Analysis of HIE-ISOLDE cavity results

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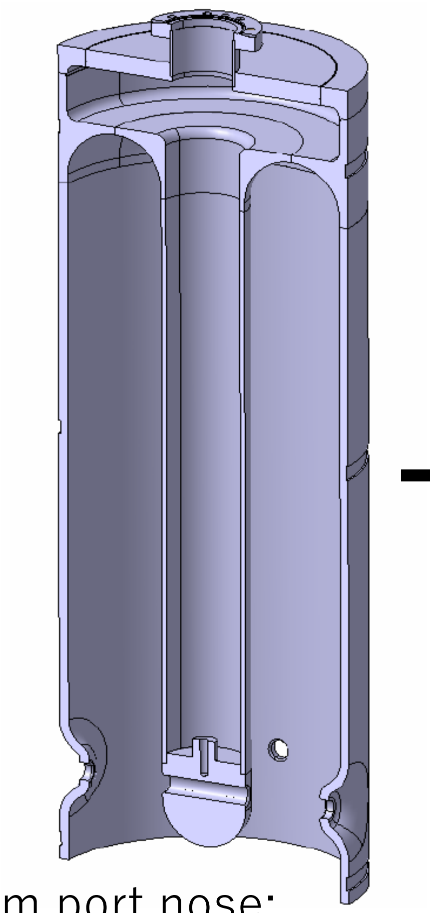
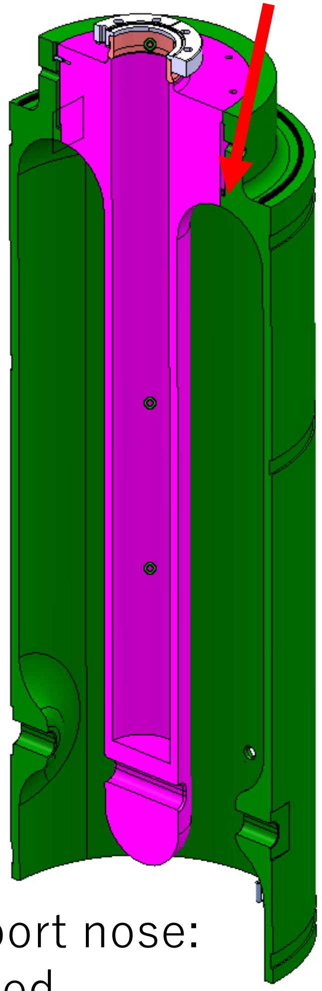
HIE-ISOLDE Nb/Cu Quarter-wave resonators (101MHz)

Prototype: rolled sheet + **a number of welding**



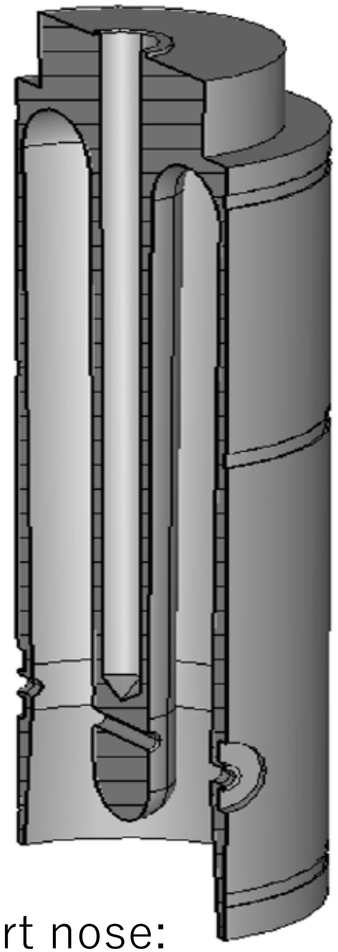
Beam port nose:
Punch pressed

Series production: machined + **one** welding



Beam port nose:
Machined

New design: fully machined + no welding

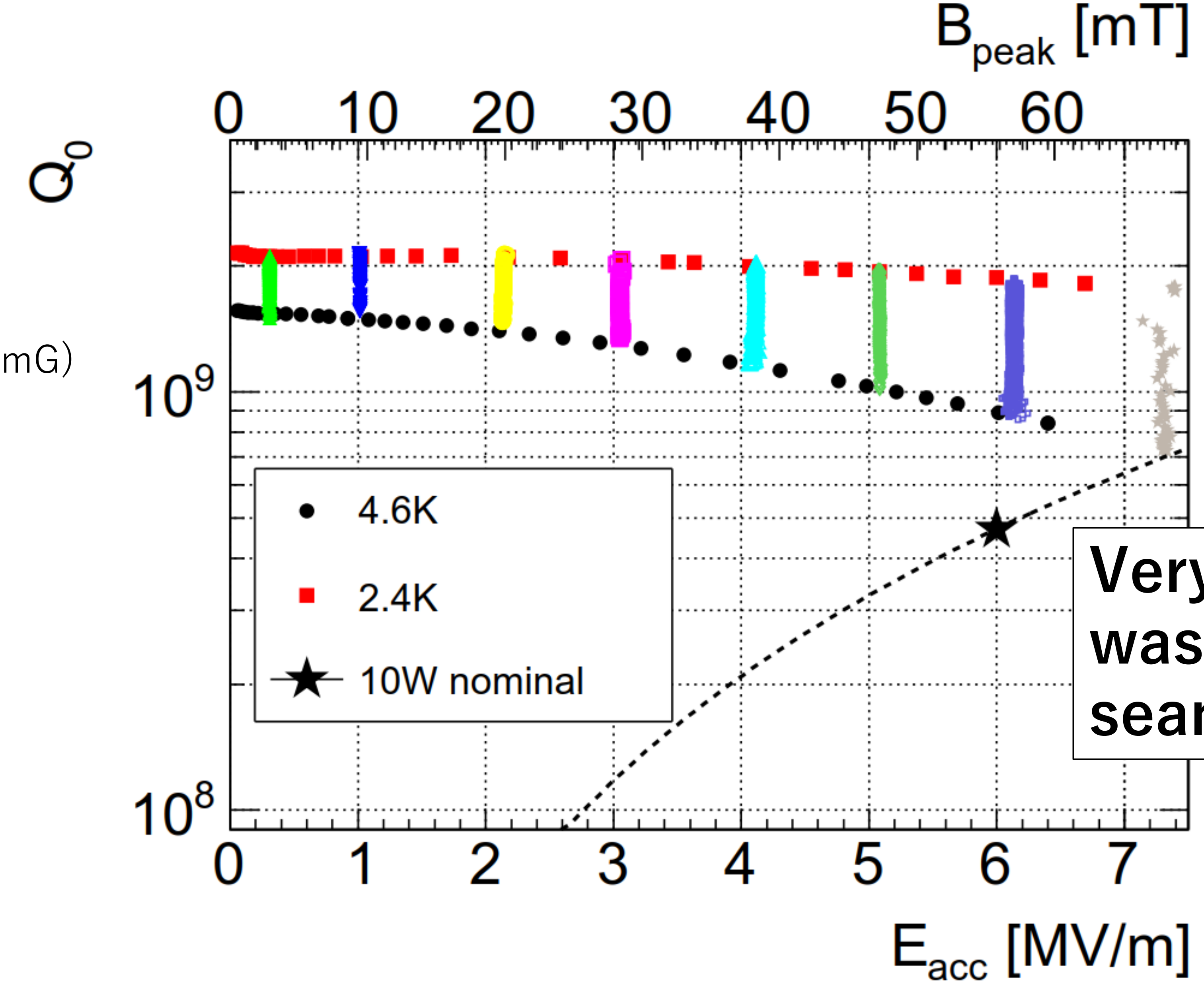


Seamless cavity

Beam port nose:
Removed (conical wall)

Q vs E cooled down under a compensated magnetic field

H_{ext}~5 μT (50mG)

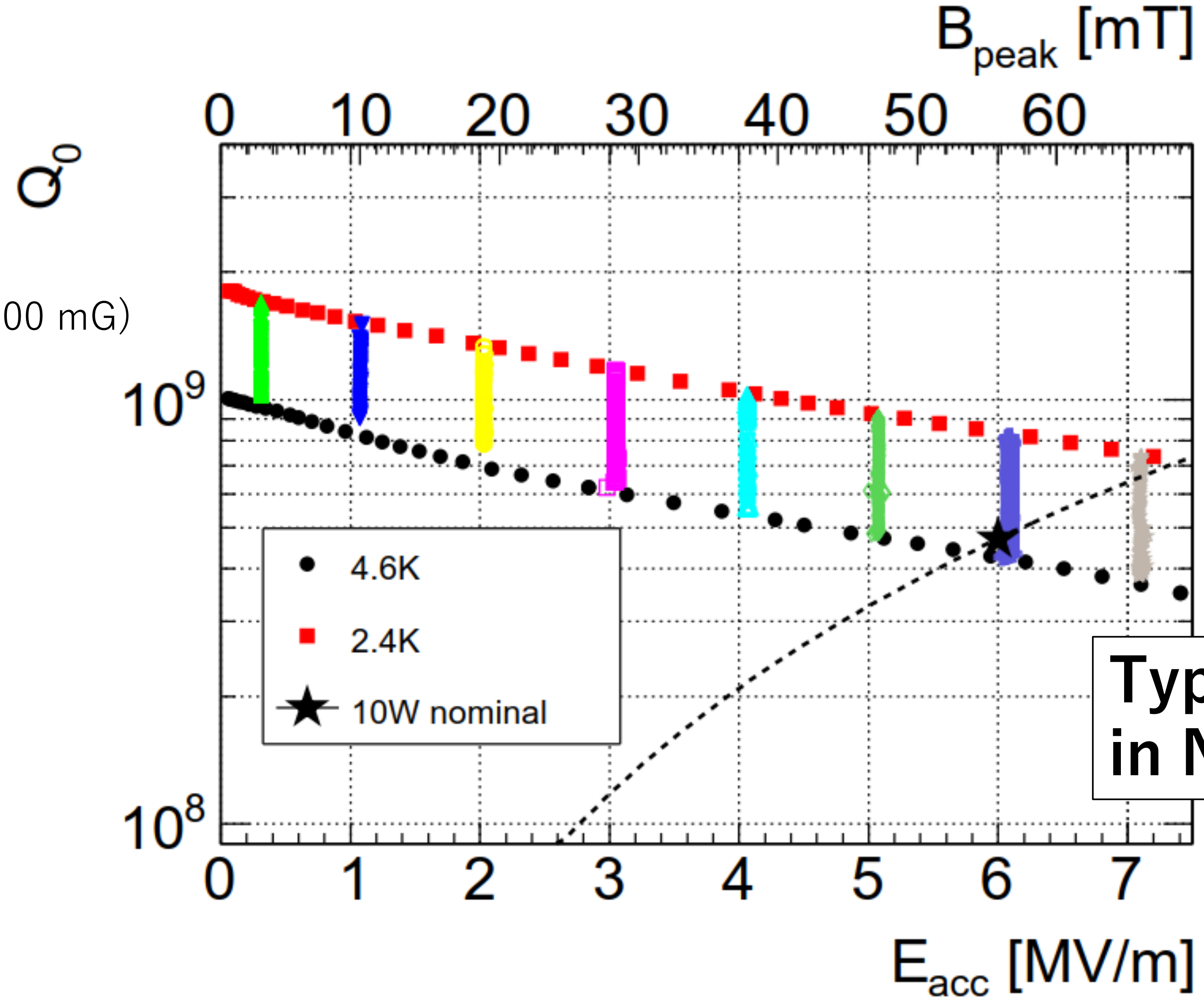


Based on the discussion in TTC topical workshop 2017 in Fermilab

Very small Q-slope was found in the seamless cavity

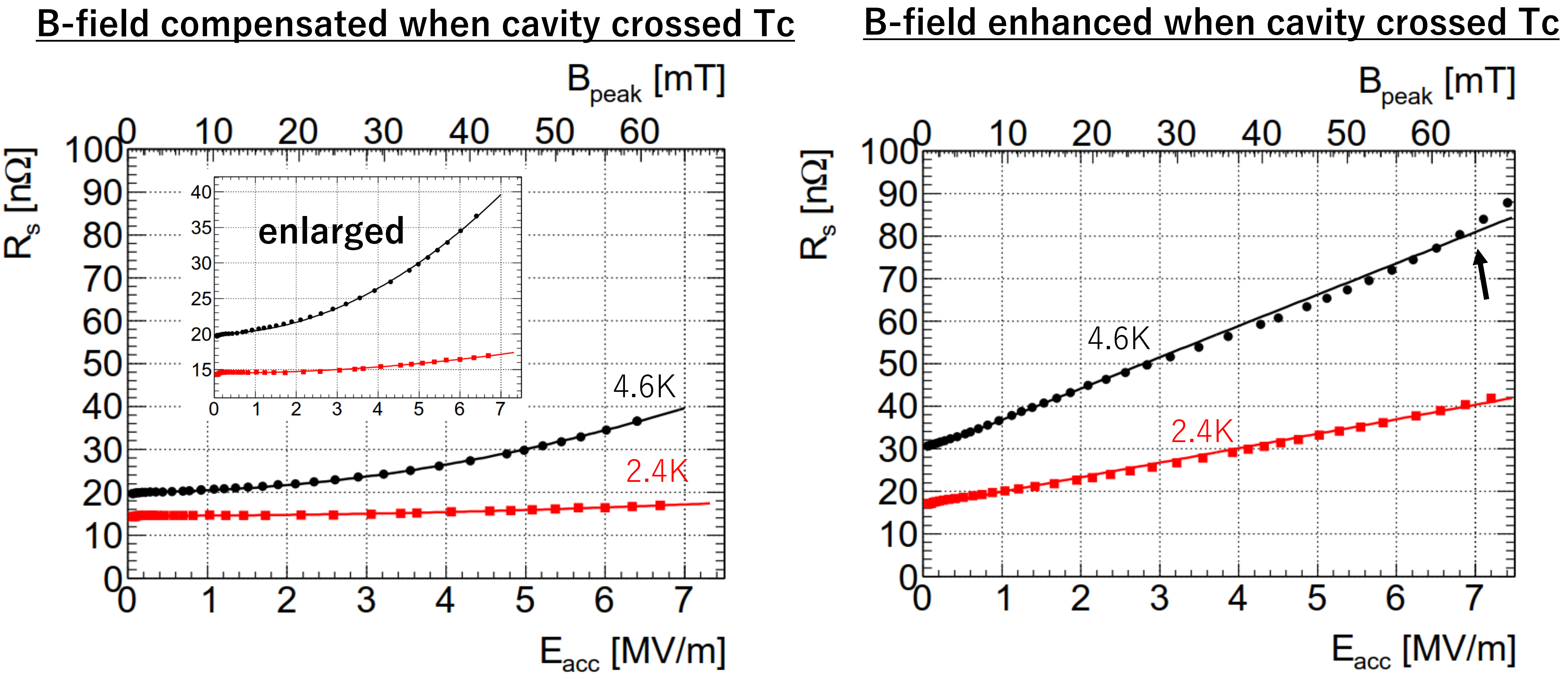
Q vs E cooled down **under a static magnetic field**

H_{ext}~100 μT (1000 mG)



Typical Q-slope in Nb/Cu cavities

Function of Q-slope (seamless cavity): empirical Rs vs E fitting



Intrinsic Q-slope is ***temperature dependent curvature*** component

Q-slope by trapped vortex is ***close to linear*** at low fields and ***weakly temperature dependent***

Trapped vortex effect by the collective weak pinning

- **RF field oscillates the trapped vortex under statistical sum of many pinning centers**
- D. B. Liarte's (Cornell) analytical approximation resulted in

$$R_{fl} \propto \frac{4}{3}\frac{f\lambda^2\mu_0}{B_c^2\xi}\frac{J_0}{J_c}H_{ext}H_{RF}$$

$$\frac{R_{fl}}{H_{ext}H_{RF}} \sim \mathbf{1.7\times10^{-3}}\ \mathrm{n\Omega(mT)^{-1}(\mu T)^{-1}}$$

- On the other hand, experiment showed

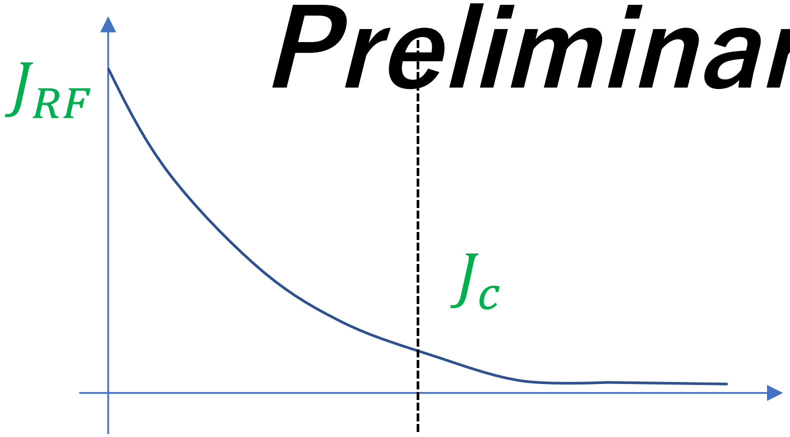
$$\frac{R_{fl}}{H_{ext}H_{RF.peak}} \sim \mathbf{3\times10^{-3}}\ \mathrm{n\Omega(mT)^{-1}(\mu T)^{-1}}$$

→ Good agreement! Only a factor of two!

- Different material parameters $(\xi_0, \lambda_L, R_n, J_c)$
  → Different sensitivity to the trapped vortices
  → Parameter determination is important!

(See A. Miyazaki's presentations in topical TTC at FNAL)

Preliminary



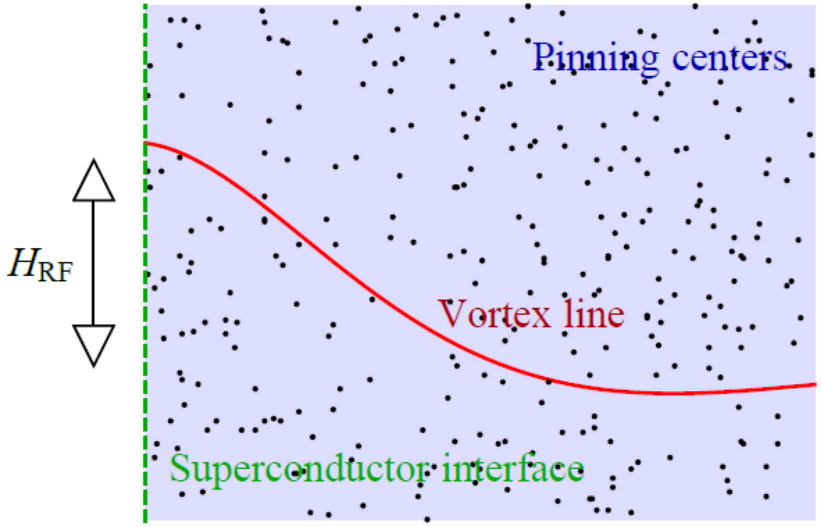
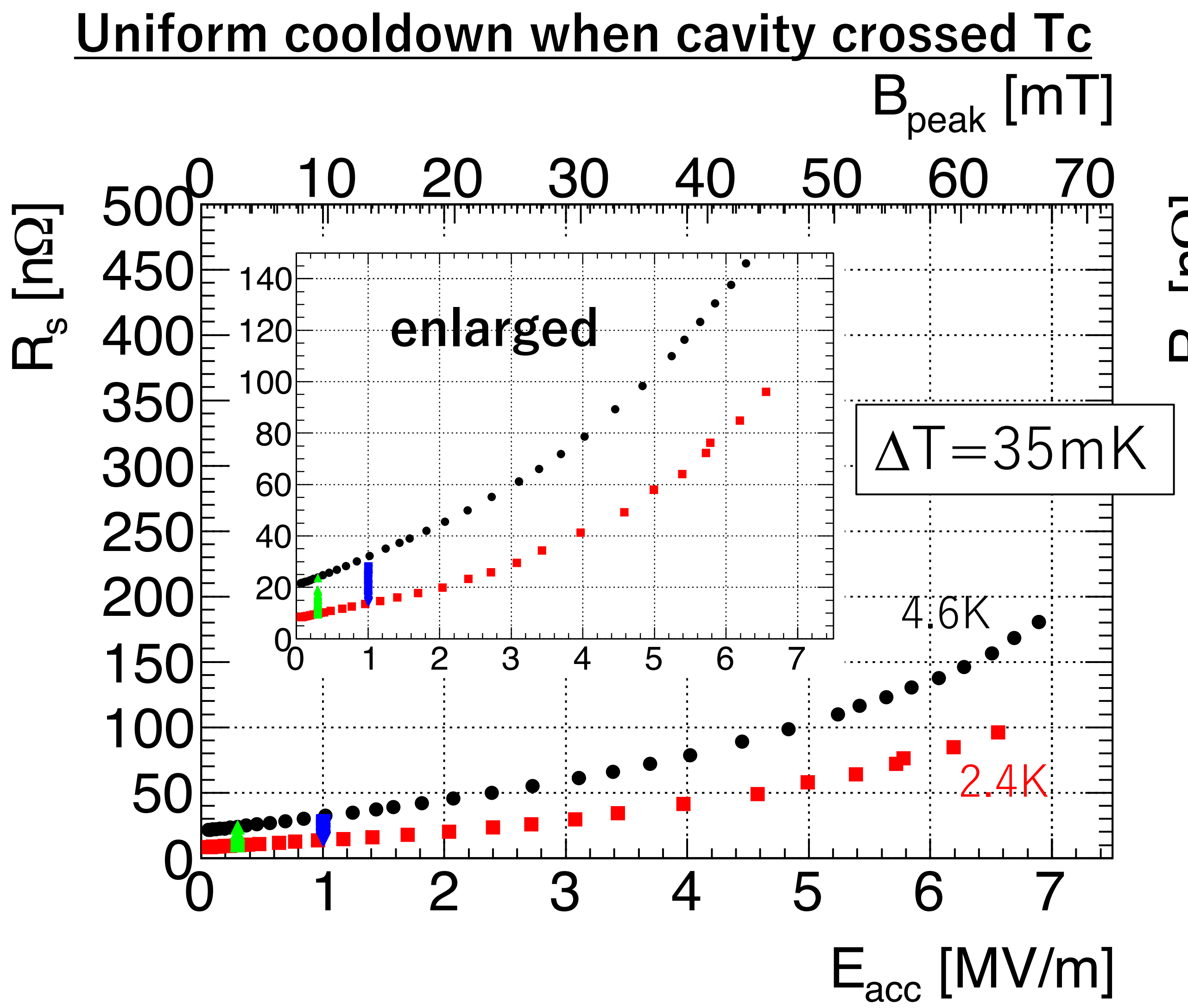
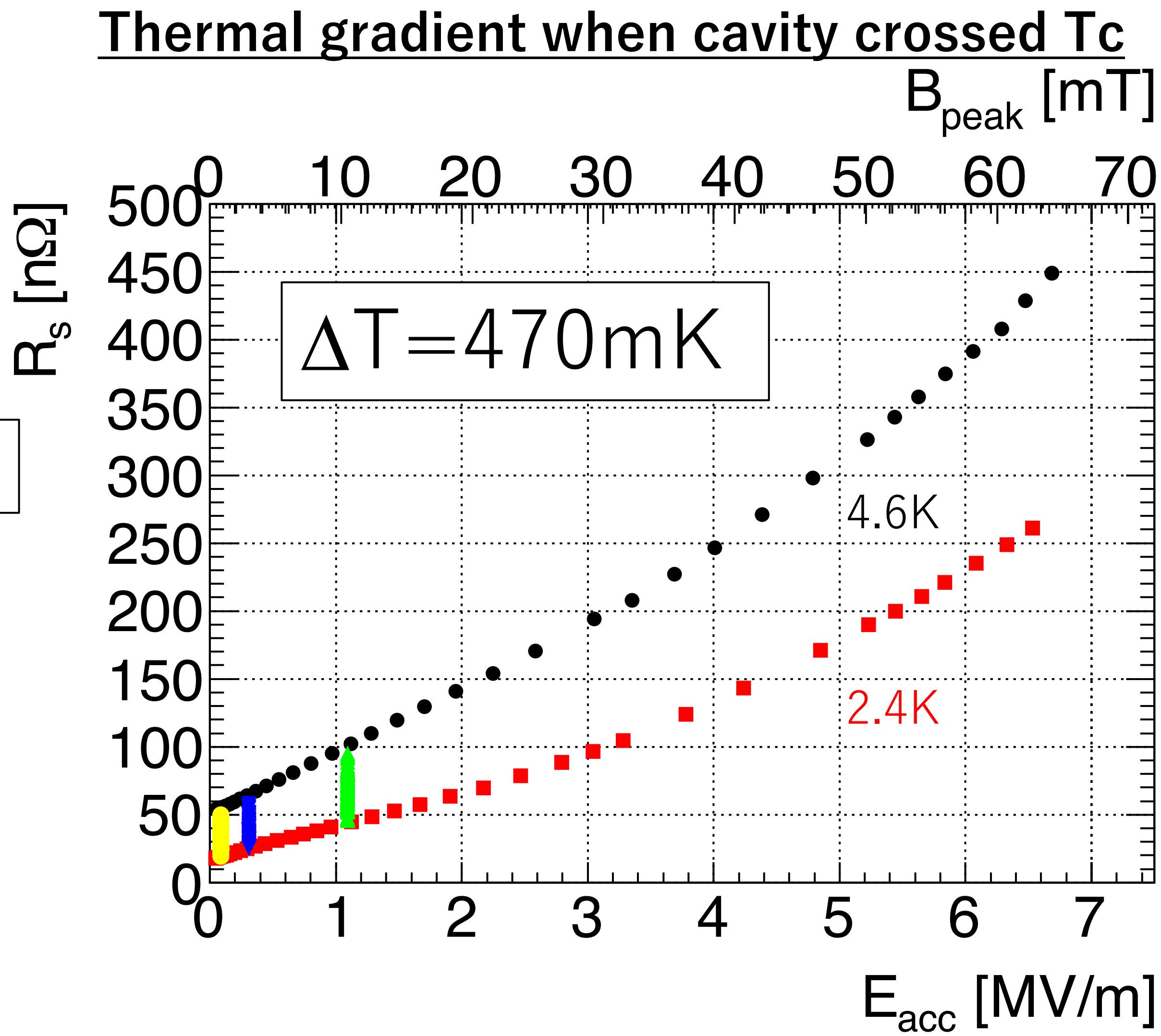


FIG. 4 Motion of a single trapped vortex subject to an RF field and collective pinning forces.

Curtesy of D. B. Liarte

Welded cavity → sensitive to thermal gradient ΔT



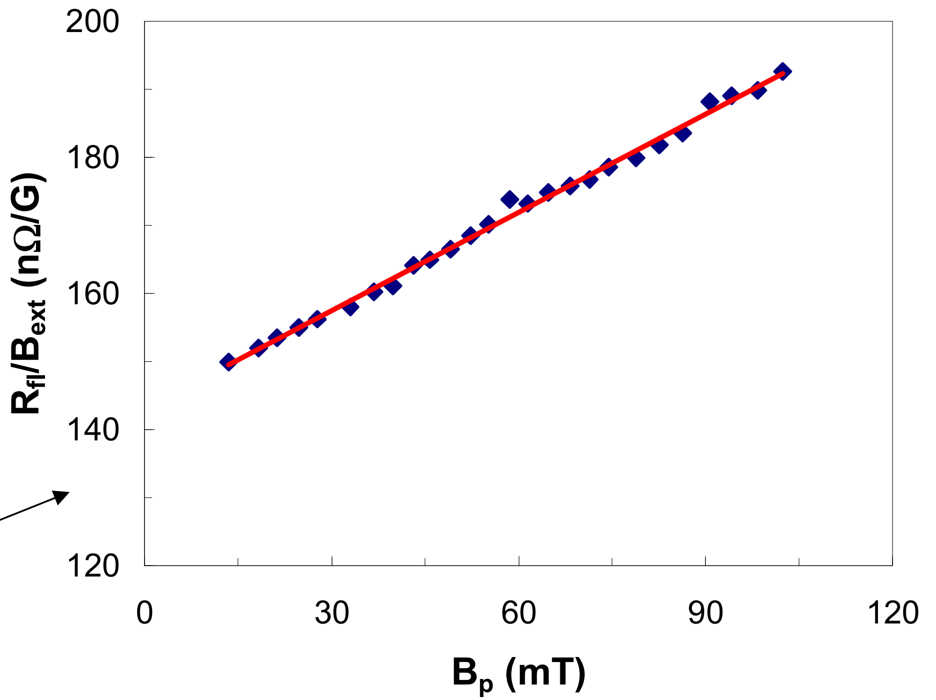


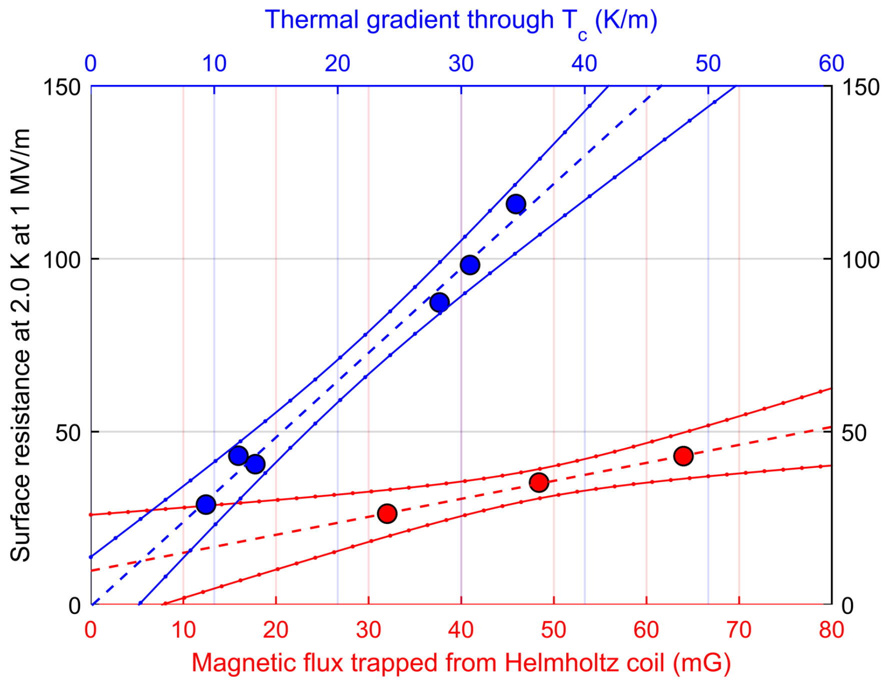
The best possible cooldown ***still contains linear term***
→ Severe trapped vortex contamination?

The physics from ΔT→ trapped vortex is still a missing link (only speculations)

Comments on the trapped flux effect

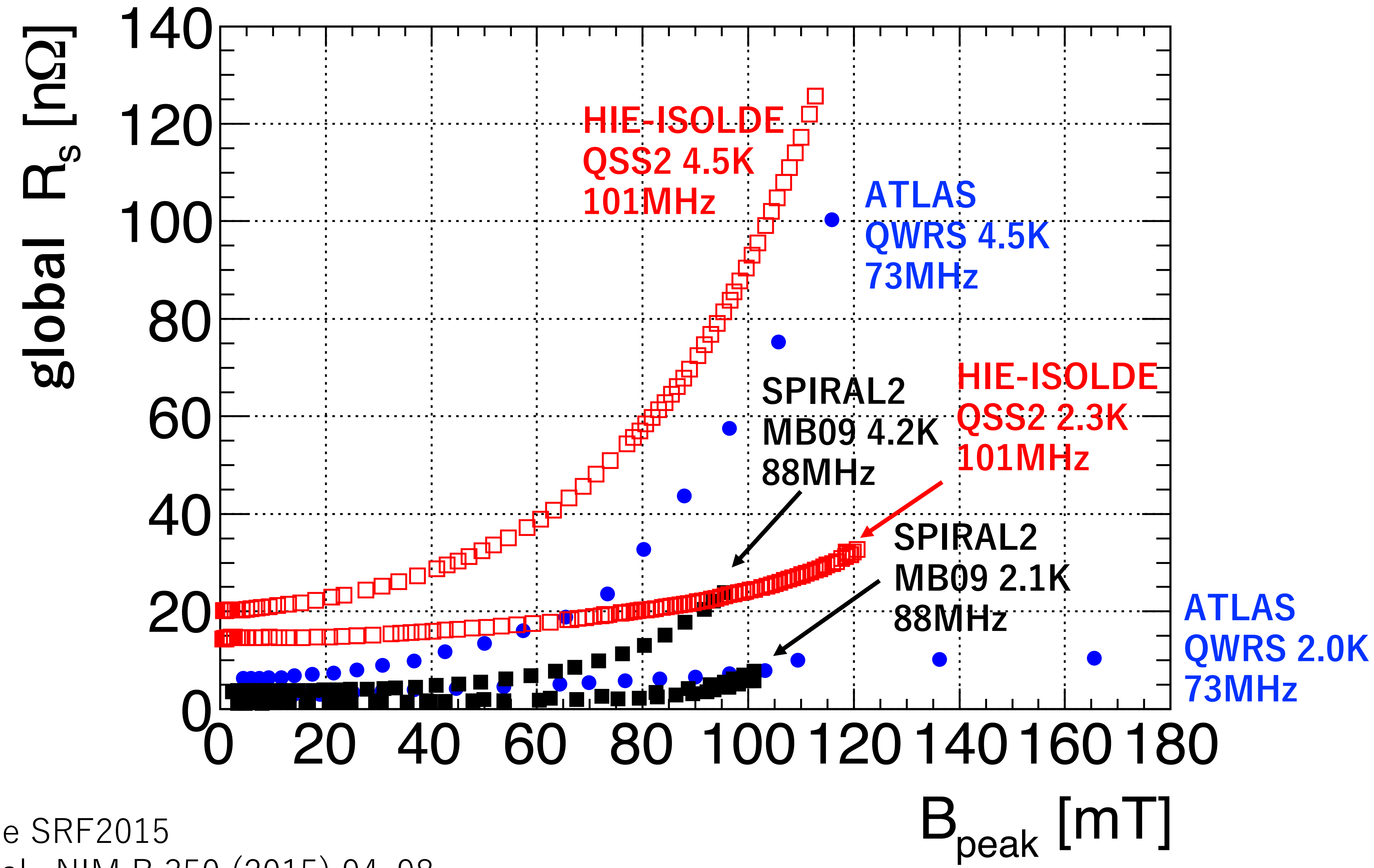
- Our findings
  - Linear Q-slope in residual resistance caused by trapped flux
  - A similar phenomenon was produced by thermal gradient when crossing T_c
  - Commonly found in historical Nb/Cu cavities (Q-slope problem)
- Bulk Nb cavity [G. Ciovati and A. Gurevich SRF2007]
  - Linear Q-slope caused by trapped lux
- Nb_3Sn/Nb cavity [D. Hall SRF2017]
  - Linear Q-slope caused by trapped flux
  - Thermal gradient effect
- **This linear Q-slope might be a universal phenomenon in SRF cavities**
  - Just a different material parameters and environment
  - De-pinning current, mean free path, B-shield, …
- Thermal gradient problem seems a unique problem of bimetal cavities





Intrinsic Q-slope (non-linear)

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



D. Longuevergne SRF2015
Z.A. Conway et al., NIM B 350 (2015) 94–98

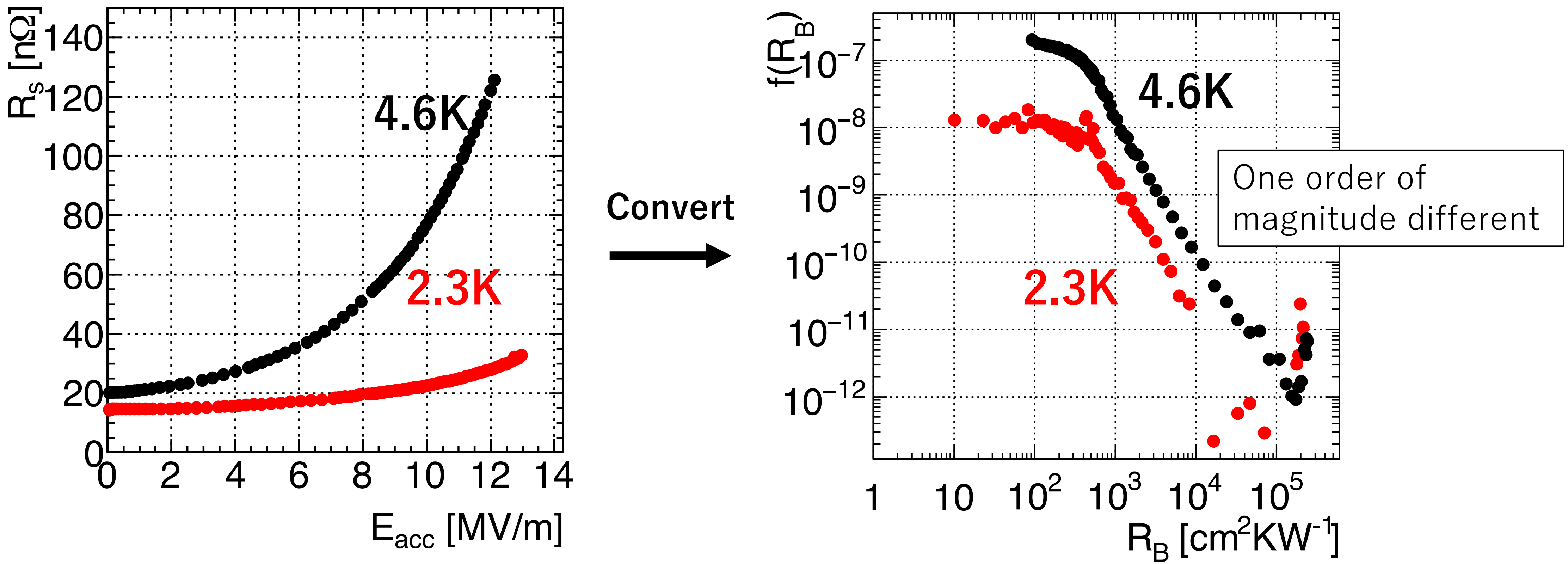
Vaglio-Palmieri model

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

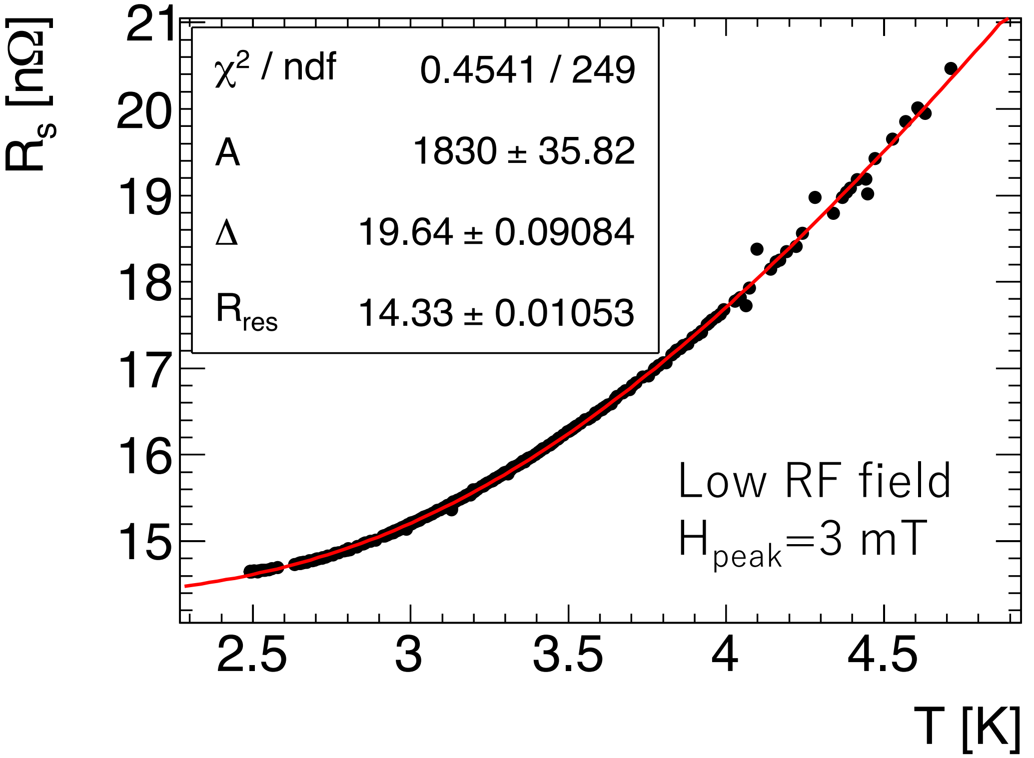


This model is not consistent with the T-dependence of this Q-slope

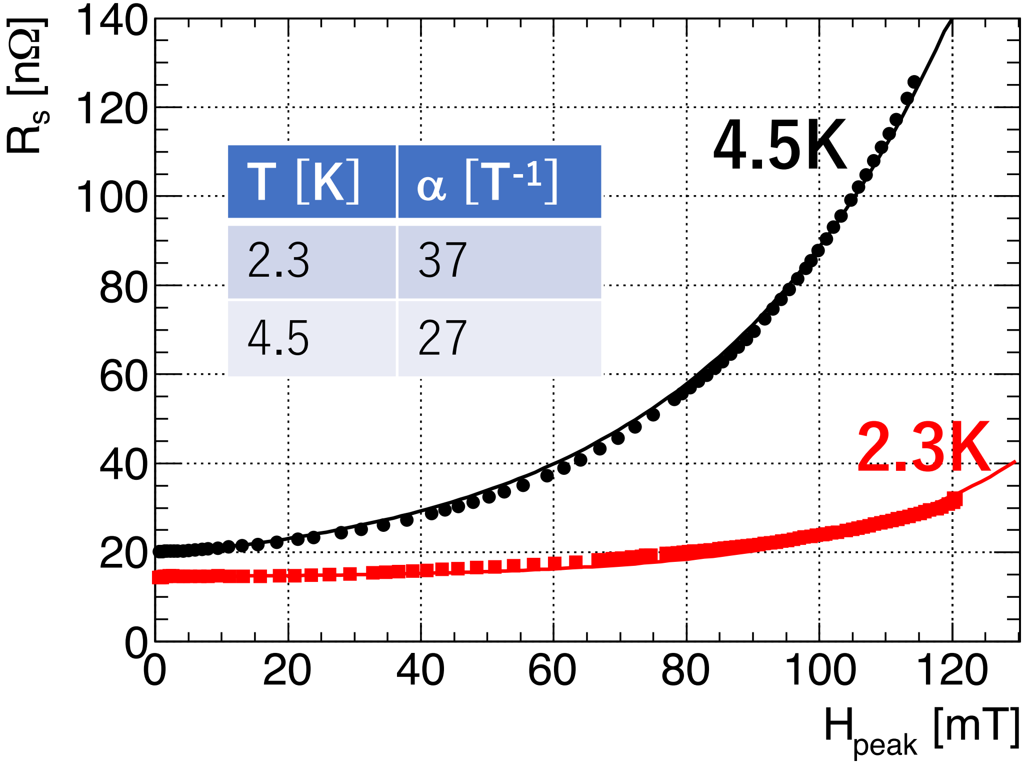
An empirically found formula to fit the data

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

(A, Δ, R_{res}) from Rs vs T data



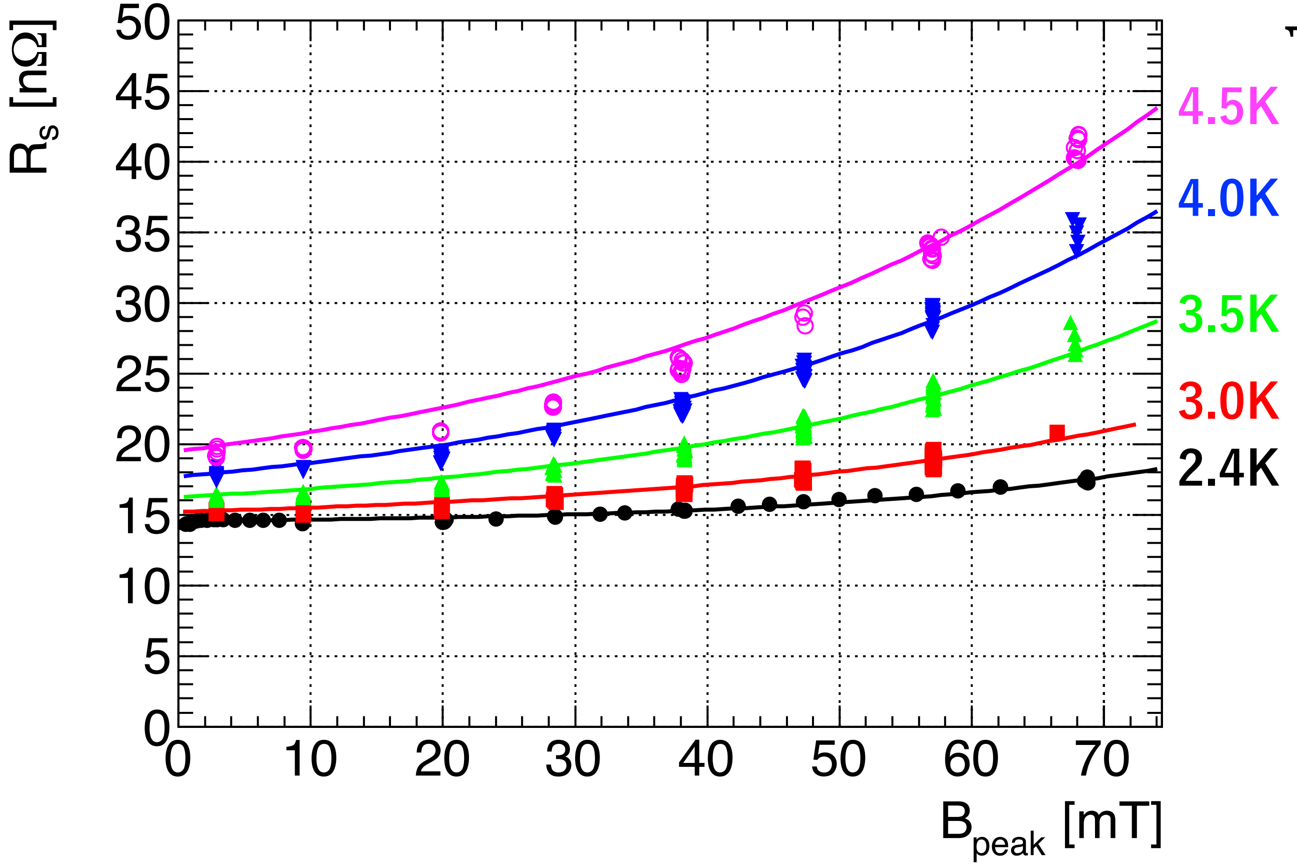
Fit Rs vs H and determine α

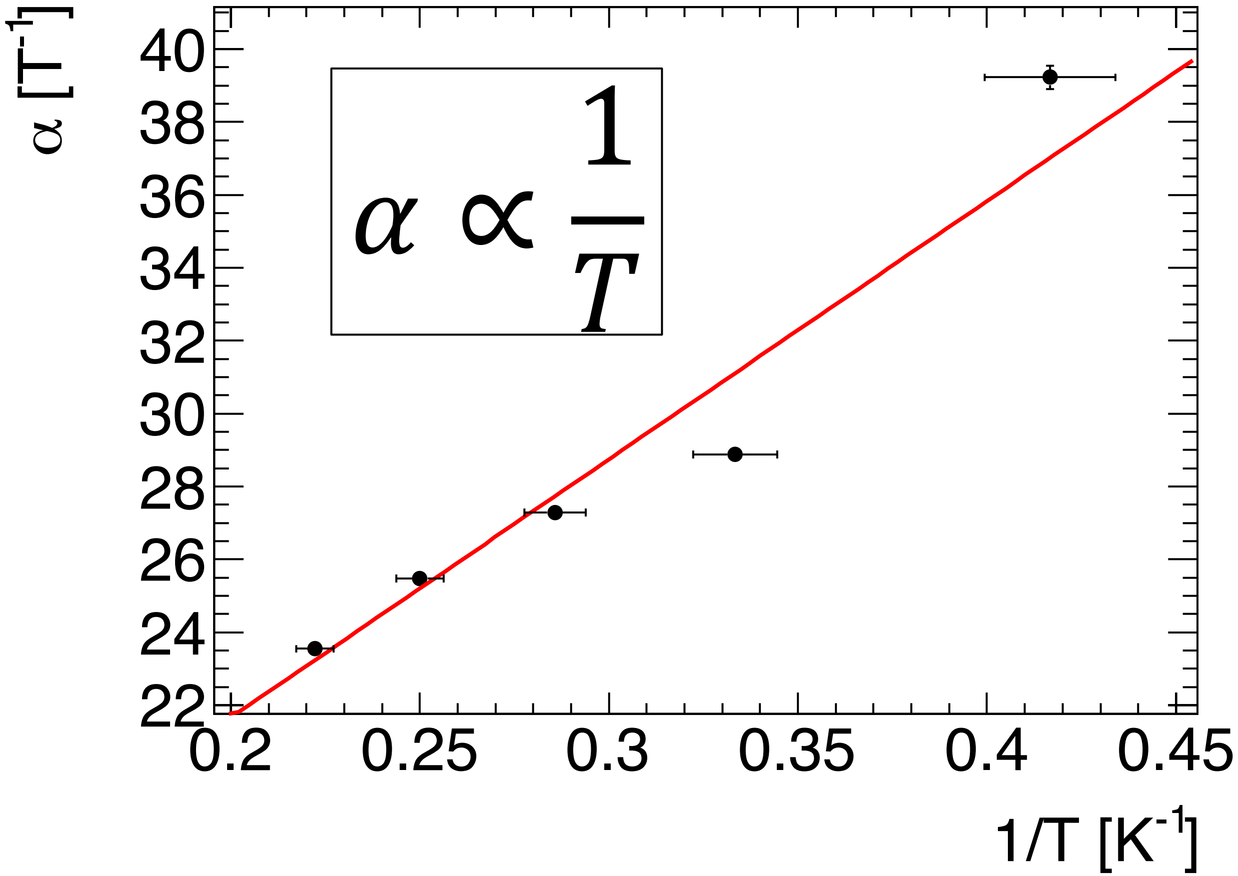


Such an exponential dependence has been reported by others (bulk Nb and Nb/Cu)

1. R. L. Geng (Cornell) "Thermal analysis of a 200MHz Nb/Cu cavity" SRF2001 [ad hoc]
2. D. Longuevergne (IPNO) "Magnetic dependence of the energy gap:…" SRF2013 [exp(B^2)]

Temperature dependence of α





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

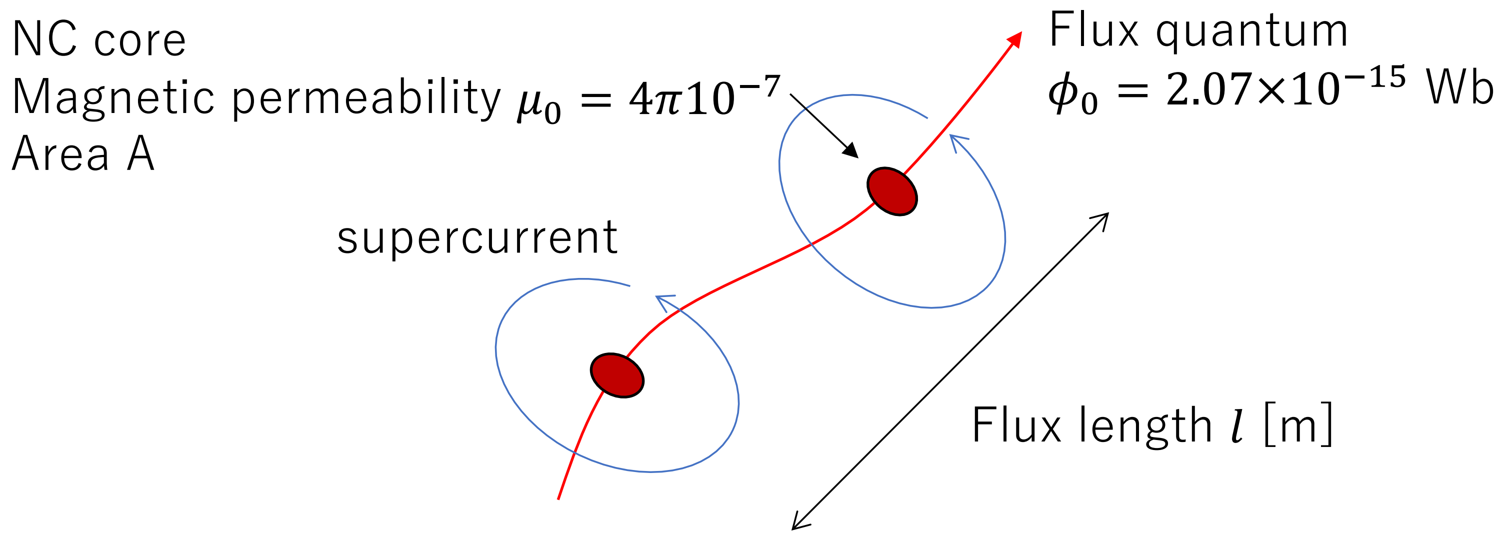
$$R_s(T,B) = \frac{A}{T}\exp\left(-\frac{\Delta}{k_B T} + \frac{MB}{k_B T}\right) + R_{res} \rightarrow R_s(T,B) = \frac{A}{T}\exp\left(-\frac{\boxed{\Delta - MB}}{k_B T}\right) + R_{res}$$

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

Comparison of magnetic momenta

	formula	Value [JT^{-1}]	ref.
This experiment	$M = \alpha(T) k_B T$	9.8×10^{-22}	
Pair breaking by RF supercurrent	$p_F v_s \rightarrow \frac{\lambda_0 e v_F}{\sqrt{\rho_s}}$	$> 2.7 \times 10^{-21}$	V. Palmieri SRF2005 T. Junginger's thesis 2012
Bohr magneton (electron spin)	$\mu_B = \frac{e\hbar}{2m_e}$	9.3×10^{-24}	
Trapped flux quantum	$\frac{1}{2}\mu_0 \phi_0 l$	$1.3 \times 10^{-21} \times l$	

$\lambda_0 = 30\mathrm{nm}$
$v_F = 0.57 \times 10^6 \mathrm{m/s}$
$0 < \rho_s < 1$



Total energy of one flux quantum stored in the magnetic field in the NC core

$$U = \frac{1}{2}\mu_0 B^2 A l$$

Average flux density in the NC Core

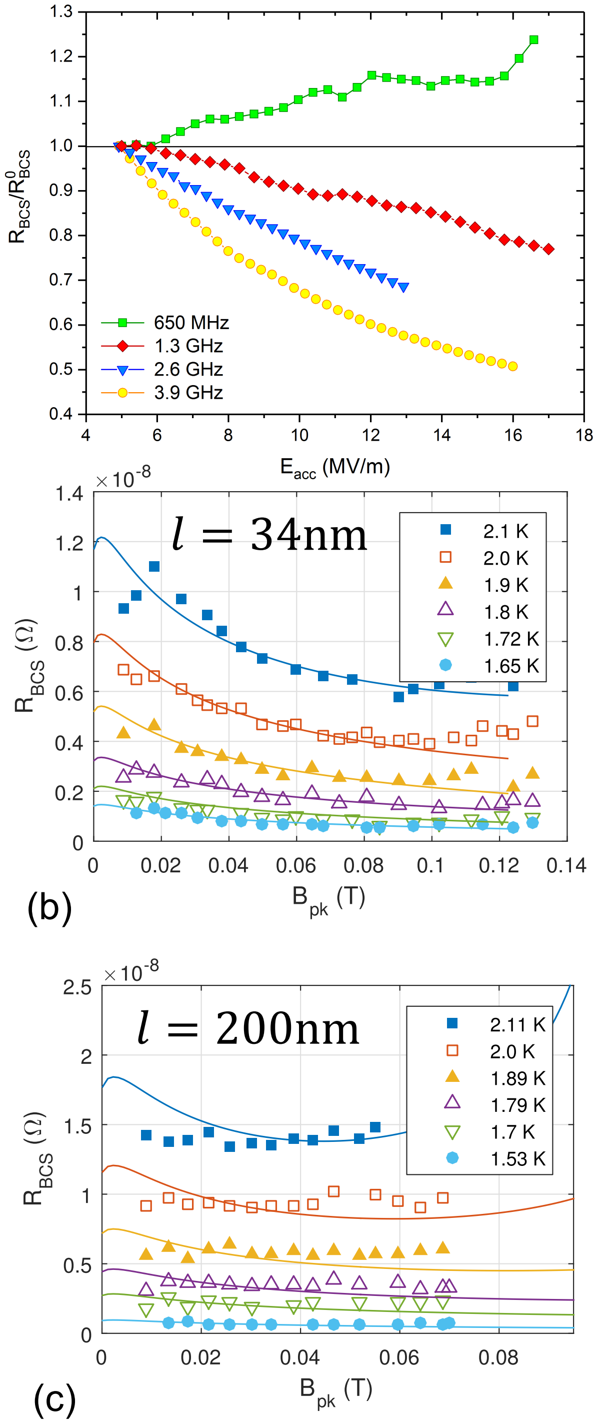
$$B = \frac{\phi_0}{A}$$

Magnetic momentum

$$m = \frac{U}{B} = \frac{1}{2}\mu_0 \phi_0 l$$

Comments on gap reduction

- Our findings in the HIE-ISOLDE Nb/Cu cavity
  - The naïve gap reduction explains field and temperature dependence very well
  - **Frequency ~ 100MHz**
  - **Mean free path >50 nm** [A. Miyazaki TTC Topical 2017 @ FNAL]
  - Quarter-wave resonator
  - Similar phenomenon in bulk Nb QWRs (high RRR) as well
- Relation to the N-doped bulk Nb cavities
  - The pair breaking effect is overwhelmed by DoS smearing
    →anti-Q-slope [in the dirty limit; Gurevich PRL 113 087001]
  - **Frequency >> 100 MHz** [M. Martinello TTC Topical 2017@FNAL]
  - **Mean free path < 50 nm** [J.T. Maniscalco et al., J. Appl. Phys. 121 043910 (2010)]
  - Elliptical cavity
- **We might see different aspects of the same physics**
- Different parameters → different observable Q-slope



Conclusion

- The Q-slope in the seamless Nb/Cu cavity was decomposed into
  - The linear term caused by the trapped flux
  - The more intrinsic T-dependent exponential term
- The linear term can be explained by the collective weak pinning model
  - Thermal gradient causes the similar result but the effect of cooldown dynamics to trapped flux is not yet known
  - This term was seen in most of the Nb/Cu cavities and also in other cavities
- The intrinsic Q-slope seems a universal problem of low frequency QWRs
  - The similar T-dependences were found in bulk Nb
  - The function can be fitted by exponential but the naïve model of gap reduction deserves deeper theoretical consideration
  - Frequency dependence is the key → Harmonics measurement, QPR, …
- The Q-slope may not be the limiting factor of Nb/Cu technology
  - Just a matter of different material parameters and environmental condition
  - Optimizing for lower residual resistance and compatibility to optimized RF design will be the next steps