Chapter 3

Superconducting RF Technology

3.1 Cryomodule design including quadrupole and cryogenic systems

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(**Author:** *Need to complete reference list and cross-referencing)*

3.1.1 Overview

Cryomodules are the modular building blocks of the ILC superconducting main linacs, and need to fulfil the following main functions: (i) provide mechanical support for beamline elements as cavities and focussing elements; (ii) allow to achieve the necessary alignment tolerance and stability according to beam dynamics specifications; (iii) create and maintain in an efficient way the cold environment needed for the cavity and magnet operation. As the cryomodules represent the region where the major heat loads to the cold temperatures are located, they play an important role in the overall cryogenic system optimization.

Accelerators with superconducting RF cavities typically have many separate cryogenic supply boxes and associated warm-to-cold transitions, which represent a significant fraction of the cost and lead to an increase in the machine footprint (due to the decrease of the real estate gradient with respect to the cavity nominal gradient performances) and introduce additional heat losses to the cold mass. The concept adopted for the ILC cryomodule is to significantly reduce the machine footprint, decrease the cost and enhance the cryogenic efficiency by increasing the filling factor, i.e. having a single long continuous string of cryomodules of a few km—called a cryogenic unit—which is connected to one cryogenic supply box at the beginning and one end box. The km-size cryogenic unit of connected modules is composed by smaller units (called cryostrings) to achieve segmentation of the vacuum envelope. In this design concept each cryomodule contains—within its insulating vessel—nine cavities, their supporting structure, the thermal shields and integrates all the associated cryogenic piping for the coolant flow distribution along the cryogenic unit, without the need of additional external cryogenic distribution lines. Every third cryomodule in the main linac contains a superconducting quadrupole/corrector/BPM package in place of the center cavity, keeping the same cryomodule slot length.

All the $\approx$ 15,000 cavities in the ILC main linacs are therefore grouped in $\approx$ 1,700 cryomodules of these two types, with the same length of 12.652 m. Another 150 cryomodules are located in the e^+ and e^- sources and RTML bunch compressors. Most of these are the standard linac configuration of 9 cavities or 8 cavities plus magnet package. A few have special configurations of cavities and quadrupoles. (**Author:** *Consistency within main linac component numbers to be checked across the TDR)*

The size of the cryogenic units is slightly different for the two main linac layouts (Mountain site and Flat site) described in the following chapters, according to the different tunnel layouts and access shafts, which lead to small differences in the cryogenic sectioning. Besides this difference, which will be described in the relative sections of this document, the main characteristics of the cryomodules in the two layouts are identical and are reviewed in the following. (**Author:** *Should come with a better phrasing...need to resolve this forward reference to the different cryogenic layout in agreement with Tom Peterson)*

3.1.2 Beamline Components in the Cryomodule and Slot Length

The ILC cryomodule design is a modification of the type developed and used in the TESLA Test Facility (TTF) at DESY, with three separate vacuum envelopes (beam vacuum, isolation vacuum and power coupler vacuum). The ILC cryomodules contain either a string of nine 9-cell cavities or a string of eight cavities plus a magnet package (quadrupole, steering correctors and BPM) at its center, and have the uniform length of 12.652 m. The cavity spacing within the cryomodule is (6-1/4) λ_0 = 1.327 m. (**Author:** *Keep or trash the following RDR statement? This facilitates powering the cavities in pairs via 3 db hybrids with reflection cancelation in an alternate distribution scheme that may allow the elimination of circulators.)*

As a result of the promising R&D activities initiated at FNAL and KEK on the conduction–cooled split quadrupole described in section **??** of TDR Part 1, the ILC cryomodule will make use of this technical solution, to benefit from the simplification in clean room operation and from the decrease in the risk of contaminating the RF surfaces. The magnet package fits in the same cavity spacing length, allowing a uniform length for the cryomodule slots over all the main linacs, irrespective of their type. (**Author:** *I used a reference to TDR Part 1, don't know how this mechanism work for cross referencing between parts)*

Flanged bellows are located between beamline components, and RF- and HOM-couplers lines are connected to the cavity beam tubes. Manually operated valves required by the clean-room assembly terminate the beam pipe at both module ends. The valves are fitted with simple RF shields.

The decision to place the quadrupole/corrector package in the middle of the cryomodule (as in the Type IV design) implies the possibility of defining a standard interconnection interface for all main linac cryomodules, irrespective of their sub-type, streamlining the tunnel assembly procedures for module connections.

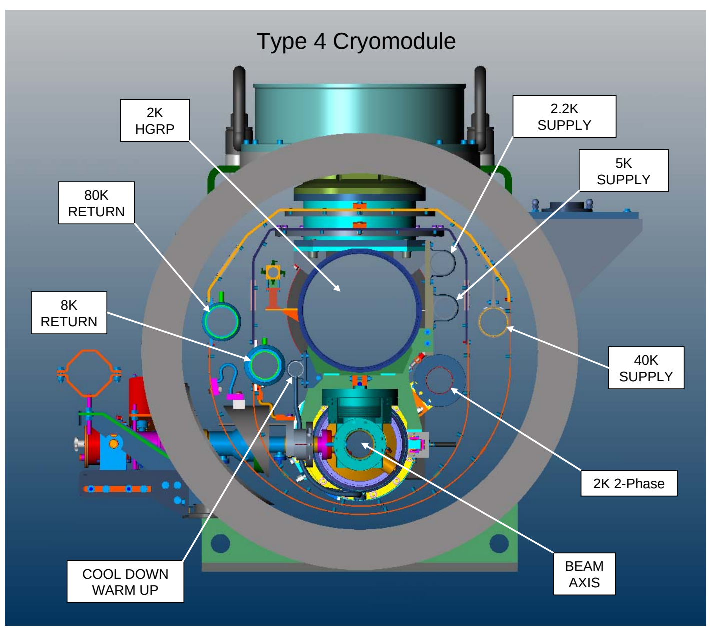

Figure 3.1: Representative Cryomodule Cross-Section.

3.1.3 Technical Description

The Cryomodule Cross Section

Figure 3.1 shows a cross-section of a TTF-III cryomodule [1]–[2]. (**Author:** *Small RDR inconsistency. Text states it is TTF-III, figure indicates Type 4.)* The largest component of the transverse cross section is the 300 mm diameter helium gas return pipe (GRP) which acts as the structural backbone for supporting the string of beamline elements and allows recovery of the mass flow of He vapors at a negligible pressure drop along the cryostrings, to preserve temperature stability.

The GRP is supported from the top by three composite posts with small thermal conduction from the room temperature environment. The posts are connected to adjustable suspension brackets resting on large flanges placed on the upper part of the vacuum vessel. This suspension scheme allows to correctly align the axis of the cavities and quadrupoles indipendently from the flange position, without the requiring expensive precision machining on these vacuum vessel components. The center post is fixed to the vacuum vessel, while the lateral adjustable posts can slide on the flanges to allow the GRP longitudinal contraction/expansion with respect to the vacuum vessel during thermal cycling. Each post consists of a fiberglass pipe terminated by two shrink-fit stainless steel flanges. Two additional shrink-fit aluminum flanges are provided to allow intermediate heat flow intercept connections to the 5-8 K and 40-80 K thermal shields; the exact location of these flanges has been optimized to minimize the heat leakage [3].

Transverse / longitudinal cavity positioning and alignment

The cavities are supported from the GRP by means of stainless steel brackets holding the four titanium pads on their helium vessel via a longitudinal sliding mechanism, which provides also adjusting screws and pushers for alignment in the transverse (vertical-horizontal) planes. A mechanical, coaxial (blade) and a piezo-electric tuner are mounted on the cavity vessels.

During cool down the two ends of the ~12 m long gas return pipe move by up to 18 mm toward the center of the module. The cavity sliding support allows to completely decouple the cavity position from the large GRP contraction induced by the cooldown, and avoids large stresses acting on the cavities due to differential shrinkage. To maintain the longitudinal position of the cavity coupler flange within 1 mm from the coupler port on the warm vacuum vessel—in order to limit large coupler movements occurring with differential contraction—each cavity is clamped to a long invar rod, which is in turn longitudinally anchored at the neutral fixed point of the GRP at the center post.

The beam pipe interconnection between the cryomodules consists of a 0.38 m long section between the end valves that incorporates a Higher Order Mode (HOM) absorber, a bellows, and a vacuum pumping port; the latter connected to a flange in the vacuum vessel every ninth cryomodule.

Thermal Radiation Shields

The cryostat includes two aluminum radiation shields operating in the temperature range of 5-8 K and 40-80 K respectively [4]. The use of a double thermal shielding allows to reduce the radiative thermal load at 2 K to a negligible amount. Each shield is constructed from a stiff upper part, and multiple lower sections (according to the number of the cold active components, e.g. cavities, magnets). The upper part is supported by the intermediate flanges on the fiberglass posts; constrained at the center post but sliding on the two lateral posts, to which they are still thermally connected. The 'finger–welding' technique [4] is used both to connect each thermal shield to its properly shaped aluminum cooling pipe, and the lower shield parts to the upper ones, by providing good thermal conduction without inducing high stresses on the structure.

Blankets of multi-layer insulation (MLI) are placed on the outside of the 5-8 K and the 40-80 K shields. The 5-8 K shield blanket is made of 10 layers of doubly aluminized mylar separated by an insulating spacer while the 40-80 K blanket contains 30 layers. In addition the cavity and quadrupole helium vessels, gas return pipe and 5-8 K pipes are wrapped with 5 layers of MLI as a mitigating provision to reduce heat transfer in the event of a vacuum failure.

The Vacuum Vessel

The cryostat outer vacuum vessel is constructed from carbon steel and has a standard diameter of 38". Adjacent vacuum vessels are connected to each other by means of a cylindrical sleeve with a bellows, which is welded to the vessels during installation. (**Author:** *Is the sleeve welded at installation? TTF/XFEL/Type4 are all clamped with a gasket seal.)* Adjacent vessels have a flange-to-flange distance of 0.85 m, allowing sufficient space for performing the cryogenic connections between modules by means of automated orbital welders. In the event of accidental spills of liquid helium from the cavity vessels, a relief valve on the main vessel body together with venting holes on the shields prevent excessive pressure build-up in the vacuum vessel. Wires and cables of each module are extracted from the module using metallic sealed flanges with vacuum tight connectors. The insulating vacuum system is pumped during normal operation by permanent pump stations located at appropriate intervals. Additional pumping ports are available for movable pump stations, which are used for initial pump down, and in the event of a helium leak. The RF power coupler needs an additional vacuum system on its room temperature side; this is provided by a common pump line for all couplers in a module, which is equipped with an ion getter and a titanium sublimation pump.

Cryogenic lines in the module

The following helium lines [5] are integrated into the cryomodules:

- The 2 K forward line transfers pressurized single phase helium through the cryomodule to the end of the cryogenic unit.
- The titanium 2 K two phase supply line is connected to the cavity and magnet helium vessels. It supplies the cavities and the magnet package with liquid helium and returns cold gas to the 300 mm GRP at each module interconnection.
- The 2 K GRP returns the cold gas pumped off the saturated He II baths to the refrigeration plant. It is also a key structural component of the cryomodule
- The 5-8 K forward and return lines. The 5K forward line is used to transfer the He gas to the end of the cryogenic unit. The 5-8 K return line directly cools the 5-8 K radiation shield and, through the shield, provides the heat flow intercept for the main coupler and diagnostic cables, and the higher-order mode (HOM) absorber located in the module interconnection region.
- The 40-80 K forward and return lines. The 40 K forward line is used to transfer He gas to the cryogenic unit end and cools the high temperature superconductor (HTS) current leads for the quadrupole and correction magnets. The 40-80 K return line directly cools the 40-80K radiation shield and the HOM absorber and, through the shield, provides an additional heat flow intercept for the main coupler and diagnostic cables.
- The warm-up/cool-down line connects to the bottom of each cavity and magnet helium vessel. It is used during the cool down and warm up of the cryostat.

The helium lines connected to the cavities and the magnets withstand a maximum pressure of 4 bar; all other cryogenic lines withstand a maximum pressure of 20 bar. The helium lines of adjacent modules are welded at the module interconnection regions. Transition joints (similar to those used in the HERA magnets and in TTF and XFEL) are used for the aluminum to stainless steel transition on the thermal shield cooling lines. The cryostat maintains the cavities and magnets at their operating temperature of 2 K. (**Author:** *The implication of the above description is that the MAWP for the cavity package need to be set to 4 bar. Need to check with the cavity technical description, especially according provisions for pressure vessel compliance.)*

Thermal design and module heat loss estimations

A low static heat load is an essential feature of the cryostat design; the total heat load is dominated by the RF losses, and is thus principally determined by the cavity performance (and its spread). Table 3.1 lists the heat load table per cryomodule. The table reports the average values corresponding one Main Linac unit, composed of the two main cryomodule variants, i.e. the sequence of two 9-cavity modules followed by an 8-cavity module containing the magnet. Values reported here are scaled from the 12-cavity cryomodule heat loads calculated for TESLA, documented in the TESLA TDR, and include further assessments and static load measurements obtained during the Technical Design Phase with the measurements at S1-Global and for the XFEL prototypes. For the scaling to the ILC parameters, it is assumed that the gradient is 31.5 MV/m, the cavity Q_0 is 1×10^{10}, and the beam and RF parameters are those listed in section **??**. These values are used for the dimensioning of the two variants of cryogenic systems for the Mountain and Flat Regions. (**Author:** *Need reference to RF parameters and beam parameters (and check). Using TP table of 26/June/2012. Will provide reference to EDMS documents.)*

Most losses occur at frequencies where the resistance of the superconducting surfaces is several orders lower than that of normal conducting walls. Frequencies above the 1.3 GHz operating frequency and below the beam pipe cutoff are extracted by input-and HOM-couplers, but higher frequency fields will propagate along the structure and be reflected at normal and superconducting surfaces. In order to reduce the losses at normal conducting surfaces at 2 K and 4 K, the cryomodule includes a special HOM absorber that operates at 70 K, where the cooling efficiency is much higher. The absorber basically consists of a pipe of absorbing material mounted in a cavity-like shielding, and integrated into the connection between two modules. As the inner surface area of this absorber (about 280 cm^2) is small compared to that of all the normal conductors in one cryomodule, the absorber has to absorb a significant part of all the RF power incident upon it. In field propagation studies,

Table 3.1: Average heat loads per module. All values are in watts.

	2 K		5-8 K		40-80 K	
	Static	Dynamic	Static	Dynamic	Static	Dynamic
RF Load		8.02	4.20		97.5	
Radiation Load			1.41		32.49	
Supports	0.60		2.40		18.0	
Input coupler	0.17	0.41	1.73	3.06	16.47	41.78
HOM coupler (cables)	0.01	0.12	0.29	1.17	1.84	5.8
HOM absorber	0.14	0.01	3.13	0.36	-3.27	7.09
Beam tube bellows		0.39				
Current leads	0.28	0.28	0.47	0.47	4.13	4.13
HOM to structure		0.56				
Coax cable (4)	0.05					
Instrumentation taps	0.07					
Diagnostic cable			1.39		5.38	
Sum	1.32	9.79	10.82	5.05	75.04	58.80
Total	11.11		15.87		133.84	

which assume a gas-like behavior for photons, it has been shown that an absorber with a reflectivity below 50% is sufficient. Theoretical and experimental studies have suggested that the required absorption may be obtained with ceramics like MACOR or with artificial dielectrics. (**Author:** *Check with current XFEL design for HOM absorber)*

It is worth noting here that a substantial effort has been performed during the Technical Design Phase for the S1-Global module and for the European XFEL Project in the consolidation and benchmarking of the static heat load assessments, as reported in **??** . (**Author:** *Reference to TDR Part 1 section.)* The S1-Global measurements show a very good consistency with heat load estimations when all conduction paths and heat transfer mechanisms are taken properly into account in the budget (see Table **??**), showing that the module design is well understood and proven. Values for the static loads in Table 3.1 are consistent with such an experience gained in the TDP, and the low estimates for static losses reflect the assumption of the reduced diagnostic instrumentation foreseen for the ILC modules with respect to R&D activities as the S1-Global module tests.

The experience reported with the European XFEL prototypes has highlighted the importance of the assembly procedures in achieving nominal loads, and "training" effects for the most sensitive 2 K environment, as shown in Fig. ??.

The S1-Global 5 K shield thermal measurements have shown that, with an alternate flow scheme in the cryogenic shield circuits, it would be possible to partially remove the bottom part of the inner thermal shields without increasing the static 2 K loads. While this leads to some simplification in the module assembly procedures, the proper handling and rerouting of thermal sinks usually provided throught the shield surfaces, would require a substantial redesign of the module cross section. As this could introduce deviations form the consolidated experience achieved by the evolution of these modules and which will be available in the short future from the European XFEL modules, the ILC basline design still is based on a double thermal shield design.

As a final remark on thermal loads it must be noted from Table 3.1 that dynamic loads induced by RF are dominant in the 2 K region, and are intrinsically influenced by the spread of cavity performances (Q_0 values) and operating point (gradient setting). Much less experience and data is available on dynamic loads, and uncertainty factors need to be taken into account from the values reported here for their propagation into the cryosystem heat load assessments, as it will discussed in the relevant sections.(**Author:** *Again, forward reference to cryo design for the two layouts.)*

Shielding from magnetic field

The ambient magnetic field in the cavity region must not exceed 0.5 μT to preserve the low surface resistance. The magnetic field tolerance is achieved by demagnetizing the vacuum vessel before assembly of the cryomodule, and placing a passive shield made of Cryoperm around the cavity surfaces. The design of a magnetic shield internal to the helium tank developed by KEK has been proven effective both in vertical tests and during S1-Global operation, and has been chosen as the reference solution, leading to simplified string and module assembly operations. (**Author:** *Need to estabilish a citation to TDR part 1 and part 2 cavity integration parts on the description of magnetic shielding)*

Quadrupole/Corrector/BPM Package

The baseline design for the ILC quadrupole/corrector/BPM package makes use of the conduction-cooled splittable quadrupole developed by FNAL and KEK—described in TDR Part 1—as it greatly simplifies the string assembly operation in the clean room. The split-quadrupole is installed outside of the clean room around a beam pipe, thus decreasing possible contamination of the cavity RF surfaces. (**Author:**

Need to estabilish reference to TDR Part 1 on split quad) An important feature that must be addressed with the final technical design is the package fiducialization and subsequent transfer of these features to reproducible, external cryomodule fiducials to assure the correct alignment of the package with respect to the cryomodule string.

Damping Ring and Beam Delivery Cryomodules

The damping ring accelerating RF is single 650 MHz cavities in individual cryomodules. The beam delivery also uses superconducting crab cavities with individual cryomodules. This system is discussed in Section **??**. (**Author:** *Check where the technical description of these elements goes in TDR2 and estabilish references)*

Shipping of Cryomodules between Regions

To date, there is limited experience on the shipping of completed cryomodules across the main regions of the ILC collaboration. FNAL shipped by air transport the complete ACC39 module for FLASH (a special short module derived from the TTF design for the 3.9 GHz cavities), to DESY, where the module has been successfully tested up to its specification. The European XFEL will report within 2015 the experience of road transportation of 100 complete modules from the string and module assembly facility at CEA/Saclay to the AMTF testing area at DESY, providing a useful statistical sample of data. It is essential that a reliable method for overseas transport of complete modules be developed and incorporated into the final ILC cryomodule design, incorporating this experience.

3.1.4 Cost Estimation

(**Author:** *The following is the actual RDR text, should be updated with respect to the TDR update of cost studies)*

The cryomodules represent nearly one third of the total ILC project cost. Cost studies have been conducted in all three regions , Americas, Asia and Europe. Much of the original effort relied on the TESLA TDR costing as a basis for comparison. However, independent regional studies and the cost study for the XFEL have proved useful in improving the reliability of the ILC cost numbers.

Significant effort has been expended to understand the cost drivers for cryomodules. The cavities are the largest item, with over 40% of the cryomodule cost for cavity fabrication, processing, dressing and qualification. The next largest items are the power couplers, the helium vessel fabrication, the quad package and the tuners, which represent another 30%. It is anticipated that joint studies between

ILC engineers and designers and industrial partners utilizing design for manufacture methodology and value engineering principles will lead to significantly reduced cryomodule component and assembly costs.

Bibliography

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