5 April 2010

Cryomodule 1
Requirements and Specification

5500-ES-371083 Rev --

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Revision	ER / ECO	Date	Description	Approval(s)
---	ER 9527	5 Apr 2010	Initial Release	H. Carter

Overview

The SRF Development Department of the Technical Division has assembled the Cryomodule 1 (CM1), an eight-cavity module operating at 1.3-GHz. The design of the CM1 is known as type III+ cryomodule. The design is an iteration of the third generation, or type III design, that is presently being used in the TESLA Test Facility (TTF) at DESY. Eight SRF dressed cavities, their supporting structure, thermal shields and associated cryogenic piping, a quadrupole/corrector/BPM (beam position monitor) package, and the insulating vacuum vessel comprise the CM1. The cryomodule is approximately 12 m long. A cross-section of a type III+ cryomodule at a dressed cavity is shown in Figure 1 and a longitudinal view is shown in Figure 2. The final CM1 assembly will be installed in Fermilab's New Muon Lab (NML) Beam Enclosure.

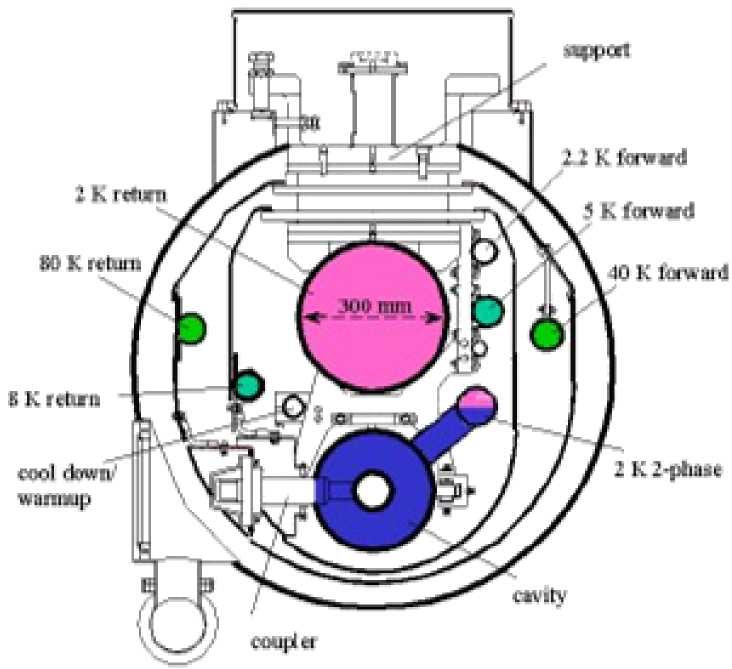

Figure 1 - Representative Type III+ cryomodule cross-section.

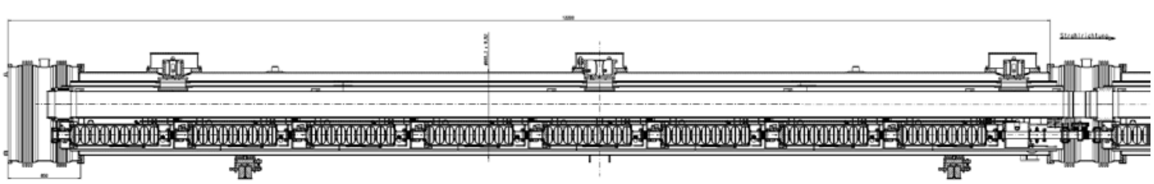

Figure 2 - Longitudinal view of a Type III+ cryomodule.

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.

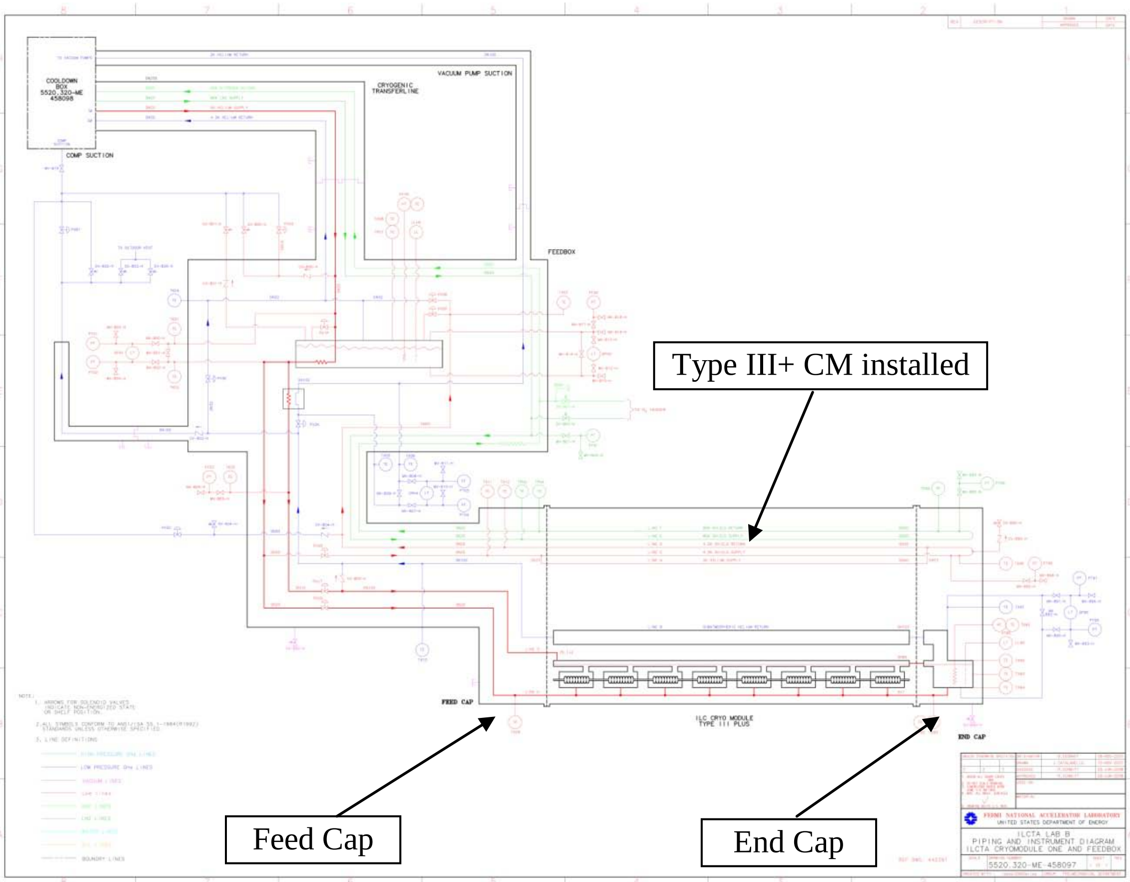

Figure 3 – P&ID of Beam Enclosure at New Muon Lab, showing the Cryomodule installed (Drawing 5520.000-ME-458097)

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

List of Parameters and Requirements

Table 1 lists the parameters of the Type III+ cryomodule. [1]

Table 1 – List of Parameters for the CM1 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
Δf/ΔL	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

Description of the Type III+ Cryomodule [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 1 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.

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 $\pm$0.5 mm, and quadrupole axes to within $\pm$0.2 mm. The quadrupoles have an additional `roll' tolerance of $\pm$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.

Specification of pressures and temperatures of cryogenic circuits within the cryostat

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 connected to the cavities and the magnets withstand a pressure of 4 bar; all other cryogenic lines withstand a pressure of 20 bar. All lines are pressure tested to 1.5 times the design pressure.

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.

Pressure Vessel Requirements [3]

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 at pressure vessel according to the FESHM Chapter 5031. The pressure vessel engineering note presents in detail how the vessel follows the guidelines of FESHM 5031 as an exceptional vessel. Table 2 lists the areas of the vessel that are exceptions to the ASME BPVC ("the Code").

Table 2 – 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	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	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.
No information about the vessel's weld design is available.	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 weld efficiency of 0.5. This weld efficiency is lower than the lowest efficiency specified by the Code for any weld.
No information about liquid penetrant testing on the titanium sub-assembly is available.	All joints in titanium vessels must be examined by the liquid penetrant method (see the Code, Div. 1, UNF-58(b)).	The evaluation of these welds is based on a weld efficiency of 0.5. This weld efficiency is lower than the lowest efficiency specified by the Code for any weld.
No information about ultrasonically testing the electron beam welds in the niobium and niobium-titanium assemblies is available.	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 these welds is based on a weld efficiency of 0.5. This weld efficiency is lower than the lowest efficiency specified by the Code for any weld.

Item or Procedure	Explanation for Exception	How the Vessel is Safe
No information about radiography inspection on the titanium welds is available.	All titanium welds require radiography inspection (see the Code, UNF-57(b))	The evaluation of these welds is based on a weld efficiency of 0.5. This weld efficiency is lower than the lowest efficiency specified by the Code for any weld.
Calculated stresses for longitudinal weld in titanium bellows exceed allowable stresses.	Calculated stresses must be at or less than allowable stresses. The allowable stresses include a 0.7 weld joint efficiency due to lack of examination results.	The calculated stress does not exceed the allowable stress with a joint efficiency of 1.0. This design of the bellows has been used extensively at DESY for over the past decade.
Calculated stress in the bellows using FEA shows a higher membrane plus bending stress than allowed.	Calculated stresses must be at or less than allowable stresses.	The design of the bellows is addressed by the Code in Div 1, Appendix 26. The sum S_3+S_4 is less than allowed K_fS.
Use of enhanced material properties at cryogenic temperatures in stress analysis	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.
Weld documents, including the WPS, PQR, or WPQ, are not available.	All welds must follow the rules of specifying the weld procedure, qualifying the weld procedure, and qualifying the welder according to Part UW, which refers to the Code, Sec. IX.	• The evaluation of these welds is based on a weld efficiency of 0.5. This weld efficiency is lower than the lowest efficiency specified by the Code for any weld. • The RF performance of the niobium cavity is acceptable, showing indirectly that all welds in the cavity are full penetration
Pressure test results are not available.	All Exceptional Vessels require a pressure test, according to FESHM 5034.	The analysis shows that the stresses in the vessel, when pressurized at room temperature (Load Case No. 1), are within the allowable stress.

History of CM1

As part of an agreement between FNAL and DESY, a cryomodule "kit" was put together jointly by DESY and INFN-Milano and shipped to FNAL in July, 2007. The kit included the vacuum vessel and cold mass assemblies, as well as eight individual 1.3-GHz dressed cavities. The complete assembly was named Cryomodule 1. The cryomodule was assembled at Fermilab by FNAL personnel assisted by DESY personnel. Now completed, the CM1 resides at its final location at the Beam Enclosure in the New Muon Lab in preparation for the commissioning of the cryogenic system at that facility.

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. B. Wands and M. Wong, "Pressure Vessel Engineering Note For the 1.3-GHz Helium Vessel #1 in Cryomodule 1," IND-116, TBD.