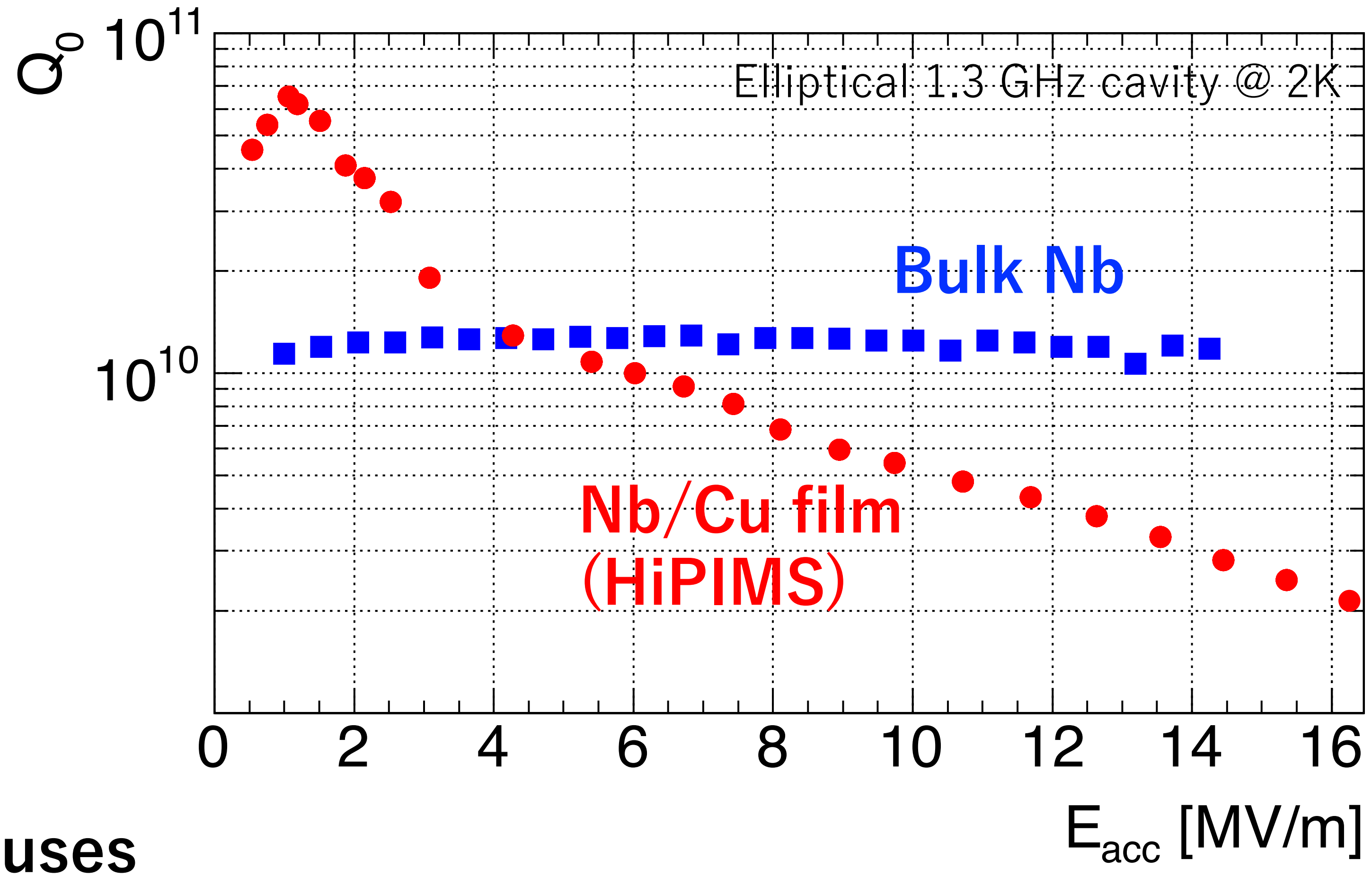
Q-slope problem of Nb/Cu cavities

–**thermal model** vs **trapped vortex** –

A. Miyazaki

CERN and University of Manchester

Common issue of Nb/Cu cavities: Q-slope problem



Courtesy Sarah Aull

Possible causes

- Thermal issues?
- Trapped flux dynamics?
- …

Recent progress will be shown in this talk

Thermal feed-back and its extension

Thermal instability caused by BCS-MB's exponential dependence on T

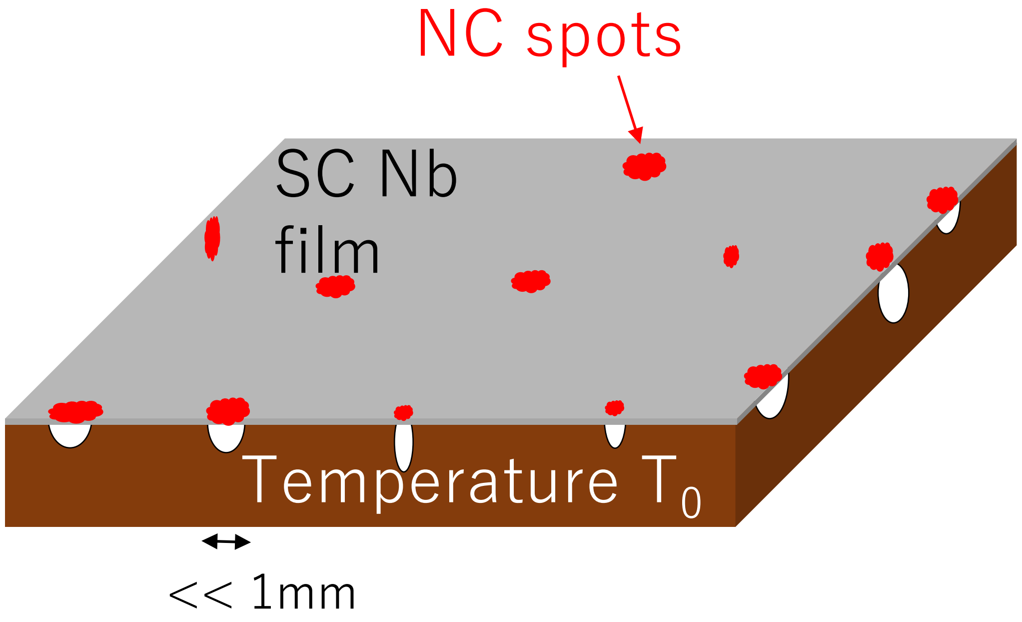
$$R_s(T_0) \rightarrow T_1 \sim T_0 + \alpha R_s H^2 \rightarrow R_s(T_1) \rightarrow T_2 \sim T_1 + \alpha R_s H^2 \ \ldots$$

Property: small Q-slope at low field, sudden quench at certain field

→ Middle-field Q-slope in bulk Nb was explained but different from Nb/Cu's slope

A new model by V. Palmieri , R. Vaglio [Supercond. Sci. Technol, **29** ,015004 (2016)]

Thermal runway by imperfect interfaces between Nb/Cu

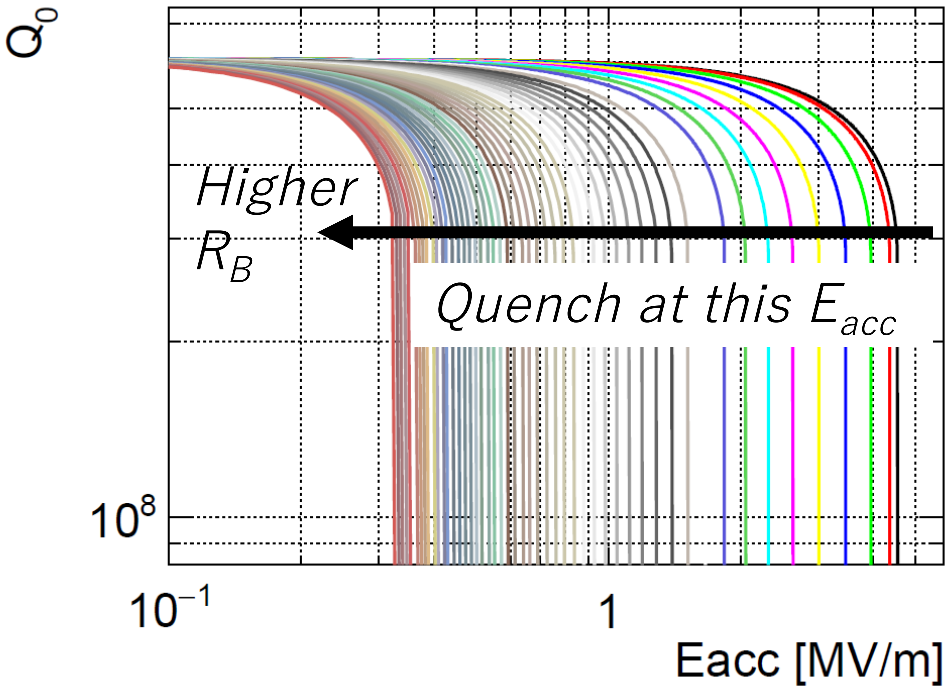


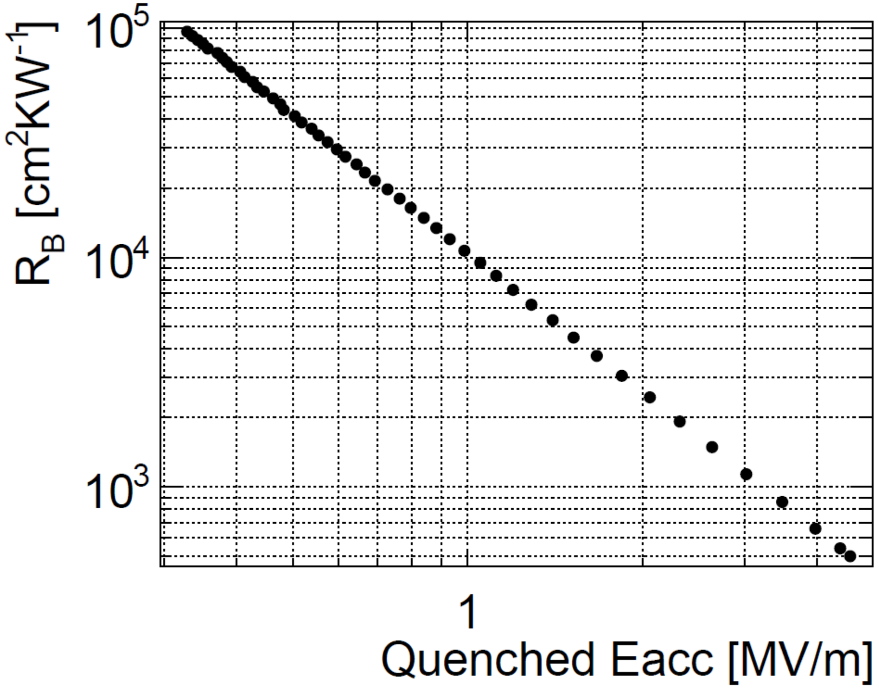
Even a very small (<<1mm) imperfection between Nb/Cu could make a huge thermal boundary $\mathbf{R_B}$ and could cause ***thermal runaway*** and could eventually create a local quenched spot on the film

→ This quench never gets catastrophic but may cause **Q-slope**

R_B → Local Quench field → Q_0

A lot of Q vs E of different R_B Convert! R_B vs quench field



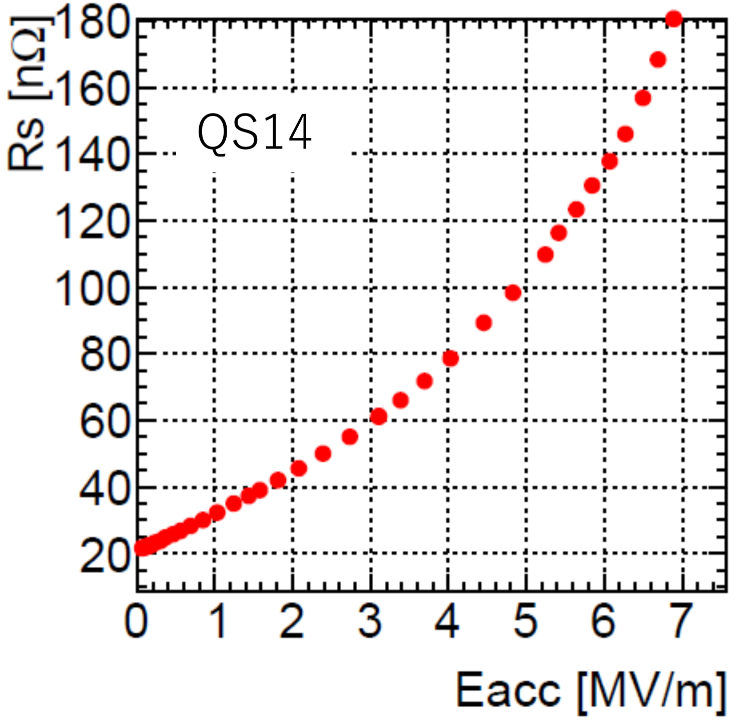


The experimental observable is an average over all thermal boundary R_B

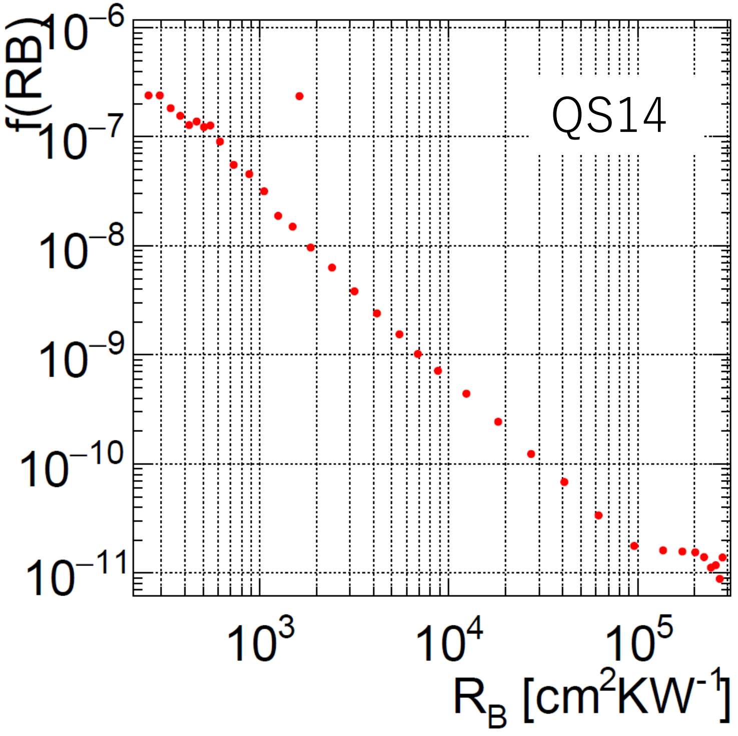
$$1/Q_0 \propto \overline{R_s(T_0, E_{acc})} = \int_0^{\infty} R_s(T_0, E_{acc}, R_B)\boldsymbol{f(R_B)}dR_B$$

$f(R_B)$ is the (**unknown**) distribution function of R_B due to imperfect interface.

Conversion: $Rs(E_{acc}) \rightarrow f(R_B)$ @ 4.5 K



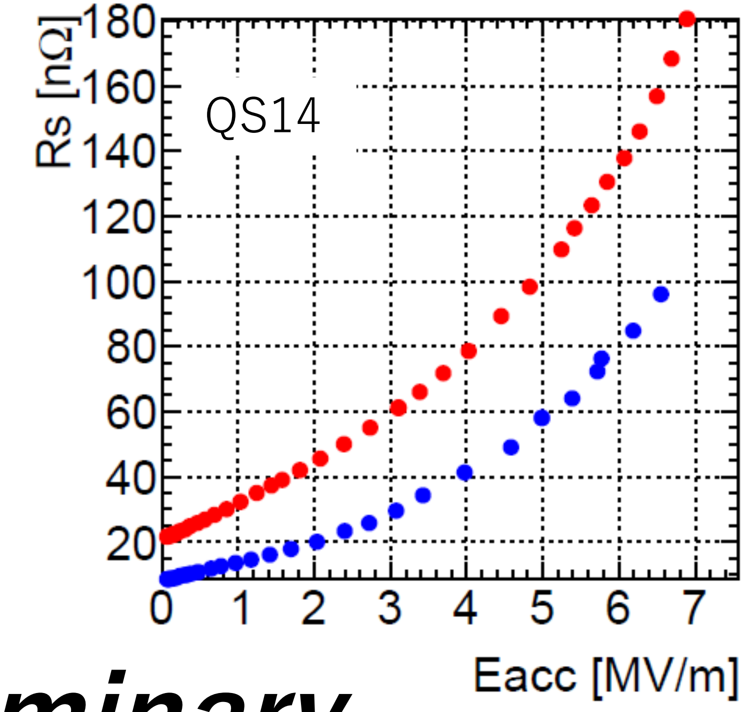
Map:
$Rs(E_{acc}) \rightarrow f(R_B)$
$(T_0;\ R_{res},\ A,\ \Delta)$



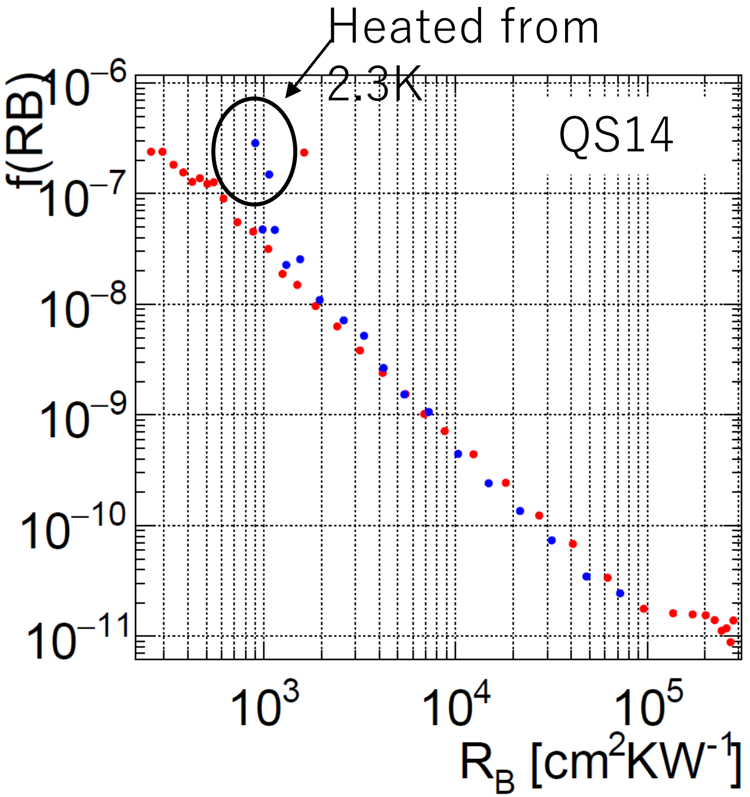
As a function of the bath temperature T_0
Rs [Q-slope] is converted to the distribution of thermal boundary

This is just a conversion (not a fit!) because $f(R_B)$ is unknown

Conversion: $Rs(E_{acc}) \rightarrow f(R_B)$ @ 2.3 K



Map:
$Rs(E_{acc}) \rightarrow f(R_B)$
$(T_0; R_{res}, A, \Delta)$

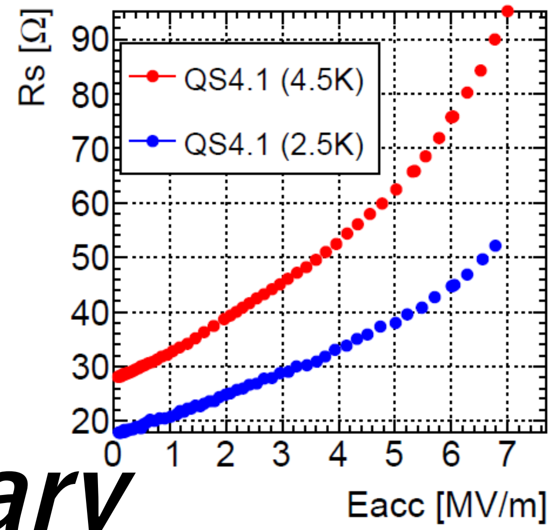


Preliminary

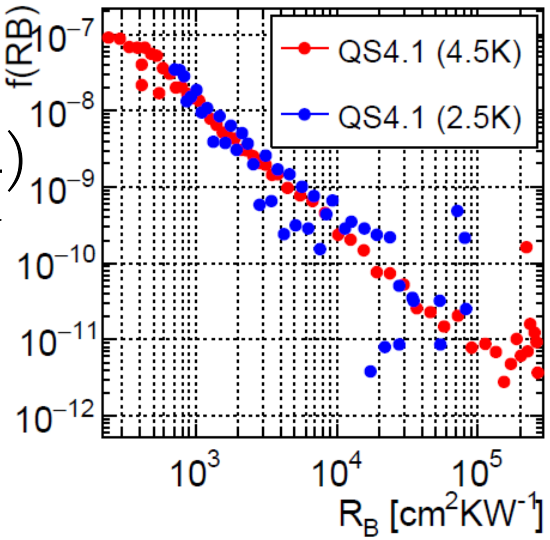
Two different Q-slopes at different temperatures are converted to the identical distribution of the thermal boundary !

How about the other cavities?

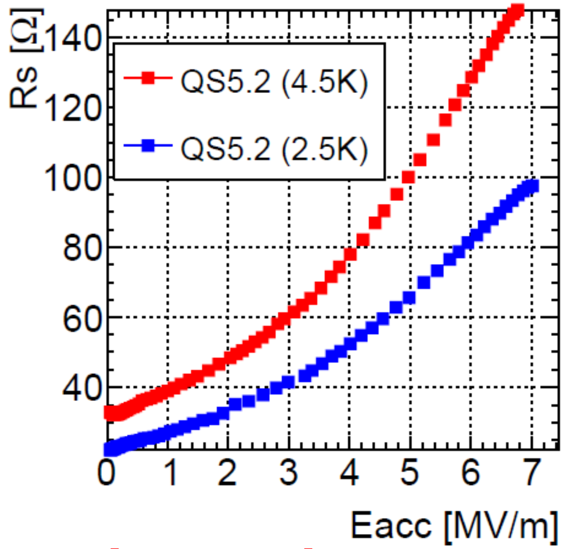
$Rs(E_{acc},T_0) \rightarrow f(R_B)$ other cavities



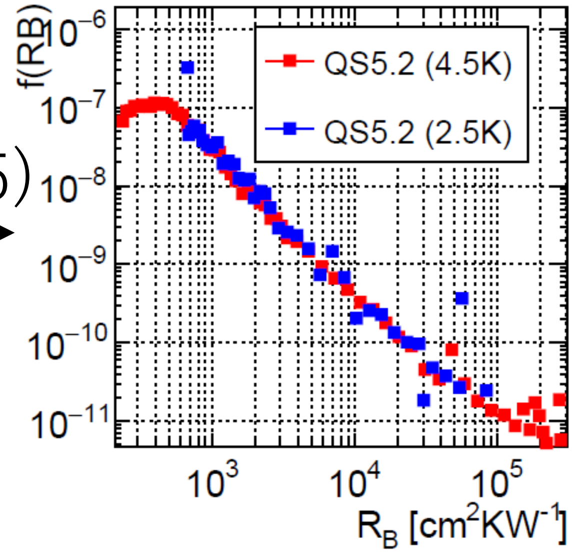
QS4.1 (2014)



Preliminary



QS5.2 (2015)



$f(R_B)$ does not depend on temperature → intrinsic property of the cavity?

On the thermal boundary problem…

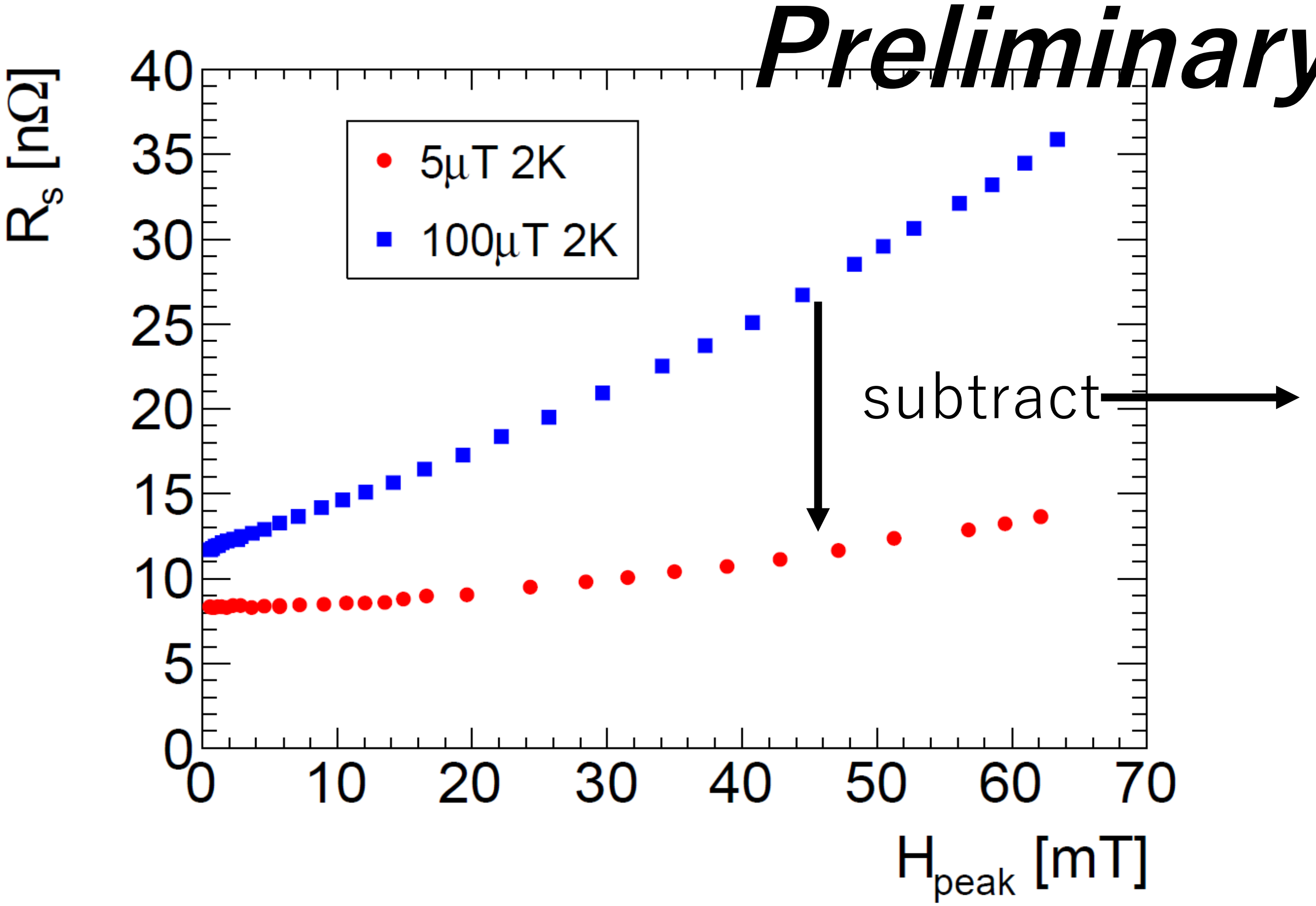
- Similar studies on Nb/Cu
  - A. Aull "Trapped flux measurements & thermal boundary resistance analysis for an ECR Nb film", 7th International Workshop on Thin Films, 27-29 July 2016, Jefferson Lab, US
  - R. Vaglio "Thermal boundary resistance model and defect statistical distribution in Nb/Cu cavities", SRF2017, 17-21 July 2017, Lanzhou, China

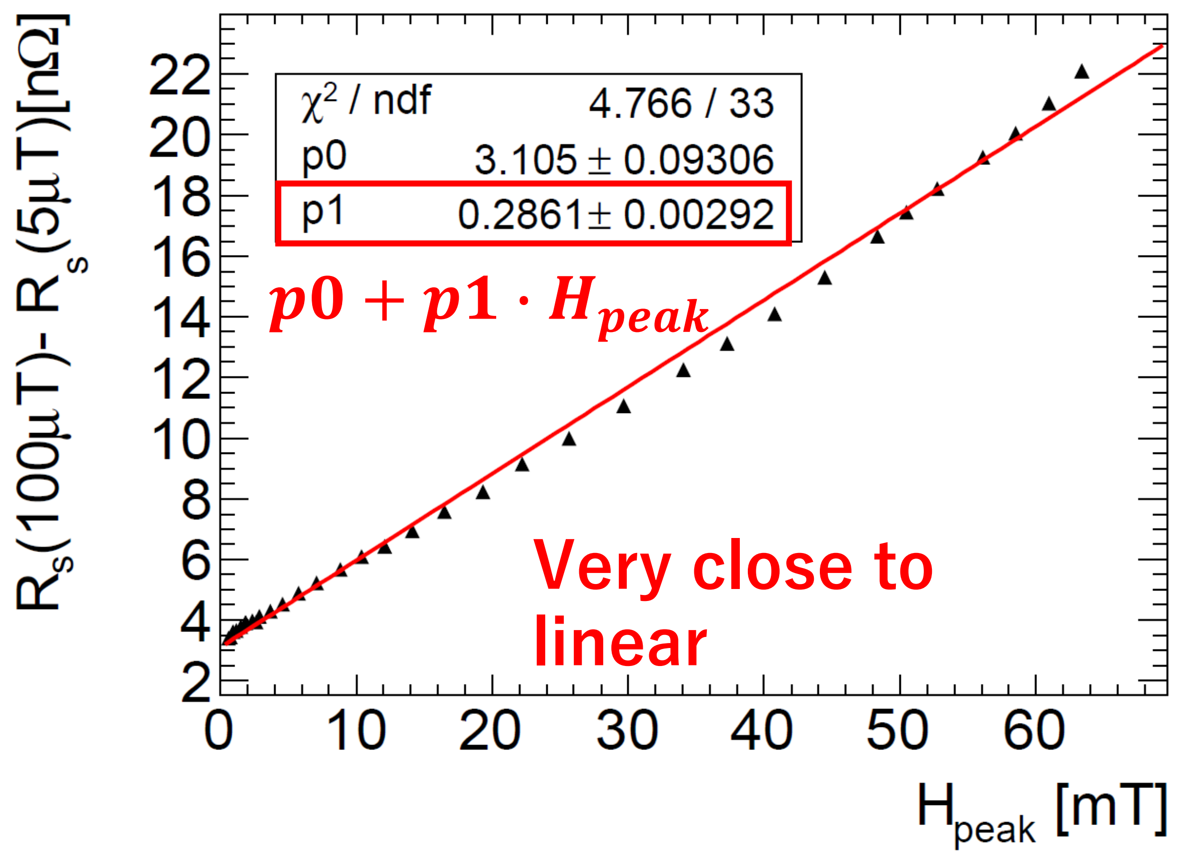
- This model should only be valid after the removal of cool down and the trapped vortex effect
- **However, $f(R_B)$ coincidence was also observed for vortex-trapped cavity or badly thermal-cycled cases**
- **Hernan Furci in SRF2017 presented that the thermal stability of micro quench requires relatively big defects**

➢ **The converted $f(R_B)$ may not be the distribution of the simple thermal boundary resistance**

- **This model is on hold → A different approach was investigated**

R_s caused by trapped flux in the film cavity is $\propto H_{RF}$





Surface resistance produced by a cool down under DC magnetic field is not constant of RF field

$$R_{fl} \sim H_{RF} \rightarrow P \sim H_{RF}^3$$

$$\boldsymbol{R_s / H_{RF,peak} H_{ext} \sim 3\times10^{-3}\ \mathrm{n\Omega (mT)^{-1} (\mu T)^{-1}}}$$

Bardeen-Stephen model

$$M\frac{\partial^2 \boldsymbol{u}}{\partial t^2} = -\boldsymbol{f}_v - \boldsymbol{f}_t + \boldsymbol{f}_L - \boldsymbol{f}_M + \boldsymbol{f}_p$$

M :effective inertial mass per unit length

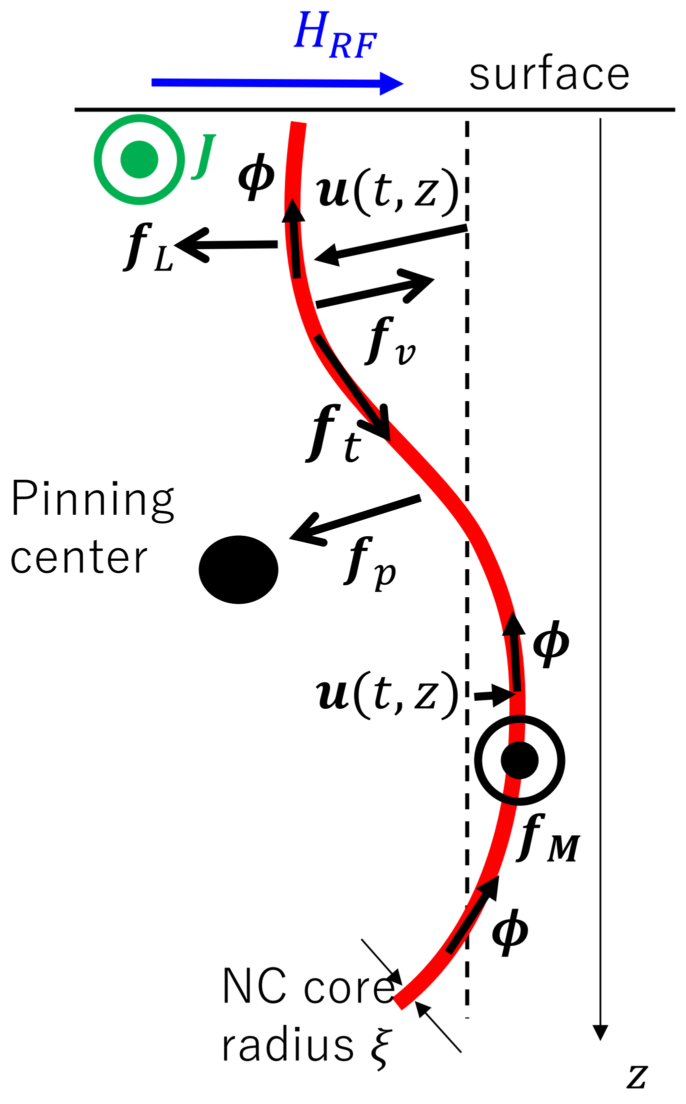
$\boldsymbol{f}_v = \eta\frac{\partial \boldsymbol{u}}{\partial t}$: viscos force

$\boldsymbol{f}_t = \frac{\delta F_e}{\delta \boldsymbol{u}} \propto \frac{\partial^2 \boldsymbol{u}}{\partial z^2}$: string tension force

$\boldsymbol{f}_L = \boldsymbol{J}\times\boldsymbol{\phi}$: Lorentz force

$\boldsymbol{f}_M = f n_s e\frac{\partial \boldsymbol{u}}{\partial t}\times\boldsymbol{\phi}$: Magnus force

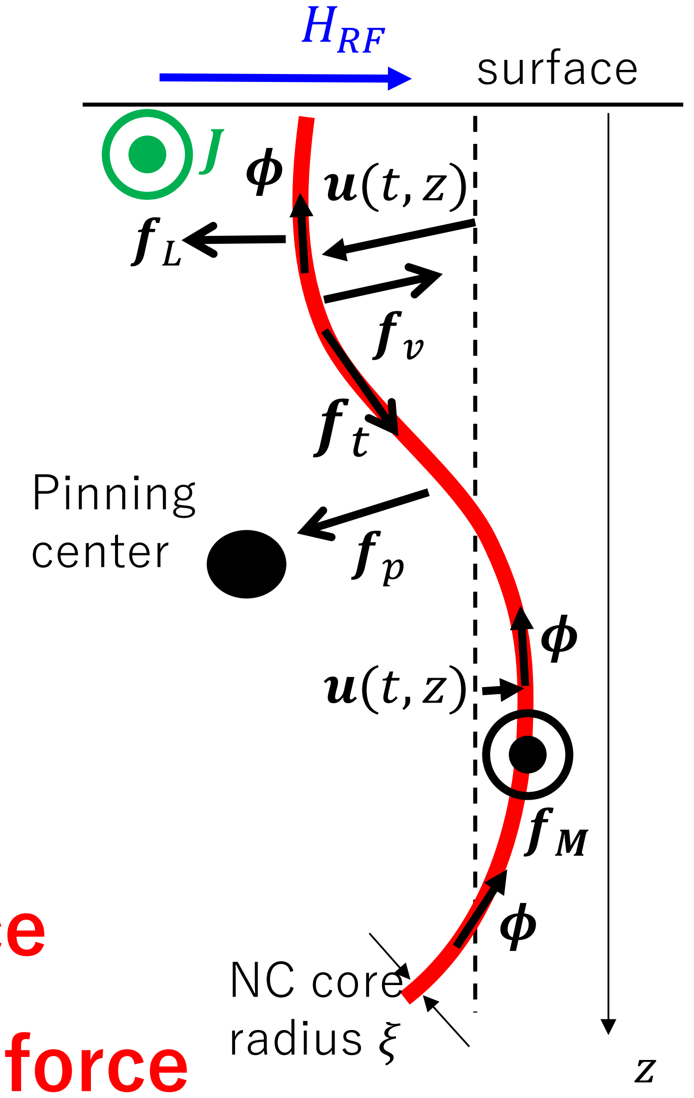
$\boldsymbol{f}_p$: Pinning force



Conventional calculations are linearized and does not predict $R_s \propto H_{RF}$

Rigid string model (J. I. Gittleman and B. Rosenblum, Phys. Rev. Lett. **16**, 734, 1966)

$$M\frac{\partial^2 \boldsymbol{u}}{\partial t^2} = -\boldsymbol{f}_v - \cancel{\boldsymbol{f}_t} + \boldsymbol{f}_L - \cancel{\boldsymbol{f}_M} + \boldsymbol{f}_p$$



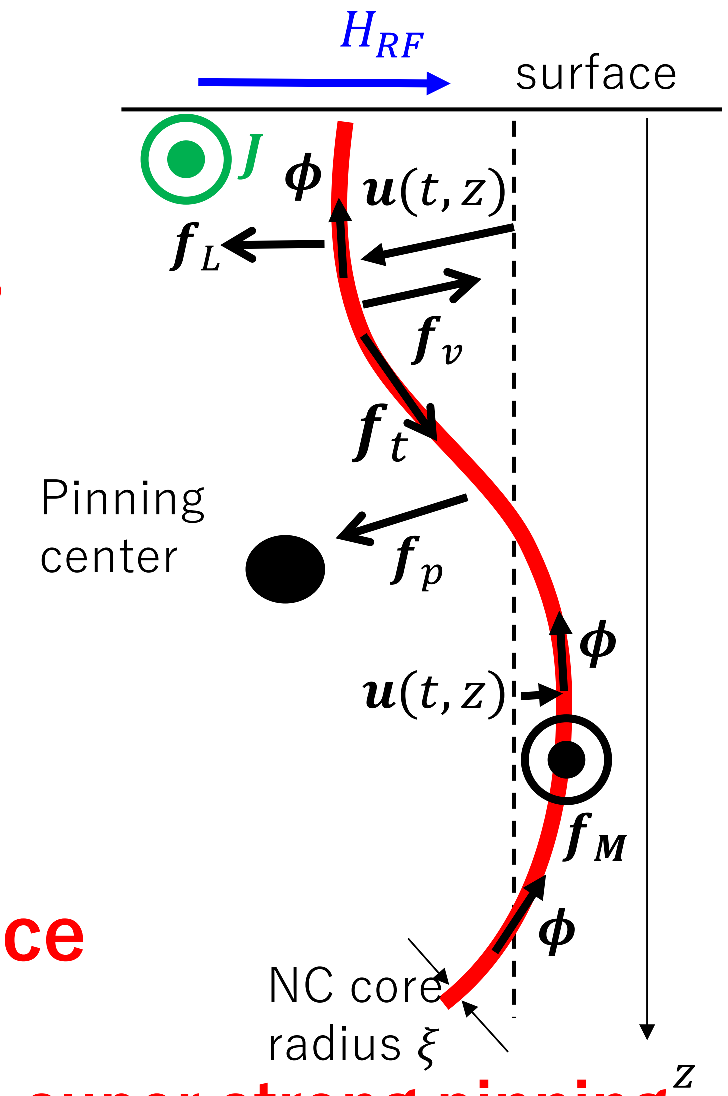
- M :effective inertial mass per unit length
- $\boldsymbol{f}_v = \eta\frac{\partial \boldsymbol{u}}{\partial t}$: viscos force
- $\cancel{\boldsymbol{f}_t = \frac{\delta F_e}{\delta \boldsymbol{u}} \propto \frac{\partial^2 \boldsymbol{u}}{\partial z^2}}$: string tension force **No tension**
- $\boldsymbol{f}_L = \boldsymbol{J}\times\boldsymbol{\phi}$: Lorentz force
- $\boldsymbol{f}_M = \cancel{f n_s e\frac{\partial \boldsymbol{u}}{\partial t}}\times\boldsymbol{\phi}$: Magnus force **No Magnus force**
- $\boldsymbol{f}_p$: Pinning force $\sim -\sum_i k\boldsymbol{u}(\boldsymbol{z}_i)$ **Linearized pinning force**

Linear ordinary differential equation → $u \propto J \propto H_{RF}$ → $P \propto \dot{u} f_L \propto H_{RF}^2$ → $\boldsymbol{R_s}$**: constant ☹**

Gurevich model (A. Gurevich and G. Ciovati, Phys. Rev. Lett. B **77**, 104501, 2008)

$$\cancel{M\frac{\partial^2 \boldsymbol{u}}{\partial t^2}} = -\boldsymbol{f}_v - \boldsymbol{f}_t + \boldsymbol{f}_L - \cancel{\boldsymbol{f}_M} + \cancel{\boldsymbol{f}_p}$$

- ~~M :effective inertial mass per unit length~~ **No mass**
- $\boldsymbol{f}_v = \eta \frac{\partial \boldsymbol{u}}{\partial t}$: viscos force
- $\boldsymbol{f}_t = \frac{\delta F_e}{\delta \boldsymbol{u}} \propto \frac{\partial^2 \boldsymbol{u}}{\partial z^2}$: string tension force
- $\boldsymbol{f}_L = \boldsymbol{J} \times \boldsymbol{\phi}$: Lorentz force
- $\cancel{\boldsymbol{f}_M = f n_s e \frac{\partial \boldsymbol{u}}{\partial t} \times \boldsymbol{\phi}}$: Magnus force **No Magnus force**
- ~~$\boldsymbol{f}_p$: Pinning force~~

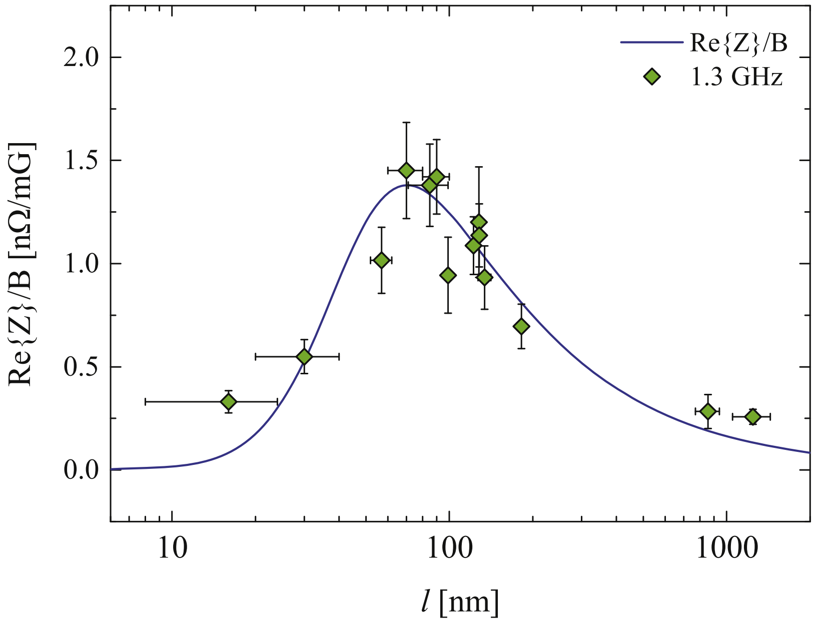


No pinning force → fix $\boldsymbol{u}(z_i) = 0$ → super strong pinning

Linear partial differential equation → $u \propto J \propto H_{RF}$ → $P \propto \dot{u} f_L \propto H_{RF}^2$ → $\boldsymbol{R_s}$**: constant ☹**

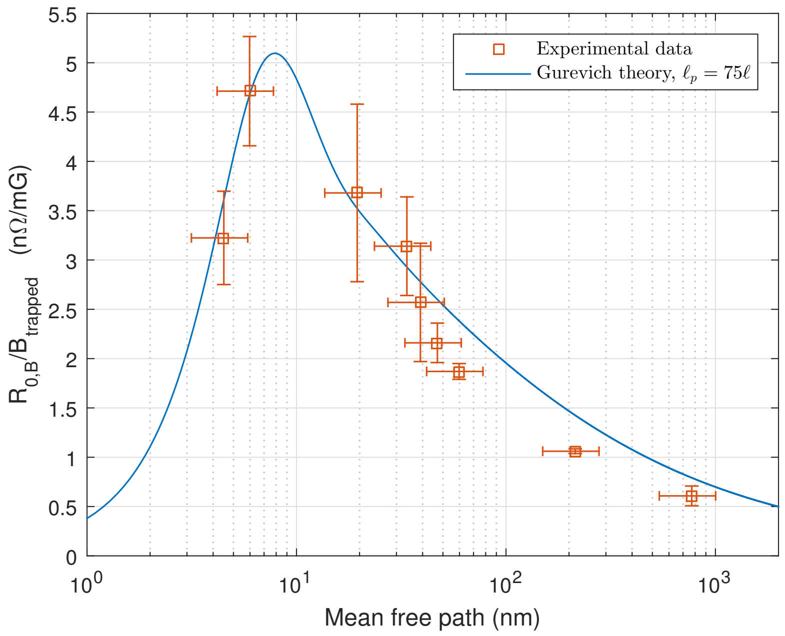
R_{fl} vs m.f.p.

Bulk Nb fitted by G-R model



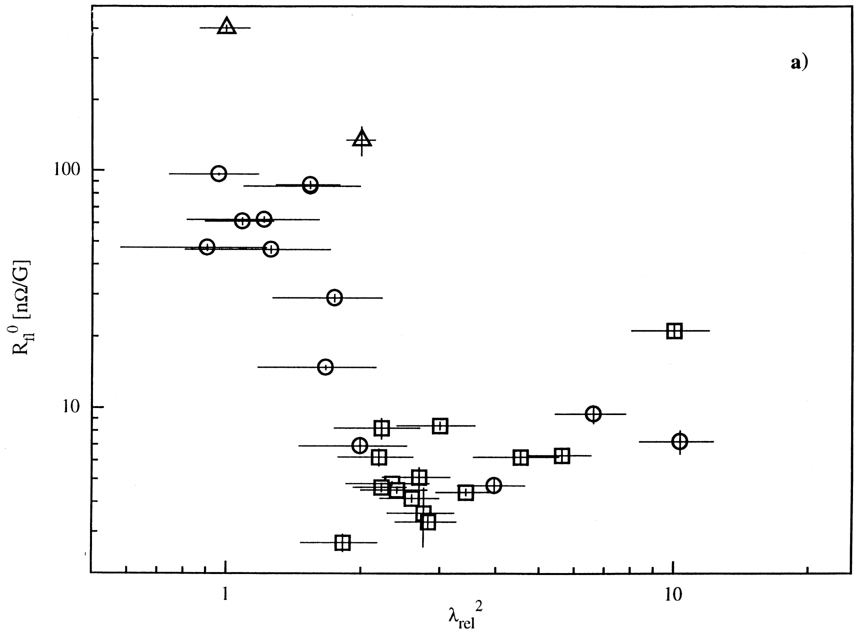
M. Checchin et al., Supercond. Sci. Technol. 30, 034003 (2017)

N-doped Nb fitted by Gurevich model



Gonnella, D., J. Kaufman, and M. Liepe, J. of Appl. Phys. 119, 073904 (2016)

Nb/Cu 1.5 GHz elliptical



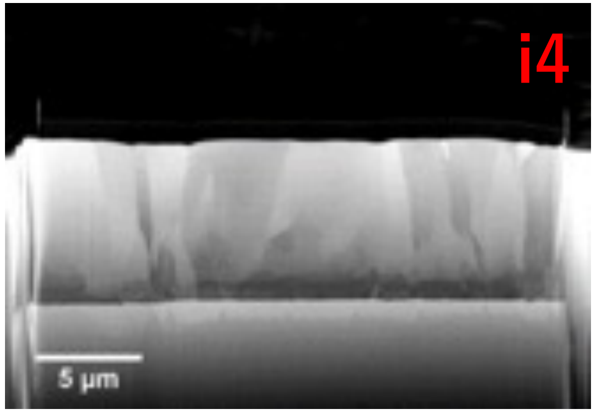
C. Benvenuti et al., Physica C. 316, 153 (1999)

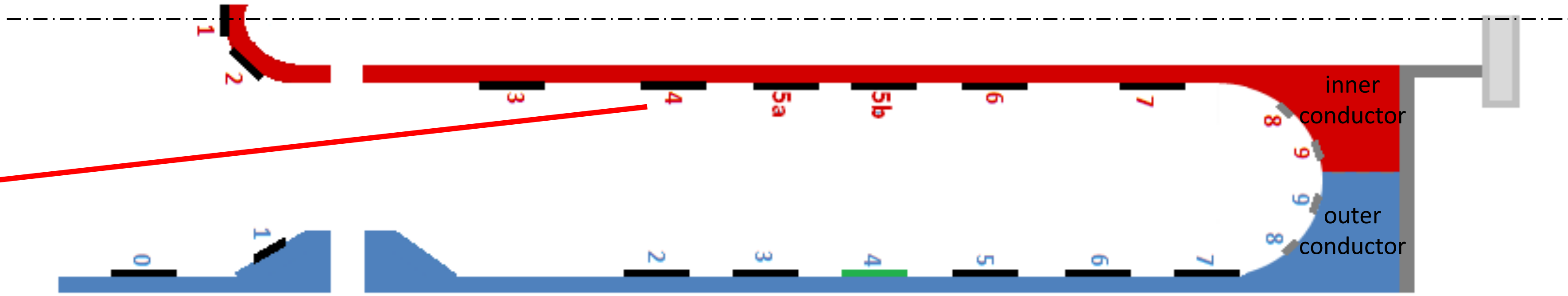
Not only the linearity, but old study showed dependence on mean free path opposite to bulk Nb and N-doped Nb.

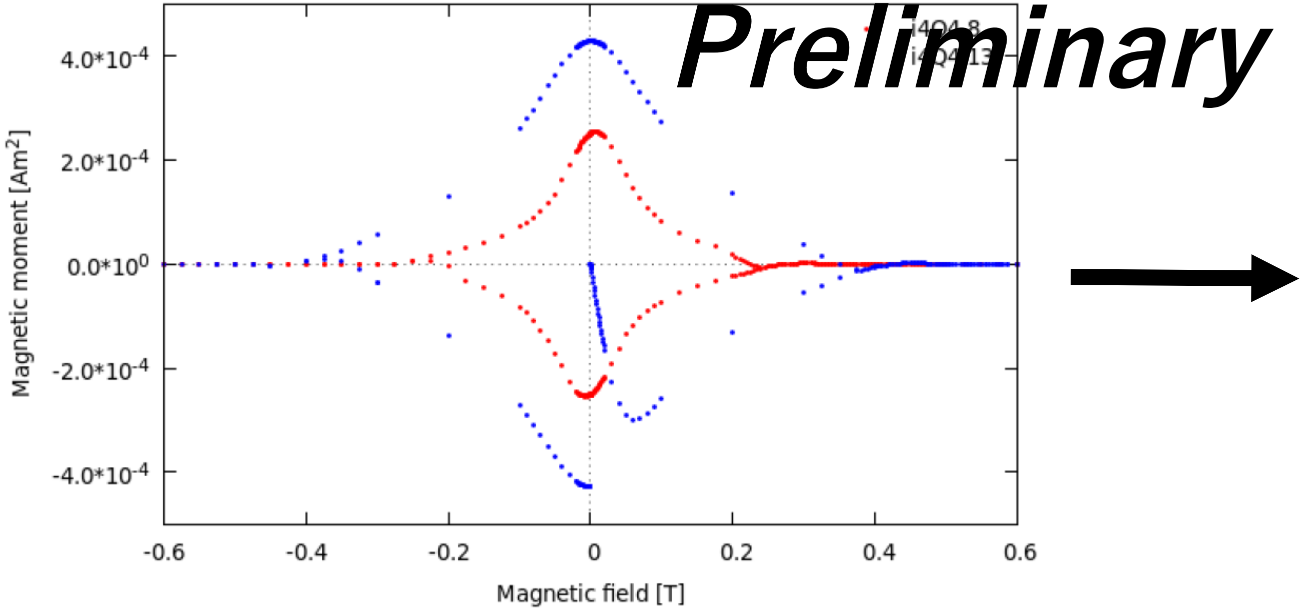
→Where are we, in flux-pinning or flux-flow regime?

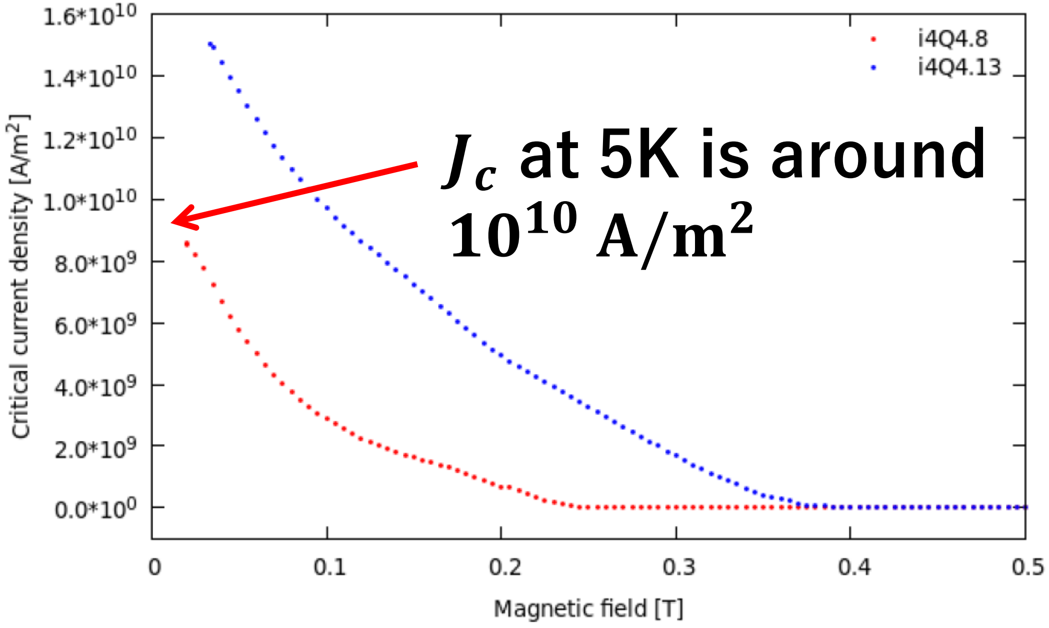
Pinning force → De-pinning critical current J_c

The de-pinning critical current J_c can be obtained by the hysteresis loop of M(H)





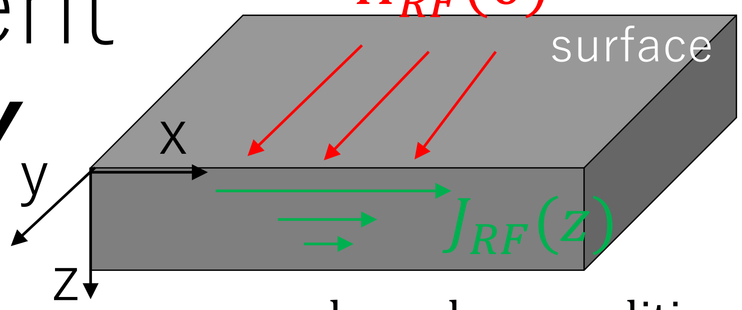




Comparison with peak RF current

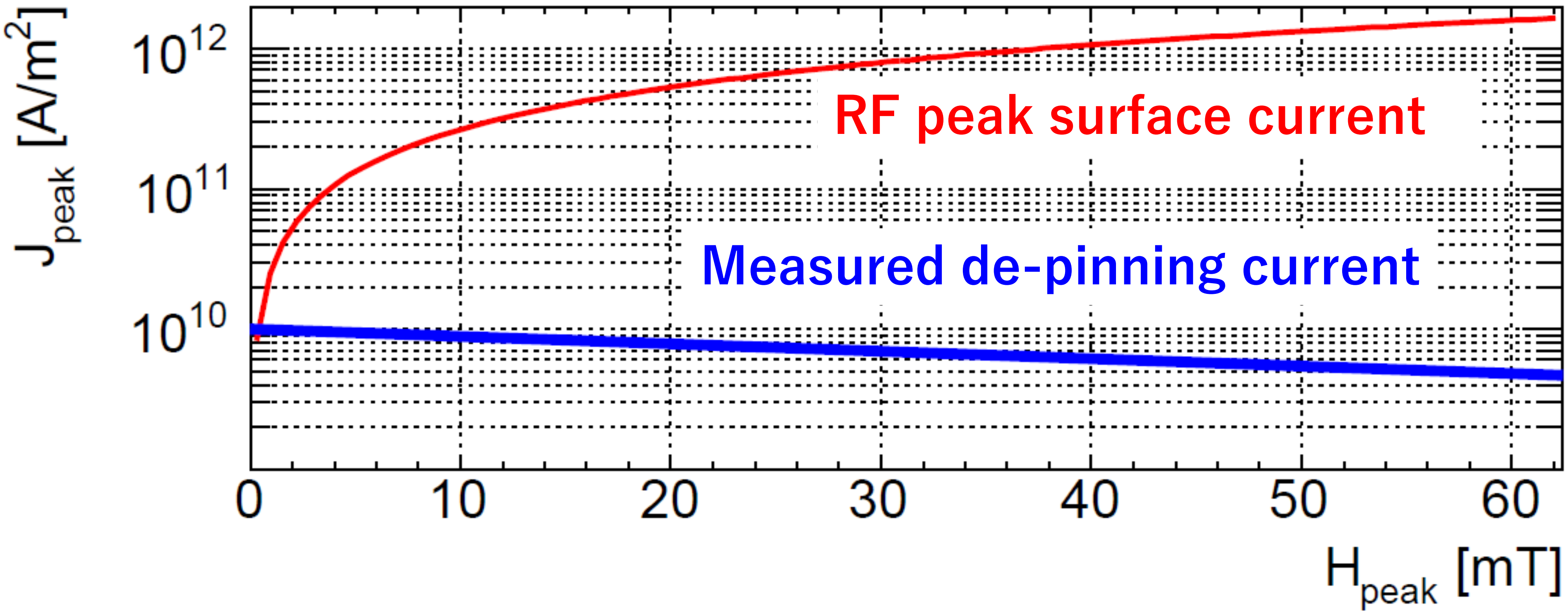
Ampere's law: $\int_{z=0}^{\infty} J_{RF}(z')dz' = H_{RF}$ ***Preliminary***

$\rightarrow J_{RF}(0) = H_{RF}/\lambda\ [\mathrm{A/m^2}]$



boundary condition

$\lim_{z\to\infty} |\vec{J}(z)| = 0$



<u>**The peak RF current is one or two orders of magnitude higher than the de-pinning current**</u>

→ The pinning force is "weak"

The description by the collective weak pinning

Preliminary

- The vortex near the surface becomes free from single pinning center during its RF cycle
  → **statistical sum of many pinning centers**

- Cornell's analytical approximation resulted in

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

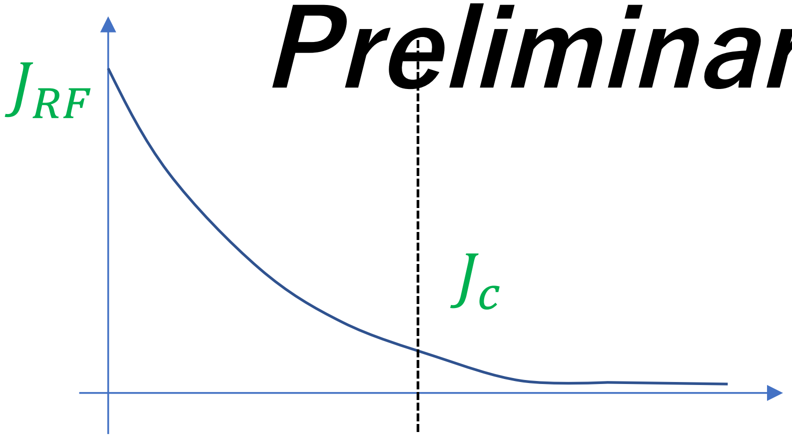
$$\frac{R_{fl}}{H_{ext}H_{RF}} \sim {\color{red}\mathbf{1.7\times10^{-3}}}\ \mathrm{n\Omega(mT)^{-1}(\mu T)^{-1}}$$

- On the other hand, experiment showed

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

→ Good agreement! Only a factor of two!

- HIE-ISOLDE cavity: f = 100 MHz



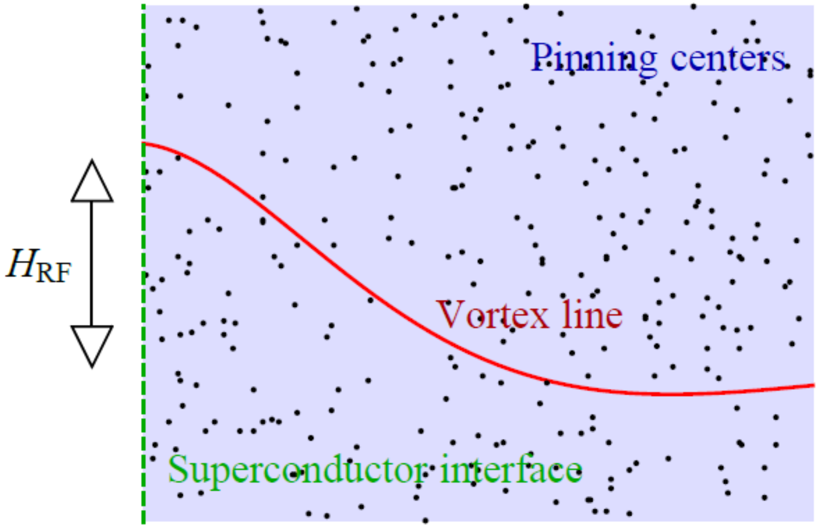


FIG. 4 Motion of a single trapped vortex subject to an RF field and collective pinning forces.

D. B. Liarte SRF2017

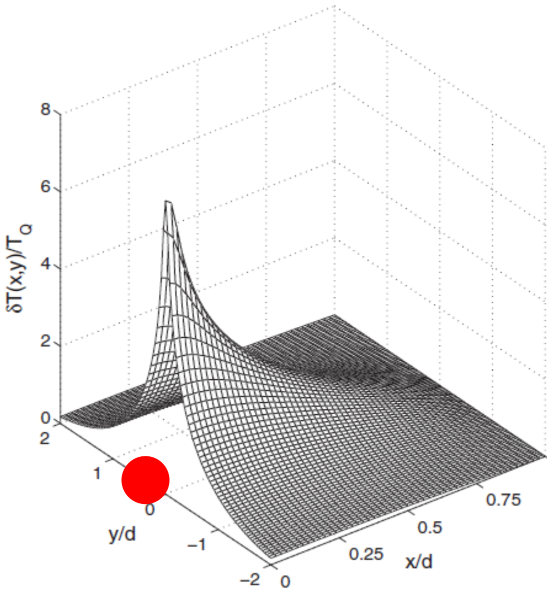
Summary & outlook & open questions

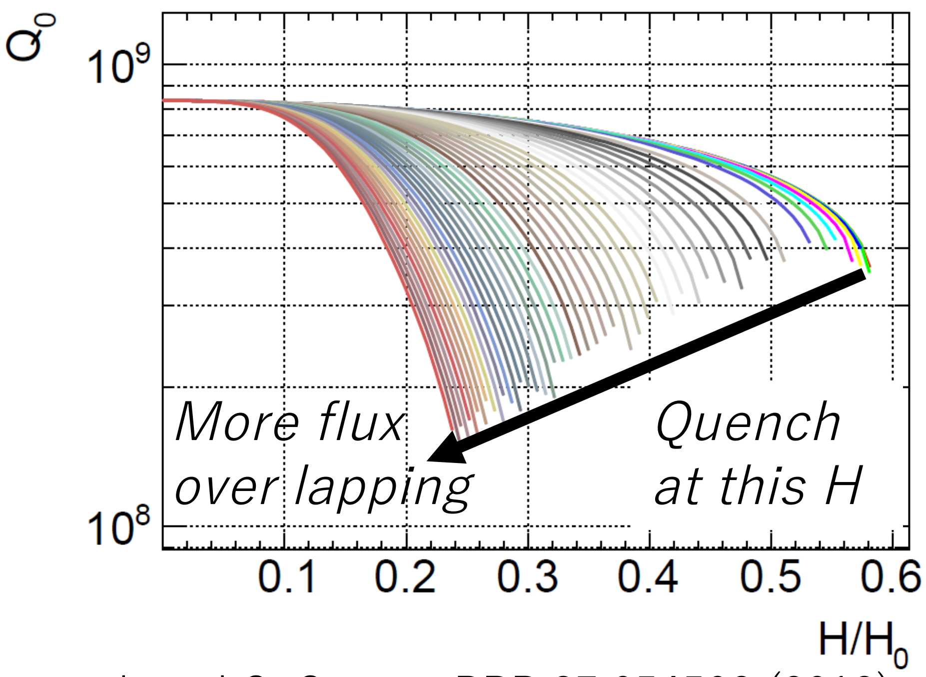
- Q-slope may have the same temperature dependence as the thermal boundary problem
  - However, this was unreasonably valid for bad thermal cycled cases or trapped vortex cases
- Q-slope caused by the trapped vortex cannot be explained by the conventional models of vortex motion because they are linearized
- The de-pinning current measurement resulted in a good agreement with the recently proposed collective weak pinning model
  - **A similar study for Nb_3Sn/Nb cavities will be desired**
  - **Can this model explain m.f.p. dependence?**
  - **Why was the Q-slope explained by the thermal problem?**
- Possible discriminant: harmonics production (Thanks to S. Calatroni)
  - Thermal problem → slow → averaged over RF period
  - Vortex oscillation → fast → harmonics production
  - $H(t) \equiv H_0 \cos(\omega t) + a_{2nd} H_0^2 \cos(2\omega t) + a_{3rd} H_0^3 \cos(3\omega t) + \cdots$
  - Dedicated measurement will be interesting
- Non phenomenological approach (quasi-classical theory)?

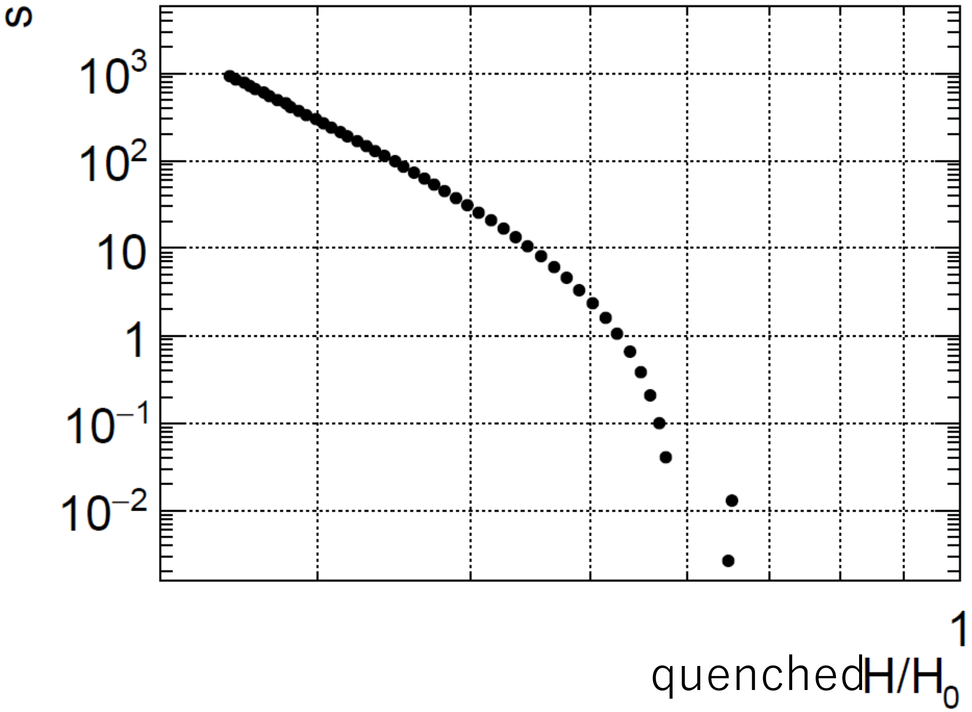
backup

Vortex lighter?

$$1/Q_0 \propto \overline{R_s(T_0, E_{acc})} = \int_0^\infty R_s(T_0, E_{acc}, s)\boldsymbol{f(s)}ds$$







A. Gurevich and G. Ciovati, PRB 87 054502 (2013)

- Condensation of trapped vortex → local quench → Similar plot as R_B was obtained

$$1/Q_0 \propto \overline{R_s(T_0, E_{acc})} = \int_0^\infty \boldsymbol{f(R_B)}dR_B \int_0^\infty \boldsymbol{f(s)}ds R_s(T_0, E_{acc}, s)$$

- The converted function could be a distribution of micro-quench's cause