Table of Contents

1 Purpose of this Document 3

2 Overview of Technical Design Phase 2 4

3 Superconducting RF Technology 5
3.1 Achieving (assessing) the average accelerating gradient 8
  3.1.1 Superconducting cavity R&D to improve the gradient yield 12
  3.1.2 Fabrication QA/QC and fabrication improvement and optimisation 13
  3.1.3 Material improvement and optimisation 13
  3.1.4 Post-fabrication improvement, optimisation and remediation 14
3.2 Justification for the ILC accelerating gradient .エラー! ブックマークが定義されていません。
3.3 Towards a global cryomodule design (plug compatibility) 15
  3.3.1 Cavity integration 15
  3.3.2 Cryomodule assembly and the global Collaboration for cryomodule testing: S1-Global 16
  3.3.3 Thermal test of the S1-Global cryomodule 17
  3.3.4 Distributed RF System(DRFS) tests at S1-Global 17
3.4 ILC Cryomodule design 18
  3.4.1 Thermal shield design 18
  3.4.2 Magnetic shield design 18
  3.4.3 Design to limit vibration 18
  3.4.4 Plug-compatibility 18
3.5 Preparation for industrialisation 19
  3.5.1 European Approach 19
  3.5.2 Asian Approach 19
  3.5.3 Americas Approach 19
  3.5.4 Industrialization models and the TDR VALUE estimate 20
3.6 Cryogenics design study and R&D .. エラー! ブックマークが定義されていません。
3.7 Development of High-Level RF solutions 21
  3.7.1 Modulator 21
  3.7.2 Power Distribution System 21
  3.7.3 Klystron Cluster Scheme R&D 22
  3.7.4 Distributed RF System R&D 24
3.8 System integration testing ("string tests") 25
  3.8.1 Motivation for System Test 25
  3.8.2 Goals of the System Tests 26
  3.8.3 Global Competence and Diversified Strategy 27
  3.8.4 Main Linac Technology Test Facilities 27

4 Accelerator Systems Beam Test Facilities (BTF) and other R&D 31
4.1 Beam Test Facilities 31
4.2 Cesr-TA (electron cloud mitigation) 31
4.3 ATF-2 (Final Focus optics and stabilisation) 34
4.4 Other Accelerator Systems R&D 35
  4.4.1 Electron source R&D 35
  4.4.2 Positron source R&D 35
  4.4.3 Damping Ring R&D 36
  4.4.4 RTML R&D 36

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.

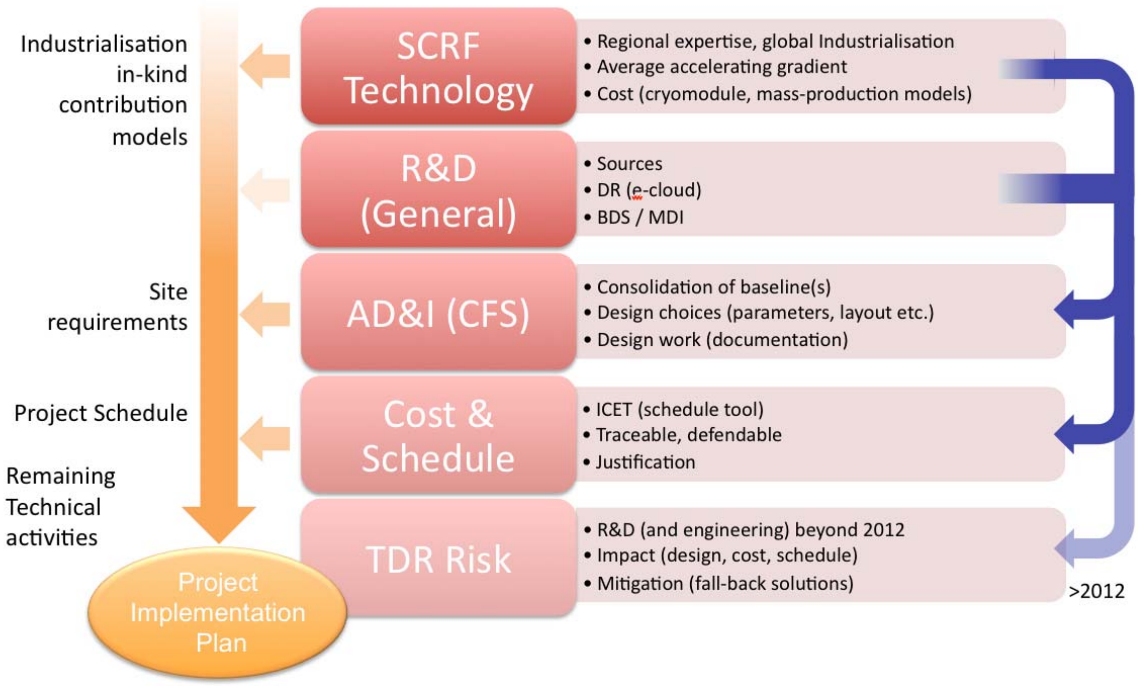

Figure 2.1: TD Phase 2 technical themes (scope of the Technical Design Report).

Figure 2.1 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. Figure 2.2 shows the schedule including top-level milestones for Phase 2.

Figure 2.2: Top-level milestones for TD Phase 2

3 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 industrialization of SCRF components and
3. adoption of different kinds of site topography, each of which 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 increase cost and complexity of the increased 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-loading 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 interchangeable, 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 the 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 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 wake-field and HOM calculations.

The milestones for the TD Phase SCRF goals outlined in section 3.1.1 (notably the S0, S1 and S2 programs) are summarized in Table 3-1.

Table 3-1: 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 TDP1, and 90% in TDP2 1), 2)	2010/ 2012
S1	Cavity-string	31.5 MV/m, on average, at $Q_0 \geq 10^{10}$, in one	2010

		cryomodule, including a global effort	
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 for the radiation emission is to be included in the milestone list in near future.*

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 the a critical review of the R&D results and an assessment of the perceived technical risk. Table 3-2 summarises the key ILC design parameters and their relationship to the R&D programmes described in the remainder of this section.

Table 3-2: 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*

3.1 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 the emitted radiation, measurement techniques are not yet mature and no suitable calibrated monitor exists. This is an important goals for TD Phase 2.

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 electro-polish 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 8E9, 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 3.1, and the raw number of cavities as a function of maximum gradient is shown in Figure 3.2. The sample averages and standard deviations are shown as a function of the minimum accepted gradient in Figure 3.1. These data samples shall continue to be updated periodically as additional test data become available.

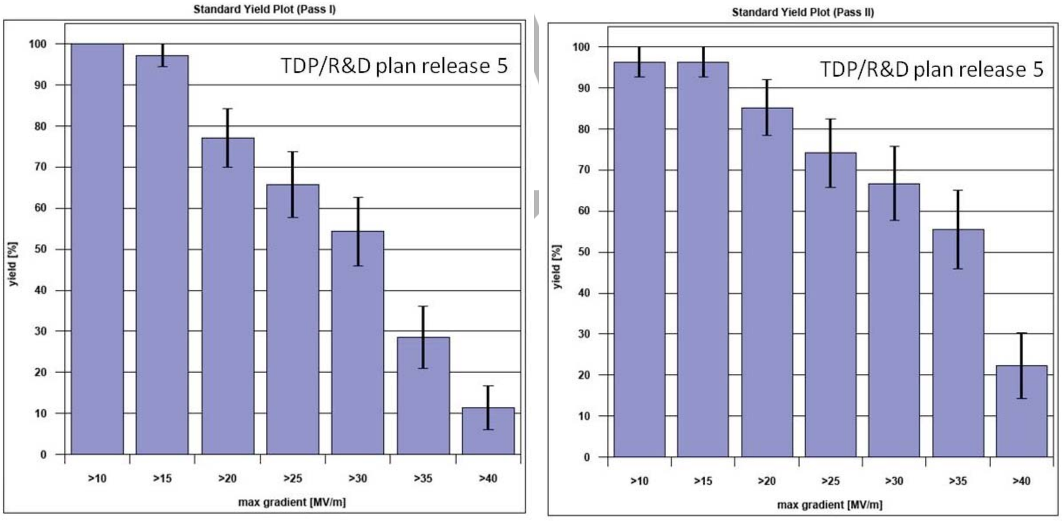

Figure 3.1: First-pass (left) and second-pass (right) yields as a function of maximum gradient. [updated data by June 30.]

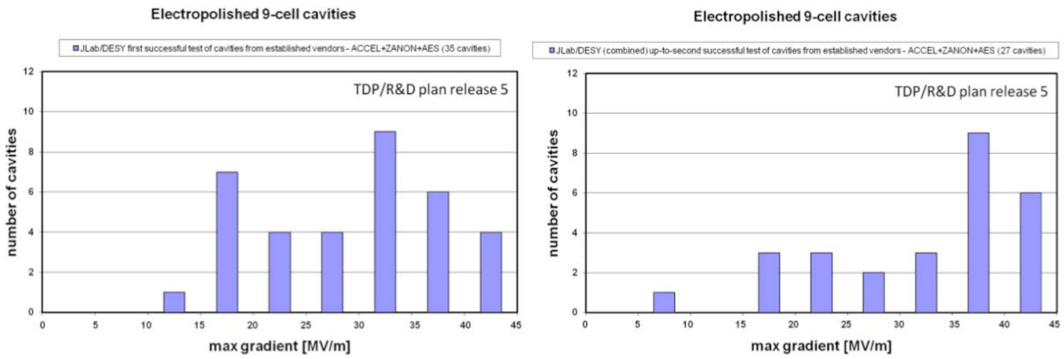

Figure 3.2: Number of cavities as a function of maximum gradient, for first-pass (left) and second-pass (right) data samples. [updated data by June 30.]

Figure 3.3 shows the 1st and 2nd pass 'average gradient yield' achieved if a spread in the gradient limit of <u>individual</u> 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 20 – 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.

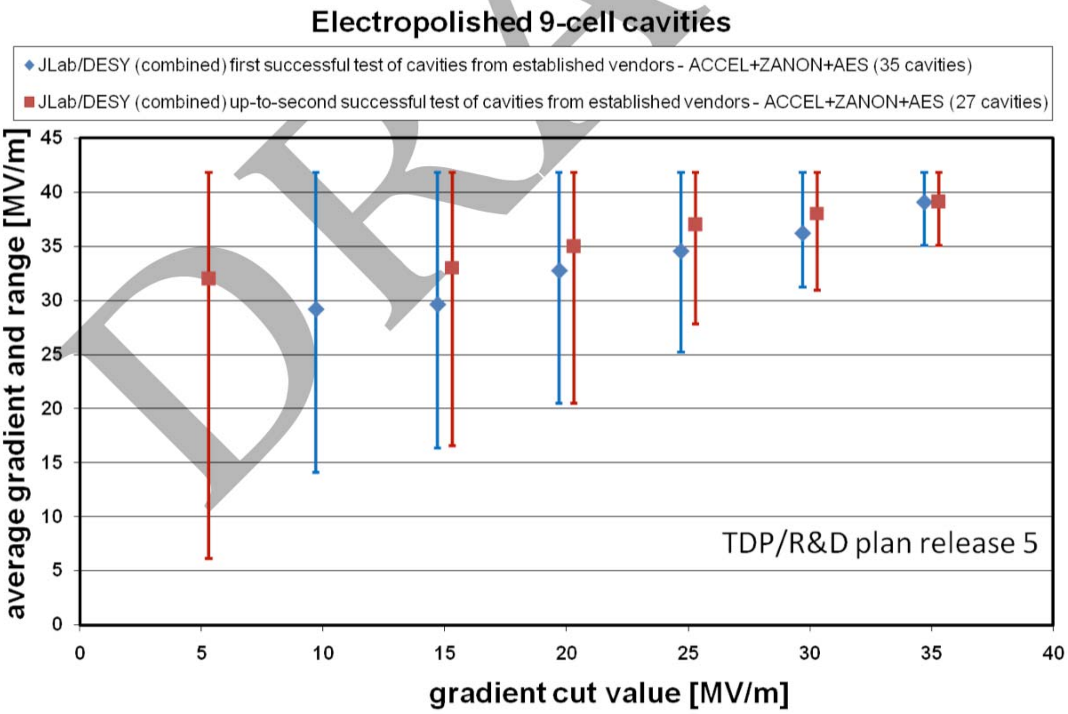

Figure 3.3: Average gradient (data points) and range (error bars) of the first-pass and second-pass data samples after excluding cavities which fail to meet the minimum gradient shown on the horizontal axis. The two data samples have been artificially offset from each other for clarity. [updated data by June 30.]

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, at 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 using the ILC-like process in Europe for the European XFEL (end of 2011 until early 2014) will provide a very large statistical sample directly applicable to the 1st pass statistics without any bias. Although the ~640 cavities required for the construction of the XFEL linac will only undergo one EC cycle (the acceptance criteria for XFEL is lower than ILC), ~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 summarize the projected numbers of cavities procured by the end of TD Phase 2.

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

	Before TDP	FY2008	FY2009	FY2010	TDP1, sum	TDP2 2011-2012
Americas	36	0	12	30+10	88	+? (TBD)
Asia JP	15	3	13*		31	+10 (TBD)
CN			1	1	2	
Europe	68	-		26*	26	+? (TBD)
(XFEL)				(640**)	(640)	
Total	119	4	52	41	147 (+640)	+10+? (TBD)

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[1] By the 1st Baseline Assessment Workshop – see section 5.1.1.

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

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

3.1.1 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, (Ref: H. Weise et al., TTC Report 2008-2, 2008) have been used in all major SRF facilities in all three regions, based on a recommendation given the TTC collaboration (Ref: TTC document). 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 $Q_0 \geq 8\times10^9$ is being achieved up to a second-pass processing (see Section 3.1).

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 3.1). 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 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 side 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.

3.1.2 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 the goal gradient of XFEL is different from 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 (see Section 3.1).

The established fabrication technology such as forming, machining and electron beam welding have room for improvement and optimization. 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 in 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 eliminates 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.

3.1.3 Material improvement and optimisation

Improvement in the gradient yield is also expected from material improvement and optimization. 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.

3.1.4 Post-fabrication improvement, optimisation and remediation

Post-fabrication improvement and optimization 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 should 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 localized 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, possibly over 40 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 SRF facilities.

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

Table 3-3: 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/Industry) Bare 9-cell cavities w/ in-house welder

			(JLAB) XFEL and HighGrade Project (DESY)
High.	Mechanical polishing prior to heavy EP	Eliminates 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	Large-grain cavities and multi-wire slicing (KEK), Processing and evaluation of 8 existing 9-cell large grain cavities,
High	Seamless cavity	Eliminate weld prep machining and EBW	Hydroform and test muti-cell cavities, (DESY-JLab) Hydroform and test multi-cell cavities (FNAL/Ind.)
Mid.	Material improvement	Nb with low Ta concentration	Material characterization and 1-cell cavity testing (FNAL) Material characterization 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 horizonatal test FE as well as dark current in linac beam operation, Comparison across facilities world-wide,

3.2 Towards a global cryomodule design (plug compatibility)

3.2.1 Cavity integration

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

- Tuner including integration with He jacket
- RF input-couplers
- Cavity assembly with plug-compatibility
- Preparation for industrialization

There are 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 install 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 phase2 cryomodules for the slide-jack tuner. In 2010, the S1-Global cryomodule experiment at KEK-STF supplies 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 be also be directly compared, together with frequency control sensitivity, and the performance of the repetitive pulse compensation action.

The R&D for the high-power coupler will focus on achieving a compatible design between tuneablity, easiness 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 will be operated and directly compared.

3.2.2 Cryomodule assembly and the global Collaboration for cryomodule testing: S1-Global

The ‘S1-Global’ project is currently in progress, with an aim to demonstrate the ILC accelerating field gradient with an international constructed cryomodule (eight 9-cell cavities). It has been successfully assembled at KEK, and is scheduled to have cold tests from June 2010 to December 2010 at KEK-STF. The cryomodule consists of the two half-length cryostats which house 4 cavities each. Table 3-4 indicates the configuration of cavities, tuners and high-powered couplers used.

Table 3-4: The S1-Global cryomodule configuration.

Cryostat	Cavities	Tuner	Coupler
A	4× KEK	Side-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 experiences gain of these different components, the assembly processes and man-hours are able to be compared and reviewed. The data provide important input for the estimate of the assembly cost for the ILC cryomodule.

The experiment items for these cavities are summarized in Table 3-5.

The S1-Global programme will run until the end of December 2010, after which the STF phase-2 accelerator construction will begin (January 2011) which represents a hard cut-off. It is therefore important to keep the S1-Global programme on schedule.

Table 3-5: R&D issues which will be evaluated in S1-Global

Subject	Contents	Contributed by
Cool-down and cryogenic performance	Alignment and Frequency deviation	KEK, IHEP, DESY

	Heat load	
Low-power RF	Tuner (motor and Piezo) test and frequency tuning Qt calibration HOM property Single pulse response to Piezo tuner, General tuner test	KEK, FNAL, INFN
High-power RF Dynamic Heat Load	High gradient test With high-power RF, High-gradient test	KEK, FNAL
LLRF control/feedback Dynamic Heat Load High-power RF	With high-power RF, High gradient test, DRFS with high-power RF,	KEK, FNAL, KEK, FNAL
HLRF- LLRF control/feedback Dynamic Heat Load	DRFS With high-power RF,	KEK, FNAL

3.2.3 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 in order to evaluate their thermal.

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 (WPM), 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.

3.2.4 Distributed RF System(DRFS) tests at S1-Global

For the RF power source, S1-Global will use the 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 (MAK), together with the LLRF control. Each klystron will be connected to two cavities with a simple waveguide system eliminating the circulators.

3.3 ILC Cryomodule design

3.3.1 Thermal shield design

The proposed design of the ILC cryomodule in RDR has two sets of thermal shield of 5 K and 70 K as same as the TTF-Type-III and XFEL cryomodules. In the 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, and the total cost without the 5K shield by optimizing the cooling scheme can be less than that with 5K shield. For the ILC cryomodule design, the cryomodule components need to be designed to make the study of this thermal concept possible, and the cryomodule cost should be re-evaluated with the 12 m cryomodule for S2 (STF-2 at KEK) .

3.3.2 Magnetic shield design

The magnetic shield design itself is part of the Cavity Integration technical area (Section 3.2.1). 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.

3.3.3 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.

3.3.4 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.

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.

3.4 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 projects hosted by KEK. In the Americas, multiple vendors are contributing to fabrication of a numbers of cavities, and a hydroforming technology will be further investigated as a possible alternative for cost effective cavity production.

3.4.1 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 weak, 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.

3.4.2 Asian Approach

KEK will construct the KEK cavity fabrication facility (KEK-CFF), 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 installed 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 expected to be used 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 will be open to all interested industrial partners to study cost-effective manufacturing, in cooperation with KEK and other laboratories.

3.4.3 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[2] funds, and these will provide the majority of the cavities to be tested in the Americas up through 2012.

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[2] American Recovery and Reinvestment Act

The current 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 optimize the overall process. As the ILC Project becomes closer to a reality, the goal in the Americas region 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 start point has been with the vendors providing manufacturing and welding skills, with laboratories operating 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. 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, scaleable 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 Beta = 1 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 by under contract by vendors, looking at optimized production facilities, and design changes that would improve manufacturability when producing cavities in ILC quantities. To date these studies have focused on optimizations of the production / welding operations and a redesign of the helium vessel system, but in the future will continue with studies of optimized processing facilities and other improvements.

Finally, alternative manufacturing and processing methods, such as hydroforming of cavities, tumbling and eco-friendly processing will be pursued in the R&D plan due to the potential cost savings to the ILC project.

3.4.4 Industrialization models and the TDR VALUE estimate

The cavity industrialisation model is also under review, starting with an international workshop on the cavity technology and industrialization carried out as a satellite meeting of the 1st International Particle Accelerator Conference, held in Kyoto. Based on this workshop, the following observation/finding and subjects for further study are given.

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 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 amortized by the project and future business beyond the project. During the meeting there were several independent models of infrastructure needs presented, which should be pursued and cross checked leading to TDP-2 for inclusion in the updated production planning.

The learning curve to assume was also the subject of considerable discussion. Based on LHC experience, learning at vendors appeared to stop after about 1/3rd of production was complete. Other models suggest learning might stop after the first 100 units, or the pre-production stage as defined by the project. One advantage of 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 to 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 this and future workshops.

3.5 Development of High-Level RF solutions

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.

3.5.1 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 prototype Marx modulator has been developed at SLAC in order to show proof-of-principle and to establish a design that would allow a credible cost estimate. Current projections would make it possible to develop a cost estimate by mid-2010 and hence allow the adoption of the technology as part of the re-baseline to be used in TD Phase 2.

3.5.2 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 scheme (DRFS). Further investigation and R&D are under discussion in combination with a single tunnel CFS design, as it is discussed in the Section X.X.

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

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

3.5.3 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 TDP toward establishing the feasibility of this scheme.

Thus far, ten meters of 0.480 m diameter circular aluminum 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 aluminum 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 pressurized with dry nitrogen as well as with it under vacuum. It should more rf robust under vacuum, but it would be less expensive to operate it under pressurize for the ILC. Steps of our current (2010) plan are detailed below.

Current program:

- High-power vacuum test the aluminum 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 10 m run of 0.480 m diameter aluminum circular waveguide (WC1890) with perforated pumpout spool in center 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 input assembly to input CTO and cold test from magic-T to output CTO, with WC1890 tapers inserted. Insert WC1890 tapers and connect output assemblies (including windows, directional couplers, and loads) to 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 (see Fig. 1).
- Remove output CTO and short line at taper. Change input CTO shorting cap for small line coupling. Cold test and adjust line length for resonance by using ¼ wave spacer if necessary and final machining 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 traveling waves.
- Pressurize 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 2-4 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 the combining of two sources. Finally, it is desirable to transport the power over longer distances in a traveling 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 CTO's.
- Obtain 70 m more WC1890 waveguide and add to assembly.

- Incorporate bends into long waveguide run between CTO's and repeat high power transmission and resonant tests. Insert ¼ wave spacer and repeat resonant test.
- Make 3rd 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 resonate 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.

3.5.4 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; A circulator-less power distribution system; High-availability power supply system; and LLRF control system.
- The prototype DRFS klystron outputting a medium power of 750kW 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 diagnoses of cavity parameters at the pulsed tail are part of the S1-Global test programme.

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 the 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.

A minimum budget has been approved for these planes, and the design effort for a realistic DRFS system has been made.

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 is 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 will be learnt from the European X-FEL experience in DESY, which faces similar issues. However, additional (and independent) experiment plans to study the radiation shielding need to be made.

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

Maintenance and upgrade scenarios feasibility 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 newly manufactured DRFS klystron will be evaluated. For other equipment, studies of the individual component life-time using available published data will be made.

3.6 SCRF system integration testing (“string tests”)

3.6.1 Motivation for System Test

Full performance of multiple cryomodules will be demonstrated as part of the main linac test system test, referred to as the ‘cryomodule-string test’ or ‘S2’ (ILC-EDMS ID D*860505). The test includes beam acceleration and beam handling. The RDR RF unit consists of three cryomodules with a total of 26 cavities. Most linac systems operational studies can be completed 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 stabilization 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 with beam acceleration
- demonstration of a number of cavities in operation showing repeatability of the production process and providing an estimate of reliability
- evaluation of realistic cavity performance as a test of the industrialisation process, in order to prepare for industrialisation

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

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

The RDR 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 optimized, then the required operational gradient and HLRF power overheads will be minimized 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 3.8.4, 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 stabilize the superconducting linac accelerating RF. In many cases, equipment developed in these smaller test facilities is subsequently directly deployed in the System Tests.

3.6.3 Global Competence and Diversified Strategy

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 time scale. This is partly due to institutional commitments to support parallel projects as well as more fundamental conventional facilities infrastructure limitations. Also, the baseline design itself will 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.

3.6.4 Main Linac 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 EU-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 (3x5MW and 1.3 MW). The and accelerating gradient for one of the seven meets the ILC goal. 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 prioritization. As noted above, three elements are dominant: 1) Lorentz Force detuning (LDF) 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 stabilization 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 characterized 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 error.

In order of priority, the TTF / FLASH 9mA 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 minimize 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 Lorentz Force detuning 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) (Section 3.3.1).

- 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 is quite close to the goal performance for the 9 mA experiment, we expect to deploy the above changes, and take full advantage of long-pulse FEL operation, to achieve the intensity and stability goals in early 2011.

Superconducting Test Facility (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 the 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 STF accelerator. At the end of 2012, the first ILC-type cryomodule will be assembled and installed in the tunnel. STF RF and beam operation will begin in 2013.

Anticipated beam parameters

Beam parameters of the "quantum beam experiment" are 162.5MHz bunch repetition rate within a 1ms RF pulse with 62pC bunch charge. The beam loading (10mA) is slightly higher than that of ILC. For STF phase 2 operation, the injector beam parameters will be changed to 3MHz bunch repetition and 3.2nC bunch charge within the nominal 1ms 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 162.5MHz 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 3.4.2). 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 are constructed in two years (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 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 needed technology and expertise, the injector single-cavity cryomodule is operational and under test for stabilization 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 1 ½ 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 minimizing the impact of Lorentz Force detuning. This system will be applied to control pulse-driven microphonic instability 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.