Sensitivity of Surface Resistance to Trapped Flux in High-Purity Large-Grain Niobium

Based on SRF Cavity Measurements

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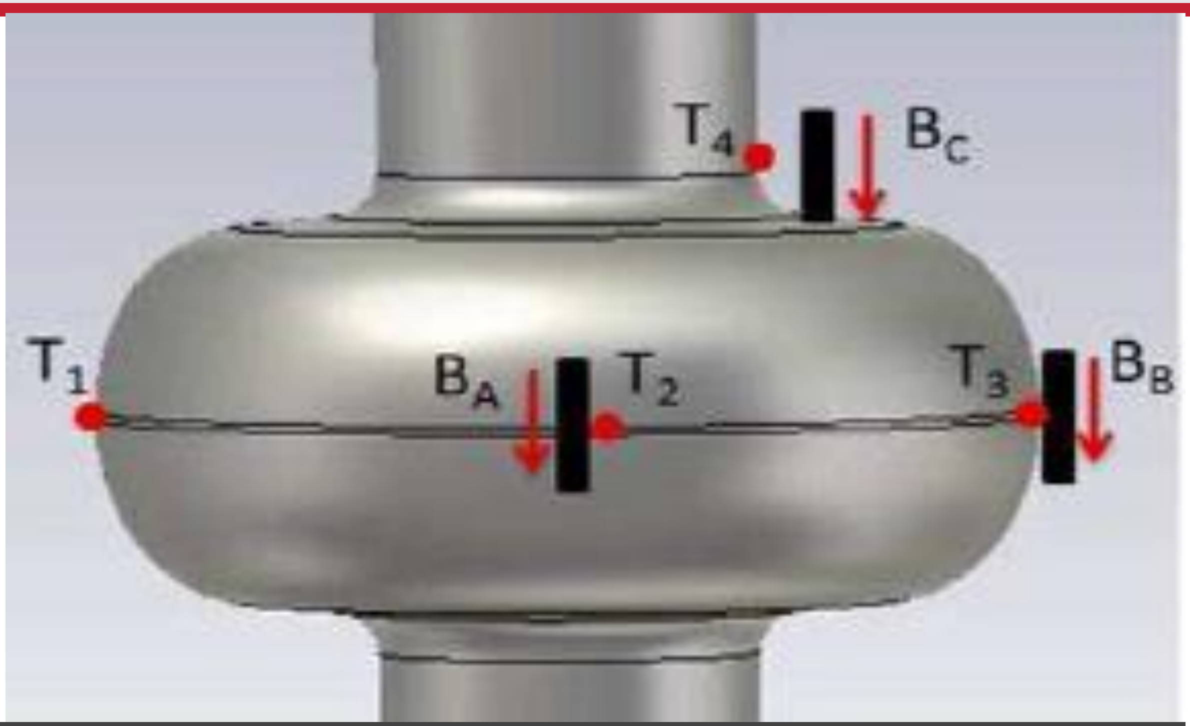

TTC/ARIES topical workshop on flux trapping and magnetic shielding

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31-3-004 - IT Amphitheatre (CERN)

Frank Gerigk (CERN), Walter Venturini Delsolaro (CERN)

Abstract

Surface resistance arising from trapped flux is experimentally measured, by which the sensitivity to trapped flux is derived. Measurements are carried out with single-cell L-band SRF cavities made of high-purity large-grain niobium materials, immersed in a uniform externally applied magnetic field generated by a solenoid with its axis overlapping the cavity axis. The surface resistance is found by using the standard technique for Q_0 measurement and the customary G/Q_0 analysis. Q_0 values at a fixed low surface field are used. The trapped flux is found by measuring flux densities at a selected location using a single-axis fluxgate magnetometer attached to the cavity outer surface: B_a*[1-(B_{sc}-B_{nc})/(B_{sc}^0-B_{nc})], where B_a is the applied external field, B_{nc} and B_{sc} is the local flux density measured just above and below T_c, respectively, during a field-cooling of the cavity and afterwards its Q_0 is measured, B_{sc}^0 is measured in a separate zero-field-cooling while the cavity being kept in the same location after turning on the identical applied field B_a at a temperature well below T_c . Several magnetometers are placed at various locations. It is found that the sensitivity to trapped flux in high-purity large-grain niobium to be 1.9 nΩ/µT on average. This is to be compared to 3-9 nΩ/µT in high purity fine-grain niobium and 10-50 nΩ/µT in nitrogen-doped high-purity niobium reported by other groups. We will discuss the measurement results as well as the measurement techniques.

This talk is adapted from this publication: PHYSICAL REVIEW ACCELERATORS AND BEAMS 19, 082001 (2016)

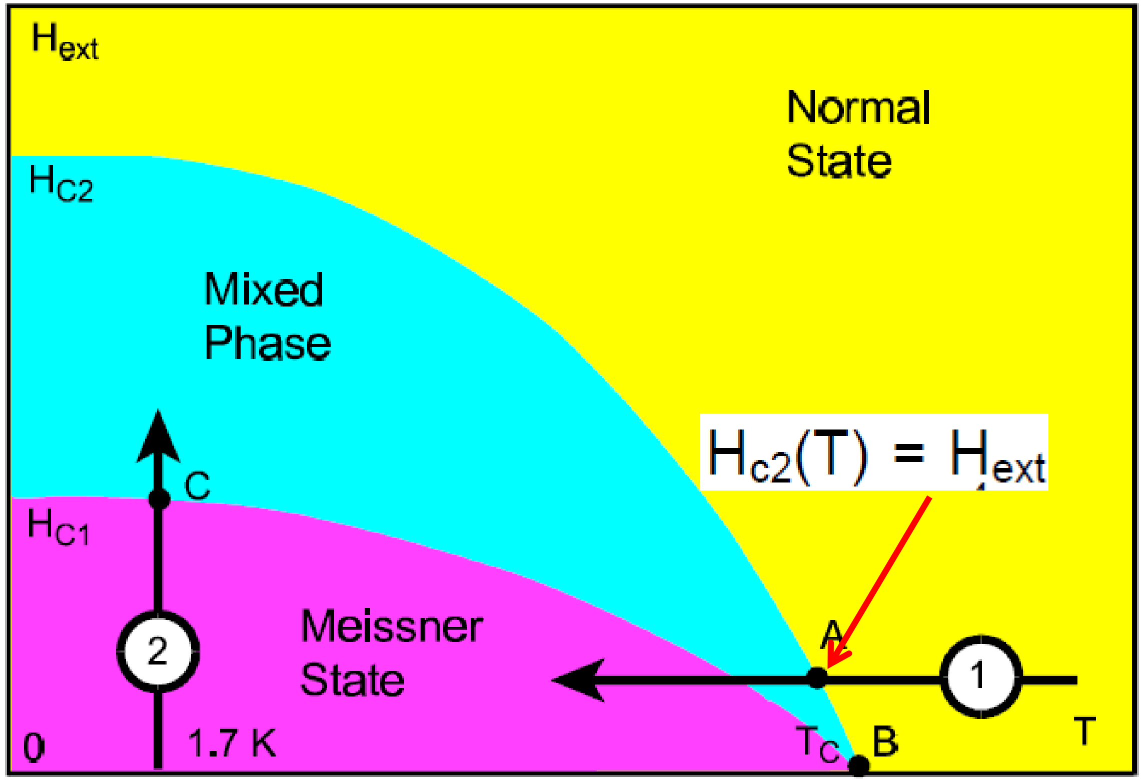
Outline

- Background
- Experimental techniques
  - Measure cavity-based flux expulsion ratio $\boldsymbol{\varepsilon_{eq}}$ to find flux trapping ratio $\boldsymbol{\tau_{eq}}$
  - Isolate residual surface resistance arising from trapped flux $\boldsymbol{R_{fl}}$
  - Determine local temperature gradient at NC/SC phase transition front $\boldsymbol{\frac{dT}{ds}|_{t_c}}$
- Examples
- Finding trapped flux density $\boldsymbol{B_{trap}}$ and sensitivity of surface resistance to it $\boldsymbol{r_{fl}}$
  - Identify r_{fl} to be an intrinsic material property
- Understanding gained w.r.t. origin of higher Q_0 in large-grain Nb cavities
- Concluding remarks

Background

- Residual resistance brought about by trapped flux a well known effect
- Flux trapping occurs when cooling down across Tc even for small H_{ext}, if pining centers available in cavity wall
  - bulk or surfaces
- Conventional technique to measure its sensitivity is straight-forward in case 100% flux trapping ($\tau = 1$): $r_{fl}=R_{fl}/B_a$
  - Heat treated FG Nb cavity (C. Vallet et al, EPAC'92)
  - Thin film Nb-Cu cavity (C. Benvenuti et al., SRF'97)
- Single crystal Nb does not trap 100% (or $\tau < 1$) as established by Aull, Kugeler, and Knobloch, PRST-AB 15, 062001 (2012)
- LG Nb expected to behave more like single-crystal Nb except along GB's
- Must isolate sensitivity r_{fl} and trapping ratio τ :

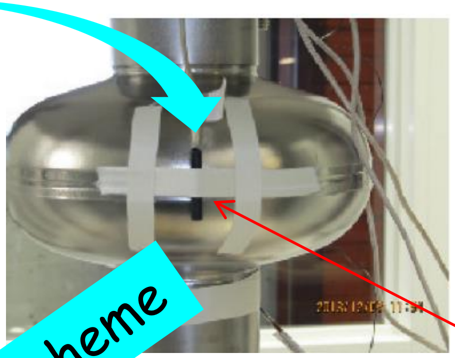
$$\boxed{R_{fl} = r_{fl} \cdot \tau \cdot B_a}$$



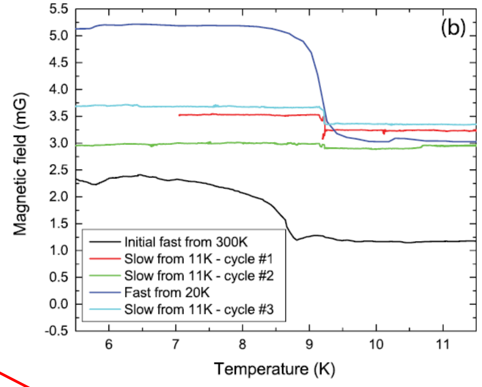
C. Benvenuti et al., SRF1997

Qualitative and Relative Quantitative Measure of Trapped Flux in Nb Cavity

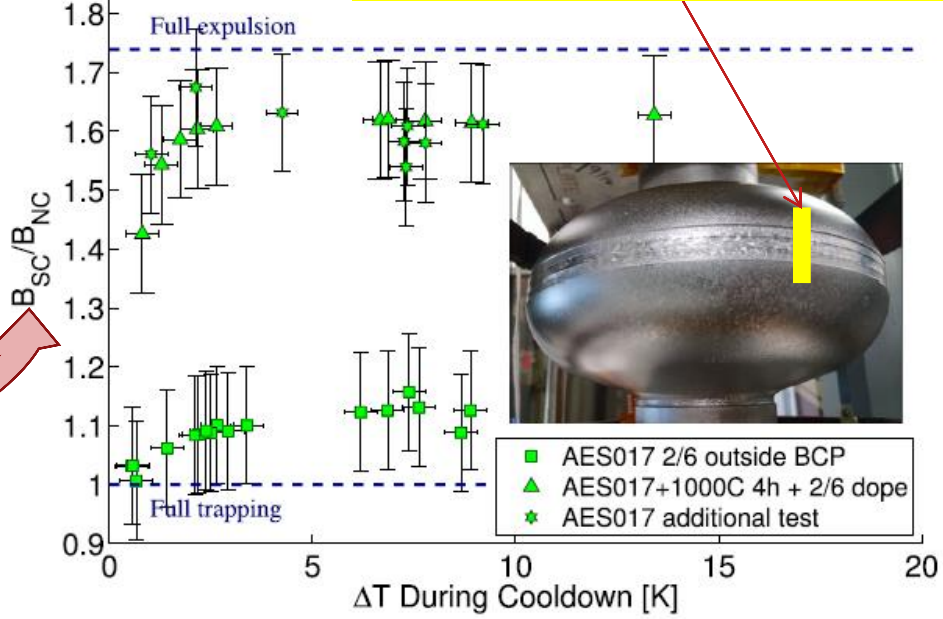
- Sensitivity of fluxgate magnetometer attached to outer cavity surface at equator in direction of cavity axis, to externally applied axial magnetic field established by Romanenko et al, JAP 115, 184903 (2014).
  - Step increase in detected flux density at Tc crossing
  - *Qualitative* indication of flux expulsion
- Method extended by Posen et al, JAP 119, 213903 (2016)
  - B_{sc}/B_{nc}
  - *Relative quantitative* measure of τ



Romanenko Scheme



Bartington MAG 01-H , Probe F, single-axis



Posen Quotient

Absolute Quantitative Measure of Trapped Flux in Nb Cavity

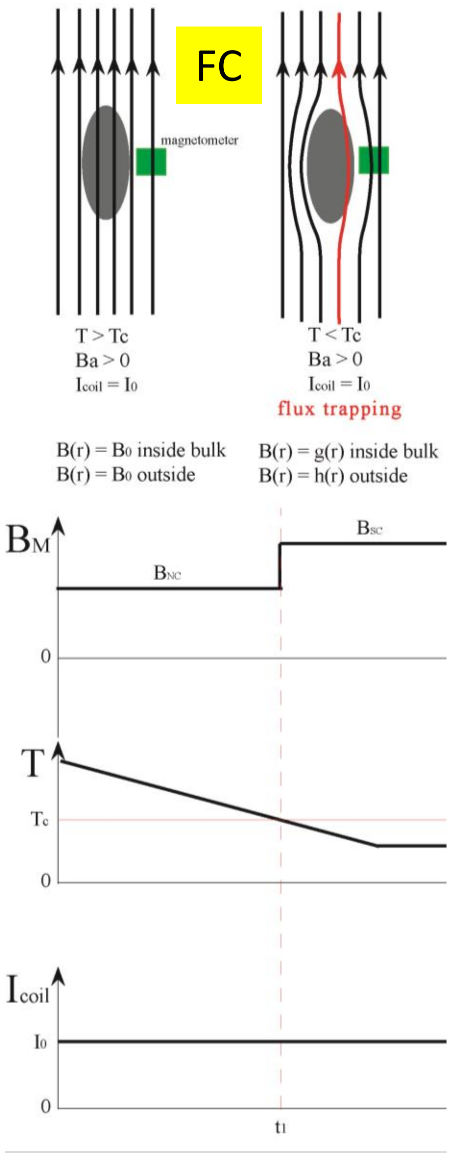
- Magnetometer attached to outer surface at equator
- Uniform B_a applied from solenoid at given current
- FC cavity, measure B_{NC} ($=B_a$) , B_{SC}
- Measure $Q_0(E_{acc})$ at 1.4K with standard method
- Separate cool down ZFC, measure $Q_0(E_{acc})$ at 1.4K & $B_{SC}^{(0)}$
  - cavity and magnetometer remains unmoved
  - Same solenoid current

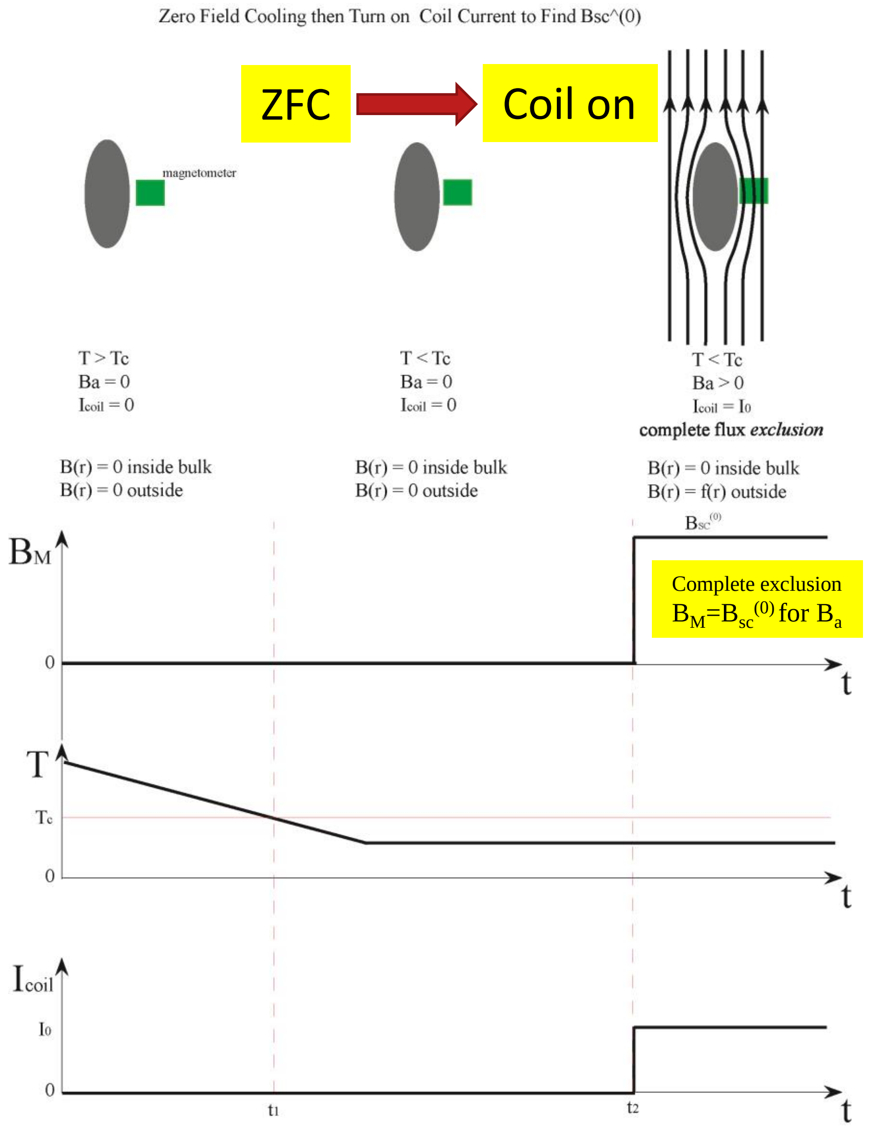
Flux expulsion ratio

$$\epsilon_{\mathrm{eq}} = \frac{B_{\mathrm{SC,eq}} - B_{\mathrm{NC,eq}}}{B^{(0)}_{\mathrm{SC,eq}} - B_{\mathrm{NC,eq}}} = \frac{\frac{B_{\mathrm{SC,eq}}}{B_{\mathrm{NC,eq}}} - 1}{\frac{B^{(0)}_{\mathrm{SC,eq}}}{B_{\mathrm{NC,eq}}} - 1}$$

Flux trapping ratio

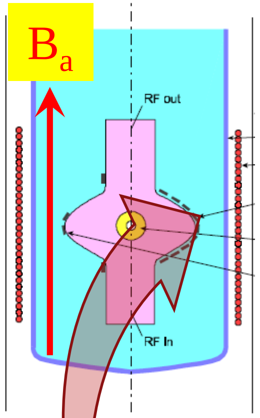
$$\tau_{\mathrm{eq}} = 1 - \epsilon_{\mathrm{eq}}$$

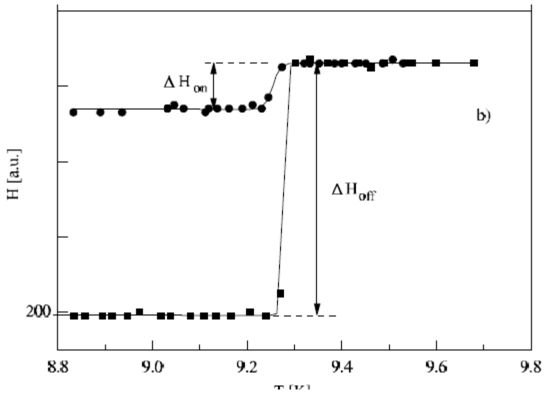


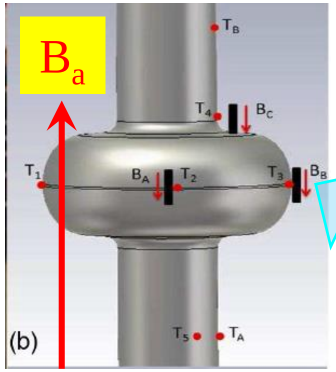


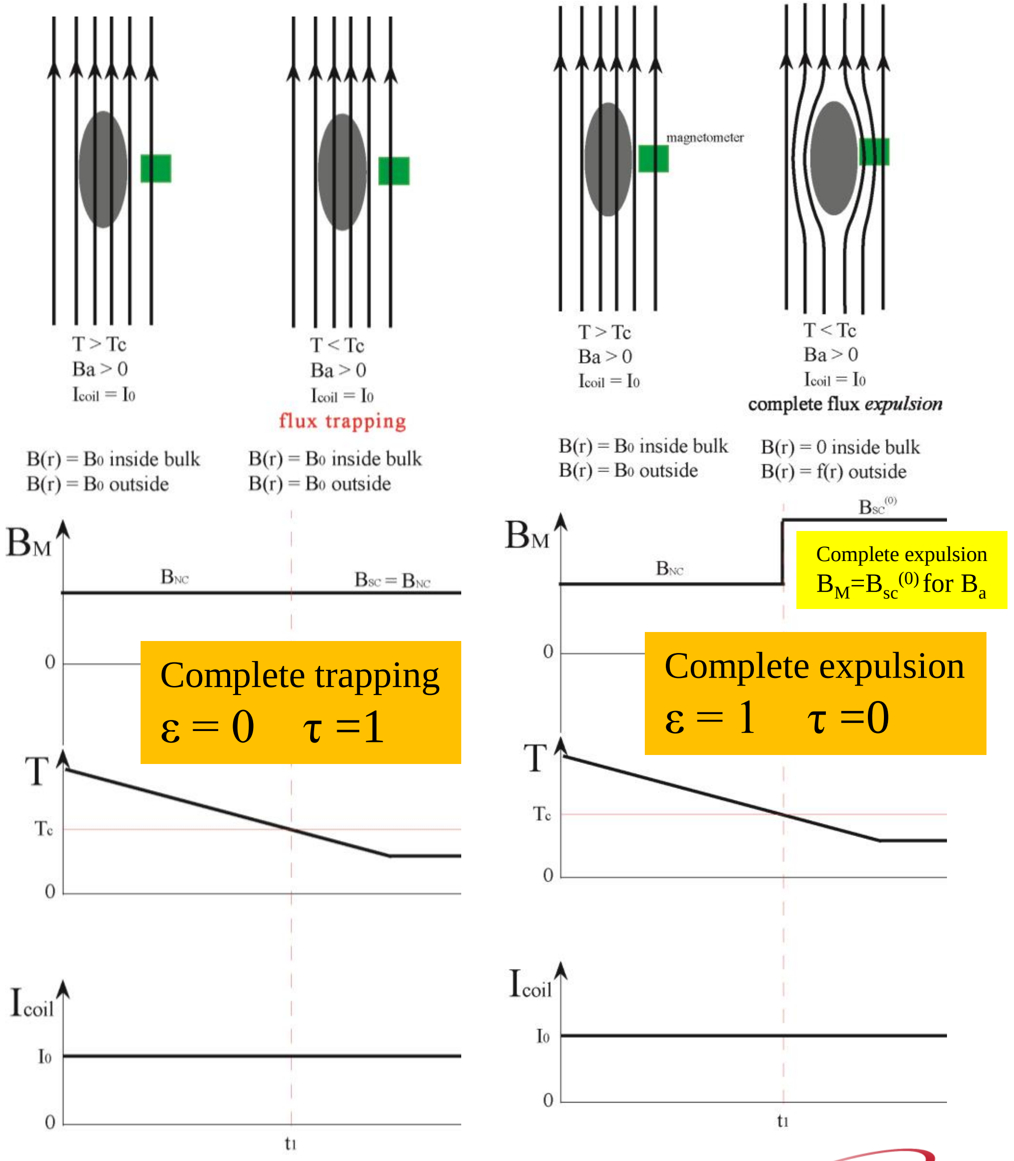
Absolute Quantitative Measure of Trapped Flux in Nb Cavity (cont.)

- Limiting cases
  - Complete trapping $\tau = 1, \varepsilon = 0$
  - Complete expulsion $\tau = 0, \varepsilon = 1$
- Method similar to C. Benvenuti et al., SRF97B05, SRF1997









Complete trapping
$\varepsilon = 0 \quad \tau = 1$

Complete expulsion
$B_M = B_{sc}^{(0)}$ for B_a

Complete expulsion
$\varepsilon = 1 \quad \tau = 0$

	CERN 1997	JLAB 2016
Flux sensor	Hall probe	Fluxgate magnetometer
Sensor number and location	entire cell, 9 sensor along meridian	3 sensors, 2 at equator and 1 at upper iris
flux component	Normal to surface	Vertical (parallel to B_a)

Isolate Residual Surface Resistance Arising from Trapped Flux R_{fl}

- Effective surface resistance defined
  - $R_s \equiv R_s|_{1.4K,5MV/m} = \frac{G}{Q_0}|_{1.4K,5MV/m}$
    - $R_s^{(0)}$, ZFC (residual ambient field < 2mG)
    - R_s, FC
- R_s decomposed
  - $R_s^{(0)} = R_{fl}(B_{trap}^{(0)}) + \boxed{R_{BCS} + R_0}$
  - $R_s = R_{fl}(B_{trap}) + \boxed{R_{BCS} + R_0}$
- R_{fl} isolated
  - $\boldsymbol{R_{fl} = R_s - R_s^{(0)} + r_{fl} \cdot B_{trap}^{(0)}}$
- Byproduct: R_0
  - 2-3 nΩ

BCS resistance and residual resistance of physical origin other than trapped flux are common term as no change in cavity/surface

Trapped flux due to residual field (< 2mG) in ZFC

- $R_{fl}(B_{trap}^{(0)}) = r_{fl} \cdot B_{trap}^{(0)}$

- Benchmark evaluation of r_{fl} at $\tau_{eq} \approx 1$
- $r_{fl} = \frac{R_s - R_0}{B_a} = \frac{25n\Omega - R_0}{10\mu T}$, FC B_a=10μT
  - $B_{trap} \cong B_a$, $(\varepsilon = 0.04, \tau = 0.96)$
  - $R_{BCS}(1.4K)$ *estimated* ~0.4nΩ ignored for large Rs = 25 nΩ
- Finally $\boxed{r_{fl} = \frac{22.4\ \text{n}\Omega + R_{BCS}(1.4\ \text{K})}{10\ \mu\text{T} - B_{trap}^{(0)}} \simeq 2.24\ \text{n}\Omega/\mu\text{T}}$
  - R_{BCS}(1.4K)~0.4nΩ << 22.4nΩ
  - $B_{trap}^{(0)} \ll 10\mu T$
- $R_{fl}(B_{trap}^{(0)}) = r_{fl} \cdot B_{trap}^{(0)}$ =0.1-0.5nΩ
  - Assuming residual field all trapped in ZFC

Determine Local Temperature Gradient $\frac{dT}{ds}|_{t_c}$ at NC/SC Phase Transition Front (PTF)

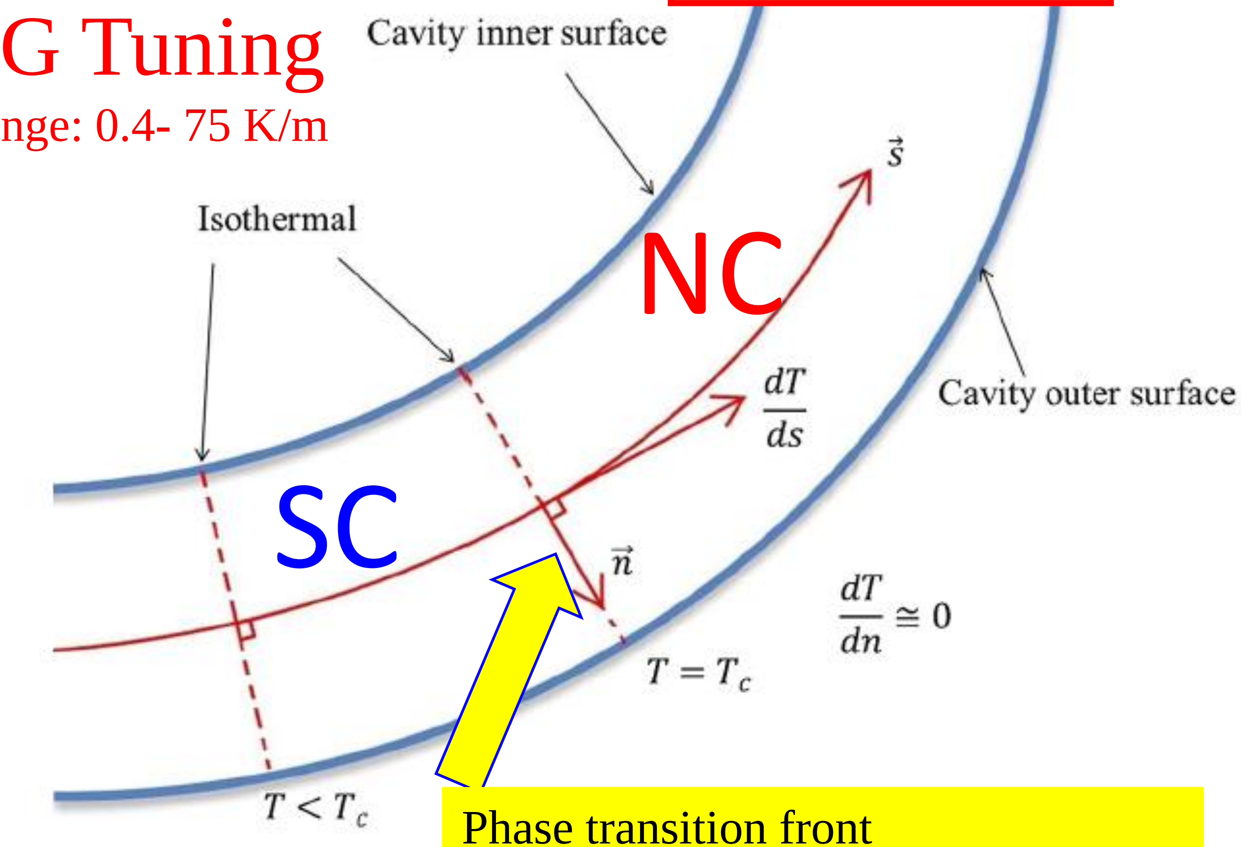
Ruling parameter

Temperature Gradient @ PTF

$$\boxed{\left.\frac{dT}{ds}\right|_{t_c} = \left.\frac{dT}{dt}\right|_{t_c}\frac{dt_c}{ds}}$$

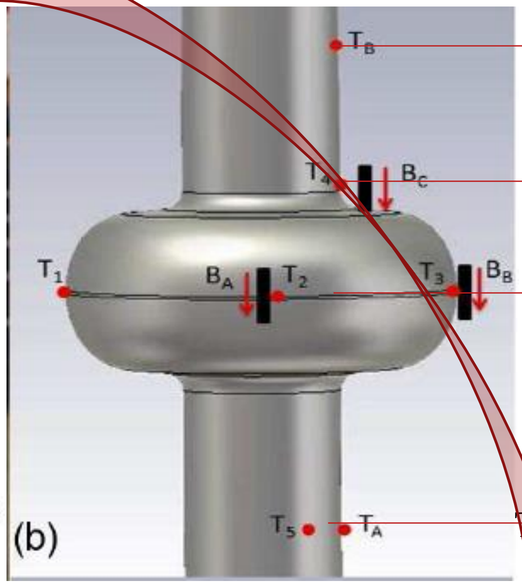
TG Tuning

Range: 0.4- 75 K/m



Phase transition front

"boarder" between SC & NC domain



T_B=9.2K, PTF arrives upper flange at t_4

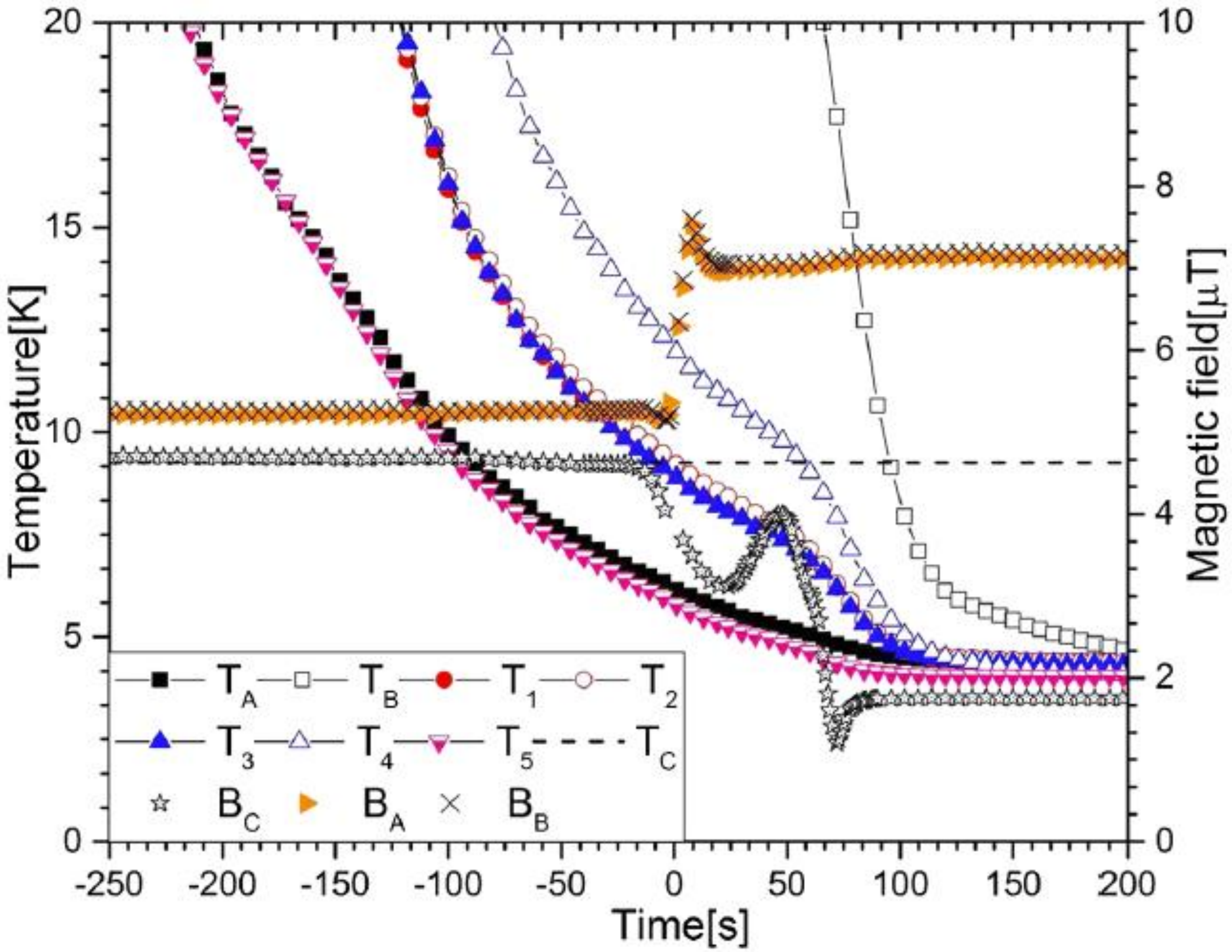
T_4=9.2K, PTF arrives upper iris at t_3

T_3=9.2K, PTF arrives equator at t_2

T_A=9.2K, PTF arrives lower flange at t_1

- SC/NC border enters bottom flange, moves upward, and exits upper flange for typical orderly cool down
- Time of PTF arrival at selected locations recorded, speed of PTF propagation v_c found
- Inverse of v_c is $\frac{dt_c}{ds}$
- v_c Range: 0.8 – 149 mm/s
- Straightforward to find local cool down rate at PTF $\frac{dT}{dt}|_{t_c}$. Range 3.5x10^{-3} – 2.0x10^{-1} K/s

Examples



Temperature[K]
Magnetic field[μT]
Time[s]
20
15
10
5
0
10
8
6
4
2
0
-250
-200
-150
-100
-50
0
50
100
150
200
T_A
T_B
T_1
T_2
T_3
T_4
T_5
T_C
B_C
B_A
B_B

Test	dT/dt (K/sec)	v_c^{-1} (sec/m)	dT/ds (K/m)	$B_{\mathrm{NC,eq}} = B_a (\mu\mathrm{T})$	$B_{\mathrm{SC,eq}}$ (μT)	$B_{\mathrm{SC,eq}}^{(0)}$ (μT)	ϵ_{eq}	R_s (nΩ)	R_{fl} (nΩ)
Mag1.2	0.2010	−7.9	−1.60	5.04	5.15	8.16	0.03	…	…
RF2.1	…	…	…	…	…	…	…	2.33	…
RF2.2	0.0082	383.9	3.14	5.19	6.23	8.16	0.35	6.84	5.03
RF2.3	0.0253	127.4	3.23	5.22	5.99	8.16	0.26	8.14	6.33
RF2.4	0.0113	35.4	0.40	5.19	5.80	8.16	0.20	9.6	7.79
RF2.5	0.0425	684.3	29.08	5.25	7.16	8.16	0.65	5.26	3.45
Mag2.6	0.0263	235.6	6.21	5.17	6.23	8.16	0.35	…	…
Mag2.7	0.0142	38.8	0.55	5.19	5.77	8.16	0.20	…	…
RF3.1	…	…	…	…	…	…	…	2.6	…
RF3.2	0.0660	1141.7	75.35	10.25	13.77	14.96	0.75	8.35	5.88
RF3.3	0.2010	−6.9	−1.39	10.02	10.23	14.96	0.04	25	22.53
Mag3.4	0.0262	166	4.34	10.11	11.46	14.96	0.28	…	…
Mag3.5	0.0035	−682	−2.39	10.12	10.70	14.96	0.12	…	…
Mag3.6	0.0395	364.5	14.4	10.10	12.68	14.96	0.53	…	…
Mag3.7	0.0372	352.2	13.09	15.3	[illegible]	22.70	0.43	…	…
Mag3.8	0.0852	192.6	16.41	15.31	[illegible]	22.70	0.49	…	…
Mag3.9	0.0563	244.9	13.79	15.30	[illegible]	22.70	0.48	…	…
Mag3.10	0.0668	749	50.06	[illegible]	[illegible]	22.70	0.67	…	…
Mag3.11	0.0153	202.4	3.10	[illegible]	22.40	30.44	0.19	…	…
Mag3.12	0.0592	126.5	7.49	[illegible]	23.22	30.44	0.28	…	…
RF4.1	…	…	…	…	…	…	…	3.57	…
RF4.2	0.0293	1276.7	37.45	15.02	19.48	22.27	0.62	12.74	9.38
RF4.3	0.0318	269.6	8.58	15.28	18.57	22.64	0.45	15.7	12.34
RF4.4	0.0377	88.6	3.34	20.09	22.66	29.98	0.26	28.59	25.24
RF4.5	0.0275	169.5	4.66	20.35	22.48	30.36	0.21	33.81	30.46
RF4.6	0.1795	6.7	1.21	20.35	21.20	30.36	0.09	46.15	42.8
Mag4.7	0.0171	−103.1	−1.77	20.33	21.25	30.36	0.09	…	…
Mag4.8	0.0251	972.4	24.37	20.33	25.65	30.36	0.53	…	…

TG Tuning

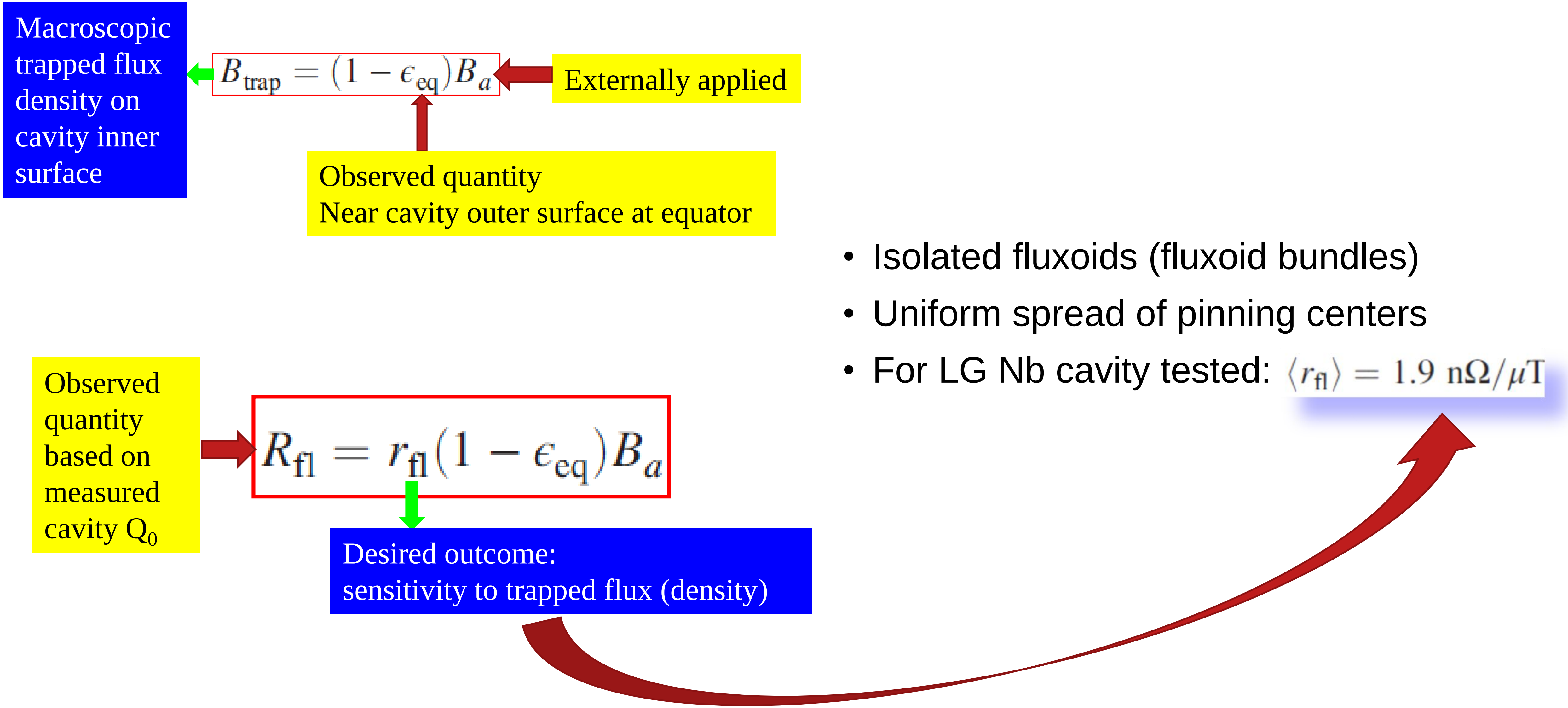
Benchmark r_{fl}
at $\tau_{eq} \approx 1$

Nearly complete trapping (96%) at Ba = 10 μT, resulting $B_{trap} \cong B_a$ and negligible $R_{BCS}(1.4K)$ and $B_{trap}{}^{(0)}$, permitting initial estimation of r_{fl}

ZFC

FC
Ba = 15 μT
Ba = 20 μT

Find Trapped Flux B_{trap} and Sensitivity of Surface Resistance to It r_{fl}



Macroscopic trapped flux density on cavity inner surface

$$B_{\text{trap}} = (1 - \epsilon_{\text{eq}})B_a$$

Externally applied

Observed quantity
Near cavity outer surface at equator

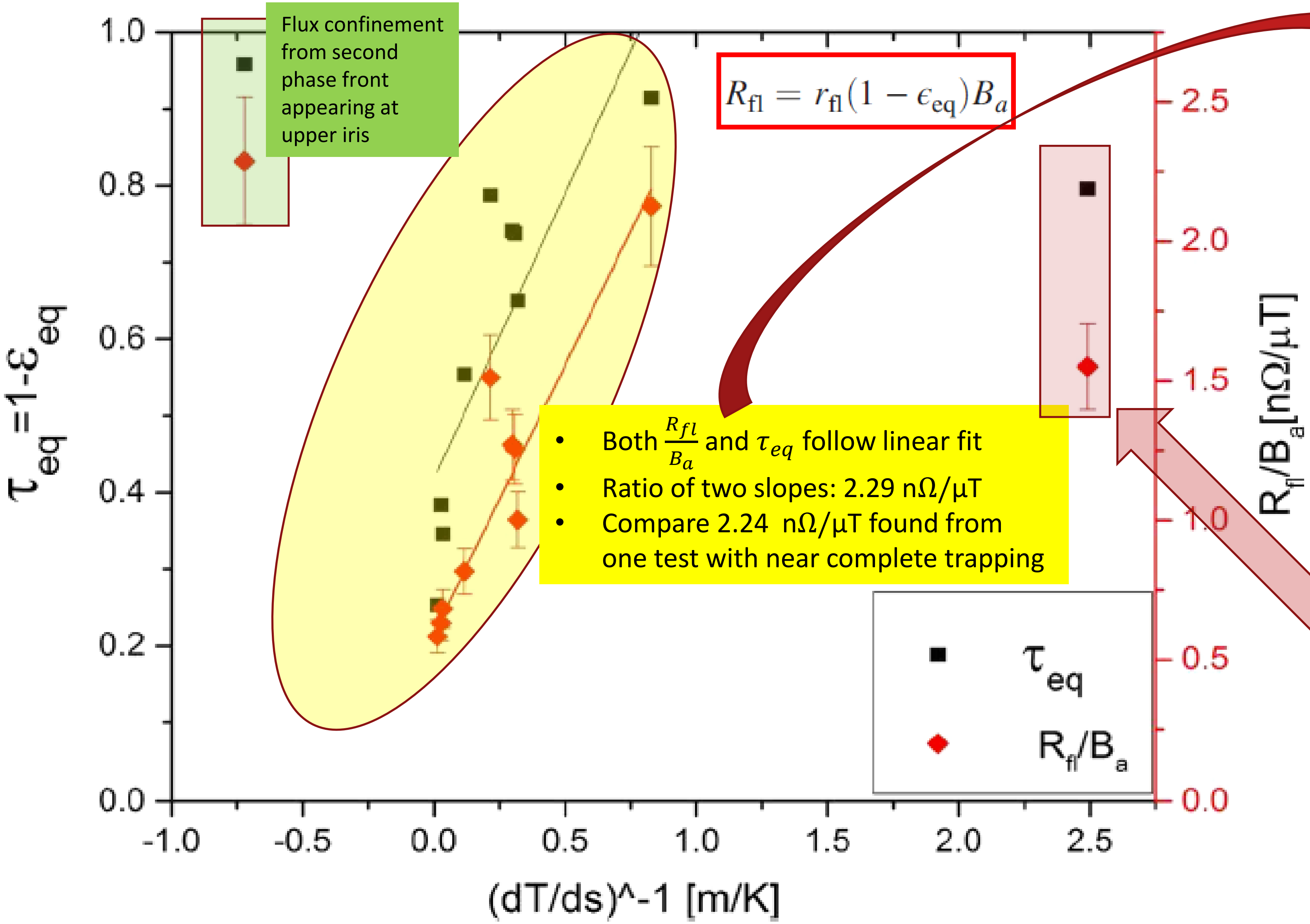
Observed quantity based on measured cavity Q_0

$$R_{\text{fl}} = r_{\text{fl}}(1 - \epsilon_{\text{eq}})B_a$$

Desired outcome:
sensitivity to trapped flux (density)

- Isolated fluxoids (fluxoid bundles)
- Uniform spread of pinning centers
- For LG Nb cavity tested: $\langle r_{\text{fl}} \rangle = 1.9\ \text{n}\Omega/\mu\text{T}$

Identify r_{fl} to be an Intrinsic Material Property by TG Tuning



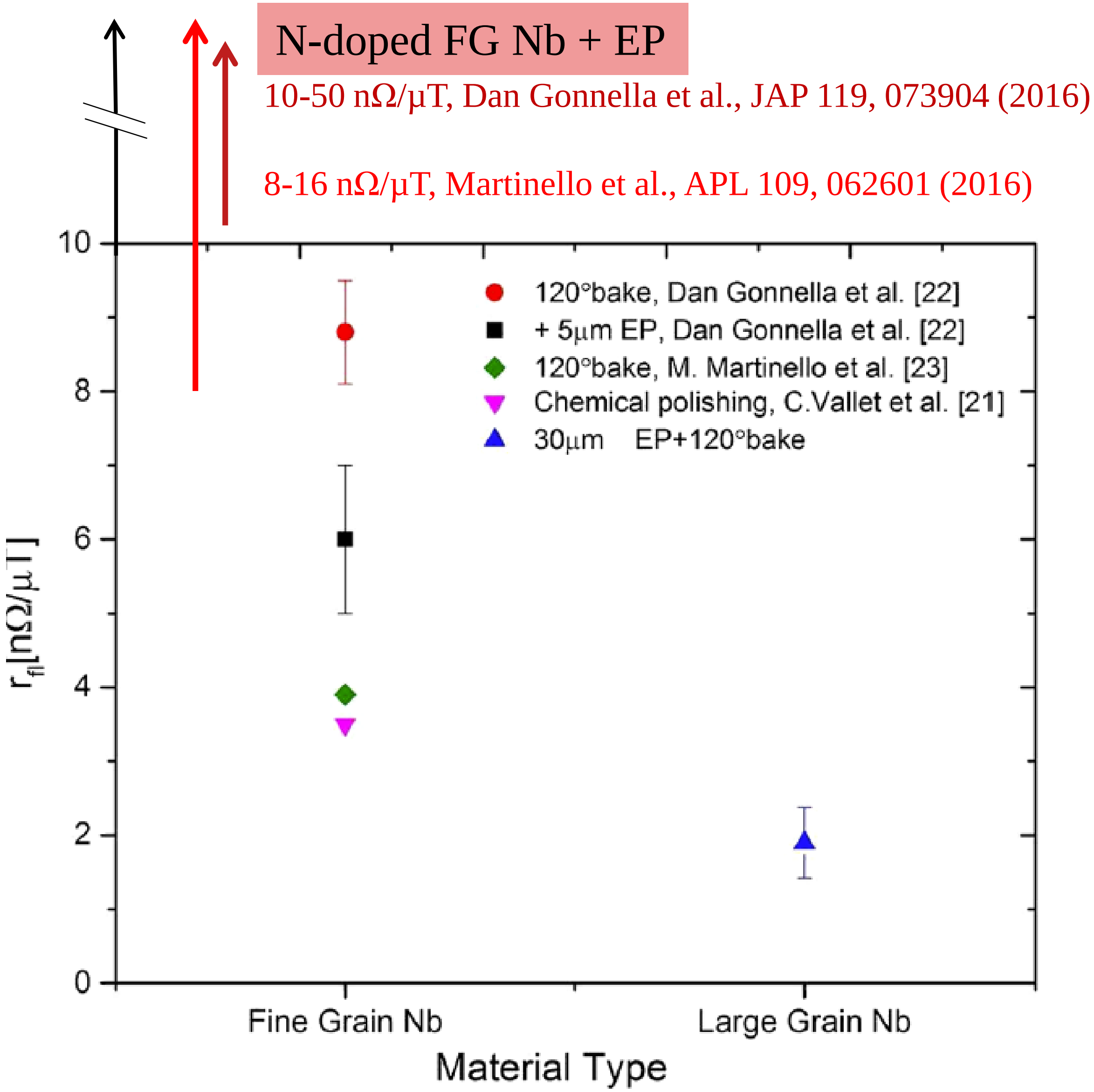
Flux confinement from second phase front appearing at upper iris

$$R_{\rm fl} = r_{\rm fl}(1-\epsilon_{\rm eq})B_a$$

- Both $\frac{R_{fl}}{B_a}$ and τ_{eq} follow linear fit
- Ratio of two slopes: 2.29 nΩ/µT
- Compare 2.24 nΩ/µT found from one test with near complete trapping

- Validates approach in finding B_{trap} on cavity inner RF surface via flux trapping ratio $\tau_{eq} = 1 - \varepsilon_{eq}$ measured near outer surface at cavity equator
- r_{fl} intrinsic material property
- Flux expulsion ratio τ_{eq} alone sensitive to cool-down condition
- Breakdown of linear dependence for large $(dT/ds)^{-1}$ or small dT/ds ~ 0.4K/m (uniform temperature distribution)
  - Kubo Theory (Prog. Theor. Exp. Phys. 2016, 053G01 (2016)) expects linear dependence valid within lower and upper limit

Understanding Gained w.r.t. Origin of Higher Q_0 in Large-Grain Nb Cavities



N-doped FG Nb + EP

10-50 nΩ/μT, Dan Gonnella et al., JAP 119, 073904 (2016)

8-16 nΩ/μT, Martinello et al., APL 109, 062601 (2016)

- Previous observation of 25-30% higher Q_0 at 2K in 9-cell LG high purity Nb cavities in comparison to 9-cell FG high purity Nb cavities at JLAB and DESY
  - Similar EP, LTB
  - Tested in same facilities with ambient magnetic field shielded to ~ 1.5 μT
- Previous data analysis at JLAB indicated this higher Q_0 is a result of a lower (factor 2-3) residual resistance
- Now it is understood this is originated from an intrinsic material property of LG Nb material: lower r_{fl}

Concluding Remarks (1 of 2)

- A technique, based on SRF cavity, for measurement of absolute quantitative trapped flux ratio τ_{eq} and residual surface resistance brought about by trapped flux R_{fl} introduced.

- A technique for determining local temperature gradient at NC/SC PTF $\frac{dT}{ds}|_{t_c}$ though local cool-down rate and PTF propagation speed introduced.
  - $\frac{dT}{ds}|_{t_c}$ enabled realization r_{fl} being an intrinsic material property, independent of cool-down conditions
  - Flux expulsion ratio an extrinsic parameter and it alone sensitive to cool-down conditions

- Measurement of trapped flux density on cavity inner RF surface B_{trap} though τ_{eq} measured near outer surface at equator demonstrated, through benchmarking measurement with $\tau_{eq} \approx 1$ and systematic variation of τ_{eq} controlled by PTF Temperature Gradient Tuning (**TG Tuning**).
  - Lingering question " *Does flux expulsion measured near outer cavity surface in cold helium gas has any bearing with trapped flux on the RF inner surface under vacuum?* " answered:
    - Yes for EP+LTB cavities !
  - Hint pining centers in the bulk of cavity wall play a large role for flux trapping in this case?
  - Good news for work done adopting Romanenko scheme for Posen Quotient.
    - Test our procedure for cavities of other material/surface treatment?
  - *Can techniques for cavity flux expulsion measurement be unified?* **see Shichun's talk.**

Concluding Remarks (2 of 2)

- Sensitivity of surface resistance to trapped flux, $\boldsymbol{r_{fl}}$, of a 1.5 GHz 1-cell LG Nb cavity experimentally measured – via controlled applied field and TG tuning.

- Previously observed 25-30% higher Q_0 (large statistics) in LG high-purity 9-cell cavities at JLAB and DESY in comparison to their FG counterparts measured in comparable conditions understood.
  - LG high-purity Nb cavity a predictable robust solution for improved SRF efficiency
    - Standard magnetic shield
    - Insensitive to cooldown conditions
    - High (up to 45 MV/m in 9-cell cavities as demonstrated at DESY) gradient reach