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TEST OF MULTI-FREQUENCY COAXIAL RESONATORS*

Z. Yao†, J. Keir, P. Kolb, A. Kong, R.E. Laxdal, B. Matheson, E. Thoeng, B.S. Waraich, Q. Zheng, V. Zvyagintsev, TRIUMF, V6T2A3 Vancouver, Canada

Abstract

A significant issue in low β resonators is the 4K medium field Q-slope (MFQS). To systemically study the field dependence of surface resistance in TEM mode resonators, a quarter-wave resonator (QWR) and a half-wave resonator (HWR) were designed to resonant at integer harmonic frequencies of 200 MHz, and up to 1.6 GHz. A series of cavity treatments were proposed to these cavities. It provides opportunity to investigate the field dependent surface resistance as a function of frequency, temperature, and treatment, including heat treatments and doping. The preparation for the baseline cold test and the preliminary test result will be reported in this paper.

COAXIAL RESONATORS

The resonant frequency of low β cavities, operating in TEM mode, of proton or heavy ions linac applications are normally in the range of 80 MHz to 350 MHz. These frequencies provide opportunity of 4 K operation to reduce the cost of cryogenics system. However, strong Q-slope in the medium field regime reduces cavity performance at the operational field level. To developing systemic study tools for MFQS in low β resonators, two delegated QWR and HWR cavities are designed and fabricated, shown in Fig. 1. The coaxial structure is chosen to represent the common geometry of low β resonators. The RF performances can be measured at different harmonic frequencies in the same cold test cycle. The consistent surface field distributions between various TEM modes mitigate the geometry effect on surface resistance. The role of RF frequency on the field dependent resistance and the optimum treatments for low β resonators can be investigated with these coaxial resonators.

Figure 1: HWR (left) and QWR (right).

The resonators are designed as the 'single cell' for the fundamental R&D programs. To be distinct from acceleration purpose SRF cavities, some common features, such as beam ports and helium jacket, are eliminated to simplify the cavity geometries. In accordance to research proposal, the cavities are required to fit TRIUMF RF induction furnace. The lowest resonant frequency is limited by the cavity length. In addition, four cleaning ports are set at the same end of each cavity. A uniform cylinder inner conductor is chosen to employ a common mobile T-map insert to characterize the local RF heating in addition to the global Q measurement. The detail design of these resonators can be found in [1].

The cavities are fabricated with RRR grade and reactor grade niobium. Reactor grade niobium is used for flanges and the cavity parts at the low magnetic field region, such as bottom plate and port tubes of QWR. Indium seal is required on niobium flange for the hermitic unit assembly. There was not frequency tuning step during manufacture as the absolute resonant frequencies are not critical. The harmonic frequencies at room temperature and atmosphere pressure were measured after received from manufacturer and are shown in Table 1. The To-Be-Tested modes are highlighted in bold and italic. The measurement results are well conformed to the design. The closest TE mode is separated by 37 MHz and its transmission signal is more than 10 dB lower with the same RF couplers. A bandpass filter is required in LLRF for each test mode to eliminates the undesired resonances in cold test.

Table 1: Resonant Frequencies of Coaxial Resonators

QWR	Simu. /MHz	Meas. /MHz
TEM	***217***	***217.4***
TEM	***647***	***647.3***
TE111	892	–
TEM	1055	1054.2
TE112	1103	1100.8/1103.5
HWR	**Simu. /MHz**	**Meas. /MHz**
TEM	***389***	***388.6***
TEM	***778***	***777.4***
TE111	905	901.9/906.6
TE112	1128	1125.4/1129.1
TEM	***1166***	***1166.1***
TE113	1424	1421.9/1424.8
TEM	***1555***	***1554.8***
TE211	1602	1600.7

RF AND CONTROLS

Coaxial resonators are to be tested at the harmonic frequencies of 200 MHz and up to 1.6 GHz. Two wide band

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† zyyao@triumf.ca

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RF power amplifiers are required to cover the full frequency range of all tested modes. The in-situ 500 W solid states RF amplifier operates in the frequency range from 69 MHz to 651 MHz. Another 250 W RF amplifier covering 650 MHz to 2 GHz is going to be ordered.

Self-excited loop (SEL) is utilized in LLRF control of cryostat cold tests at TRIUMF. The SEL frequency tracks the resonant frequency of the cavity. The resonance is stable in either open or closed amplitude loop and free of ponderomotive instability. SEL in absence of phase loop feedback is ideal for cavity performance characteristics, multipacting conditioning and high-power pulse conditioning. LLRF developed for ISC-II and ARIEL e-Linac projects [2] controls at 140 MHz. An intermedium frequency is employed to down convert RF frequency to 140 MHz for input, and to up convert the output signal to cavity resonant frequency for driving RF amplifier. The essential part of the frequency convertor is the high-performance bandpass filter. Discrete filters with < -20 dBc at ±30 MHz were chosen for 200 MHz and 400 MHz, while cavity filters with < -30 dBc in the same range for higher frequencies. The intermedium frequency and the RF filter should be switched when changing test modes.

The variable capacitance RF coupler developed at TRIUMF for general purpose tests < 650 MHz is to be used for the QWR tests. The external Q varies 5 orders of magnitude with 30 mm stroke. The coupler mechanism allows more than 40 mm travelling range and provides sufficient margin of coupling adjustment for various purposes during cold test. A variable induction RF coupler was designed and fabricated for HWR tests. The coupler mechanical housing is same as capacitance coupler. A set of 50 Ω concentric copper wire and tube connects coupling loop and RF feedthrough. Major RF power is delivered within the copper tube. An impedance matching section with a 2 mm alumina spacer between feedthrough and 50 Ω part is optimized to maintain SWR < 1.2 for all tested modes. 4 orders of magnitude of coupling factor can be adjusted in 30 mm travelling range.

CAVITY PROCESSINGS

A series of cavity treatments, including chemical polishing, heat treatments and doping, were proposed to these coaxial resonates. For the baseline cold tests, ultrasound degreasing, 120 μm buffer chemical polishing (BCP) and high-pressure rinsing (HPR) were applied.

As all opening ports locating on the same end of cavity, a delegated etching fixture is designed to fill and pump acid from top. The fixture assembly with HWR is shown in Figure 2. A water tank contains and circulates cooling water around cavity walls during the whole procedure. Four tubes connected to acid circulation system penetrate through cleaning ports to the bottom. One is the filling pipe, and the opposite one is the pumping pipe. The remaining two tubes are circulating acid in the cavity during the etching process. They are added to prevent trapping gases at the upper flat face or accumulating niobium concentration on the closed end plate which causes gravitational etching discrepancies.

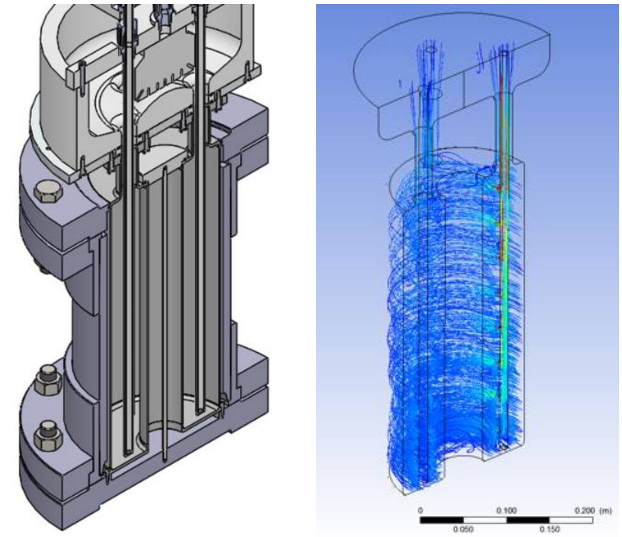

Figure 2: The chemical etching fixture of HWR (left) and the simulated velocity distribution of the acid circulation during BCP process (right).

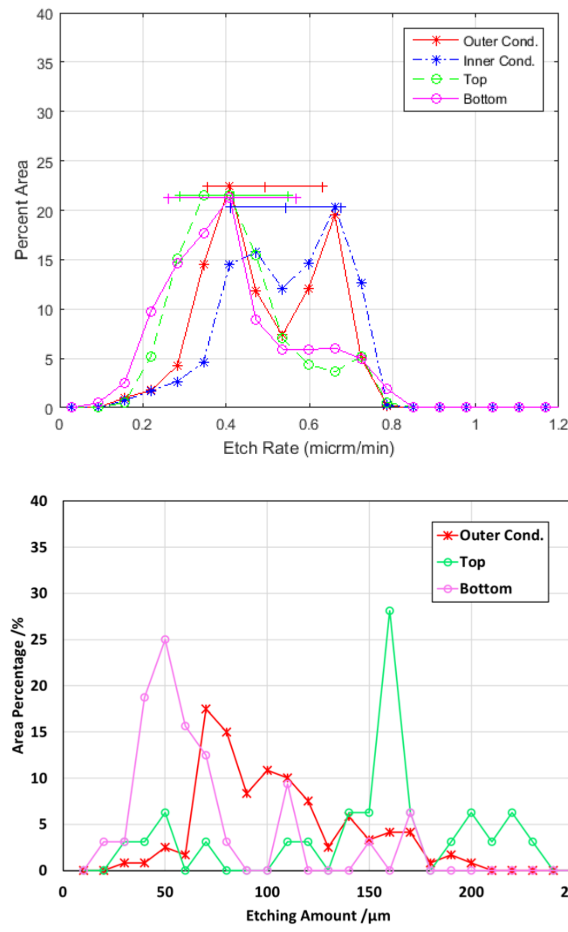

Figure 3: The histogram of the simulated etching rate (top) and the measured etching amount after 120 μm BCP (bottom) of HWR. Various colours represent different parts of cavity.

The number, position, and jet angle of acid diffusion and suction holes on tubes were optimized to achieve an even

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etching on the RF surface by using ANSYS Fluent [3]. The velocity dependent etching rate is calculated with turbulent kinetic energy [4]. The optimized average etching rate of HWR is 0.49 μm/min. The deviations of each part from the whole cavity is within ±20 %. The histogram of the simulated etching rate of HWR is shown in the top plot of Figure 3. To further obtain a uniform etching, the 120 μm BCP was divided into 60 μm plus 60 μm. The acid circulation tubes were rotated by 90° after the first 60 μm BCP. Cavity wall thickness was measured with ultrasound prior and after BCP. 120 spots were mapped on the outer conductor, while 32 points on the top plate and bottom plate. The measured etching amount is shown in the bottom plot of Figure 3. The average etching amount on the outer conductor is 104 μm, and the distribution profile is consistent with the simulation. The top plate with opening ports is over etched, while the bottom plate is under etched comparing to the desired amount. The hypothesis is the non-straight acid circulation tubes cause the diffusion holes slightly facing up and introduce stronger turbulence on the top than the bottom. The acid circulation tubes are required to be aligned for future BCP to achieve better result.

HWR was high pressure rinsed through all cleaning ports on the vertical rinsing stand, shown in Figure 4. Because of the limited diameter of opening ports, a Teflon spacer was added to the being rinsed port flange to prevent the wand vibration and touching down the cavity inner surface. The cavity was dried, assembled and leak checked in Class 10 cleanroom. The hermetic unit of HWR which is ready for test is shown in Figure 4.

Figure 4: HPR of HWR on the vertical rinsing stand (left) and the hermetic assembly of HWR (right).

PRELIMINARY COLD TEST

The baseline test of HWR is completed after 120 μm BCP. The cavity coaxial axis is in the horizontal direction. Only the fundamental mode is tested at the moment due to the limitation of the frequency range of the RF amplifier. The resonant frequency is 389.15 MHz at 4 K. Few low level multipacting barriers were easily conditioned away.

The 4 K and 2 K $Q_0 - B_p$ (surface peak magnetic field) curves are shown in Figure 5. The initial Q_0 is 7.9×10^8 at 4 K and 2.2×10^9 at 2 K. The residual resistance extracted from the Q – T data is 47 nΩ at 10 mT. Cavity has obvious and similar Q-slope in the measured field range at both temperatures. The pronounced residual resistance and strong Q-slope in the field range of below 20 mT indicate hydrogen Q-disease.

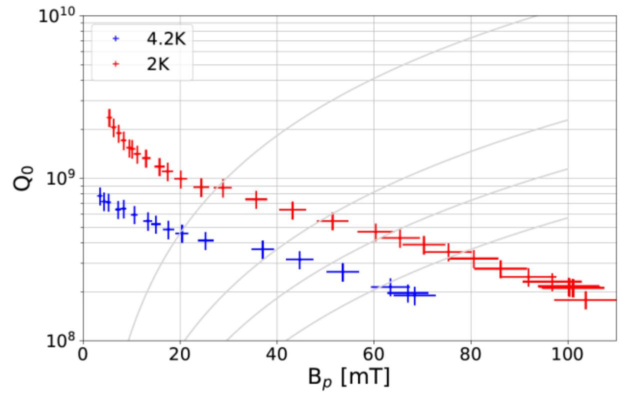

Figure 5: 4 K and 2 K $Q_0 - B_p$ curves of the fundamental mode of HWR baseline test with the constant power lines at 1 W, 5 W, 10 W, and 20 W.

4 K test is limited by cavity quench at 70 mT. But this quench barrier dose not present in 2 K test. Measurable X-ray starts from 80 mT. B_p exceeds 100 mT at 2 K without quench, corresponding to 25 MV/m in a 1.3 GHz elliptical cavity. The RF loss at the last measurement point is around 60 W. The 2 K performance is limited by low Q, which causes high RF loss and reaches the regulation capacity of the 2 K system.

CONCLUSIONS

To systemically study the MFQS and the field dependent surface resistance of low β resonators, a QWR and an HWR are designed and fabricated as the coaxial style 'single cell' cavities. The fundamental mode and its higher harmonic modes will be tested in one cold cycle. To accommodate TRIUMF's SEL LLRF to all required frequencies, the frequency convertor is modified. The existing general-purpose antennas adapts QWR requirements, while a new set of loop coupler and pickup are designed for HWR. A delegated etching fixture was designed to achieve an even etching. The baseline test of HWR is completed after 120 μm BCP. The peak surface magnetic field exceeds 100 mT without quench. The 2K performance is limited by low Q. The high residual resistance and the strong Q-slope in the low field regime indicate Q-disease. Hydrogen degassing will be applied as the next step.

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