for producing the initial updated estimate for these systems is mid 2011.

7.4 Construction Schedule

The TDR is also expected to contain an updated construction schedule. This will require both the review of the existing RDR models, as well as inclusion of more detailed results of other relevant discussions. Specifically:

- Realistic and cost-optimised civil construction schedule for the updated baselines.

- Inclusion of the models for mass-production for the major components (namely SCRF), including realistic start-up of fabrication facilities etc.
- Installation schedules, including manpower.
- Support of early commissioning strategies (where possible and/or cost-effective).

The construction schedule and VALUE estimate cannot be developed independently as one can clearly influence the other. An early model for a construction schedule (including all the points above) is desirable on which to assess the initial cost estimates, after which studies of optimisation can be made.

Methods for developing the construction schedule are not yet specified, and should be developed over the remainder of the year (end of 2010).

7.5 Basic methodology and tools

7.5.1 Methodology

As of writing, it is assumed that the TDR will contain a VALUE estimate using essentially the same definition as the RDR:

- A least-common international estimate (representing lowest bid for a global tender).
- Quoted in 2012 (TDR) costs – no escalation to projected construction completion.
- No contingency.
- Institutional (laboratory) labour quoted separately in person-hours.

The costing methodology for the TDR will remain essentially unchanged from that developed for the RDR. Specifically:

- Cost Estimate (and date of estimate) & Laboratory Labour Estimate – in Hours, separately for Engineers, Scientists, Technicians, and Administration.
- WBS Dictionary – definition/description for each entry.
- Basis of Estimate – description how the estimate was done and why it should be believed (including where relevant methods to extrapolate to large quantity production).
- Cost optimisation considerations – capital costs relative to operating costs.
- Uncertainty range for cost estimate and shape of probability distribution function (cost risk analysis).

More detailed instructions and guidelines for the RDR cost estimate can be found here:

- RDR costing guidelines[5].
- RDR Cost Estimating Instructions[6].

Both these documents will be reviewed and updated for the TDR effort by the end of 2010.

[5] http://www-ilcdcb.fnal.gov/RDR_costing_guidelines.pdf

[6] http://www-ilcdcb.fnal.gov/RDR_Cost_Estimating_Instructions_23may06.pdf

7.5.2 VALUE unit

The RDR VALUE estimate was published in units of ILCU, defined as 2007 year US dollars. The exchange rates used for converting (primarily) Japanese and European estimates (Yen and Euro respectively) were fixed at the average rates for 2006.

It is proposed to provide the TDR estimate in 2012 costs. However, it is critically important to maintain a clear and unambiguous comparison to the original published RDR VALUE estimate. This will require careful escalation of the RDR estimate to 2012 costs. Care will also need to be taken in dealing with fluctuating exchange rates. (Note also this escalation is also required for those unit costs which will not be re-estimated as part of the TD Phase 2 activities.)

An exact approach (definition) of the TDR VALUE unit will be published at the end of 2010 (together with the updated guidelines – see Section 7.5.1).

7.5.3 Tools and documentation

During TD Phase 1, a new ILC Cost Estimating Tool has been developed called ICET. Use of this tool will formalise both the documentation and development of the VALUE estimate. The current RDR estimates have been implemented in this tool as a starting point for the TDR costing activities.

An important goal for the TDR is to provide an integrated and consistent set of design documentation which directly supports the VALUE estimate. It is intended that the ICET tool together with ILC-EDMS will support the required traceability between costs and design, in a formal environment.

Early prerequisites for the design and cost effort is the development of WBS structures for both design documentation and the cost breakdown (ideally, but not necessarily the same). A goal is to accomplish this by the end of 2010.

Once in place, the tools should allow careful auditing of the estimates with respect to the design documentation (component counts, power requirements etc.). Once the base documentation is established, (controlled) changes to it should be relatively straightforward to reflect in the cost estimates.

If implemented correctly, the tools should support design iterations during the cost consolidation phase currently foreseen in the first half of 2012, leading up to the final estimate for TDR publication.

Use of these tools will require training for those responsible for the estimate and design documentation.

8 Technical Risk

8.1.1 General definition of Technical Risk for the TDR

An important element of the TDR is an assessment of the remaining technical risk of the project, together with an estimate of the scope of the remaining risk-mitigating R&D required. Shortly after the publication of the RDR, a technical *risk register* was developed. Technical risk is defined as risk associated with achieving a specific technical objective (specification), and is separated from the risk associated with the VALUE estimate, which reflects the uncertainty in the estimate itself for the baseline machine configuration described. However, technical risk clearly has a potential cost impact, given that failure to achieve an R&D goal would have to be mitigated by a design modification, which in general either infers a change in scope or an increase in cost.

For the TDR, it is intended to further formalise the risk register method adopted for the RDR, and to attempt to *quantify* as far as possible the perceived technical risk in the design. Quantification of risk requires the definition of a clear and unambiguous methodology, several examples of which exist. In general, such methodologies require consensus expert opinion since the perception of risk tends to be subjective. Ultimately the Project Management is responsible for providing an overall balanced assessment of the TDR risk.

8.1.2 Risk Assessment – the process

Risk is defined as the probability of failure. The risk assessment process is intended to evaluate the impact a given failure has on the project and the likelihood of that failure. A typical risk scoring matrix approach (see GAO-09-3SP, chapter 14) considers 6 kinds of failure:

1) basic technology
2) engineering
3) production yield
4) product reliability
5) existence of a viable backup
6) schedule.

The project can respond to perceived risk at any time, and it is generally accepted that the penalty for doing so increases with time. The initial and more detailed focus will be on the first two: basic technology and engineering. The remaining four kinds of failure are more project-focused and are to be assessed more qualitatively as part of the Project Implementation Plan. Commonly, ‘basic technology’ refers to the scientific underpinning of the subsystem in question and ‘engineering’ refers to the deployment of a given technology to a specific application. Often, engineering related efforts are not initiated until basic technical and scientific evaluations and tests are complete, and the two sets of scores naturally represent a single sequence and can be merged.

The assessment of risk is derived from a series of simple questions which refer to status and plans at the nominal ‘point in time’. The questions focus directly on the development life cycle of a given subsystem or application of technology and it is assumed that risk is roughly proportional to the scope of the needed R&D effort (and vice-versa). The anticipated penalty is based on how the project would respond and apply a mitigation strategy once failure is evident or the risk becomes too great. Both the risk (probability) and penalty (cost of responding to failure) must be considered in order to gauge the impact. It is the 'impact' which is recorded and summarised in the technical risk register.

The project-wide comprehensive process of estimating risk is a task for TD Phase 2:

1) Develop a clear and agreed-upon methodology a suitable matrix scoring system.
2) Clearly identify those design elements which remain high technical risk (across the entire project).
3) Score each component based on the status of the risk-mitigating R&D based on the prescribed methodology. This process will require a consensus-building approach across the TAG leaders and key experts.
4) Develop a practical mitigation strategy model. For example, what would the project do if post TDR progress was deemed unsatisfactory before construction start?
5) Estimate the cost for the mitigation effort, using costing guidelines similar to those used for the TDR.
6) Roll the resulting scoring and associated mitigation costs up to create a summary 'risk assessment' to be entered at the top level of the register.
7) Review the most serious register elements in detail to ensure the scoring, mitigation strategy and costing have been done consistently according to basic guidelines.

A comprehensive initial estimate for the Risk Register across the project should be an early goal in TD Phase 2. The register should then be maintained an updated as the remainder of the TD Phase R&D and AD&I activities progress, concluding with the publication of the TDR.

Milestones:

- Development and publication of methodology (end 2010)
- Initial canvassing of qualitative risk assessment across the Technical Areas (March 2011)
- Development of scores and ranking and final publication of final consensus (end 2011)
- Review / update of risk register for TDR (mid 2012)

Appendix A: Global Resource Estimates for TD Phase 2

The resource base information for the TD Phase R&D activities is shown in Tables A.1-3, for each of the three Technical Areas (Superconducting RF Technology, Conventional Facilities & Siting and Global Systems and Accelerator Systems). The tables show anticipated person-years of labour effort and, separately, funds expected to be applied during the TD Phase from 2010 to 2012 inclusive for each participating country. The resource information is consistent with possible funding scenarios supplied by institutional and funding program managers. The data in these tables are not those that are guaranteed to be provided. They include not only the resources directed to ILC R&D, but also resources for technology developments that are useful for the ILC.

Table A-1: Anticipated Resources available in each country (including CERN) for the TD Phase 2 (2010-2012) activities – Superconducting RF Technology Technical Area.

FTE		Tech Area Group					
Region	Country	Cavities	Cryogenics	Cryomodule	HLRF	ML Integration	Grand Total
Americas	Canada	18.0					18.0
	US	67.7		21.6	47.3		136.6
Asia	China	21.0	12.0	15.0	6.0		54.0
	India	18.0		9.0			27.0
	Japan	38.4	6.2	5.7	9.0	9.6	68.9
Europe	France	18.8					18.8
	Germany	56.4	3.0	3.0	3.0	1.1	66.5
	Italy	10.5	0.9	3.6			15.0
	Russia	6.0		24.0			30.0
	Spain			2.3		4.0	6.3
Grand Total		254.8	22.1	84.2	65.3	14.7	441.1

M&S totals		Tech Area Group						
Region	Country	Cavities	Cryogenics	Cryomodule	HLRF	ML Integration	Grand Total	
Americas	Canada	1050					1050	k$
	US	5329		2652	4230		12211	k$
Asia	China	7000	39999	3000	3000		52999	kRMB
	India	1170		675			1845	k$
	Japan	968	194	312	213	282	1969	MJPY
Europe	France	1123					1123	k€
	Germany	2548	193	193	193	12	3139	k€
	Italy	450	30	60			540	k€
	Russia	40		50			90	k$
	Spain			150		50	200	k€

Table A-2: Anticipated Resources available in each country (including CERN) for the TD Phase 2 (2010-2012) activities – CFS & Global Technical Area.

FTE		Tech Area Group		
Region	Country	CFS	Controls	Grand Total
Americas	US	3.0	13.3	16.3
Asia	Japan	8.2	4.8	13.0
Europe	EU	2.4		2.4
	France		3.7	3.7
	Germany	2.4	17.2	19.6
	Poland		1.9	1.9
	Russia	9.0		9.0
	Switzerland		1.5	1.5
Grand Total		25.0	42.4	67.4

M&S totals		Tech Area Group			
Region	Country	CFS	Controls	Grand Total	
Americas	US	2925	830	3755	k$
Asia	Japan	90	82	172	MJPY
Europe	EU	60		60	k€
	France				k€
	Germany	154	478	632	k€
	Poland		94	94	k€
	Russia	125		125	k$
	Switzerland		45	45	k€

Table A-3: Anticipated Resources available in each country (including CERN) for the TD Phase 2 (2010-2012) activities – Accelerator Systems Technical Area.

FTE		Tech Area Group							
Region	Country	BDS	DR	Electron Source	Positron Source	RTML	Simulation	Damping Ring	**Grand Total**
Americas	**Canada**		3.8						3.8
	US	39.4	22.7	11.4	9.7	9.5		4.2	96.9
Asia	**China**		15.0		9.0		6.0		30.0
	Japan	20.7	23.1	4.2	5.4		1.6		55.0
	Korea	6.0	1.5			1.5	1.5		10.5
Europe	**EU**	2.1	1.5		1.5		1.5		6.6
	France	5.9			9.0				14.9
	Germany	0.5	0.5	0.5	4.8	0.5	0.5		7.3
	Italy		8.1						8.1
	Russia			28.0	16.5				44.5
	Spain	12.0							12.0
	UK	8.5	0.3		4.0				12.8
Grand Total		95.0	76.5	44.1	59.9	11.5	11.1	4.2	302.3

M&S totals		Tech Area Group								
Region	Country	BDS	DR	Electron Source	Positron Source	RTML	Simulation	Damping Ring	**Grand Total**	
Americas	**Canada**		15						15	k$
	US	2097	1723	699	480			50	5049	k$
Asia	**China**		500		500		100		1100	kRMB
	Japan	11	444		3				458	MJPY
	Korea	40	20			20	20		100	Mwon
Europe	**EU**	45							45	k€
	France				260				260	k€
	Germany	32	32	32	45	32	32		205	k€
	Italy		150						150	k€
	Russia			60					60	k$
	Spain	100							100	k€
	UK	95	5		20				120	k£

Appendix B: Summary of Participating Institutes (TD Phase 2)

Table B-1: Institutes participating in TD Phase 2 activities for the SCRF Technology Technical Area.

Cavities		
Americas	Canada	Triumf
	USA	ANL, Cornell, FNAL, FSU, LLNL, Jlab, SLAC
Asia	China	IHEP, PKU, Tsinghua University
	India	BARC, IUAC, RRCAT, TIFR, U. Delhi, VECC
	Japan	KEK
	Korea	KNU, PAL
Europe	France	LAL/Orsay, Saclay
	Germany	DESY
	Italy	INFN
Cryomodules		
Americas	US	ANL, FNAL, Jlab, SLAC
Asia	China	IHEP, TIPC
	India	BARC, IUAC, RRCAT, TIFR, U. Delhi, VECC
	Japan	KEK
Europe		CERN
	France	Saclay
	Germany	DESY
	Italy	INFN
Cryogenics		
Americas	Canada	Triumf
	USA	ANL, BNL, FNAL, Jlab, SLAC
Asia	India	BARC, IUAC, RRCAT
	Japan	KEK
Europe		CERN
	Germany	DESY
High Level RF		
Americas	US	FNAL, SLAC
Asia	China	IHEP
	India	BARC, RRCAT
	Japan	KEK
	Korea	KNU
Europe	Germany	DESY
Main Linac Integration		
Americas	US	FNAL, SLAC
Asia	China	IHEP
	Japan	KEK
Europe	Germany	DESY
	Spain	CIEMAT

Table B-2: Institutes participating in TD Phase 2 activities for the CFS & Global Systems Technical Area.

CF&S		
Americas	USA	FNAL, SLAC
Asia	Japan	KEK
Europe	 Germany Russia	CERN DESY JINR
Controls		
Americas	USA	ANL, LBNL, FNAL, Jlab, SLAC, UIUC, UPEN
Asia	China Japan	IHEP KEK
Europe	Italy Germany	INFN DESY

Table B-3: Institutes participating in TD Phase 2 activities for the Accelerator Systems Technical Area.

Electron Source		
Americas	USA	SLAC, FNAL, Jlab
Asia	China	Tsinghua University
	Japan	Hiroshima U, KEK, Nagoya U
Positron Source		
Americas	USA	ANL, BNL, Cornell, LLNL
Asia	China	IHEP
	Japan	Hiroshima U, KEK
Europe	 France Germany UK Ukraine	CERN Orsay DESY, Hamburg U. Cockcroft Inst., Daresbury Lab., Lancaster U., Liverpool U., Durham U., Manchester U., RAL. KIPT
Damping Ring		
Americas	USA	ANL, Cornell U., FNAL, LBNL, SLAC
Asia	China Japan Korea	IHEP KEK KNU
Europe	Italy UK	INFN Cockcroft Inst.
RTML		
Americas	USA	Cornell U., FNAL
Asia	China Japan Korea	IHEP KEK KNU
Europe	Germany Russia	DESY Efremov, JINR
BDS		
Americas	USA	BNL, Colorado U., FNAL, Iowa U., Jlab, LANL, LLNL, LBNL, MSU, Notre Dame U., Oregon U., SLAC, Wisconsin U., Yale U.
Asia	China India Japan Korea	IHEP BARC, RRCAT KEK, Kyoto U., Tohoku U., Tokyo U. KNU, PAL

Europe		CERN
	France	LAL/Orsay, LAPP, Saclay
	Germany	DESY
	Russia	BINP, JINR, Moscow U.
	Spain	IFIC
	UK	Abertay U., Birmingham U., Cockcroft Inst., Cambridge U., Dundee U., IPPP Durham, Lancaster U., Liverpool U., Manchester U., JAI, Oxford U., RHUL, UCL
Simulation		
Americas	USA	Cornell U., FNAL, SLAC
Asia	China	IHEP
	India	BARC, RRCAT
	Japan	KEK
	Korea	KNU
Europe		CERN
	France	LAL/Orsay
	Germany	DESY
	UK	Cockcroft Inst., IPPP Durham, Liverpool U., Manchester U., Oxford U., RHUL

Table B-4: Participating institutes in alphabetical order

Institute	*Country*	*Abbreviation used in Tables B-1 to 3*
Abertay University	UK	Abertay U.
Argonne National Laboratory	USA	ANL
Bhabha Atomic Research Center	India	BARC
Birmingham University	UK	Birmingham U.
Budker Institute of Nuclear Physics	Russia	BINP
Brookhaven National Laboratory	USA	BNL
Cambridge University	UK	Cambridge U.
CEA, Centre de Saclay	France	Saclay
Centro de Investigaciones Energeticas, Medioambientales y Tecnologicas	Spain	CIEMAT
Cockroft Institute	UK	Cockcroft Inst.
Colorado University	USA	Colorado U.
Cornell University	USA	Cornell U.
Daresbury Laboratory	UK	Daresbury Lab.
Deutsches Elektronen-Synchrotron	Germany	DESY
Dundee University	UK	Dundee U.
Durham University	UK	Dundee U.
European Organization for Nuclear Research	EU	CERN
Efremov Scientific Research Institute	Russia	Efremov
Fermi National Accelerator Laboratory	USA	FNAL
Florida State University	USA	FSU
Hiroshima University	Japan	Hiroshima U.
Instituto de Fisica Corpuscular	Spain	IFIC
Institute of High Energy Physics	China	IHEP
Institute for Particle Physics Phenomenology	UK	IPPP
Inter University Accelerator Centre	India	IUAC

Istituto Nazionale di Fisica Nucleare	Italy	INFN
John Adams Institute	UK	JAI
Joint Institute for Nuclear Research	Russia	JINR
High Energy Accelerator Research Organization	Japan	KEK
Kharkov Institute of Physics and Technology	Ukraine	KIPT
Kyoto University	Japan	Kyoto U.
Kyungpook National University	Korea	KNU
Laboratoire de l'accelérateur linéaire Orsay	France	LAL Orsay
Laboratoire d'Annecy-le-Vieux de Physique des Particules	France	LAPP
Laboratori Nazionale di Frascati	Italy	INFN-LNF
Lancaster University	UK	Lancaster U.
Lawrence Berkeley National Laboratory	USA	LBNL
Lawrence Livermore National Laboratory	USA	LLNL
Liverpool University	UK	Liverpool U.
Los Alamos National Laboratory	USA	LANL
Manchester University	UK	Manchester U.
Moscow University	Russia	Moscow U.
Michigan State University	USA	MSU
Nagoya University	Japan	Nagoya U.
Oxford University	UK	Oxford U.
Pohang Accelerator Laboratory	Korea	PAL
Royal Holloway, University of London	UK	RHUL
Raja Ramanna Centre for Advanced Technology	India	RRCAT
Stanford Linear Accelerator Laboratory	USA	SLAC
Tata Institute of Fundamental Research	??	TIFR
Technical Institute of Physics and Chemistry	China	TIPC
Thomas Jefferson National Accelerator Facility	USA	JLab
Tohoku University	Japan	Tohoku U.
Tokyo University	Japan	Tokyo U.
Tri-University Meson Facility	Canada	Triumf
Tsinghua University	China	Tsinghua U.
University of British Columbia	Canada	UBC
University College London	UK	UCL
University of Delhi	India	Delhi U.
University of Illinois at Urbana Champaign	USA	UIUC
University of Iowa	USA	Iowa U.
University of Michigan	USA	UM
University of Notre Dame	USA	Notre Dame U.
University of Oregon	USA	Oregon U.
University of Pennsylvania	USA	UPEN
University of Wisconsin	USA	Wisconsin U.
Variable Energy Cyclotron Centre	India	VECC
Yale University	USA	Yale U.