1 May 2012

Cryomodule 2
Requirements and Specification

5500-ES-371080 Rev --

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Rev	ER / ECO	Date	Description	TD Approval	AD Approval
---	ER 9527	1 May 2012	Initial Release	Tom Peterson	

Overview

The SRF Development Department of the Technical Division has assembled the Cryomodule 2 (CM2), an eight-cavity module operating at 1.3-GHz. Eight SRF dressed cavities, their supporting structure, thermal shields and associated cryogenic piping, a dipole corrector magnet, and the insulating vacuum vessel comprise the CM2. The cryomodule is approximately 12 m long. A model image of the cryomodule showing the internal structures at the cutaway is shown in Figure 1 and a longitudinal view is shown in Figure 2. The final CM2 assembly will be installed in Fermilab's New Muon Lab (NML) Beam Enclosure.

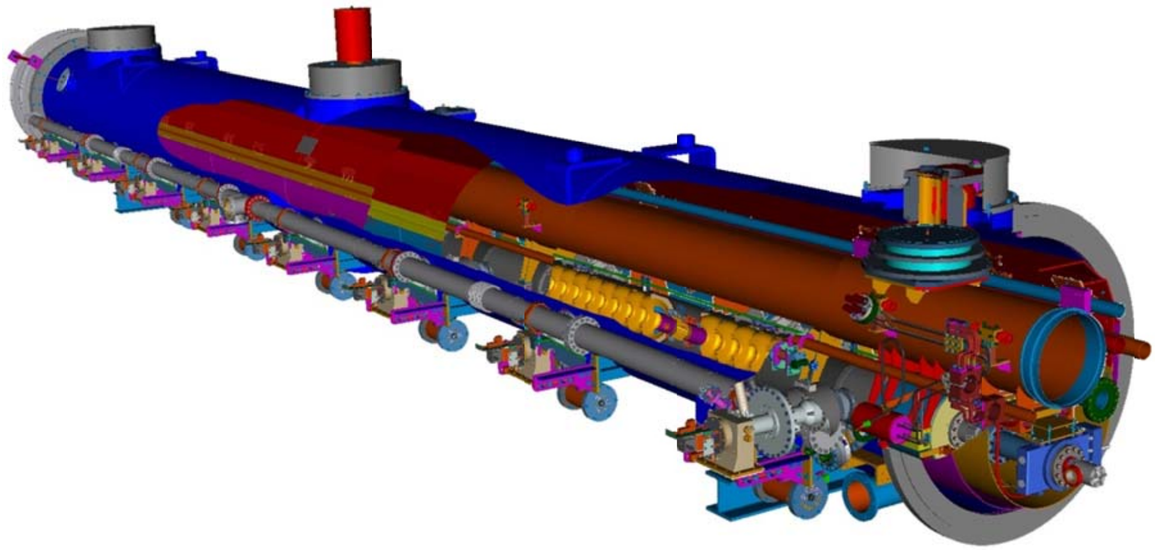

Figure 1 – Model image of CM2 showing internal structures at the cutaway.

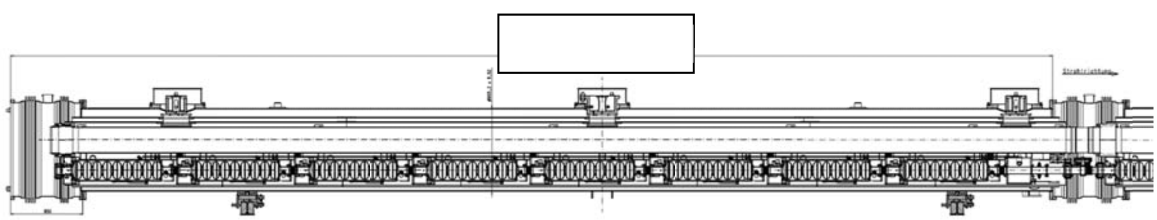

Figure 2 - Longitudinal view of a Type III+ cryomodule. Slot length from CM2 assembly drawing D933265

Figure 3 shows a schematic of the Beam Enclosure at NML (drawing 5520.000-ME-458097). The cryomodule is installed between the feed cap and the end cap.

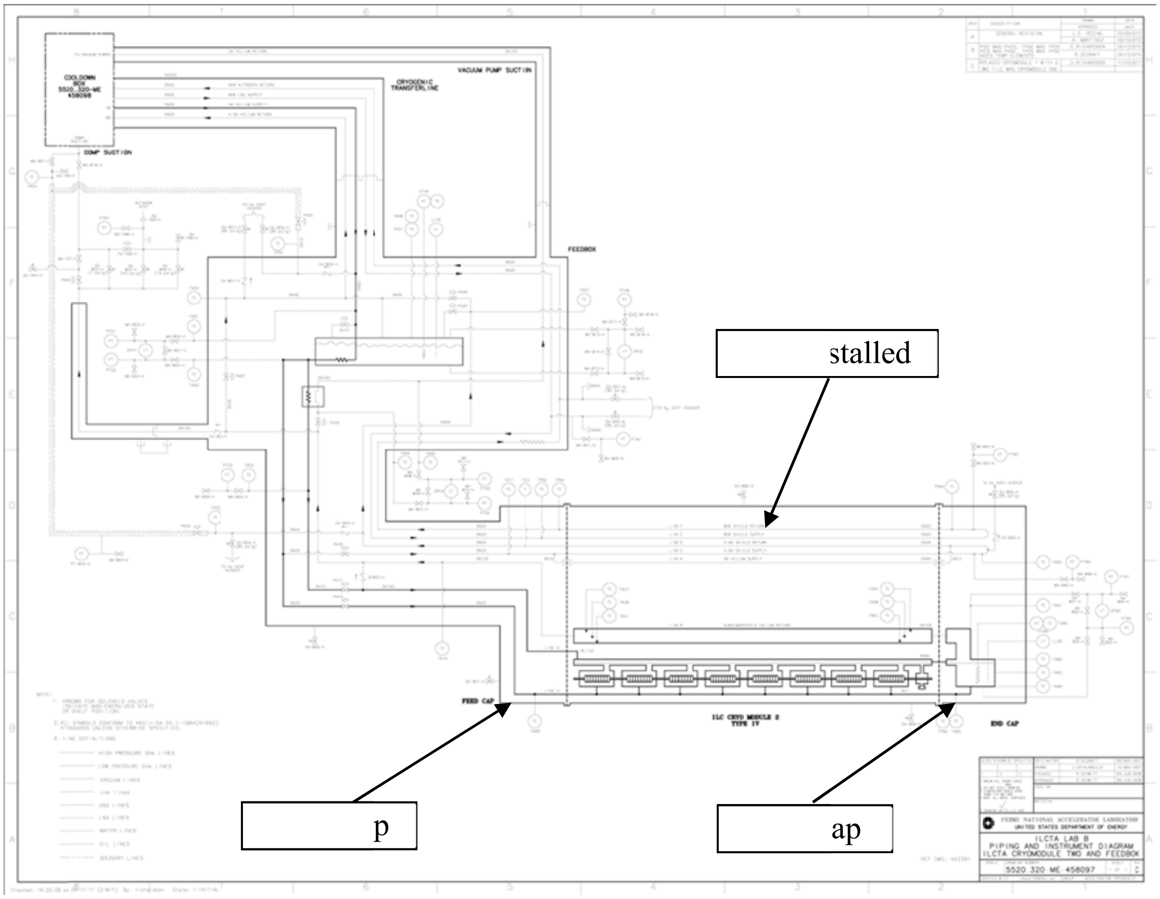

Figure 3 – P&ID of Beam Enclosure at New Muon Lab, showing the Cryomodule installed (Drawing 5520.000-ME-458097)

As installed the 1.3-GHz system will include:

1) The RF power source
  - Modulator
  - Klystron and auxiliaries
  - Modulator controls/interlocks
  - Low Level RF (LLRF)
  - Coupler interlock
  - RF distribution- Waveguide, Load, Isolator, etc

2) Cryomodule (the operating goal of each cavity is 31.5 MV/m at Q_0 of 10^{10})
  - Cavities- eight 9-cell cavities with helium vessels
  - Couplers
  - Tuners
  - Module cold mass, vacuum vessel, etc
  - 300-mm diameter helium gas return pipe
  - Coupler vacuum manifold
  - Dipole corrector magnet

Design Goals

Table 1 lists the design goals for CM2, taken from the ILC-RDR. [1]

Table 1 – Design Goals for the CM2 1.3-GHz Cavities

Type of structure	standing wave
Accelerating mode	π-mode
Average Voltage	32.7 MV
Average accelerating gradient, E_{acc}	31.5 MV/m
Qualification gradient	35.0 MV/m
Cell to cell coupling	1.9 %
Stored energy	126 J
Frequency	1.3 GHz
cavity	9 - cell
R/Q of fundamental mode	1036 Ohm
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT/ (MV/m)
Tuning range	±300 kHz
$\Delta f/\Delta L$	315 MHz/mm
Number of cavities	8
Beam current	9 mA
Average installed quality factor Q_0 at 31.5 MV/m	1.0×10^{10}
Quality factor at E_{acc} = 35.0 MV/m during qualification	0.8×10^{10}
Average Q_{ext}	3.5×10^6
Total Energy	500 – 1000 GeV
Cavity resonance width	370 Hz

Active length	1038 mm
Iris diameter	70 mm
Total length (end flange to end flange)	1247.4 mm

CM2 was designed originally with a goal of satisfying TESLA requirements and serves as an ILC prototype cryomodule. NML serves as a "test stand" for this cryomodule. Thus, Table 1 and the following description consist of the design goals for ILC, rather than NML-specific features. We follow that description with a list of requirements which impact the NML system, such as MAWP of the piping and vessels. The NML requirements are summed up in the Appendix.

Description of the Cryomodule 2[2]

The 300mm diameter helium gas return pipe (GRP) is the main support structure for the string of dressed cavities and the quadrupole/corrector/BPM package. The GRP is supported from above by three posts which provide the necessary thermal insulation to room temperature. The posts are fastened to large flanges on the upper part of the vacuum vessel by adjustable suspension brackets, allowing the axis of the cavities and quadrupole to be correctly aligned, independent of the flange position. The support system is designed to allow the GRP to contract/expand longitudinally with respect to the vacuum vessel during thermal cycling. The center post is fixed to the vacuum vessel, while the two end brackets can move in the axial (z) direction to accommodate differential shrinkage. A 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 5-8K and 40- 80K thermal shields; the exact location of these flanges has been optimized to minimize the heat leakage.

Each of the 8 dressed cavities is encased in a titanium helium vessel, supported by the GRP by means of stainless steel brackets connected to four titanium pads on the helium vessel itself; each bracket is equipped with a longitudinal sliding mechanism and adjusting screws and pushers for alignment. A mechanical, coaxial (blade) and a piezo-electric tuner are mounted to the vessel. The inter-cavity spacing---which accommodates RF- and Higher Order Mode (HOM)-couplers and a flanged interconnecting bellows---amounts to 136.75-mm.

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.

During cool down the two ends of the ~12m long gas return pipe move by up to 18mm toward the center of the module. To keep the cold input coupler head of each cavity fixed longitudinally within an accuracy of 1 mm, each cavity is anchored to a long invar rod attached to the longitudinal center of the gas return pipe.

The beam pipe interconnection between the cryomodules consists of a 0.38m long section that incorporates a HOM absorber, a bellows, and a vacuum pumping port; the latter will be connected to a flange in the vacuum vessel every ninth cryomodule.

The cryostat includes two aluminum radiation shields operating in the temperature range of 5-8K and 40-80K respectively. Each shield is constructed from a stiff upper part (divided into two halves), and multiple lower sections (according to the number of the cold active components, e.g. cavities, magnets). The upper parts are supported by the intermediate flanges on the fiberglass posts; they are screwed to the center post but can axially slide on the other two posts, to which they are still thermally connected. The `finger welding' technique is used both to connect each thermal shield to its properly shaped aluminum cooling pipe, and the lower shield parts to the upper ones.

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

Figure 4 shows a cross section of the cryomodule at a dressed cavity. 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. Radiation shield bridges are also provided. In the event of accidental spills of liquid helium from the cavity vessels, a relief valve on the sleeve 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 will be 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 case 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 8 couplers per module, equipped with an ion getter and a titanium sublimation pump.

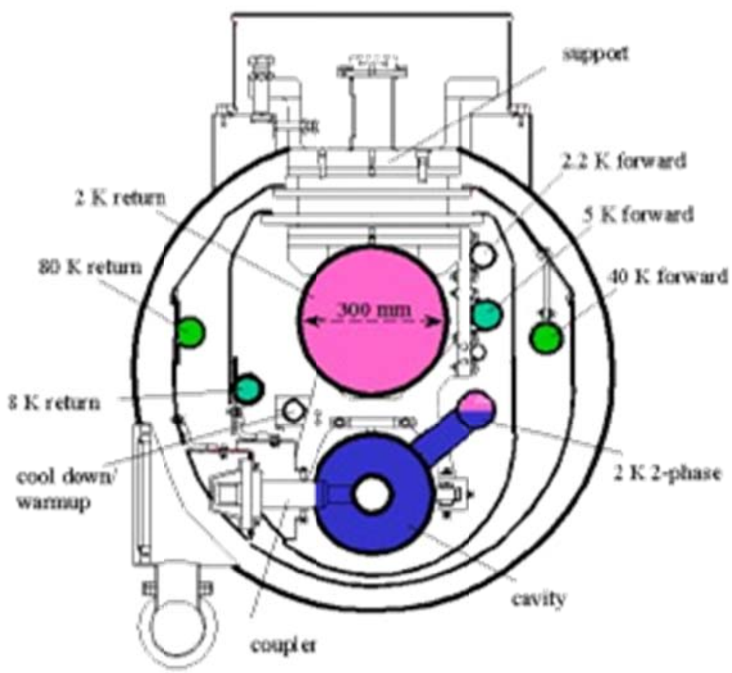

Figure 4 – Cross Section of CM2 at a Dressed Cavity

The cryostat maintains the cavities and magnets at their operating temperature of 2 K. 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 cavity performance.

Most losses occur at lower frequencies where the conductivity of the superconducting surfaces is several orders higher than that of normal conducting walls. Part of this power is extracted by input- and HOM-couplers, but high 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 2K and 4 K, a special HOM absorber is foreseen which 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 of the RF power incident upon it. In field propagation studies, 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.

The axes of the 8 cavities must be aligned to the ideal beam axis to within ±0.5 mm, and quadrupole axes to within ±0.2 mm. The quadrupoles have an additional `roll' tolerance of ±0.1 mrad.

The ambient magnetic field in the cavity region must not exceed 0.5 μT to preserve the low surface resistance. At TTF this has been achieved by demagnetizing the vacuum vessel (made of soft steel) before assembly of the cryomodule, and placing a passive shield (made of Cryoperm) around each cavity helium vessel.

The following helium lines are integrated into the cryomodules:

- The 2K forward line transfers pressurized single phase helium through the cryomodule to the end of the cryogenic unit.
- The 2K two phase supply line (made from titanium) 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 300mm GRP at each module interconnection.
- The 2K 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 5-8K forward and return lines. The 5K forward line is used to transfer the He gas to the end of the cryogenic unit. The 5-8K return line directly cools the 5-8K 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 40-80K forward and return lines. The 40K 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 40-80K 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 of adjacent modules are connected by welding, as was done for the HERA superconducting magnets. Transition joints (similar to those used in the HERA magnets) are used for the aluminum to stainless steel transition on the thermal shield cooling lines.

Requirements Impacting the NML System

Specification of pressures and temperatures of cryogenic circuits within the cryostat at NML

The 2-phase helium lines connected to the cavities and the magnets have a MAWP of 2 bar at room temperature and 4 bar at 2K; all other cryogenic lines have a MAWP of 20 bar. All lines are pressure tested to 1.1 times the MAWP. The exception is the 2K two phase helium supply line, which has a test pressure of 2.2-bar with both the cavity string and the cryomodule's insulating vacuum evacuated at room temperature. This results in the helium pipe experiencing a 2.2-bar pressure differential, which is 1.1 times its design pressure at room temperature. All other cryogenic lines will have a test pressure of 22-bar.

As parts of the 2K two phase helium supply line, each helium vessel and the corrector magnet has a MAWP of 2-bar at room temperature and 4-bar at 2K. They are pressure tested at 2.2-bar at room temperature.

Displacement and Temperature Limits of the Blade Tuner System at NML

The limits of displacement that cause the slim blade tuner to change the length of the vessel are defined by deformation of the tuner assembly and thus the frequency of the cavity. During operation, the cavity's default position is in a stretched state. However, during pressure testing of the two-phase helium supply line, the cavity must be compressed to prevent damage to the cavity due to external pressure of helium. Table 2 lists the displacement limits of the blade tuner, where 0-mm is the relaxed position of the cavity, a positive number describes the cavity in the stretched position, and a negative number describes the cavity in a compressed position.

Table 2 – Displacement Limits of Blade Tuner

Cavity Temperature	Max. Allowed Displacement	0 mm = cavity relaxed + = cavity stretched - = cavity compressed
300K	-0.3 mm to +1.0 mm	
2K	-1.0 mm to +3.0 mm	

The temperature of the motor is monitored by a Cernox RTD that is installed on the body of the each stepper motor. The typical temperature of the motor after the cryomodule is cooled down is ~40K. It is good practice to keep the motor temperature less than 100K.

Pressure Vessel Requirements

The helium vessel has an internal maximum allowable working pressure of 2-bar at room temperature and 4-bar at the operating cryogenic temperature. Thus, the vessel is considered a pressure vessel according to the FESHM Chapter 5031 and must follow the guidelines in the ASME BPVC.

FESHM Chapter 5031.6 is a guideline for the design, fabrication, testing and quality control of dressed SRF cavities. The chapter recognizes the unique features of SRF cavities as pressure vessels, including containment of cryogens and the use of niobium and niobium-titanium material. With the use of niobium and niobium-titanium materials, the SRF cavities fall outside the scope of the ASME BPVC. Additional provisions, which are spelled out in 5031.6, are made to ensure safe design and operation.

Each dressed cavity has its own pressure vessel engineering note. Once 5031.6 was published, all subsequent notes followed its policy. Pressure vessel note number RI-019 is typical for the notes following 5031.6. [3] Dressed cavities that were made before the publishing of 5031.6 followed the standard pressure vessel guidelines in 5031. [4] All notes present in detail how each vessel follows the guidelines of FESHM as an exceptional vessel. Table 3 lists the areas of the vessel that are exceptions to the ASME BPVC ("the Code").

Table 3 – Areas of Exception to the Code and How the Vessel is Safe

Item or Procedure	Explanation for Exception	How the Vessel is Safe
Niobium material *(*Not an exception when following 5031.6)*	Used for its superconducting properties; Not an established material listed by the Code	There has been extensive testing done on the niobium used in the cavity. The Code procedure for determining Div.1 allowable stresses (see Section II, Part D, Mandatory Appendix 1) are conservatively applied to the measured yield and ultimate stresses to establish allowable stresses which are consistent with Code philosophy.
Niobium-Titanium material *(*Not an exception when following 5031.6)*	Used for as a transition material between niobium and titanium materials for welding purposes; Not an established material listed by the Code	Material properties were provided by the vendor of the material.
Some category B (circumferential) welds in the titanium sub-assembly are Type 3 butt welds (welded from one side with no backing strip).	Category B joints in titanium must be either Type 1 butt welds (welded from both sides) or Type 2 butt welds (welded from one side with backing strip) only (see the Code, Div. 1, UNF-19(a)).	The evaluation of these welds is based on a de-rating of the allowable stress by a factor of 0.6, the factor given in Div. 1, Table UW-12 for a Type 3 weld when not radiographed.

No liquid penetrant testing was performed on the titanium sub-assembly.	All joints in titanium vessels must be examined by the liquid penetrant method (see the Code, Div. 1, UNF-58(b)).	The evaluation of all welds is based on a de-rating of the allowable stress by a factor given in Div. 1, Table UW-12 for such welds when not radiographed. For the corner joints, the joint efficiency has to be less than 1.00.
No electron beam welds were ultrasonically examined in their entire length	All electron beam welds in any material are required to be ultrasonically examined along their entire length (see the Code, UW-11(e)).	The evaluation of all welds is based on a de-rating of the allowable stress by a factor given in Div. 1, Table UW-12 for such welds when not radiographed.
Use of enhanced material properties at cryogenic temperatures in stress analysis *(*Not an exception when following 5031.6)*	Titanium is not a material with established material properties at temperatures less than 38°C by the Code (see the Code, ULT-5(b))	Published material properties for titanium (outside the Code) at cryogenic temperatures were used.
Fabrication procedure for the niobium cavity assembly does not include WPS, PQR, or WPQ	The fabrication procedure for the niobium cavity is propriety. Detailed information on the procedure is not available.	The RF performance of the niobium cavity is acceptable, showing indirectly that all welds in the cavity are full penetration
Weld at the 2-phase helium pipe stub attachment to the vessel *(only applicable in vessels AES-008, AES-009, AES-010)*	• Not a Code-approved design (Fig. UW-16.1) • X-ray report shows that there is not complete fusion.	Video examination of the weld shows that it is greater in size than the minimum required thickness.
Weld at the bellows assembly attachment to the vessel tube	X-ray report shows that one section does not have complete fusion.	Radiographic examination of the weld reveals that porous regions of the weld extend approximately 1/8th of its length. The weld evaluation is thus de-rated by a factor of 7/8. The weld stresses are well within the allowable value.
Longitudinal seam weld of the titanium vessel did not pass radiography inspection *(only applicable in vessels AES-008, AES-009, AES-010, RI-019, RI-018, ACC-016)*	All titanium welds require radiography inspection (see the Code, UNF-57(b))	Non-conformance due to “incomplete fusion” at the weld root---primarily because of joint edge mismatches at the rolled tube inside diameter. Visual inspection shows that weld integrity is not affected. The evaluation of all welds is based on a de-rating of the allowable stress by a factor given in Div. 1, Table UW-12 for welds not radiographed.

References

1. International Linear Collider (ILC), Reference Design Report, Volumes 1 and 3, August 2007. Available online at http://www.linearcollider.org/cms/?pid=1000437
2. TESLA Technical Design Report, March 2001. Available online as TESLA Report 2001-23 at http://tesla.desy.de/new_pages/TESLA/TTFnot01.html
3. R. Patel, "Pressure Vessel Engineering Note for the 1.3-GHz Helium Vessel, Cavity RI-019," IND-165, February 2011.
4. B. Wands and M. Wong, "Pressure Vessel Engineering Note For the 1.3-GHz Helium Vessel, Cavity AES-009," IND-144, April 2010.

Appendix

Cryomodule Safety Information at NML

The following table lists requirements for cooldown, warm-up, and testing at NML.

Cryomodule Safety Information
Arkadiy Klebaner, April 16th, 2008
Tom Peterson, April 24, 2008
Harry Carter, Phil Pfund, April 29, 2008
Mayling Wong, Timergali Khabiboulline, May 1, 2012

Entries in **RED** are the primary constraints.

Item description	Cryogenic circuit			Notes
	80 K Shield	5 K Shield	2K	
Cooldown requirements				
Maximum cooldown rate, [degree/hr]	10 K/hr	10 K/hr	10 K/hr	300 K to 4 K > 30 hours (Lange) so >10 K/hr
Minimum cooldown rate, [degree/hr]			none	
Maximum cooldown gradient inlet to outlet, dT/dz	**50 K/module**	**50 K/module**	50 K/module	(Rolf Lange talk 5-dec-06, e-mail 28 Aug 07)
Minimum cooldown gradient inlet to outlet, dT/dz			none	
Maximum vertical cooldown gradient, dT/dx			**15 K**	300 mm tube top to bottom
Minimum vertical cooldown gradient, dT/dx			none	
Maximum cooldown flow rate, [kg/sec]	none	none	none	a free parameter within other constraints
Does max cooldown rate vary with temperature?	YES/NO	YES/NO	YES/NO	Judgement (TJP): Constraint is relaxed as temp goes down.
Does max cooldown rate vary with pressure?	YES/NO	YES/NO	YES/NO	Judgement (TJP): Constraint is relaxed as temp goes down.
Can cryogenic circuit be cooldown independently of others	YES/NO	YES/NO	YES/NO	Not desireable (Q disease?).
Warm-up requirements				
Maximum warm-up rate, [degree/hr]	10 K/hr	10 K/hr	10 K/hr	symmetrical constraint relative to cool-down
Minimum warm-up rate, [degree/hr]			none	
Maximum warm-up gradient inlet to outlet, dT/dz	50 K/module	50 K/module	50 K/module	symmetrical constraint relative to cool-down
Minimum warm-up gradient inlet to outlet, dT/dz			none	
Maximum vertical warm-up gradient, dT/dx			**15 K**	
Minimum vertical warm-up gradient, dT/dx			none	
Maximum warm-up flow rate, [kg/sec]	none	none	none	a free parameter within other constraints
Minimum warm-up flow rate, [kg/sec]	none	none	none	
Does max warm-up rate varies with temperature?	YES/NO	YES/NO	YES/NO	Judgement (TJP): Constraint is relaxed at low temp.
Does max warm-up rate varies with pressure?	YES/NO	YES/NO	YES/NO	Judgement (TJP): Constraint is relaxed at low temp.
Can cryogenic circuit be warm-up independently of others	YES/NO	YES/NO	YES/NO	Not recommended.
Pressure relief requirements				
Absolute MAWP of the circuit, [bar]	20	20		
For dual MAWP (cold and warm)				
Warm MAWP, [bar]			2	
Cold MAWP, [bar]			4	
MAWP vs. temperature function				2 bar down to 20 K, 4 bar below 20 K
Test pressure and temperature, [bar]	22	22	2.2 bar, 300 K	
What reliving scenario is considered?				loss of beam vacuum and, separately, loss of insulating vacuum
Primary relief valve				
Preferred type or model				
Capacity, [kg/sec]				
Set pressure, [bar]				
Relieving temperature, [K]				
Secondary relief valve				
Preferred type or model				
Capacity, [kg/sec]				
Set pressure, [bar]				
Relieving temperature, [K]				
Maximum allowable pressure drop in the relief line				
Upstream from the relief valve				
Downstream form the relief valve				
ODH				
Expected failure rate (pi) for a cryomodule				
Flowrate due to circuit rupture, [kg/sec]				
Other				
Displacement Limits of the Blade Tuner				
Cavity Temperature	Max. Allowed Displacement			0 mm = cavity relaxed
300-K	-0.3mm to +1.0mm			+ = cavity stretched
2-K	-1.0mm to +3.0mm			- = cavity compressed