New insight into flux trapping ratio and added surface losses due to trapped flux

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Background

The unloaded quality factor (Q_0) of an SRF cavity is inversely proportional to the surface resistance (R_s) of the inner surface of the cavity.

$$R_s = R_{BCS}(B_{pk}, T) + \overbrace{R_{fl}(B_{pk}, B_{trap}, T) + R_0(B_{pk})}^{R_{res}(B_{pk}, B_{trap}, T)} \quad (1)$$

Contribution from vortices (R_{fl})

Something others(precipitates , subgap, etc. (R_0)

- R_{fl} was calculated from the RF measurement result.
- Define a parameter of flux expulsion ratio from experimental data.
- Discuss the dependence of flux expulsion ratio and R_{fl} of a large-grain Nb cavity on the spatial temperature gradient.

Experiment

We used a single cell cavity named PJ1-2,which is a 1.5 GHz CEBAF upgrade end-cell shape cavity ($G = 285\Omega$) made of a high-purity large-grain Nb material.

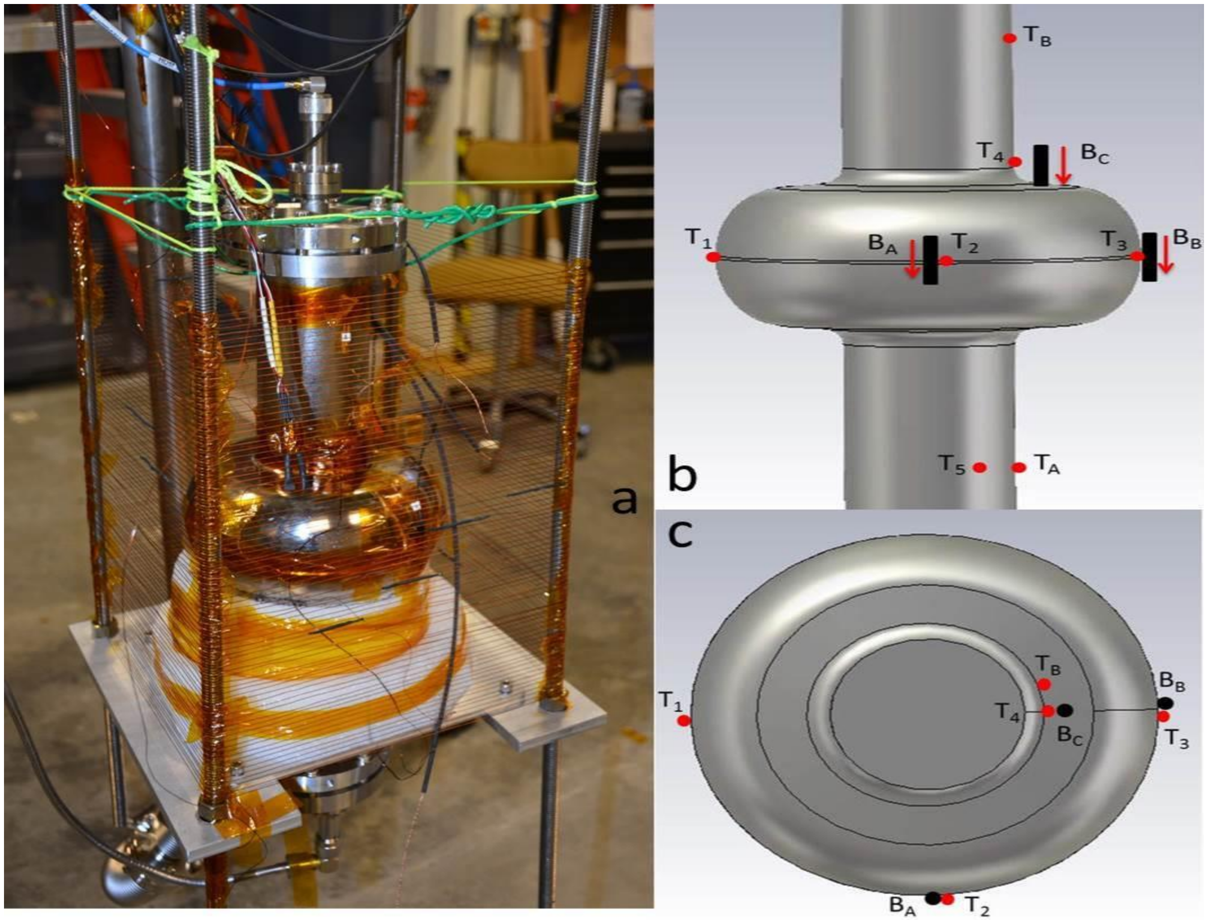


Fig.1. Experimental setup

Experiment(cont.)

1. Measure the generated magnetic field as a function of a coil current at room temperature.
2. Turn off the coil current and cool down the cavity from room temperature to 1.4K under a background field(zero-field cooling).
3. Measure Q_0 and E_{acc} at 1.4K.
4. Measure the magnetic flux density, $B_{sc,eq}^{(0)} \equiv {}^{(B_A+B_B)}/_2$ as a function of a coil current at 1.4K,which approximately corresponds to that for the ideal Meissner state with all applied flux expelled.
5. Warm up the cavity to a temperature above Tc and set the applied magnetic field $B_{applied}$ by using a coil current recorded in step1.
6. Cool down the cavity under the applied magnetic field $B_{applied}$.
7. Measure Q_0 and E_{acc} at 1.4K.
8. Measure the magnetic flux density at the equator:$B_{sc,eq} \equiv {}^{(B_A+B_B)}/_2$.
9. Repeat 5-8 under different cool-down conditions.
10. Repeat 1-9 under a different applied magnetic field $B_{applied}$.

Flux Trapping Ratio τ

B_A *and* B_B at equator

B_c at top Iris

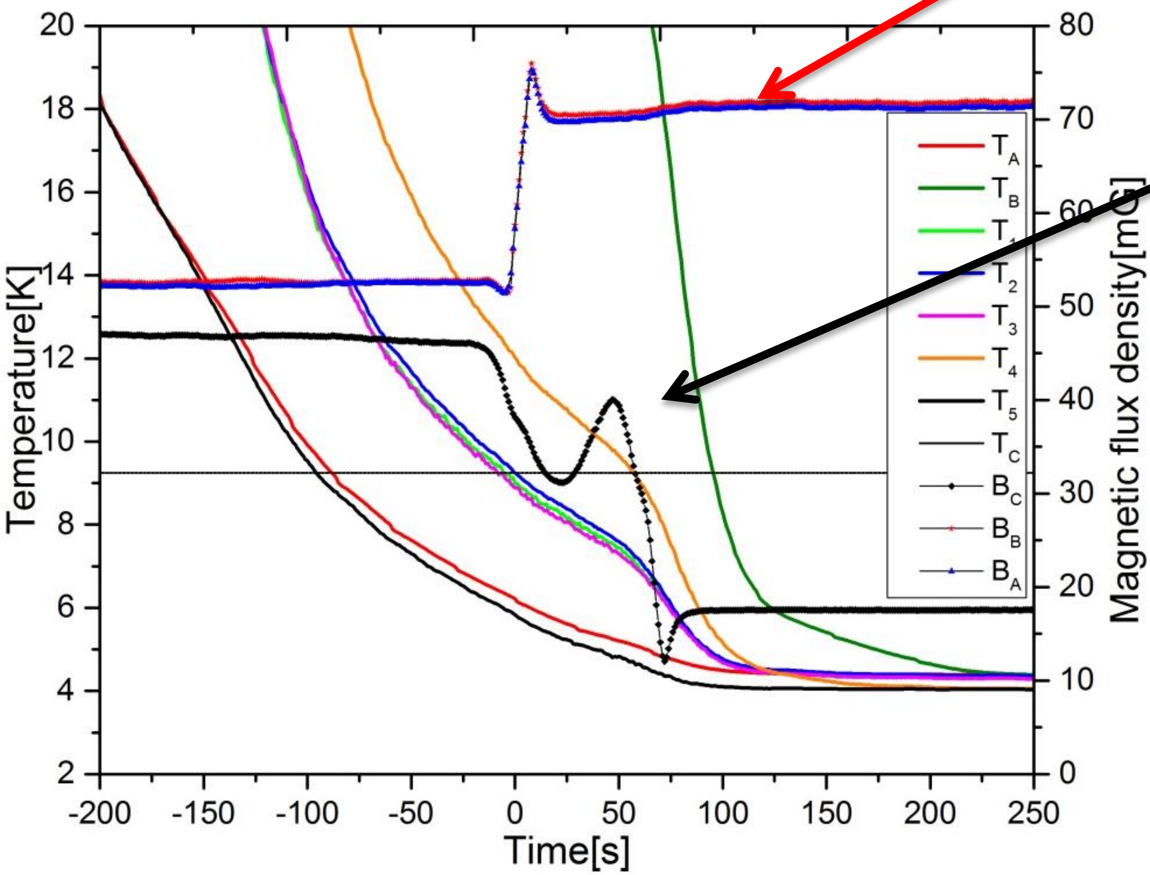


Fig.2. Examples of measured temperatures and magnetic flux densities as functions of time during a cool-down process, where the applied magnetic field is $5\mu T$.

Flux Trapping Ratio τ(cont.)

The jumps in the measured magnetic flux densities at the equator shows the magnetic flux expulsion due to the phase transition from NC state to SC state at that location. A value before the jump, $B_{NC,eq}$, corresponds to the applied magnetic field $B_{applied}$, and that after the jump corresponds to $B_{SC,eq}$. A parameter that represents the magnetic flux expulsion ratio can be defined as follow:

$$\varepsilon_{eq} = \frac{B_{SC,eq} - B_{NC,eq}}{B_{SC,eq}^{(0)} - B_{NC,eq}} \quad (2)$$

Measured from step 4

Where the denominator corresponds to the increase of magnetic flux density for the ideal expulsion of an applied magnetic field, and the numerator is the increase of magnetic flux density when the cavity is cooled down with the same applied magnetic field.

$$\tau_{eq} = 1 - \varepsilon_{eq} \quad (3)$$

$$B_{trap} = \tau_{eq} * B_{applied} \quad (4)$$

Flux Trapping Ratio τ(cont.)

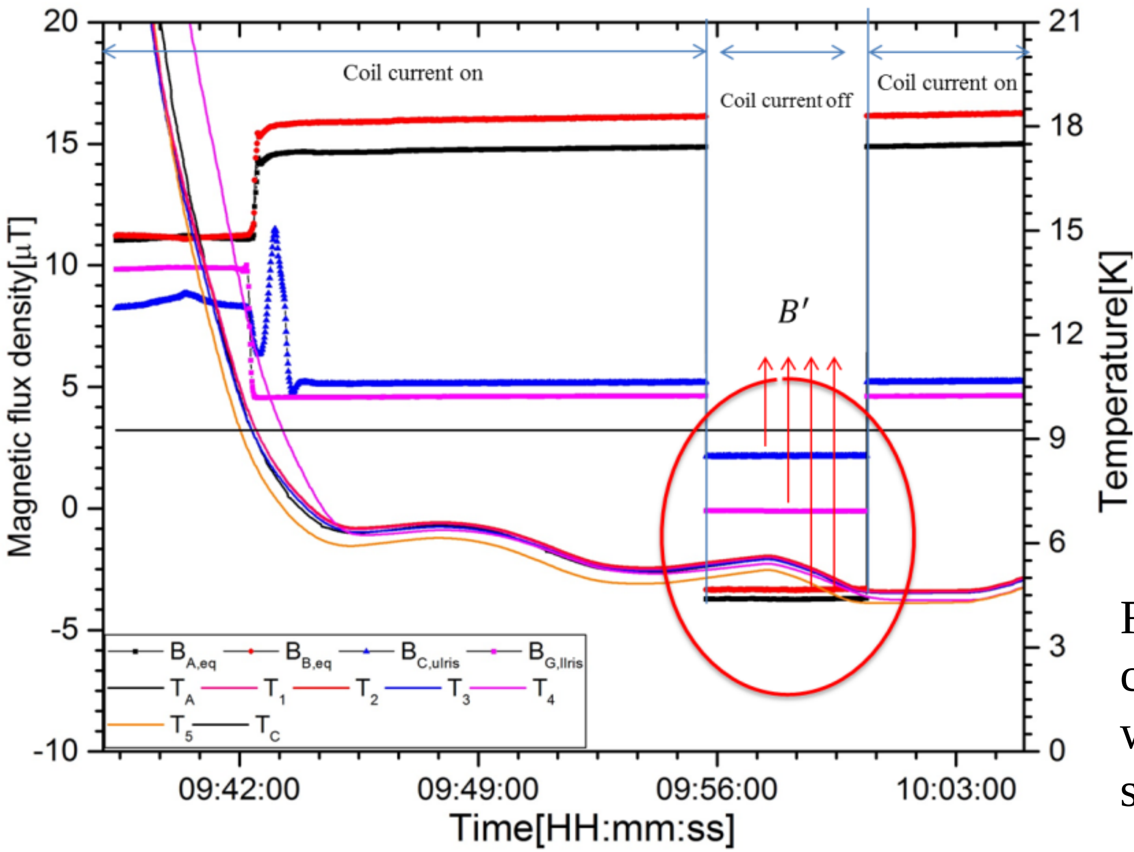


Fig.3. Measured magnetic flux density before (B_{sc}), after (B') turning off, then back on (B_{sc}) coil current.

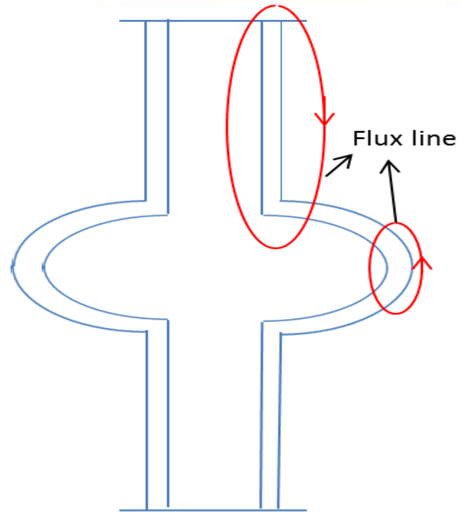


Fig.4. Model of flux distribution on cavity wall after turning off coil current when cavity is completely in Meissner state

Following conjecture based on our model in Fig.4.

$$B'_{eq} = B^{(0)}_{SC,eq} - B_{sc,eq} \quad (5)$$

$$B'_{Iris} = B_{sc,Iris} - B^{(0)}_{SC,Iris} \quad (6)$$

Flux Trapping Ratio τ(cont.)

$$B'_{eq} = B^{(0)}_{SC,eq} - B_{sc,eq} \qquad (5)$$

$$B'_{Iris} = B_{sc,Iris} - B^{(0)}_{SC,Iris} \qquad (6)$$

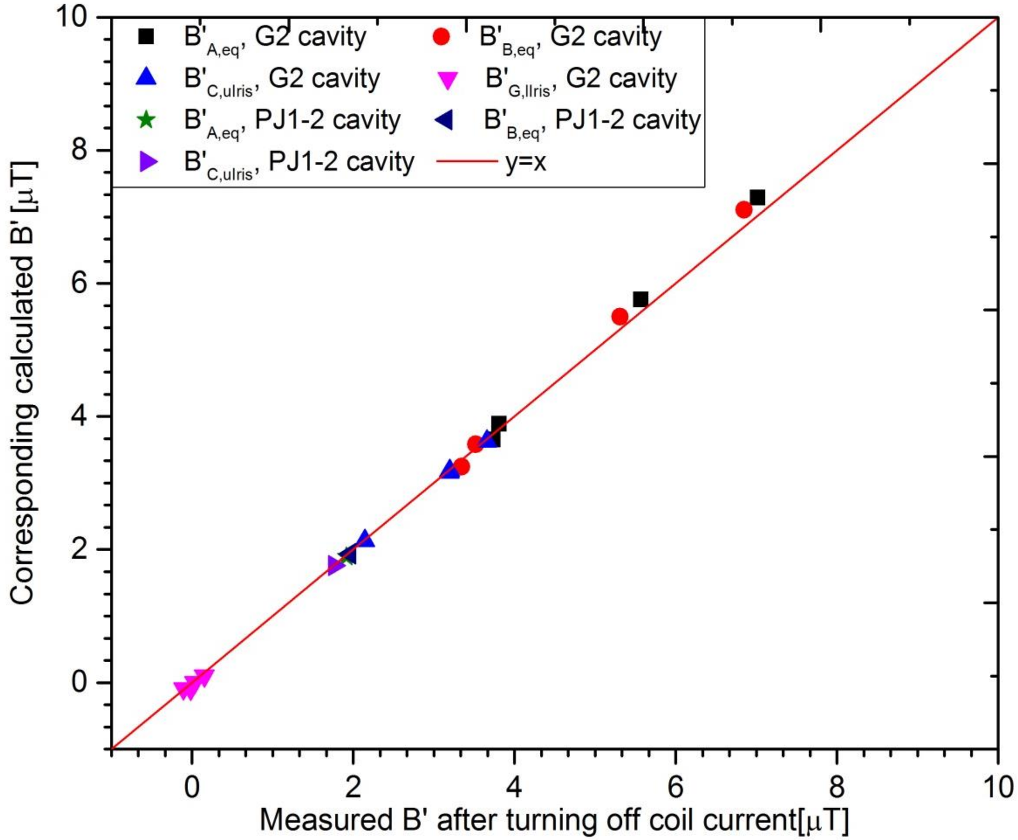


Fig.5. Calculated magnetic flux density from formula (5-6) (Bsc^0-B_{sc}) versus measured magnetic flux density in Meissner state (- B').

In reference[1], B' was used to defined B_{trap}. No more Coil off needed for B' with above empirical formulas.

Ref.[1]. D. Gonnella, J. Kaufman, and M. Liepe, J. Appl. Phys119, 073904 (2016).

Flux Trapping Ratio τ(cont.)

For any given cavity location, the cooling rate at the moment of the phase transition $dT/_{dt}\,|_{t=t_c}$,can be extracted from the temperature data ,where t_c is the time when the sensor at that location showed $T = T_c$ .By using tc of the sensors placed at different levels, the inverse of the propagation speed of the phase front,$v_c^{-1} = {dt_c}/_{ds}$, can be evaluated.

$$\frac{dT}{ds}|_{t_c} = \frac{dT}{dt}|_{t_c} * \frac{dt_c}{ds} \qquad (7)$$

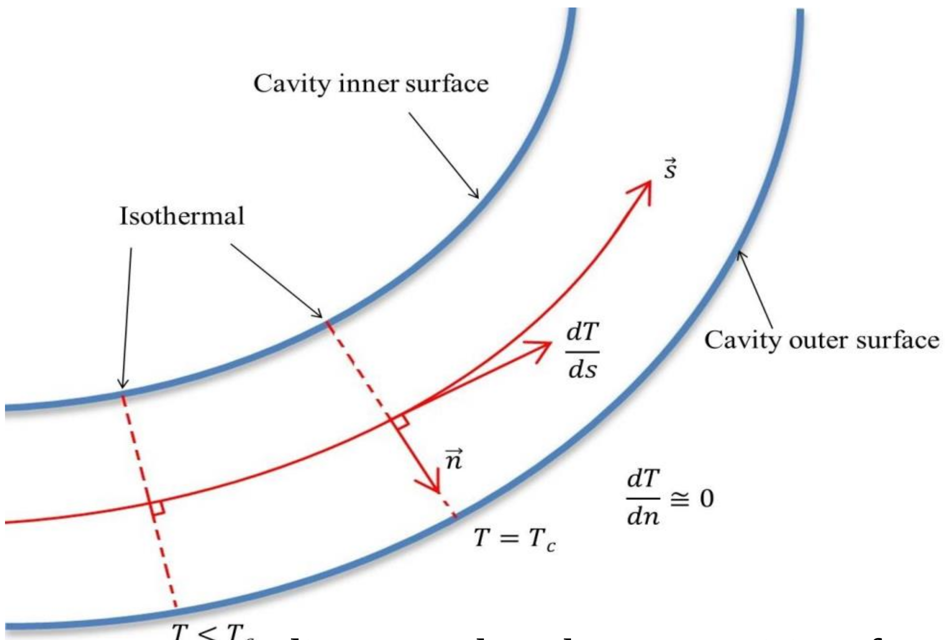


Fig.6. Model of the temperature gradients at the phase transition front along the curved cavity wall.

Flux Trapping Ratio τ(cont.)

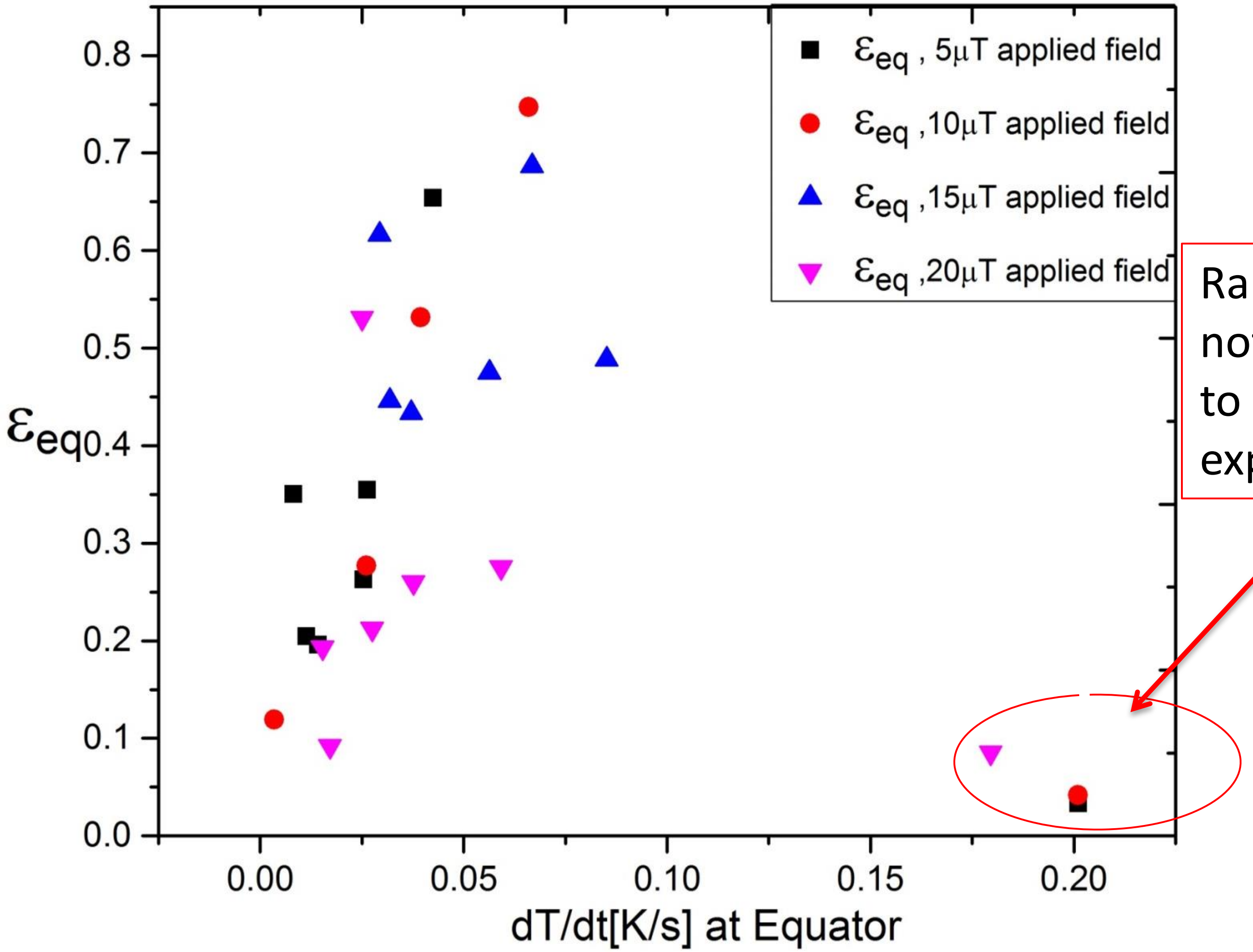


Fig.7. Flux expulsion ratio ϵ_{eq} as a function of the cooling rate.

Rapid cool-down does not necessarily leads to a good flux expulsion

Flux Trapping Ratio τ(cont.)

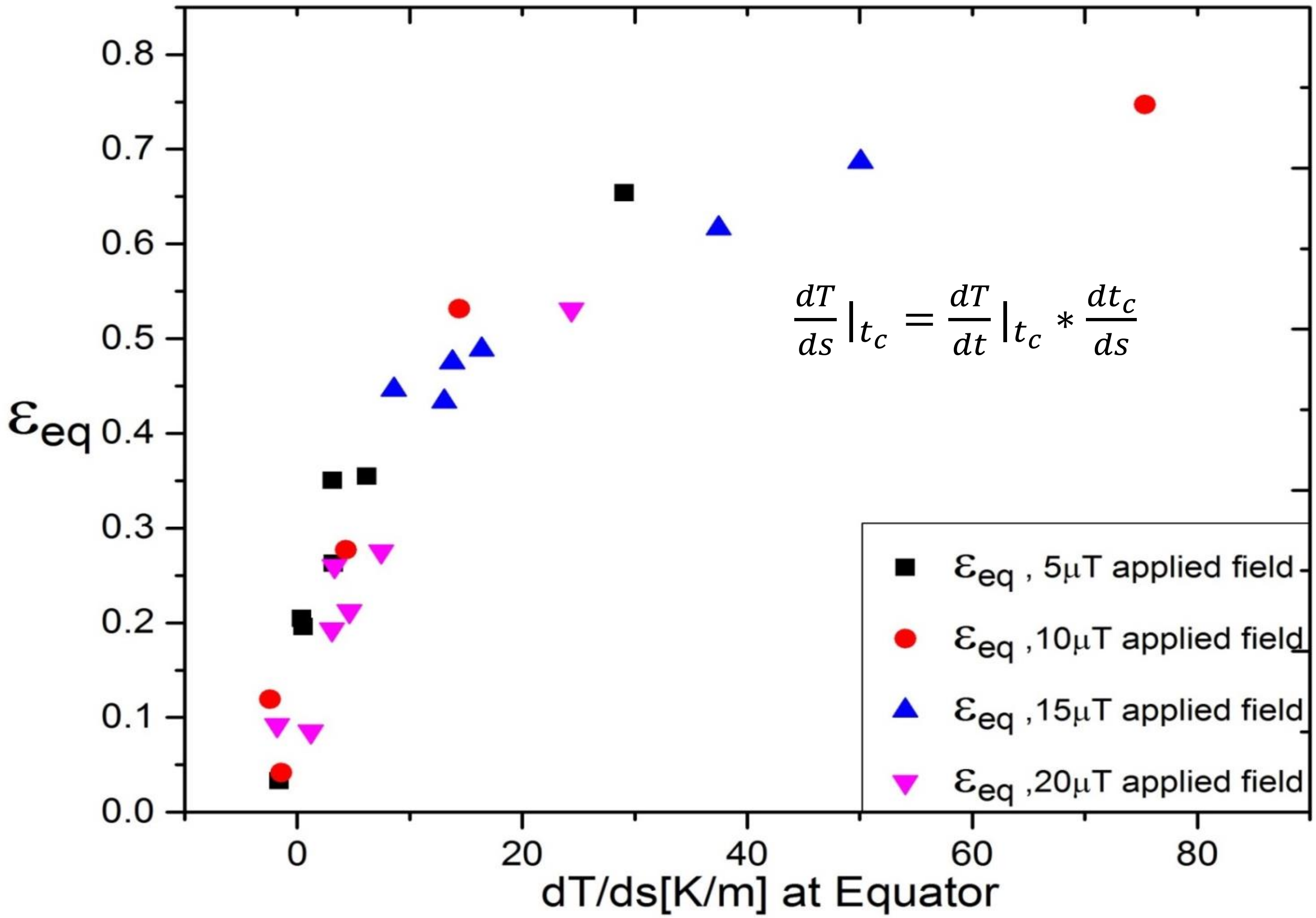


Fig.8. Flux expulsion ratio ϵ_{eq} as a function of the temperature gradient at equator

Our current result supports and enforces Romanenko's conclusion

Added surface losses due to trapped flux

The surface resistance of the cavity is defined at T=1.4K and Eacc=5MV/m;

$$R_s \equiv R_s|_{1.4K,5MV/m} = \frac{G}{Q_0}|_{1.4k,5MV/m} \qquad (8)$$

Where $G = 285\Omega$.

For the test following zero-field cooling(without applied magnetic field):

$$R_s^{(0)} = R_{BCS} + R_{fl}\left(B_{trap}^{(0)}\right) + R_0 \qquad (9)$$

Since the surface of the cavity is unchanged during the experiment, so R_{BCS} and R_0 are common between R_s and $R_s^{(0)}$.

$$R_{fl}(B_{trap}) = R_s - R_s^{(0)} + B_{trap}^{(0)} r_{fl} \qquad (10)$$

Where r_{fl} is the sensitivity defined by $r_{fl} = R_{fl}/B_{trap}$.

Added surface losses due to trapped flux(cont.)

When the $Btrap$ is large enough and a resultant R_{fl} is much larger than R_{BCS}(1.4K):

$$R_s \approx R_{fl} + R_0 \rightarrow r_{fl} = {}^{(R_s - R_0)}/_{B_{trap}} \tag{11}$$

When almost all field is trapped and $B_{trap} \cong B_{applied}$:

$$r_{fl} = {}^{(R_s - R_0)}/_{B_{applied}} \tag{12}$$

In one of our measurement, the $\epsilon_{eq} = 0.04$ is so small that we may regard:$B_{trap} \cong B_{applied} = 10\mu T$, and $R_s = 25n\Omega$ are so large that the contribution from R_{BCS}(1.4K) is negligible:

$$r_{fl} = {}^{(25n\Omega - R_0)}/_{10\mu T} \tag{13}$$

Added surface losses due to trapped flux(cont.)

Substitute r_{fl} into $R_s^{(0)} = R_{BCS} + B_{trap}^{(0)} r_{fl} + R_0$,and use $r_{fl} = {}^{(25n\Omega - R_0)}/_{10\mu T}$ we obtain

$$r_{fl} = \frac{22.4n\Omega + R_{BCS}(1.4K)}{10\mu T - B_{trap}^{(0)}} \cong 2.24\, {}^{n\Omega}/_{\mu T} \qquad (14)$$

Where $R_{BCS}(1.4K) \ll 22.4n\Omega$ and $B_{trap}^{(0)} \ll 10\mu T$ was used.

$$R_{fl} = R_s - R_s^{(0)} + B_{trap}^{(0)} r_{fl} \qquad (10)$$

Note: $B_{trap}^{(0)} \cong 0.23\mu T, 0.06\mu T\ and\ 0.13\mu T$, so $R_{fl}(B_{trap}^{(0)}) = B_{trap}^{(0)} r_{fl} \cong 0.52n\Omega, 0.13n\Omega\ and\ 0.22n\Omega$

Background magnetic field: $0.23\mu T, 0.06\mu T\ and\ 0.13\mu T$

Added surface losses due to trapped flux(cont.)

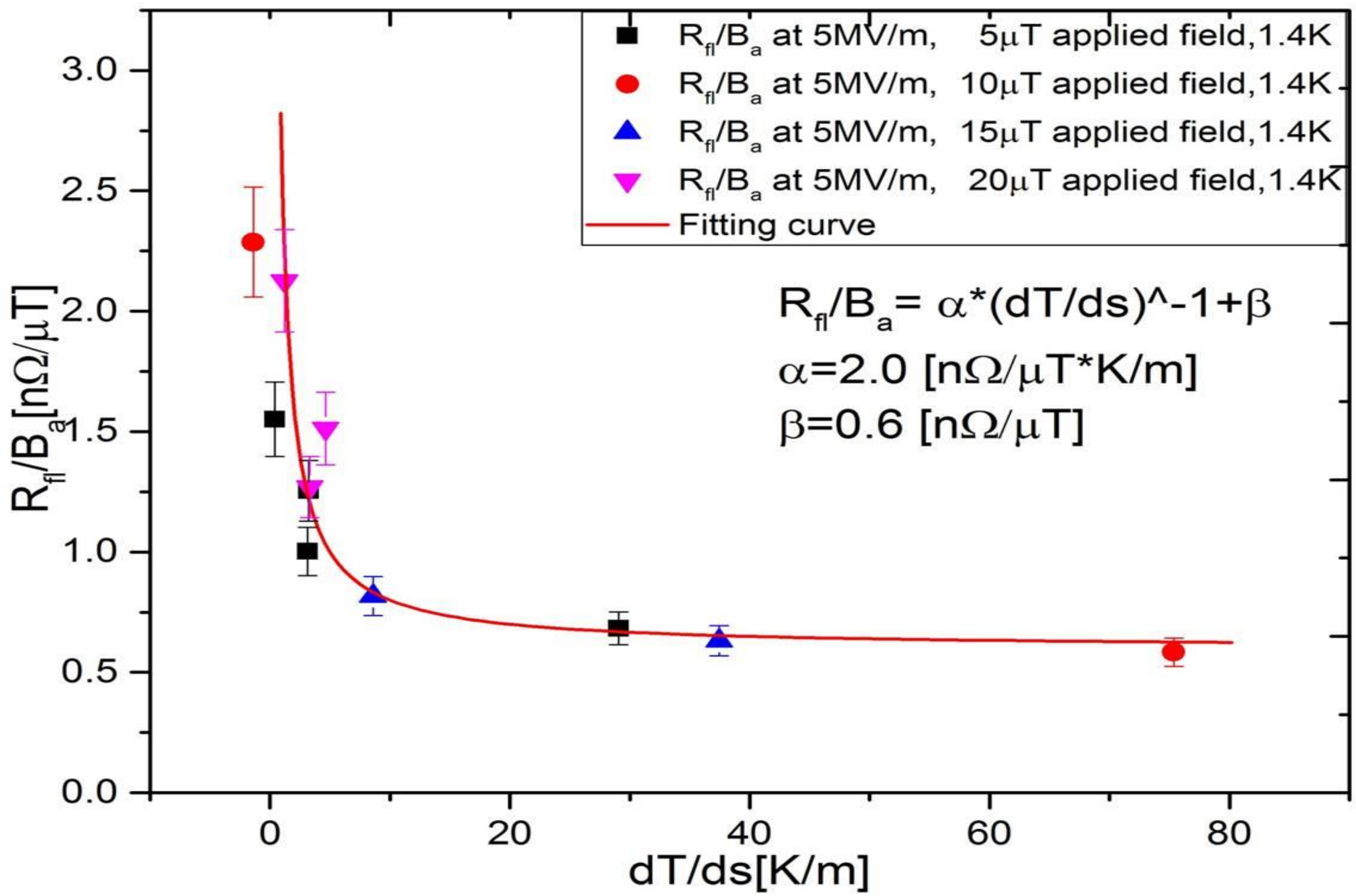


Fig.9. Rfl normalized by an applied field Ba as a function of ${}^{dT}/_{ds}$.

$$R_{fl} = R_s - R_s^{(0)} + B_{trap}^{(0)} r_{fl}$$

Added surface losses due to trapped flux(cont.)

$$R_{fl} = B_{applied}[\alpha * ({}^{dT}/_{ds})^{-1} + \beta] \quad (15)$$

Where $\alpha = 2.0\, {}^{n\Omega}/_{\mu T} * {}^{K}/_{m}$, $\beta = 0.6\, {}^{n\Omega}/_{\mu T}$. α and β are independent of $B_{applied}$, there are strong material dependence.

Note: The α value of our cavity is more than one order of magnitude smaller than that of Fermilab's cavity ($28.5\, {}^{n\Omega}/_{\mu T} * {}^{K}/_{m}$)[1-2], which was made of fine grain niobium, nitrogen doped and surface processed with EP.

Ref. [2]. A. Romanenko et al., Appl. Phys. Lett. 105, 234103 (2014).
Ref. [3]. T. Kubo, Prog. Theor. Exp. Phys. 2015, 073G01 (2015).

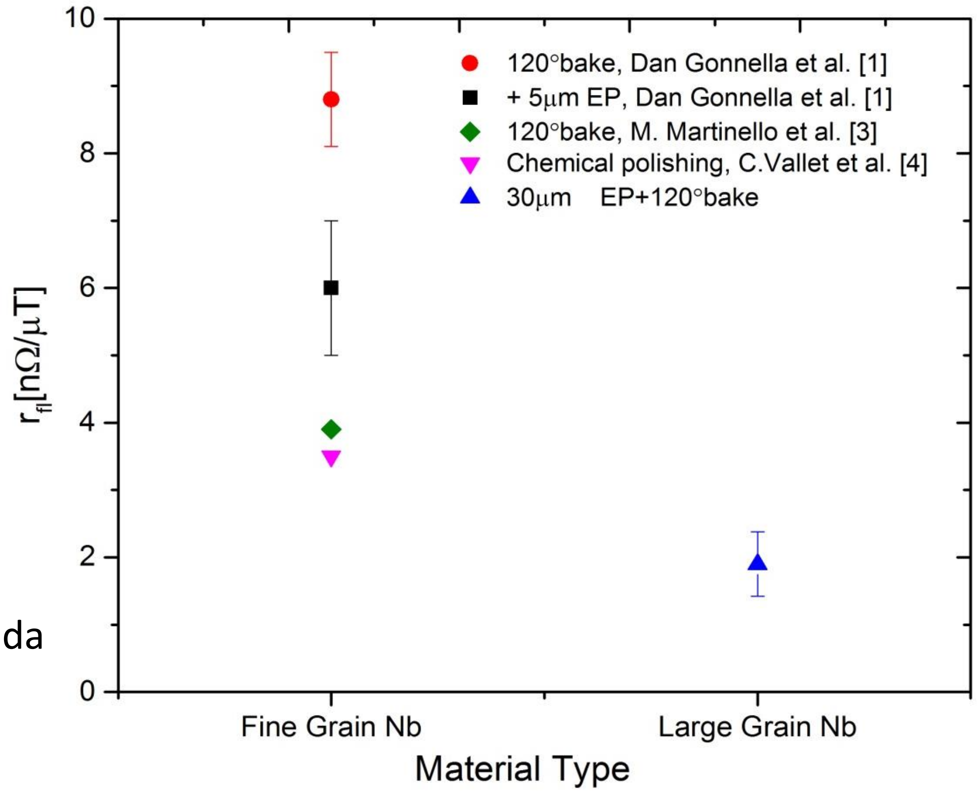
Added surface losses due to trapped flux(cont.)

Each trapped fluxon in the RF penetration depth individually contributes to RF dissipation:

$$R_{fl} = r_{fl}\left(1 - \varepsilon_{eq}\right) * B_{applied} \qquad (16)$$

The average r_{fl} is 1.9 $^{n\Omega}/_{\mu T}$ evaluated by Eq. (16), it is consistent within 15% with the value found previously (2.24 $^{n\Omega}/_{\mu T}$) in Eq. (14).

Fig.10. Sensitivity r_{fl} of cavities made from fine-grain and large-grain niobium material with different surface treatments.



Ref.[3]. M. Martinello et al., SRF2015, Whistler, Canada (2015), MOPB015.
Ref.[4]. C. Vallet et al., in Proceedings of EPAC1992, Berlin, Germany (1992), p. 1295.

Conclusion

- Trapped flux defined in Ref.[1] can be evaluated as follows:

$$B_{trap,eq} \approx B'_{eq} = B^{(0)}_{SC,eq} - B_{sc,eq} \quad (5)$$

$$B_{trap,Iris} \approx B'_{Iris} = B_{sc,Iris} - B^{(0)}_{SC,Iris} \quad (6)$$

- Magnetic flux expulsion ratio ε_{eq} improves as the spatial temperature gradient increases, independent of the applied magnetic field.

- An empirical formula: $R_{fl} = B_{\text{applied}}[\alpha * ({}^{dT}/_{ds})^{-1} + \beta]$,was obtained.

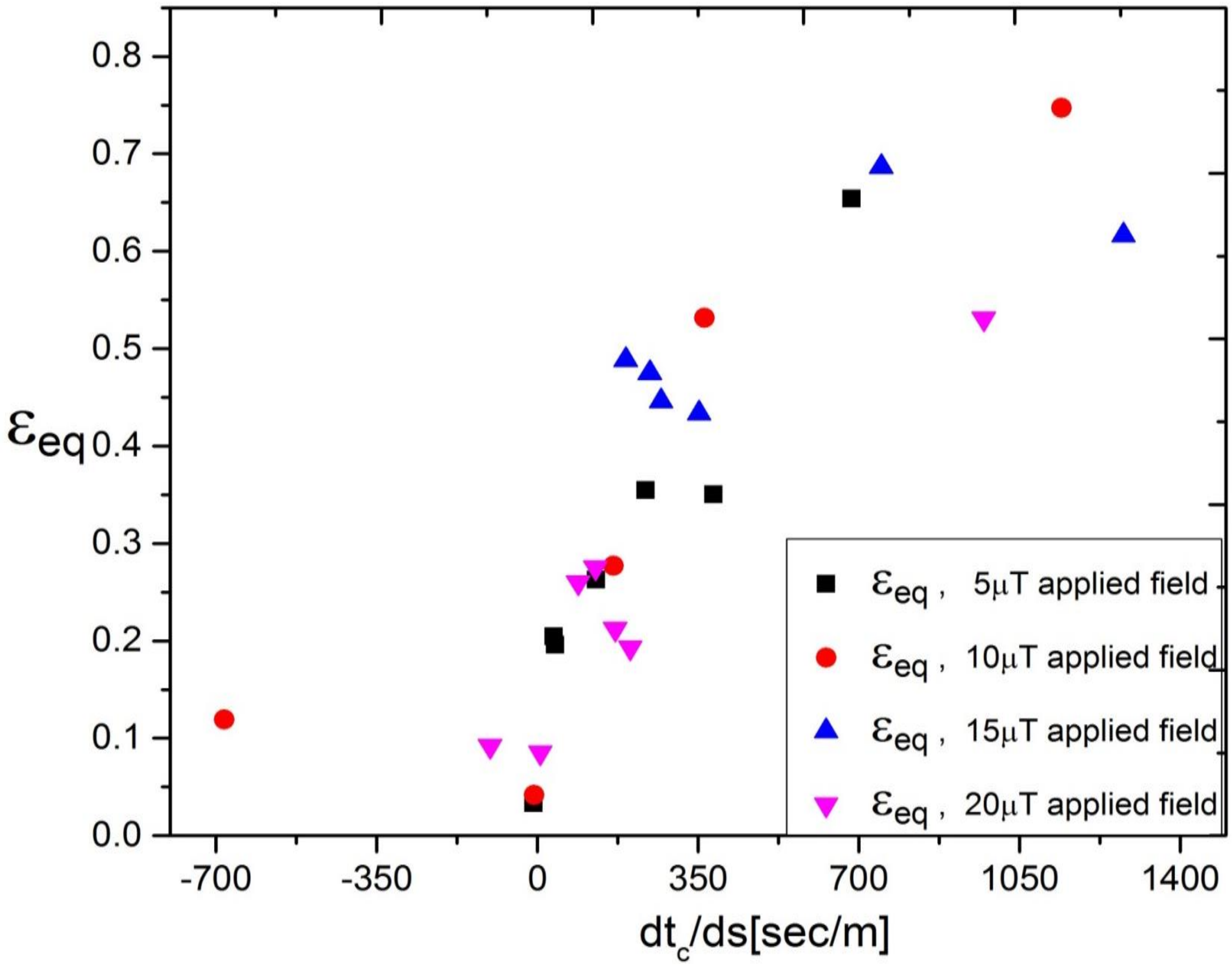
  α has strong material dependence.

- $R_{fl} = r_{fl}(1 - \varepsilon_{eq}) * B_{\text{applied}}$, the sensitivity r_{fl} is material dependence.

Backup

Surface processing history:90μm removal by BCP with HP:HNO3:H3P04=1:1:1 at room temperature , vacuum funace out gassing at 800°C for 3 hours, additional 60μm removal by BCP with HP:HNO3:H3P04=1:1:2 at temperature between $8-10$°C, in-situ baking at 120°C for 12 hours, 30μm removal by EP, and another in-situ baking at 120°C for 12 hours.

Backup



Flux expulsion ratio ϵ_{eq} as a function of the reciprocal of the propagation speed of the phase front