STATUS REPORT ON MULTI-CELL SUPERCONDUCTING CAVITY DEVELOPMENT FOR MEDIUM-VELOCITY BEAMS*

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INTRODUCTION

The Rare Isotope Accelerator (RIA) is being designed to supply an intense beam of exotic isotopes for nuclear physics research [1]. Superconducting cavities are to be used to accelerate the CW beam of heavy ions to 400 MeV per nucleon, with a beam power of up to 400 kW. Because of the varying beam velocity, several types of superconducting structures are needed [2].

Since the RIA driver linac will accelerate heavy ions over the same velocity range as the Spallation Neutron Source (SNS) proton linac, the 6-cell axisymmetric 805 MHz cavities and cryostats of SNS can be used for part of the RIA linac. Prototypes for both SNS cavities ($\beta_g = 0.61$ and $\beta_g = 0.81$) have been tested [3]. (Herein, β is the particle velocity divided by c and β_g is the geometric β.)

The SNS cavity design is being extended to lower velocity ($\beta_g = 0.47$) for RIA [4, 5]. Other single-cell cavities for $\beta = 0.47$ to 0.5 have also been prototyped at various laboratories [6, 7, 8]; in all cases, gradients and Q's have exceeded the design goals. A 5-cell $\beta = 0.5$ cavity has also been prototyped at JAERI [9].

This paper covers the fabrication of three prototype RIA 6-cell $\beta_g = 0.47$ cavities and the RF tests on the first and second of these cavities.

CAVITY DESIGN

The SNS $\beta_g = 0.81$ and $\beta_g = 0.61$ cavities are the basis for the RIA $\beta_g = 0.47$ cell shape [4, 5]. The beam tube is enlarged on one side of the SNS cavities in order to provide stronger input coupling. Less coupling is needed for RIA, so no enlargement of the beam tube is needed for the $\beta_g = 0.47$ cavity [10]. This simplifies the cavity fabrication and yields a slight improvement in the RF parameters. Selected cavity parameters are given in Table 1. In Table 1, E_p and B_p are the peak surface electric and magnetic field, respectively, and E_a is the accelerating gradient (transit time included) for a particle travelling at the design velocity.

An analysis was done of the excitation of higher-order modes (HOMs) in the cavity by the beam and coupling of the HOMs to the input coupler and pick-up antenna. This analysis indicates that HOM couplers are not required for operation of the $\beta_g = 0.47$ cavity in RIA, allowing for further simplification of the system [10].

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Table 1. Parameters of the symmetric 6-cell $\beta_g = 0.47$ cavity; R_s is the shunt impedance (linac definition). RF quantities were calculated with SUPERFISH [11].

Mode	$TM_{010}\pi$
Resonant frequency f	805 MHz
Cell-to-cell coupling	1.5%
E_p/E_a	3.34
cB_p/E_a	1.98
R_s/Q	173 Ω
Geometry factor	155 Ω
Active length	527 mm
Inner diameter at iris (aperture)	77.2 mm
Inner diameter at equator	329 mm

SINGLE-CELL CAVITY PROTOTYPING

Two single-cell prototypes of the $\beta_g = 0.47$ cavity were fabricated and tested. The highest gradient reached in the first round of tests [4] was about 15 MV/m. The Q values at 15 MV/m were about 10^{10}; the low-field Q values were between $2 \cdot 10^{10}$ and $4 \cdot 10^{10}$. These measurements were done at 2 K in a vertical cryostat at Jefferson Lab.

Additional tests were done on the second of the two single-cell cavities while commissioning the facilities at NSCL for etching, high-pressure rinsing, clean assembly, RF testing, and helium processing of superconducting cavities. The highest gradient reached in these tests was about 18 MV/m, albeit with a slightly lower Q; however, the Q still exceeded 10^{10} at the design gradient of 8 MV/m [12].

MULTI-CELL CAVITY PROTOTYPING

Cavity Fabrication and Preparation

Sheet Nb 4 mm in thickness with a nominal Residual Resistivity Ratio (RRR) of 250 was used for the 6-cell cavities. The forming and joining of half-cells were done by the standard deep drawing and electron beam welding techniques used for SNS cavity fabrication. As with the SNS cavities, Nb-Ti flanges and Al alloy gaskets were used for the vacuum seal on the beam tubes.

The first 6-cell cavity (Figures 1a and 1b) was a simplified version without stiffening rings, dishes for attachment of the helium vessel, or side ports for the RF couplers; these features were included in the second and third cavities (Figures 1c and 1d).

The first cavity was etched with a Buffered Chemical Polishing solution to remove about 100 μm from the inside surface. The cavity was then fired in a vacuum furnace

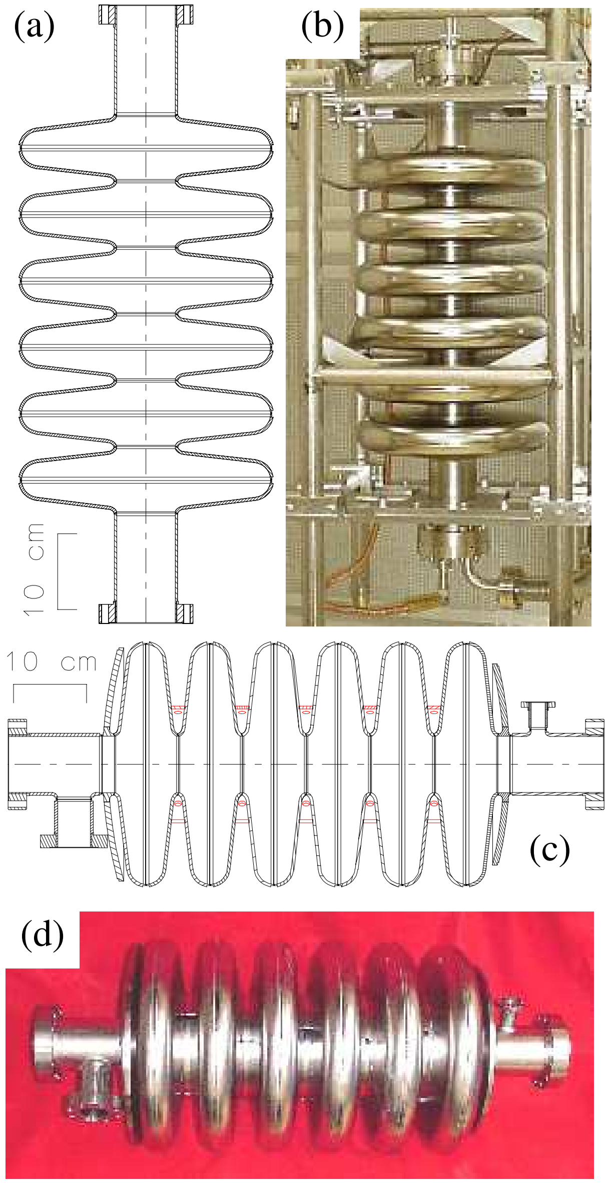

Figure 1. (a) Drawing of the first six-cell $\beta_g = 0.47$ Nb cavity and (b) photograph of the cavity on the RF test stand. (c) Drawing and (d) photograph of the second cavity.

for 10 hours at 600°C to inoculate it against the "Q disease." The pressure in the furnace was $\leq 10^{-6}$ torr during the heat treatment. Field flatness tuning was done next (see below). The final preparation steps were etching of an additional 60 μm from the inner surface and high-pressure rinsing with ultra-pure water in a clean room to remove particulates from the inside surface of the cavity.

The second cavity was etched to remove 150 μm and rinsed with the high-pressure water; it was not fired.

Tuning

Field flatness tuning was done on the first two niobium 6-cells; ancillary tuning was also done on a 5-cell copper model. The goal was a field unflatness parameter ($\Delta E/E$) of 10% or less. The first cavity and the copper model were tuned with a tuning jig designed for the SNS cavities. After tuning, $\Delta E/E$ was 7% for the Cu cavity and 12% for the Nb cavity. The second Nb cavity was tuned with a new custom-built jig for the $\beta_g = 0.47$ cavity. This made the tuning easier; a $\Delta E/E$ of 5% was reached in one iteration (see Figure 2).

First RF Test on the First Cavity

A vertical RF test was done on the first 6-cell cavity in September 2002. The cryostat was cooled down rapidly to 4.2 K and then pumped to 2 K. As shown in Figure 3 (squares), the low-field Q was about $2 \cdot 10^{10}$ and the Q remained above 10^{10} up to $E_a = 11$ MV/m approximately. A gradient of about 16 MV/m was reached. The test was stopped at that field due to the failure of an RF cable. Some x-rays were observed at high field, indicating that the decrease in the Q at high field was likely due to field emission. Modest RF conditioning was required in order to reach a gradient of 16 MV/m. A small leak into the cavity vacuum manifested itself when the cryostat was cooled down; the pressure in the cavity was about 10^{-6} torr at 2 K.

Follow-Up RF Tests on the First Cavity

The failed RF cable was replaced, the leak in the cavity vacuum was fixed, and the cavity was retested 1 week after the first RF test (without exposure of the inside of the cavity to air). A gradient of about 7 MV/m was reached. It was thought that helium processing might be beneficial, but the test had to be stopped early due to scheduled maintenance of the cavity testing facility.

The next opportunity for an RF test was in January 2003. In between tests, the cavity was etched again to remove another 50 μm from the inner surface and the high-pressure water rinsing was repeated. The final filter on the high-pressure rinsing system (between the pump and the nozzle) was temporarily unavailable at the time of this rinse.

The results of the January 2003 test are shown in Figure 3 (circles). The low-field Q was smaller than in the first test, although the difference is within the margin of reproducibility for the measurement. A gradient of about 11 MV/m was reached. The decrease in Q between 9 and 11 MV/m is likely due to field emission; the x-ray signals were larger than those seen in the first RF test. Thus the differ-

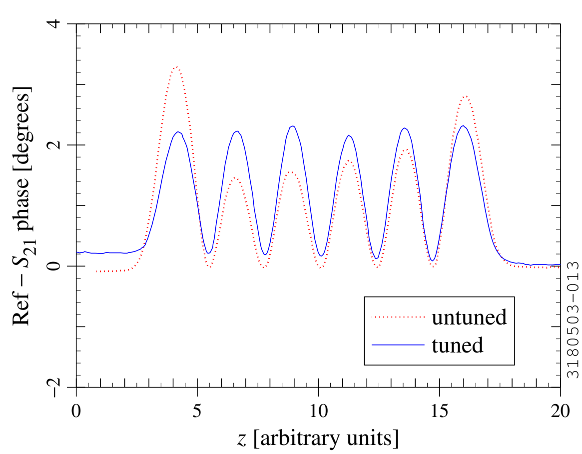

Figure 2. Bead pulls for the second six-cell niobium cavity.

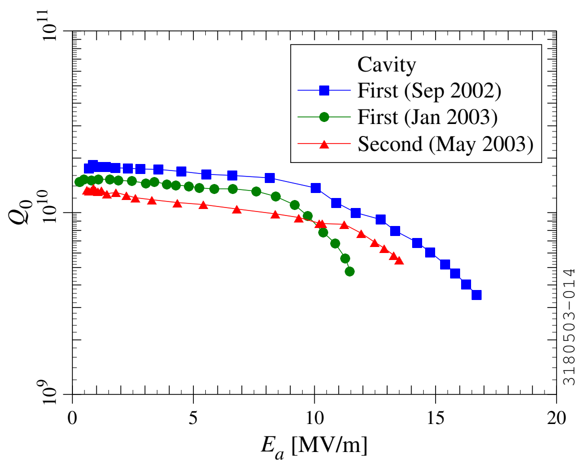

Figure 3. Measured dependence of the quality factor on the accelerating gradient at 2 K for the first and second 6-cell cavities.

ence between the September 2002 and January 2003 tests could be due to particulate contamination during the high-pressure rinse without the final filter. Although the field level was not as high as in the first test, the design goal of 8 MV/m was nevertheless reached with a Q in excess of 10^{10}.

In the January 2003 tests, measurements of Q as a function of gradient were done at several different temperatures. The low-field Q at 1.8 K was higher ($2 \cdot 10^{10}$) than at 2 K, which indicates that the BCS losses are still contributing to the surface resistance. However, the maximum gradient at 1.8 K was only slightly higher than at 2 K. A value of $Q = 2 \cdot 10^{10}$ corresponds to a surface resistance of 8 nΩ.

RF Tests on the Second Cavity

Vertical RF testing on the second cavity was done in May 2003. In the first RF test, a gradient of 8 MV/m was reached at 2 K. The Q was a bit low ($8 \cdot 10^9$) and some Q-switching was seen, indicating that more etching was needed.

In preparation for a second RF test, another 150 μm was removed from the inner surface, and the high-pressure rinse was repeated. Results from the second RF test are shown in Figure 3 (triangles). A gradient of 13 MV/m was reached. The Q was 10^{10} at the design gradient of 8 MV/m. The field was limited by the available RF power (the input coupling was weaker than planned).

MICROPHONICS AND MULTIPACTING

Microphonics are more serious for RIA than for SNS due to the lower RIA beam current. The lateral brace and stiffening rings of the SNS $\beta_g = 0.61$ cavity will be used on the $\beta_g = 0.47$ cavity to reduce microphonic excitation. The RIA cavities will be over-coupled in order to ensure that the gradient can be maintained in the presence of microphonics [10]. Some microphonic measurements were done on a single-cell cavity [12]. Modelling of the vibrations in multi-cell cavities is in progress. The predictions will be compared with measurements on the 6-cell cavity.

The RF tests on single-cell cavities showed that there are no hard multipacting barriers. A soft barrier was seen occasionally at very low field. Multipacting simulations [5, 13] also indicate that there should be no hard barriers in the single-cell cavities. Likewise, no multipacting problems were encountered in the tests on the two 6-cell cavities.

CONCLUSION

RF tests have been done on two single-cell $\beta_g = 0.47$ cavity prototypes and two 6-cell cavities with encouraging results: all of the cavities exceeded the desired accelerating gradient, with a $Q \geq 10^{10}$ at the design gradient of 8 MV/m. The first 6-cell and both single-cell cavities exceeded the design gradient by a factor of 2; the second 6-cell reached 13 MV/m. Two niobium multi-cells and one copper multi-cell have been tuned for field flatness. The next step will be a horizontal test of 2 fully-equipped $\beta_g = 0.47$ cavities in a prototype cryomodule [14].

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