BCS parameter determination of Nb/Cu cavities

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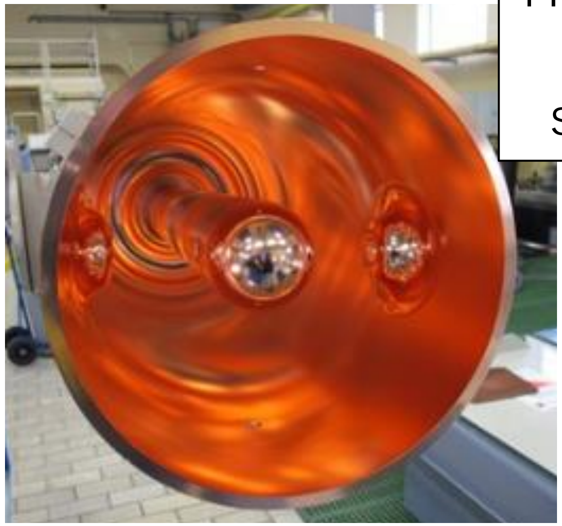
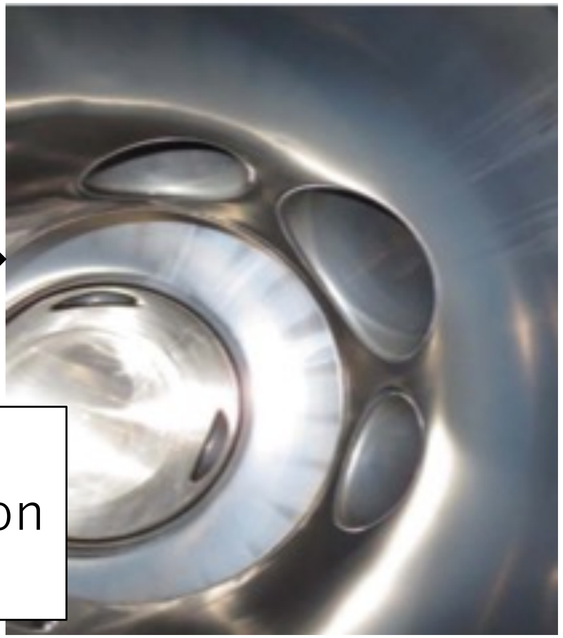
CERN SRF cavities: Nb film (a few μm) on Cu



HIE-ISOLDE
DC-bias
sputtering

LHC
DC-magnetron
sputtering



<u>Several advantages compare with bulk Nb</u>

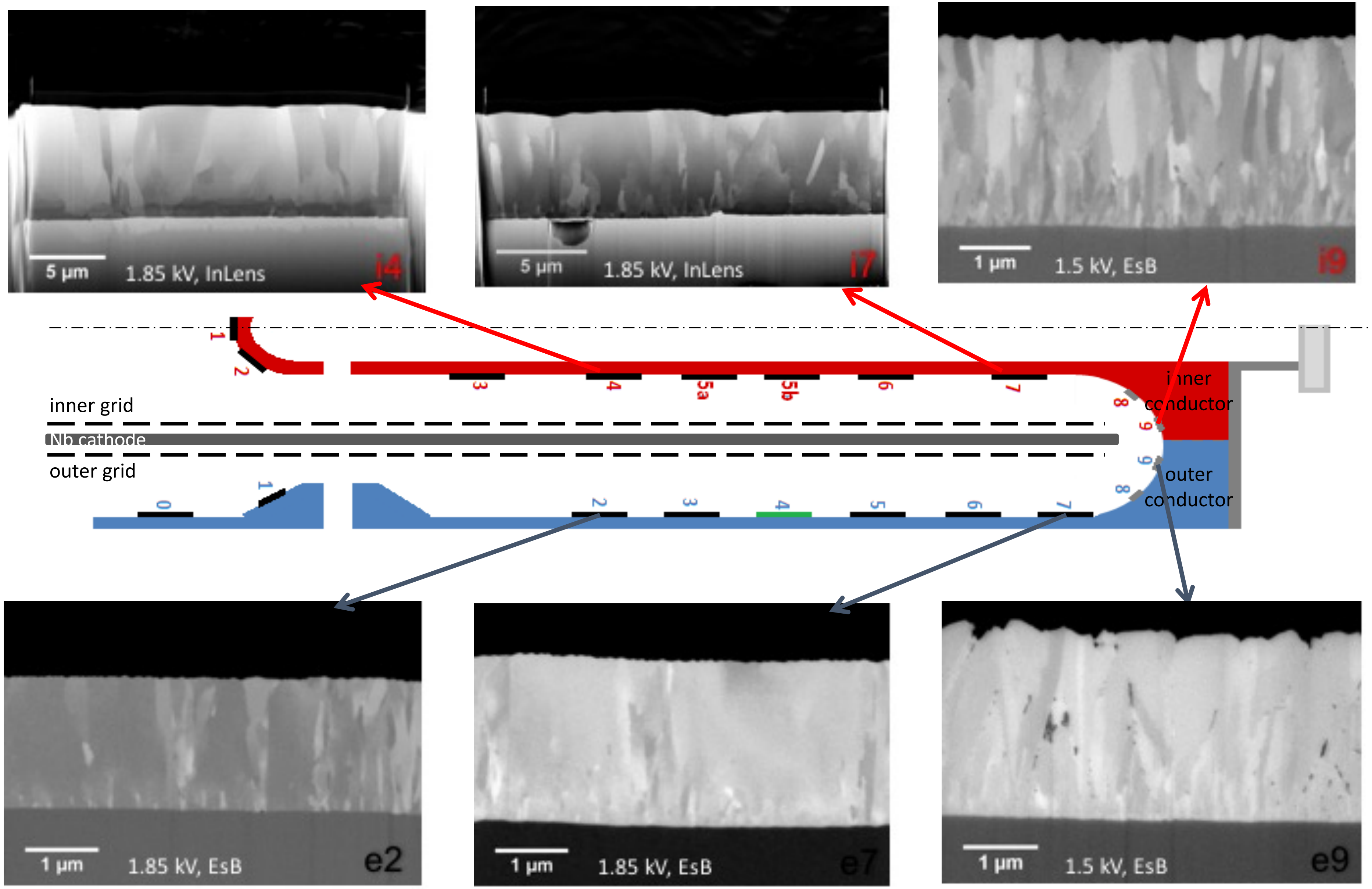
i) No global quench (κ_{Cu} = 400 W/mK)
ii) Mechanically stiff
iii) Cheaper raw material
iv) Insensitive to the external magnetic field

Mechanically, thermodynamically, and economically better than bulk Nb!

How about the superconducting properties?

Use HIE-ISOLDE project data for systematic analysis

FIB-SEM cross section imaging



FIB-SEM cross section imaging

Fine grain structure (<< 1µm)

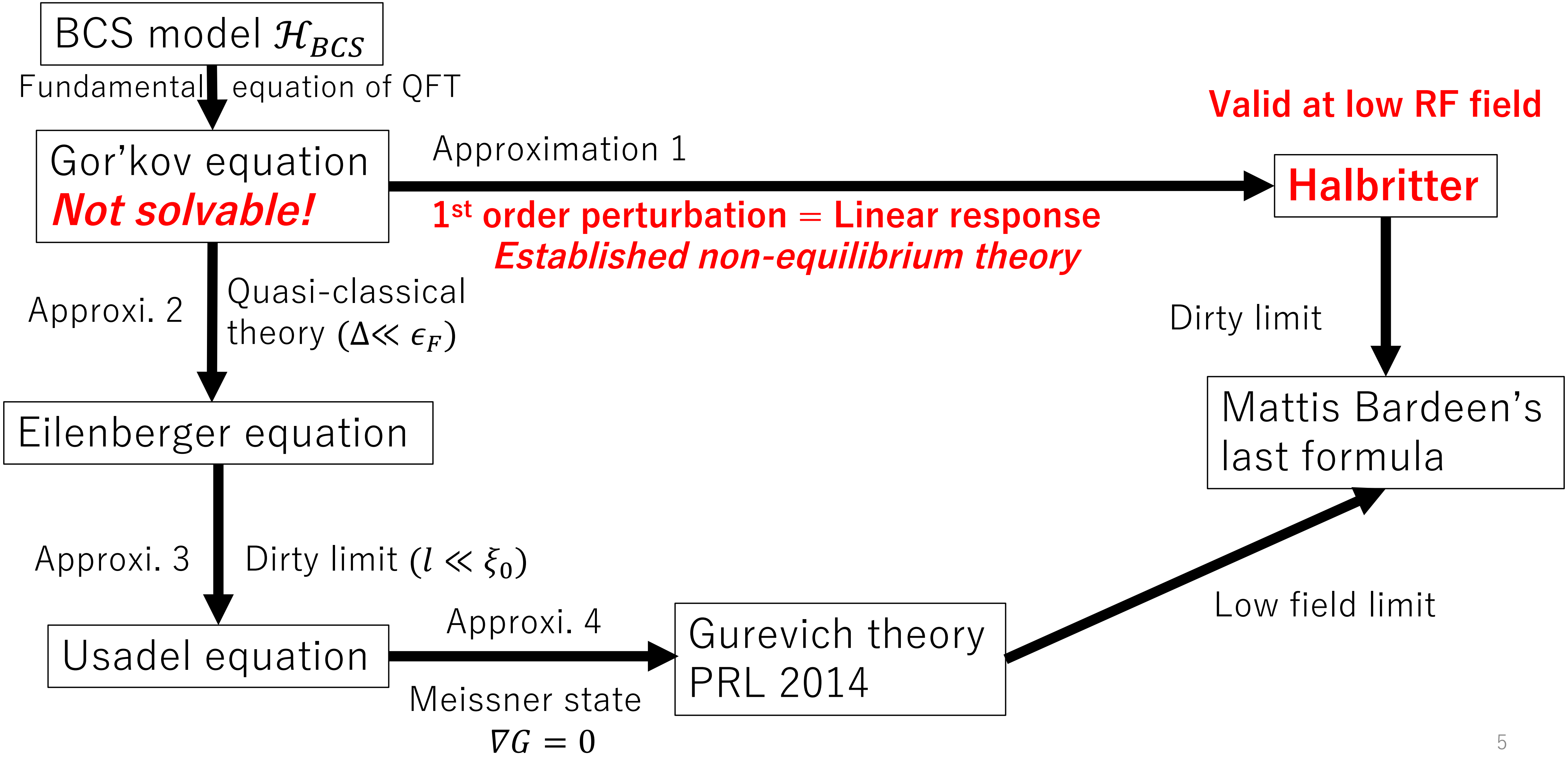
→ Parameter determination **without literature** of clean bulk Nb

<u>Material parameters</u>

1. BCS coherence length ξ_0
2. London penetration depth λ_L
3. Mean free path l
4. Coupling $\Delta_0/k_B T_c$

→ Based only on experimental results and BCS theory

Non-equilibrium BCS theory for Z_s calculation



RF data fitting by BCS impedance

Theoretical calculation

Surface resistance $R_{BCS}(T; \xi_0, \lambda_L, l, \Delta_0/k_B T_c)$

Effective penetration depth $\lambda_{BCS}(T; \xi_0, \lambda_L, l, \Delta_0/k_B T_c)$

Experimental data

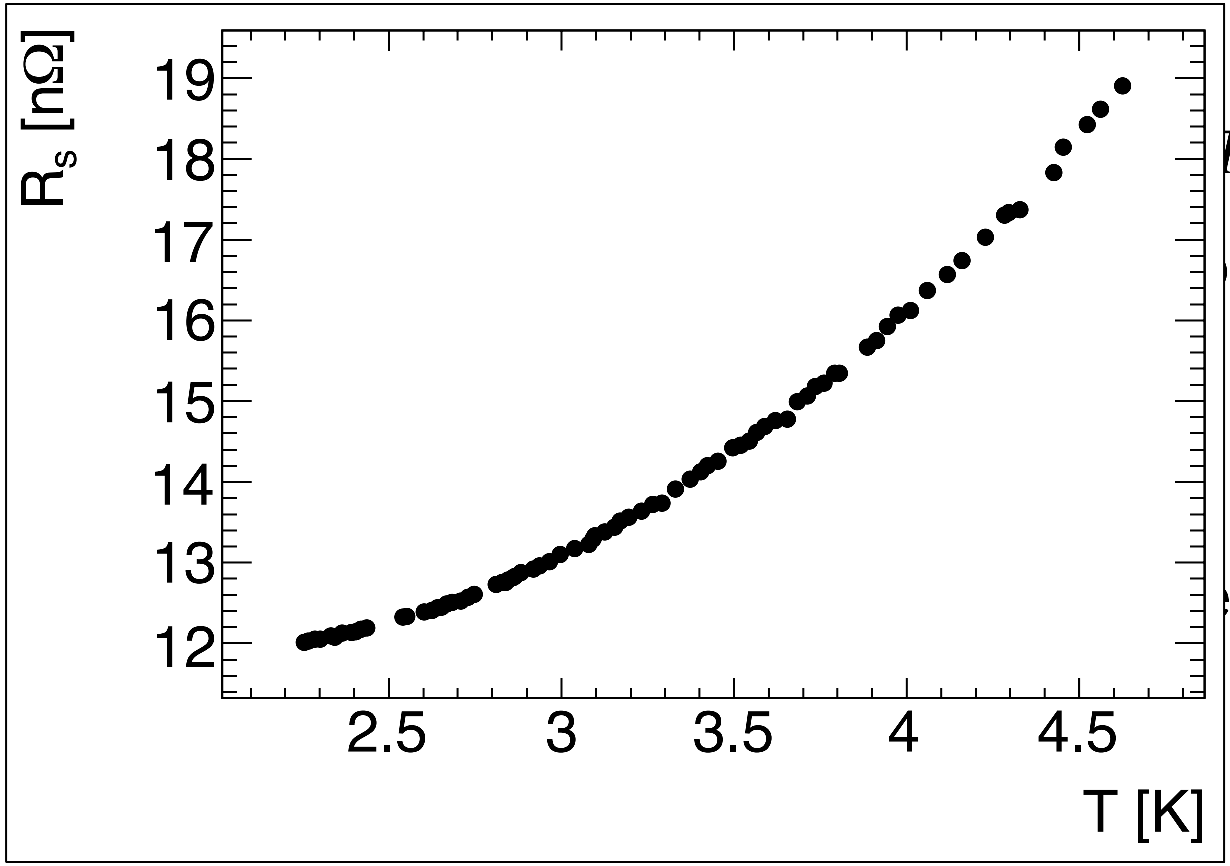
Surface resistance $R_{data} = R_s(T) - R_{res}$

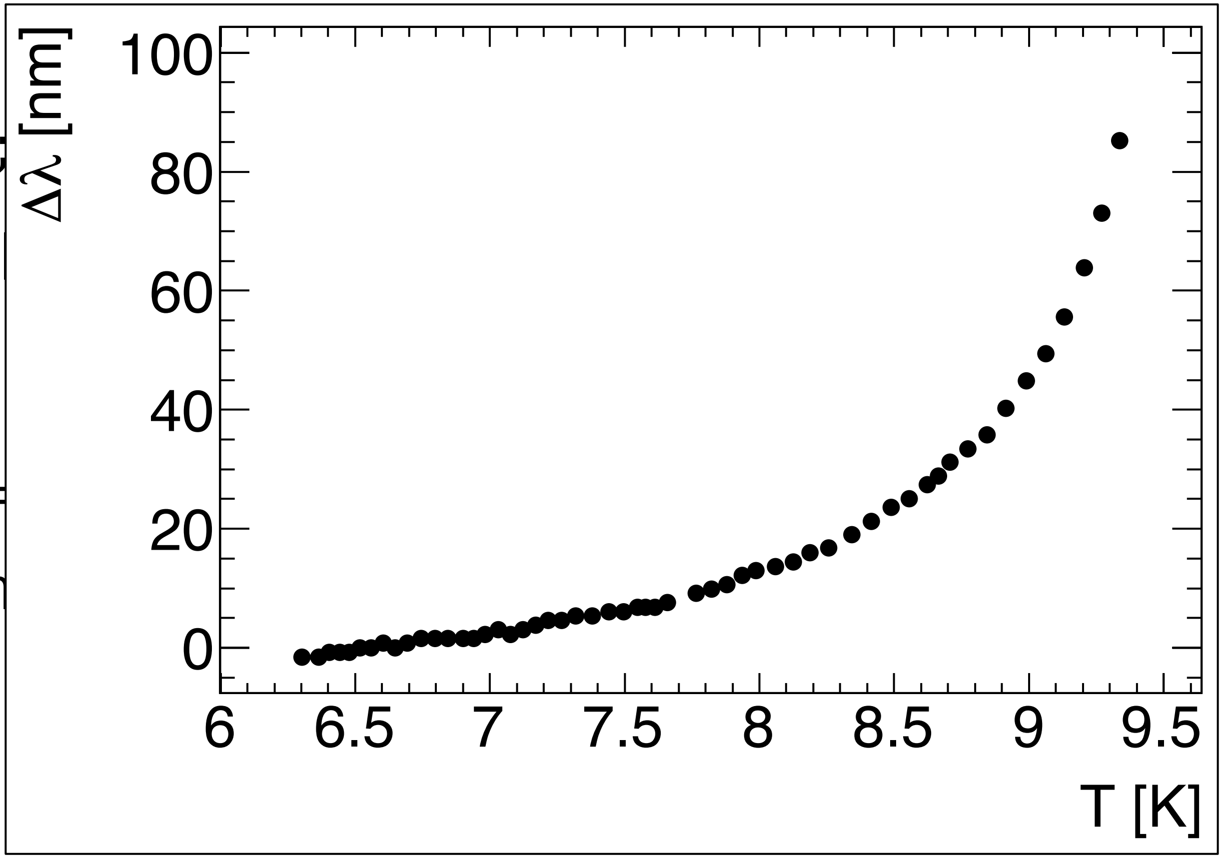
Shift in resonance frequency $\Delta f(T) \propto \Delta\lambda(T)$

χ^2 to be minimized

$$\chi^2_{R_s} = \sum_{j=1}^{n_{R_s}} \left[\frac{R_{BCS}(T_j) - R_{data}(j)}{\sigma_{R_s}(j)} \right]^2 \qquad \chi^2_{\lambda} = \sum_{j=1}^{n_{\lambda}} \left[\frac{\Delta\lambda_{BCS}(T_j) - \Delta\lambda(j)}{\sigma_{\lambda}(j)} \right]^2$$

RF data fitting by BCS impedance



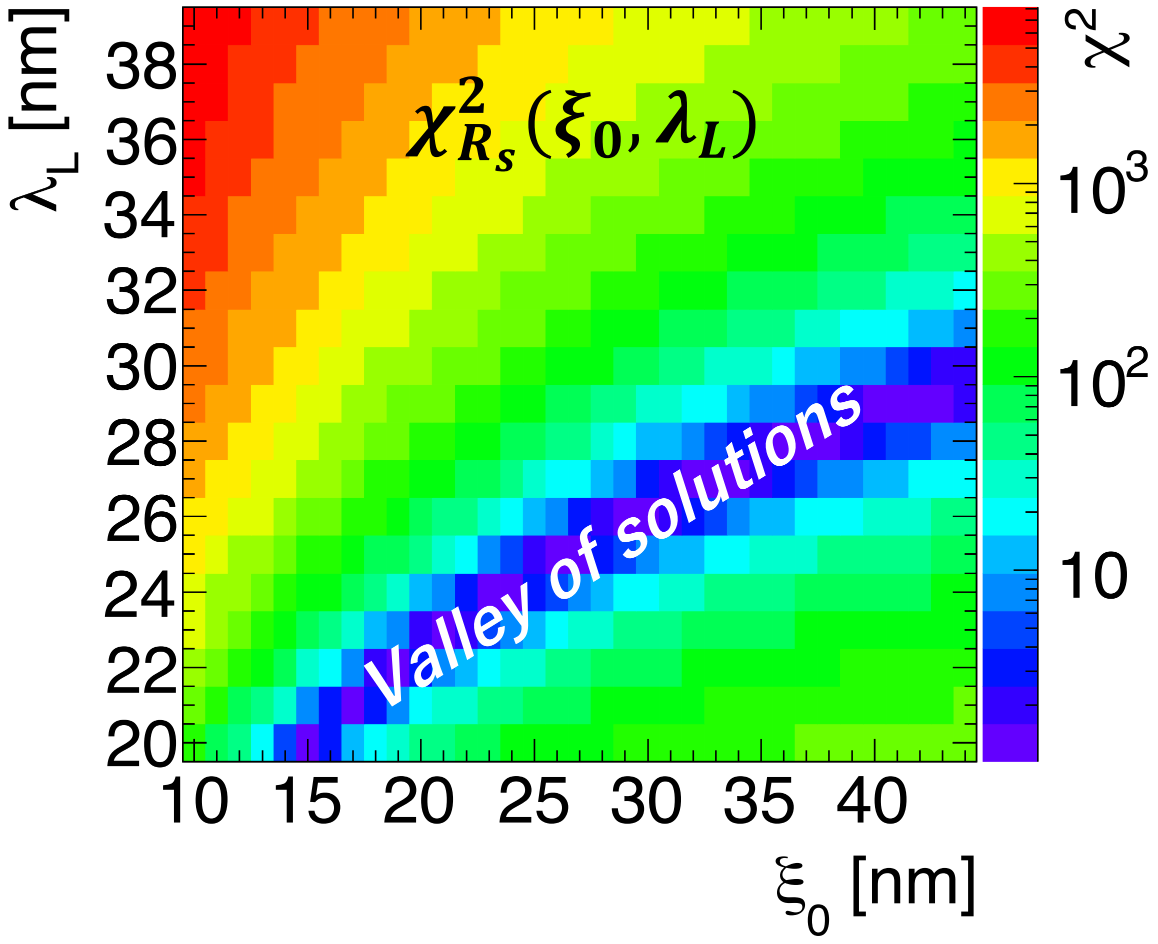


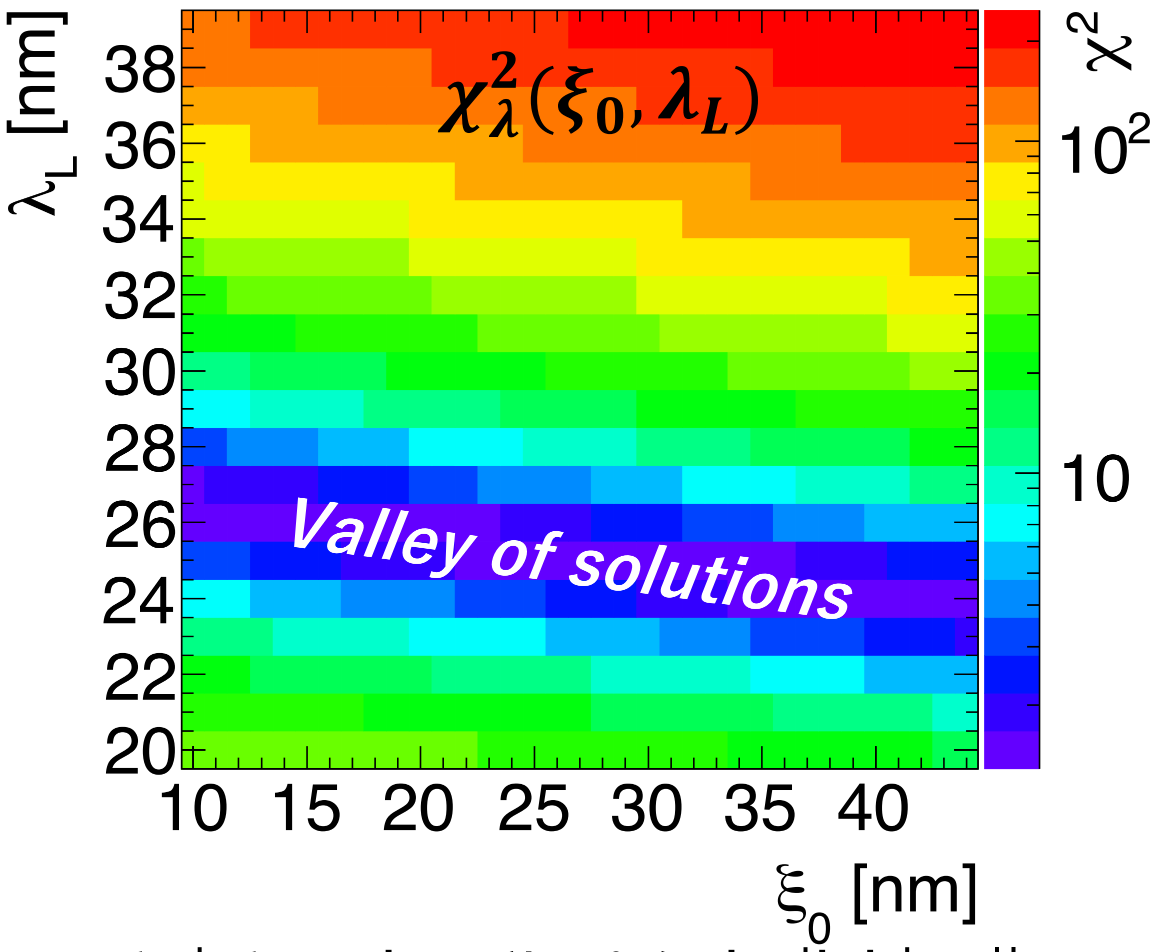
$$\chi^2_{R_s} = \sum_{j=1}^{n_{R_s}} \left[\frac{R_{BCS}(T_j) - R_{data}(j)}{\sigma_{R_s}(j)} \right]^2$$

$$\chi^2_{\lambda} = \sum_{j=1}^{n_{\lambda}} \left[\frac{\Delta\lambda_{BCS}(T_j) - \Delta\lambda(j)}{\sigma_{\lambda}(j)} \right]^2$$

Correlation among parameters → Simultaneous fit required

Example: 4D hyper-surface → 2D cross-section in ξ_0-λ_L plane ($l = 99$ nm, $\Delta_0/k_BT_c = 1.7$)

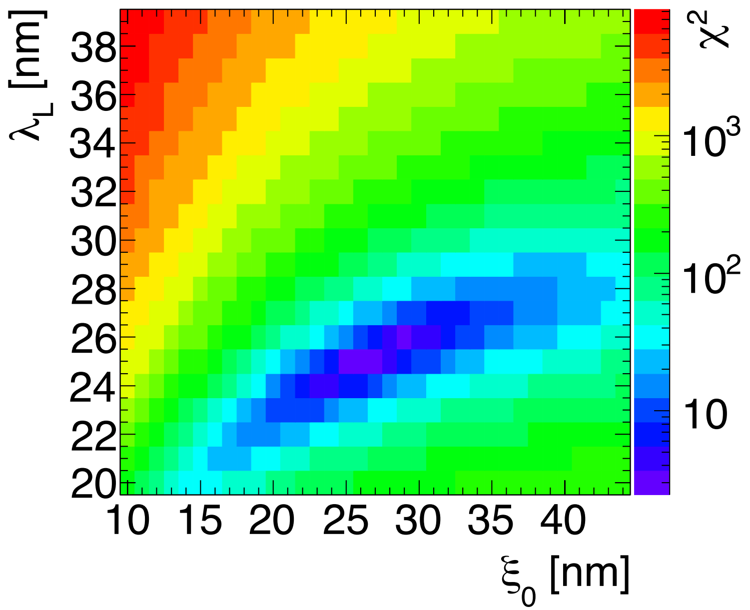


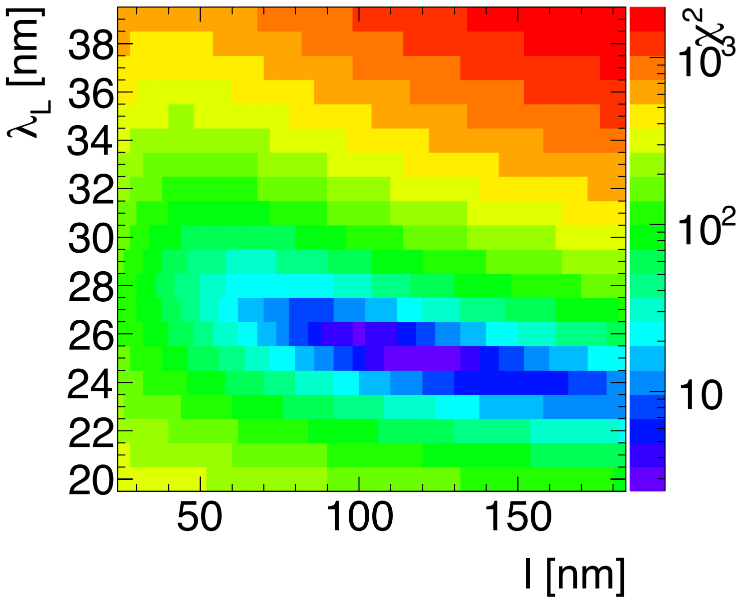


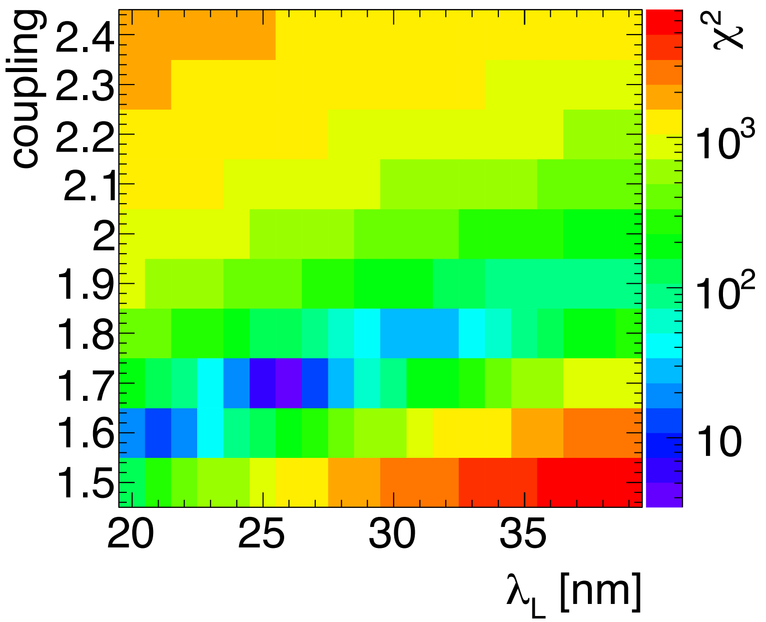
Surface resistance and penetration depth cannot determine (ξ_0, λ_L) individually

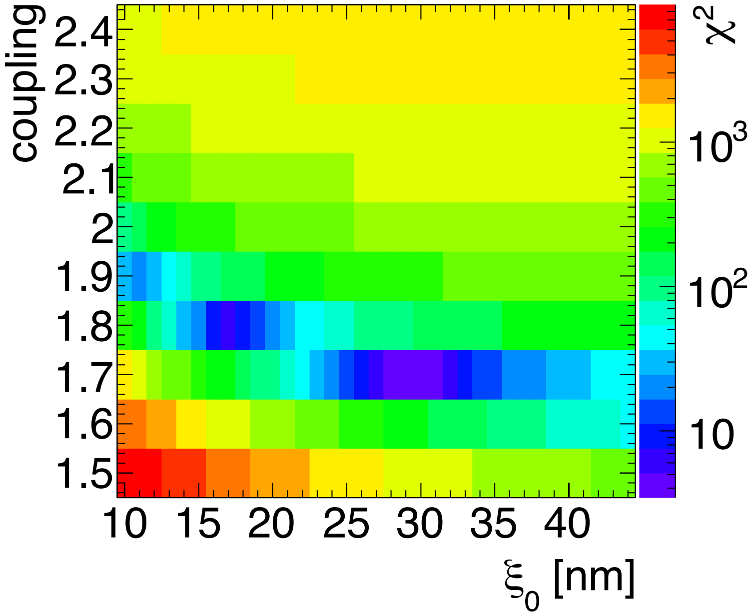
→ Intersection by merging χ^2 may give the true solution (*See Sam Posen's PhD thesis*)

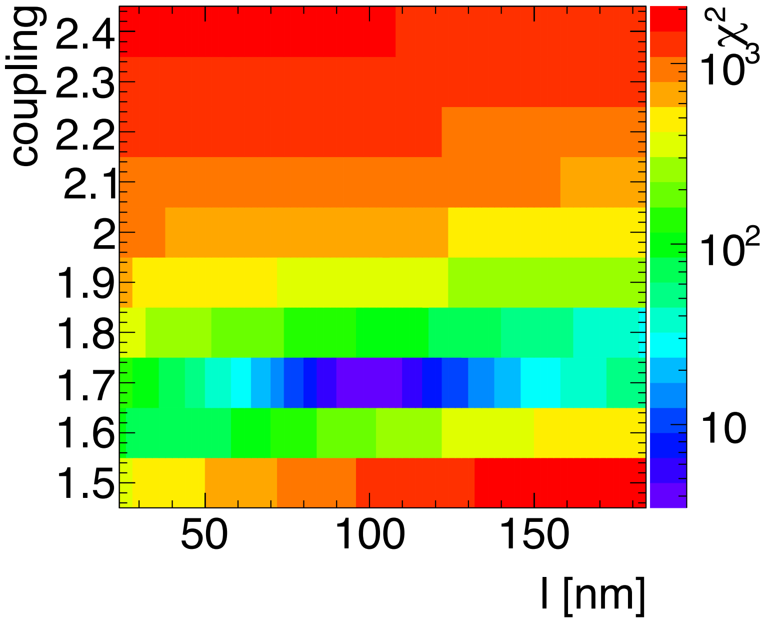
Aid by Merged χ^2











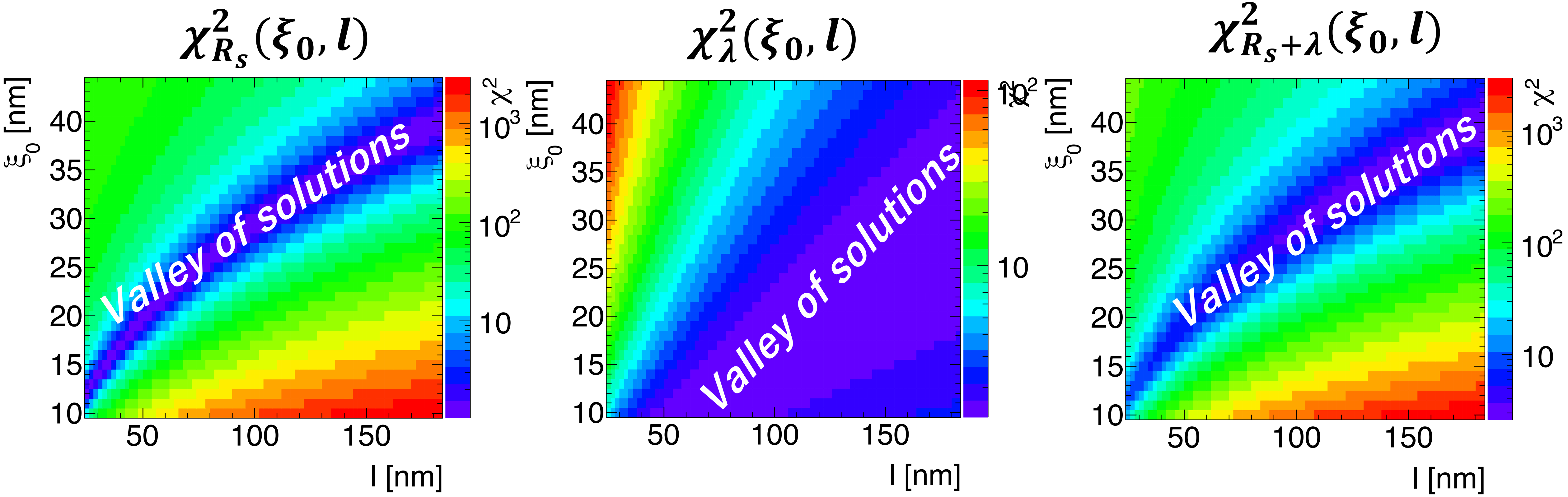
4parameters → 6 correlations

5/6 correlations disappeared

BUT
1 correlation remains

(ξ_0, l)

(ξ_0, l) is still strongly correlated



Surface resistance and penetration depth depend similarly on (ξ_0, l)

→ Merged χ^2 does not help to confine the fitting parameter

→ RF surface impedance measurement cannot determine parameters

→ **An independent observable** is necessary

$B_{c2}(T)$ → $\xi_{GL}(T)$ → (ξ_0, l) by BCS-Gor'kov

Ginzburg-Landau theory gives

$$B_{c2}(T) = \frac{\Phi_0}{2\pi\xi_{GL}(T)^2}$$

$$\xi_{GL}(T) \propto \frac{1}{\sqrt{1-(T/T_c)}}$$

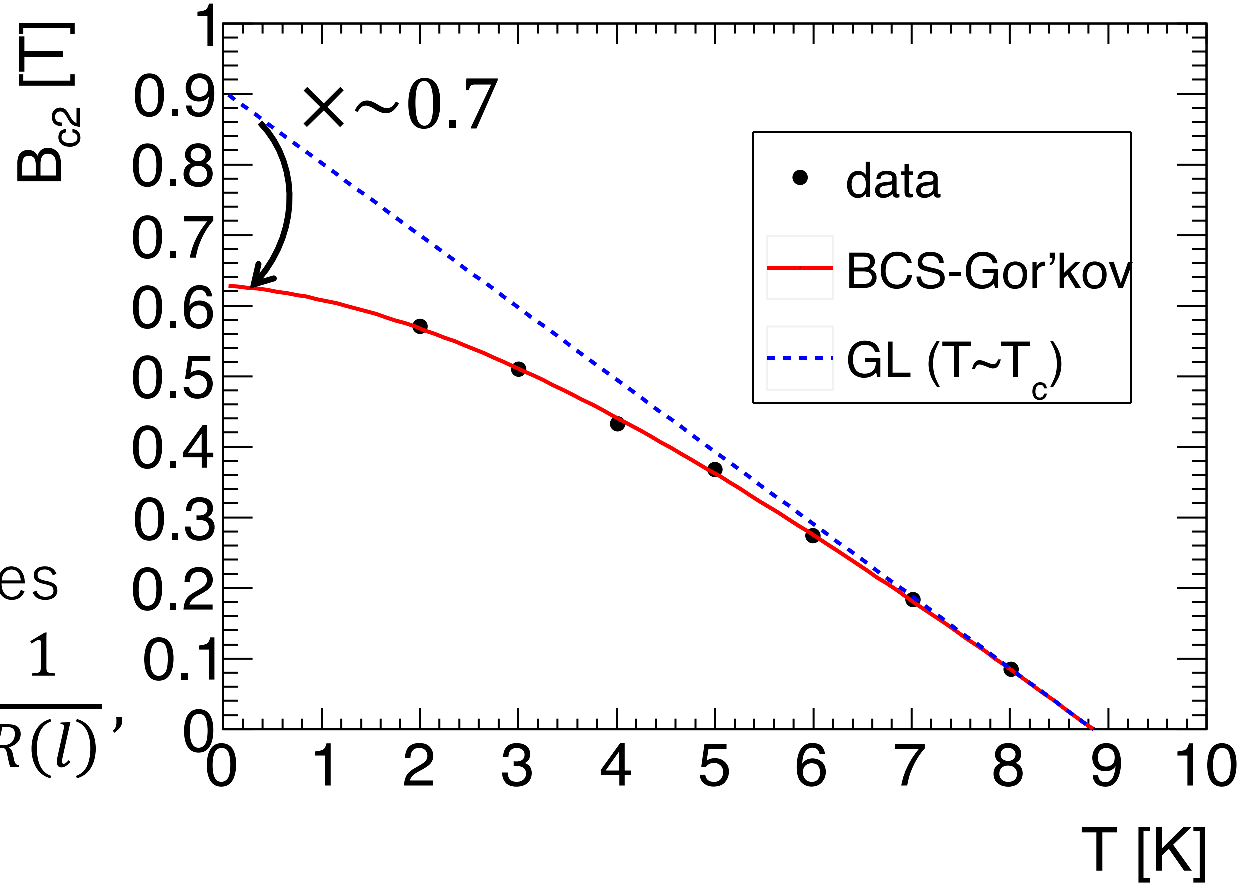
→ $B_{c2}(T \to T_c) \propto 1-(T/T_c)$

The tangential linear fit @ T_c was done

BCS-Gor'kov theory expanded near T_c gives

$$\lim_{T\to T_c}\left(-\frac{dB_{c2}}{dT}\right) = \frac{\Phi_0}{2\pi}\frac{T_c}{0.739^2}\left[\frac{1}{\boldsymbol{\xi_0^2}} + 0.882\frac{1}{\boldsymbol{\xi_0 l}}\right]\frac{1}{R(l)},$$

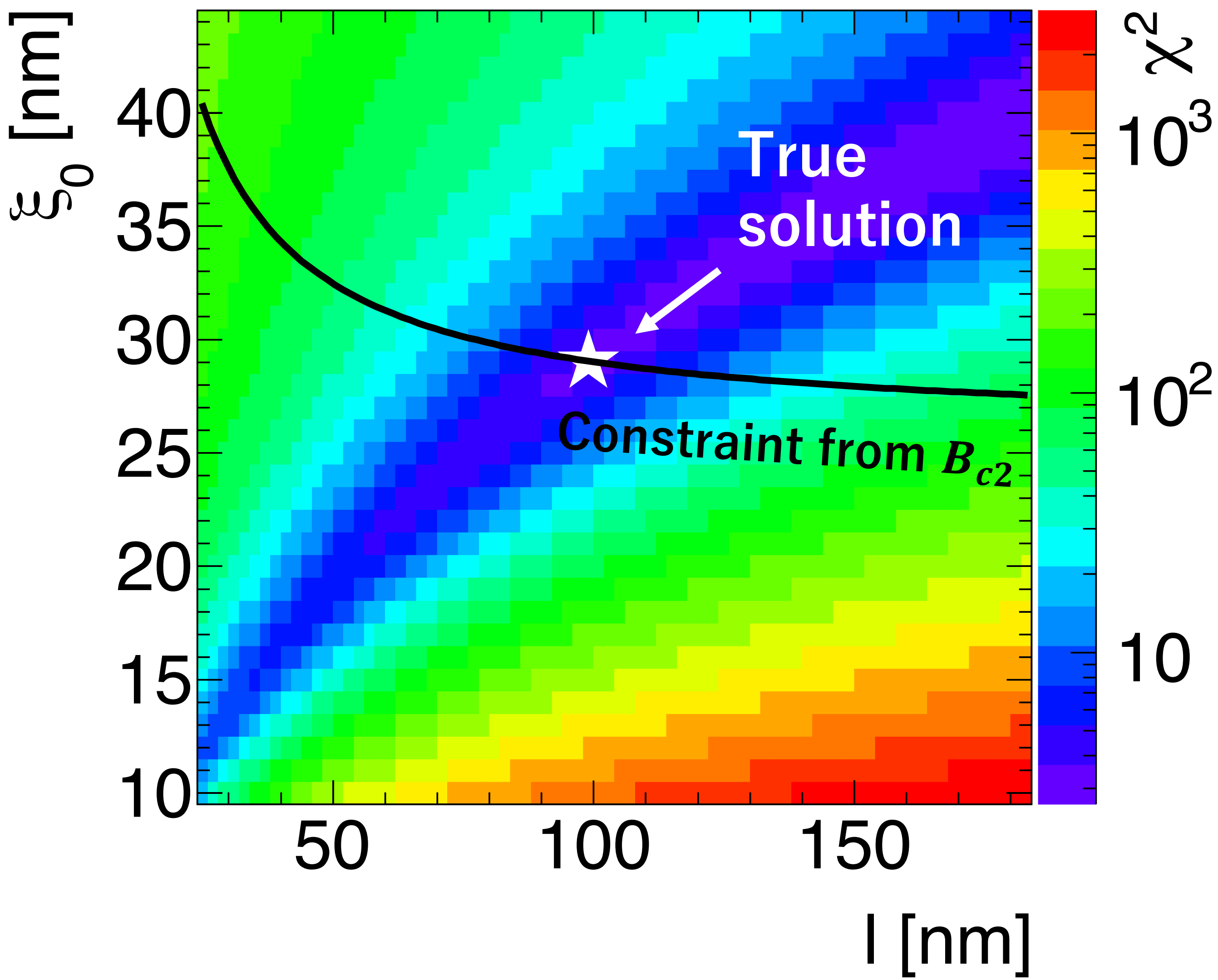
where $1 = R(0) < R(l) < R(\infty) = 1.17$



→ From the fitted slope another constraint on (ξ_0, l) was obtained for arbitrary impurity

L. P. Gor'kov, JTEP, 9, 1364 (1959).
T. P. Orlando, et al., Phy. Rev. B 19, 4545 (1979).

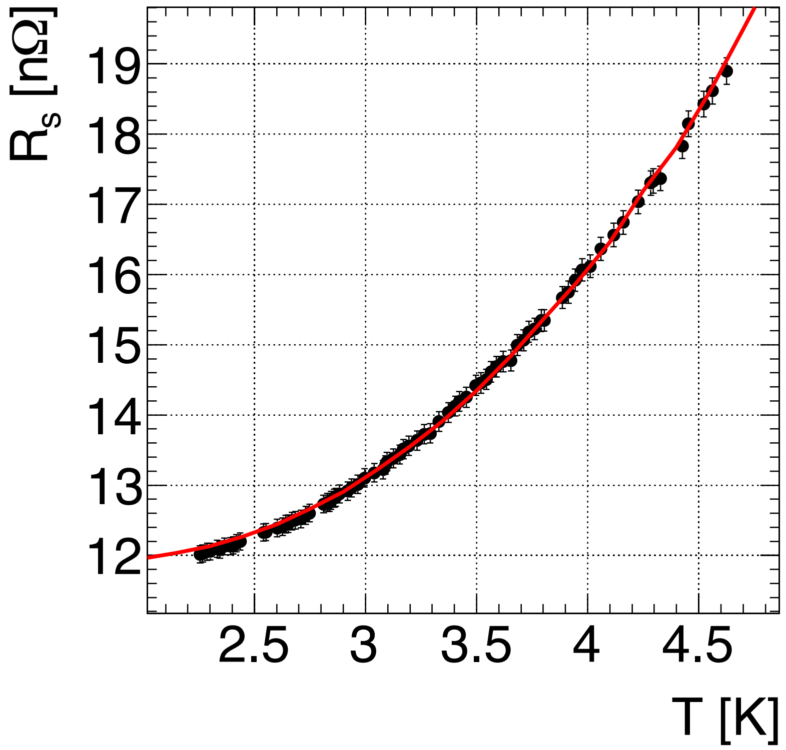
Combination of RF measurement and magnetometry

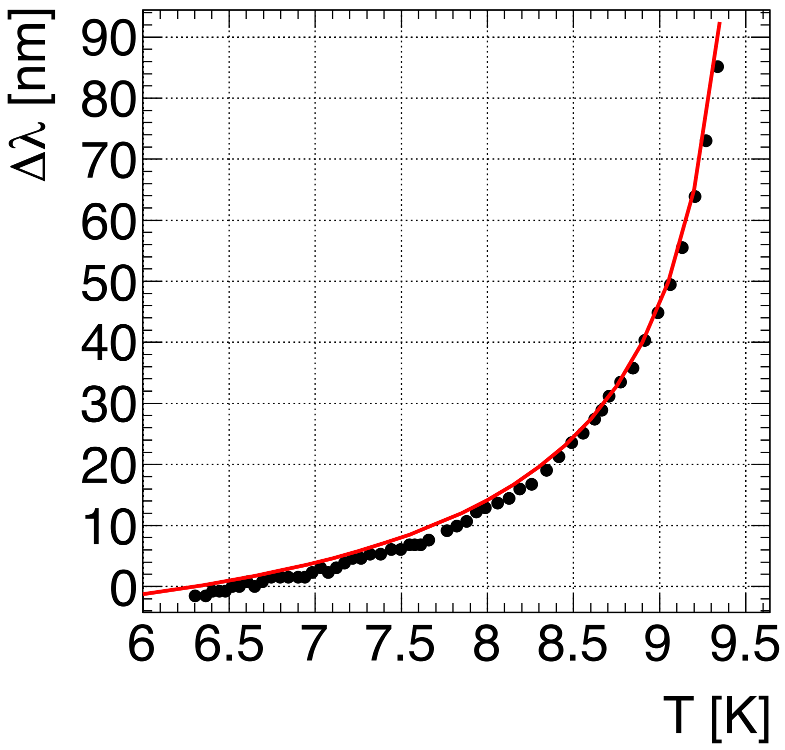


BCS fitting of RF impedance and B_{c2} by BCS-Gor'kov are complementary

Result

Preliminary





Best cavity **Worst cavity**

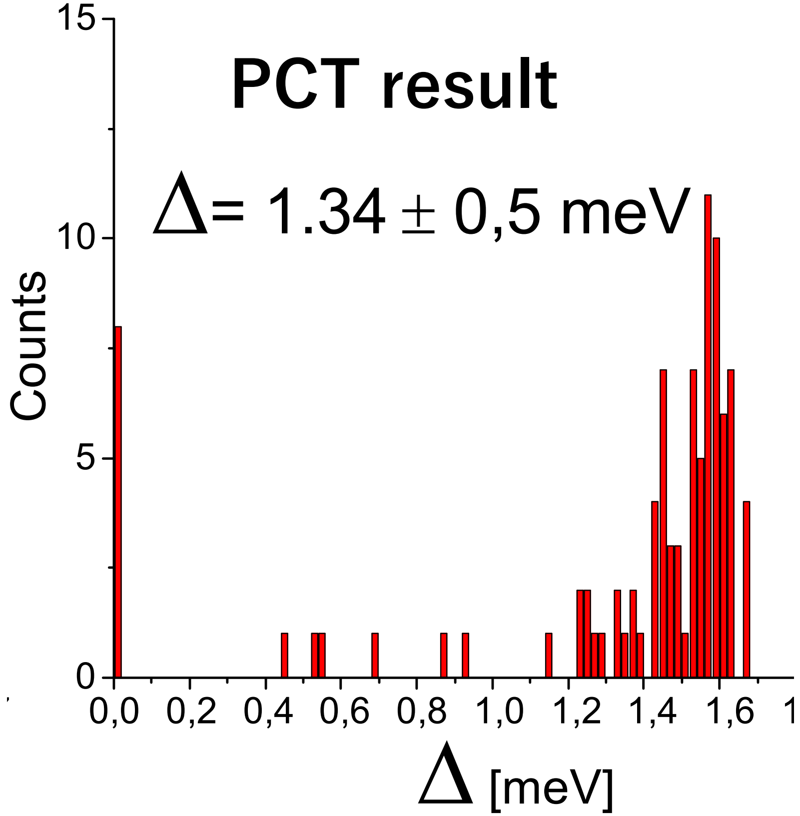
	cavity 1	cavity 2	PCT	μSR	DC 4-contact	[13]	[15]
ξ_0 nm	29(7)	28(7)				36(4)	39
λ_L nm	26(7)	28(7)				29(3)	32
l nm	99(25)	139(30)			95(27)	6-1300	
$\Delta_0/k_B T_c$	1.7(1)	1.5(1)	1.6(6)			1.87	1.75-1.93
R_{res} nΩ	11.8	9.0					
T_c K	9.6	9.6				9.54	8.95-9.2
T_0 K	6.3	7.1					
λ_{eff} nm	31	32		29(5)			

The data was well fitted

T. Junginger, et al., accepted by Supercond. Sci. Technol. (https://doi.org/10.1088/1361-6668/aa8926

[13] C. Benvenuti, et al., Physica C 316, 153 (1999).
[15] J. P. Turneaure, et at., J. Supercond. 4, 341 (1991).

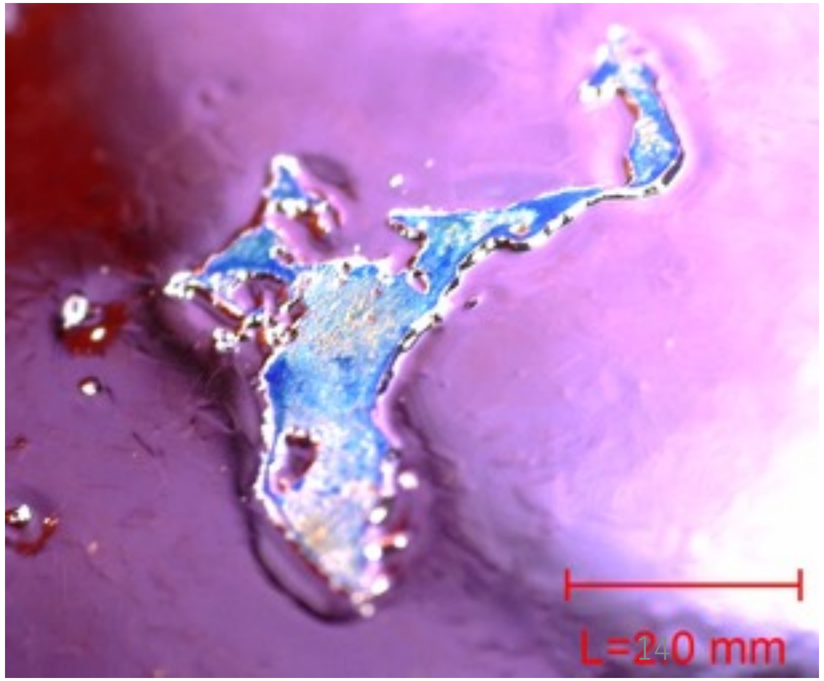
Discussion: weak Δ_0



- RF + magnetometry fitting showed weak Δ_0 averaged over the cavity surface
- Direct but local measurement of Δ_0 by Point Contact Tunneling (PCT) showed broad histogram of Δ_0 and even zero gap states

→ The HIE-ISOLDE film may have some issues

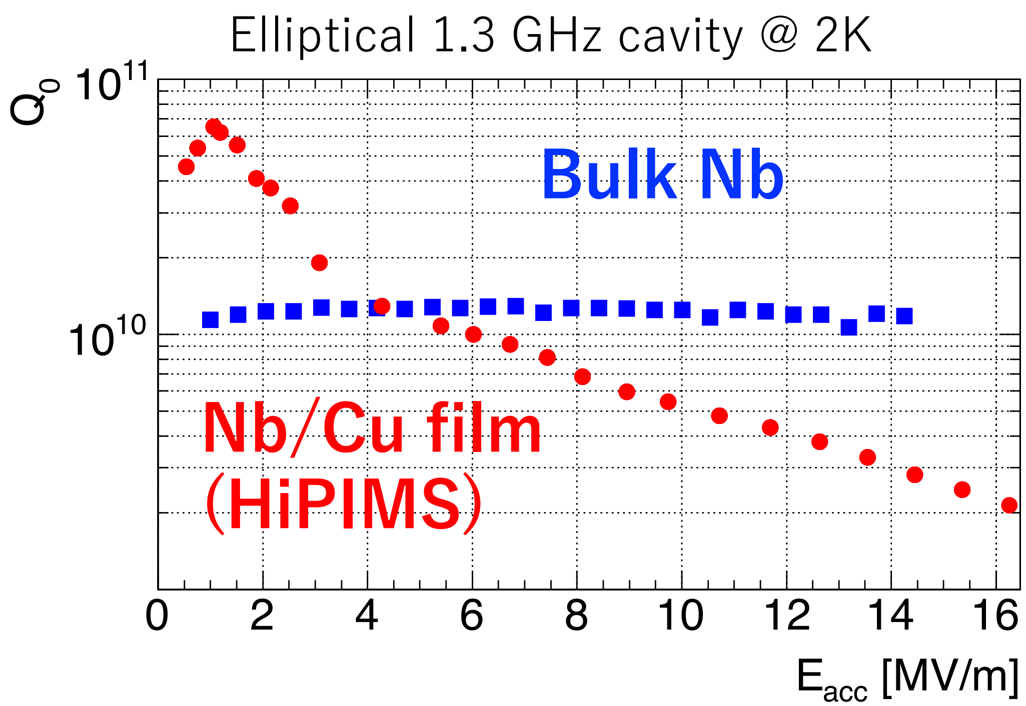
- **DC-bias sputtering**
- **Coating parameter**
- **Geometry**
- **Contamination**
- …

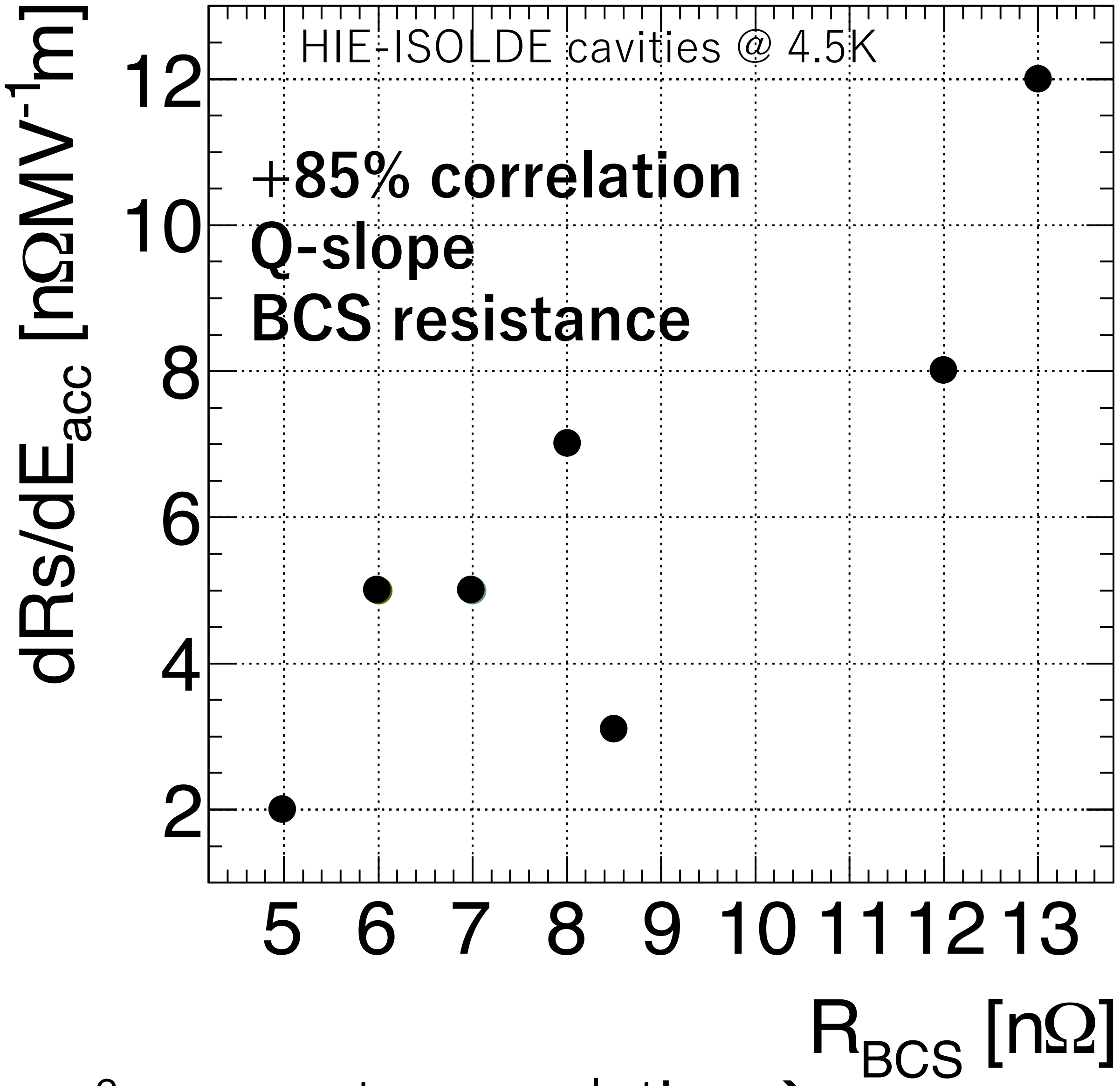


- The worst performed cavity showed even lower Δ_0
- A rather huge (2mm) feature found on the inner antenna after the chemistry (degreasing, SUBU)
- Contamination to the film?

Toward understanding of the Q-slope problem

Common issues in Nb/Cu cavities → Q-slope problem





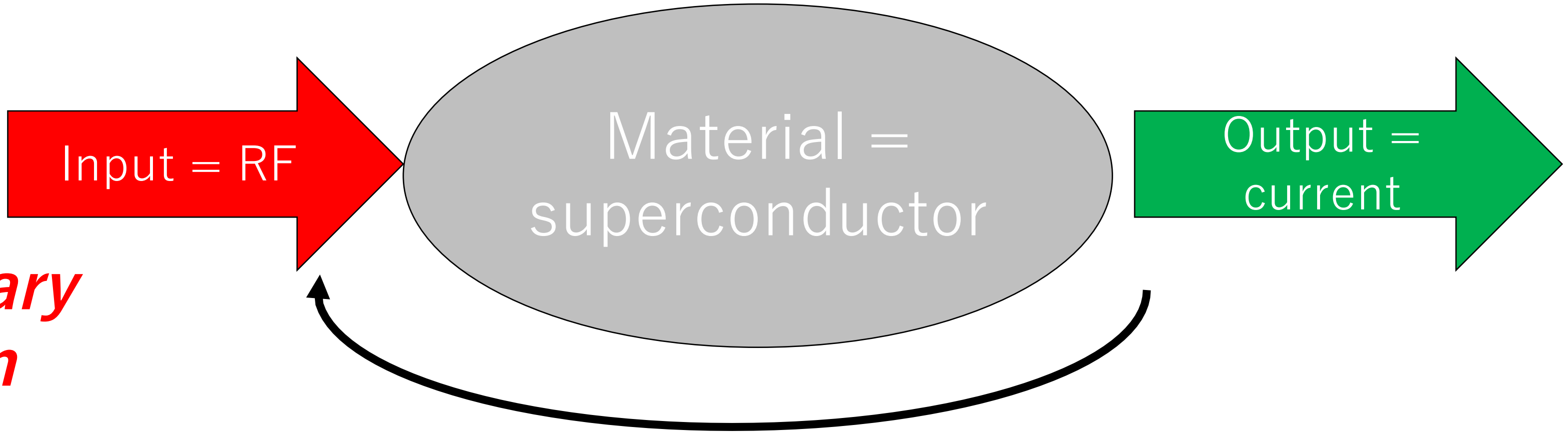
Q-slope & BCS correlation → Q-slope & parameter correlation → common cause?

Summary

- The surface impedance of the HIE-ISOLDE cavities were fitted by BCS theory
- Strong correlations among the material parameters were pointed out and partially eliminated by simultaneous fitting of surface resistance and penetration depth
- The upper critical field measured provided another constraints with BCS-Gor'kov theory
- The material parameters were determined and well fitted the data
- Physics interpretation is important especially because systematic study for Q-slope is desired

backup

Surface impedance Z_s : non-equilibrium statistical physics



Non-stationary phenomenon

Reaction coefficient = impedance

A definition of surface impedance

$$Z_s(\omega, T, E) \equiv \frac{E_x(z=0)}{\int_{z=0}^{\infty} J_x(z')dz'}$$

$$= \frac{E_x(0)}{H_y(0)}$$

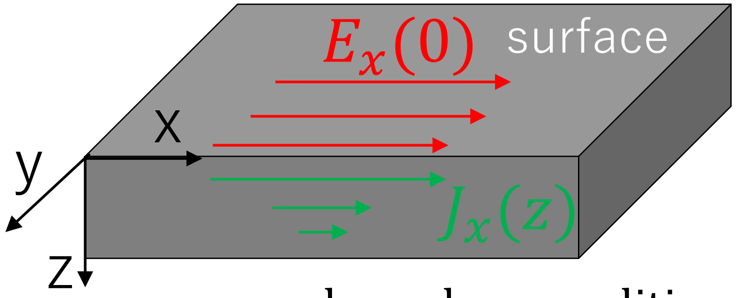
From Ampere's law

$$H_y(z) = \int_z^{\infty} J_x(z')dz'$$

$$\equiv R_s + iX_s$$

Definition of **surface resistance** and reactance

The huge $E_z(z=0_-)$ does not appear



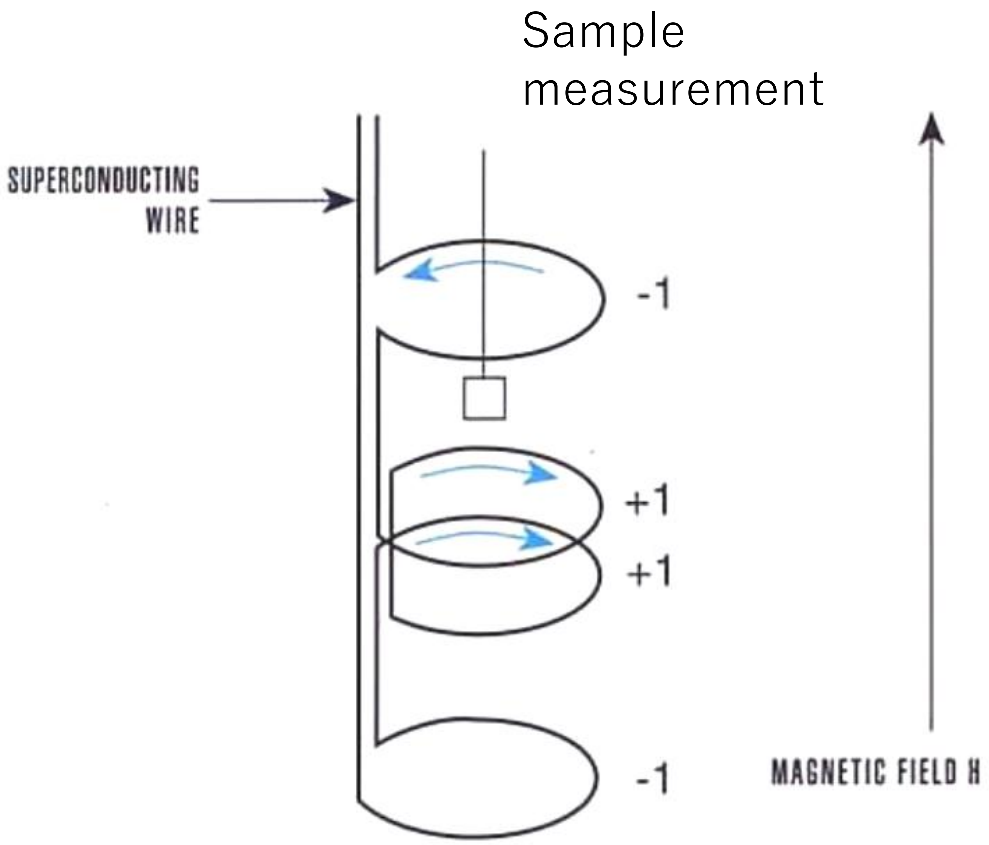
boundary condition

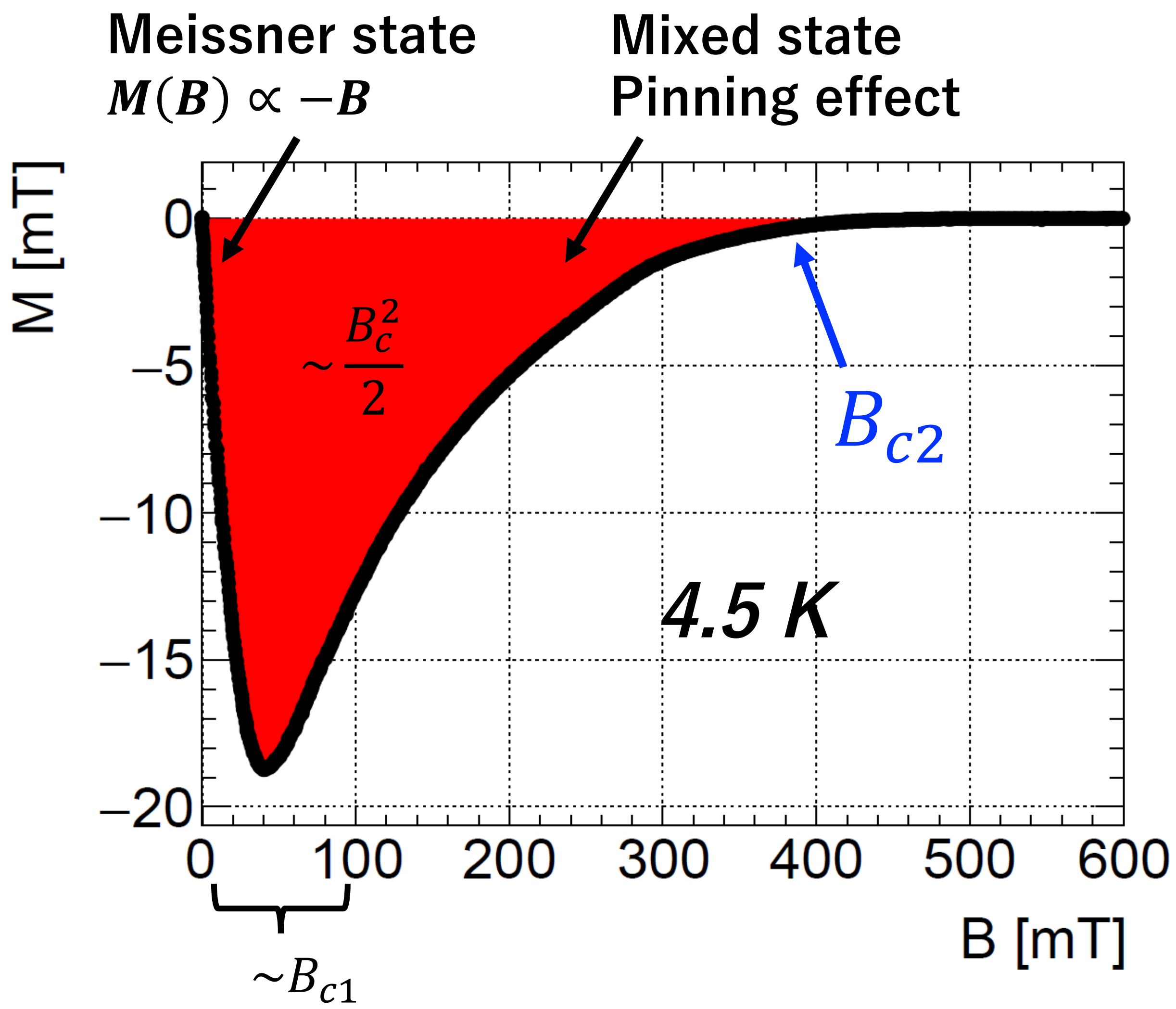
$$\lim_{z\to\infty} |\vec{J}(z)| = 0$$

Averaged R_s can be obtained by cavity quality factor Q_0 and geometrical factor G

$$\overline{R_s} = G/Q_0$$

Magnetization $M(B)$ measurement by SQUID





The upper critical field $B_{c2}(T)$ is a precise observable by $M(B)$ measurement

(thermodynamical critical field B_c(T) and lower critical field $B_{c1}(T)$ are less precise)