Two different origins of Q-slope problem in Nb film cavity for HIE-ISOLDE

A. Miyazaki[1,2] W. Venturini Delsolaro[1]

[1] *Organisation européenne pour la recherche nucléaire* (CERN), Switzerland

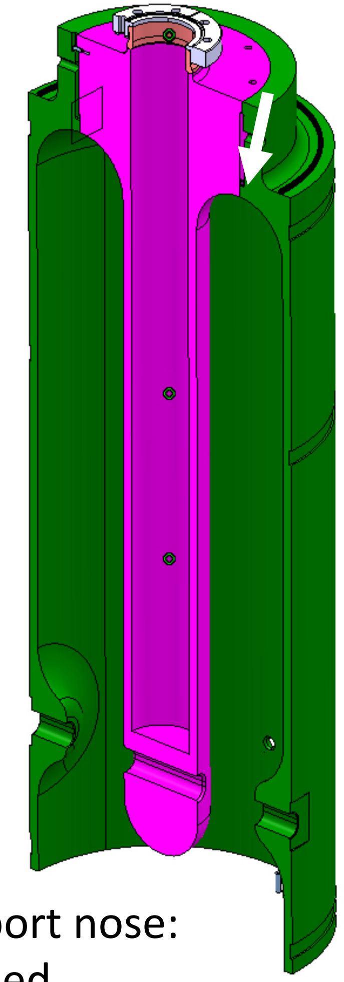
[2] *School of Physics and Astronomy, the University of Manchester, UK*

Email: Akira.Miyazaki@cern.ch

ThinFilm Workshop 2018 @ Legnaro

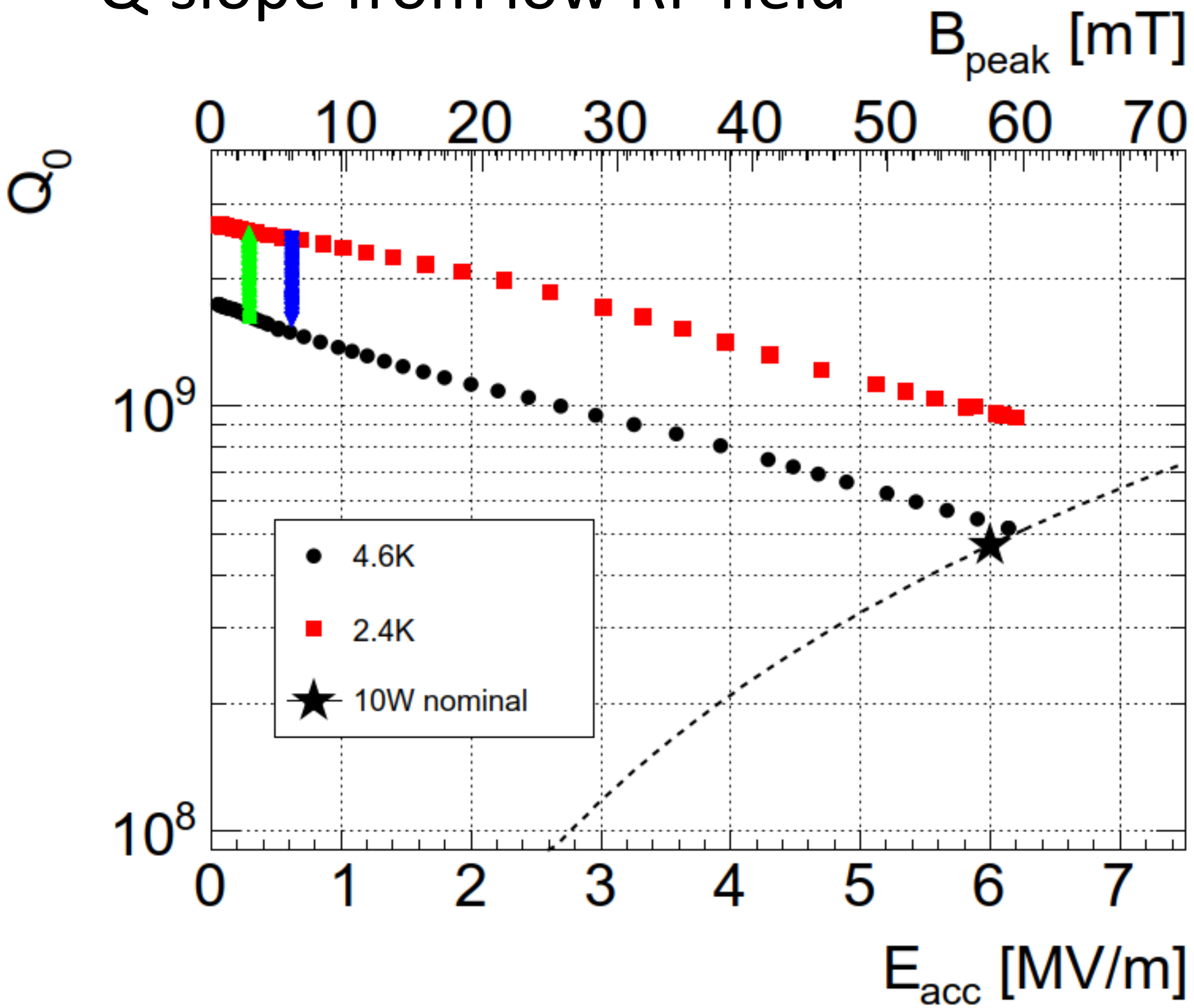
HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

Series production: machined
+ **one** welding



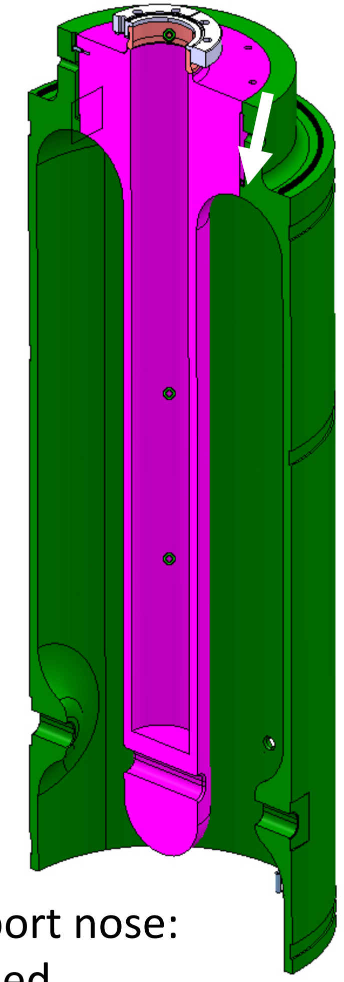
Beam port nose:
Machined

The **typical** Q-slope in Nb/Cu cavities
Q-slope from low RF field



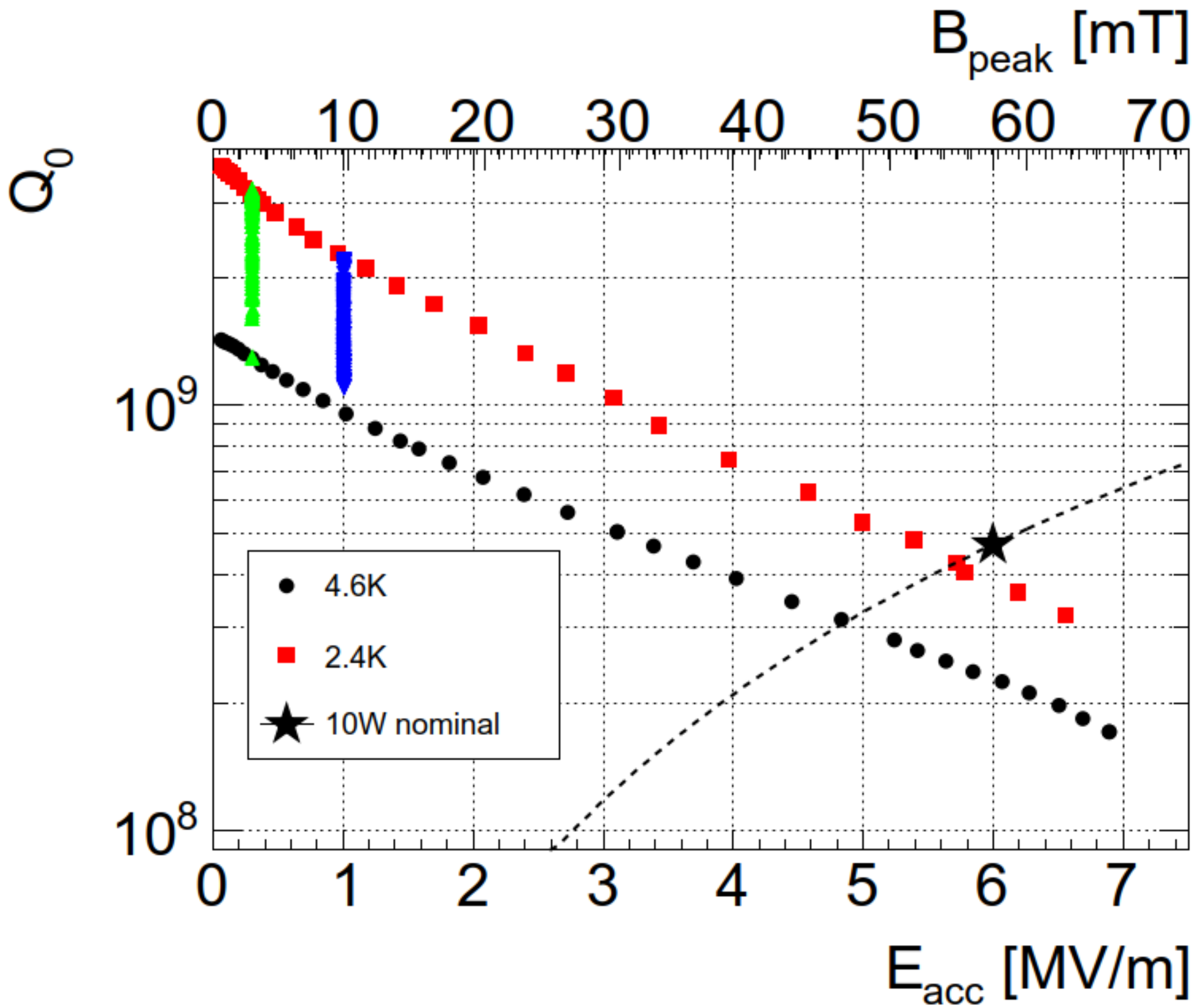
HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

Series production: machined + **one** welding



Beam port nose: Machined

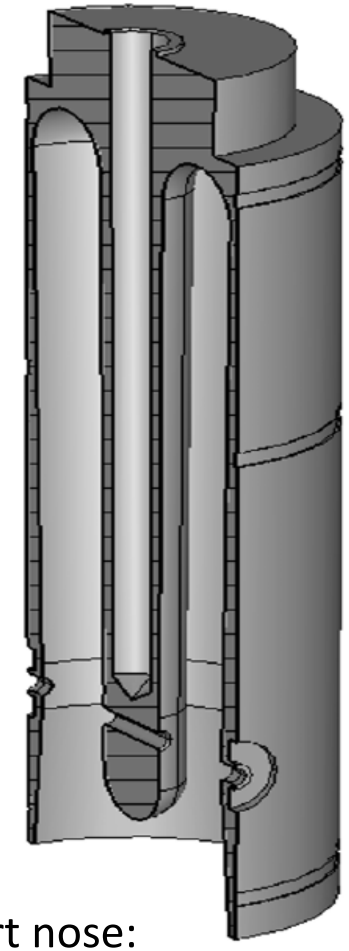
The worst cavity in the production



HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

New design: fully machined

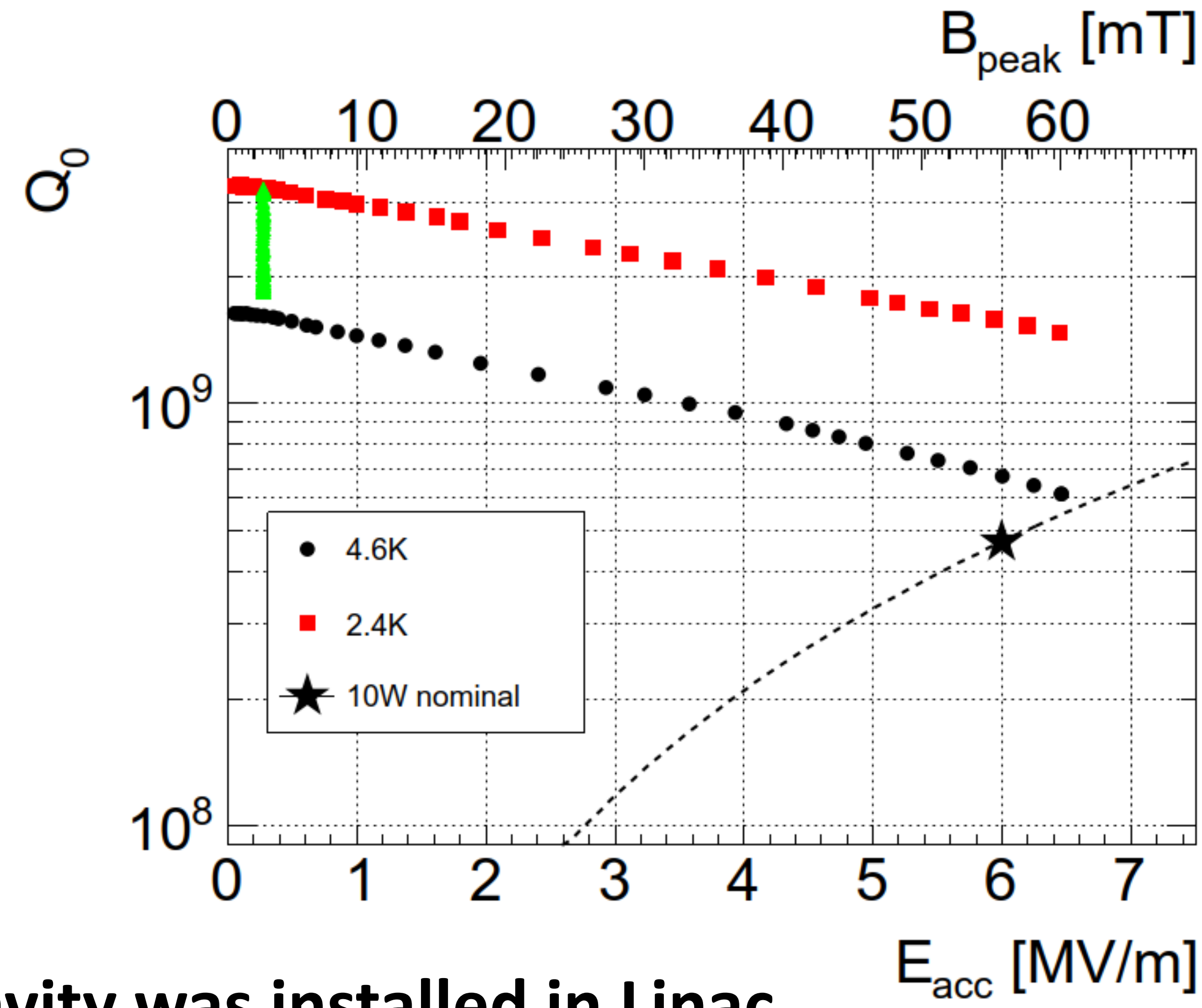
+ no welding



Seamless cavity

Beam port nose:
Removed (conical wall)

1st cavity: good but no big surprise

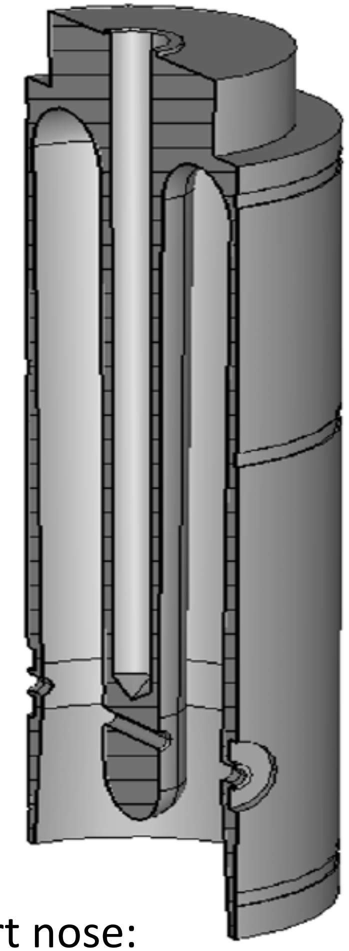


This cavity was installed in Linac

HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

New design: fully machined

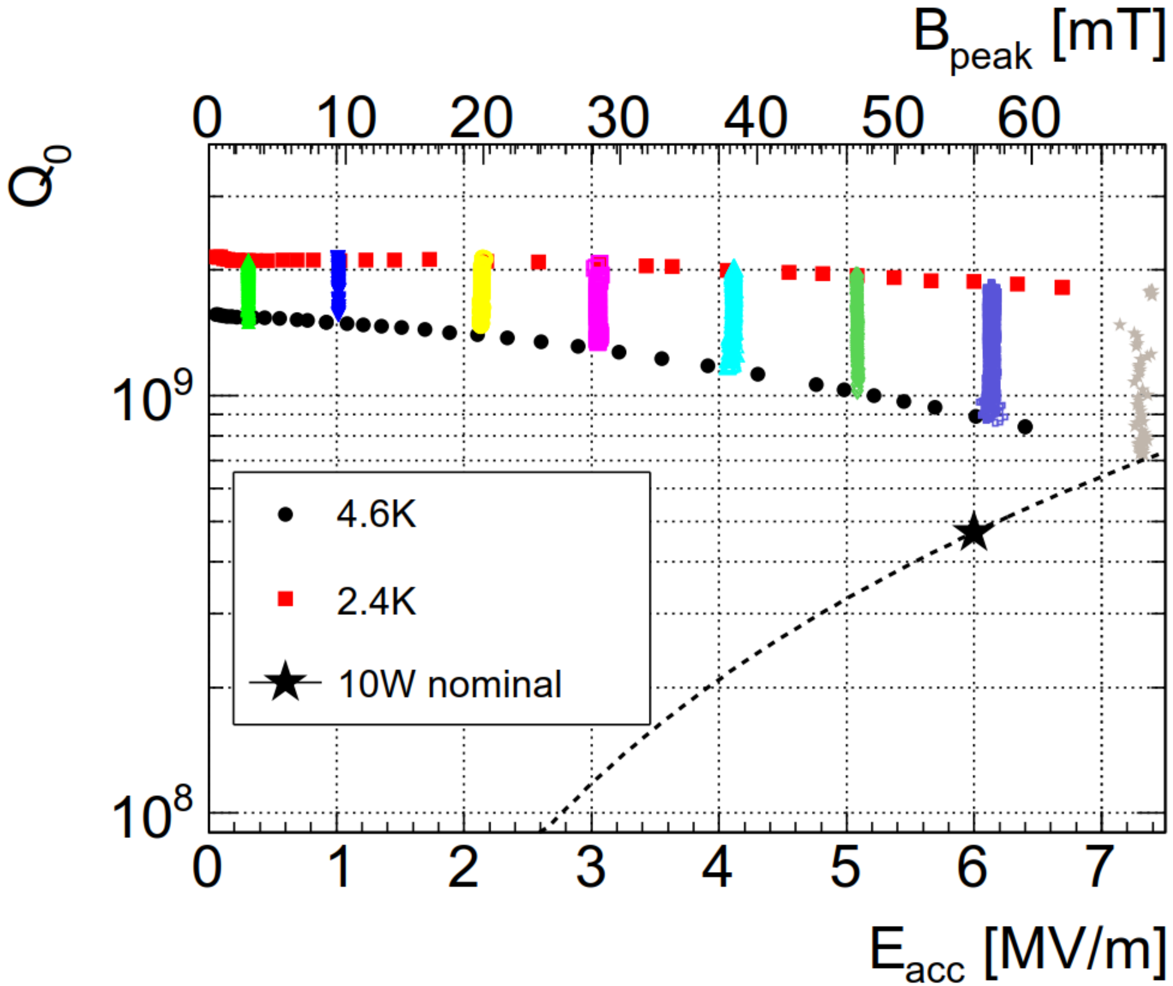
+ no welding



Seamless cavity

Beam port nose:
Removed (conical wall)

2nd cavity with reduced B-field (fully trapped)

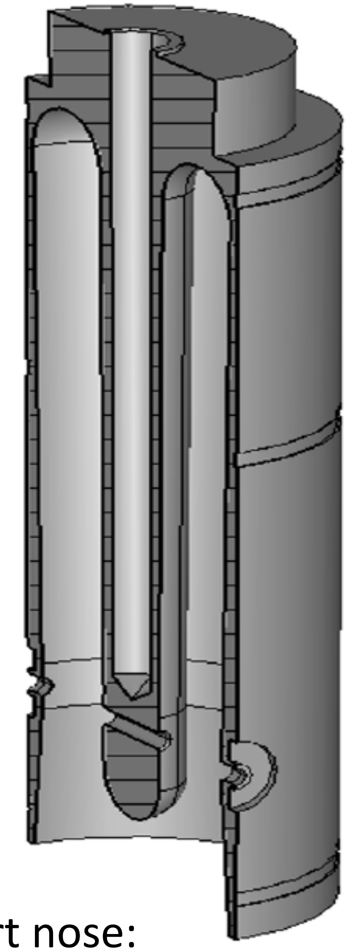


Surprisingly, Q-slope at 2.4K disappeared

HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

New design: fully machined

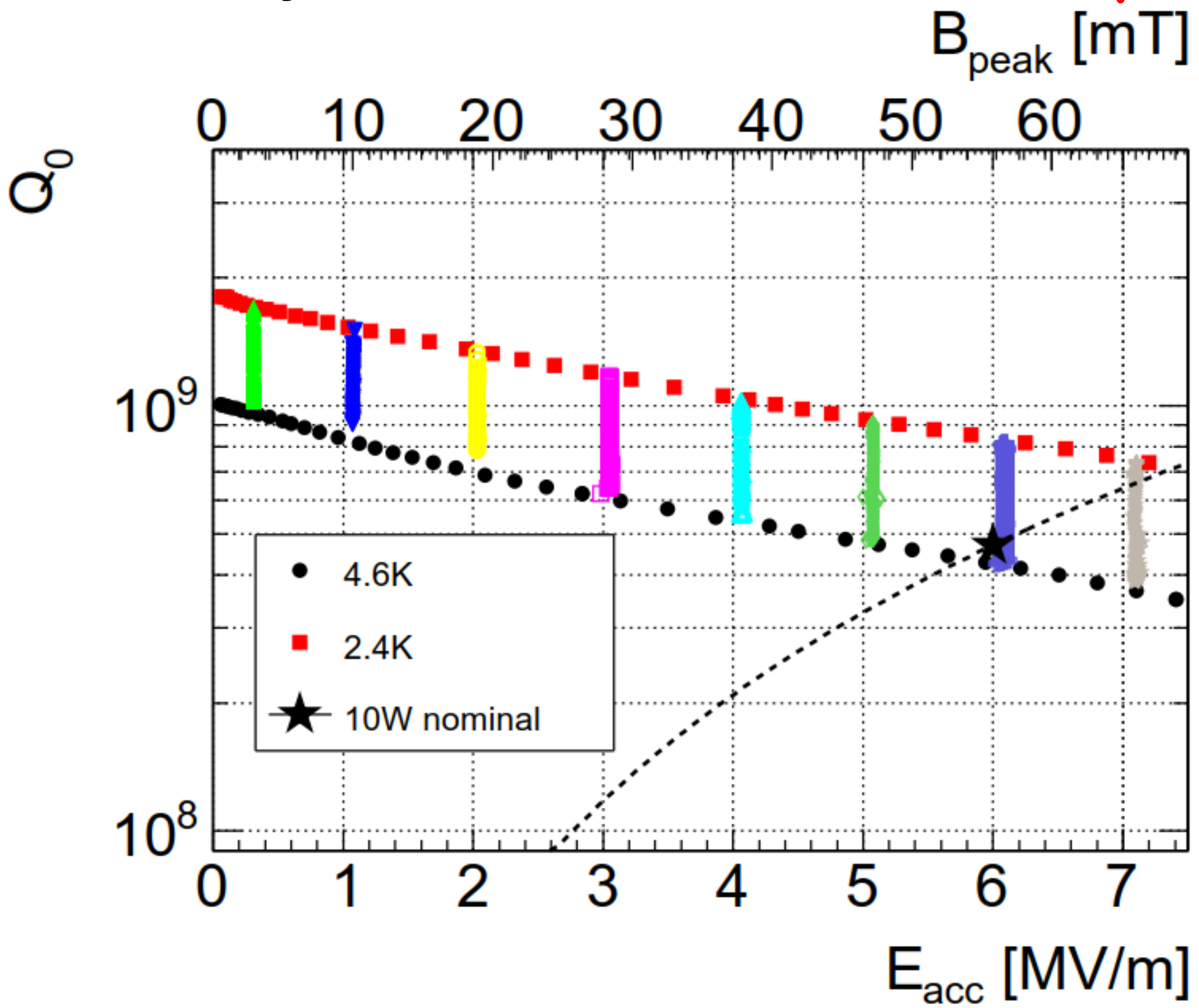
+ no welding



Seamless cavity

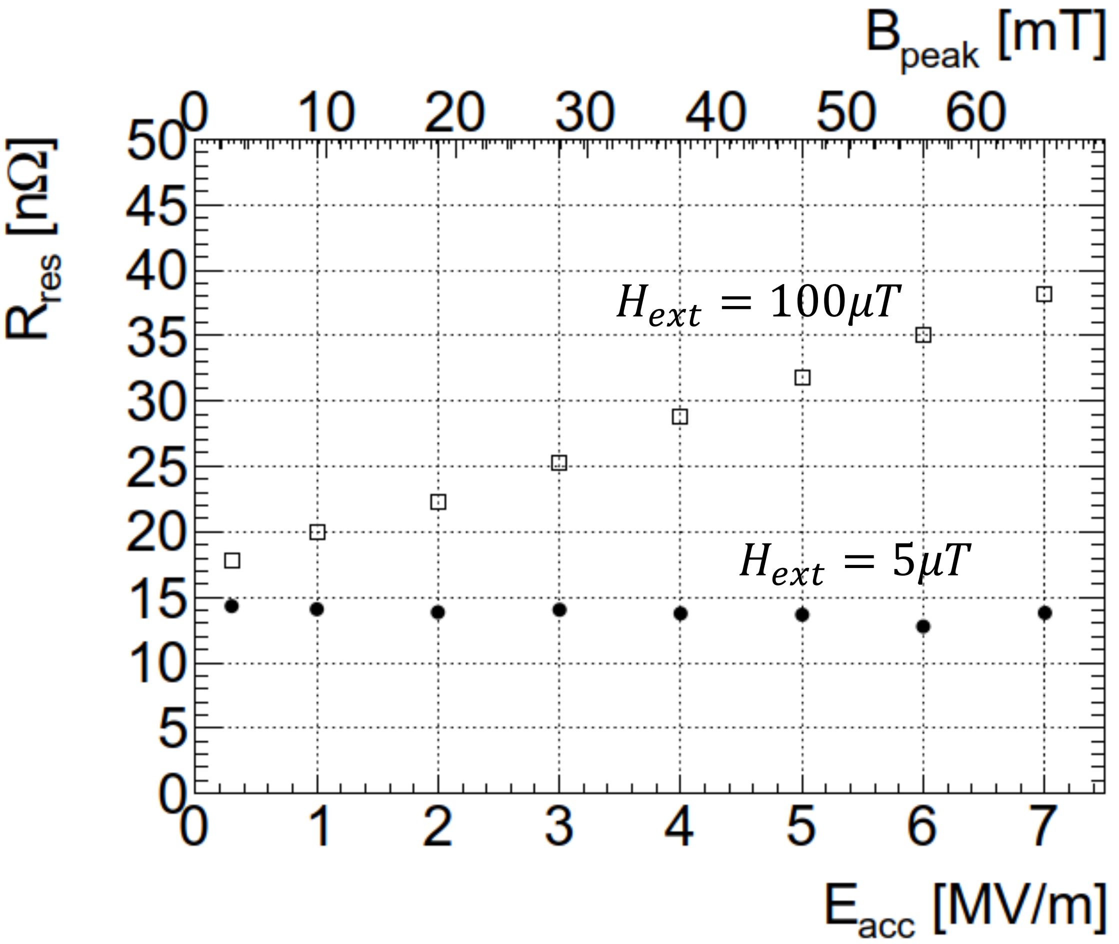
Beam port nose:
Removed (conical wall)

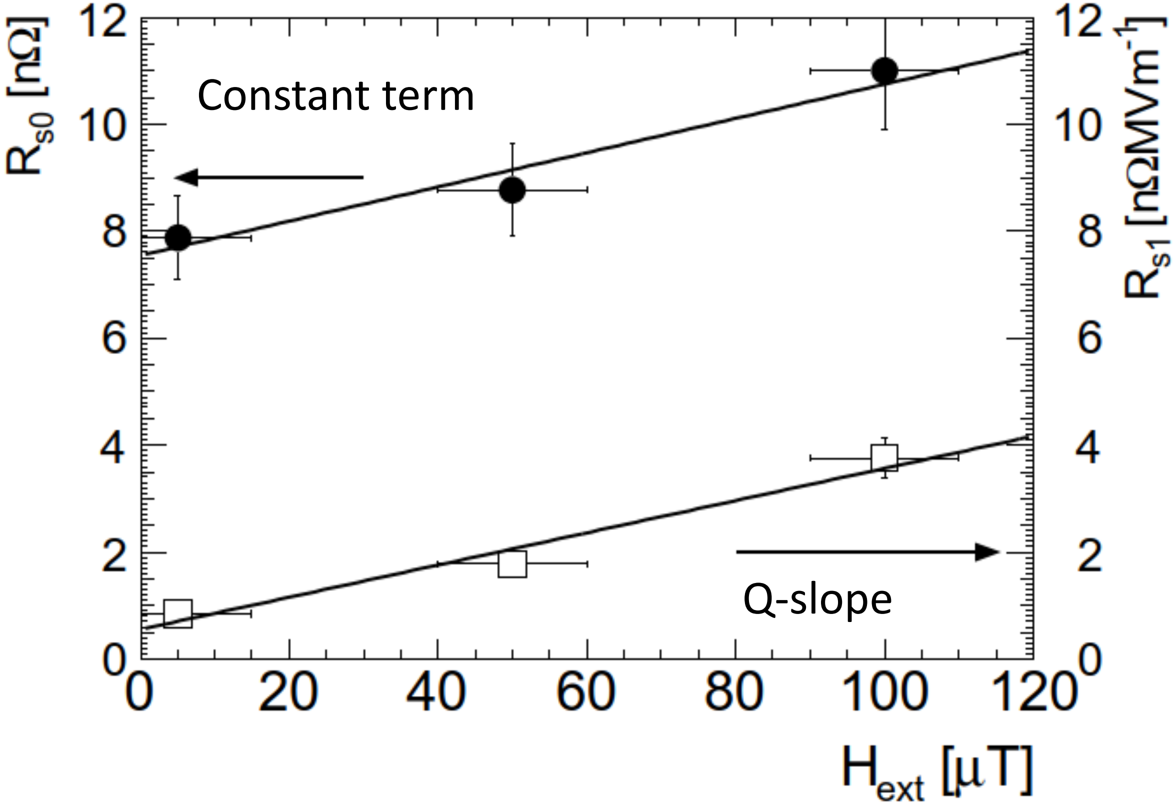
2^{nd} cavity with enhanced B-field 100μT (fully trapped)



→ The origin of Q-slope at 2.4K (R_{res}) is trapped flux

Trapped flux effect in residual resistance $R_{res}(E)$





$$
\begin{aligned}
R_{\mathrm{res}} &= R_{\mathrm{fl}}(E_{\mathrm{acc}}, H_{\mathrm{ext}}) + R_{\mathrm{res},0} \\
&= [R_{\mathrm{fl},0} + R_{\mathrm{fl},1} \times E_{\mathrm{acc}}] \times H_{\mathrm{ext}} + R_{\mathrm{res},0}
\end{aligned}
$$

Vortex oscillation model (Bardeen-Stephen)

$$M\frac{d^2\boldsymbol{x}}{dt^2} + f_t + f_d + f_p = \phi J_0 e^{i\omega t}$$

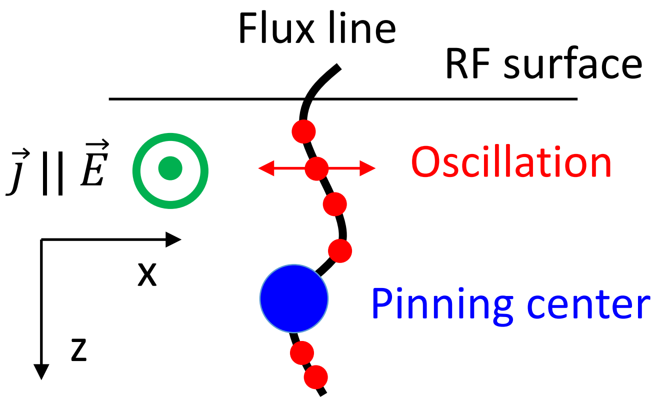
Effective mass

Vortex tension

Power dissipation

pinning force

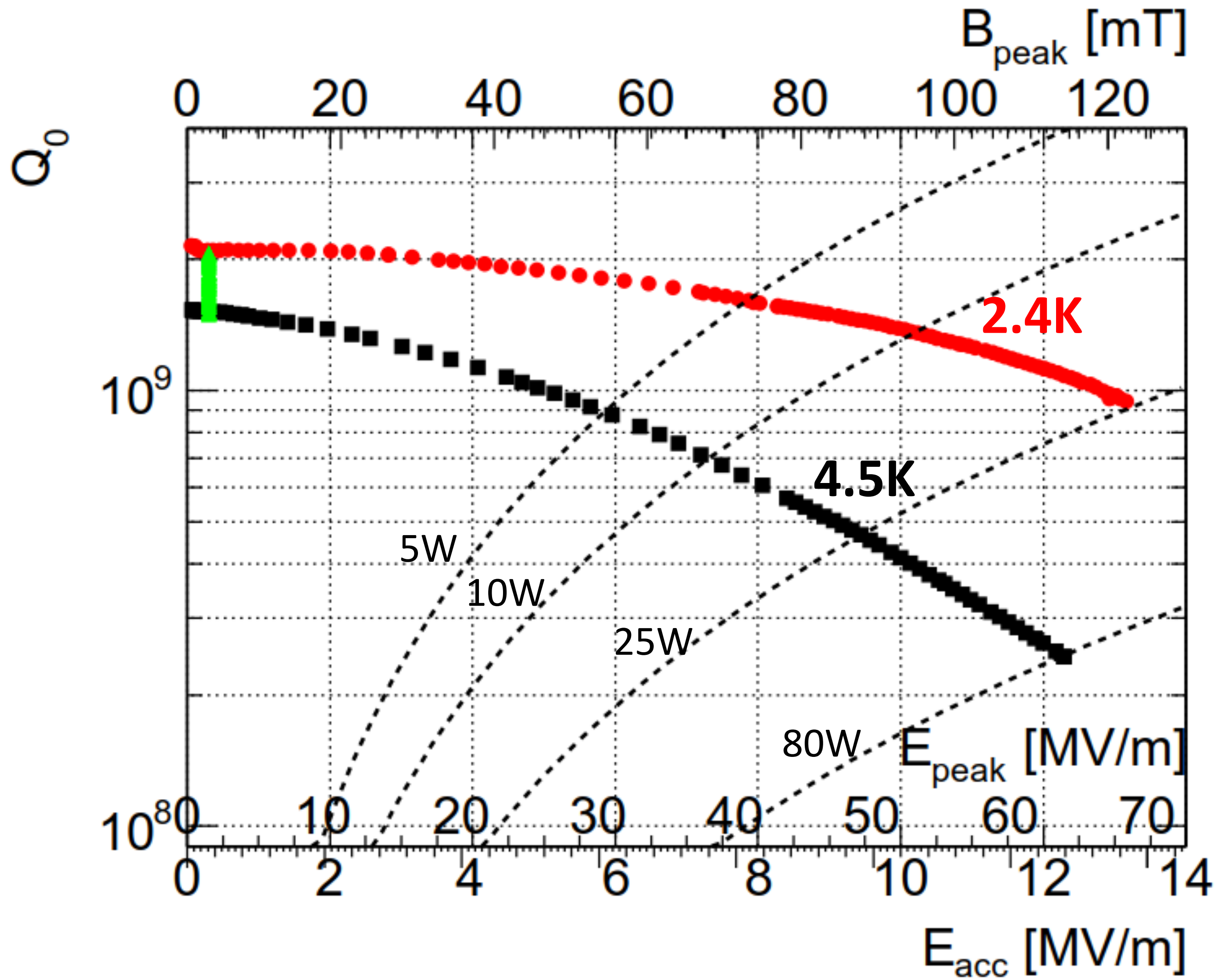
Lorentz force



- Conventional models: linearized forces
  → Constant resistance $R_{fl,0}H_{ext}$ and no prediction on $R_{fl,1}H_{ext}E_{acc}$
- Thermal instability? Non-linear effect??
- Collective pinning model (D. Liarte et al **arXiv:1808.01293**), non-linear pinning potential (see Ruggero's talk **arXiv:1810.00540**)

You are welcome to WG3 in TTC/ARIES topical workshop on flux trapping and magnetic shielding @ CERN 8-9 Nov 2018

Trapped flux effect can be removed by magnetic shielding



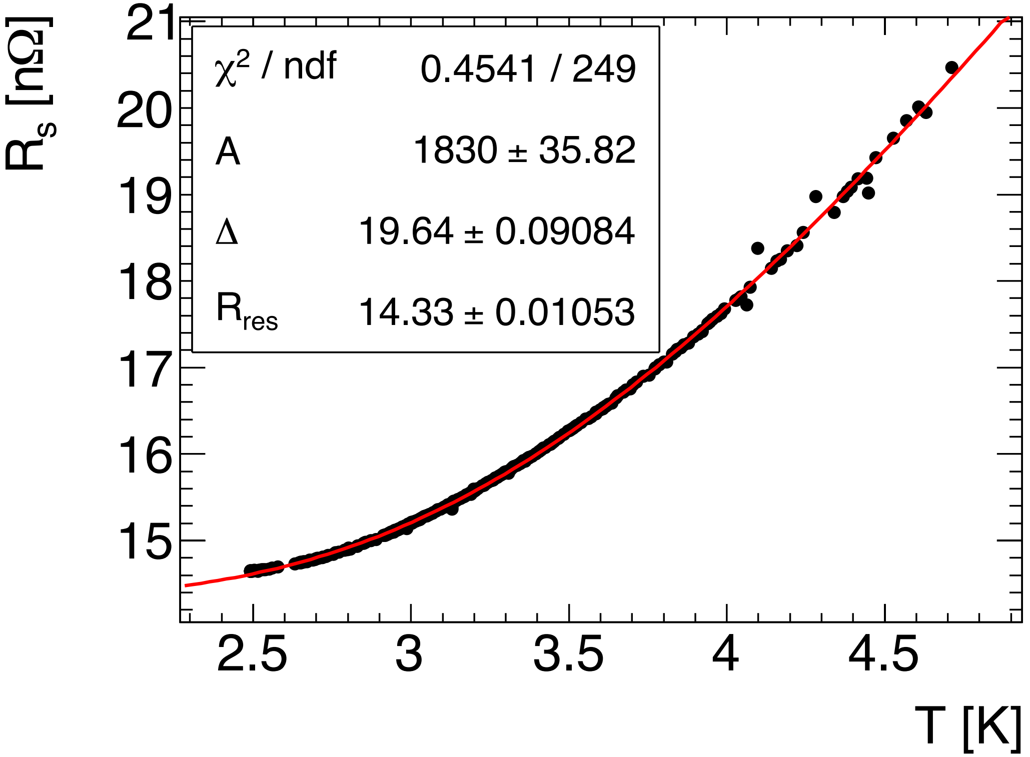
Another Q-slope appears **by temperature**: Medium-field Q-slope

→ Conventionally explained by non-linear BCS + thermal feedback

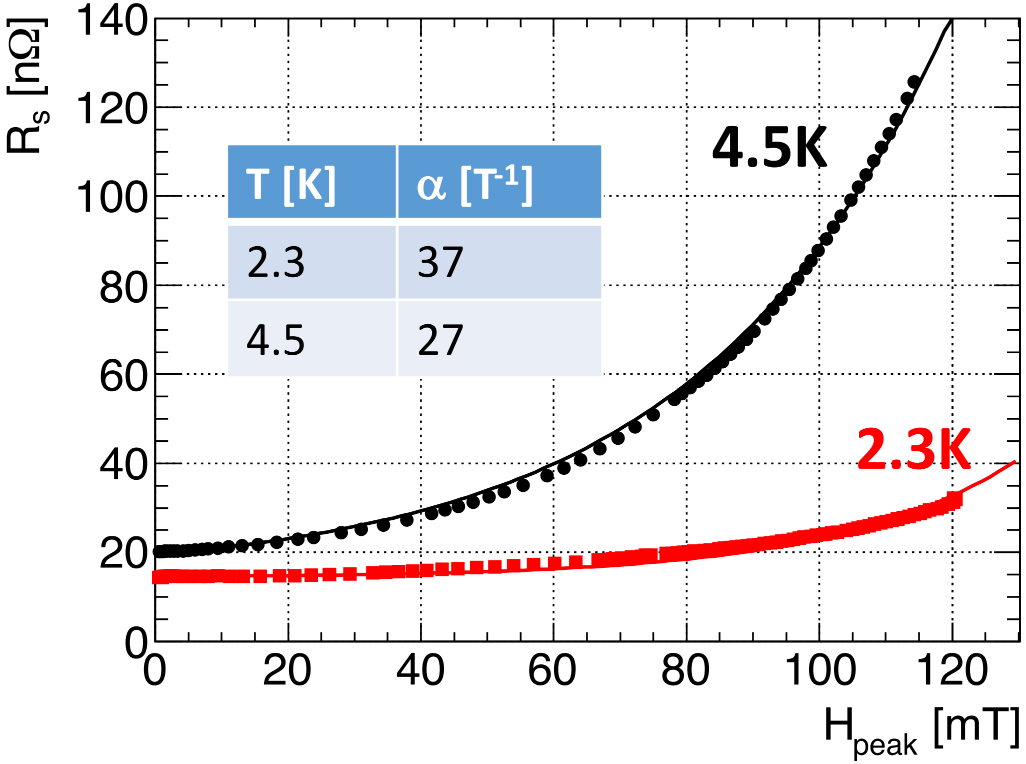
An empirically found formula to fit the data

$$R_s(T,B) = \frac{A}{T}\exp\left(-\frac{\Delta}{k_B T} + \alpha B\right) + R_{res}$$

(A, Δ, R_{res}) from Rs vs T data



Fit Rs vs H and determine α

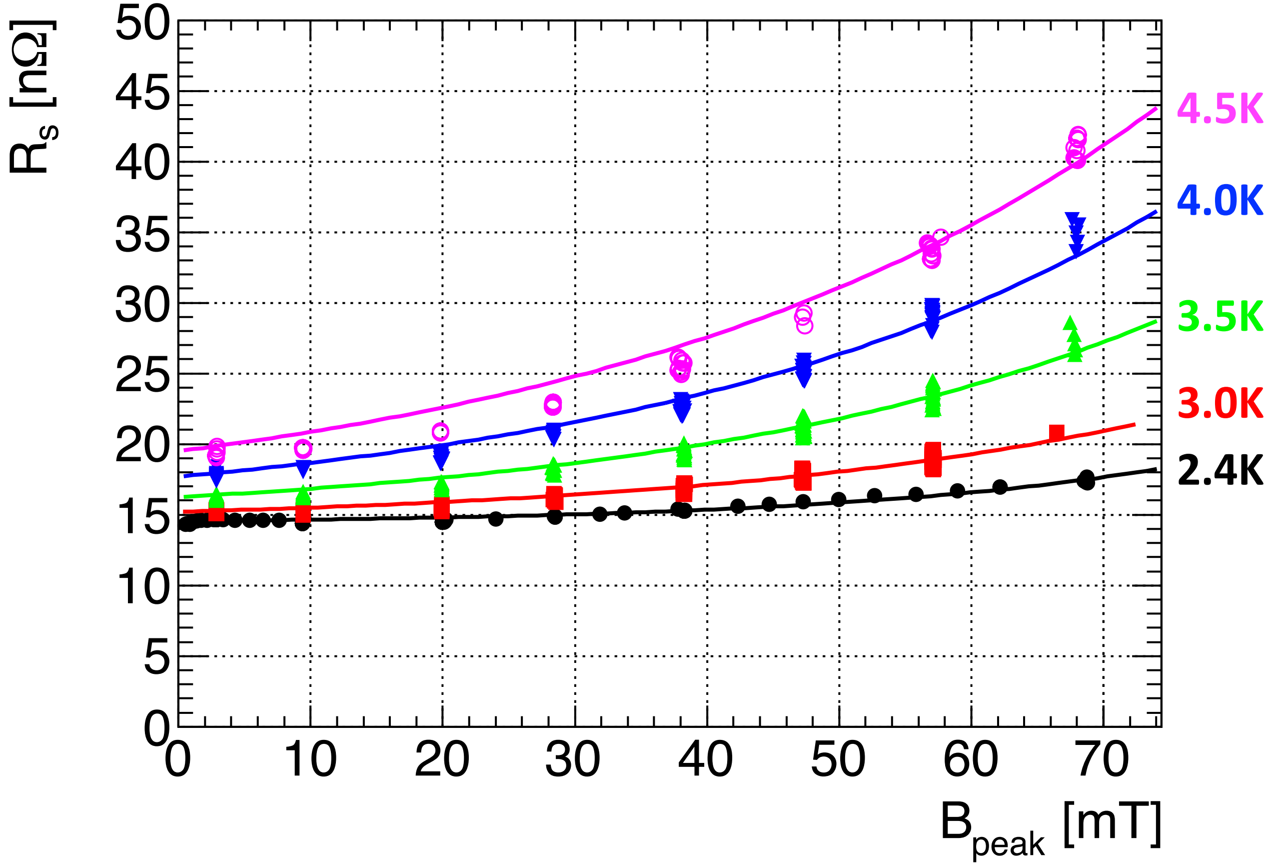


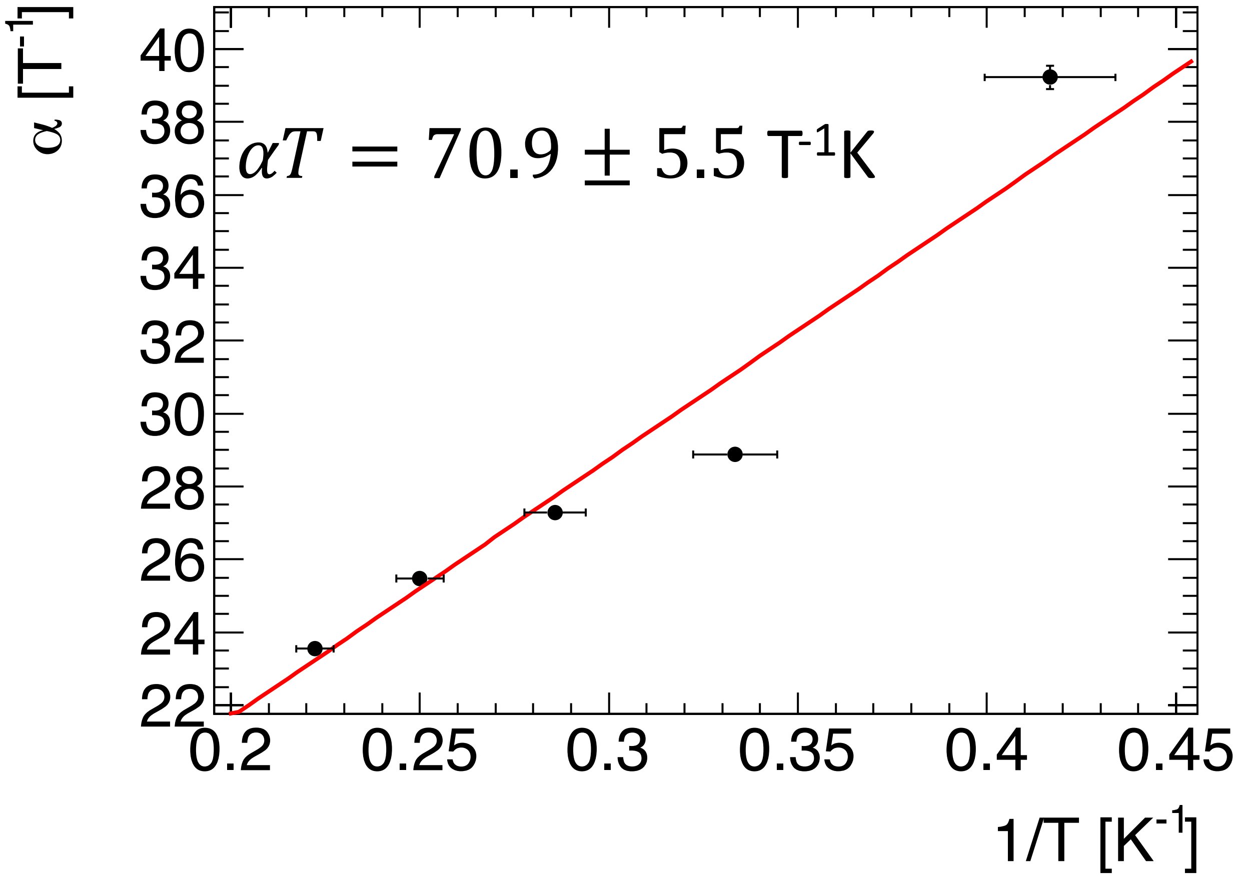
T [K]	α [T^{-1}]
2.3	37
4.5	27

Such an exponential dependence has been reported by others (bulk Nb and Nb/Cu)

1. R. L. Geng (Cornell) ”Thermal analysis of a 200MHz Nb/Cu cavity” SRF2001
2. D. Longuevergne (IPNO) ”Magnetic dependence of the enegy gap:…” SRF2013

Temperature dependence of α





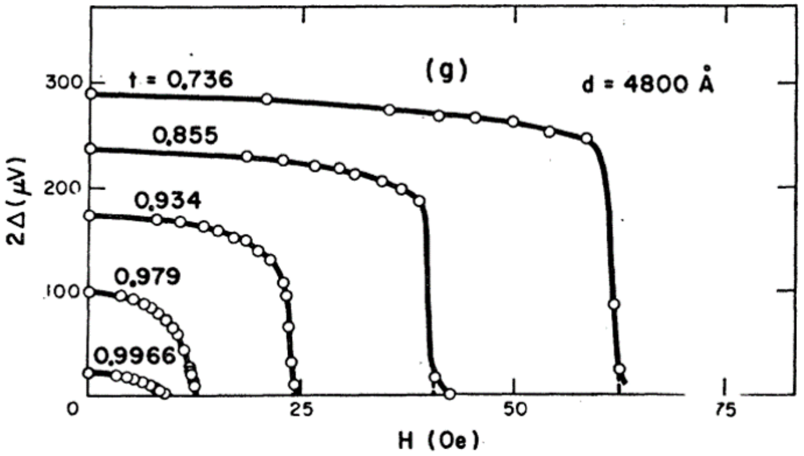
$\alpha \propto T^{-1}$ from the data → change the parameter by $\alpha = M/k_B T$

$$R_s(T,B) = \frac{A}{T}\exp\left(-\frac{\Delta}{k_B T} + \frac{MB}{k_B T}\right) + R_{res} \rightarrow R_s(T,B) = \frac{A}{T}\exp\left(-\frac{\boxed{\Delta - MB}}{k_B T}\right) + R_{res}$$

This new constant M has a dimension of magnetic moment [JT^{-1}]

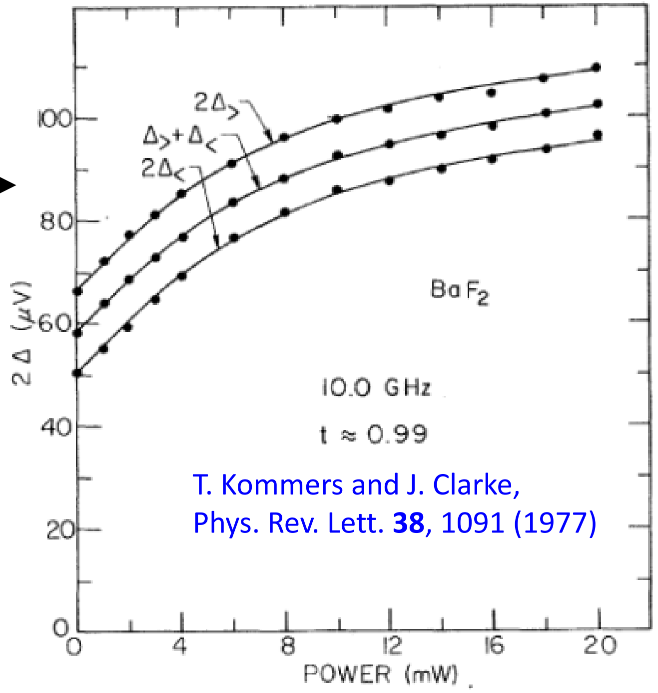
About gap reduction: two different scenarios

At low temperature, gap reduction by DC magnetic field is linear $\Delta = \Delta_0 - MB_{DC}$



High frequency low power

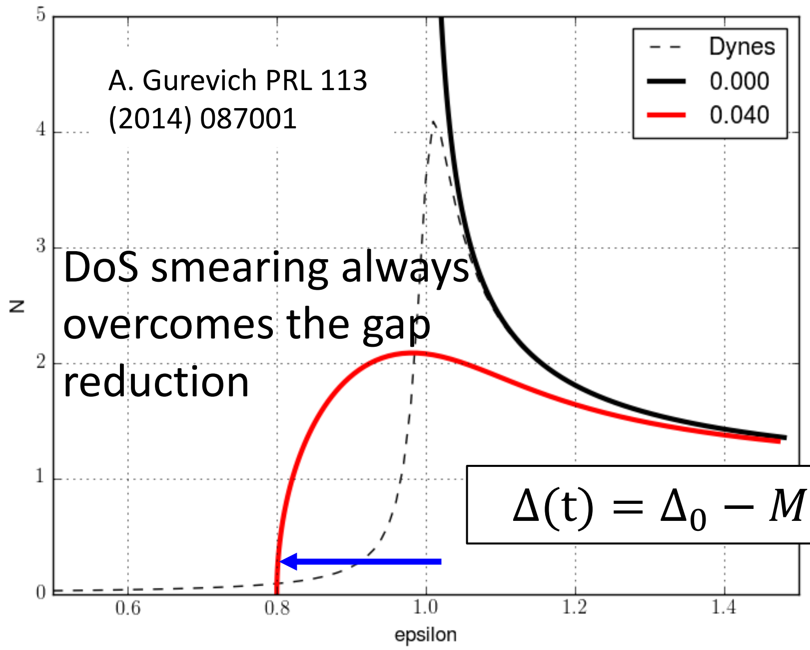
Eliashberg's model showed effective gap increase by RF magnetic field



T. Kommers and J. Clarke, Phys. Rev. Lett. **38**, 1091 (1977)

$\Delta \uparrow$

10 GHz
20mW



A. Gurevich PRL 113 (2014) 087001

DoS smearing always overcomes the gap reduction

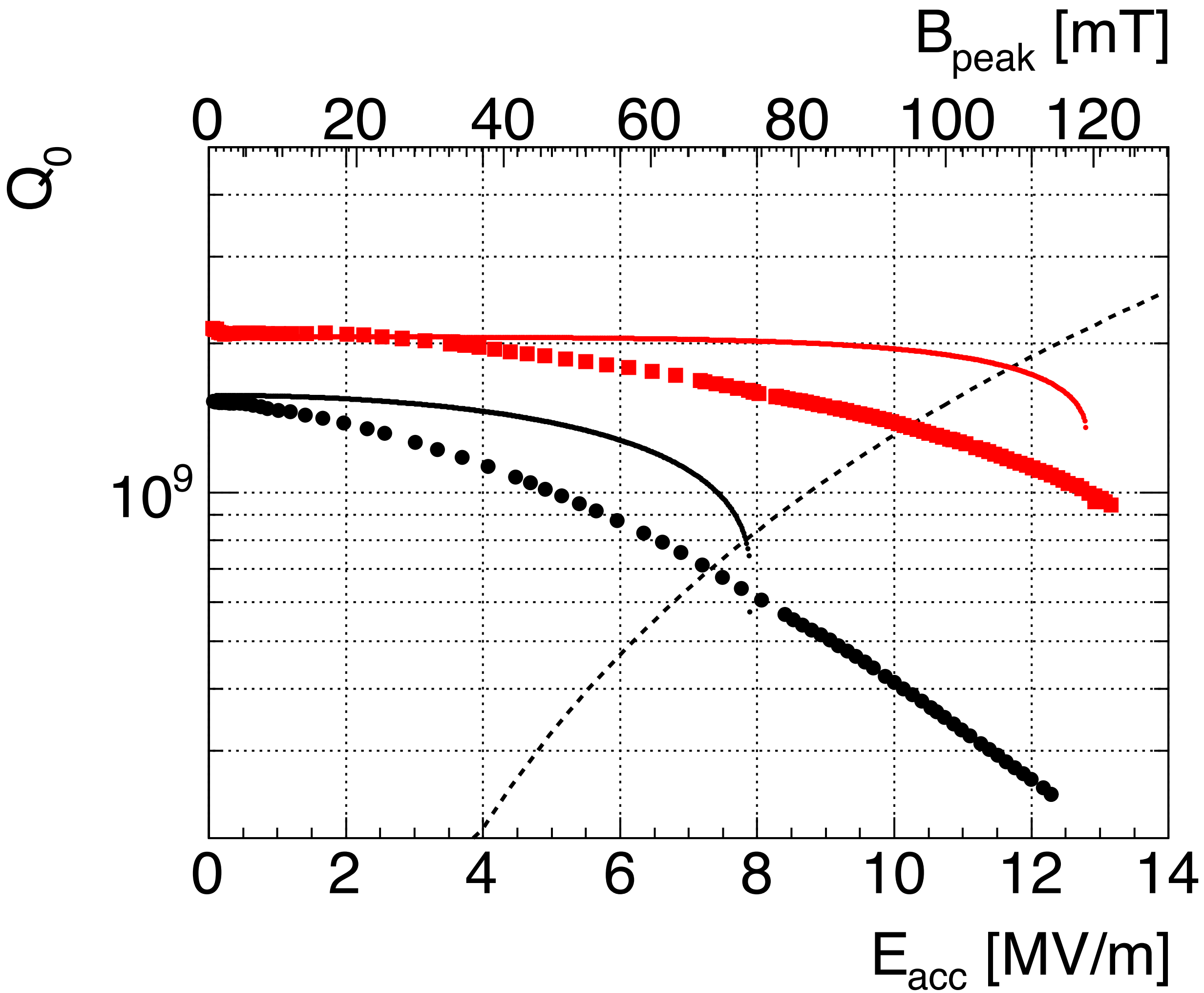
$$\Delta(t) = \Delta_0 - MB_0|\sin(\omega t)|$$

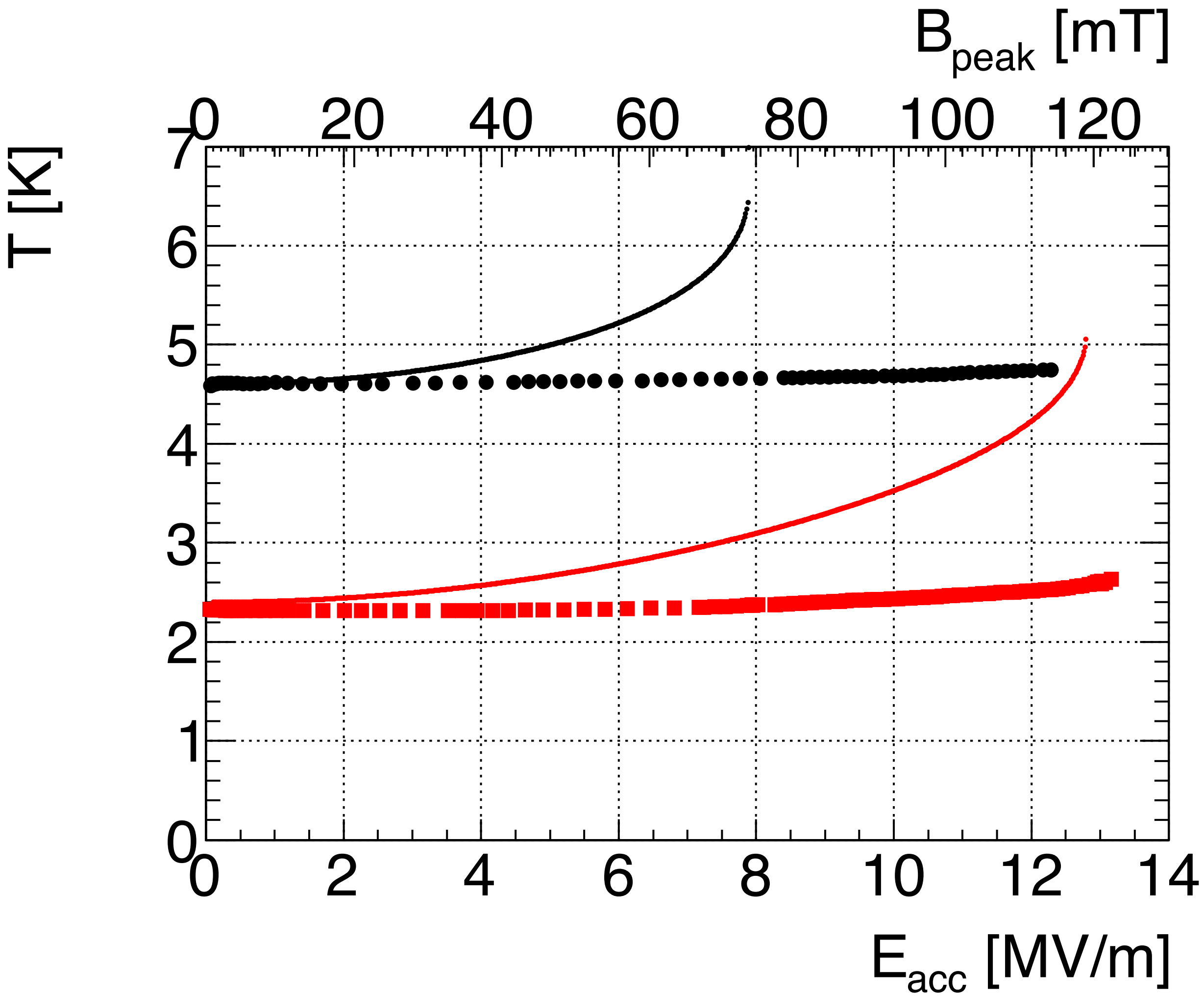
My questions

1. Can we extend different theory (DC or low-power high-frequency) to SRF physics?
2. What determines Q-slope or anti-Q-slope?

Global thermal feedback model

Manually adjust the thermal resistance R_B to get reasonable $R_s^{FB}(T_0, H, R_B)$





This model never explains this Q-slope and its T-dependence

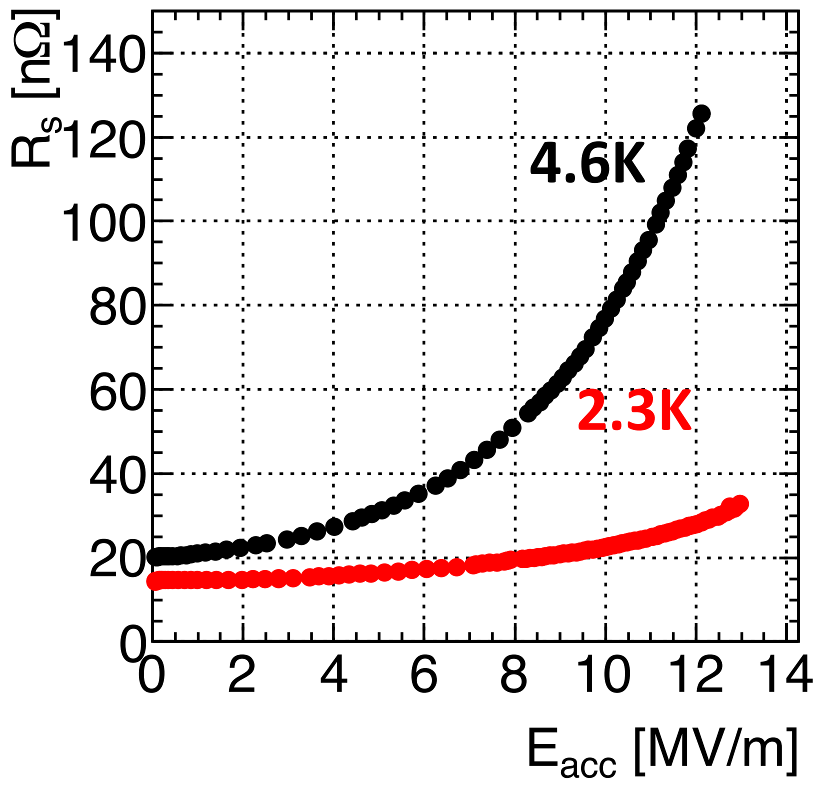
Vaglio-Palmieri model

V. Palmieri and R. Vaglio, Supercond. Sci. Technol, **29** ,015004 (2016)

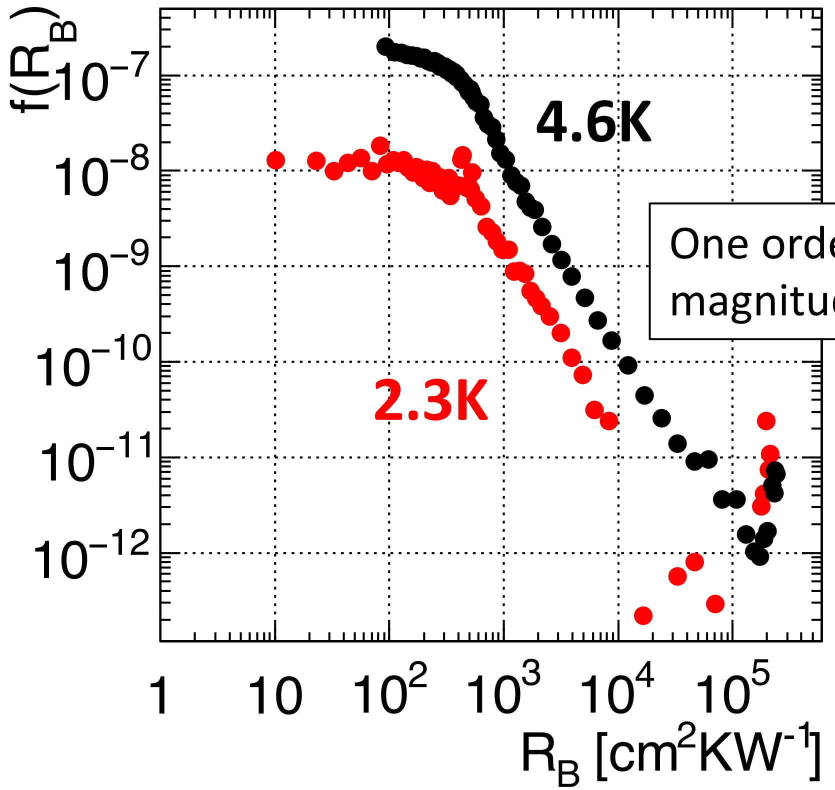
Surface resistance increased by ***quenched hot spots*** can be expressed as

$$\overline{R_s}(T,H) = \int_0^\infty R_s^{FB}(T_0, H, R_B)\boldsymbol{f(R_B)}dR_B\,,$$

Distribution function of thermal boundary resistance can be obtained from Q-slope



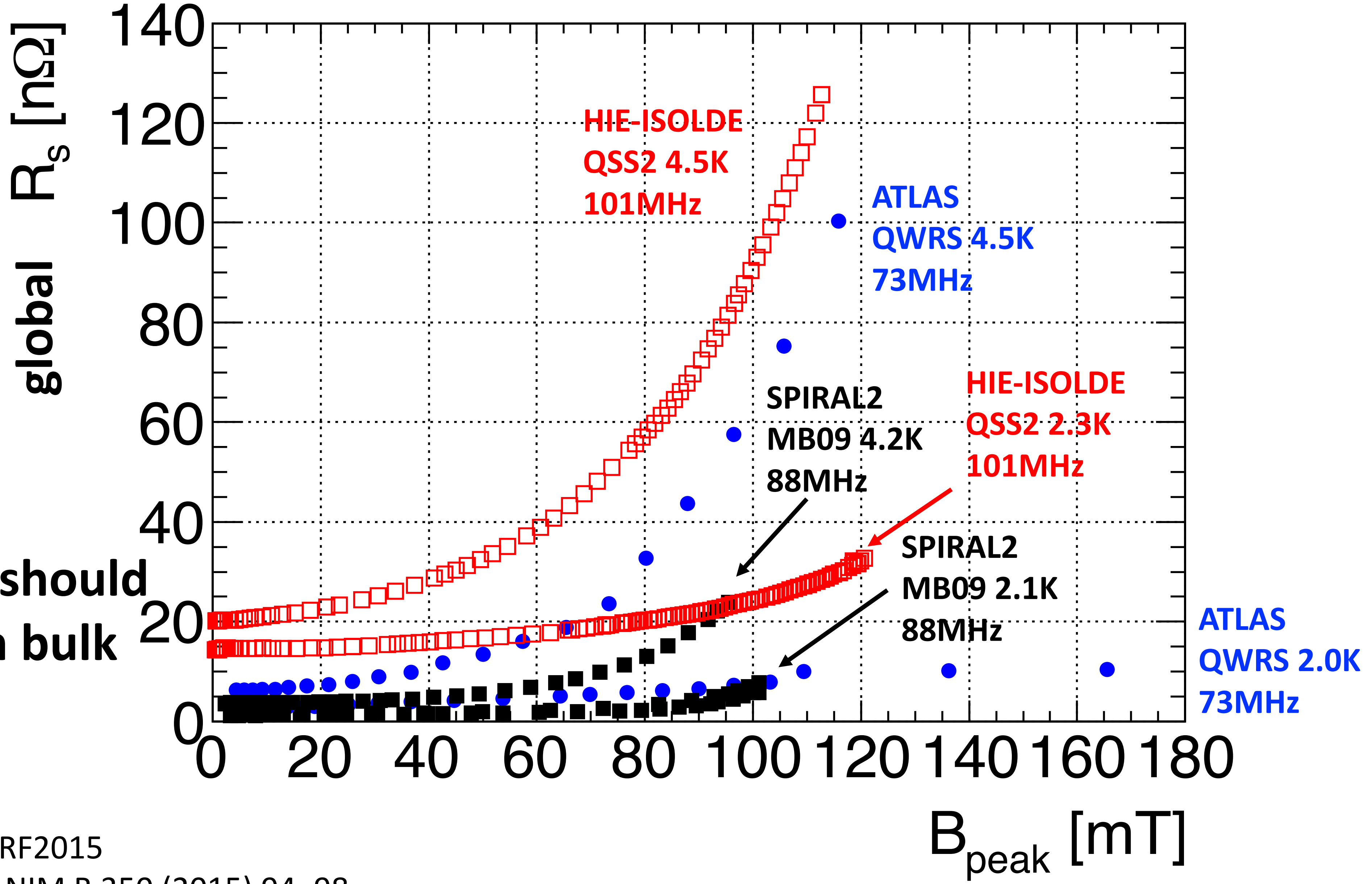
Convert



One order of magnitude different

This model is not consistent with the T-dependence of this Q-slope

T-dependent Q-slope is a universal phenomenon in QWRs



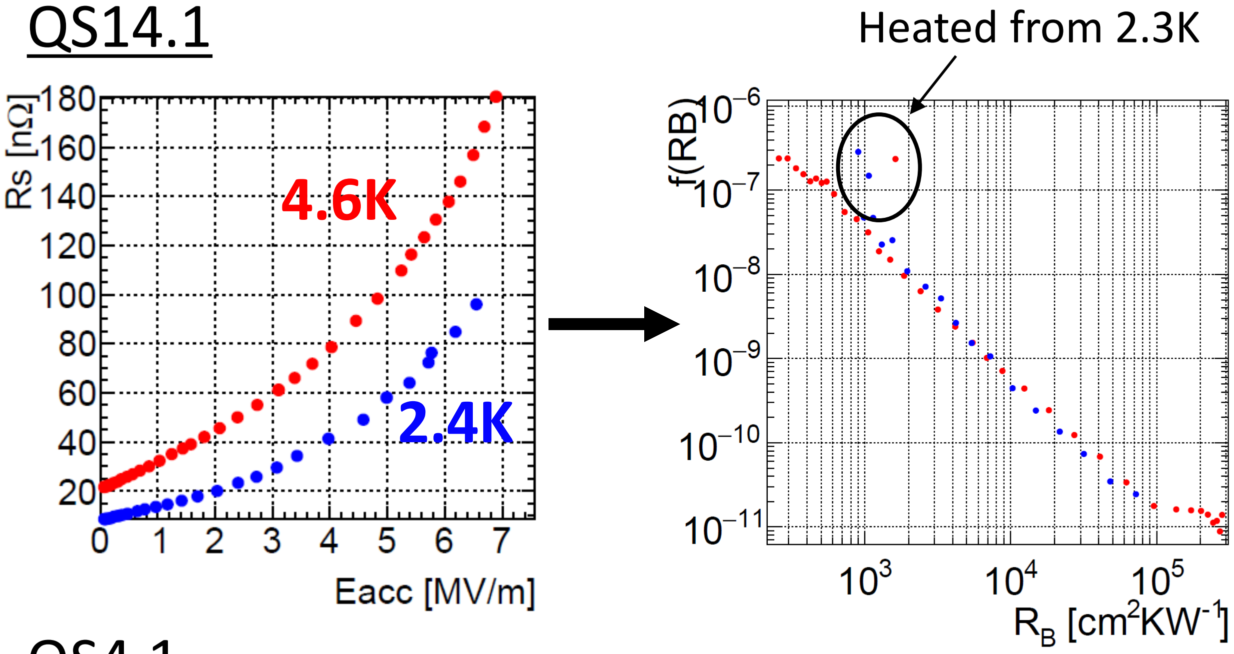
V-P model should not explain bulk Nb results

D. Longuevergne SRF2015

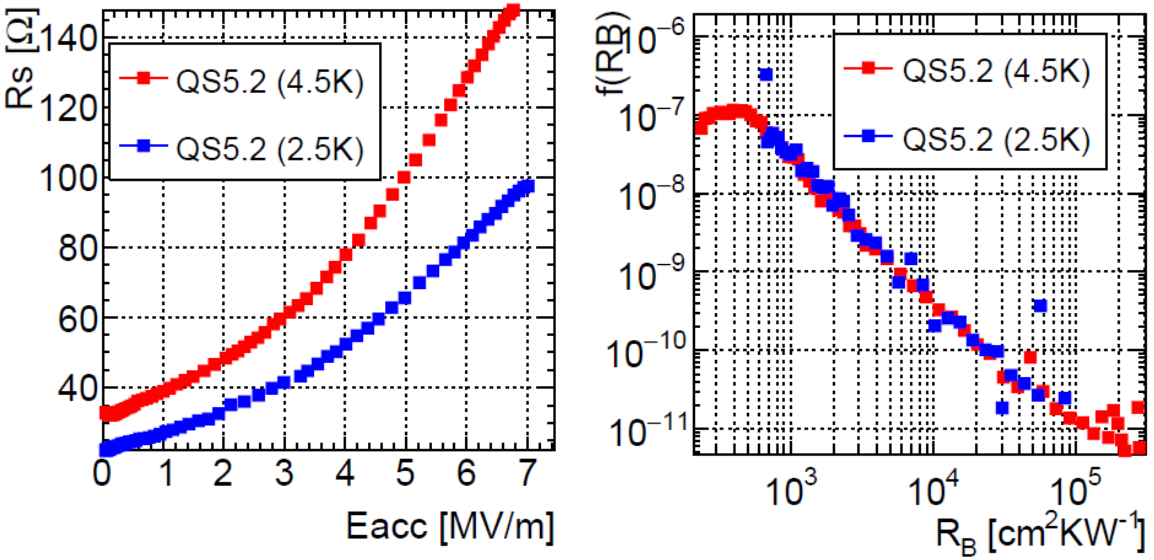
Z.A. Conway et al., NIM B 350 (2015) 94–98

Reminder: what did we see in the welded cavities?

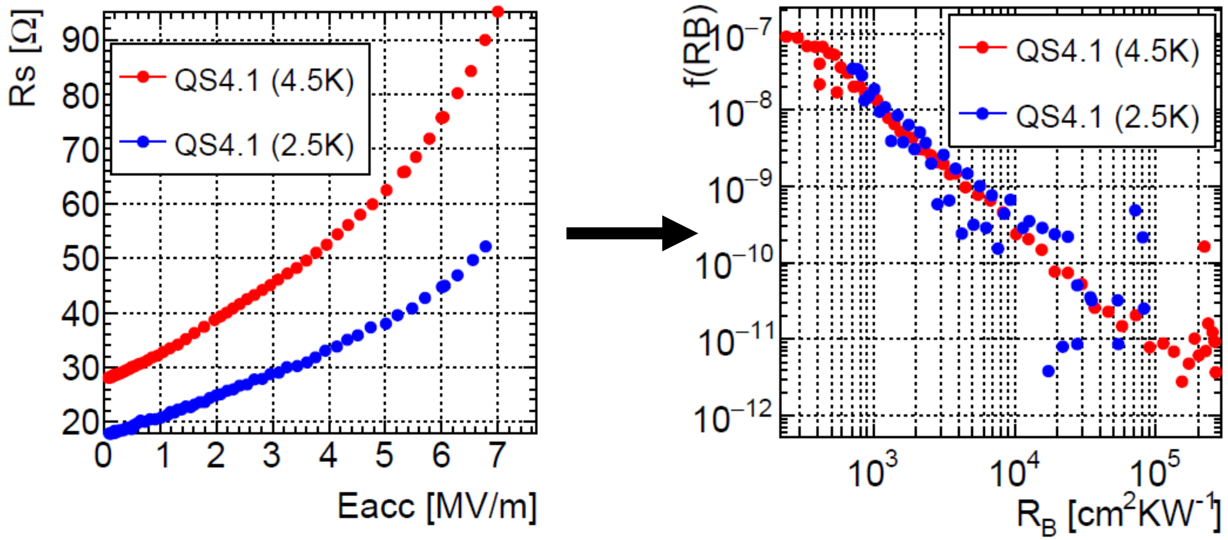
QS14.1



QS5.2



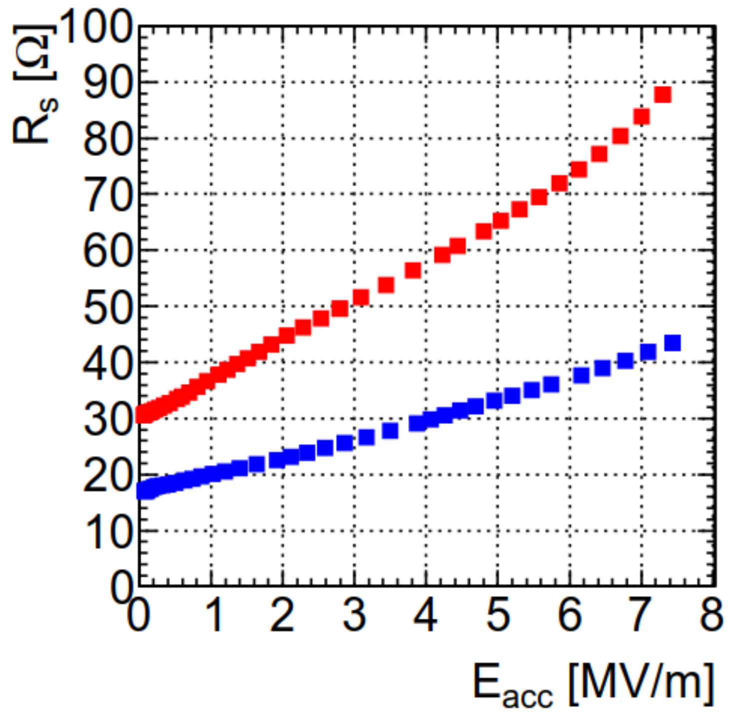
QS4.1



- The two different temperatures were converted to the same distribution
- See S. Aull's presentation in ThinFilm2016
- https://www.jlab.org/indico/event/156/session/9/contribution/12
- See R. Vaglio's presentation in SRF2017
- http://vrws.de/srf2017/html/author.htm
- However, these data are taken at **non-ideal thermal cycle → linear term by trapped flux**

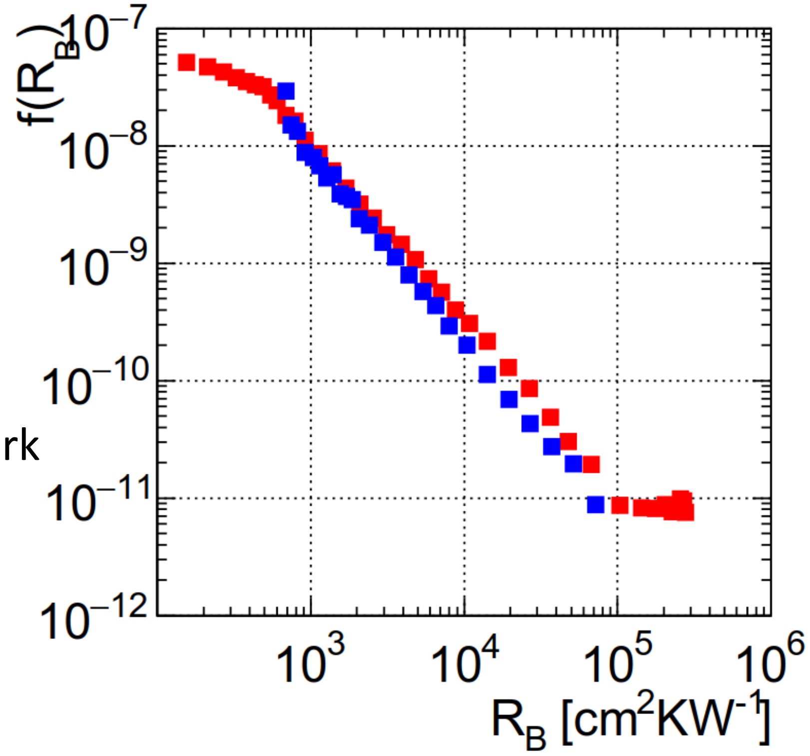
Let’s apply Vaglio-Palimieri algorithm for **enhanced-B data**

<u>Enhanced-B of the seamless cavity</u>



Convert

Physically,
should not work



More or less
Worked…☹

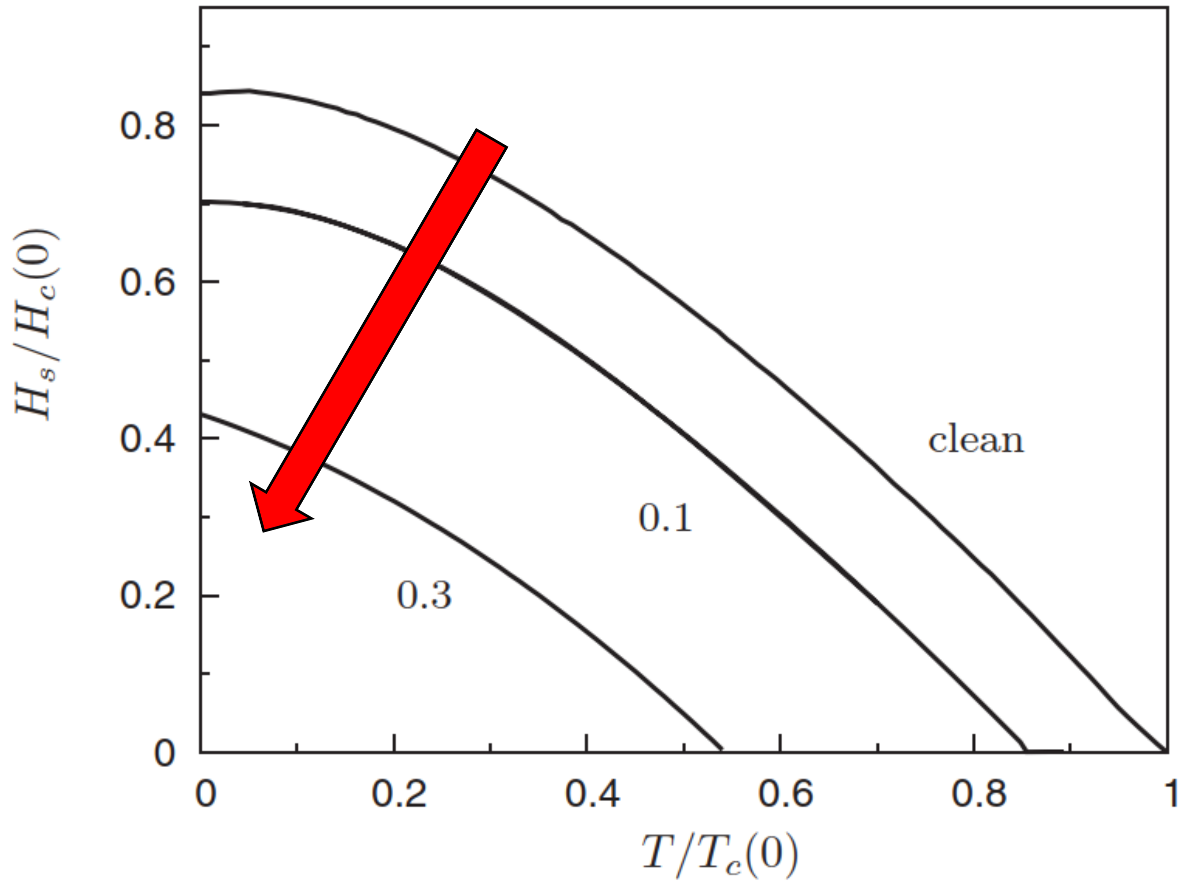
- On contrary to the assumption of the model, this model does not work for the intrinsic Q-slope but works for non-ideal Q-slope caused by trapped field or thermal gradient effect
- The linear slope usually might show similar observation accidentally…

A new model: spatial distribution in H_{sh}

Nb/Cu film could have a distribution on its quality

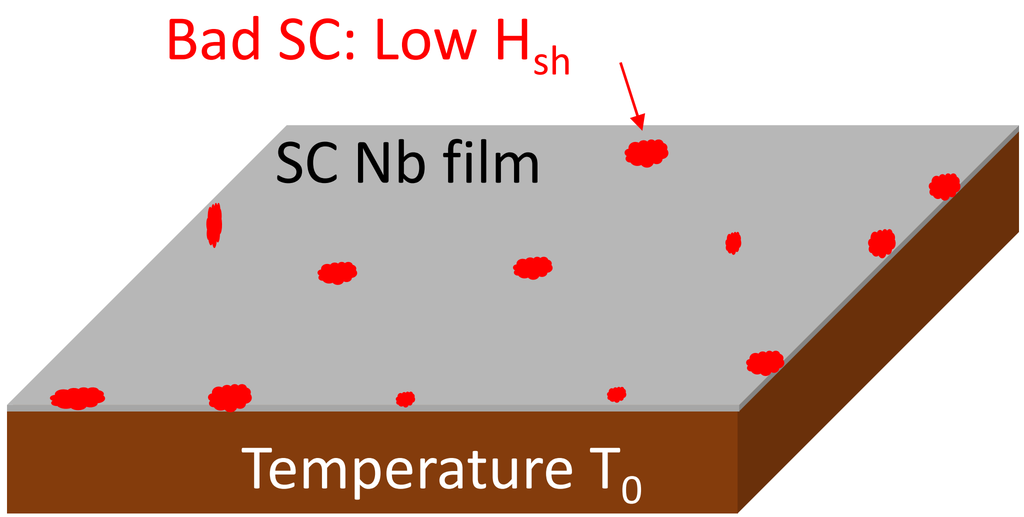
Inspired by the thermal boundary approach proposed by Vaglio-Palmieri

Magnetic impurity $\alpha = \pi\xi_0/l_m$ reduces H_{sh} and T_c



F. Pei-Jen Lin and A. Gurevich, PRB 85, 054513 (2012)

Local defects on H_{sh}

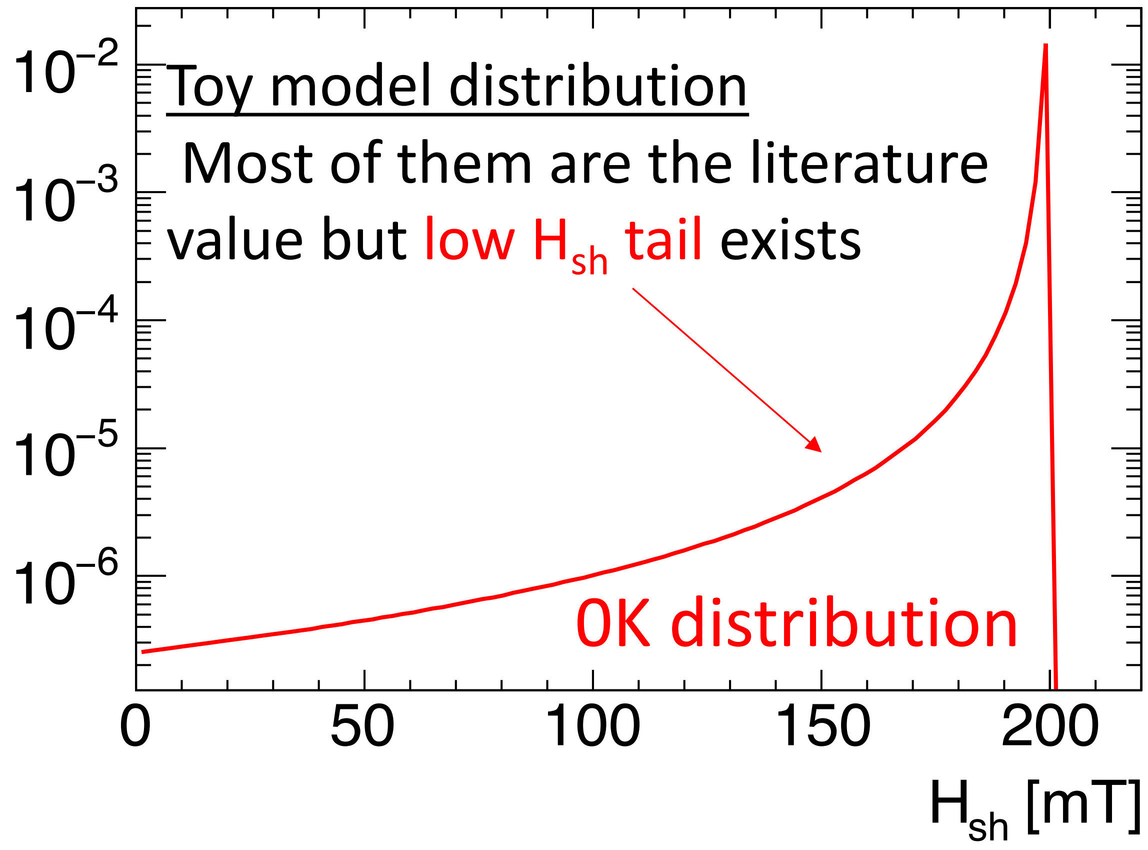


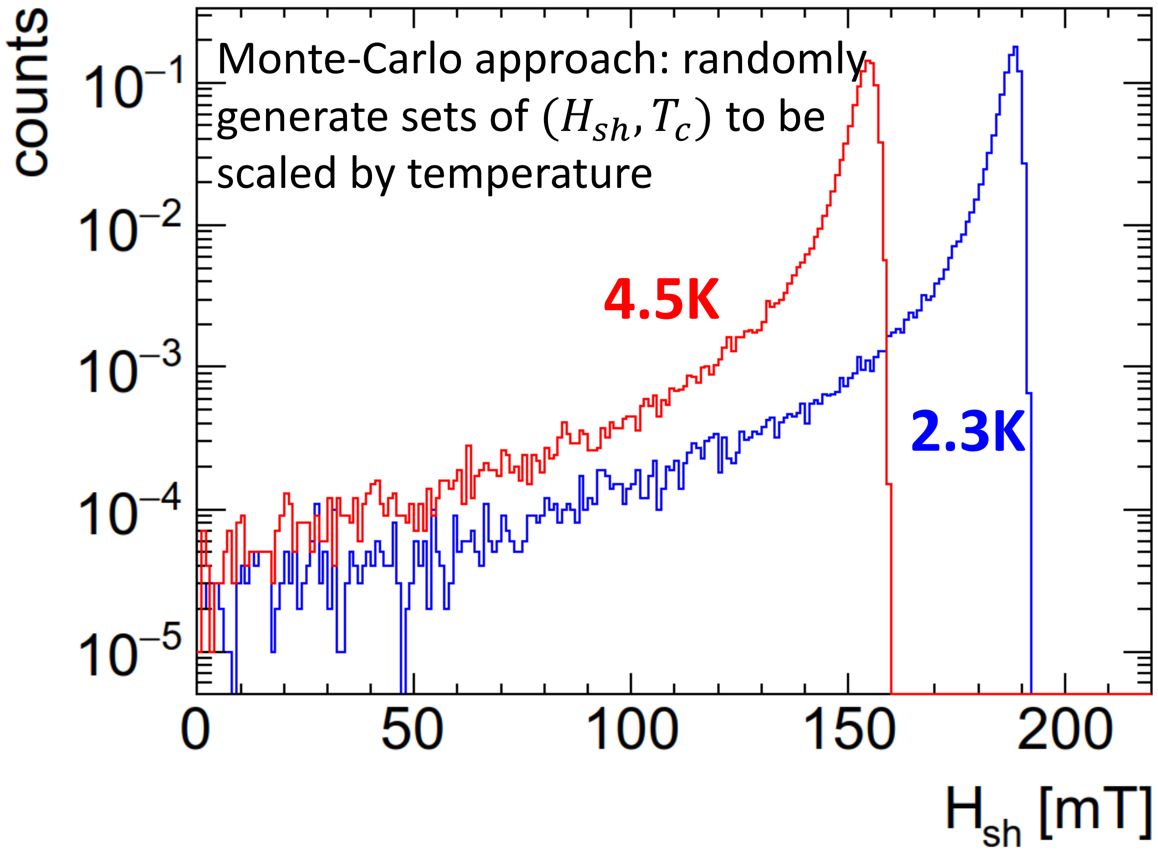
- Most of the surface is clean, but there could be local defects where H_{sh} and T_c are reduced
- Inhomogeneous impurity (V. Ngampruetikorn and J. A. Sauls arXiv:1809.04057) may not affect because sputtered surface is clean in λ_L

Temperature dependence of the distribution

H_{sh} is supposed to be scaled by

$$H_{sh}(T) \sim H_{sh}(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$





Global surface resistance $\overline{R_s}(H_{RF})$

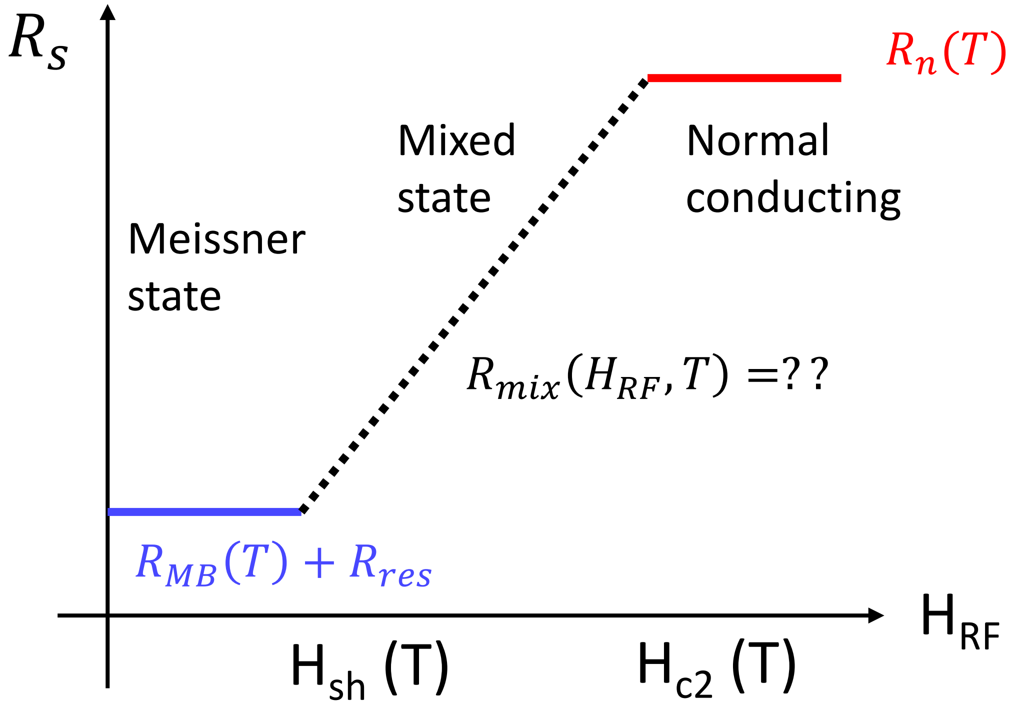
For simplicity, RF field distribution in the cavity is assumed to be constant H_{RF}
The observable surface resistance from Q_0 measurement is

$$\overline{R_s}(H_{RF},T) = \int_0^{\infty} R_s(H_{RF},H_{sh},T) f(H_{sh},T) dH_{sh} ,$$

where $f(H_{sh})$ is the distribution of H_{sh} we suppose, and $R_s(H_{RF},H_{sh},T)$ is the local surface resistance.

A phenomenological model of the local surface resistance is tricky.
The simplest estimate is

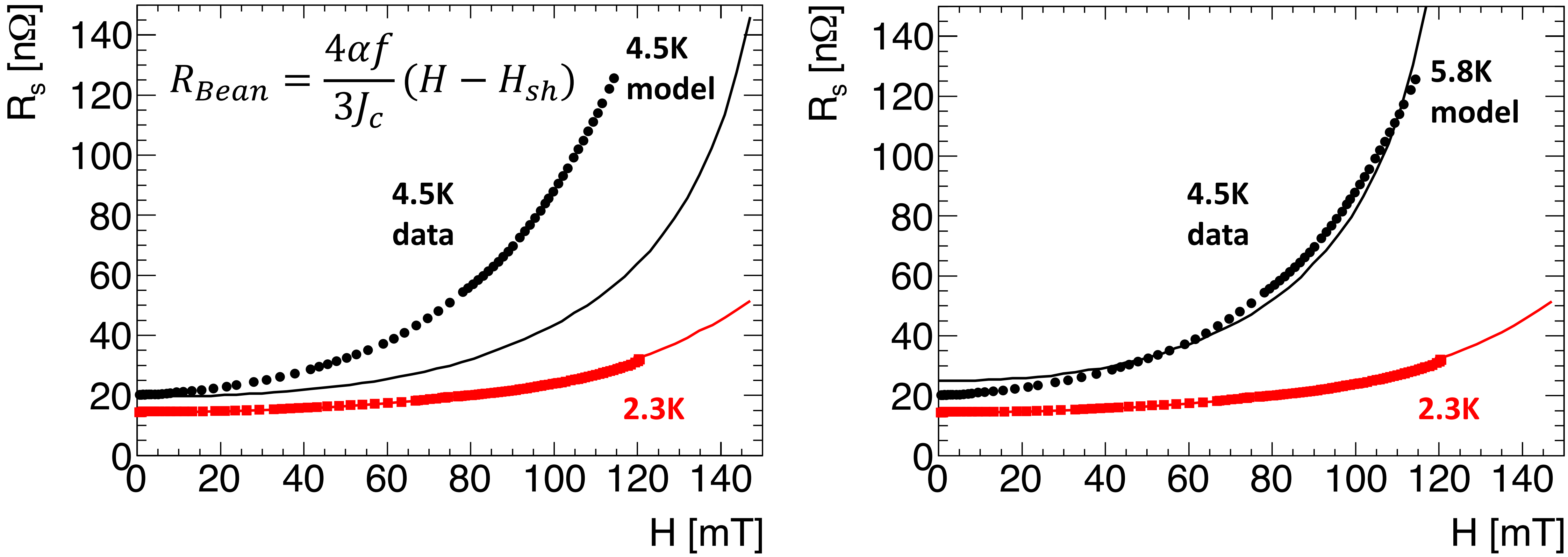
1. $H_{RF} < H_{sh}(T)$ [H_{sh} >H_c>H_{c1}]
   - Non-equilibrium BCS resistance in Mixed state is not fully understood (Cf. anti-Q-slope by Gurevich PRL 2014)
   - Extrapolate BCS-MB is a honest guess (constant in H_{RF})
2. $H_{sh}(T) < H_{RF} < H_{c2}(T)$
   - **The Beam model predicts $R_s \propto H_{RF}$**
   - Isn't it applicable only near $H_{sh}(T)$? (Taylor expansion??)
3. $H_{c2}(T) < H_{RF}$
   - Non-linear Ohmic loss is a thermal problem we don't care
   - Constant R_n may be enough



Comparison with the measurement

Optimize the width of the H_{sh} distribution and the slope of the Bean model to fit 2K data

Manually increase the temperature of the model to fit the 4.5K data



- This model does not quantitatively reproduce the temperature dependence of the Q-slope
- But qualitatively close → Measurement of H_{sh} (H_{c1}) distribution will be a key

Summary

- The new seamless cavity gave an insight to two different origins of Q-slope (QWR shape, 100MHz, DC-bias sputtering)
  - Linear term caused by trapped flux
  - Curvature (exponential) term depends on temperature like BCS resistance
- Trapped flux oscillation requires non-linear extension of conventional theories
- An empirical approach shows that the data can be fitted by naïve gap reduction
  - Missing justification from microscopic theory
- Pure thermal models were disfavored
  - Global thermal feedback did not work
  - Local quenched thermal feedback did not work
- H_{sh}-distribution model behaves qualitatively similar to the data
  - A toy distribution of H_{sh} caused by local defects
  - Temperature dependence is qualitatively similar to the data but not perfect
  - Comparison to direct measurement of H_{c1} distribution is of interest

<u>Future prospects</u>

- Application of seamless Nb/Cu QWR for different projects: low-β performance does not require high-gradient and our cavity is competitive to bulk Nb
- Magnetic shielding in film cavities → contrary to literature!
- Elliptical cavity 1.3 GHz → different substrate and coating
- Q-slope study in other films: Nb_3Sn/Cu → See Marco Arzeo's talk