MECHANICAL DESIGN OF THE CRYOGENIC SUB-SYSTEMS FOR ReA6 QUARTER WAVE RESONATOR CRYOMODULE*

M. Shuptar#, F. Casagrande, A. Fox, M. Johnson, M. Leitner, S. Miller, T. Nellis, M. Patil, T. Xu, Y. Xu, Facility for Rare Isotope Beams (FRIB), East Lansing, MI 48824, USA

Abstract

The driver linac for the Facility for Rare Isotope Beams (FRIB) consists of 49 cryomodules operated at 2 K utilizing 4 different types of superconducting resonators and 2 solenoid lengths which in turn requires 7 individual cryomodule configurations. The mechanical design requirements of the internal cryogenics of an FRIB cryomodule are determined by the piping and instrumentation diagram, which is discussed in the paper based on the FRIB quarter wave cryomodule type. In addition, heat load requirements and spatial constraints of other cryomodule sub-systems influence the cryomodule cryogenics design. The paper describes detailed design choices for the cryogenic headers and piping, a 2 K heat exchanger inside the cryomodule, solenoid current leads, and the bayonet connections to the cryogenic distribution system inside the accelerator tunnel. Different operating modes, which influence the cryogenic design, are summarized.

INTRODUCTION

FRIB is a US $700 million nuclear physics project to be built at the Michigan State University under a corporate agreement with the US Department of Energy (DOE) with a 7-year timetable [1]. According to the current FRIB baseline schedule fabrication and procurement of linac components will start mid-2014. Actual linac installation will begin end of 2016 after completion of conventional facilities and cryoplant construction [2].

Due to the heavy mass and correspondingly low velocity of the accelerated ions the FRIB driver linac [1] utilizes four different low-beta SRF resonator designs in cryomodules. Each cryomodule is equipped with niobium cavities which will operate at 2 K providing acceleration to the heavy ions. Due to the large number of cryomodules the FRIB project lends itself to a manufacturing mind-set that incorporates large scale production into the design of individual modules types. As a part of the manufacturing mind-set FRIB is currently developing a prototype cryomodule that will utilize 8 superconducting quarter-wave cavities, and is referred to as the ReA6 cryomodule. Upon completion the ReA6 cryomodule will test not only the general cryomodule design, but also the manufacturing methodology [3]. Even though ReA6 is a prototype module it will implement some design choices that differ from a typical FRIB cryomodule. The usefulness of the ReA6 module will not end with proof of concept of mechanical and manufacturing principals; after testing the module becomes a permanent part of FRIB's Re-Accelerator located in the experimental area of the facility.

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shuptar@frib.msu.edu

BASIS OF REQUIREMENTS

Each cryomodule design starts by obtaining the system's requirements and then designing the specifications. For the cryogenics inside the ReA6 Quarter Wave Resonator (QWR) cryomodule the requirements are defined by; piping and instrumentation diagram (P&ID), heat load budget, cost and spatial constraints.

The ReA6 P&ID differs from an FRIB module because the operating constraints of the ReA6 are slightly different from an FRIB module. Since the ReA6 module will be built ahead of the FRIB cryoplant and will not be located in the tunnel its cryogenic layout specified on the P&ID includes a liquid nitrogen circuit not present in FRIB Cryomodules. ReA6 Resonators will also operate a 4.5 K compared to an FRIB module's resonators operating a 2 K [4].

Heat Load Budget

The heat load calculations outline the allowed heat load for each module. Constraining the heat load to each module budget ensures that the cryoplant is sized correctly. The heat load budget requirement for ReA6 cryomodule is shown in Table 1 [5].

Table 1: ReA6 β=0.085 Cryomodule Heat Loads

	Resonators (4.5 K)	**Focusing Magnets (4.5 K)**	**Thermal Shield (80 K)**
Static (W)	6.0	50.7	180.6
Dynamic (W)	80.0	1.3	23.2
Total (W)	**86**	**52**	**204**

The heat load budgets are also necessary to estimate the mass flow for three separate cryogenic loops. Calculation of the helium and nitrogen interfaces to the cryogenic distribution are given in (Table 2) [5]. To minimize vapour velocity and maximize helium capacity the headers needs to be sized effectively.

Table 2: Flow Conditions for ReA6 Cryomodule

	T (K)	P (atm)	ṁ (g/s)
Nitrogen Supply	82	1.6 – 1.7	1.1
Helium Supply	4.5 – 5	3.0 – 3.5	8.5 – 9.9
Cavity Helium Return	4.5	1.286	4.6 – 5.4
Solenoid Helium Return	4.5	1.286	3.9 – 4.6
Megnet Leads Return	300	1.1	0.09
Nitrogen Return	82	1.6 – 1.7	1.1

Using Equation 1, the velocity vapour can be estimated.

$$\dot{m} = v\rho A. \quad (1)$$

Where $\dot{m}$ is the mass flow rate, v is velocity of the vapour, ρ is the density of the gas and A is the minimal cross-sectional area needed to achieve the desired vapour velocity. The mass flow is taken from the heat budget and a vapour velocity limit of 7 m/s was imposed [6]. This limit prevents drag on the liquid within the header and also minimizes any vibratory disturbances. The calculation was done for each of the cryogenic circuits in the module.

The resonator circuit has a design contingency of facilitating 2 K helium. The header for resonators was calculated to need a minimum cross-sectional area of 18.08 cm^2 (or pipe with an inner diameter greater than 4.79 cm). The resonator header, magnet header and thermal radiation header have been sized with a 6" Schedule 5 and 4" Schedule 5 IPS pipe respectively. The benefit of a larger helium inventory inside the cryomodule will allow static pumping for 2 K operation given cryoplant and pumping limitations.

Spatial Constraints

The physical layout of the cryogenics within the cryomodule is constrained spatially by the other sub-systems; super-conducting resonators, thermal radiation shield, magnetic shield, alignment support structure and vacuum vessel as seen in figure 1.

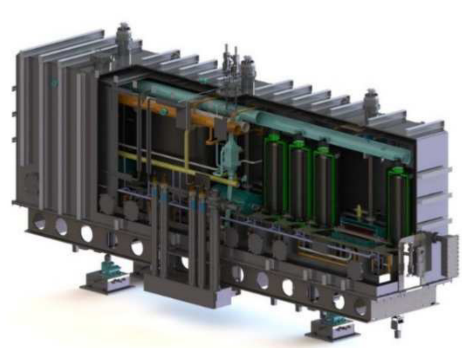

Figure 1: Cross-Section of ReA6 β=0.085 QWR Cryomodule.

Structurally the cryogenics will be supported from the vacuum vessel via G-10 plates and preloaded bellville spring washers to allow for thermal contraction. The cryogenic circuits are connected to the sub-systems using flexible couplings to minimize the transmission of micro-phonics.

CRYOGENIC CIRCUITS

The cryogenics of the ReA6 cryomodule is composed of three circuits: resonator, focusing magnet and thermal shield. The resonators and focusing magnets are placed on independent circuits so that they can be warmed and cooled independently which allows the resonators to be warmed above T_c and perform solenoid degaussing cycles [7]. Each circuit is based on a thermal siphon. The headers in the thermal siphon function as a liquid-gas phase separator; supplying liquid to the components and allowing gas from boil-off to be sent to the gas return. Each cryogenic circuit's temperature is dictated by the cryomodule's operating mode.

Resonator Helium Circuit

To reduce the number of components and simplify the fabrication, a single supply line supplies helium to the resonators and focusing/steering magnet circuits within the module. One circuit is used exclusively for cooling the resonators. For the resonators; the 4.5 – 5.0 K flow passes through a heat exchanger in series with a Joule Thomson (JT) valve to isenthalpically expand the helium. The heat exchanger for the ReA6 is sized for 10 g/s of flow. Even though ReA6 is designed to operate at 4 K but will have the ability to test at 2 K with batch pumping mode.

Focusing Magnet Helium Circuit

The focusing magnet helium circuit cools the focusing magnets (solenoids), magnet leads and thermally intercepting conductive components. The vapour cooled magnet leads will be purchased from a commercial vender. The circuit's other function is to minimize the heat loads to the resonators by thermally intercepting all components that provide a thermal heat load to the resonators. The helium from the 4.5 – 5.0 K supply passes through a JT valve to reduce its temperature before it enters a 4.5 K helium bath. To minimize the temperature of the liquid to each thermal intercept the circuit runs parallel flow to each intercept location. Intercepting components in parallel prevents excessive formation of large bubbles in the cryogen, reducing the effective heat transfer between the fluid and the thermally intercepted component.

Thermal Shield Nitrogen Circuit

The nitrogen circuit, which is unique to the ReA6 module, primary function is to reduce thermal radiation heat loads to the coldmass (the string 8 cavities and 3 solenoids within the module). The nitrogen circuit thermally intercepts all sub-systems between the room temperature vacuum vessel and the 4.5 K coldmass. The

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circuit also supplies nitrogen to the thermal shield which is responsible for minimizing the radiant heat loads.

BAYONET BOX

The nitrogen and helium are supplied to the cryomodule circuits by a bayonet box as shown in figure 2. The bayonet box is integrated into the cryomodule as its own sub-system. The modular box is utilized on the 49 cryomodules in the linac. This sub-system is geared toward a large scale manufacturing methodology. It is designed to be fabricated independently and then later mounted onto the cryomodule. From there the cryogenic circuits are welded to the bayonet box creating a permanent leak tight assembly. The bayonet box interfaces with the main cryodistribution by U-tube bayonets. The effective implementation of assembly line manufacturing is very important design for FRIB. ReA6 will be an important part of testing this manufacturing process.

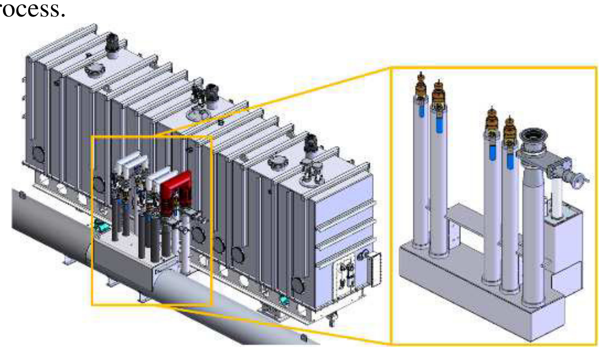

Figure 2: Cryomodule bayonet box interface to the helium distribution line.

CRYOGENIC PIPING & SAFETY

To design for manufacture, the cryogenic circuits were modelled after industrial piping systems. This approach reduces the number of custom made speciality parts without compromising quality and safety. Custom parts were minimized by using readily available industrial weldable components. Cryogenic piping was selected that adhere to the process piping code (ASME B31.3) and BVPC section VIII. Commercial piping selected adheres to the ASME Design by Rule and need for Design by Analysis was minimized. Commercially available formed bellows have been used which have been verified as per the ASME BPVC section VIII, Div. 2 code. Commercially available flexible metal hoses with welded end connection which are designed in accordance with ASME BPVC by the vendor have also been selected to couple the cryogenics circuits to the sub-systems. Welded bellows and the final system will be pressure tested in accordance with UG-99 (hydrostatic test) or UG-100 (pneumatic test).

Circuits have been equipped with lift-off plates and pressure relief valves to ensure that the cryogenic circuits do not produce pressures which would reach the yield stresses of the niobium resonators. The pressure relief valves are sized with a mass-flow rating for a failure mode during cryomodule cool down which would occur when there was a closed return valve and open supply valve. The lift-off disks operate for an operation failure mode. This failure mode would occur during accidental beamline or insulating vacuum loss with operating levels of liquid helium in the resonator and focusing magnet circuits [8].

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