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Correction of Field-Emission-Induced Surface Resistance in HWR Cavities

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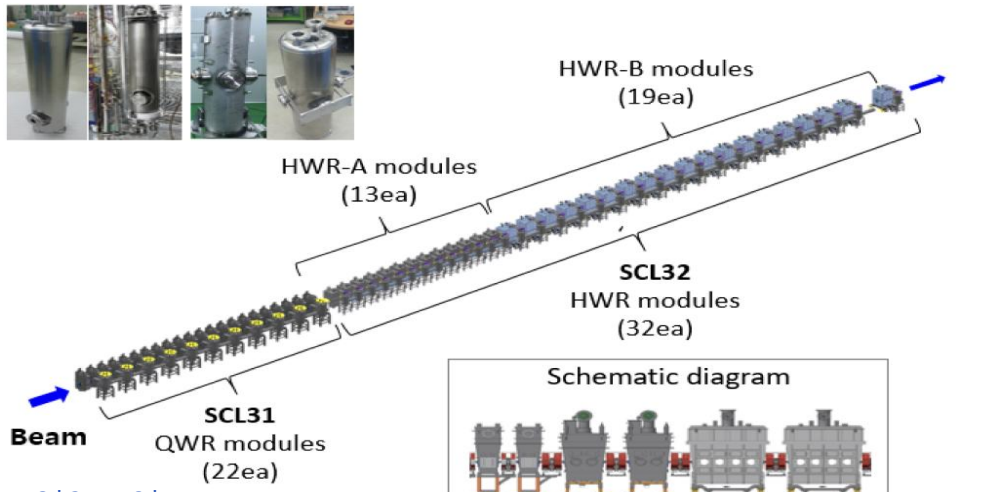
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1. Introduction
– Current status of RAON

Superconducting Linac 3 (SCL3, Low-energy section)



22*1 + 13*2 + 19*4

Superconducting Cavity (QWR/HWR)	Total (124 cavities)

Specification of HWR

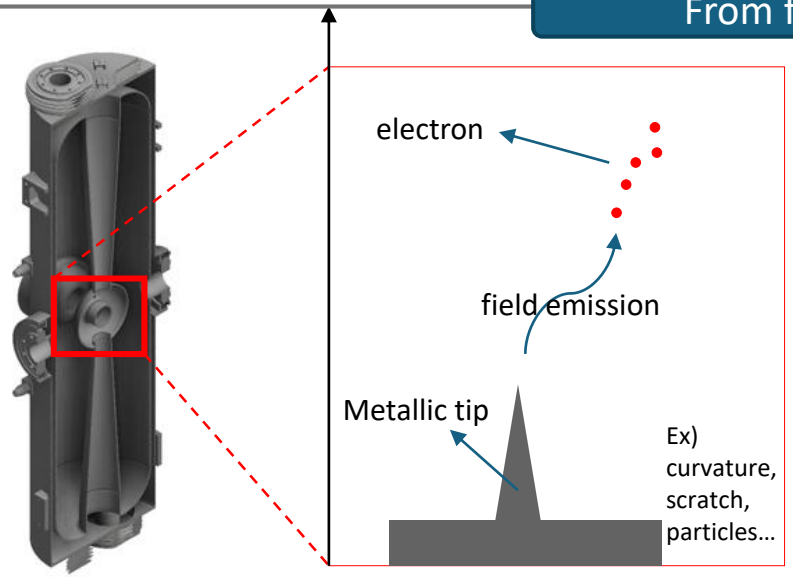


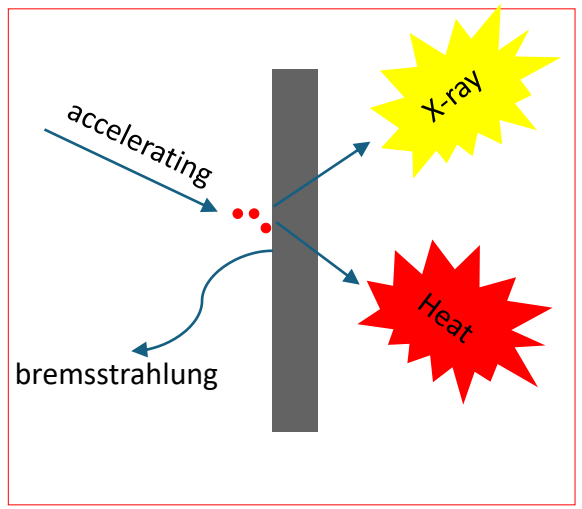
Frequency	162.5 MHz
Eacc [MV/m]	6.6
Vacc [MV]	1.46
R/Q [Ω]	295
L_{eff} [mm]	221.5
$E_{\mathrm{peak}}/E_{\mathrm{acc}}$	5.2
$B_{\mathrm{peak}}/E_{\mathrm{acc}}$	9.0

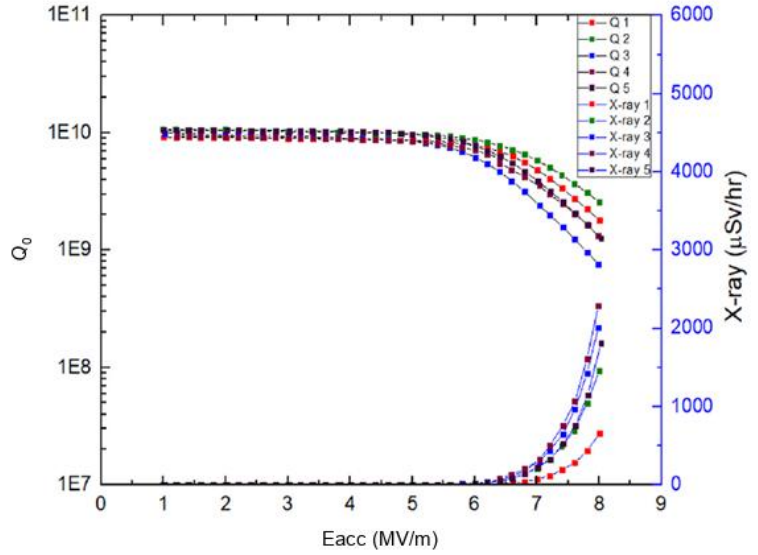
- The SCL3 low-energy section has been completed using QWR and HWR cavities.
- During SCL3 construction, field emission was one of the most critical performance-limiting issues
- Various studies on FE characteristics of HWR are ongoing.

1. Introduction
– Field emission in SRF cavities

From field emission to Q_0 degradation and X-ray generation







Field emission → X-ray & heat generation → Q_0 degradation

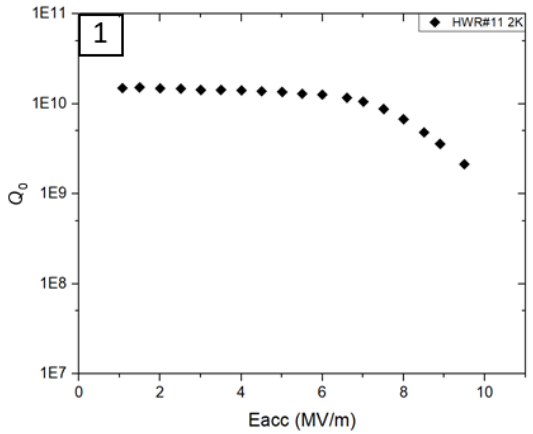
- Emitted FE electrons are accelerated by the RF field inside the cavity.
- Their impact on the cavity surface produces bremsstrahlung X-rays and local heating.
- These effects appear in VT as X-ray increase, Q_o degradation, and field limitation.

1. Introduction
– Q_0 and X-ray measurements

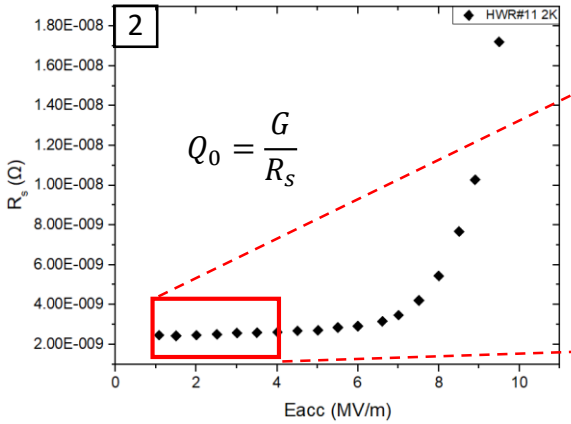
- FE can be observed using two signals: Q_0 degradation and X-ray dose rate.
- The field enhancement factor and emitting area can be extracted from each observable to evaluate FE characteristics.
- The advantages and limitations of each method are summarized below.

Method	Advantages	Limitations
Q_0- based	• **Less dependent on measurement conditions**. • Reflects RF performance degradation directly.	• Weak FE may not be clearly observable. • Includes non-FE losses and temperature-dependent RF losses.
X-ray- based	• More sensitive than Q_0-based measurements. • Less affected by temperature variation.	• **Depends on detector position, shielding, and impact location.**

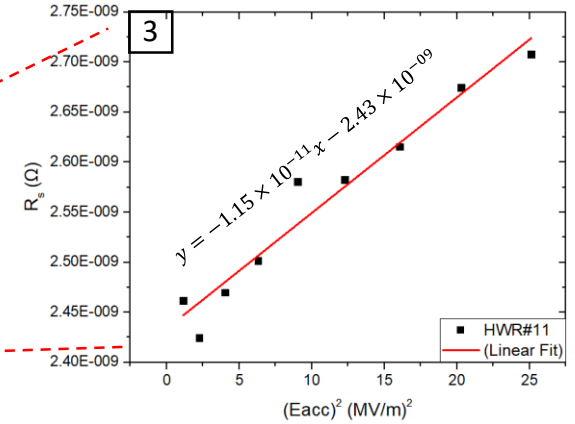
2. Field enhancement factor from Q_0



(1) Q_0 of HWR# 11



(2) Convert to surface resistance using equation G/R_s



(3) Obtain linear fitting parameter at field emission free region.

$$I_{RF}(E) = \frac{A_{\mathrm{FN}} A_e (\beta_{FN} E)^{2.5}}{\phi} \exp\left(-\frac{B_{\mathrm{FN}} \phi^{\frac{3}{2}}}{\beta_{FN} E}\right)$$

$$* P_{\mathrm{FE}} = \frac{I_{RF}\epsilon}{e} \propto E^{3.5} \exp\left(-\frac{B_{\mathrm{FN}} \phi^{\frac{3}{2}}}{\beta_{FN} E}\right) \propto \Delta\frac{1}{Q} \cdot E^2$$

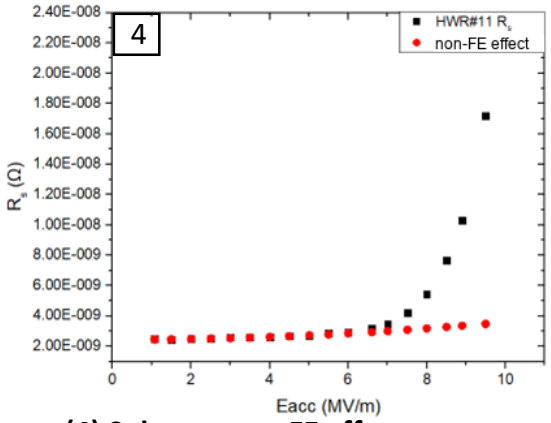
$$\Delta\frac{1}{Q} \propto E^{1.5} \exp\left(-\frac{B_{\mathrm{FN}} \phi^{\frac{3}{2}}}{\beta_{FN} E}\right)$$

$$\Delta\frac{1}{Q} / E^{1.5} = A \cdot \exp\left(-\frac{B_{\mathrm{FN}} \phi^{\frac{3}{2}}}{\beta_{FN} E}\right)$$

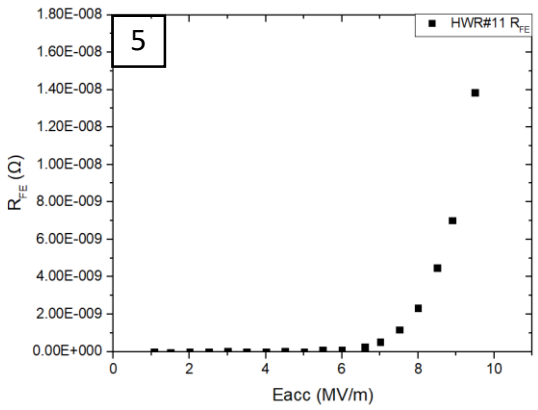
$$\ln(\Delta\frac{1}{Q} / E^{1.5}) = \ln(A) - \frac{B_{\mathrm{FN}} \phi^{\frac{3}{2}}}{\beta_{FN} E} \cdots (R_{el} \propto P_{el})$$

$\boldsymbol{P_{FE}(E)}$ is power dissipated by FE electrons

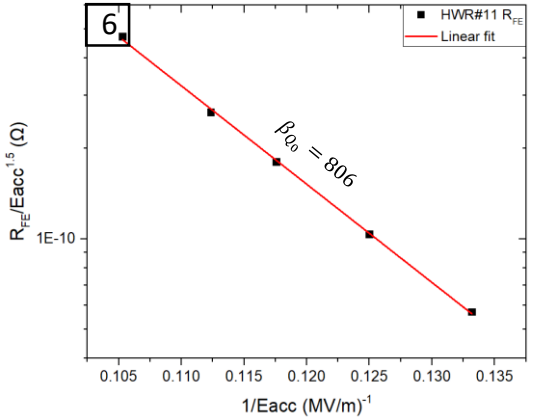
ϵ **is the average energy gain of electrons (**$\epsilon \propto E$ **)**



(4) Subtract non-FE effect



(5) Obtain FE-induced resistance R_{FE}



(6) FN plot of result. Field enhancement factor is obtained

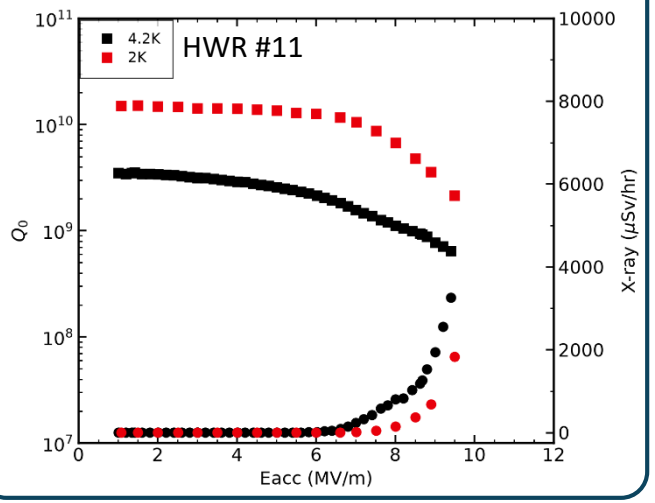
β_{Q_0} is β_{FN} obtained from Q_0

*MEASUREMENT OF A SUPERCONDUCTING 500 MHz Nb CAVITY IN THE TM010-MODE. Sh. NOGUCHI, Y. KOJIMA and J. HALBRITTER. Nuclear Instruments and Methods 179 (1981) 205-215

3. Correction of 4.2 K data

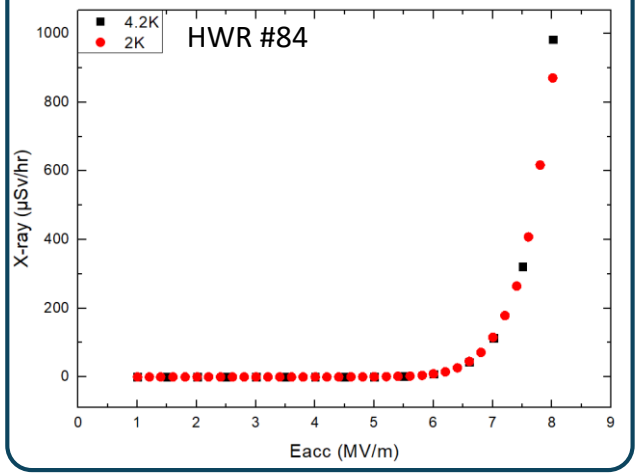
– Temperature dependence of FE-induced resistance

VT results at 4.2 K & 2 K

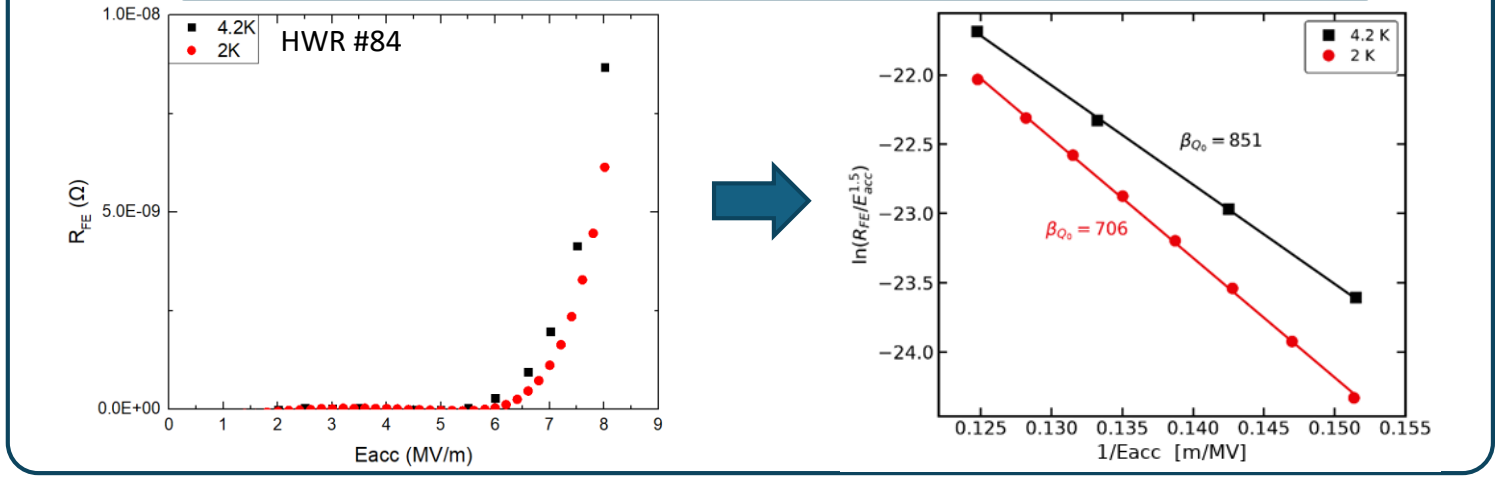


- 4.2 K and 2 K measurements were performed to analyze temperature-dependence characteristics.
- Most of the results show that the X-ray changes at 2 K due to FE conditioning.
- However, even with the same X-ray pattern, R_{FE} **and** β_{Q_0} **are larger at 4.2 K than 2 K.**
- It is suspected that FE causes additional BCS resistance at 4.2 K and **needs correction** for accurate FE analysis.

X-ray measurements



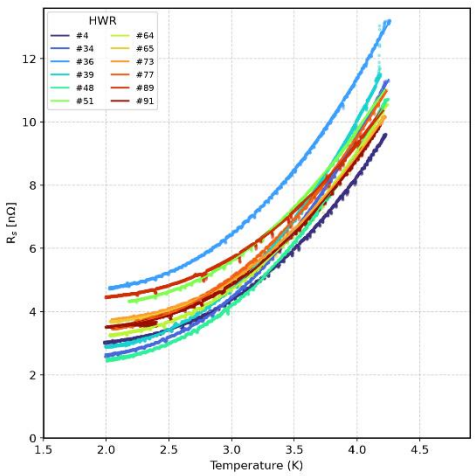
R_{FE} and β_{Q_0} at 4.2 K vs 2 K



3. Correction of 4.2 K data

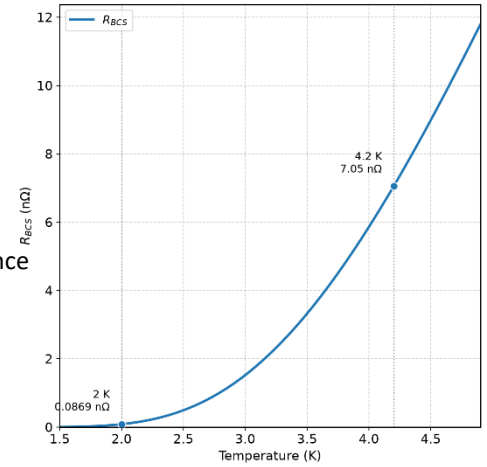
– Temperature sensitivity of BCS resistance

R_{BCS} and dR_{BCS}/dT



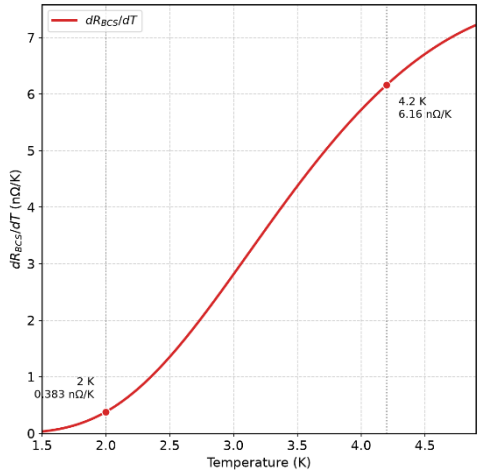
R_s vs T_b

calculate BCS resistance



Representative R_{BCS}

derivative



Derivative of R_{BCS}

$$R_{\mathrm{BCS}} \approx 2.7 \times 10^{-4} \left(\frac{f[\mathrm{MHz}]}{1500}\right)^2 \frac{1}{T_b} e^{\left(-\frac{\Delta}{k_B T_b}\right)}$$

- f is the resonance frequency of cavity
- T_b is helium bath temperature
- k_B is Boltzmann constant
- Δ is the energy gap of Nb (≈ 1.69 meV)

	R_{BCS}	dR_{BCS}/dT_b
2 K	0.09 nΩ	0.38 nΩ/K
4.2 K	7.05 nΩ	6.16 nΩ/K

- R_s was measured as a function of LHe bath temperature for 12 HWRs, from which R_{res} and R_{BCS} were calculated.
- The median R_{BCS} curve was chosen as the representative curve.
- It is confirmed that dR_{BCS}/dT_b is around 16 times higher at 4.2 K than at 2 K.
- Therefore, the same FE-induced temperature rise causes a much larger R_{BCS} increase at 4.2 K.

3. Correction of 4.2 K data
– Correction strategy

- $R_{\mathrm{FE}}(E;T_b)$ which is **considered additional BCS resistance originated from FE** can be expressed as follows,

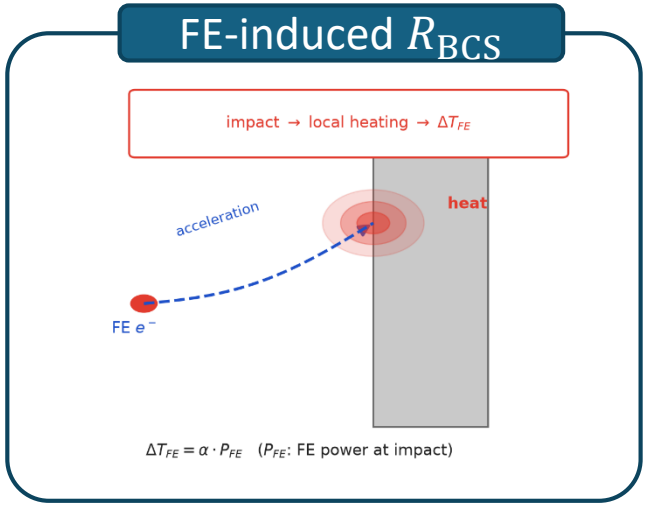
$$R_{\mathrm{FE}}(E;T_b) = \underbrace{R_{\mathrm{BCS}}\left(T_b + \Delta T_{\mathrm{FE}}(E)\right) - R_{\mathrm{BCS}}(T_b)}_{\Delta R_{\mathrm{BCS}}} + \underbrace{R_{\mathrm{FE}}(E)}_{\text{FE resistance}}$$

- As $R_{\mathrm{BCS}}(T_b)$ is less sensitive to temperature variation at 2 K, it can be assumed that $R_{\mathrm{BCS}}\left(2\ K + \Delta T_{\mathrm{FE}}(E)\right) \approx R_{\mathrm{BCS}}(2\ K)$.

Then $R_{FE}(E;2K\ ) \approx R_{FE}(E)$.

$$R_{\mathrm{FE}}\ (E;4.2\ K\ ) = R_{\mathrm{BCS}}(4.2\ K + \Delta T_{\mathrm{FE}}) - R_{\mathrm{BCS}}(4.2\ K) + R_{FE}(E) = R_{\mathrm{BCS}}(4.2\ K + \Delta T_{\mathrm{FE}}) - R_{\mathrm{BCS}}(4.2\ K) + R_{FE}(E;2\ K\ )$$

$$\boldsymbol{\Delta R_{\mathrm{BCS}}} = R_{\mathrm{FE}}\ (E;\ 4.2\ \mathrm{K}) - R_{\mathrm{FE}}\ (E;\ 2\ \mathrm{K}) = R_{\mathrm{BCS}}(4.2\ K + \Delta T_{\mathrm{FE}}) - \underbrace{R_{\mathrm{BCS}}(4.2\ K)}_{\approx 7.05\ \mathrm{n\Omega}}$$



- ΔT_{FE} is effective temperature rise caused by the impact of FE electrons.
- Effective thermal resistance α is defined as follows,

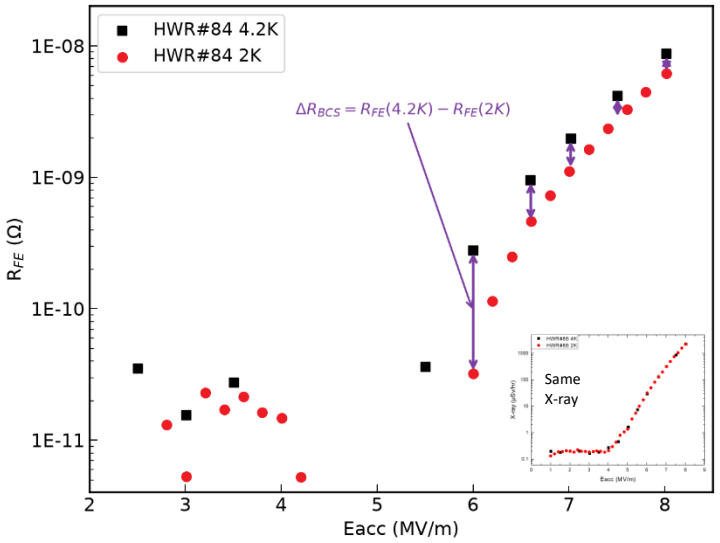
$$\Delta T_{\mathrm{FE}} = \alpha \cdot P_{\mathrm{FE}}(E) \rightarrow \boldsymbol{\alpha} \equiv {\Delta \boldsymbol{T_{FE}}}/{\boldsymbol{P_{FE}(E)}}\ [{K}/{W}] \quad ,[\boldsymbol{P_{\mathrm{FE}}} = \frac{(E_{\mathrm{acc}} L_{\mathrm{eff}})^2}{\left({R}/{Q}\right)G}\boldsymbol{R_{\mathrm{FE}}}]$$

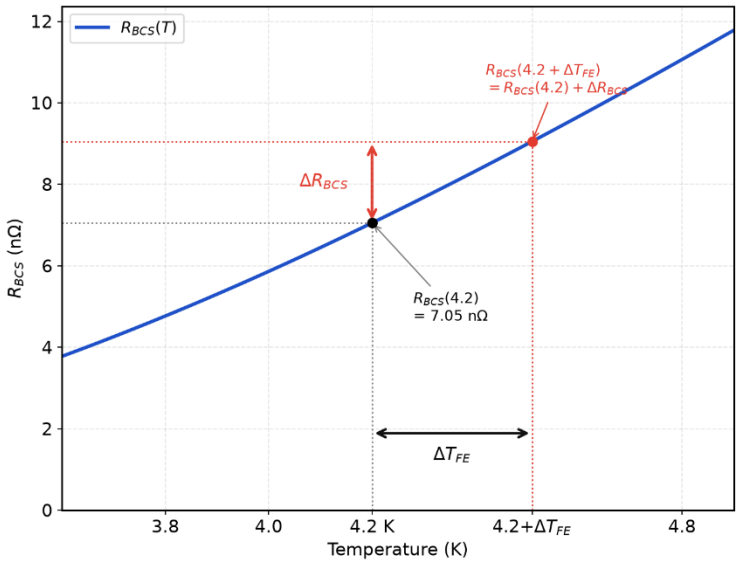
- α can indicate **how strongly a given field-emission heating warms** the RF surface, giving a temperature rise
- Using α, FE-induced BCS resistance $\boldsymbol{\Delta R_{\mathrm{BCS}}}$ is calculated and used to correct the 4.2 K data

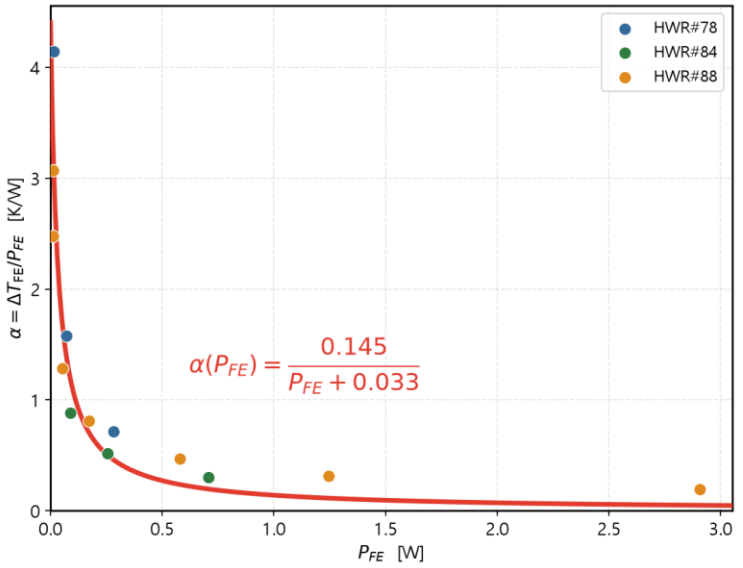
3. Correction of 4.2 K data

– Obtaining the thermal resistance α

Process for obtaining $\alpha(P_{\mathrm{FE}})$ curve







- α is obtained for 3 HWR cavities that have the same X-ray pattern at 4.2 K and 2 K (same X-ray → same P_{FE}).
- Converting ΔR_{BCS} to ΔT_{FE} through the $R_{\mathrm{BCS}}(T)$ curve gives $\boldsymbol{\alpha = {}^{\Delta T_{FE}}/_{P_{FE}(E)}}$ at each field point, and fitting these yields an empirical curve $\alpha(P_{\mathrm{FE}}) = \frac{0.145}{P_{\mathrm{FE}}+0.033}$.
- Other 4.2 K data that have a **different X-ray pattern from 2 K** are corrected by numerically calculating the following relation:

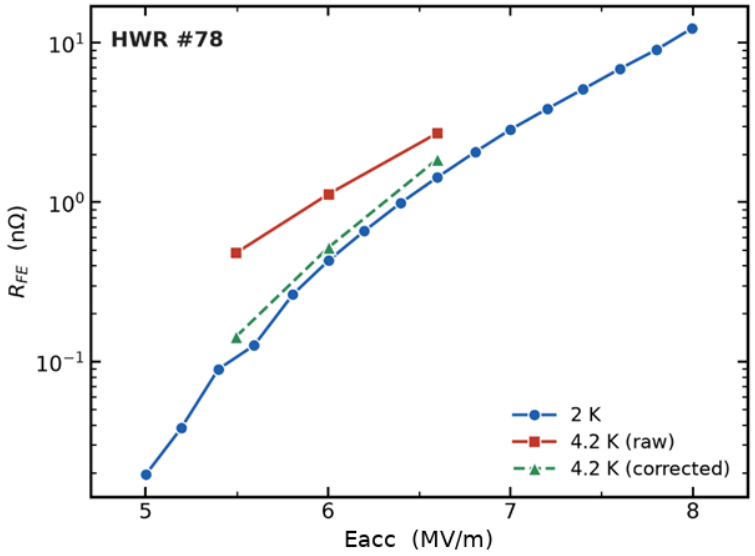
$$R_{\mathrm{FE}}(E; 4.2K) = \boldsymbol{R_{\mathrm{FE}}(E)} + R_{BCS}\left(4.2\ K + \frac{0.145}{P_{\mathrm{FE}} + 0.033} \cdot P_{\mathrm{FE}}\ (E)\right) - R_{\mathrm{BCS}}(4.2K)$$

Obtaining R_{FE} from 4.2 K data

3. Correction of 4.2 K data

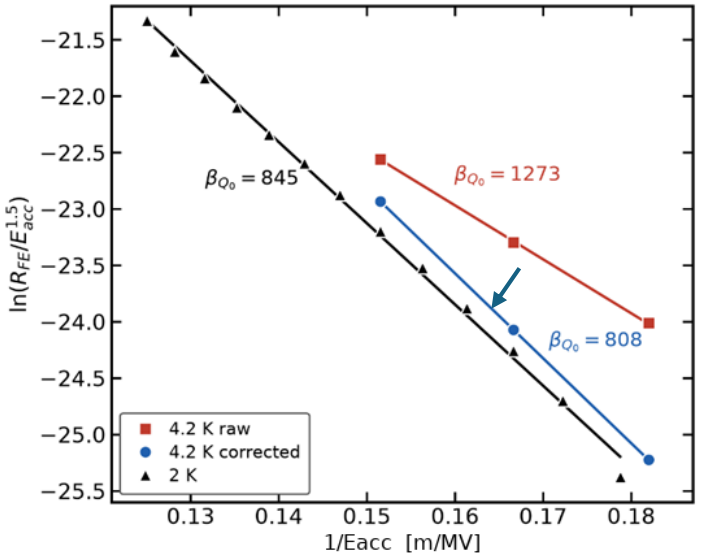
– Correction results (30 HWR cavities)

Correction results



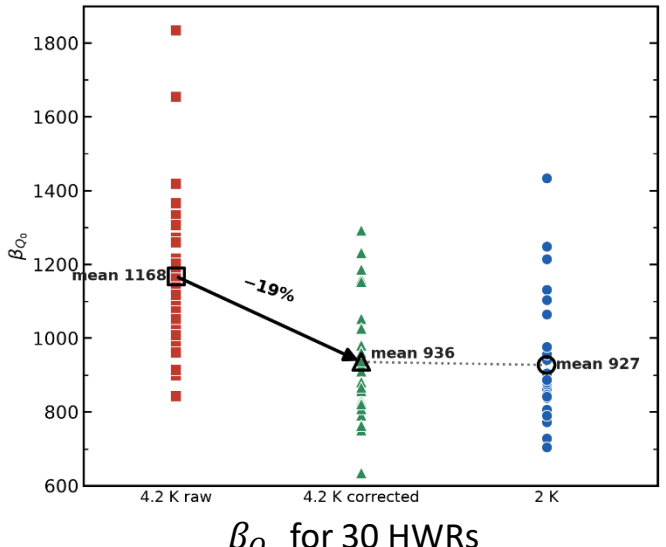
R_{FE} correction for HWR #78

FN plot



β_{Q_0} re-extraction (corrected 4.2 K ≈ 2 K)

30 HWRs



β_{Q_0} for 30 HWRs
(corrected 4.2 K mean ≈ 2 K mean)

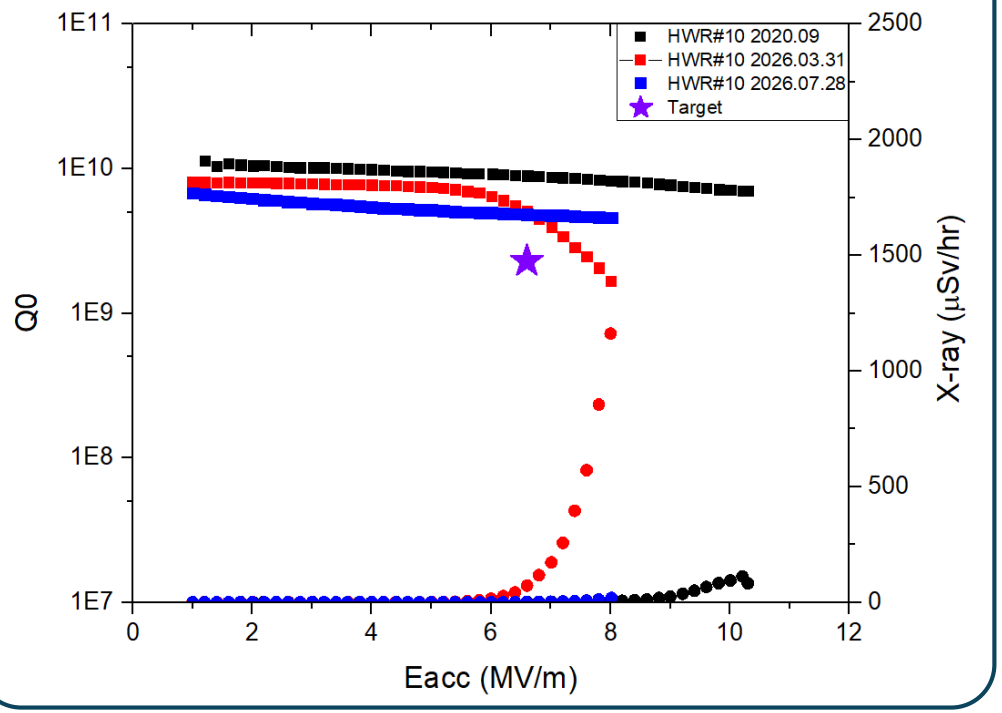
- Using the effective thermal resistance α, the FE-induced BCS resistance is removed and β_{Q_0} is re-extracted from the FN plot.
- For HWR #78, the 4.2 K β_{Q_0} decreases from 1273 (raw) to 809 (corrected), approaching the 2 K value of 812.
- Over all 30 HWR cavities, the mean 4.2 K β_{Q_0} decreases by ~19 % (1168 → 936), in good agreement with the 2 K mean (927).

4. Conclusion

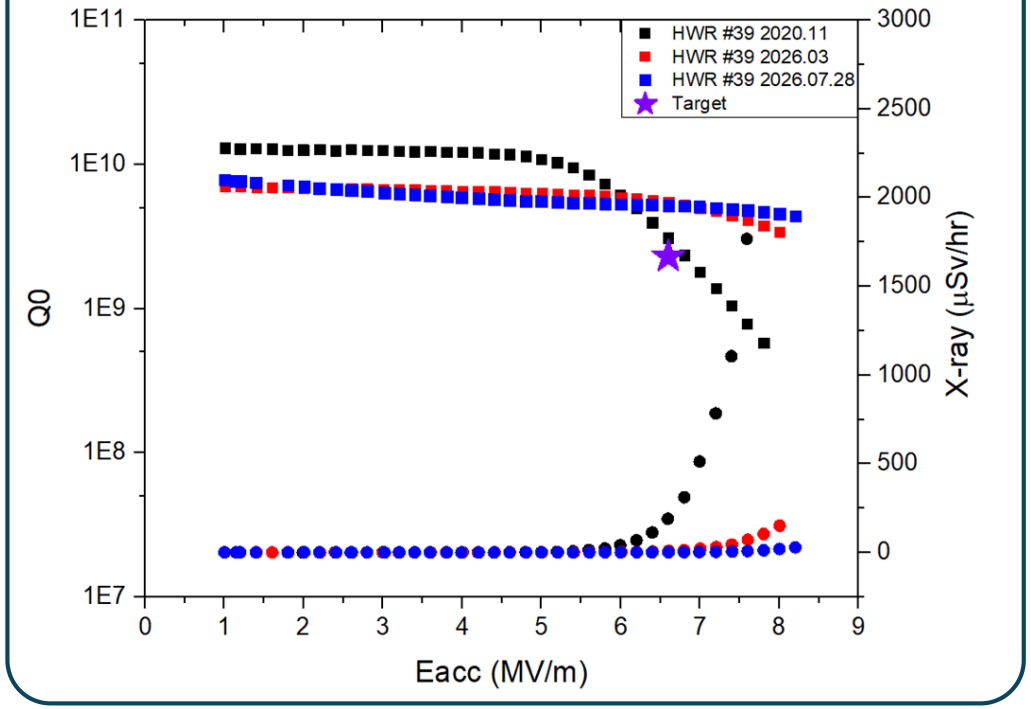
- At 4.2 K, the Q_0 -based field enhancement factor β_{Q_0} is overestimated: FE heating raises the RF-surface temperature and adds an extra BCS contribution.
- An effective thermal resistance $\alpha = {}^{\Delta T_{FE}}/_{P_{FE}(E)}$ was introduced to quantify this temperature rise and remove the FE-induced BCS resistance.
- Applied to 30 HWR cavities, the correction lowered the 4.2 K β_{Q_0} by ~19 % on average (1168 → 936), good agreement with the 2 K results (927).
- This enables reliable FE analysis from 4.2 K VT data.

5. Recent VT results of HWR cavities

HWR #10



HWR #39



- The upgrade process for the HWR cryomodule is ongoing.
- Two HWR cavities were re-tested after an improved surface treatment process (DI water, HPR, etc.).
- FE was mitigated, and improved performance was confirmed.

Thank you for your attention!

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