# DESIGN OF MULTI-FREQUENCY COAXIAL TEST RESONATORS

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## Abstract

A significant issue in low beta resonators is medium field Q-slope (MFQS) at 4 K. To study the MFQS and the field dependence of surface resistance in low beta resonators, a quarter-wave resonator (QWR) and a half-wave resonator (HWR) were designed to be tested at integer harmonic frequencies of 200 MHz, and up to 1.2 GHz. A series of chemistry and heat treatments will be applied to these cavities so that a systemic study on the surface resistance of the coaxial resonators associating with post-processing, RF field, and frequency can be done. The detail design of these cavities is reported in this paper.

## INTRODUCTION

The resonant frequency of low beta cavities, operating in TEM mode, of proton or heavy ions linac applications are normally in the range of 80 MHz to 350 MHz. [1 - 4] These frequencies provide opportunity of 4 K operation to reduce the cost of cryogenics system. However, at 4 K strong Q-slope in the medium field regime, which is in general the operational field level, reduces cavity performance. Presently the large facilities under construction or in design stage are choosing to operate at 2 K even at low frequency to avoid this performance degradation. [5]

A preliminary study on MFQS and field dependent surface resistance was reported based on vertical tests of an 81 MHz QWR and a 162 MHz HWR. [6] 48 hours 120 ˚C baking takes the edge off MFQS and improve operational quality factor at 4 K for both QWR and HWR. The low temperature bake reduces BCS resistance and weaken field dependence of BCS component simultaneously. Further investigation on QWRs demonstrates the energy gap is increased by 120 ˚C bake and the field dependence of that is eliminated, shown in Fig. 1.
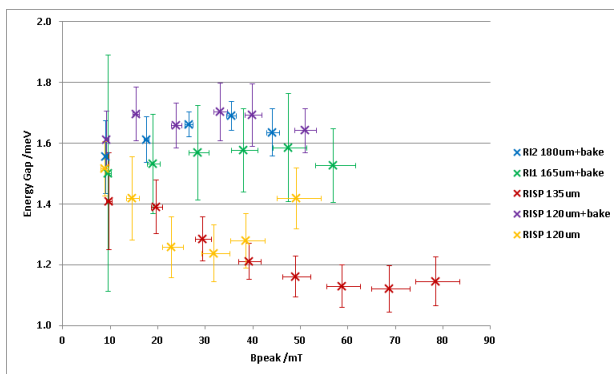


Figure 1: The comparison of the field dependent energy gaps of baked and unbaked 81 MHz beta=0.047 QWRs.

For the purpose of developing systemic study tools for MFQS of low beta resonators, two delegated QWR and

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HWR cavities are designed and being fabricated at TRIUMF, shown in Fig. 2. The coaxial structure is chosen to represent the common geometry of low beta resonators. They are proposed to be the low beta style 'single cell' cavities to investigate field dependent surface resistance as functions of surface treatment, heat treatment, and RF frequency. Doping of the low beta resonators could be further explored on them combining with the development of RF induction furnace in house.
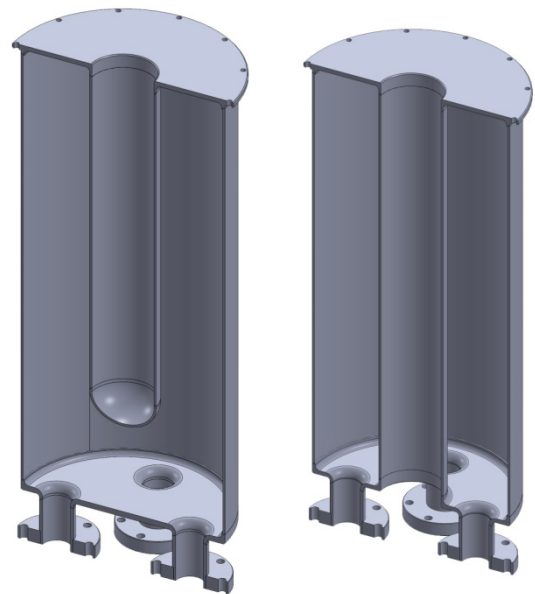


Figure 2: The cross section views of multi-mode QWR and HWR cavities.

## CAVITIES SPECIFICATIONS

The cavities are designed as 'single cell' purpose resonators for the fundamental SRF R&D programs. They will be tested in cryostat at various electromagnetic field levels, temperatures, and resonant frequencies, to study the field dependent surface resistance in low beta resonators correlated to the different surface treatments or heat treatments. To be distinct from acceleration purpose superconducting cavities, the high shunt impendence and the low peak field ratio ($E_{peak}/E_{acc}$ and $B_{peak}/E_{acc}$) for fundamental mode (accelerating mode) is not critical. Some common features, such as beam ports and helium jacket, are eliminated to simplify the cavity design. However, in accordance with research proposal, some specific requirements are requested for the design.

- The cavities are required to be tested at various frequencies in TEM modes. The resonant frequency window should cover the common operational fre-

quencies of low beta cavities in proton and heavy ions linacs.

- The cavities are designed to each fit in the RF induction furnace to allow a correlation study of heat treatments and RF surface resistance.
- The design is optimized to give similar ratios of peak electric fields and peak magnetic fields ($E_{peak}/B_{peak}$) for each of the harmonics, so that field dependent performance can be compared for various modes.
- To simplify the design there are no beam ports, cavity jacket nor stiffeners but cleaning ports for chemical etching and high pressure water rinsing (HPR) are included.
- The geometry of the inner conductor is the same in each cavity so that a common T-map insert can be employed to characterize the surface losses locally in addition to the global Q-measurement.

## GENERAL DESIGN

### Resonant Frequency

Each cavity is designed to fit in the RF induction furnace for various heat treatments. The cavities' overall dimensions, including cleaning ports and flanges, are limited by the acceptance of the furnace, which is Φ 200 mm x 490 mm. According to the common operational resonant mode in low beta resonators, the fundamental TEM mode and its higher harmonics are selected as testing modes. The lowest resonant frequency is mostly dependent on the cavity length. 490 mm length acceptance limits the frequency of the 1st order harmonic in QWR higher than 153 MHz, regardless of capacitance gap, wall thickness, cleaning ports and flanges. Considering a realistic cavity, the fundamental resonance frequency of the QWR is chosen around 200 MHz. And the higher harmonics' frequencies are around $(2n-1)\cdot 200$ MHz (n=1, 2, 3…). As for the HWR with similar dimension, the reso-

nance frequencies start from 400 MHz, and work at $2n\cdot 400$ MHz (n=1, 2, 3…) for TEM modes.

### Material

The cavities are proposed to be heated to various temperatures. To expand the allowance of cavities to fully annealing temperature of niobium, and to avoid contamination of foreign materials, cavities will be fabricated with sole material, niobium, including flanges. The major parts of cavities are using high RRR niobium, while reactor grade niobium to be used for the parts located at the low magnetic field regions.

### Cavity Geometry

To simplify the design and optimize the cost efficiency, the experience and tools of ISAC-II cavities [7] are referred. The cylinder inner conductor shape promises a mobile T-mapping insert. The diameters of inner and outer conducting are respectively 60mm and 180mm for sharing forming dies of ISAC-II cavities. In addition, the flat short plate is to eliminate the higher level MP barriers. It will also be machined out from a thick plate material without deep drawing..

### Peak Field Ratio ($E_{peak}/B_{peak}$)

The magnetic field is more interested than the electric field for MFQS and field dependent surface resistance studies. To prevent being limited by field emission related to $E_{peak}$, a low ratio of $E_{peak}/B_{peak}$ is one of the design criteria. The analytical analysis demonstrates that $E_{peak}/B_{peak}$ in an ideal coaxial resonator is 0.3 (MV/m)/mT, and independent of cavity dimensions and harmonics. HWR is almost the case. As for QWR, due to the existing of bottom gap capacitance, $E_{peak}/B_{peak}$ should be higher than the theoretical value and various for different modes. The optimization is required to be done with numeral simulations.
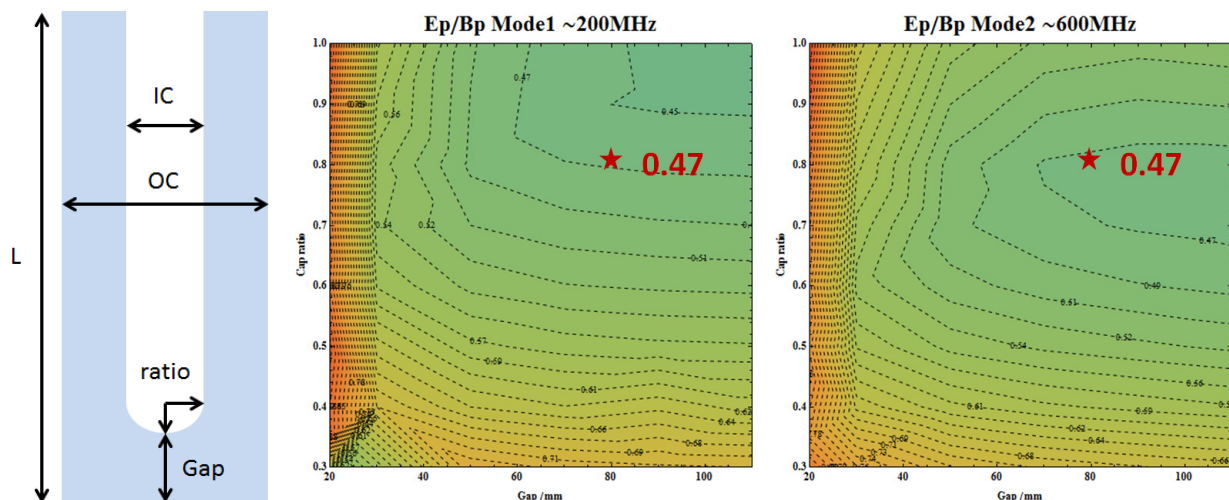


Figure 3. Left: The parametric simulation model of QWR, in which blue color shows the RF space in cavity. Right: counter plots of $E_{peak}/B_{peak}$ as a function of geometry parameters of cap ratio and gap. Fundamental mode shows in the middle and the 2nd harmonic on the right. Green color means lower ratio value.

## QWR DESIGN

### $E_{peak}/B_{peak}$

The peak field ratios should be simultaneously optimized for various TEM modes. As the diameters of inner and outer conductors are pre-set by manufacture considerations, the geometry optimization focuses on the gap capacitance region, including inner conductor cap shape (cap ratio) and gap, shown in Fig. 3. The optimized peak field ratios show up with different geometries for different modes. To achieve a minimal and similar ratio value for the 1st and the 2nd harmonics, gap is determined to 80mm while cap ratio to 0.8. The optimized $E_{peak}/B_{peak}$ is 0.47 (MV/m)/mT for the modes around 200 MHz and 600 MHz, shown in Fig. 3. Based on the experience of QWR tests at TRIUMF, this ratio promises to achieve $B_{peak}$ up to 120mT before field emission onset, which has already exceed the medium field range. The higher order harmonics are given up for testing due to higher peak field ratio.

### Mechanical Analysis

The cavities will be tested with a self-excited loop without phase lock and frequency regulation. The pressure sensitivity and Lorentz force detuning are not issues in this case, even though slight plastic deformation exists. Cavities are required to withstand maximal 1.3 bar external pressure load during cooldown. For QWR, 2mm thickness niobium sheets are used for inner and outer conductors. 4mm and 5mm niobium plates are chosen for top plate (short plate) and bottom plate respectively. It provides QWR 80% margin to the ultimate tensile strength of full annealed niobium. Thicker short plate is not preferred to avoid the impact of enhanced thermal feedback effect.

### Modes Separations

In coaxial resonators, the mode separation of fundamental mode and higher order modes are normally large. As cavities will also be tested in higher order TEM modes, the frequencies of several higher order modes of QWR are checked and listed in Table 1. For the most interested modes (first 2 modes), they are well separated.

Table 1: The Resonant Frequencies of QWR

| Mode # | Frequency | Mode Type |
|--------|-----------|-----------|
| 1 | 217 MHz | TEM |
| 2 | 647 MHz | TEM |
| 3 | 892 MHz | TE111 |
| 4 | 1055 MHz | TEM |
| 5 | 1103 MHz | TE112 |
| 6 | 1361 MHz | TEM* |
| 7 | 1400 MHz | TE113 |
| 8 | 1600 MHz | TE211 |
| 9 | 1604 MHz | TEM* |

* Mixed with other type of mode around bottom capacitance gap.

## HWR DESIGN

### $E_{peak}/B_{peak}$

The HWR geometry is close to the ideal coaxial resonators, except the short plate with cleaning ports. $E_{peak}/B_{peak}$ is constant at 0.3 (MV/m)/mT along the inner conductor. Because of the opening ports at high RF current area, magnetic field could be enhanced at the transition edge of cleaning ports, shown in Fig. 4. The fillet radius was optimized to prevent this effect.
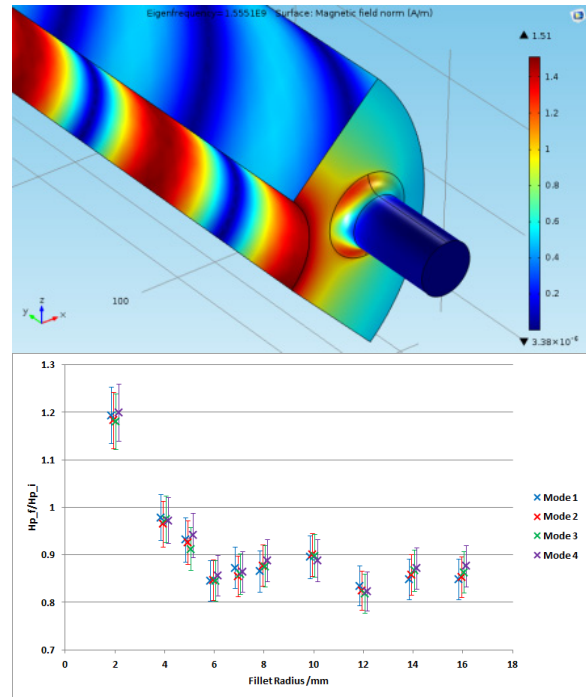


Figure 4: Top: Magnetic field distribution of higher order TEM mode in HWR. Bottom: Peak magnetic field ratio of that on port fillets and on inner conductor as a function of fillet radius for the first 4 orders harmonics in HWR.

### Cleaning Ports

4 cleaning ports locate on one short plate of HWR, while on the bottom plate of QWR. They distribute evenly around cavity axial, and on the middle line between inner and outer conductors, shown in Fig 5. The water jet from nozzle in each port covers 1/3 of inner conductor surface. It provide totally 1/3 area overlap for HPR.
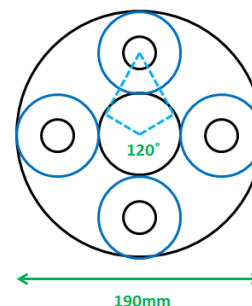


Figure 5: Schematics of cleaning ports and water jet coverage of nozzle from each port.

In addition, the cleaning port tubes are required to be longer than 60 mm for HWR, to avoid even tiny RF power loss on stainless steel flanges of the ports, which could bring in significant error to surface resistance measurement, especially to the lower frequency modes.

### Modes Separations

Modes separations are adjusted by varying cavity length. The frequencies of several higher order modes of HWR are listed in Table 2. The minimal separation between TEM modes and other types of higher order modes is 38 MHz.

Table 2: The Resonant Frequencies of QWR

| Mode # | Frequency | Mode Type |
|---|---|---|
| 1 | 389 MHz | TEM |
| 2 | 778 MHz | TEM |
| 3 | 905 MHz | TE111 |
| 4 | 1128 MHz | TE112 |
| 5 | 1166 MHz | TEM |
| 6 | 1424 MHz | TE113 |
| 7 | 1555 MHz | TEM |
| 8 | 1602 MHz | TE211 |
| 9 | 1738 MHz | TE212 |

## CONCLUSION

A QWR and a HWR, designed to study the medium field Q-slope and field dependent surface resistance. These cavities resonate in TEM modes at various frequencies spanning the range from 200 MHz to 1.2 GHz, at integer harmonic of 200 MHz. They are specified to fit in the RF induction furnace and can be used with a common T-mapping insert.

Both cavities are designed to provide good access for cleaning, and consist of more common parts. Mode separation is also required for both cavities. The QWR design is focused on minimizing the peak field ratio $E_{peak}/B_{peak}$ for the first two TEM modes at 200 MHz and 600 MHz. Mechanical properties and thermal feedback are balanced by variating the thickness of the short plate. As for the HWR design, since the cleaning ports have to be in the high magnetic field area, reducing magnetic fields at fillet rounding of cleaning ports and cavity short plate and at stainless steel flanges are the main points of optimization.

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