Field Emission Diagnostics and Magnetic Heating Effects in Superconducting Cavities

TTC 2026 Meeting

CentraleSupélec, Université Paris-Saclay Campus

France

WG-2: Effective Operation of Aging Machines for Performance and Reliability

Session 4: FE mitigation, FE diagnose, activation and root causes

(14:30-14:45)

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Contents

- Field Emission Study of HWR Cavities
- Magnetic Heating Study of QWR Cavities
- Vertical Test Results of SSR Cavities
- Summary

Field-Emission Model

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

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

$$\langle I \rangle = \frac{1}{T}\int_0^T I(t)dt$$

- Field-emission current is driven by local RF electric fields and microscopic surface geometry:

$$\langle I \rangle = \frac{0.4Ae\sqrt{E_F}F^{2.5}\beta^{2.5}}{h\sqrt{k}(\Phi_W + E_F)\Phi_W^{0.75}} e^{-4k\Phi_W^{1.5}/3F\beta}$$

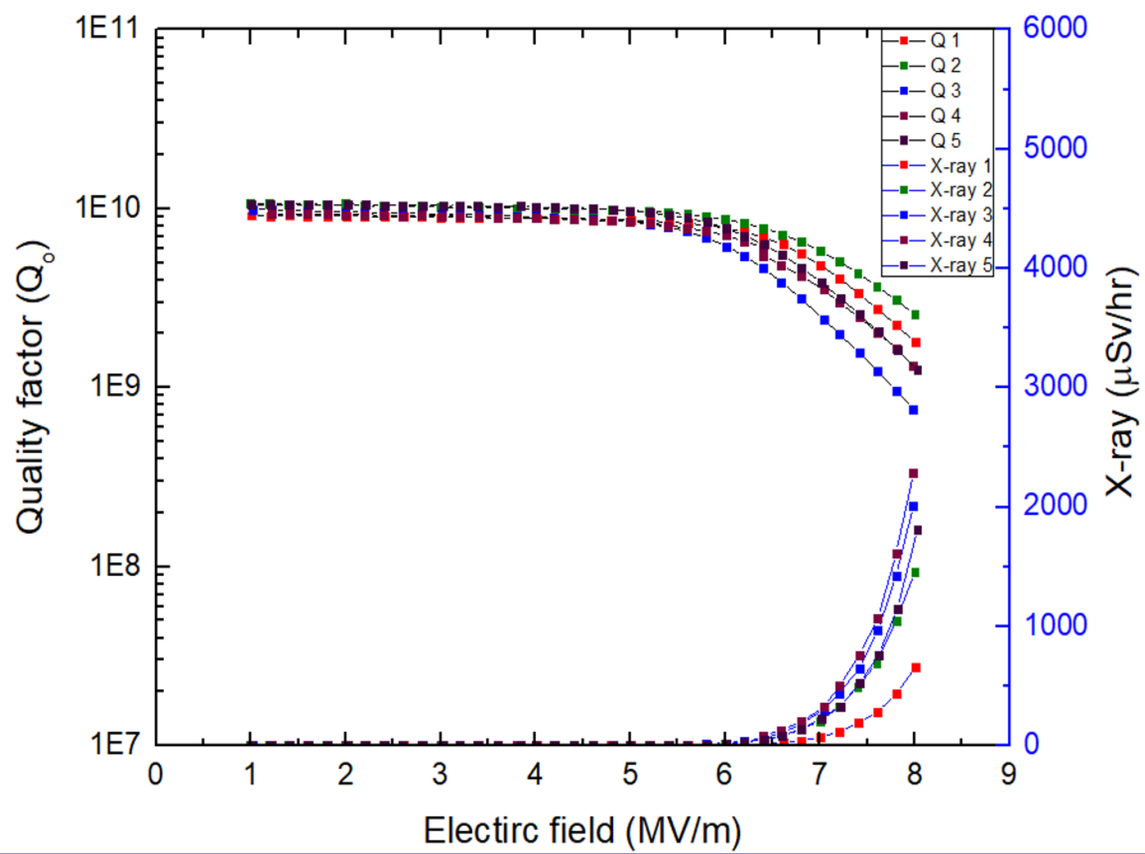
- The surface resistance can be expressed as:

$$R_S = R_0 + \frac{\alpha_R e\sqrt{E_F}F^{2.5}\beta_R^{2.5}}{h\sqrt{k}(\Phi_W + E_F)\Phi_W^{0.75}} e^{-4k\Phi_W^{1.5}/3F\beta_R}$$

high-field defect → **electron tunneling** → **RF acceleration** → **wall impact + X-rays** → **R_s increases, Q_0 decreases**

Sungmin Jeon, Heetae Kim*, Yoochul Jung, Juwan Kim, Junwoo Lee, Moosang Kim, Hyunik Kim, Sangbeen Lee, Minki Lee, Field emission and x-ray effect on RAON HWR superconducting cavity performance, *Current Applied Physics* 38, 67-75 (2022).

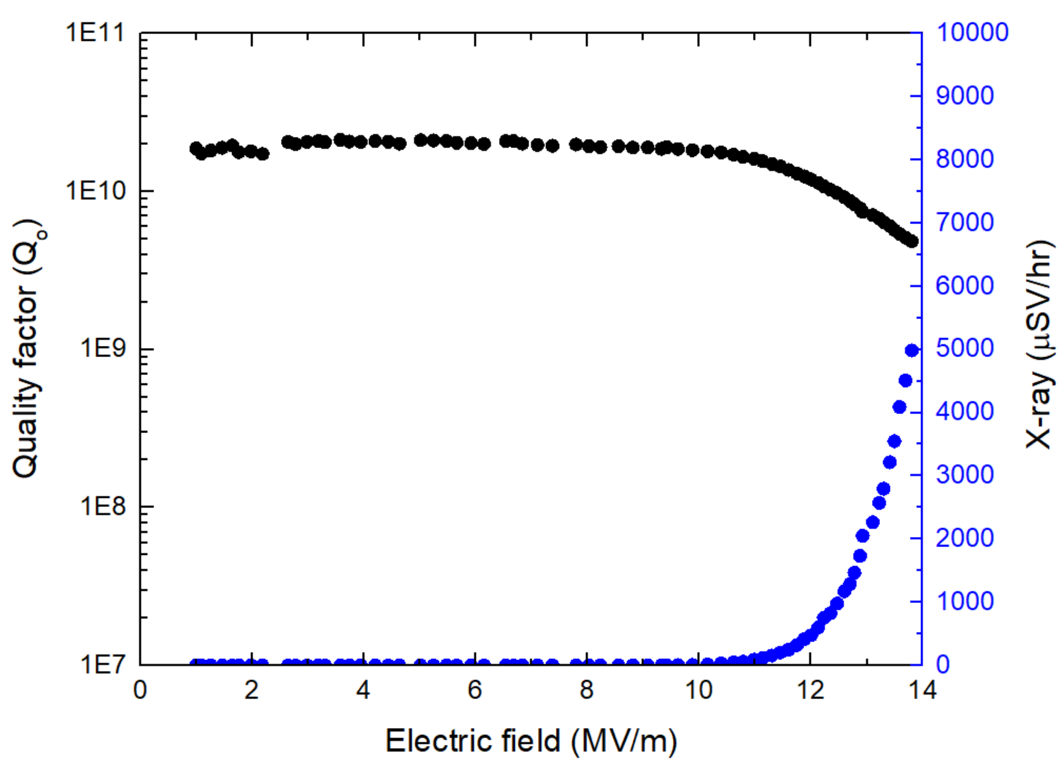
Q-Slope and X-Ray Onset in Five HWR Cavities



- Q_0 remains nearly flat at low accelerating fields.
- Above approximately 5 MV/m, X-ray radiation increases rapidly.
- The Q_0 drop follows the increase in X-ray radiation, indicating field-emission loss rather than purely magnetic heating.
- The X-ray dose rate is a practical proxy for emitted electron current during vertical testing.
- RF power consumed by dark current and impact heating appears as Q_0 degradation.

Sungmin Jeon, Heetae Kim*, Yoochul Jung, Juwan Kim, Junwoo Lee, Moosang Kim, Hyunik Kim, Sangbeen Lee, Minki Lee, Field emission and x-ray effect on RAON HWR superconducting cavity performance, *Current Applied Physics* 38, 67-75 (2022).

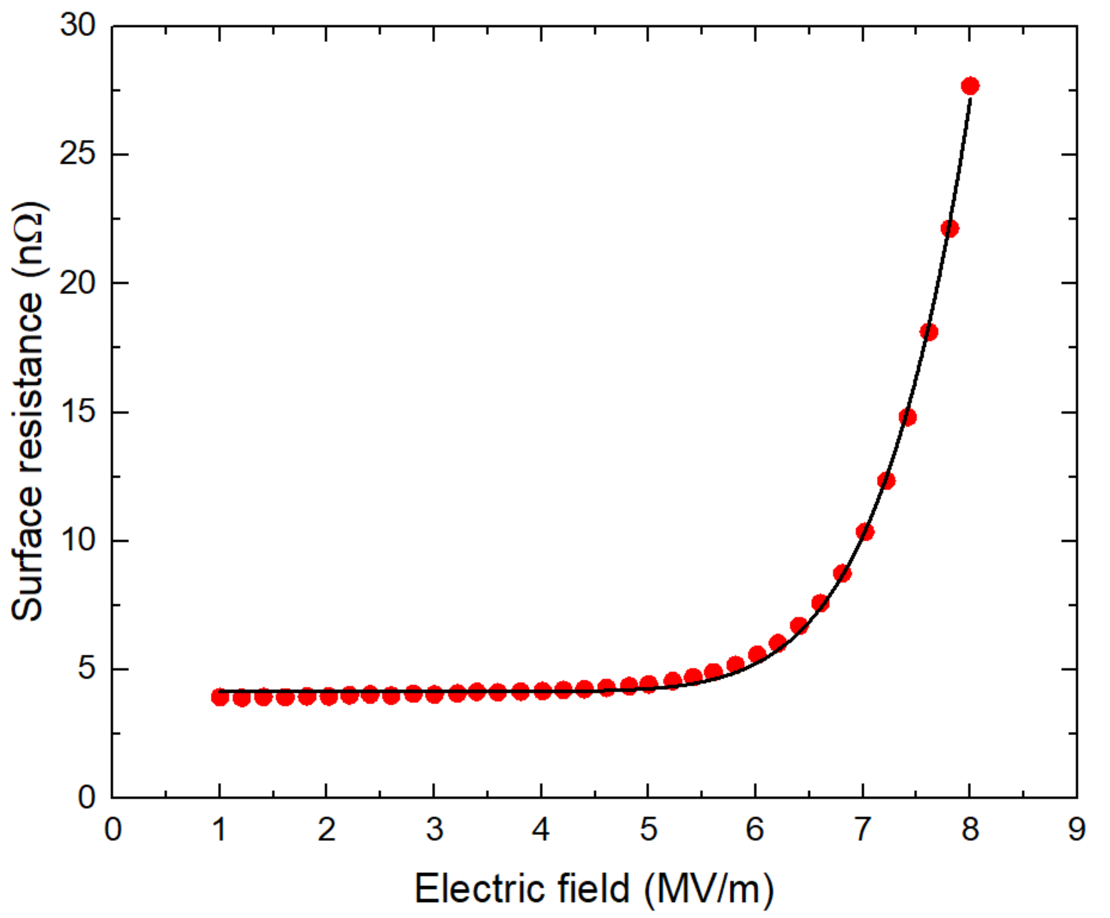
Best-Cavity Example: Delayed Onset to High Field



- In the best cavity, Q_0 remained nearly constant from 1 to 10 MV/m.
- The observed degradation therefore follows X-ray production rather than magnetic-field heating.
- The best HWR cavity shows the same physical behavior but with a higher onset field.
- Field-emission current is driven by the local RF electric field and amplified by microscopic surface geometry.
- Q_0 is nearly constant below approximately 10 MV/m.
- X-ray radiation increases above the onset field.

Sungmin Jeon, Heetae Kim*, Yoochul Jung, Juwan Kim, Junwoo Lee, Moosang Kim, Hyunik Kim, Sangbeen Lee, Minki Lee, Field emission and x-ray effect on RAON HWR superconducting cavity performance, *Current Applied Physics* 38, 67-75 (2022).

Surface Resistance



$$R_S = R_0 + \frac{\alpha_R e \sqrt{E_F} F^{2.5} \beta_R^{2.5}}{h\sqrt{k}(\Phi_W + E_F)\Phi_W^{0.75}} e^{-4k\Phi_W^{1.5}/3F\beta_R}$$

- Fitted example: R_0 = 4.16 nΩ
- β_R = 1090

- Field-emission current causes local ohmic heating.
- Local heating increases the surface resistance.
- Increased surface resistance reduces Q_0.

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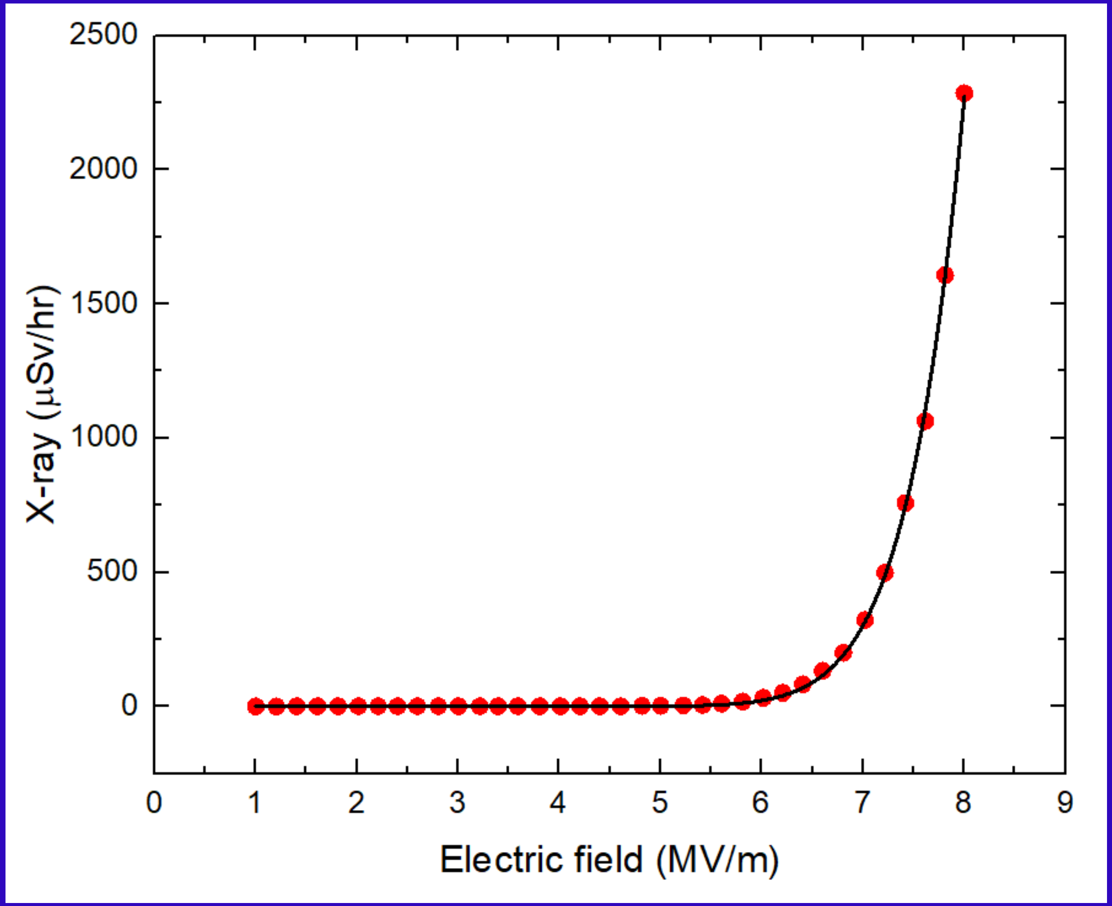
X-Ray Fitting Showing Field-Emission Severity



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

- X-ray generation follows the field-emission current model.
- Fitted background: I_0 = 0.1 μSv/h.
- Fitted X-ray field-enhancement factor: β_X = 646.
- The exponential term explains the abrupt X-ray onset above the threshold field.

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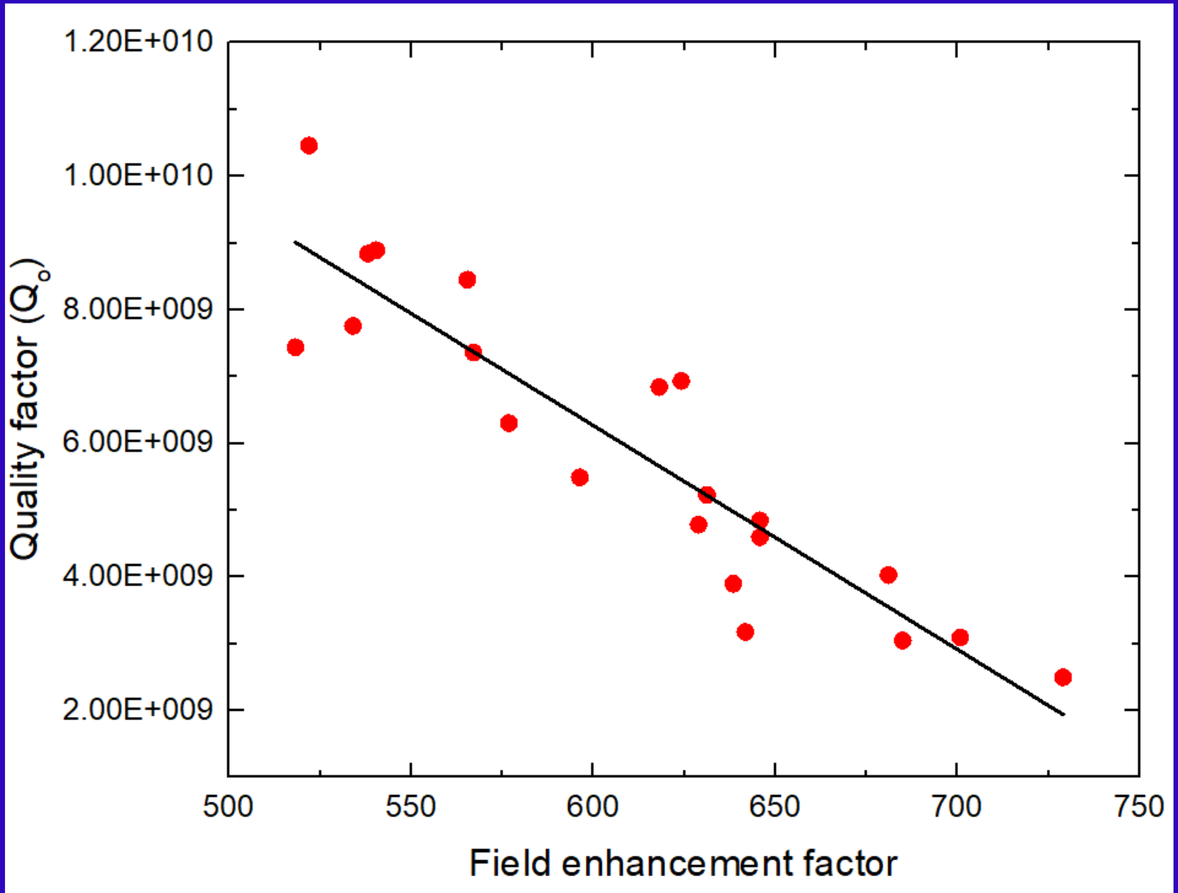
Q_0 Decreases with Field Enhancement Factor



- A higher β_X indicates stronger local field enhancement at emission sites.
- Stronger field emission produces more X-rays and greater effective RF loss.
- The linear fit translates X-ray fitting results into a cavity-quality diagnostic.
- Q_0 decreases as the field-enhancement factor increases.

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Magnetic Flux Quantization

- Action in nature is quantized as:

$$S = \int L\,dt = n\hbar$$

- The reduced Planck constant (ħ) represents the minimum quantum of action and is the origin of several quantum units, including the magnetic-flux quantum ($h/2e$), conductance quantum ($2e^2/h$), inverse conductance quantum ($h/2e^2$), von Klitzing constant (h/e^2), Josephson constant ($2e/h$), and photon energy (hf).
- Magnetic flux in a superconductor is quantized in units of the magnetic flux quantum. Trapped magnetic flux in a Nb superconducting cavity can be expressed as integer multiples of this quantum.

$$\Phi = n\frac{h}{2e}$$

Magnetic Effects in a Superconducting Cavity

$$\Phi = n\frac{h}{2e}$$

$$P_{dis} = \frac{1}{2}\int R_S |H(S)|^2 dS$$

$$R_{BCS} = \frac{Cf^2}{T}\exp(-\frac{\Delta}{k_B T})$$

$$\Delta = \Delta_0 - MB_{peak}$$

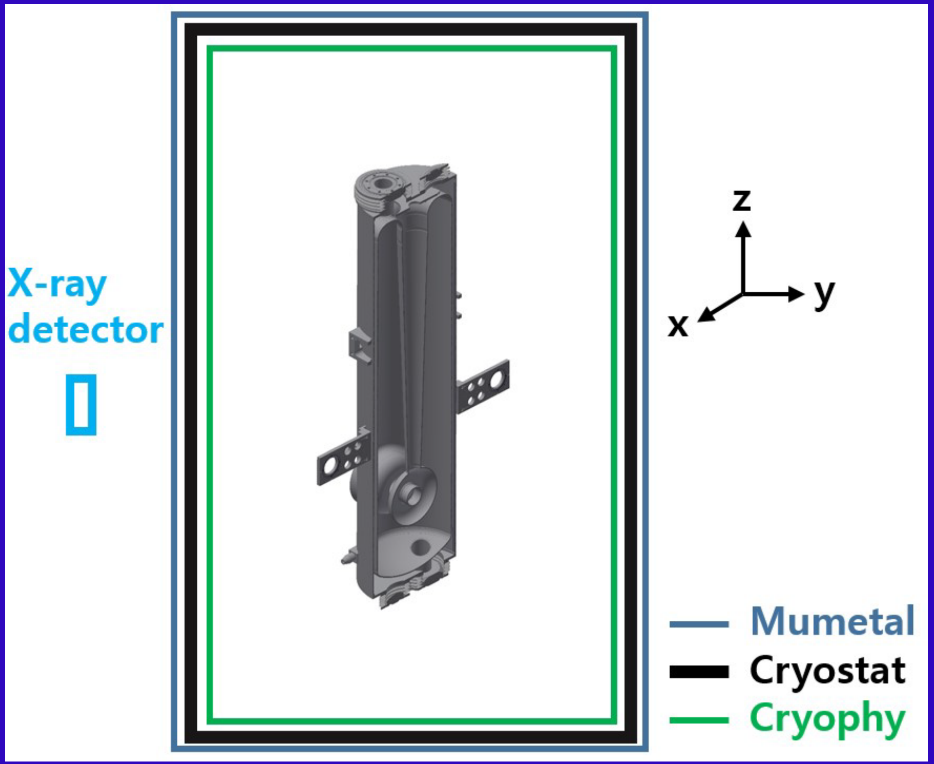
$$R_{BCS} = \frac{Cf^2}{T}\exp(-\frac{\Delta_0}{k_B T} + \frac{MB_{peak}}{k_B T})$$

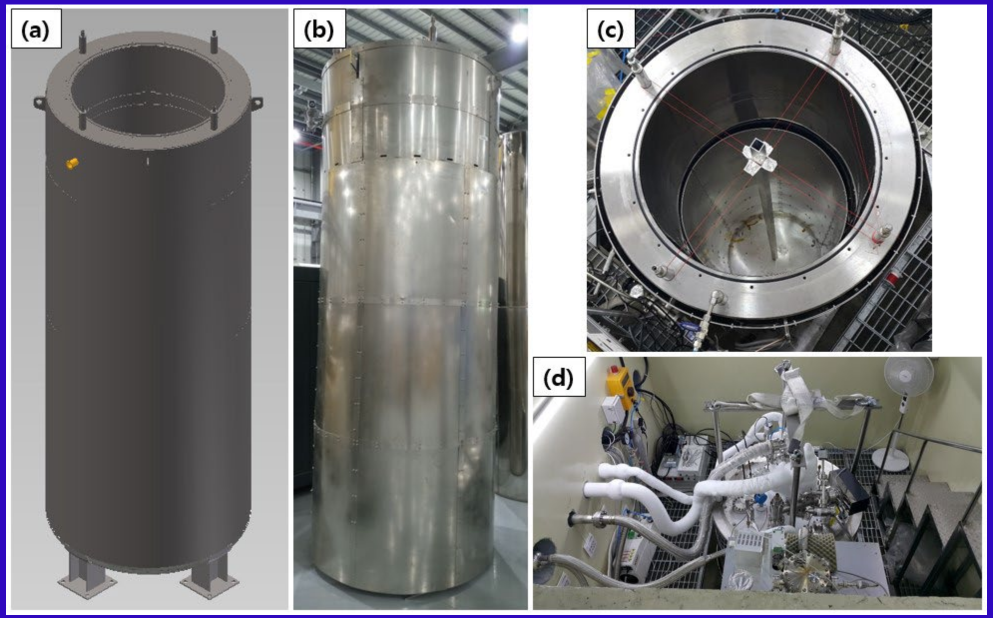
$$R_{Sur} = \frac{Cf^2}{T}\exp(-\frac{\Delta_0}{k_B T} + \frac{MB_{peak}}{k_B T}) + R_{Res}$$

- Magnetic defects cause magnetic heating, leading to pair breaking in the superconducting current and an increased density of normal-state electrons. The BCS resistance decreases as the temperature decreases from 4.2 K to 2 K. The surface-resistance model indicates that residual resistance and magnetic resistance associated with trapped flux remain even as the temperature approaches 0 K.

Heetae Kim, Sungmin Jeon, Yoochul Jung, Juwan Kim, Magnetic heating effect for Quarter-Wave Resonator (QWR) superconducting cavities, Quantum Beam Sci. 7(3), 21 (2023).

Magnetic Shielding for QWR Cavities in a Cryostat





- Schematic diagram of magnetic shielding in a cryostat. Mu-metal and Cryophy are used to reduce the external magnetic field during QWR cavity tests.

- Cryostat and magnetic shielding: (a) cryostat design, (b) photograph of the Mu-metal shield and cryostat, (c) top view of the Mu-metal shield, cryostat, and Cryophy shield from outside the cryostat, and (d) top view of the vertical test setup.

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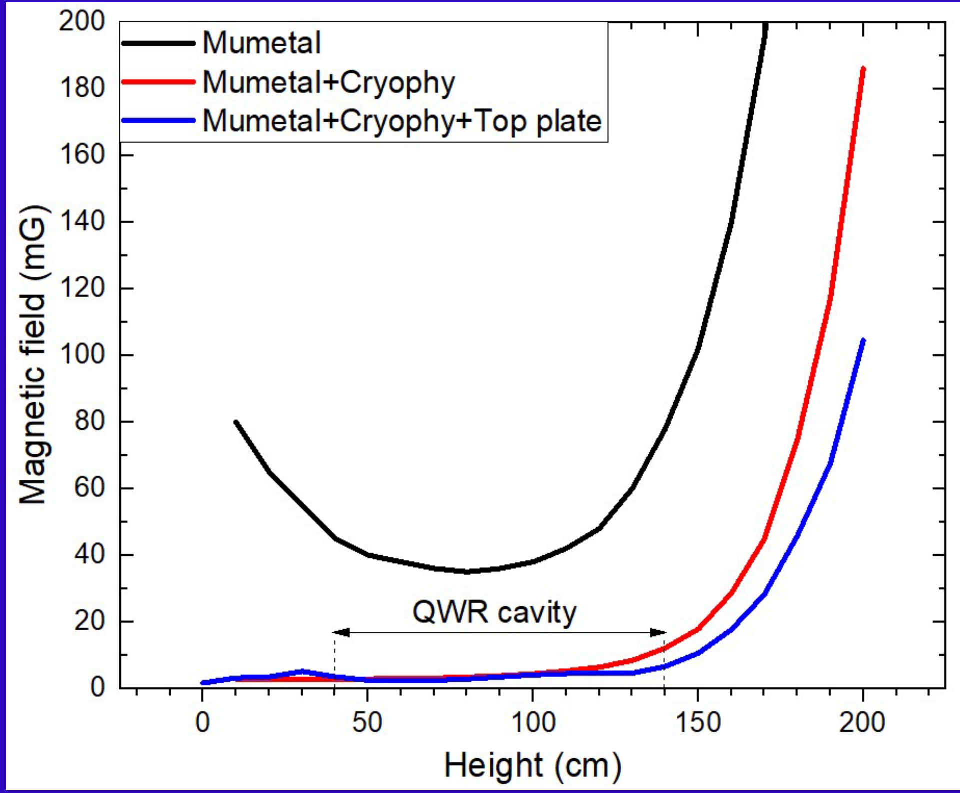
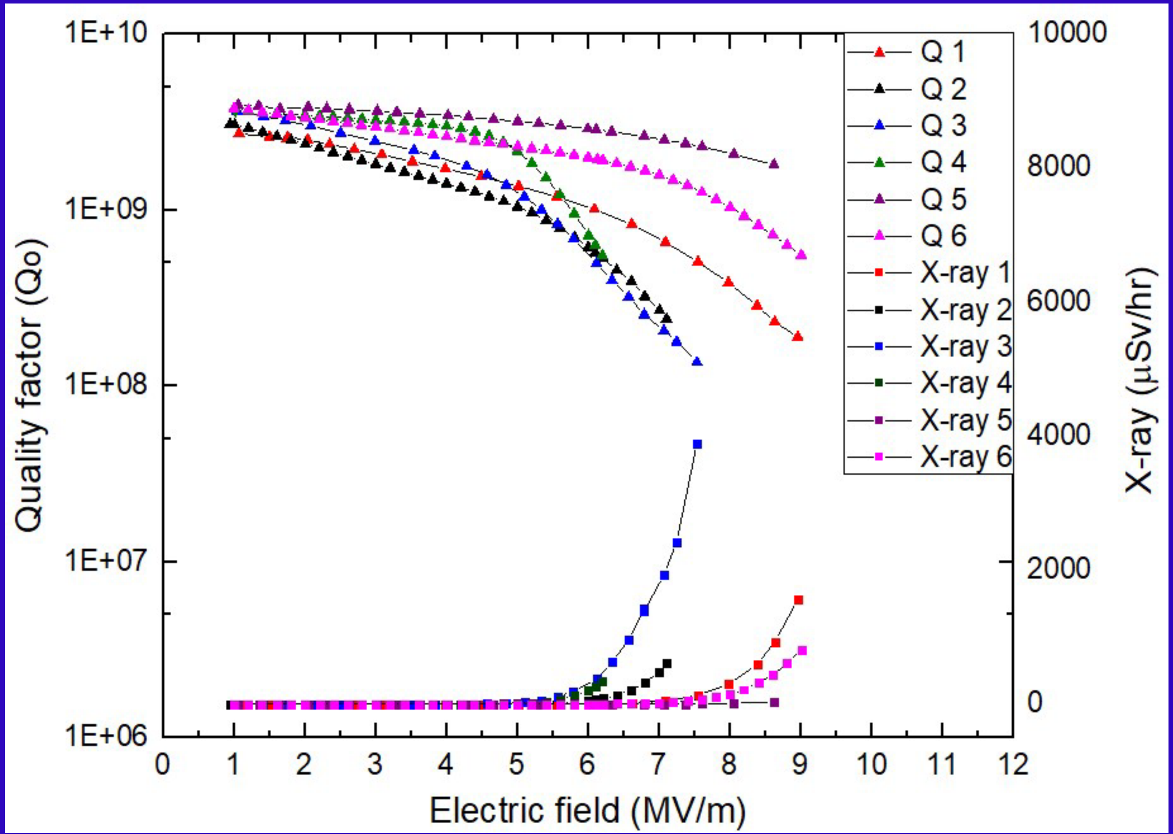
Measurement of Magnetic Field Strength



- Magnetic-field strength was measured inside the cryostat.
- At the QWR cavity location, the magnetic field was reduced to below 10 mG by installing the Mu-metal shield, Cryophy shield, and top plate.

Heetae Kim, Sungmin Jeon, Yoochul Jung, Juwan Kim, Magnetic heating effect for Quarter-Wave Resonator (QWR) superconducting cavities, Quantum Beam Sci. 7(3), 21 (2023).

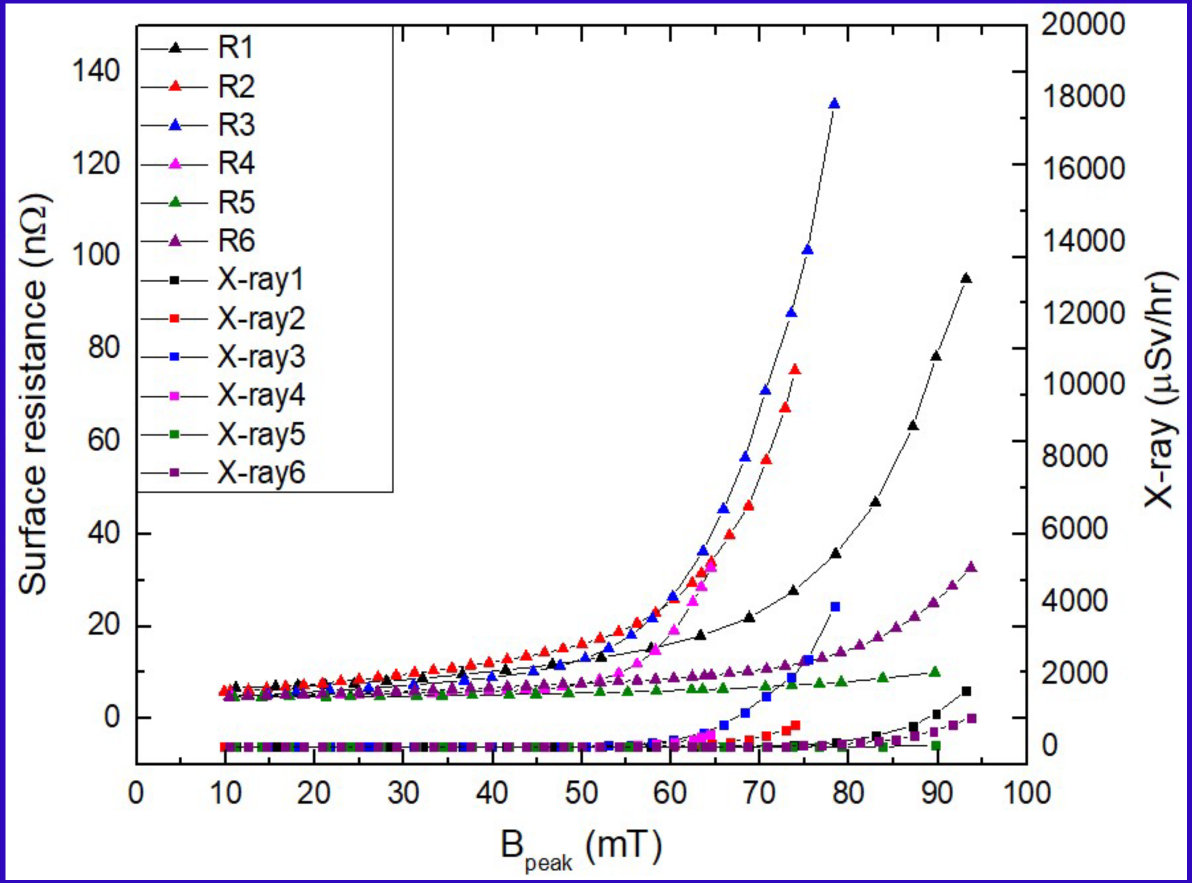
Q-Slope Measurement versus Accelerating Field for QWR Cavities



- Q curves were measured as a function of accelerating field for QWR cavities.
- The quality factor decreases with increasing field emission and X-ray generation.

Heetae Kim, Sungmin Jeon, Yoochul Jung, Juwan Kim, Magnetic heating effect for Quarter-Wave Resonator (QWR) superconducting cavities, Quantum Beam Sci. 7(3), 21 (2023).

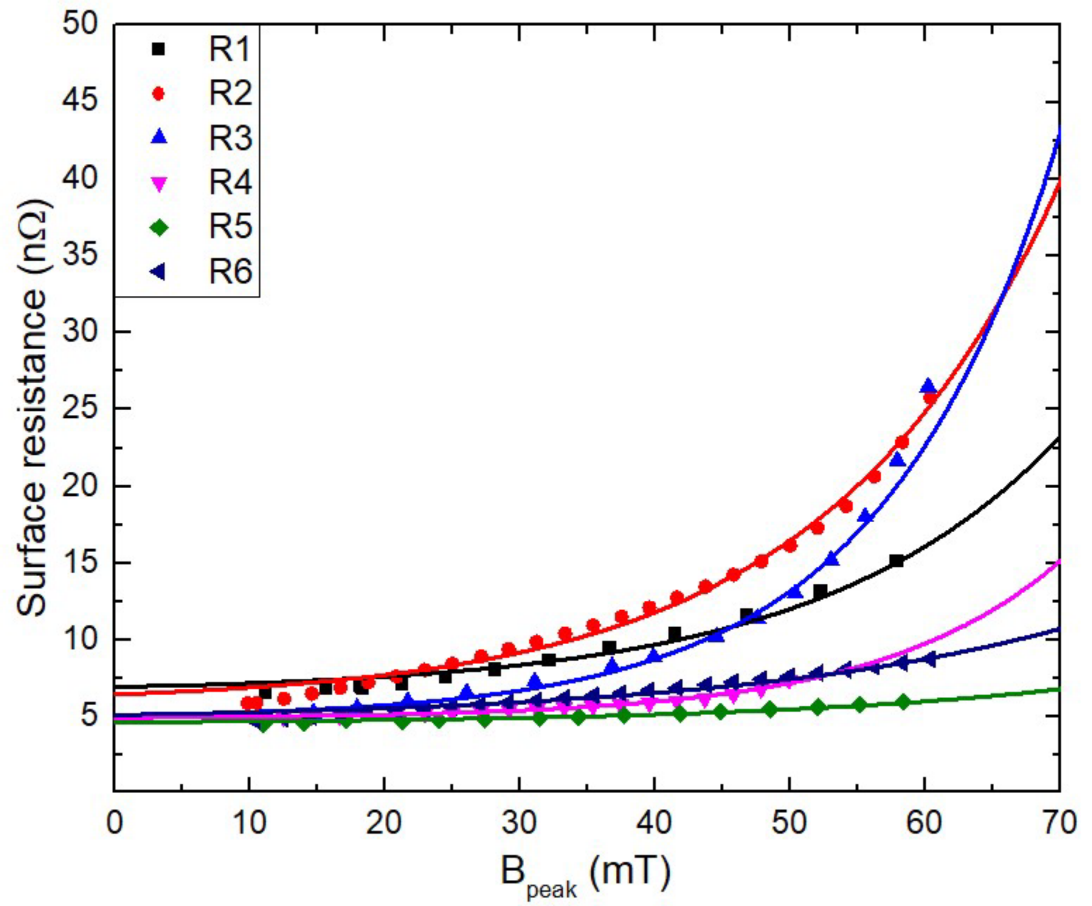
Surface Resistance Measurement versus Peak Magnetic Field for QWR Cavities



- Surface resistance was measured as a function of peak magnetic field for QWR cavities.
- The surface resistance increases as the peak magnetic field increases.

Heetae Kim, Sungmin Jeon, Yoochul Jung, Juwan Kim, Magnetic heating effect for Quarter-Wave Resonator (QWR) superconducting cavities, Quantum Beam Sci. 7(3), 21 (2023).

Surface Resistance versus Magnetic Field



- The magnetic moments for QWR cavities 1-6 are:

3.3×10^{-21} J/T

3.4×10^{-21} J/T

4.4×10^{-21} J/T

4.3×10^{-21} J/T

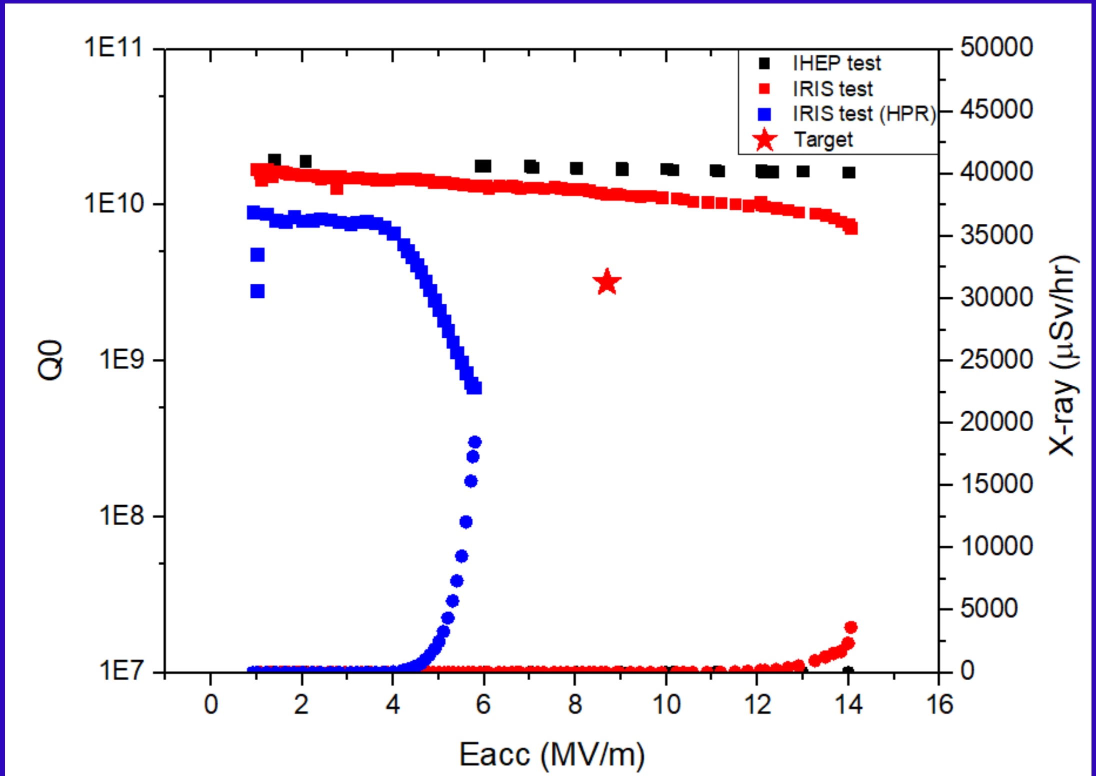
2.5×10^{-21} J/T

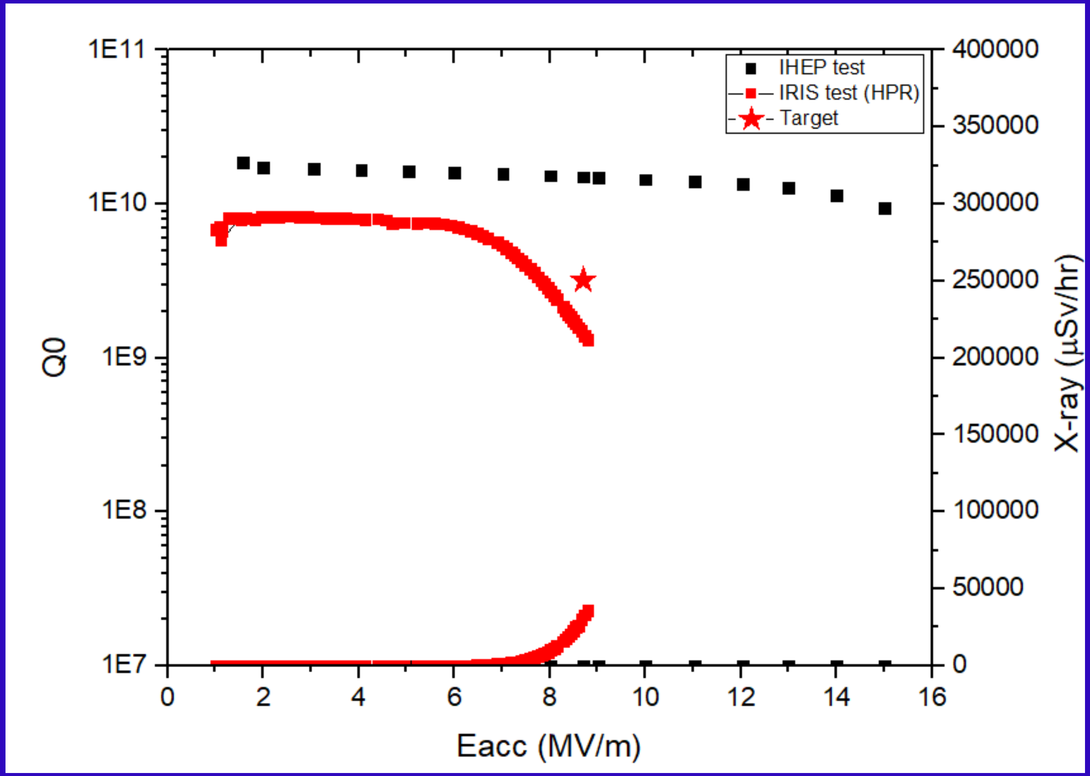
2.3×10^{-21} J/T

- Surface resistance is shown as a function of peak magnetic field.
- Dissipated power from magnetic heating depends on both the surface resistance and the magnetic field on the superconducting surface.
- The surface-resistance data were fitted using the magnetic-heating equation, and the magnetic moments were obtained for each cavity.

Heetae Kim, Sungmin Jeon, Yoochul Jung, Juwan Kim, Magnetic heating effect for Quarter-Wave Resonator (QWR) superconducting cavities, Quantum Beam Sci. 7(3), 21 (2023).

Vertical Test Results of Prototype SSR2 Cavities





- Q curve of the SSR2 spare cavity.
- The ultrapure water used at IRIS had a resistivity of 2 MΩ·cm.
- Q_0 degradation was observed after HPR at IRIS.

- Q curve of SSR2 No. 5.
- The ultrapure-water system at IRIS provides water with a resistivity of 18 MΩ·cm and a TOC level of 7 ppb.
- SSR2 No. 5 was tested after HPR at IRIS.
- Q_0 degradation was observed after HPR at IRIS.

Summary

- HWR Q-slope degradation is well explained by field-emission theory coupled with X-ray generation.
- Surface resistance and X-ray dose rate can be fitted using field-emission-based models.
- Q_0 decreases approximately linearly as the X-ray field-enhancement factor increases.
- Field emission is the dominant performance-limiting mechanism in the tested HWR cavities.
- For QWR cavities, magnetic heating and magnetic defects increase BCS-like surface resistance as Bpeak increases.
- Magnetic shielding reduced the field in the cavity region to below 10 mG for reliable vertical testing.
- The fitted magnetic moments were on the order of 10^{-21} J/T.
- SSR vertical test results show Q_0 degradation after HPR at IRIS.

Thank you for your attention