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UNDERSTANDING Q SLOPE OF SUPERCONDUCTING CAVITY WITH MAGNETIC DEFECT AND FIELD EMISSION

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Abstract

RF test for quarter-wave resonator (QWR) and half-wave resonator (HWR) superconducting cavities is performed at low temperature. The quality factors of the superconducting cavities are measured as a function of accelerating field. The magnetic heating effect for the quarter-wave resonator (QWR) is studied. For the half-wave resonator (HWR), the Q slope degradation is investigated with x-ray radiation and field emission.

INTRODUCTION

Development of superconducting cavities is very important to construct a heavy ion accelerator. Vertical test facility to test the performance of the superconducting cavities was designed and constructed [1, 2]. Field emission and thermionic emission were studied in terms of dimensions [3-5] and the unified theory for the field emission and thermionic emission was also investigated [6, 7]. The field emission of a superconducting niobium cavity was investigated [8]. The quarter-wave resonator (QWR) and the half-wave resonator (HWR) cavity of RAON accelerator at Rare Isotope Science Project (RISP) were developed [9-12], and the cryomodule and cavity for the HWR were tested at 2 K [13, 14]. In this research we show the Q slopes for the quarter-wave resonators (QWRs) and the half-wave resonators (HWRs). The Q slope degradation for the QWR cavities is studied with magnetic defects while the Q slope degradation for the HWR cavities is investigated with x-ray radiation and the field emission.

MAGNETIC HEATING AND FIELD EMISSION

The quality factor of a superconducting cavity is degraded by magnetic heating, field emission, and x-ray radiation. The quality factor of the cavity is denoted as

$$Q_o = \frac{G}{R_{\mathrm{Sur}}}, \tag{1}$$

where G is the geometric factor and R_{Sur} is the surface resistance.The surface resistance can be represented as

$$R_{\mathrm{Sur}} = R_{\mathrm{Res}} + R_{\mathrm{BCS}}, \tag{2}$$

where R_{Res} is the residual resistance and R_{BCS} is the BCS resistance.

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Dissipated power on the cavity surface is

$$P_{\mathrm{dis}} = \frac{1}{2}\int R_S |H(r)|^2\, dS, \tag{3}$$

where H is the magnetic field strength.

The BCS resistance is expressed as

$$R_{\mathrm{BCS}} = \frac{C_1 f^2}{T} exp(-\frac{\Delta}{k_B T}), \tag{4}$$

where$\Delta$is the band gap and C_1 is the constant.

The band gap is expressed as [15]

$$\Delta = \Delta_0 - \mathrm{MB}_{\mathrm{peak}}, \tag{5}$$

where M is the magnetic moment and B_{peak} is the peak magnetic field strength.

From Eq. (2), Eq. (4), and Eq. (5) the surface resistance can be denoted as

$$R_{\mathrm{Sur}} = \frac{C_1 f^2}{T} exp(-\frac{\Delta_0}{k_B T} + \frac{\mathrm{MB}_{\mathrm{peak}}}{k_B T}) + R_{\mathrm{Res}}. \tag{6}$$

The current density of field emission is denoted as

$$J = \frac{e\sqrt{E_F}F^2}{2\pi h(\Phi_W + E_F)\sqrt{\Phi_W}} e^{-4k\Phi_W^{1.5}/3F}, \tag{7}$$

where F is the electric field, $E_F$is the Fermi energy, and $\Phi_W$is the work function. The field emission current is generated by the particles and surface curvatures from the superconducting cavity.

The average current from the field emission for AC current is [14]

$$\langle I \rangle = \frac{C_2 e\sqrt{E_F}F^{2.5}\beta^{2.5}}{h\sqrt{k}(\Phi_W + E_F)\Phi_W^{0.75}} e^{-4k\Phi_W^{1.5}/3F\beta}, \tag{8}$$

where β is the field enhancement factor and C_2 is the proportional constant. The field emission site is heated with Joule heating and the electrons generated from the field emission are accelerated and generate x-ray. The x- ray generation increases with increasing pressure of gases such as hydrogen and oxygen. The counting rate of the x-ray radiation from the superconducting cavity is

$$I_{X-ray} = I_0 + \frac{C_3\sqrt{E_F}F^{2.5}\beta_X^{2.5}}{(\Phi_W + E_F)\Phi_W^{0.75}} e^{-4k\Phi_W^{1.5}/3F\beta_X}, \tag{9}$$

where β_X is the field enhancement factor of the x-ray and C_3 is the proportional constant.

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VERTICAL TEST

RF test is performed for the quarter-wave resonators (QWRs) at 4.2 K and the half-wave resonators (HWRs) at 2 K.

Figure 1 shows the Q slope measurement for the QWR cavities at 4.2 K. This data shows the failed and passed QWRs. The failed QWR cavities are retested after cavity treatment which includes the Buffered Chemical Polishing (BCP) and the High Pressure Rinsing (HPR). The total number of the QWR cavity is 22 and all of them are finally passed for RAON accelerator construction. The Q factor for the QWR should be higher than $Q = 2.4 \times 10^8$ at $E_{acc} = 6.1$ MV/m.

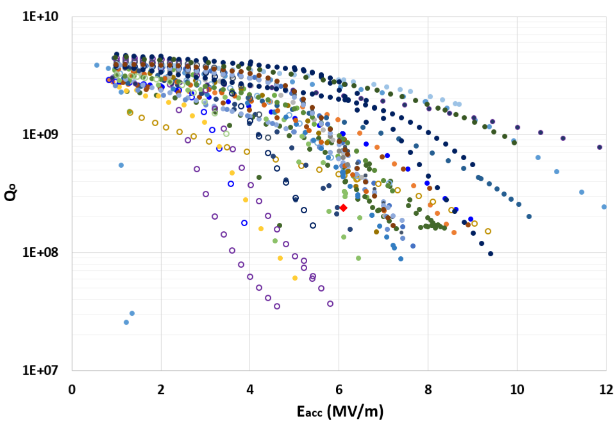

Figure 1: Q slope measurement for the QWR cavities at 4.2 K. This data shows the failed and passed QWRs. The number of the QWRs is 22 and all of them are passed.

The Q slope measurement of the HWR cavities at 2 K is shown as a function of accelerating field in Fig. 2. Figure 2 shows the failed and passed HWRs. The number of the HWRs is 106 and all of them are passed. The Q factor for the HWRs at 2 K should be higher than $Q = 2.3 \times 10^9$ at $E_{acc} = 6.6$ MV/m.

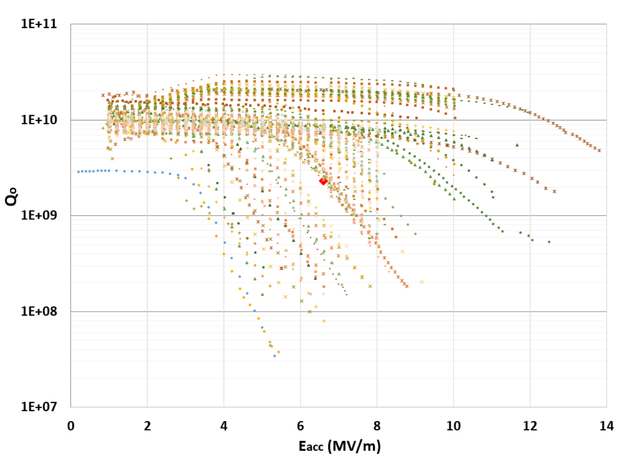

Figure 2: Q slope measurement for the HWR cavities at 2 K.

Figure 3 shows the Q slope measurement for the QWR cavities. The Q slope data in Fig. 3 comes from Fig. 1. The Q factor decreases as the accelerating field is increased.

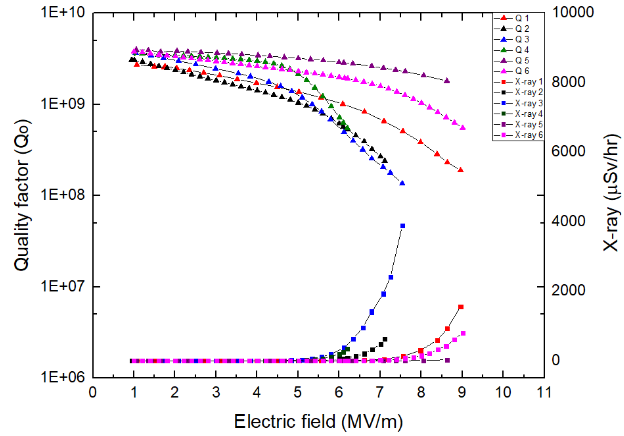

Figure 3: Q slope measurement for the QWR cavities.

The magnetic heating effect of the surface resistances for the QWR cavities is shown in Fig. 4. The magnetic heating causes the decreased quality factor of the QWRs. The surface resistances for the QWR cavities are fitted with the magnetic heating of Eq. (6). Magnetic moments for the QWR 1, 2, 3, 4, 5, and 6 are 3.3×10^{-21}, 3.4×10^{-21}, 4.4×10^{-21}, 4.3×10^{-21}, 2.5×10^{-21}, and 2.3×10^{-21} [J/T], respectively. Here we consider only magnetic defects. The field emission effect should be considered in the range of x-ray generation in future research.

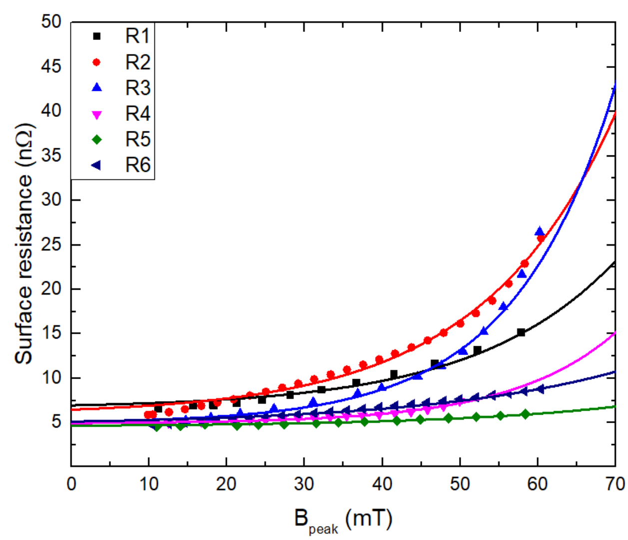

Figure 4: Magnetic heating effect of the surface resistances for the QWR cavities.

The quality factors are represented as a function of accelerating field for the HWR cavities in Fig. 5. The quality factors are not changed in the range of the low accelerating field and decreases with the x ray radiation in the range of the high accelerating field.

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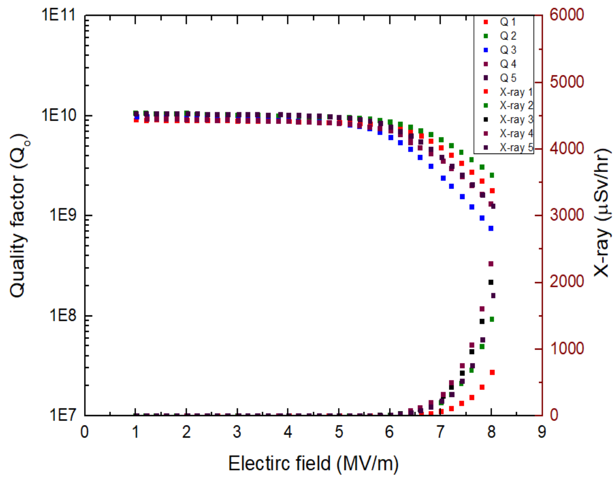

Figure 5: Quality factor vs accelerating field for the HWR cavities [14].

Figure 6 shows the x-ray data and the x-ray fitting of Eq. (9) in terms of the accelerating field for the half-wave resonators (HWR). The field emission known as Fowler-Nordheim tunneling increases with the accelerating electric field. The x-ray coming from bremsstrahlung radiation is generated when the electrons and ionized gases are accelerated. The counting rate of the x-ray radiation in terms of accelerating field is fitted with Eq. (9) having the x-ray field enhancement factor of 646 and the background radiation of 0.1 µSv/h. The x-ray increases with the accelerating field.

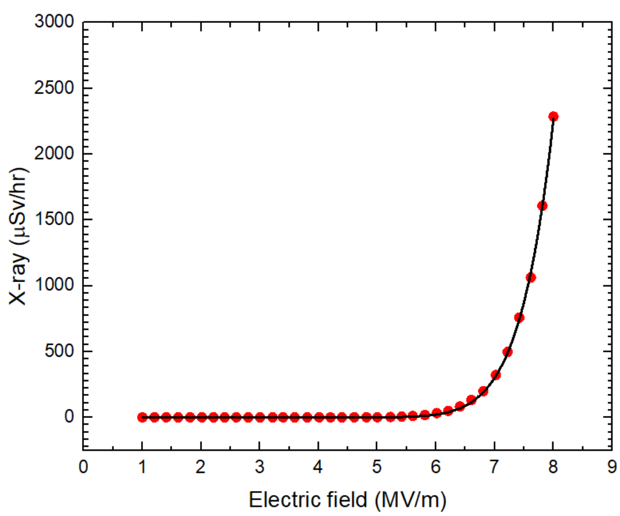

Figure 6: X-ray vs accelerating field for the half-wave resonators (HWRs) [14].

The quality factors of the HWRs are represented as a function of the x-ray field enhancement factor in Fig. 7. The quality factor for the half-wave resonators (HWRs) linearly decreases with the x-ray field enhancement factor. The x-ray generation significantly causes the decreased quality factor of the HWRs.

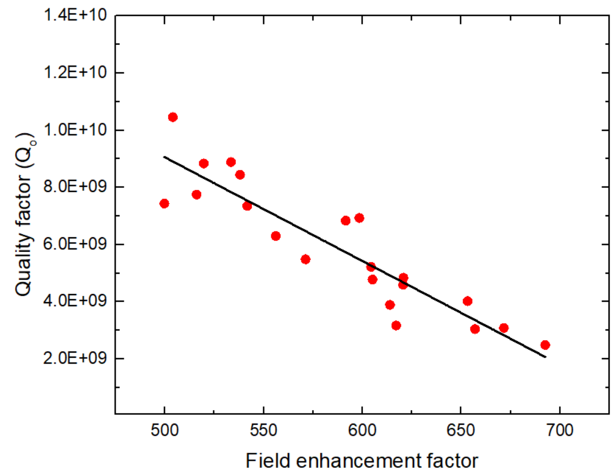

Figure 7: Quality factor vs x-ray field enhancement factor for the half-wave resonators (HWRs) [14].

SUMMARY

We have tested the QWR and HWR cavities and shown that the Q slopes of the QWR decrease due to magnetic heating effect and the Q slopes of the HWR decrease due to the x-ray radiation coming from field emission. The magnetic heating and the field emission are introduced. Vertical test is performed for the superconducting cavities. The magnetic heating effect for the QWR is measured with magnetic moments. The field emission effect for the HWR is studied and the Q slope of the HWR decreases linearly with the x-ray field enhancement factor.

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