CRYOMODULE DESIGN FOR A SUPERCONDUCTING LINAC WITH QUARTER-WAVE, HALF-WAVE AND FOCUSING ELEMENTS*

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INTRODUCTION

The Rare Isotope Accelerator (RIA) driver linac is designed to accelerate heavy ions up to 400 MeV/u ($\beta = v/c = 0.72$) with a beam power up to 400 kW [1]. To obtain these intensities, partially stripped ions are accelerated in a 1400 MV superconducting linac. A design based on the 80.5 MHz harmonic requires six cavity types.

A rectangular cryomodule design with a cryogenic alignment rail can accommodate all of the superconducting cavity and magnet types for RIA. A prototype 2-cavity cryomodule for the RIA elliptical cavities was designed in 2003 [2] and tested in 2004 [3]. This cryomodule design is suitable for all 3 elliptical cavity types. A similar cryomodule design has been developed for the lower-β quarter-wave and half-wave cavities for RIA. The cavities are interspersed with superconducting magnets for focusing, with 2 cavities between magnets for the quarter-wave cryomodules and 4 cavities between magnets for the half-wave cryomodules.

A prototype low-β cryomodule was designed and is now under construction. The prototype module is large enough for 2 cavities and 2 magnets. The cryomodule design will be presented in this paper, along with the current status of assembly and testing of the cavities, magnets, and cryomodule.

CRYOMODULE

A cross-section of the prototype cryomodule design is shown in Figure 1. The module was designed to accomodate a 80.5 MHz $\beta = 0.085$ quarter wave resonator (QWR) operating at 4.5 K and a 322 MHz $\beta = 0.285$ half wave resonator (HWR) operating at 2.0 K (operation at the two different temperatures is not simultaneous). Both niobium cavities were designed and fabricated at Michigan State University (MSU) with the electron beam welding done by industry. The cavities have titanium vessels welded around them using Nb-Ti alloy transitions.

The superconducting focusing magnets consist of a 9 T solenoid with integrated steering dipole and a 31 T/m quadrupole. The current leads for both magnets will be a commercial high temperature superconductor (HTS) lead package. HTS leads simplify the cryomodule design, as the leads would otherwise require active helium gas cooling. The solenoid was fabricated by Cryomagnetics, Inc; the quadrupole was fabricated at MSU [4]. Cavity, magnet, and cryogenic parameters are given in Table 1.

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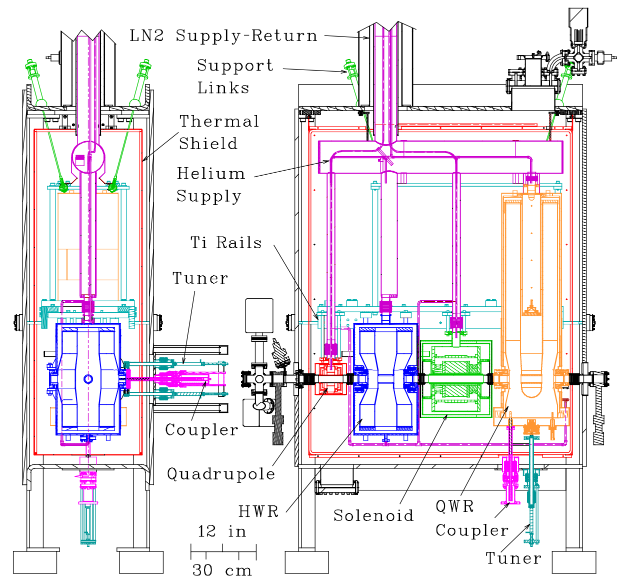

Figure 1. Sectional view of the prototype cryomodule.

Beam dynamics simulations indicate that cavity alignment tolerances for the low-β linac are ± 2 mm, while magnet alignment tolerances of ± 1 mm are needed for efficient beam transport with minimal emittance growth [5]. All beam line components are rigidly aligned on a titanium rail with optical fiducials at the ends and center of the rail that can be viewed while at operating temperature. The cold mass is assembled in a Class 100 clean room. The cavity and beam line vacuum are isolated from the insulating vacuum using metal seals. Component alignment is done using push-pull bolts that allow ± 3 mm adjustment. The cold mass is hung from the vacuum vessel top plate using 4 nitrogen alloyed stainless steel support links[1] with ball and socket connections at both ends. A stainless steel helium manifold is welded to the beam line components, with bi-metal transitions to the cavities' Ti helium vessels. The vacuum vessel is made from low carbon steel plate. Pins secure the cold mass to the vacuum vessel during transportation.

Magnetic Shielding

The magnetic fields on the cavities must be limited to acceptable levels during cool down and operation to avoid degradation of the quality factor. The maximum acceptable magnetic field during cool down for the QWR and HWR cavities are 10 μT and 2.5 μT, respectively [6].

The Earth's magnetic field is reduced from 50 μT to 10 μT using the A36 steel vacuum vessel. A cryoperm

[1]Nitronic 50, a product of Tripyramid Structures, Westford, MA.

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Table 1. Design parameters.

Cavity	QWR	HWR
Frequency	80.5 MHz	322 MHz
$\beta = v/c$	0.085	0.285
Beam Current	0.16 mA	0.35 mA
V_a	1.18 MV	1.58 MV
Max Beam Power	0.16 kW	0.48 kW
E_p	20 MV/m	25 MV/m
B_p	47 mT	69 mT
Design Q	$5 \cdot 10^8$	$5 \cdot 10^9$
RF Loss	6.7 W	2.5 W
RF input power	< 1 kW	
Magnet	**Quadrupole**	**Solenoid (Dipole)**
Effective length	50 mm	100 mm
Aperture	40 mm	40 mm
Strength	31 T/m	9 T (0.01 T·m)
Turns	78	16 813 (40)
Current	63 A	68 A (50 A)
He heat load	**QWR**	**HWR**
Input coupler	0.40 W	0.60 W
Tuner	0.63 W	0.38 W
Total/RF off	6 W	
Total/RF on	15.2 W	
Cryomodule		
77 K shield load	< 100 W	
Length	1.54 m	
Cold mass	310 kg	
Total mass	2000 kg	

mu-metal shield[2] assembled around both cavities further reduces the external field to $< 0.2\ \mu$T. Cryoperm shields are assembled around both magnets to isolate the internal remnant fields.

The 9 T solenoid has reverse wound compensation coils to reduce the stray magnetic field. A reactor grade 2 mm thick niobium shield is installed around the solenoid and heat-sunk to it. When superconducting, this niobium shield traps the field inside via the Meissner effect. The final cryoperm shield traps any remaining stray field. The quadrupole's field of 0.6 T is easier to shield; the iron return yoke is not saturated, and only the cryoperm shield is needed.

Fundamental Power Couplers

The RF input couplers for the QWR and HWR were designed using a commercially available power feed-through. The outer conductor is 0.5 mm thick 304 stainless steel with 10 μm copper plating and does not require helium gas cooling. The QWR and HWR couplers were conditioned to 1.1 kW and 2 kW, respectively. After conditioning, the couplers were stored in the Class 100 clean room until assembly onto the cavity string.

Tuners

The QWR is tuned by mechanically adjusting the distance between the bottom plate and the inner conductor nose. The tuner presses against the plate, which acts as a diaphragm, and the helium vessel, which counters the applied reaction forces. The force on the plate is always upward-directed, which reduces backlash. The frequency tuning of the HWR is done by mechanically compressing the cavity, with the forces applied axially at the beam tube flanges. Machined flex-joints are used to avoid backlash. Both tuners use an external piezoelectric actuator for fine tuning and a screw drive mechanism for coarse tuning. At room temperature, the measured ranges of the coarse tuners were $+0/-2.5$ kHz for the QWR and $+40/-80$ kHz for the HWR.

Cold Box

A schematic of the cold box is shown in Figure 2. The 4 K helium from the cryo-plant enters the box and passes through the 2 K sub-cooler. Next, the helium passes through a controlled Joule-Thomson (JT) valve and into a phase separator. During cool-down, the valve allowing gas to leave the phase separator is closed, speeding the cool-down by forcing all gas and liquid to be delivered to the cavities. Once steady state is achieved, the warm gas return is closed and the cold gas return is opened. Helium boil-off gas leaves the module via the manifold, exiting via the 2 K heat exchanger. The heat exchanger cools the incoming liquid at 4 K using the exiting gas at 2 K; it uses a stainless steel tube with radial aluminum fins. The HTS leads are placed inside the helium exit gas pipe, so that incoming heat from the lead wires is removed by the outgoing gas before it reaches the components at 2 K. The cold box is directly above the HWR. A view-port was added over the helium connection to allow a direct line of sight into the HWR; a mirror allows sighting down the helium manifold.

CAVITY AND MAGNET TESTING

Testing was done in three stages: testing the cavities alone, testing the focusing elements alone, and then testing both in proximity to each other. The first tests on the

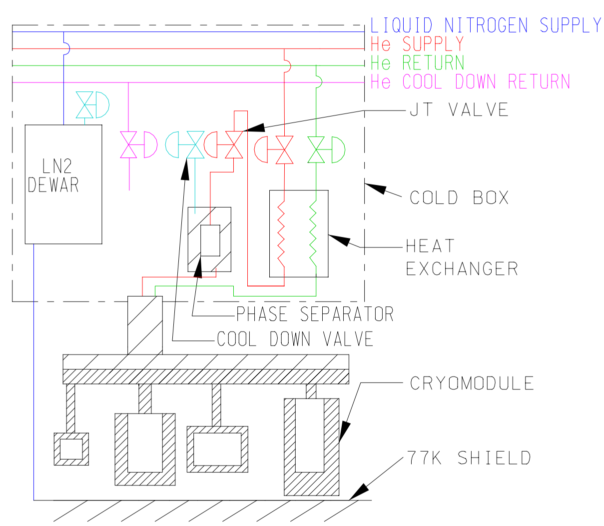

Figure 2. Schematic of cold box and prototype cryomodule.

[2]Cryoperm 10, a product of Vacuumschmelze, Hanau, Germany.

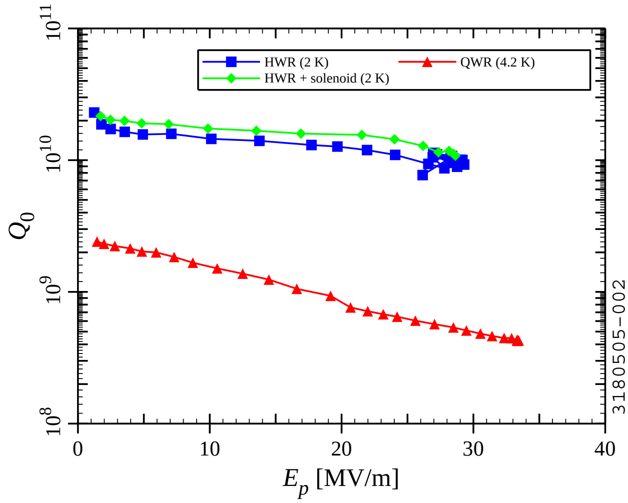

Figure 3. RF test results for the HWR, HWR in proximity to the solenoid, and QWR.

QWR and HWR were reported previously [7, 8]. Results of follow-up RF tests after installation of the helium vessels are shown in Figure 3 (squares and triangles). Both cavities show good RF performance before and after attachment of the helium vessels.

Both magnets were energized to full field to magnetize the iron and steel components. The quadrupole was energized to 48 T/m at MSU; the solenoid was tested to 9 T (92.3 A) by the vendor. After warming up, the remnant field outside the cryoperm shield of the quadrupole was 0.8–2 μT, as measured with a fluxgate magnetometer; the measured remnant field of the solenoid was 0.4–2 μT.

Both magnets were tested in proximity to a cavity to make sure the magnet field did not produce any degradation in RF performance. The HWR was used for these tests because it is more sensitive to external magnetic fields than the QWR. The cavity and magnet separation distance was chosen to match that of the final assembly inside the cryomodule.

Results of the tests of the HWR in proximity to the solenoid are shown in Figure 3 (diamonds). Before this measurement, the solenoid was energized to full current; the cavity was then warmed up above the critical temperature and cooled back down; the solenoid was energized to full current again during the RF measurements. As can be seen, no degradation in RF performance is observed due to the operating field or remnant field of the magnet. Likewise, no degradation in performance was observed in RF tests of the HWR with the quadrupole in proximity to it.

CONSTRUCTION STATUS

Construction of the prototype module is expected to be finished in 2005. The fundamental power couplers have been constructed and conditioned. The cavities have been etched and high pressure rinsed. Both superconducting magnets have been high pressure rinsed. The cavities and magnets have been attached to the alignment rails and hermetically sealed in the Class 100 clean room (Figure 4).

The copper 77 K shield was fabricated by industry. The vacuum vessel is ready for assembly. The top plate assembly has been started with the 4 support links installed, cryogenic manifold tack welded in place, and assembly legs installed. The cold box will be tested in mid-2005 before being connected to the cryomodule. The cold box heat exchanger, valves, and HTS leads have been assembled.

Figure 4. Cold mass assembly on titanium alignment rail inside the clean room. From left: QWR with RF coupler, solenoid with Nb shield, HWR with upper and lower cryoperm, quadrupole.

CONCLUSION

A prototype cryomodule for the low energy section of the RIA driver linac has been designed. The superconducting cavities and superconducting magnets for the cryomodule have been tested and have reached the design goals. Construction of the prototype cryomodule has begun. Assembly of the low β prototype cryomodule should be finished in 2005, with testing completed in 2006.

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