EXPERIMENTAL STUDY OF AN 805 MHz CRYOMODULE FOR THE RARE ISOTOPE ACCELERATOR*

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INTRODUCTION

The driver linac for the Rare Isotope Accelerator (RIA) is designed to accelerate heavy ions 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. The high energy section of the linac uses 805 MHz six-cell elliptical cavities with geometric $\beta \equiv \beta_g = 0.47$, 0.61, and 0.81. The first cavity was developed specifically for RIA [2]; the last two were developed for the Spallation Neutron Source (SNS) [3].

A rectangular cryomodule design that can accommodate all of the superconducting cavity and magnet types is proposed for RIA [4]. The proposed cryomodule is more compact than the SNS cryomodule, allowing for a smaller tunnel cross-section and a higher real estate gradient. The cold mass alignment is accomplished with titanium rails supported by adjustable nitronic links, similar to that used for superconducting magnet cryostats at MSU.

A prototype cryomodule for the RIA $\beta_g = 0.47$ elliptical cavities was completed in February 2004. The prototype contains 2 multi-cell cavities instead of the 4 cavities planned for production cryomodules, since the critical issues of cavity gradient, quality factor, and microphonics (which drive the linac cost via module count, cryo-plant capacity, and RF amplifier power) can still be addressed. The first cryogenic and RF tests on the prototype cryomodule were completed in May 2004. Experimental results will be presented in this paper, including alignment, cryogenic performance, RF performance, and frequency tuning. Measurements on microphonics and microphonics control for the cryomodule cavities are presented elsewhere [5, 6].

PROTOTYPE DESIGN AND CONSTRUCTION

Figure 1 shows the prototype cryomodule. The cavities were chemically treated and tested in a vertical cryostat at Jefferson Laboratory (JLab) to verify their performance before installation into the module [2]. The field unflatness between cells was less than 10%, and the π mode frequency was tuned for 805 MHz at 2 K.

The titanium helium vessel was TIG welded to Nb-Ti adapter flanges that were electron beam welded to the cavity beam tubes. Nb-Ti flanges with Al alloy gaskets were used for vacuum sealing. The cold mass was assembled in Jlab's class 10 clean room and shipped by truck to MSU. The cavities were shipped under partial vacuum due to a leaky valve, which was subsequently replaced.

Two μ-metal shields that also serve as passive thermal shields reduce stray fields to 0.5–1 μT. Liquid N_2 was used in the thermal shield, but in the RIA linac 50 K He gas will further decrease the static load to the liquid He.

The required RF power for beam loading and microphonics control is less than 10 kW [5]. The same ceramic window as SNS was used with a smaller diameter coaxial coupler [7, 8].

A room temperature external tuner with piezo-electric actuator was designed for ease of maintenance. Since RIA operates continuous wave (CW), Lorentz detuning will not require fast compensation.

A simple fixture was used to verify cavity alignment to the beam axis within ± 0.25 mm. Fiducials on the Ti rails were monitored through viewports during the cool-down.

COOL-DOWN

The cool-down to 20 K was done rapidly to avoid Q disease. Below 20 K, we proceeded slowly to economise liquid He while the cryomodule approached steady state. The cavities reached 24 K in about 2.5 hours and became superconducting after another 2.5 hours. He gas was introduced into the insulation vacuum space for about 3 hours during the cool-down to increase the heat transfer to the liquid N_2 shield. The cryomodule temperatures were nearly at their steady state values with a full He reservoir 16 hours after the cool-down started. The cavities were cooled from 4.3 K to 2 K by pumping on the He reservoir.

In the initial attempt to cool down to 4 K, the insulation vacuum was not spoiled and the He reservoir was filled rapidly—this caused problems due to the inner μ-metal shield and Ti rails still being warm. In the production cryomodules, it may be worthwhile to improve the heat sinking for these elements to simplify the cool-down.

In initial attempts to cool down to 2 K, there were 2 trapped gas volumes in the liquid He space, one in the supply bayonet and the other associated with a viewport on top of the module. These trapped gas volumes produced thermo-acoustic oscillations near the λ-point, resulting in a pressure instability. Once the liquid level was low enough so that the gas was no longer trapped, we were able to reach 2 K. This problem was eliminated by removing the supply bayonet and the viewport and plugging the holes with teflon-tipped G10 spears. (A supply bayonet was installed in the He reservoir to replace the original bayonet feeding liquid directly to the cavities.) Trapped gas volumes will

*Work supported by Michigan State and the U.S. Department of Energy under Grant DE-FG02-03ER41247.

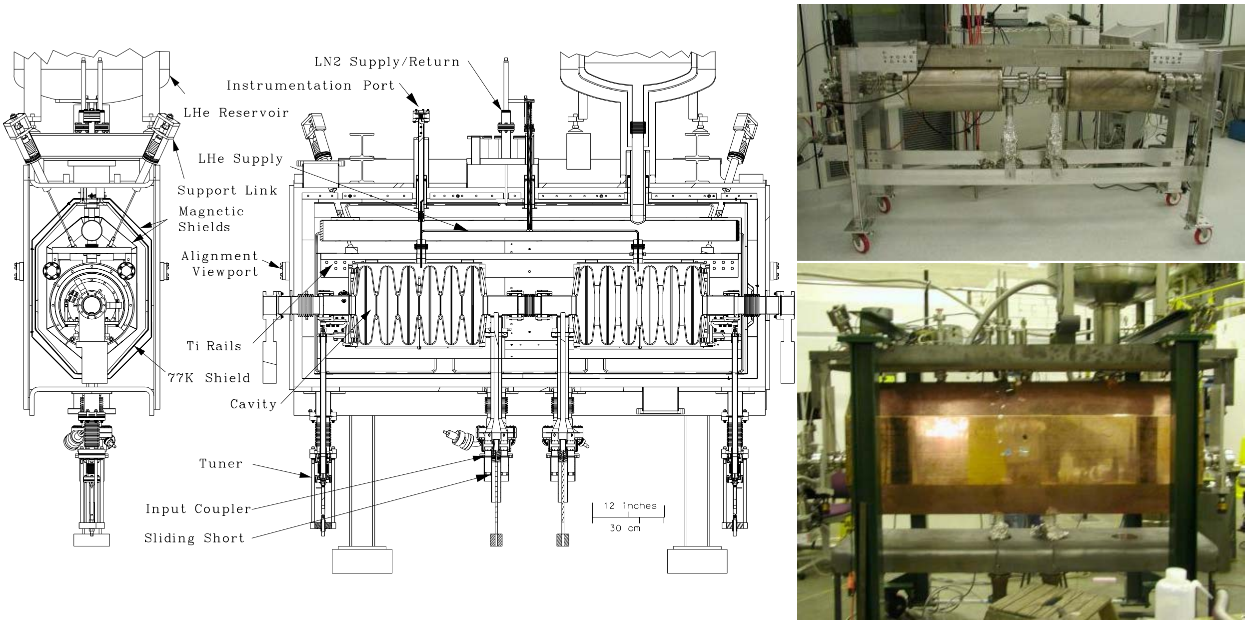

Figure 1 Left: end view and section view of the $\beta = 0.47$ prototype cryomodule. Top right: cavities inside the helium vessels after attachment of the Ti rails and input couplers. Bottom right: Cold mass after installation of the thermal shield.

be avoided in the production cryomodules.

STATIC HEAT LEAK

The static heat leak to the liquid He at 2 K was measured from the volume of He gas pumped per unit time. The pumping rate was obtained by measuring the time required to displace a known volume of water. The pumping rate was converted to heat leakage rate by calibrating it against a resistive heater in the cryomodule. In steady state conditions, the measured static heat leak to the liquid He was 10 to 11 W. The predicted heat leak was 15 W for a 4-cavity cryomodule [4], in reasonable agreement with the measurements on the 2-cavity prototype.

The static heat leak to the liquid He at 4.3 K was measured from the rate of decrease of the level in the He reservoir. As expected, the measured heat leak at 4.3 K (9 W) was similar to that at 2 K.

INPUT COUPLERS

The measured input coupling strengths were $Q_{ext} = 1.4 \cdot 10^7$ for Cavity #1 and $Q_{ext} = 1.3 \cdot 10^7$ for Cavity #2, both a bit lower than the design value ($Q_{ext} = 2 \cdot 10^7$).

Multipacting barriers were encountered at low field ($E_a \lesssim 0.1$ MV/m) with both cavities after they were cooled to 4.2 K. In both cases, we punched through the barriers after less than 1 hour of RF conditioning. Current was detected on the center conductor during the conditioning, which suggests that the multipacting was in the coupler, not in the cavity.

Since the input antennae cannot be moved, sliding shorts were installed on the coaxial lines to adjust the input coupling (see Figure 1). Loop antennae on the sliding shorts were used to couple power in and excite a standing wave in the coupler. For high field measurements, the short was moved to the detuned position to maximise the field in the cavity and minimise the field in the coupler. For low-field microphonics studies with a wide band-width, the short was moved to the tuned position. The range of measured Q_{ext} values was $6 \cdot 10^4$ to $6 \cdot 10^9$.

CAVITIES

The sliding short allowed us to set up a good match to reach high fields without high RF power, so most of the RF measurements were done with a 200 W solid state amplifier and a phase feedback loop.

The intrinsic quality factor of the cavity (Q_0) was obtained from RF measurements and checked with calorimetry. With the short present, the coaxial line has one open end and one shorted end, and hence has resonances when the length is equal to an odd integer multiple of $\lambda/4$. In the detuned position, the cavity resonance was between the frequencies of the $7\lambda/4$ and the $9\lambda/4$ resonances. We measured the Q for these adjacent resonances to estimate the power dissipation in the coupler's standing wave. We used a second loop antenna to infer the energy stored in the standing wave while we were driving the cavity. This allowed us to subtract out the estimated power dissipation in the coaxial line and calculate Q_0 directly from the RF measurements.

Field emission started at low field in the first measurements at 2 K. The field emission was especially bad in Cavity #1. Interesting images were observed with a video camera (set up to look into the cavities from a viewport on the beam tube) while driving Cavity #1. The light disappeared during RF processing of Cavity #1 and did not return. We were able to reach $E_a = 6$ MV/m in Cavity #1 and $E_a = 7.5$ MV/m in Cavity #2 after RF processing. We observed some deconditioning of Cavity #2 after conditioning of Cavity #1.

Additional pulsed processing (power ≤ 3 kW) was done to further reduce the field emission. Figure 2 shows the cavities' performance after pulsed processing. The design gradient ($E_a = 10$ MV/m) was exceeded in both cavities, but they both still show field emission at high field: after processing, the first x-ray signals were detected at $E_a \approx 8$ MV/m, and the x-ray levels near the cryomodule reached as high as 10 rem/hour at high field. Cavity #2 does not quite meet the design goal of $Q_0 = 7 \cdot 10^9$ at the design gradient. After conditioning, both cavities exhibited some "Jekyll & Hyde" behaviour in which the field emission current (along with the RF power dissipation and x-ray flux) jumped back and forth between a lower value and a higher value. This can be seen most clearly from the double-valued Q_0 versus E_a curve for Cavity #2 at high field.

Measurements on the standing wave indicated that, at low field, the power dissipation in the coaxial line was less than or about equal to the power dissipation in the cavity; at high field, a higher proportion of the power was dissipated in the cavity. To check the RF measurements, the quality factor was obtained from a calorimetric measurement of the power dissipation. As for the static heat leak measurement, the He gas pumping rate was measured and calibrated against a heater. Measurements were done on Cavity #2 before the final round of pulsed RF processing. Useful results were obtained for $4.5 \le E_a \le 7$ MV/m (at low field, the RF power dissipation was small relative to the static heat leak and the uncertainty in Q_0 was excessive). The calorimetric Q_0 values were between $5 \cdot 10^9$ and $9 \cdot 10^9$, consistent with the RF measurements.

FREQUENCY ISSUES

In the first cool-down to 2 K (both tuners locked), the resonant frequencies were 805.13 MHz (Cavity #1) and 805.24 MHz (Cavity #2). The measured travel was 10 mm, with a measured tuning range of 0.95 MHz, well above the design goal of 0.5 MHz. Thus, both cavities were well within tuning range of the design frequency. A piezoelectric element was installed for fast tuning and compensation of vibrations. The range of fast tuning with up to 100 V drive signal was about 11 kHz. The piezo element was used for active damping of microphonics [5, 6].

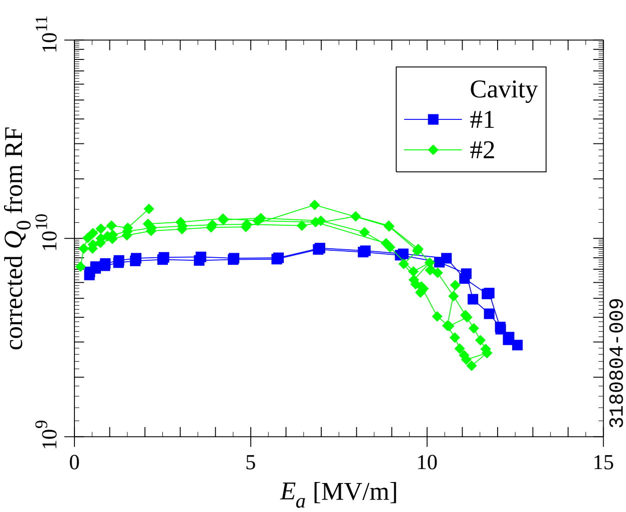

Figure 2: RF measurements on the $\beta_g = 0.47$ cavities at 2 K after RF processing.

The rate of change in the resonant frequency f as a function of the pressure P in the helium vessel was measured during the cool-down from 4.2 K to 2 K, with the result $df/dP = 0.36$ kHz/torr (Cavity #1) and $df/dP = 0.46$ kHz/torr (Cavity #2). The sign is the opposite of what was measured for single-cell cavities ($df/dP = -1.0$ kHz/torr) and vertical tests on 6-cell cavities; the pressure force on the helium vessel (present for the cryomodule cavities, absent in the vertical tests) tends to cancel the effect of the pressure force on the cavities.

The measured Lorentz detuning coefficient at 2 K was $K_L \equiv df/dE_a^2 = -16$ Hz/(MV/m)^2. This result is close to the predicted value of $K_L = -14$ Hz/(MV/m)^2 [9]. The value for the cryomodule is smaller than the measured detuning for the single-cell cavities [$K_L = -22$ Hz/(MV/m)^2], as one would expect since the single-cell cavities had no stiffening rings at the irises.

CONCLUSION

A prototype cryomodule for RIA has been constructed and tested. The cryogenic and RF performance has been demonstrated. The RF performance of one of the cavities is a bit marginal due to contamination. Note that SNS production cavities were prepared using the same facilities at about the same time (November 2003), and they showed similar problems with field emission. Corrections have since been implemented, resulting in lower field emission and better performance for SNS cavities. A valve leak might have also contributed to the contamination of the prototype module. Future goals include a demonstration of RF amplitude and phase control at full power, including microphonics control.

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