NIOBIUM QUARTER-WAVE RESONATOR DEVELOPMENT FOR A HEAVY ION RE-ACCELERATOR[*]

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Abstract

A superconducting linac is being designed for re-acceleration of exotic ions produced by the Coupled Cyclotron Facility at Michigan State University (MSU). The re-accelerator beam line will include a cyclotron gas stopper, a charge breeder, a normal conducting radio-frequency quadrupole, and two types of superconducting quarter-wave resonators (QWRs) for re-acceleration to energies of up to 3 MeV per nucleon, with the option of additional acceleration to 12 MeV per nucleon as a future upgrade. Both QWR types are based on existing cavities that are presently used at INFN-Legnaro. The second QWR (optimum $\beta = 0.085$, 80.5 MHz) was previously designed and prototyped as a collaborative effort between Legnaro and MSU. The first QWR (optimum $\beta = 0.041$, 80.5 MHz) is very similar to the corresponding QWR in use at Legnaro, but with a larger beam aperture. Separation between the cavity vacuum and the cryostat insulation vacuum is also implemented to reduce the risk of particulate contamination. Structural analysis of the QWRs is being done in collaboration with FZ Jülich. The $\beta = 0.041$ QWR design and prototyping effort is discussed in this paper.

INTRODUCTION

The National Superconducting Cyclotron Laboratory (NSCL) is building a re-accelerator for nuclear structure, nuclear chemistry, and nuclear astrophysics experiments with exotic ion beams [1]. 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. After stopping and re-accelerating the secondary beam, measurements on the exotic isotopes will be done with greater precision than can be obtained with other techniques.

The re-accelerator will consist of several stages: a gas stopper to slow down the secondary ion beam via ionisation; a charge breeder to increase the charge of the ions by removing electrons and allow for more efficient acceleration; a radio frequency quadrupole to provide initial focussing and acceleration to 0.6 MeV per nucleon; and a superconducting linac to accelerate the beam to a final energy of up to 3 MeV per nucleon. The superconducting linac will consist of quarter-wave resonators (QWRs) optimised for $\beta = 0.041$ and $\beta = 0.085$.

This paper covers the RF design and prototyping of the $\beta = 0.041$ QWR. The $\beta = 0.085$ QWR has already been prototyped as part of the development work for the Rare Isotope Accelerator [2].

CAVITY DESIGN

Quarter-wave resonators at 80 MHz are presently being used at Legnaro for the ALPI and PIAVE linacs [3]; these are the basis for the design of the QWRs for the re-accelerator. A few modifications were made, as detailed below.

A slightly larger aperture, 30 mm, is used for the re-accelerator cavities. Separation of the cavity vacuum from the insulation vacuum is implemented to reduce particulate contamination of the cavity surfaces.

The shorting plate at the top of the QWR is formed from 3 mm thick sheet Nb instead of being machined from Nb plate; the shape is similar to that used by Argonne [4] and SPIRAL 2 [5].

The tuning plate at the bottom of the QWR is made from 1.25 mm thick sheet Nb, rather than being made from copper sheet with a sputtered Nb layer. The tuning plate is slotted to reduce the tuning force; the tuning plate design is similar to that used by TRIUMF [6].

Probe couplers are attached to the bottom flange in a manner similar to that used for the $\beta = 0.085$ prototype [2].

Selected QWR parameters are given in Table 1. ANALYST[1] was used for numerical calculations and optimisation of the RF parameters. Drawings of the QWR are shown in Figure 1. Figure 2 shows the accelerating voltage that can be delivered at the design field level ($E_p = 16.5$ MV/m) as a function of the velocity of the accelerated beam, taking into account transit time effects.
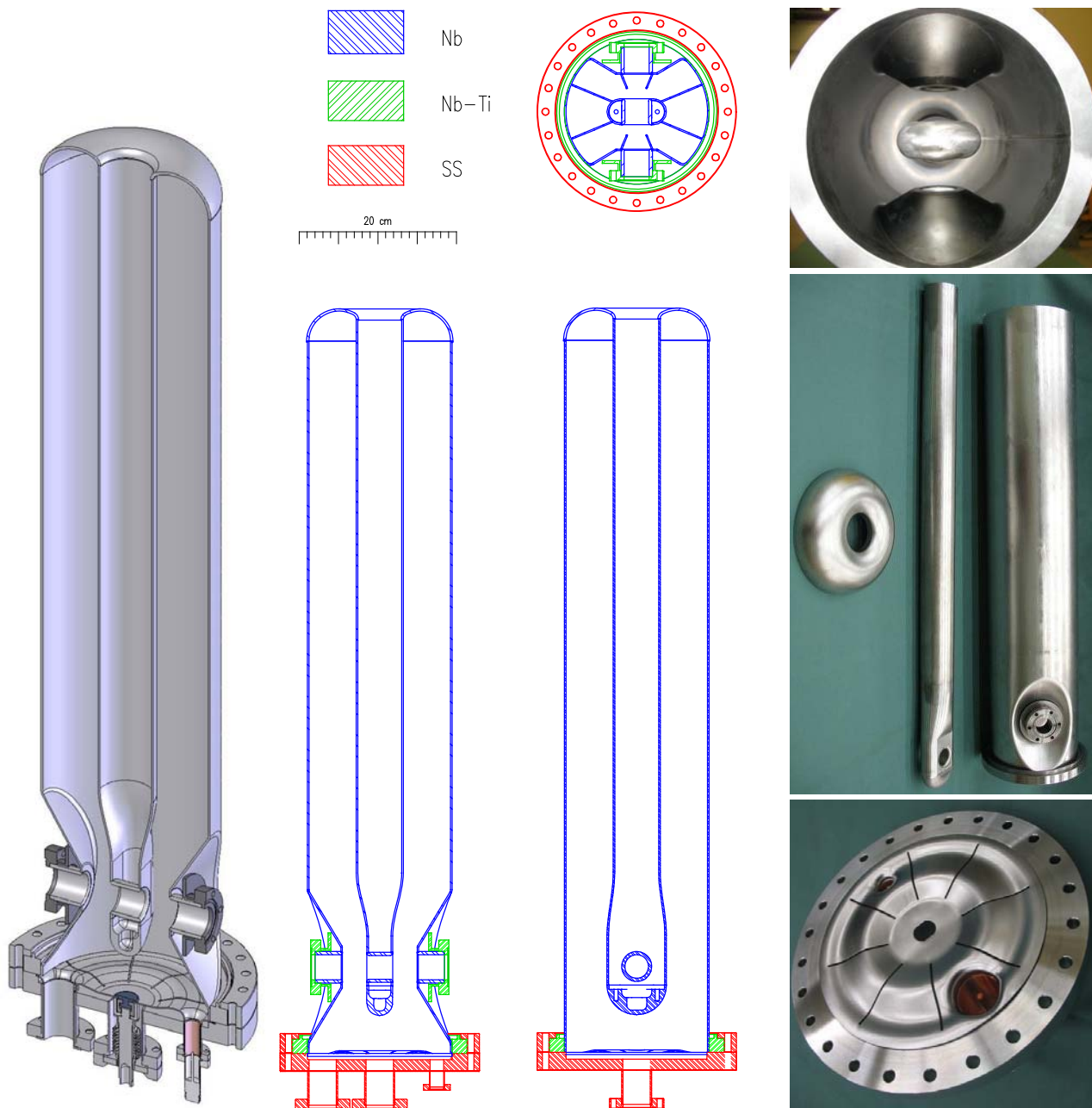
Figure 1. Drawings and photographs of the $\beta_m = 0.041$ QWR. Left: isometric sectional view. Middle: three-view drawing. Right: tuning plate with RF coupling ports (bottom), cavity parts prior to final welding (middle), and inside view of the completed cavity (top).

FABRICATION OF PROTOTYPE

Sheet Nb of thickness 2 mm and RRR ≥ 250 was used. The drift tube, the beam tubes, and the tip of the center conductor were machined from solid niobium. Holes were machined into the latter 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; the Nb tuning plate is placed in contact with the outer conductor via this flange. A slight bevel was added to the tuning plate to improve the RF contact. An indium joint is used for the vacuum seal between the cavity and the blank-off flange.

Forming of the sheet niobium was done at NSCL and in local area; electron beam welding was done with an industrial company. The beam tube flanges were made of Nb-Ti with knife-edge/Cu gasket seals. Figure 1 shows the parts for the cavity prior to the final weld, the tuning plate, and the inside of the completed cavity.

A bead pull was done after the final welding to check the field balance between the two accelerating gaps. The bead pull trace is shown in Figure 3. The field unflatness parameter ($\Delta E/E$) was 2%.

In preparation for RF testing, the cavity was etched with

Table 1. Selected RF and geometrical parameters for the quarter-wave resonator. OC and IC are the outer conductor and inner conductor, respectively. E_p is the peak surface electric field; B_p is the peak surface magnetic field; V_a is the accelerating voltage calculated at the optimum β, including transit time effects; R_s is the shunt impedance (linac definition); Q_0 is the intrinsic quality factor.

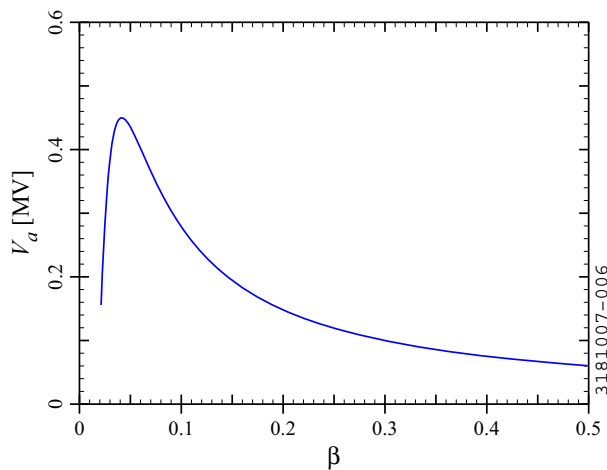|	
Optimum β	0.042
Resonant frequency f	80.5 MHz
Design E_p	16.5 MV/m
Design B_p	29.2 mT
Design V_a	0.45 MV
R_s/Q_0	433 Ω
Geometry factor	15.4 Ω
Operating temperature	4.5 K
Design Q_0	$5 \cdot 10^8$
Nominal OC diameter	180 mm
Nominal IC diameter	60 mm
Nominal height ($\lambda/4$)	931 mm
Active length	95 mm
Aperture	30 mm

Figure 2. Dependence of accelerating voltage on beam velocity for the $\beta_m = 0.041$ QWR.

a Buffered Chemical Polishing solution (1:1:2 mixture by volume of concentrated hydrofluoric, nitric, and phosphoric acid) to remove approximately 150 μm from the inside surface. The acid was circulated through a chiller in a closed loop system to maintain a temperature between 15°C and 16°C.

High-pressure rinsing with ultra-pure water was then done for about 80 minutes in a class 100 clean room. Due to interference with the inwardly-protruding beam tubes, the cavity could not be rotated continuously about the rinsing wand, so 6 fixed positions were used.

After high-pressure rinsing, the cavity was assembled onto an insert for RF testing. Photographs of the cavity during etching, rinsing, and assembly onto the insert are
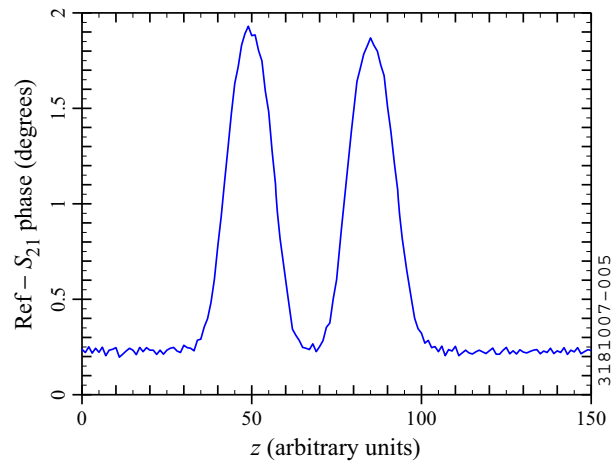

Figure 3. Bead pull for the $\beta_m = 0.041$ QWR.

shown in Figure 4.

RF TESTS

Vertical testing was done with the cavity immersed in liquid helium. A phase feedback loop was used to lock onto the resonance. 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 slightly overcoupled at low field at 4.6 K.

Multipacting barriers were observed at low field; we were able to get through them rapidly. X-rays were observed at high field (9 R/hour inside the radiation shield at the maximum field). RF conditioning produced some improvement, but we were not able to eliminate the field emission with the RF power available for the test.

Figure 5 shows RF measurements at several temperatures. Some improvement can be seen in repeated measurements at 2 K due to RF conditioning. The highest fields reached in the RF test were $E_p \approx 80$ MV/m and $B_p \approx 140$ mT, corresponding to $V_a \approx 2.2$ MV. In all cases, the field was limited by the available RF power. The forward power was about 70 W at the highest field reached in the test (2 K). We did not observe thermal breakdown.

The design goal is also indicated in Figure 5. The quality factor was significantly higher than the design goal at the design field, and the highest field reached in the test was significantly larger than the design goal. However, the design goal was a conservative choice for long-term operation of cavities in an environment which may be less ideal than that which can be achieved in a short-term vertical test.

The low-field Q_0 was measured as a function of temperature from 4.6 K to 1.5 K. The residual surface resistance inferred from this measurement is about 2 nΩ.

The measured resonant frequency at 4.5 K was too high by 225 kHz; this frequency offset will need to be corrected with production cavities. The actuator for the tuner will be outside of the cryomodule, hence no actuator was used in the vertical test. The frequency range of the tuner and

Figure 4. Left to right: etching, rinsing, and assembly of the $\beta_m = 0.041$ QWR onto the RF test stand.
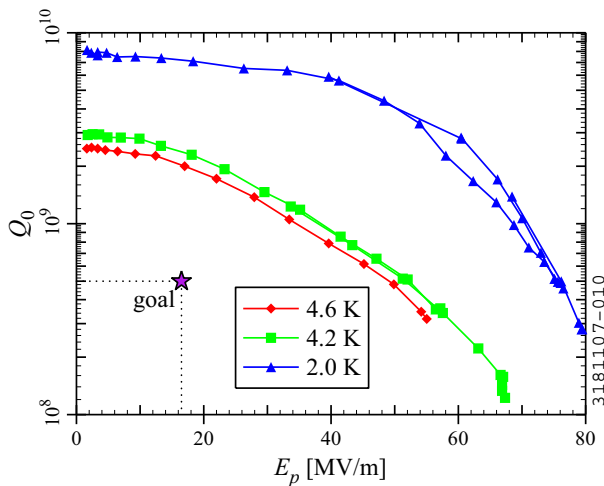

Figure 5. RF testing of the $\beta_m = 0.041$ QWR.

the tuning force will be checked and compared with predictions in future tests.

Structural analyses of the QWR are being done with ANSYS.[2] Stiffening methods are being explored with the aim of minimising frequency shifts due to pressure fluctuations and microphonics.

CONCLUSION

A $\beta = 0.041$ QWR has been fabricated and tested. RF test results exceeded the design goals by a comfortable margin. Multipacting at low field and field emission at high field were observed, but they did not prevent the cavity from reaching the design goals. The next step in this project will be to fabricate and test production $\beta = 0.041$

and $\beta = 0.085$ cavities for the NSCL re-accelerator.

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