SUPERCONDUCTING QUARTER-WAVE RESONATOR CAVITY AND CRYOMODULE DEVELOPMENT FOR A HEAVY ION RE-ACCELERATOR*

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Abstract

A superconducting linac is being planned for re-acceleration of exotic ions at the National Superconducting Cyclotron Laboratory. The linac will include two types of superconducting quarter-wave resonators (QWRs). The QWRs (80.5 MHz, optimum $\beta \equiv \beta_m = 0.041$ and 0.085, made from bulk niobium) are similar to existing cavities presently used at INFN-Legnaro. The re-accelerator's cryomodules will accommodate up to 8 cavities, along with superconducting solenoids for focussing. Active and passive shielding is required to ensure that the solenoids' field does not degrade the cavity performance. First prototypes of both QWR types have been fabricated and tested. A prototype solenoid has been procured and tested. A test cryomodule has been fabricated, containing one QWR, one solenoid, and two other beam-line elements. The QWR and solenoid have been operated successfully inside the cryomodule.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) is building a re-accelerator for exotic ion beams [1, 2]. Stable ions are produced in an ion source and accelerated in the NSCL coupled cyclotron facility. The primary beam produces a secondary beam of exotic ions by particle fragmentation.

The re-accelerator will consist of a gas stopper to slow down the secondary ion beam, a charge breeder to increase the charge of the ions by removing electrons, a multi-harmonic buncher, a radio frequency quadrupole for initial acceleration and focussing, and a superconducting linac to accelerate the beam to a final energy of 3 MeV per nucleon. Additional cryomodules can be added to increase the energy to 12 MeV per nucleon.

The superconducting linac will consist of quarter-wave resonators (QWRs) optimised for $\beta = 0.041$ [3] and $\beta = 0.085$ [4]. The cavities will be housed in a rectangular box cryomodule. A test cryomodule [5] has been designed, assembled, and tested. This paper covers design and prototyping work on the $\beta_m = 0.041$ QWR, $\beta_m = 0.085$ QWR, and cryomodules for the re-accelerator.

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CAVITY DESIGN

The QWRs developed by Legnaro for ALPI and PIAVE [6] are the basis for the design of the QWRs for the re-accelerator (see Fig. 1). Some design modifications have been implemented. A larger aperture (30 mm) is used. Separation of cavity vacuum from insulation vacuum is implemented to reduce particulate contamination of cavity surfaces. Probe couplers [7] are used instead of loop couplers.

The cavity design has undergone some evolution since the first prototype cavity was fabricated and tested. For the second and third generation of QWRs, the shorting plate is formed from sheet niobium (3 mm thick) instead of being machined and the tuning plate (1.25 mm thick) is slotted to reduce the tuning force [7]. The shorting plate design is similar to designs used by Argonne [8] and SPIRAL 2 [9].

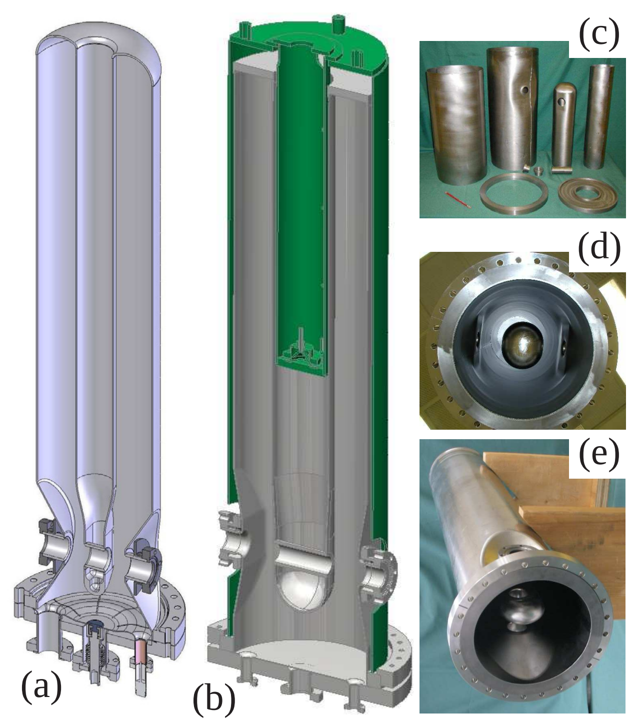

Figure 1: Drawings: (a) second generation $\beta_m = 0.041$ QWR; (b) first generation $\beta_m = 0.085$ QWR with damper and He vessel, shown in green. Photographs: (c) parts for first generation $\beta_m = 0.085$ QWR and (d) completed cavity; (e) completed second generation $\beta_m = 0.041$ QWR.

The tuning plate design is similar to designs for TRIUMF [10] and the ALPI upgrade [11].

The helium vessel is made of titanium. The vessel design includes a Legnaro-type frictional damper [6] inside the inner conductor to mitigate microphonic excitation of the cavity.

The design intrinsic quality factor is $Q_0 = 5 \cdot 10^8$ for both cavities at the operating temperature of 4.5 K. The design fields are $E_p = 16.5$ MV/m for the $\beta_m = 0.041$ cavity and $E_p = 20$ MV/m for the $\beta_m = 0.085$ cavity, where E_p is the peak surface electric field. Detailed RF parameters for the cavities have been published previously [3, 4].

PROTOTYPE CAVITY FABRICATION

Sheet Nb of thickness 2 mm and RRR ≥ 150 was used. The tip of the center conductor and the beam tubes were machined from solid Nb. The Nb tuning plate on the bottom of the cavity is held by a Nb-Ti to stainless steel flange. Forming was done at NSCL and in the local area, while electron beam welding was done with industry. Indium joints were used to seal the bottom flange. Knife-edge seals were used for beam tube flanges. Between 120 and 150 μm was etched from the inner surface via buffered chemical polishing. High-pressure rinsing was done with ultra-pure water in a Class 100 clean room for 60 to 120 minutes.

DEWAR TESTS

The Dewar test results have been reported previously for both the $\beta_m = 0.041$ QWR [3] and the $\beta_m = 0.085$ QWR [4]. Both cavities exceeded the design goals: at the design fields, the measured Q_0 exceeded 10^9 in both cases. In the RF tests on the $\beta_m = 0.041$ QWR, the highest field reached at 4.2 K was $E_p \approx 65$ MV/m; at 2 K, the measured field was $E_p \approx 80$ MV/m. In the RF tests on the $\beta_m = 0.085$ QWR, the highest field reached at 4.2 K was $E_p \approx 31$ MV/m.

TEST CRYOMODULE

A rectangular box cryomodule [5], shown in Fig. 2, was fabricated for testing of the cavities, magnets, and auxiliary elements as a unit. The test cryomodule contains one $\beta_m = 0.085$ QWR, one $\beta_m = 0.285$ half-wave resonator (HWR), one solenoid with a dipole steering coil, and one quadrupole. The QWR and HWR are both first generation prototypes without any stiffening elements. A Ti rail system is used for support and alignment. Active and passive magnetic shielding is implemented, consisting of reverse wound coils at the ends of the solenoid, a Meissner shield (Nb can) around the solenoid, and μ metal shields around the Meissner shield and the cavities.

Below 150 K, the cryomodule was cooled rapidly to minimise the risk of surface hydride formation ("Q disease"). The measured static heat leak of the module at 4 K was 4.5 W $\pm$ 1.2 W; the predicted value was 5.2 W. No degradation in cavity performance was observed with the solenoid at full field. A decrease in the low-field Q_0 of the QWR was observed near the end of one cool-down, possibly due to the Meissner shield becoming warm with the solenoid energised. The cavity performance recovered after the cryomodule was warmed to room temperature and re-cooled.

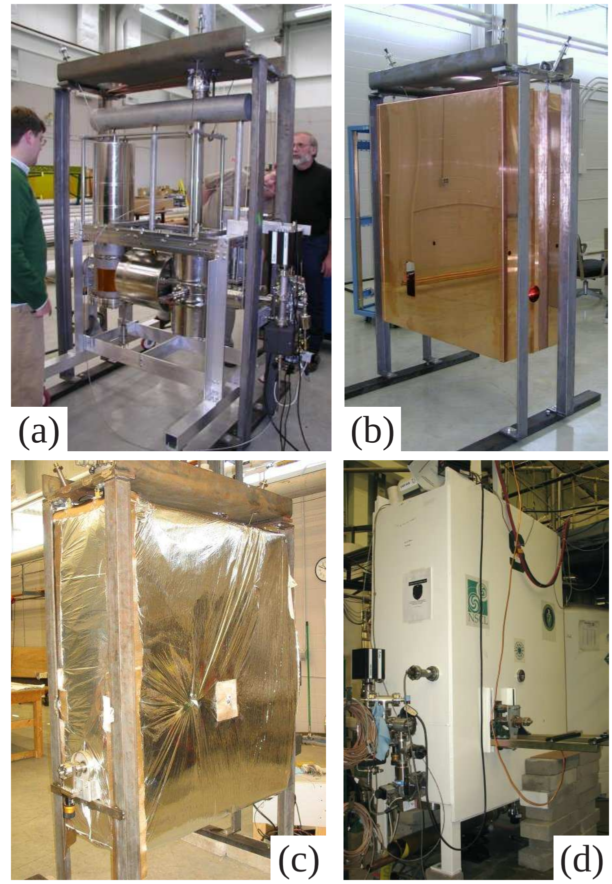

Figure 2: Construction of the low-β test cryomodule: (a) cold mass hanging from top plate; (b) 77 K shield; (c) outer multi-layer insulation; (d) vacuum vessel.

RF testing of the cavities was done first with a direct connection from the RF amplifier to the coupler, and then with a sliding short to set up a standing wave on the rigid copper coaxial transmission line. The sliding short configuration provided less mismatch and made it easier to infer the intrinsic Q of the cavity (Q_0) from the RF measurements; simple loop couplers were used to couple into the transmission line through the short and monitor the field in the line. The measured QWR input coupling strength was $Q_{ext} = 4.5 \cdot 10^6$ with a direct connection. With the sliding short set to minimise losses in the copper, the measured Q_{ext} was $1.4 \cdot 10^9$. RF conditioning and helium processing were done to mitigate field emission. As can be seen in Fig. 3, the measured performance of the QWR after He processing is similar to its performance in the Dewar test.

The tuners were operated over their full range. The pressure sensitivity of the QWR was measured (see Table 1 below).

CAVITY STIFFENING

Structural analyses of the QWRs are being done with ANSYS.[1] As shown in Fig. 4, stiffening methods are be-

[1] ANSYS, Inc., Canonsburg, Pennsylvania, USA.

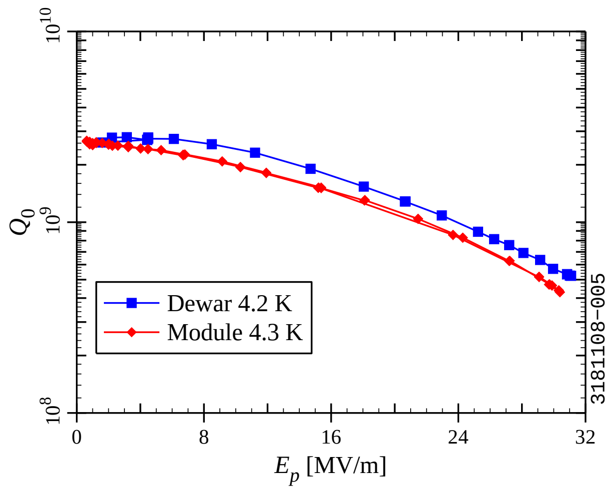

Figure 3: RF test results for the $\beta_m = 0.085$ QWR: comparison of Dewar test and cryomodule test (after solenoid operation, temperature cycling, and He processing).

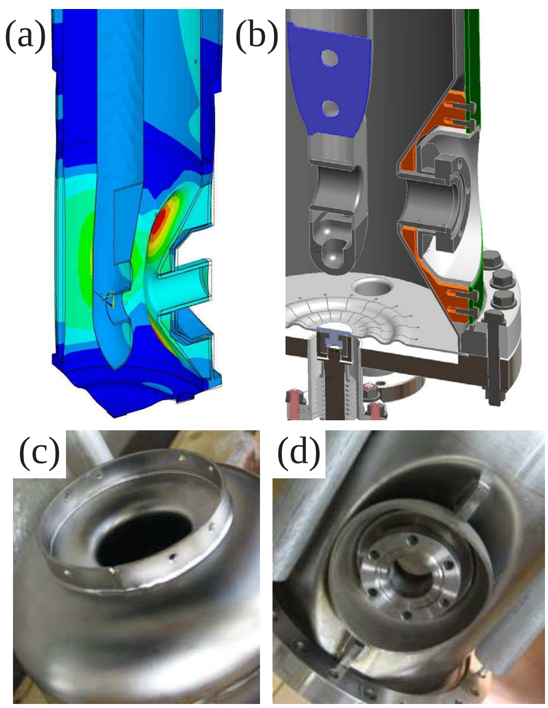

Figure 4: Stiffening of the $\beta_m = 0.041$ QWR: (a) ANSYS model showing the predicted deformation for a stiffened QWR; (b) drawing of QWR with center conductor rib (blue) and beam port buttresses (orange); (c) Nb ring welded to the top of the cavity; (d) Nb buttresses welded to the beam port region.

ing implemented for the $\beta_m = 0.041$ QWR to reduce the frequency shift due to bath pressure fluctuations. Some predicted and measured values of the frequency shift due to bath pressure are given in Table 1. The stiffening measures should reduce Lorentz detuning as well. Reduction in the pressure sensitivity of the $\beta_m = 0.085$ QWR is planned. After stiffening, it is anticipated that the QWRs' pressure sensitivities will be similar to those used elsewhere.

Table 1: Measured and predicted values of the shift in resonant frequency f with bath pressure P for the QWRs.

β_m	Stiffened	He vessel	df/dP (Hz/mbar) Predicted	Measured
0.041	no	no	−18.7	−18.5
0.041	no	yes	−11	
0.041	yes	yes	−2.7	
0.085	no	no		−19.7
0.085	no	yes	−6.8	−7.3

CONCLUSION

Prototype cavities for the NSCL re-accelerator have been fabricated and tested. The design goals for the RF performance have been achieved in Dewar tests (for both cavity types) and a cryomodule test (for one cavity type so far).

The re-accelerator will require 3 cryomodules, with a total of 15 cavities and 8 solenoids. The cavities are being fabricated at NSCL, with electron beam welding done by industry. The 9 tesla superconducting solenoids are being fabricated by industry.

ACKNOWLEDGMENTS

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