Plug Compatibility

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27.12.08

Foreword

In the following document, we (the Project Managers) would like attempt to describe our current and evolving philosophy behind plug compatibility. It is not intended as a consensus document; our intention here is to clarify as best we can our ideas, and where possible to address some of the questions that have been brought to our attention. The focus is on the conceptual aspects of plug compatibility (i.e. the rationale) rather than the technical specifications themselves (the engineering solution); the latter requires a document in its own right. The document cannot be (nor is it intended to be) a definitive document describing all aspects of plug compatibility: It should rather be treated as a proposal from the Project Managers for discussion by the global R&D community.

Introduction

When discussing plug compatibility, it is convenient to separate it into two aspects:

- the *rationale* behind adopting plug compatibility, its impact on the Technical Design Phase goals and deliverables, and its possible role in the various project phases beyond the TD phase – approval process, construction phase, operations;

- the *technical and engineering aspects of achieving* a modular plug-compatible design, via the identification of agreed-upon interfaces, specifications and requirements.

Since the concept of “plug compatible” design was first proposed for the SCRF cryomodule in 2007, the focus of attention has been on the *technical and engineering aspects*. Over the year, substantial progress has been made in defining the technical aspects of achieving modularity in sub-component design, by identifying and specifying well-defined engineering interfaces and specifications. For reference, and to show the progress we have made, we have included current status of the technical discussions as Appendix I. The remainder of this document will focus on the first bullet point, namely the *rationale*.

Over the year, the scope of the plug compatibility discussions has expanded to include many issues that go beyond the current R&D phase, ultimately touching on globally distributed mass-production models and the role plug compatibility might play in ‘in-kind’ contribution scenarios for the construction project. These still relative immature concepts have lead to questions and concerns from the community. Many of the questions require detailed answers and raise valid issues. By its nature, plug compatibility remains "work-in-progress" and will require effort over the next year to clarify the critical points; this is especially true when discussing the longer term roles in industrialisation and mass-production models, which ultimately link to project governance models, all of which are important components of the Project Implementation Plan (a key Technical Design Phase deliverable).

The two aspects summarised in the bullet points above are not independent of each other: understanding the goals of plug compatibility for the different project phases must ultimately impact the engineering requirements (the level of supported plug compatibility and modularity). It is easy to imagine that less flexibility would be desirable during mass-production than during the R&D phase. We believe the current R&D phase requires greater flexibility to allow innovation to drive (for example) the development of the SCRF technology across the three regions, maximising the potential to achieve the goal performance (gradient) while at the same time supporting local industrialisation and cost-effective design. This flexibility must be counterbalanced with a view to moving rapidly to a construction project when the time comes, and also by maximising the progress from our limited world-wide resources. In essence, plug compatibility aims to achieve these seemingly contradictory requirements during the R&D phase.

As of writing, the technical aspects of plug compatibility have been focused on the design of the SCRF cryomodule. Although many of the aspects that will be discussed below are potentially applicable to other component sub-systems, we will generally take the superconducting cavity and cryomodule as our example. Other potential areas (for example HLRF, LLRF) are still yet to be identified, however it is common practice to have plug compatible designs, klystrons for example, from multiple vendors. Clearly there is no advantage or necessity in defining plug compatibility interface specifications for all components in the machine. The SCRF is our main R&D focus globally, a primary cost driver, and one component sub-system which is expected to be mass-produced in all three regions, and is therefore a special case.

The primary stated goals of the TD Phase are (ILC TD Phase R&D Plan Release 2):

- perform risk-mitigating R&D (for example, achieving an average accelerating gradient of 31.5 MV/m);
- perform 'value engineering' to reduce and/or constrain the costs; leading to
- an updated technical design with a new associated VALUE estimate;
- develop a Project Implementation Plan, which will contain (amongst other things) one or more models for globally distributed mass-production and 'in-kind' contributions for the construction project.

The first two bullet-points can be loosely relate to the on-going global R&D programme (the focus here being SCRF). The latter two points are both related to each other and to possible models for project construction (part of the Project Implementation Plan): the cost of the cryomodule (for example) will depend on the models for regionally distributed mass-production that are presented. With this division in mind, we will address the possible role of plug compatibility as follows:

- the relevance and role of plug compatibility during the current R&D phase;
- relevance to mass-production models (construction phase), and how this will influences the TDR cost estimate;
- the advantages of plug compatibility after construction (operations phase);
- the importance of plug compatibility during an extended R&D phase (after 2012, but before project approval);

A final section will deal with the plans for implementing plug compatibility itself, and will summarise many of the identified unresolved issues that must be worked on during the TD phase.

2. Plug Compatibility in the R&D Phase (2012)

During the RDR phase, the concept of "baseline" and "alternative" were introduced. A single choice of 'baseline component' (e.g. the TESLA cavity shape) was adopted primarily for the purpose of cost estimation. Alternatives – such as the low-loss and re-entrant cavity shapes – were considered parallel R&D. An alternative design can be adopted as baseline after demonstrating that some performance and cost criteria are met.

The RDR concepts of baseline/alternative is a reflection of the strong desire to promote forward-looking innovative R&D, while at the same time maintaining a sound and feasible baseline for the machine design (and VALUE estimate). Implicit in this philosophy is the 'unknown timeline' for start of construction. When approval is finally obtained, it will be important to facilitate a rapid transition to a construction project, based on the best technology available at that time.

Although adequate for the RDR phase, several problems with the baseline-alternative approach have been identified, especially for the global SCRF development. Specifically:

- the difficulty in specifying baseline acceptance criteria in a consensus-based fashion;
- the uncoordinated (almost independent) fashion with which the R&D activities in different regions of the world proceeded;
- not acknowledging the need for innovative R&D to drive the regional development of the SCRF technology, together with the involvement of regional industry.

Plug compatibility is proposed as a way to address these issues, by effectively replacing the concept of baseline and alternative (specifically for the SCRF development). Through well-defined interface specifications, the R&D teams will indicate which components warrant development to improve performance, which dimensions and external interfaces should become rigidly fixed and which should remain flexible in order to foster development. We believe that this will:

- facilitate better coordination of the world-wide R&D, allowing the exchange of the modular components for testing and evaluation at regional centres (infrastructure);
- provide better focus for the global cryomodule development (design) while still maintaining a controlled flexibility in approach to the modular sub-component design (easy exchange of 3D CAD component models);

- maintain innovative R&D and the flexibility to achieve (or exceed!) the desired RDR performance specifications, mitigating the risk by using quasi-independent approaches;
- constrain (via the interface specifications and the level of plug compatibility) the number of supported variants;
- allow the institutional centres in each region to develop the necessary expertise and infrastructure by fostering and supporting innovation, and at the same time encouraging local regional industry involvement (cost-effective designs).

Once established, the plug compatibility interface specifications will allow innovating design in one region to be rapidly adopted in another. Plug compatibility will also both motivate "collaborative competition" between regional centres which will further push the design, while simultaneously maintaining its focus, without which the design efforts would tend to diverge in an uncoordinated (and uncontrolled!) fashion.

We believe that this approach, while not without challenges, is far better suited to arriving at a globally coordinated R&D effort at the current stage of the ILC project. The interface definitions will assure the institutions and individuals involved in the work that their product can fit properly into larger subsystems under construction in other regions for further testing and validation. We believe that the flexibility provided – together with the commitment of the community to keep certain dimensions standardized – will prove attractive to development teams, allowing us to both engage and direct them in a mutually beneficial way.

We further believe that the alternative approach – of enforcing a single baseline design and defining acceptance criteria for independent alternative concepts – would be counterproductive and unmerited at this juncture. It would not lead to a coordinated and 'compatible' effort, but would have the tendency to suppress rather than motivate innovation and lead design teams away from the core coordinated ILC effort.

Plug Compatibility during the Construction Phase (Impact on TDR VALUE estimate)

One of the most important deliverables for the Technical Design Phase in 2012 is the updated VALUE estimate. The RDR VALUE estimate is based on a set of agreed-upon international costing rules, based on a single vendor model and lowest global bid. For the SCRF, this effectively assumed that all cryomodules were constructed by a single 'vendor' somewhere in the world, and used the lowest estimate from of all three regions.

For the TD phase VALUE estimate, this approach will require review. The Project Implementation Plan will contain one or more models for globally distributed mass-production, related to possible in-kind scenarios for the project construction financing. The updated cost of the cryomodules must be consistent with these models, as well as being based on updated cost information from all the three regions. Much of the details of the VALUE estimate will depend on its final definition and ultimate use as a tool for defining 'share' in the project, as well as its interpretation by the funding agencies. This is clearly beyond the scope of this document: our goal here is to understand the possible impact and relevance of plug compatibility on mass-production and the TDR VALUE estimate, but it is important to bear in mind that all these aspects must be brought together self-consistently in the Project Implementation Plan.

There are many models which we could entertain for how cryomodules will be constructed for the ILC. These range from an RDR-like model, where there is only one central facility in the world, to having several such facilities across the regions (potentially more than one per region). The picture is further complicated when we start to ask if these 'production centres' are integrating parts which are themselves mass-produce in other regions, or locally produced close to the production centres. For the sake of this discussion, we will make the following assumptions:

- Cryomodules should be constructed (integrated) at more than one location for risk mitigation; we will assume one production centre per region (total of three, each producing one cryomodule a day at peak production rate).

- Subcomponents (cavity, tuner, *etc*.) of the cryomodules will be produced by industry assuming a global call for tender (lowest reasonable bid). At least two vendors per sub-component are assumed for risk mitigation.

In the previous section we outlined the relevance of plug compatibility to the current on-going R&D phase. The underlying philosophy is to establish and promote the regional R&D centres which would directly involve the local industry, nurturing competitive R&D towards better performance and ultimately cost-optimisation.

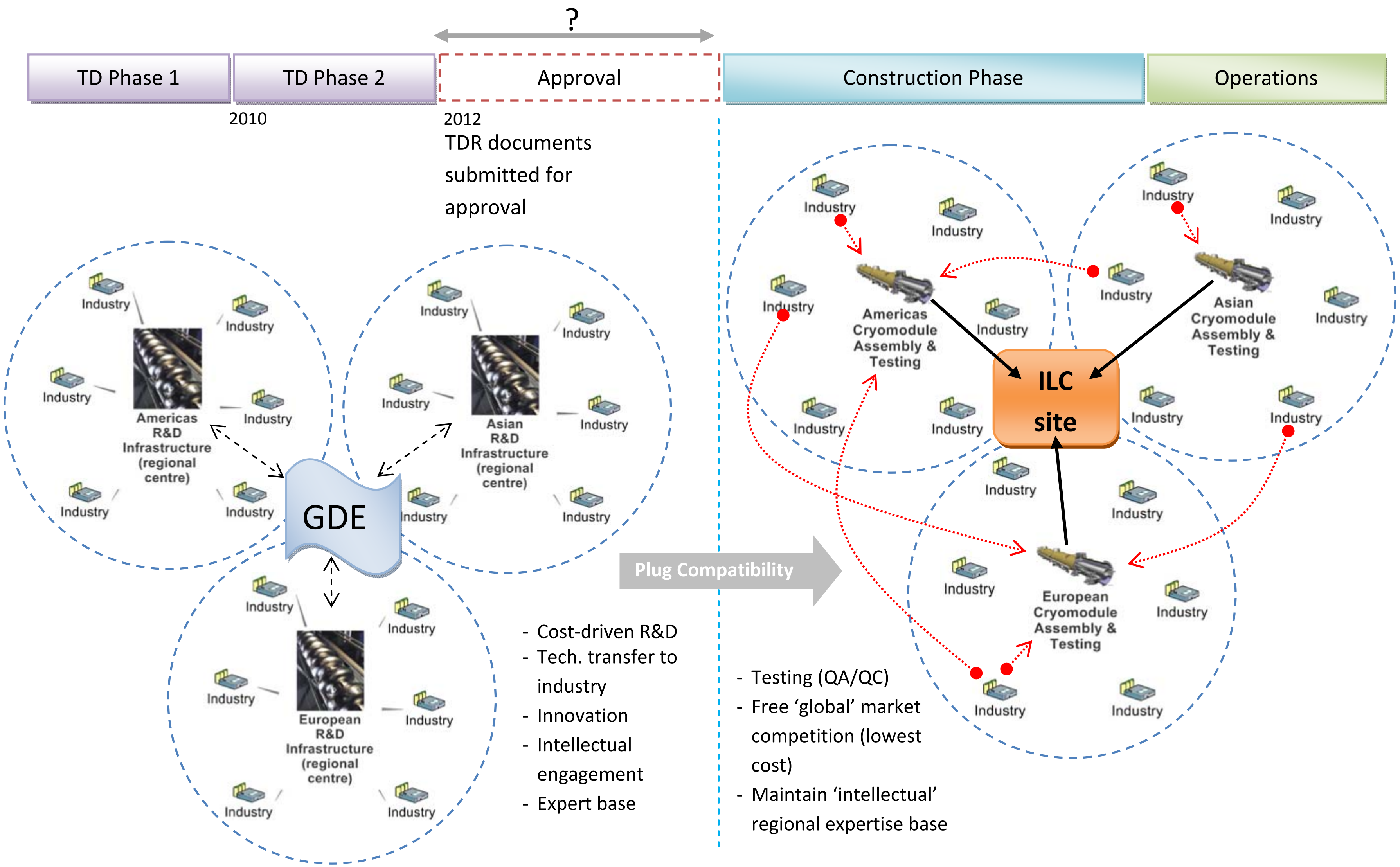


Figure 1: Evolution to regional-based R&D to project construction.

If done correctly, plug compatibility will facilitate a rapid transition from the R&D phase to construction (mass-production phase) by:

- allowing regionally developed components to compete openly on the global market, with the guarantee that – although potentially different designs – they can be easily integrated;
- maintaining the regional centres of expertise (representing years of investment), for testing and Q&A purposes of any of the globally available components;
- avoiding the need for local industries to be re-qualified for other designs (in the case of adopting a single baseline), which would cause inevitable delays in the schedule.

Figure 1 shows graphically how plug compatibility can evolve over the phases of the project and supporting a rapid transition to the construction project once approval has been obtained.

The above scenario has the following ramifications:

- Possible (plug compatible) design variants will compete on the open market. A variant from a given region that is substantially cheaper will be naturally adopted. In this case there is a natural 'free market' down-select to a single baseline. If the variants are comparable in price and performance, then clearly secondary considerations will play a role – but there is no impact on the cost or performance.
- Follow on from the above, the TDR VALUE estimate will also follows the same rules presented in the PIP – in this example we would assume the lowest market cost for the existing proposed variants. In the event that there is no obvious cost or performance advantage between two or more variants, then they can both be presented as equivalent 'alternative' solutions.
- We should note that the cost of one variant from one supplier may differ in each of the regions (for various reasons, exchange rates being one), and this may ultimately naturally select more than one plug compatible variant.
- A region (funding agency) may choose for domestic political reasons to support its local industry by preferring a regionally produce variant, irrespective if it is cheaper. This has consequences for the definition of the TDR VALUE concept as noted above.
- True plug compatibility infers that variants can be mixed even at the level of a single cryomodule. While conceptually possible, the real feasibility of this level inter-exchange of components still requires detailed engineering studies and careful definitions of interfaces. For mass-production scenarios, the entire assembly process and its required tooling must be taken into account. For some components this may prove intractable given our resources. The final agreed-upon interface definitions will ultimately dictate the level of exchangeability for any given production line. Any potential additional cost of supporting this level of exchange must also be considered (for the construction phase).

Many of the points above will be influenced at some level by the exact model adopted for mass-production, in-kind contribution and ultimately governance of the international project. While not necessarily central to these issues, we do believe that plug compatibility will be part of the discussions. Appendix II discusses two conceptual models for a possible project structure, and the possible influence that plug compatibility might have.

Plug Compatibility after Project Construction

After the initial projection construction phase (i.e. operations and beyond), there are two issues on which plug compatibility have a bearing:

- spares and replacement parts (repairs);
- future upgrades.

Again we will remain with the cryomodule as our example. For repair scenarios, we must consider the number of spares that need to be stored, and how the damaged cryomodules will be repaired. Two possible scenarios for repair are i) all cryomodules are repaired at the machine location in a central facility, ii) cryomodules are shipped back to their fabrication plant (in our previous scenario one per region). In either case, plug compatibility would insure that any variant of a sub-component (cavity package etc.) could be replaced with any of the variants to hand: hence it will not be necessary to keep multiple stores of the various variants built into the machine. When we consider the life-time of the machine (potentially tens of years), we must also consider the possibility of placing additional purchase orders to vendors, where again plug compatible variants would support better free market competition.

The upgrade potential is also greatly increased by careful definition of the interface specifications. We must assume that R&D will continue at some level in parallel to the machine operation, hopefully resulting in better performance components (higher gradient cavities are an obvious example). Plug compatibility will facilitate replacement of these components in the machine and maximise the re-use of the other (unaffected) sub-components (cold mass etc.).

Plug Compatibility in an Extended R&D Phase (post TDR, 2012)

Perhaps the strongest motivation of plug compatibility is its impact in the post-TDR phase, while proponents wait for approval. During this (possibly protracted) interval, plug compatibility will allow innovating R&D to continue, while still maintaining a rapid transition to a construction phase once approval has been obtained. Plug-compatibility can play the role of “moderator” during this extended R&D phase by preventing too much divergence and, more importantly, by continuing to support and promote the involvement of industry.

Current R&D Plan Milestones Related to Plug Compatibility

Figure 2 shows a compressed version of the schedule (taken from the current published R&D Plan), indicating milestones which are relevant to the plug compatibility discussion.

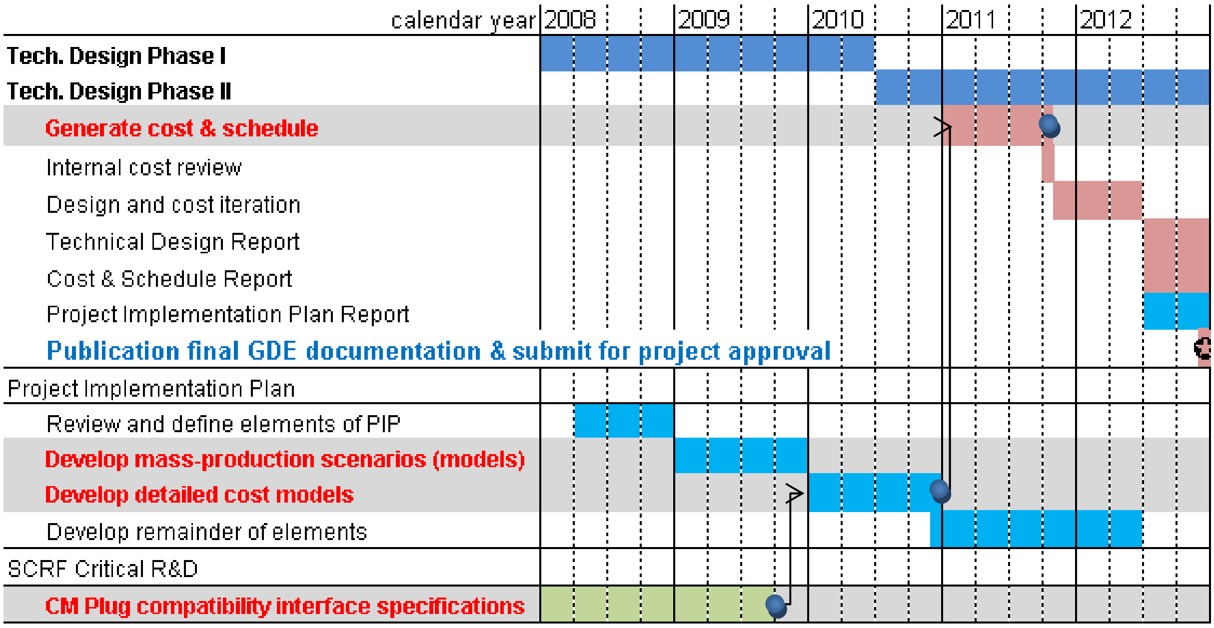


Figure 2: TDR Schedule indicating items relevant to plug compatibility (highlighted in red).

The technical interface specification document for the cryomodule (see Appendix I) should be completed towards the end of 2009. This process is currently foreseen to run in parallel with the development of the mass-production models for the PIP. Both will naturally feed into the development of the detailed cost models, foreseen for calendar year 2010. In 2011, these models will be used (in part) to generate an update VALUE estimate for the cryomodules, ready for publication as part of the TDR end of 2012.

Comments, Discussion and Identified Issues

While we believe the qualitative arguments above strongly support the case for plug compatibility, there nevertheless remain significant engineering challenges to establishing the required technical specifications, as well as further refining many of the issues discussed above (mostly with respect to the PIP models). Identifying and coming to consensus on the critical detailed issues is part of the on-going work over the next year. Specifically:

- Defining the technical specifications of the interfaces for the cryomodule (Appendix I) in a consensus driven fashion remains the first priority.
- Understanding the implications of the requirements for mass-production and how they relate to the plug compatibility specifications is crucial to allowing the concept to evolve beyond the R&D phase (as outlines above).
- Interface definitions and specifications will need to go beyond the cryomodule design itself, to include assembly and tooling issues (relevant for mass-production scenarios).
- It is understood that the complexity (difficulty) of allowing a sub-component to be plug compatible up through mass-production may – after study – prove intractable or not cost-effective; this is part of the interface definition process, which will ultimately define those elements in the cryomodule design which can be flexible and those which are fixed. Again, this requires consensus agreement of all interested parties.

- Given the on-going investment in the R&D world-wide and the lead-times involved, it is inevitable that the interface definitions will be a compromise solution between the existing designs. Once the final definitions are specified and agree-upon, it will take commitment (resources) and time by the world-wide R&D teams to bring their work inline with the standards. This effort will need to be estimated and planned. It is not unlikely that this will take longer than 2012 to implement fully.

- The scope and detail of the interface definitions is likely to be constrained by the amount of engineering resources available to us, and this should be considered carefully.

Appendix I: Plug Compatibility Interface Definitions for the SCRF Cryomodule

Introduction and Basic Guidelines

The goals and guidelines of plug-compatibility are best illustrated in the SCRF technical groups, where we must both focus design choices in order to construct and test complete accelerator systems, and encourage and support a variety of advanced R&D efforts in order to reduce risk and cost.

The TDP plug-compatibility policy seeks to selectively define performance and interface specifications such that both goals are met with an optimum use of TDP R&D resources. For cavity production and integration, the specification table includes:

- basic mechanical dimensions and characteristics;
- electromagnetic characteristics;
- mechanical and electromagnetic interface specifications;
- safety-related performance criteria;
- production procedure, quality control and testing protocols; and
- instrumentation and controls specifications.

For each of these, one by one, the policy dictates the degree to which strict, tightly-toleranced interface criteria must be adhered to in all TDP related development work, and, on the other hand the degree to which flexibility and innovation is encouraged through loosely-toleranced interface specifications.

Thus, for example, nine-cell cavity end-flange and beam duct mechanical dimensions must be very strictly defined so that the series connection can be made of cavities from various sources. But cavity shape, cavity processing and tuning mechanics may be much more flexibly defined in order to promote development work.

Examples of the former, strictly defined interfaces include those mechanical characteristics required to satisfy cryogenic safety reviews and mechanical dimensions needed to ensure proper fit with cryomodule support and alignment systems. Examples of the latter include material choices for non-safety-related components and assembly practices for such components. It is our intention to indicate the degree to which compatibility is required within the specification table itself.

- Cavity package to be plug-compatible and replaceable with any other cavity packages, and its envelope include:
    - Cavity, beam-pipe, LHe vessel, Tuner, Input coupler,
    - Flexible R&D and improvement can be made within the envelope,
- Cryomodule unit to be plug-compatible and replaceable with any other cryomodule packages, and the cryomodule unit include:

- Vacuum vessel, cold-mass support, pipes, (5K shield), 80 K shield, *etc*.

Boundary conditions

We assume the following boundary conditions as described in the main text as follows:

- R&D is still required to improve the field gradient;
- Multiple sources of production may be necessary and important to allow for redundant production capability with "insurance" for risk mitigation in any failure of participating companies or their performance;
- Three regions need to share tasks in production/construction and to share intellectual knowledge in an appropriately equitable fashion;

Plug-compatibility for the ILC-SCRF Cryomodule

Cavity

Cavity	Plug-compatibility Standard	Can be flexible - R&D remains	Alternate designs: need to be fitted to standard
Material		large/fine grain	
Shape		TESLA/LL/RE	
Main-body length	1,247.4 mm		
Interconnect length	78.6 mm		
Support bearing-lug spacing	750 mm (+/- 375)		
Beam pipe dia.	78 mm		(80 mm)
Beam pipe flange	NW 78		(conversion through interconnet -region acceptable)
Beam pipe seal	Diamond Hex Seal,		(Helicoflex)
Jacket/cone	NbTi - Ti		Nb/Sus-SUS
He-vessel OD	<= 240 mm		
Tuner type		Blade / slide-jack	
Tuner location	Middle between bearing lugs		
Tuner slow	Control/wiring spec.		
Tuner fast (piezo)	Control/wiring spec.		
Mag. shield		Inside / outside	
Coupler position	e-: downstream-end e+: upstream end		
Coupler Tunability	Tunable		

Diameter (cold)	TBD (40 or 60 mm)		
(warm)	TBD		
High pr. code	TBD		
Design pressure	2 bar (delta-P)		
Material	Nb, …. SUS	NbTi, Ti,	

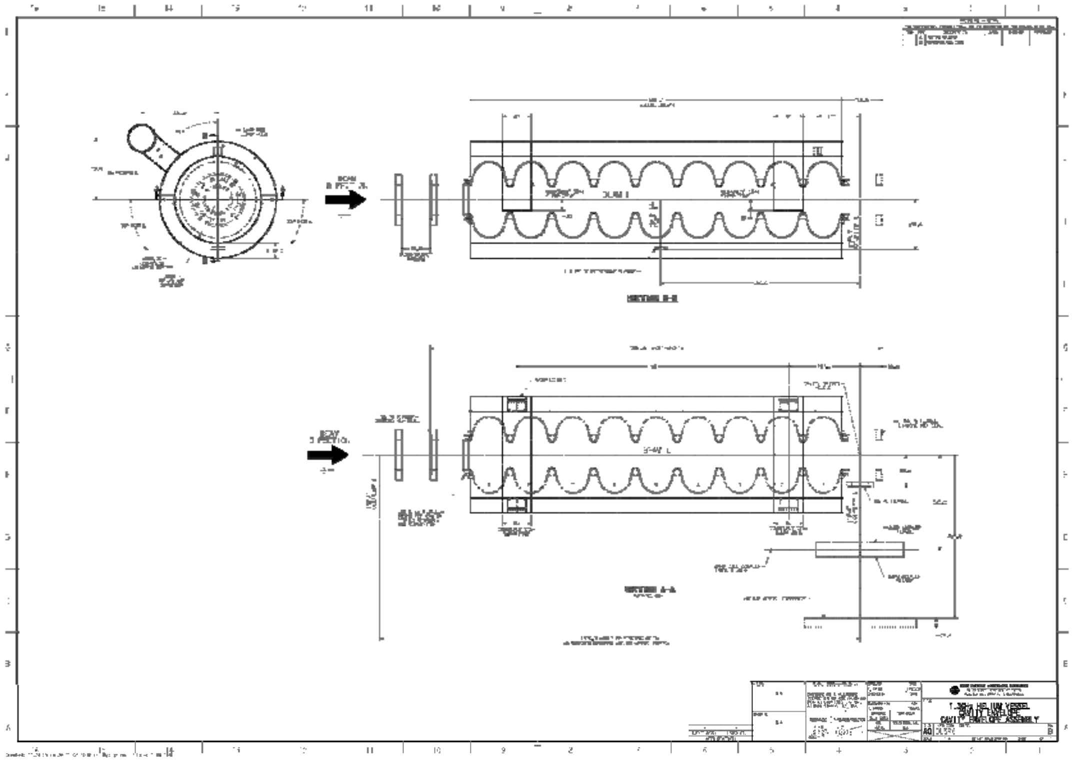
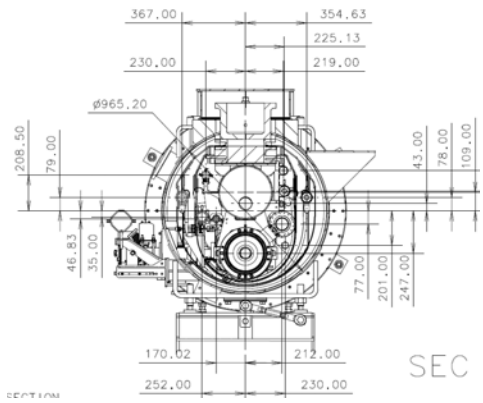


Fig. A1. Plug compatible envelope for cavity package (as of Dec. 3, 2008).

Cryomodule

Cryomodule	Plug-compatible	Flexible	Note
Vacuum Vessel			
Material	Carbon steel		
Inn. diameter	946.2 mm		
Slot length	12,680 mm		
Length (w/o bellow)	11,830 mm		

He jacket of cavity			
Material	(hopefully SUS)	(currently, Ti/SUS)	
Outer diameter	<= 240 mm		
Cavity/coupler slot L.	1326 mm		
Cav. Vertical position	Mid-plane		
Cav. Support-lug pitch.	750 mm		
T-operation	2 K		
Inner-shield (5K)	Envelope to be fixed	To be simplified	
Outer-shield(40-60 K)	40 – 60 K		
Cryogen	GHe		
Heat load at 2 K	< 11.7 / < 11.2 W		
Magnet			
Field Gradient Int.	36 T		
Aperture	78 mm		
Effective length	600 mm		
T-operation	2 K		
Type of winding		Cos-theta or Block	



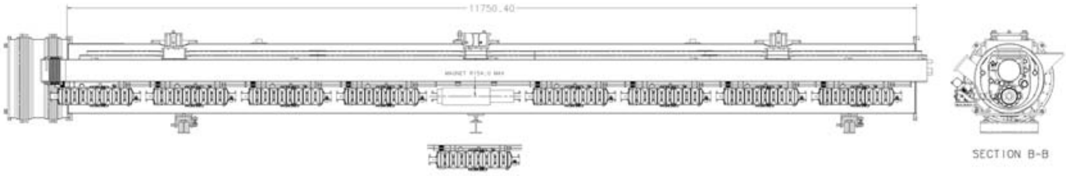


Fig. A2. Cryomodule Assembly and plug-compatible conditions.

General Specification for the ILC-SCRF Cryomodule

The plug-compatible conditions described above are based on the following general specification discussed in RDR with minor updates in TD-phase R&D plan.

Component	Category	Item	Specification	Note
Cavity	RF properties	Frequency	1.3 GHz	
		No. Cells	9 cells	
		Gradient (VT)	35 MV/m	
		Gradient (Beam)	31.5 MV/m	
		Q0 at 31.5 MV/m	1.0 E10	
	Cryogenic prop.	Temperature	2.0 K	
	Mechanical prop.	Pressure	2 Bar	
		Length	1247 mm	Tesla-short
		Aperture	TBD	
		Alignment acc.	0.3 mm	
	Tuner (slow)	Lorentz detuning	1.00 kHz	@ 35 MV/m
		Tuning range	> 600 kHz	
		Magnetic shield.	20 mgauss	@ equater
		Motor heat load	< 50 mW	@ 2 K
	Tuner (fast)	Lorentz detuning	< 50 Hz	@ 31.5 MV/m
		Tuning range	1 KHz	
		Magnetic shield.	< 20 mgauss	

		Piezo Heat load	< 50 MW	
	Coupler	Power (operation)	> 400 KW	160 μs
		Power (process)	>1,200 (> 400) kW	< 400 (> 400) μs
		Heat load (2K)	< 0.063 / 0.018 W	Static/dynamic
		Tuning range	1-10 E6	
Cryomodule	Vaccum Vessel	Inner Diamter	946.2 mm	
		Slot Length	12,680 mm	
		Coupler port pitch	1326 mm	
	GHe return Pipe	Diameter	300 mm	
	LHe supply pipe	Diameter	xxx	
	Pre-cooling pipe	Diameter	xxx	
	5 K shield	Yes/no	TBD	Default: yes
	Support			
	Cryogenic prop.	Heat Load	To be filled	

Appendix II: Mass Production Models

For purposes of discussion, we introduce two project governance models and examine the impact plug compatibility could have on each one.

The first is called the 'CERN-like' (or LHC) model. In this model:

- a Central Lab (CL) is set-up which is given an international budget;
- CL then controls the budget/project;
- CL accepts the 'risk' and responsibility for budget/schedule (and making the project work);
- mass production can still be distributed, but completely controlled by CL.

The second is a Regional Centre (RC) model:

- regional financial contributions to CL are predominantly via 'in-kind' (e.g. cryomodules);
- RC's are set-up to develop and mass-produce cryomodules;
- RC's have their own (regional) budgets and control;
- RC's assume risk of producing on-spec/on-time/on-schedule delivery of in-kind contribution to CL;
- as integrator and overall project management, the central laboratory (where the machine is constructed) must assume some of the risk/responsibility and maintain some control over the RC's.

Implicit in concept of 'risk' is adequate QC and associated test and acceptance procedures.

We believe that, in either model, there should be at least two vendors (per major sub-component) and at least two cryomodule assembly and testing plants for risk mitigation. One plant per region (i.e. three) would require a production rate of approximately one cryomodule per day.

As we noted in the body of the report, plug compatibility would allow the technical innovation during the R&D phase to be directly applicable to the construction phase. Multiple vendors can compete on the open-market with their developed and mature 'variant' designs. Competition will push further cost-reduction development. Note that this only really works if all variants have more or less the same performance/cost. A large cost differential between two plug-compatible design variants should automatically favour the cheaper one. This naturally will limit the number of design variants to a manageable number. Plug-compatibility specifications must also consider assembly and tooling.

The basic difference between the two models is in how the money flows and who accepts the risk. The Central Lab (CERN-like) model will result in a more monolithic (i.e. uniform construction) by favouring fewer vendors overall and providing a uniform contracting interface with each one. Note that this does not preclude that vendor solutions could still be plug-compatibility orientated. The Regional Centres model will likely promote more vendors through the strengthened regional basis.

Individual RCs may have slightly different approaches to risk mitigation, and have somewhat different (regional) constraints.