NIOBIUM QUARTER-WAVE RESONATOR DEVELOPMENT FOR THE RARE ISOTOPE ACCELERATOR*

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INTRODUCTION

There is a growing interest in the production of intense beams of exotic isotopes for research in nuclear physics and laboratory astrophysics [1]. The Rare Isotope Accelerator (RIA) is one such project being pursued by the nuclear physics community in the USA [2]. RIA calls for a superconducting cavity linac to accelerate the CW beam of heavy ions to $\geq$ 400 MeV per nucleon, with a beam power of up to 400 kW. Several types of superconducting structures are needed due to the changing velocity of the beam [3].

Design studies are in progress at Michigan State University (MSU) for a 10th-harmonic driver linac consisting of quarter-wave resonators (QWRs), half-wave resonators, and elliptical cavities [4]. Three different types of QWRs have been designed for the first segment of the driver linac. The first QWR type (optimum $\beta \equiv \beta_m = 0.041$, 80.5 MHz) is very similar to existing QWRs in use at INFN-Legnaro (β is the beam velocity divided by the speed of light). The second ($\beta_m = 0.085$, 80.5 MHz) and third ($\beta_m = 0.16$, 161 MHz) types are being developed as a collaborative effort between Legnaro and MSU.

This paper covers the RF design, prototyping, and preliminary RF testing of simplified versions of the $\beta_m =$ 0.085 and $\beta_m = 0.16$ QWRs. The next step, the development of a complete $\beta_m = 0.16$ cavity with an integrated helium vessel, is also underway [5].

CAVITY DESIGN

The quarter-wave resonators developed by Legnaro for ALPI are the basis for the design of the RIA quarter-wave cavities. QWRs at 80 MHz are presently being used at Legnaro for the ALPI and PIAVE linacs [6]; a 160 MHz QWR has also been prototyped at Legnaro [7].

The ALPI cavities have a outer conductor diameter of 180 mm; this was enlarged to 240 mm for the $\beta_m = 0.085$ and $\beta_m = 0.16$ RIA cavities. A larger aperture (30 mm) is also used for the RIA cavities. Another new feature is to separate the cavity vacuum from the insulation vacuum to reduce particulate contamination of the cavity surfaces.

A recent development is the identification of beam steering due to the vertical asymmetry in QWR structures [8]. The steering is not a major problem for the $\beta_m = 0.085$ QWR due to the long wavelength, but it is significant in the $\beta_m = 0.16$ QWR. It has been shown theoretically that the steering can be partially compensated by asymmetric shaping of the cavity in the vicinity of the beam ports [9]. The $\beta_m = 0.16$ QWR incorporates asymmetric cavity walls to compensate for the steering. Beam dynamics studies indicate that the compensation should eliminate the emittance growth due to steering [10].

Table 1 shows some of the parameters of the structures. RF parameters were calculated with ANALYST.[1] Drawings of the structures are shown in Figure 1. Figure 2 shows the accelerating voltage that can be delivered by each of the cavity types at the design field level ($E_p = 20$ MV/m) as a function of the velocity of the accelerated beam, including transit time effects.

Table 1: Selected RF and geometrical parameters for the quarter-wave resonators. OC and IC are the outer conductor and inner conductor, respectively.

Optimum $\beta \equiv \beta_m$	0.085	0.16
Resonant frequency f	80.5 MHz	161 MHz
Design E_p	20 MV/m	
Design B_p	49.2 mT	43.4 mT
Design V_a	1.18 MV	0.99 MV
R_s/Q	416 Ω	380 Ω
Geometry factor	19 Ω	35 Ω
Nominal OC diameter	240 mm	
Nominal IC diameter	105 mm	
Nominal height ($\lambda/4$)	931 mm	466 mm
Active length	210 mm	190 mm
Aperture	30 mm	

FABRICATION OF PROTOTYPES

Sheet Nb of thickness 2 mm and RRR $\geq$ 150 was used. The top plate, the beam tubes, and the tip of the center conductor were machined from solid Nb. Holes were machined into the latter (see Figure 1) to improve the contact with the liquid helium. The bottom flange consists of a Nb-Ti ring welded to the Nb outer conductor, mating with a stainless steel (SS) blank-off flange; a Nb tuning plate is bolted to the outer conductor via this flange. Forming of the Nb parts was done at MSU and in the local area. Electron beam welding was done by industry. Figure 3 shows

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[1] A product of Simulation Technology & Applied Research, Inc., Mequon, Wisconsin.

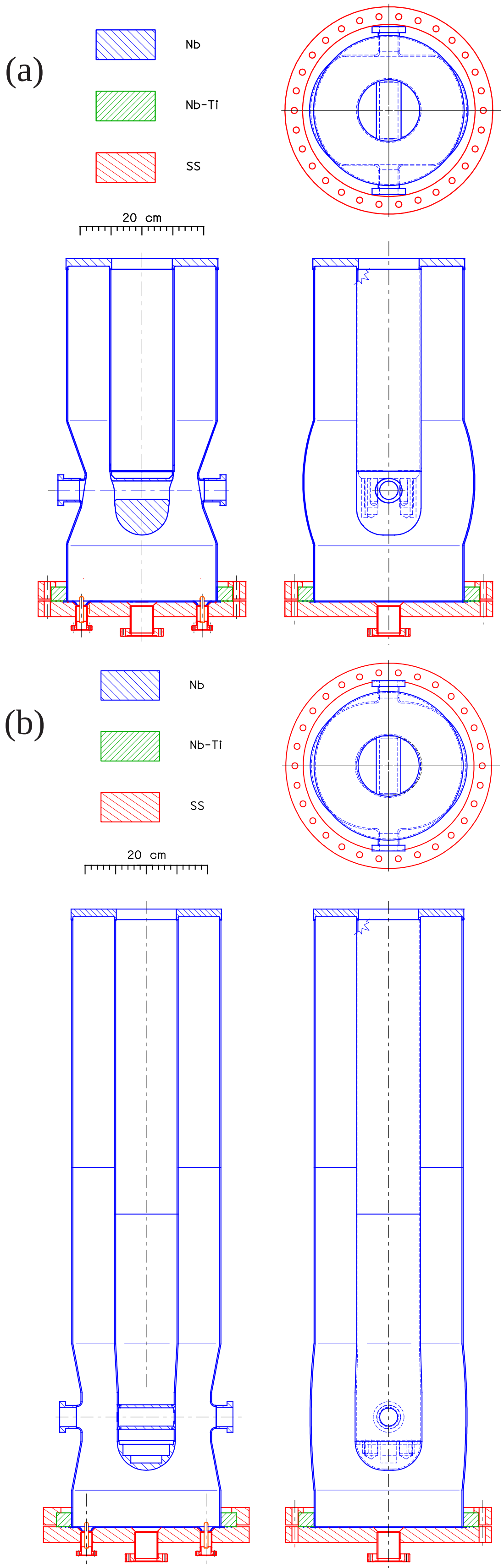

Figure 1: Three-view drawing of (a) the $\beta_m = 0.16$ QWR and (b) the $\beta_m = 0.085$ QWR.

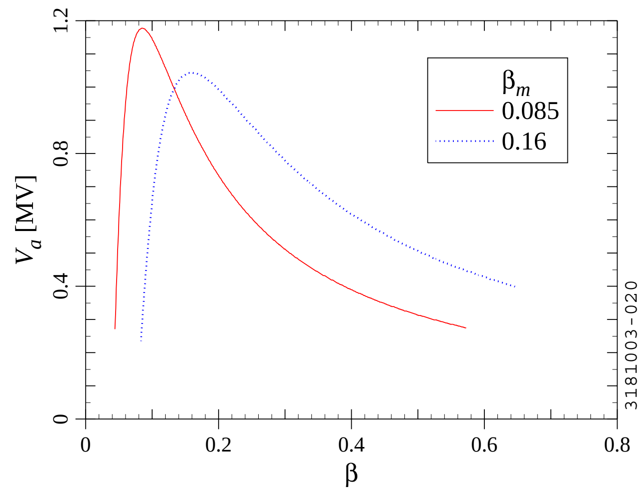

Figure 2: Dependence of accelerating voltage on beam velocity for the $\beta_m = 0.16$ and $\beta_m = 0.085$ QWRs.

the Nb parts before and after welding of the $\beta_m = 0.16$ cavity. Indium joints were used to provide a vacuum seal on the bottom flange and beam tube flanges. Electrical contact between the tuning plate and the outer conductor was made via pressure from the bottom flange (thus the indium provides a vacuum seal, but not an RF seal). At $E_p = 20$ MV/m, the magnetic field at the joint is about 0.7 mT for the $\beta_m = 0.16$ QWR and about 0.5 mT for the $\beta_m = 0.085$ QWR.

Bead pulls were done to check the field flatness. Figure 4 shows the bead pull traces. The field unflatness parameter $(\Delta E/E)$ was 3.8% for the $\beta_m = 0.085$ cavity and 0.6% for the $\beta_m = 0.16$ cavity.

The completed QWRs were etched with a Buffered Chemical Polishing solution (1:1:2 mixture by volume of concentrated hydrofluoric, nitric, and phosphoric acid) to remove 120 μm from the inside surface. The acid was circulated through a chiller in a closed loop system to maintain a temperature $\leq 15°$C. After etching, a high-pressure rinse with ultra-pure water was done in a Class 100 clean room for 60 to 120 minutes. The cavity was then assembled onto an insert for subsequent RF testing. Figure 5a shows the $\beta_m = 0.16$ cavity during assembly onto the insert. Figure 5b shows the $\beta_m = 0.085$ cavity just prior to insertion into the cryostat.

RF TESTS

RF testing was done with the cavity immersed in a liquid helium bath at 4.2 K; some additional measurements were done at 1.5 K or 2 K. A phase feedback loop was used to lock onto the resonance. The RF power was provided by a 50 W amplifier protected by a circulator. Copper probe antennae (mounted on the bottom flange, see Figure 1) were used to couple the power into the cavity and pick up the transmitted power signal. The input antenna length was chosen to be near unity coupling at low field at 4.2 K.

Multipacting barriers were encountered at low field in

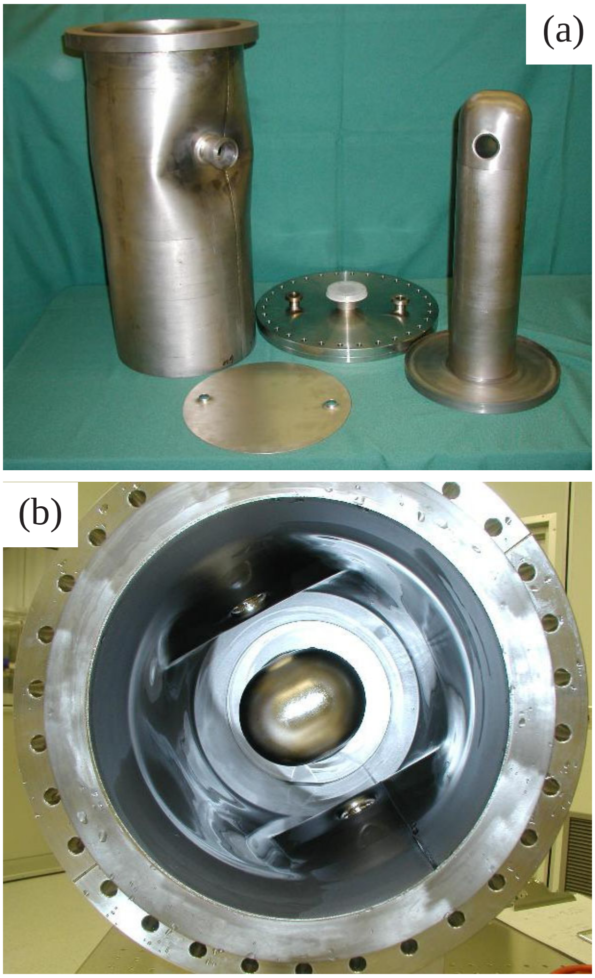

Figure 3: (a) Nb parts for $\beta_m = 0.16$ QWR and (b) inside view of the completed cavity.

both cavities. We were able to get through the barriers with 1 to 2 days of RF conditioning at 4.2 K. The barriers were not completely eliminated by conditioning; reconditioning was required in some circumstances. No conditioning was done at higher temperatures.

$\beta_m = 0.16$ *QWR*

The first RF test on the $\beta_m = 0.16$ QWR was done in May 2003. Results are shown in Figure 6a (circles). The maximum field level reached in the first test was $E_p = 8$ MV/m. After the first test, the cavity was disassembled, and grinding was done to remove a suspicious area on the shorting plate. An imbedded bit of foreign metal was also found and ground out. After grinding, the cavity was etched and rinsed again.

A second RF test was done in July 2003. A field level of $E_p = 19$ MV/m was reached in steady state (see Figure 6a, squares). A higher field ($E_p = 23$ MV/m) could be reached with modulated RF (see Figure 6a, diamonds). These levels were reached after some improvement from RF processing. Helium processing was also attempted, but this did not further improve the performance. Modest x-ray signals were observed during the test (110 mR/hour was the largest radiation level measured inside the radiation shield).

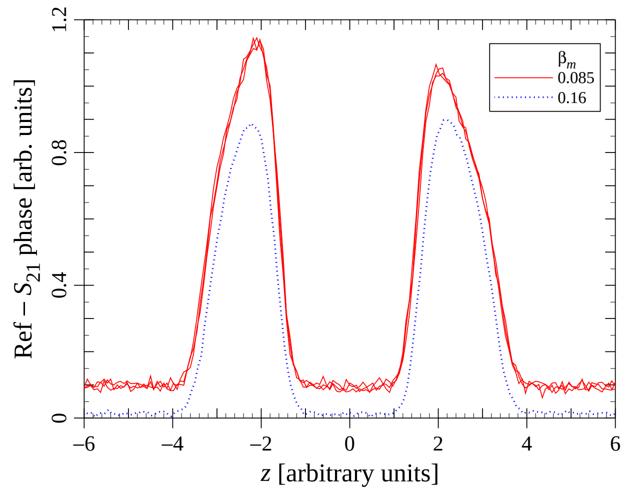

Figure 4: Bead pulls for the $\beta_m = 0.16$ and $\beta_m = 0.085$ QWRs.

Figure 5: Photographs of (a) $\beta_m = 0.16$ QWR and (b) $\beta_m = 0.085$ QWR on the RF test stand.

A system of mirrors was used to view the outside of the cavity with a video camera placed on top of the cryostat. At high field, bubbles in the helium bath were observed to come from the bottom flange of the cavity, indicating that the dominant losses were not in the high magnetic field region.

As indicated in Figure 6a, there was a decrease in Q_0 at very low field, possibly due to resistive losses in the RF joint between the outer conductor and the tuning plate. The low-field Q_0 value of $1.8 \cdot 10^9$ at 4.2 K corresponds to a surface resistance (R_s) of 19 nΩ; the expected contribution from the BCS term is 12 nΩ. The low-field Q_0 was $3 \cdot 10^9$ at $T = 2$ K, corresponding to a residual surface resistance (R_0) of 12 nΩ. Thus, the measured R_s at 4.2 K is a bit smaller than expected from the sum of the expected BCS R_s and measured R_0. For $E_p > 2$ MV/m, the Q_0 was the same at 2 K as at 4.2 K.

$\beta_m = 0.085$ *QWR*

Two changes were made for the $\beta_m = 0.085$ QWR test (in light of the problems encountered in the tests on the $\beta_m = 0.16$ QWR and the suspected causes). First, a ridge was added to the Nb tuning plate for better RF contact with the outer conductor. Second, a hollow tube was installed on the bottom flange to touch the center of the tuning plate for improved heat sinking to the helium bath.

The first RF test on the $\beta_m = 0.085$ QWR was done in September 2003. Results are shown in Figure 6b. A field level of $E_p = 31$ MV/m was reached. Above that field level,

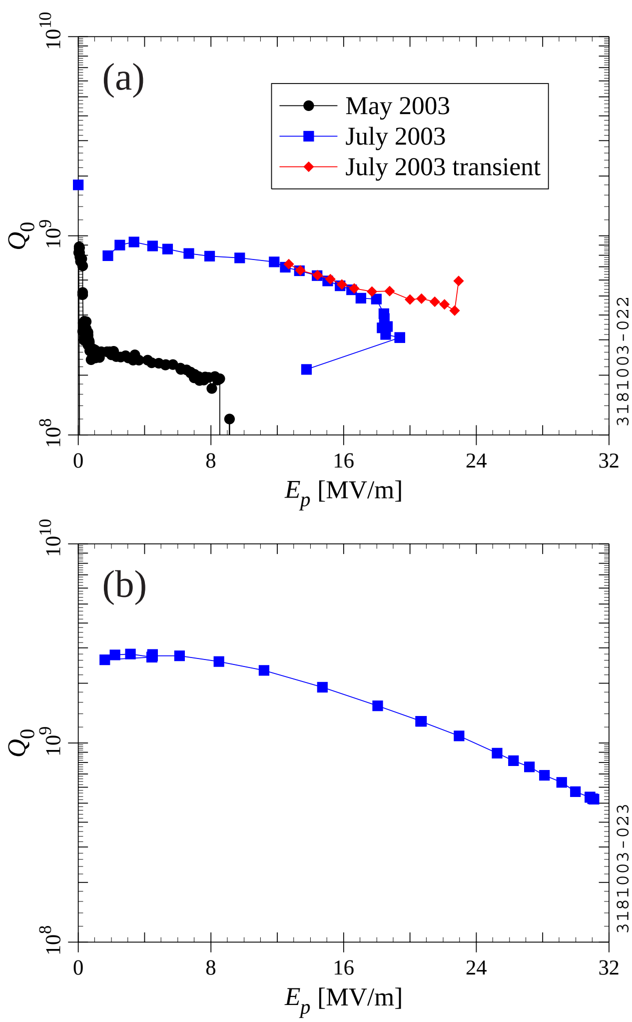

Figure 6: RF tests of (a) the $\beta_m = 0.16$ QWR at 4.2 to 4.3 K and (b) the $\beta_m = 0.085$ QWR at 4.2 K.

we reproducibly lost lock on the feedback loop, possibly due to thermal breakdown. The measured x-ray signals were ≤ 50 mR/hour. The video images indicated that bubbles were being nucleated more or less uniformly near the top of the cavity, as one would expect for losses due to the magnetic field.

The low-field Q_0 value of about $3 \cdot 10^9$ at 4.2 K corresponds to $R_s = 6.3$ nΩ; the expected contribution from the BCS term is 2.9 nΩ. The low-field Q_0 was $6 \cdot 10^9$ at $T = 1.5$ K, corresponding to $R_0 = 3.2$ nΩ, in good agreement with the measured R_s at 4.2 K and expected BCS contribution.

CONCLUSION

A $\beta_m = 0.16$ QWR and a $\beta_m = 0.085$ QWR have been fabricated and tested. RF test results for the $\beta_m = 0.16$ QWR are marginal. Further tests with improved RF contact and better heat sinking of the Nb tuning plate are planned. RF test results for the $\beta_m = 0.085$ QWR have exceeded the design field level by a comfortable margin, with $Q_0 > 10^9$ at the design field (at $T = 4.2$ K). We were able to condition through low-field multipacting barriers without a variable coupler (1 to 2 days of conditioning were required). The next steps in this QWR prototyping effort will be the fabrication of complete cavities with integrated He vessels and the characterisation of microphonics.

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