Understanding Q slope of superconducting cavity with magnetic defect and field emission

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Vertical test facility

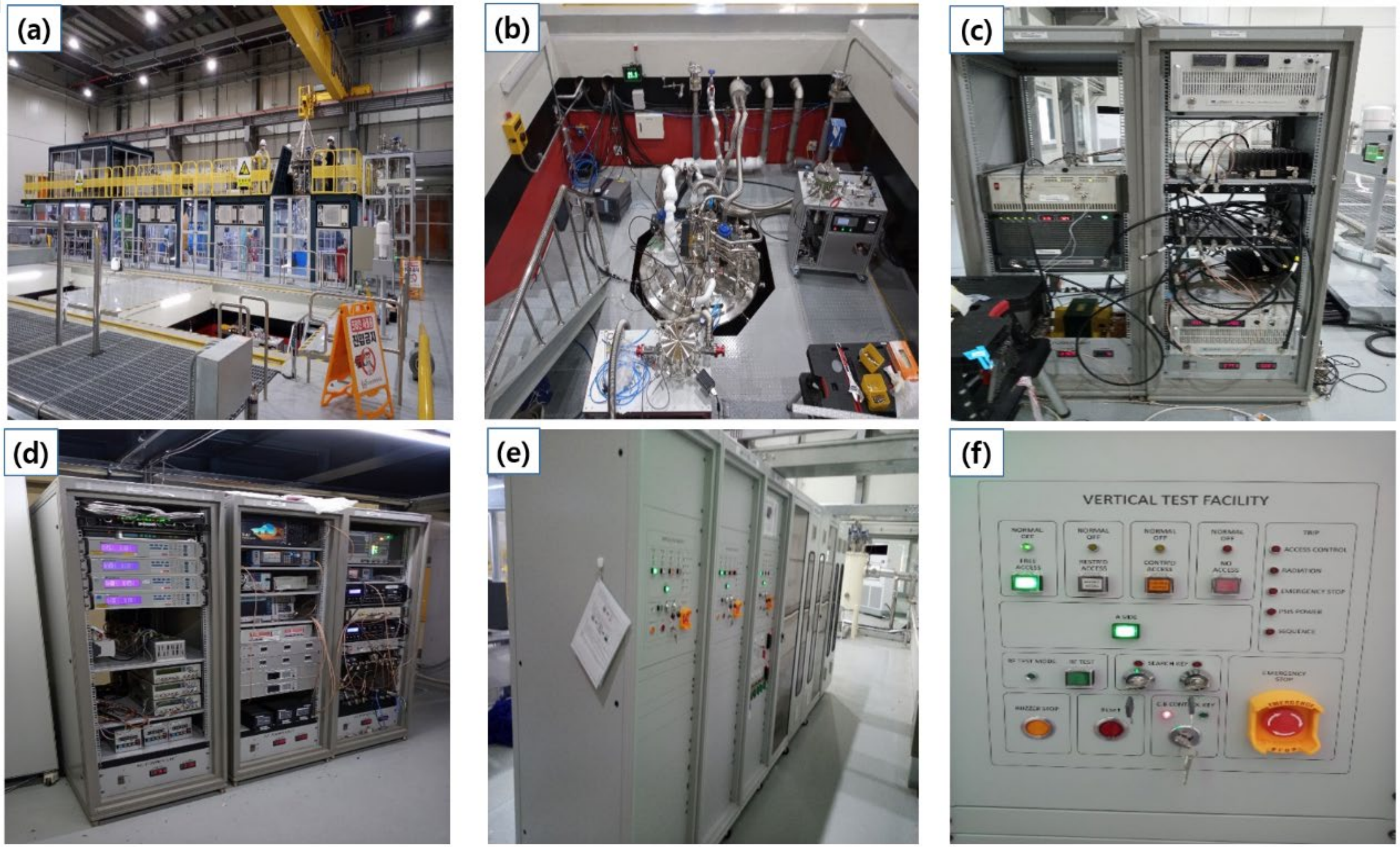


Figure 1: Pictures of the vertical test facility. (a) shows the overview of the vertical test site, (b) shows both the vertical test pit and the cryostat, (c) shows the solid state power amplifier (SSPA), (d) shows the control racks, (e) shows the personal safety interlock system (PSIS), and (f) shows the control panel for the PSIS.

Human-machine interface (HMI)

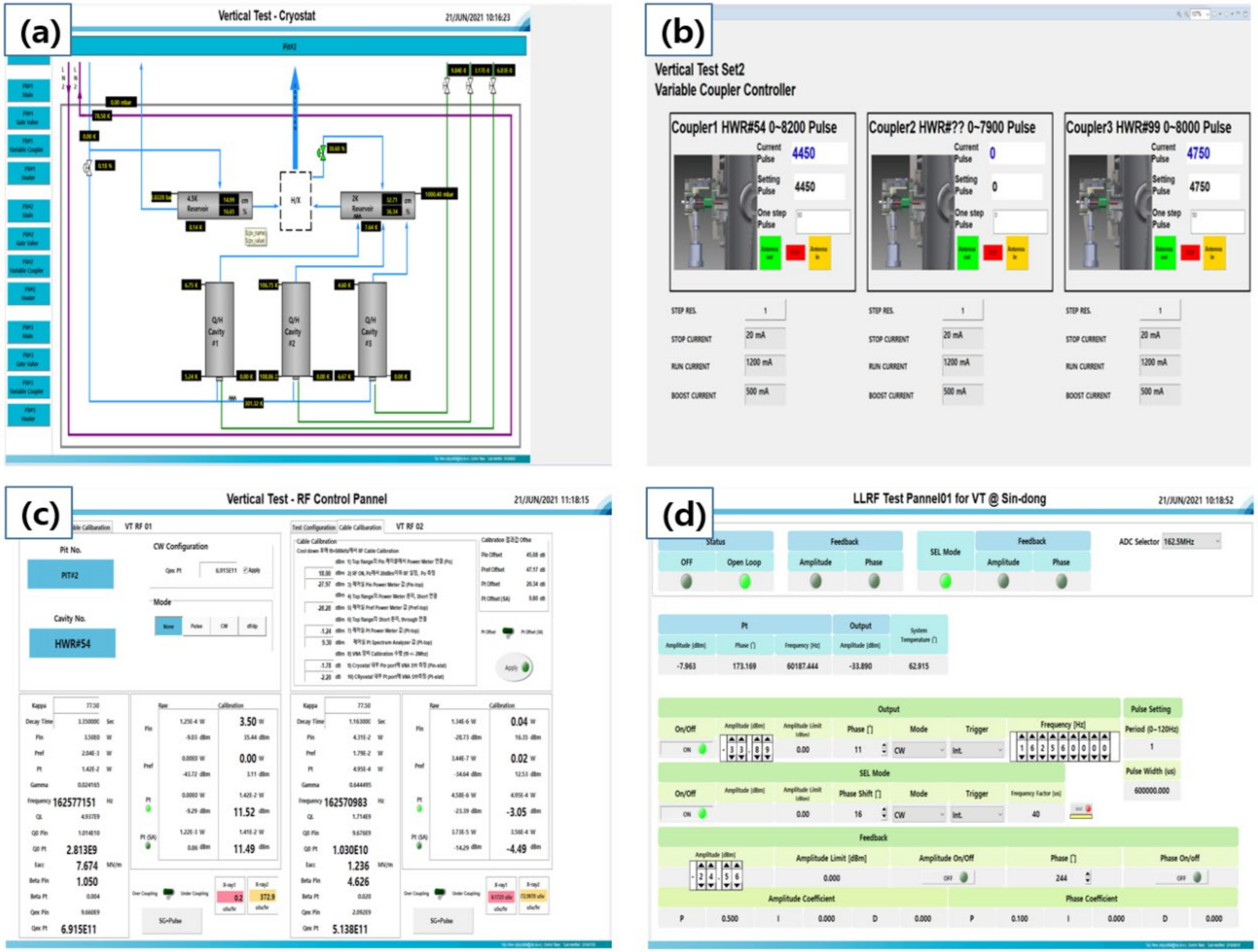


Figure 2: Pictures of the human-machine interface (HMI) for vertical test. (a) shows the control panel of the cryostat, (b) shows the control panel of the variable couplers, and both (c) and (d) show the control panels of the low-level radio frequency (LLRF).

Magnetic heating effect on cavity surface

- $$Q_o = \frac{2\pi f \mu \int |H(r)|^2 dV}{\int R_{\mathrm{Sur}} |H(r)|^2 dS}$$: Quality factor is expressed with magnetic field

$$Q_o = \frac{G}{R_{\mathrm{Sur}}}$$: Quality factor is expressed with surface resistance

$$R_{\mathrm{Sur}} = R_{\mathrm{Res}} + R_{\mathrm{BCS}}$$: Surface resistance

$$P_{dis} = \frac{1}{2} \int R_{\mathrm{S}} |H(r)|^2 dS$$: Dissipated power on cavity surface

$$R_{\mathrm{BCS}} = \frac{C_1 f^2}{T} \exp\left(-\frac{\Delta}{k_B T}\right)$$: BCS resistance comes from AC current

$$\Delta = \Delta_0 - \mathrm{MB}_{\mathrm{peak}}$$: Band gap is reduced by magnetic defects

$$R_{\mathrm{Sur}} = \frac{C_1 f^2}{T} \exp\left(-\frac{\Delta_0}{k_B T} + \frac{\mathrm{MB}_{\mathrm{peak}}}{k_B T}\right) + R_{\mathrm{Res}}$$: Surface resistance is expressed with magnetic moment and residual resistance

Field emission and x-ray

- **Field emission and x-ray counting rate**

Fermi energy of Nb : 5.3 eV

Work function of Nb : 4.3 eV

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

: Field emission (FE) current density

$$I = \frac{Ae\sqrt{E_F}F^2\beta^2\sin^2\omega t}{2\pi h(\Phi_W + E_F)\sqrt{\Phi_W}} e^{-4k\Phi_W^{1.5}/3F\beta\sin\omega t}$$

: Field emission current for AC

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

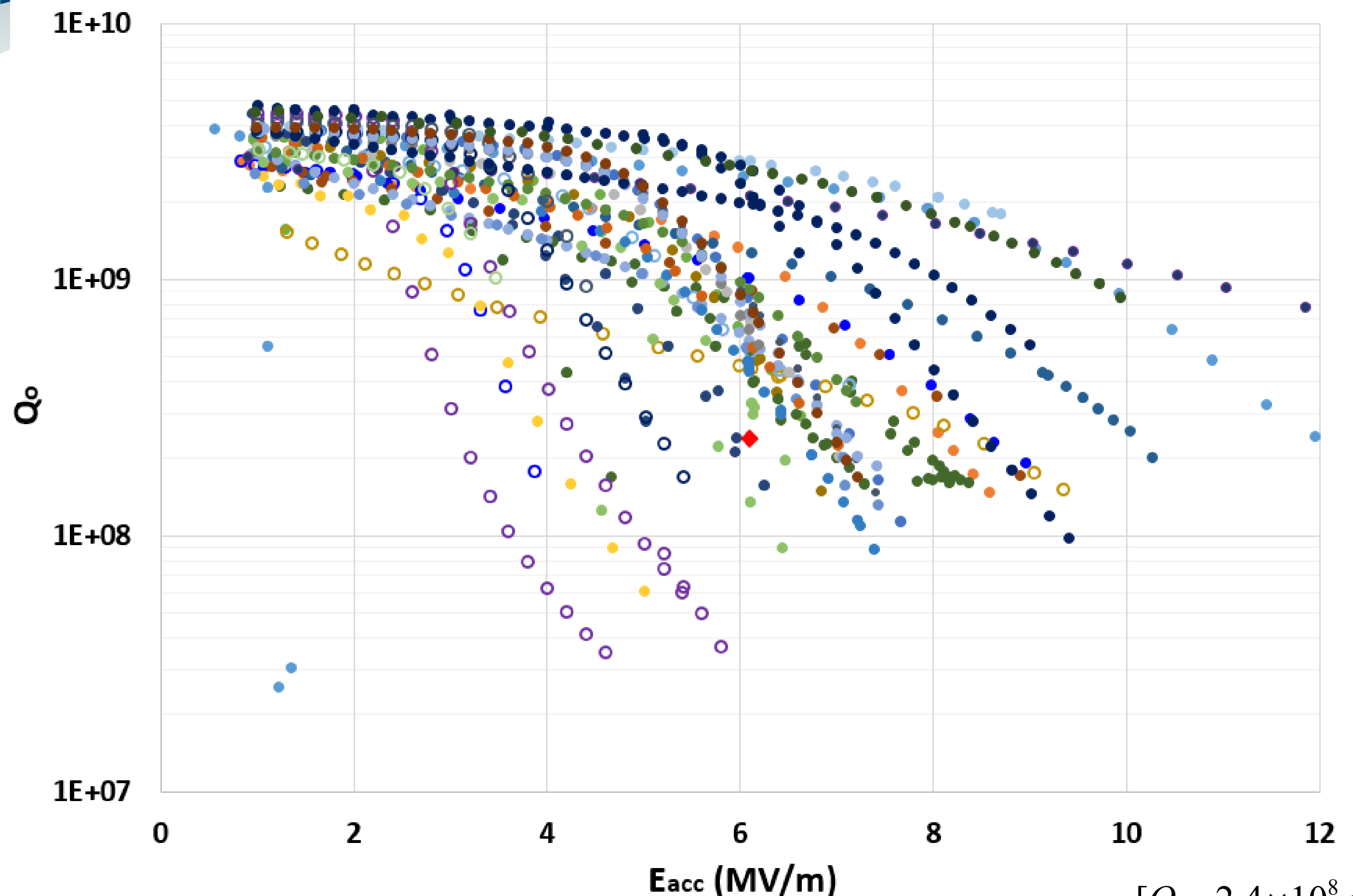
: Average FE current for AC

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

: X-ray counting rate with x-ray field enhancement factor

- **The field emission generates electrons from the surface of the superconducting cavity. The generated electrons and ionized ions are accelerated and eventually generate x-ray in the cavity, which is called bremsstrahlung radiation. It is expected that the generated x-ray is proportional to the current coming from the field emission.**

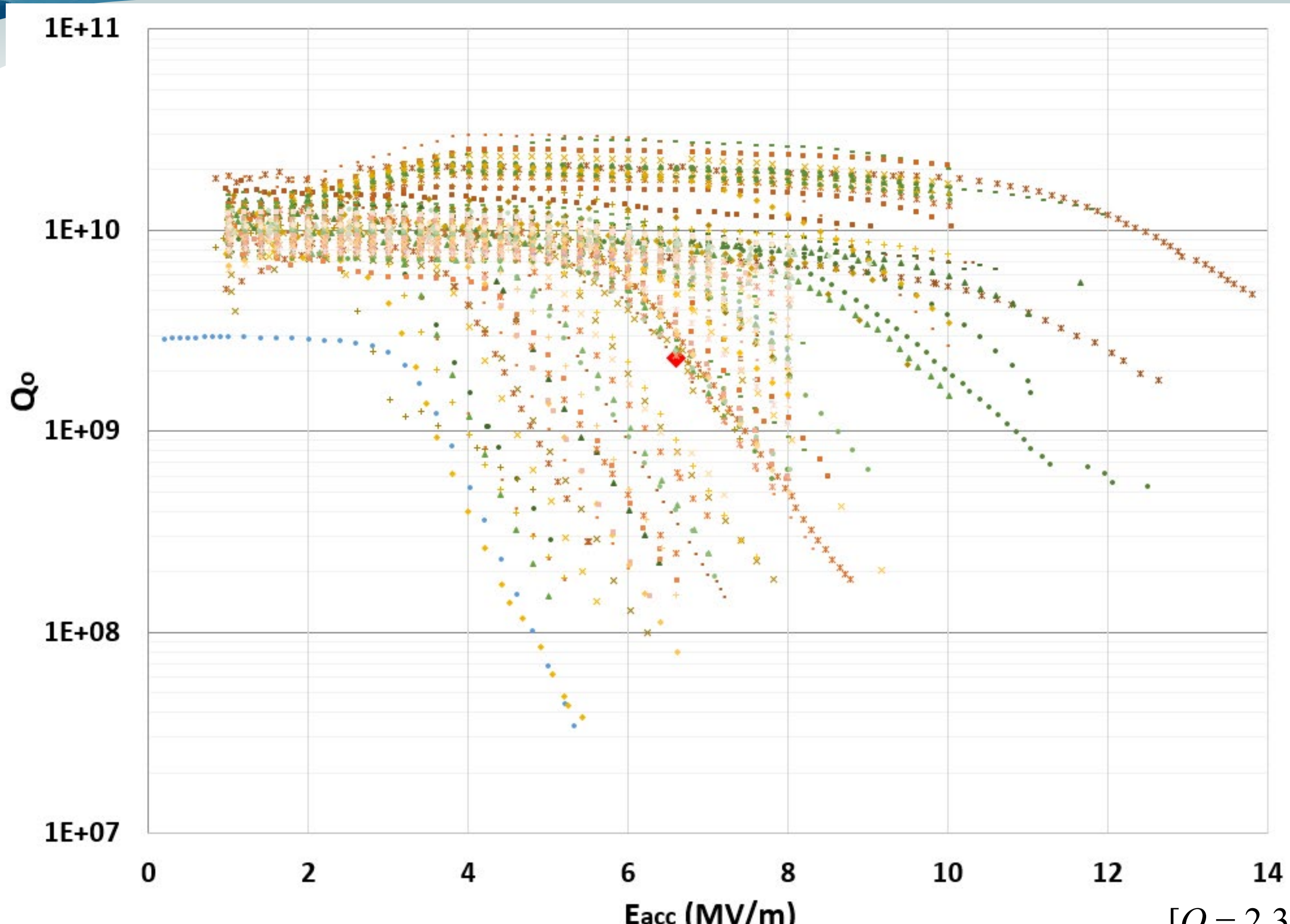
Q slope for QWR



$[Q = 2.4 \times 10^{8}\ at\ E_{acc} = 6.1\ MV/m]$

Figure 3: Q slope measurement as a function of accelerating electric field for the quarter-wave resonator (QWR) cavities at 4.2 K. This data shows the failed and passed QWR. The total number of the QWRs is 22 and all of them are passed.

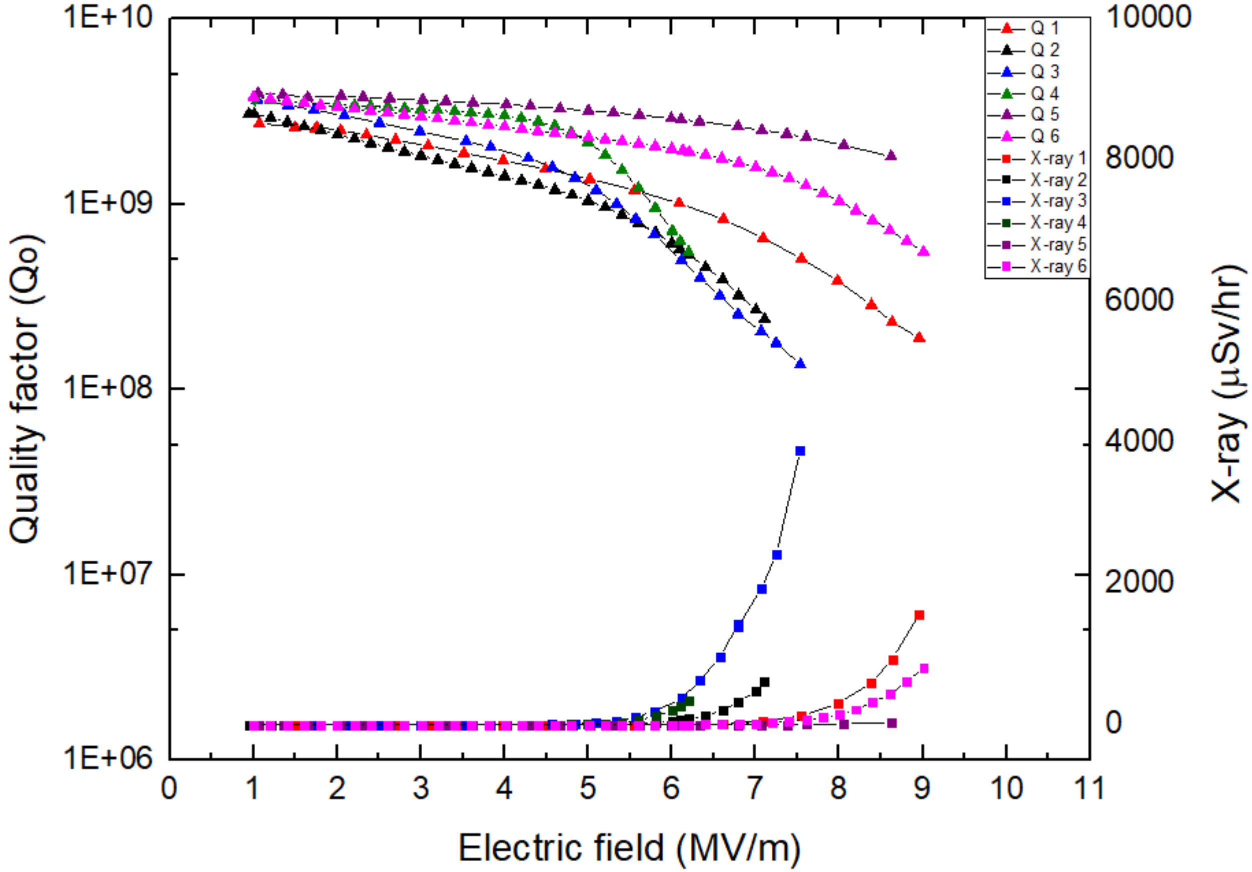
Q slope for HWR



$[Q = 2.3 \times 10^9 \text{ at } E_{acc} = 6.6\, MV/m]$

Figure 4: Q slope measurement as a function of accelerating electric field for the half-wave resonator (HWR) cavities at 2 K. This data shows the failed and passed HWR. The total number of the HWRs is 106 and all of them are passed.

Q slope measurements for QWR



Requirement for QWR :

$Q = 2.4 \times 10^8$

at $E_{acc} = 6.1\, MV/m$

at $4.2\ K$

$f = 81.25\text{Mhz}$

Figure 5: Q slope measurement as a function of accelerating electric field for the quarter-wave resonator (QWR) cavities.

- **The Q factor decreases as the accelerating electric field is increased.**

Magnetic heating effect for QWR

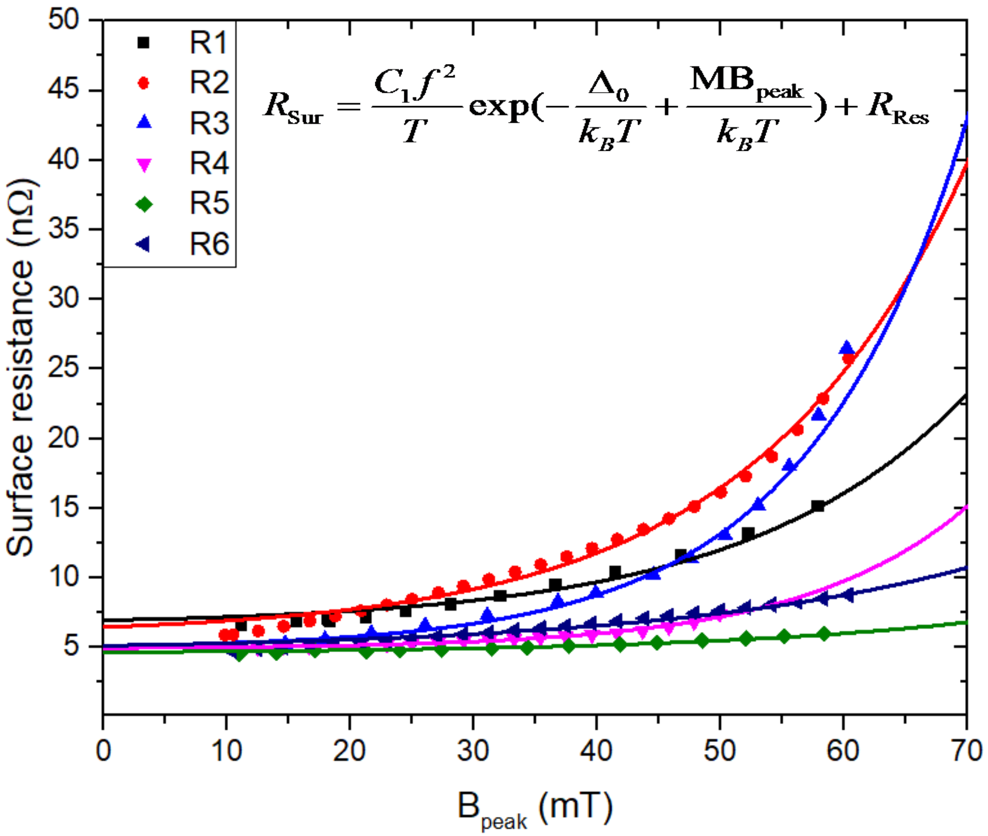
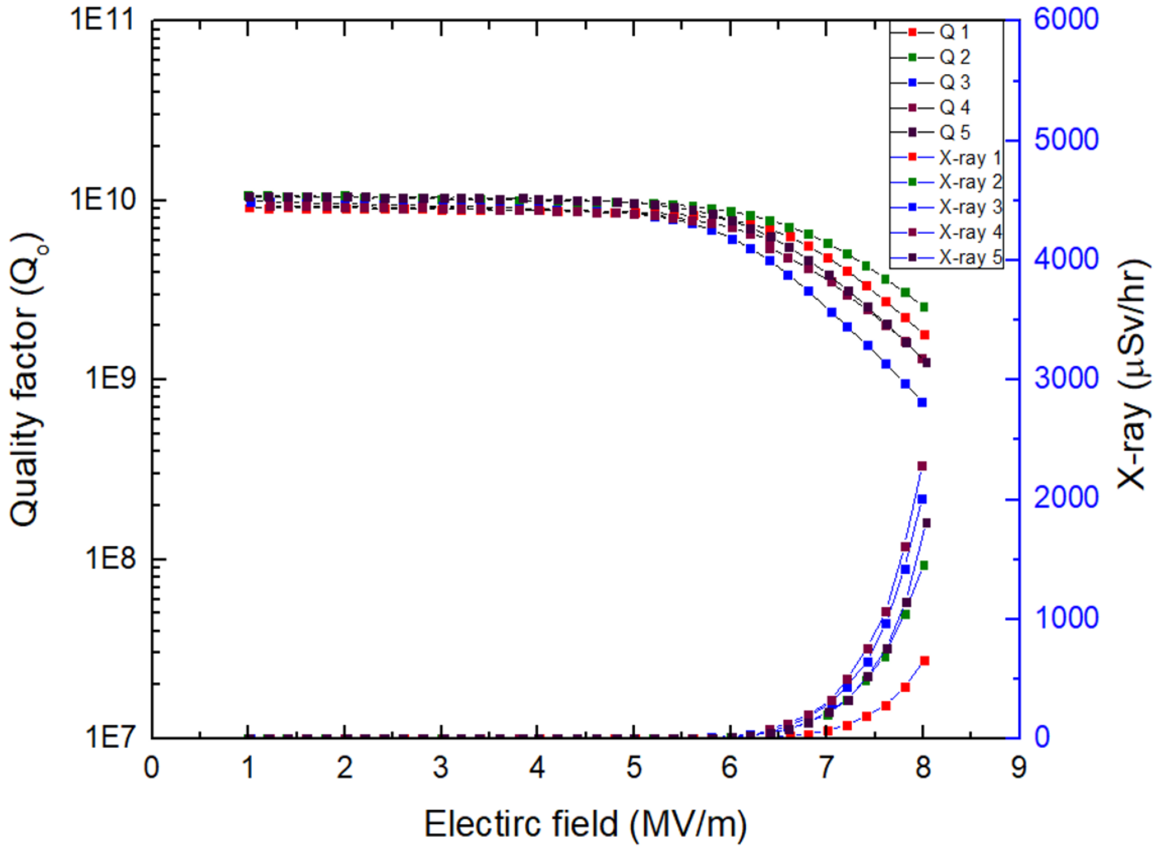


Figure 6: Magnetic heating effect of the surface resistances for quarter-wave resonator (QWR) cavities. The magnetic heating causes the quality factor decreases. The surface resistances for the QWR cavities are fitted with the magnetic heating equation. Magnetic moments for QWR 1, 2, 3, 4, 5 and 6 are as follows:

$$M = 3.3\times10^{-21}, 3.4\times10^{-21}, 4.4\times10^{-21}, 4.3\times10^{-21}, 2.5\times10^{-21}, \text{and } 2.3\times10^{-21} [\text{J/T}].$$

- **Surface resistance increases with the magnetic moment of QWR cavity.**

Quality factors vs electric field for HWR



Requirement for HWR :

$Q = 2.3 \times 10^9$

at $E_{acc} = 6.6\, MV/m$

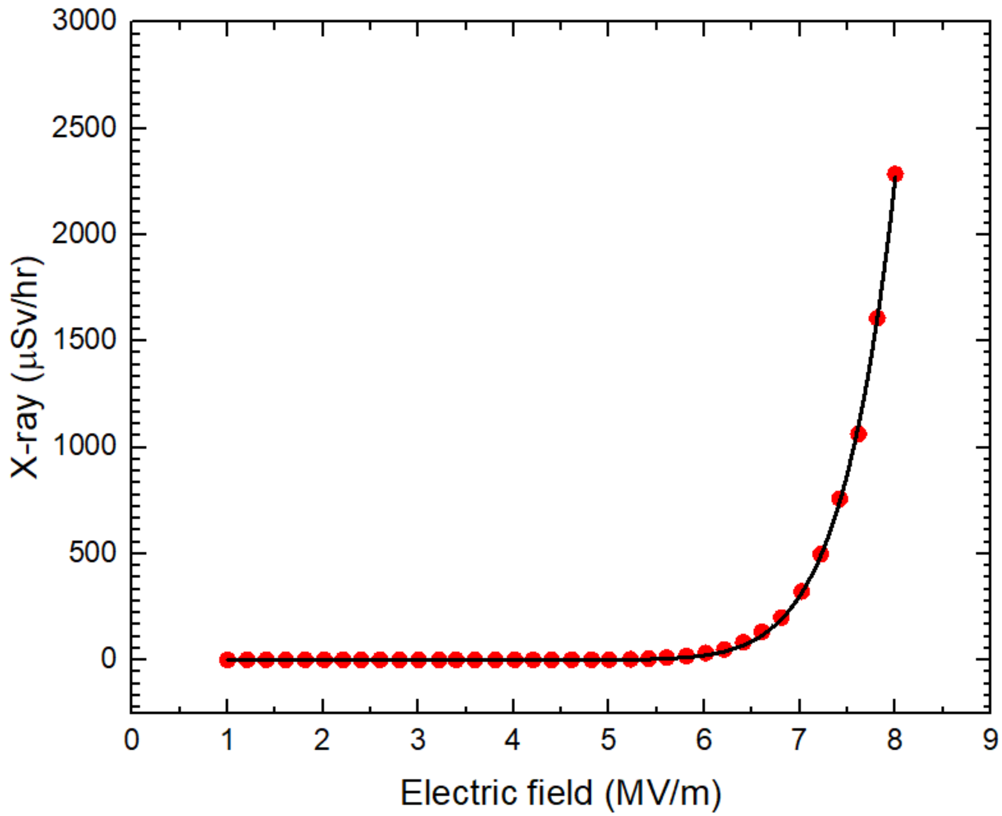
at $2\, K$

$f = 162.5\mathrm{Mhz}$

Figure 7: Quality factors shown as a function of electric field for five different half-wave resonator (HWR) cavities.

- **The quality factors are almost constant in the range of low accelerating electric field below 5 MV/m and decreases as the x ray radiation is increased in the range of the accelerating electric field above 5 MV/m.**

X-ray vs electric field for HWR



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

$$I_0 = 0.1\,\mu Sv/h$$

$$\beta_X = 646$$

Figure 8: X-ray counting rate shown as a function of accelerating electric field for the half-wave resonator (HWR). The field emission increases as the accelerating electric field is increased. The x-ray is generated when the electrons emitted from the field emission and ionized gases are decelerated due to bremsstrahlung radiation.

- **The x-ray increases as the accelerating electric field is increased.**

Quality factor vs x-ray field enhancement factor

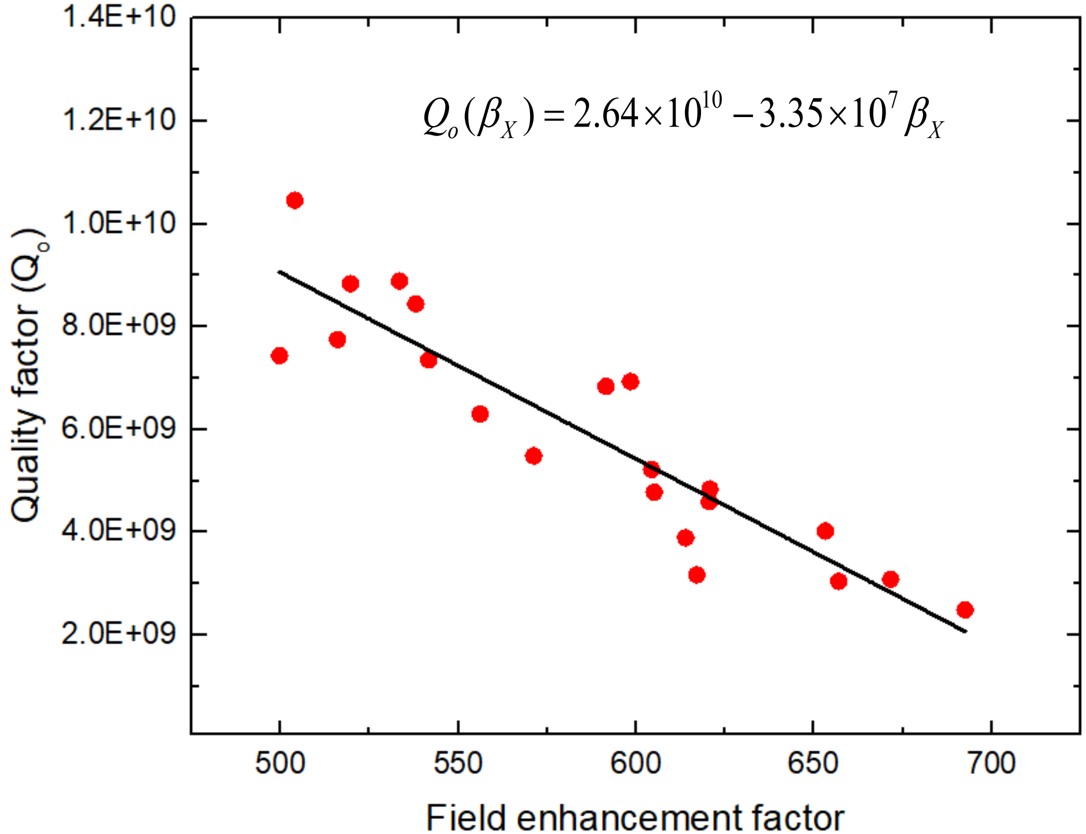


Figure 9: Quality factor of the half-wave resonators (HWRs) shown as a function of x-ray field enhancement factor.

- **The quality factor for the half-wave resonators (HWRs) decreases linearly as the x-ray field enhancement factor is increased.**

Summary

- Magnetic heating and field emission are introduced.
- Vertical test is performed for the QWRs and HWRs.
- Q slopes for the QWRs and HWRs are measured.
- Magnetic heating effect for the QWRs is investigated.
- Field emission effect for the HWRs is studied.
- Quality factor of the HWRs decreases linearly with the x-ray field enhancement factor.

Thank you for your attention