# Can Present Techniques for Cavity Flux Expulsion Efficacy Measurements be Unified?

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# Outline

- Background
- Experimental setup
- Results and discussion
- Conclusion

# Background

- Trapped-flux-induced surface resistance $R_{fl}$ can be a major contributor to $R_{res}$

$$R_{fl} = r_{fl}(B_{pk}, T) \times B_{trap}$$

- Measurement of $B_{trap}$ is essential
  - Determine the sensitivity $r_{fl}(B_{pk}, T)$
  - Understand the dynamics of magnetic flux trapping during the cavity phase transition

- Presently, three methods are used for measurement of trapped flux density
  - Consistency and equivalency not cross examined
  - This work attempts to address this unfilled gap

# Three Methods

*Method adopted at JLAB[1]*

$\mathrm{B_{trap}} = (1 - \varepsilon_{\mathrm{Eq}}) \times \mathrm{B_a}$

**Method J**

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

*Method adopted at FNAL[2]*

**Method F**

$$B_{trap} = B_{NC}\left(1 - \frac{\frac{B_{SC,eq}}{B_{NC,eq}} - 1}{R_{PD} - 1}\right)$$

Numerically Calculated Ratio
Modeling perfect dia-gmagnetism
$\mathrm{R_{PD}}$ = 1.7 for 1-cell TESLA end cell shape
Varies with cavity geometry

*Method adopted at Cornell[3]*

$$B_{trapped} = B_{left} - B_{amb}$$

**Method C**


[1]. S. Huang, Takayuki Kubo, and R.L. Geng, Phys, Rev. ST Accel. Beams 19, 082001(2016).
[2]. M. Martinello et al., in Proceedings of SRF2015, Whistler, BC, Canada, MOPB015.
[3]. D. Gonnella, J. Kaufman, and M. Liepe, J. Appl. Phys119, 073904 (2016).

# Experimental setup

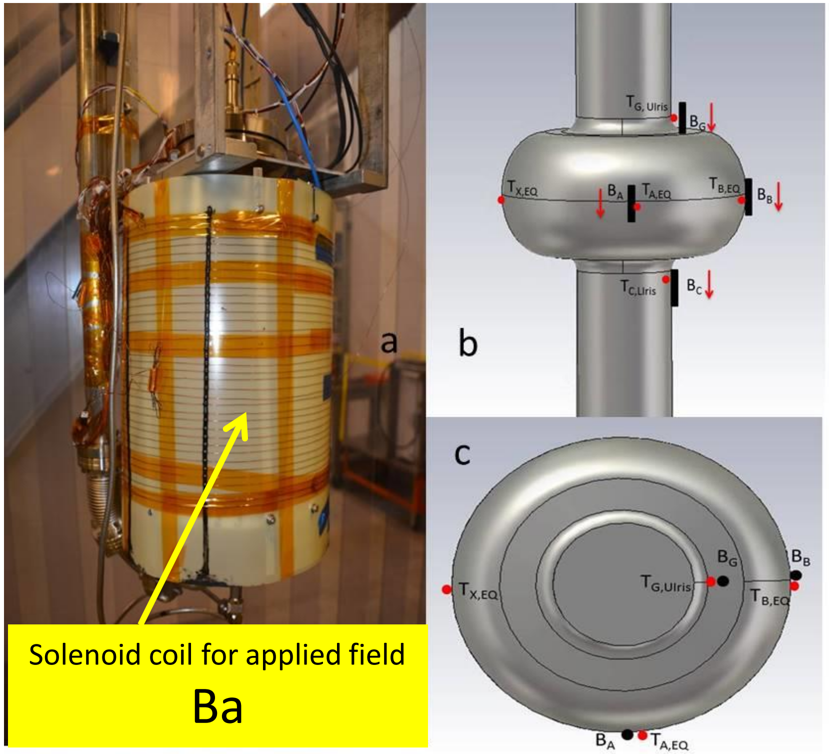



Fig.1 Experimental setup

Two types of cavity shape:
PJ1-2: 1.5GHz CEBAF upgrade end-cell shape
G2: 1.3GHz TESLA end-cell shape

1. Record magnetic flux densities measured by all magnetometers while scanning coil current at room temperature.

2. Cool down cavity with coil current off (ZFC) from room temperature to 1.4 K (residual background field of $< 0.3\mu T$). At 1.4 K, record magnetic flux densities by all magnetometers ($B_{SC}^{(0)}$) while scanning the coil current.

3. Warm up the cavity to a temperature above $T_c$.

4. Cool down the cavity with an applied field generated by setting the coil current at a chosen value (FC). The current is maintained at that vale onward.

5. Turn off the solenoid current at 4K for 3 minutes, then switch it back on (at the same set current as in step 4).

6. Repeat step 3-5 for different applied fields up to $20\mu T$.

# Method J Explained

$$B_{trap} = (1 - \varepsilon_{Eq}) \times B_a$$

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

all exp. measured quantities

100% flux trapping. $\varepsilon_{Eq} = 0$ ($\tau_{Eq} = 1$).

100% flux expulsion. $\varepsilon_{Eq} = 1$ ($\tau_{Eq} = 0$).

$B_{NC,Eq}$: Flux density at equator, local temperature just above Tc ( = Ba )

$B_{SC,Eq}$: Flux density at equator, local temperature just below Tc for given Ba

FC

$B^{(0)}_{SC,Eq}$: Flux density at equator, measured by same probe, after ZFC to 1.4 K (in Meissner state) then turn on coil current for the same Ba applied during FC

>>> 100% flux exclusion

ZFC

# Comparing Method J with Method F

| | Method J | Method F |
|---|---|---|
| Target quantity | $\dfrac{{B_{SC,eq}}^{(0)}}{B_{NC,eq}}$ | $R_{PD}$ |
| TESLA end long end cell | 1.51±0.04 | 1.54 |
| CEBAF 12 GeV end cell | 1.67±0.02 | 1.71 |

Method J and F confirmed to be consistent within 3%

# Comparing Method J and Method C

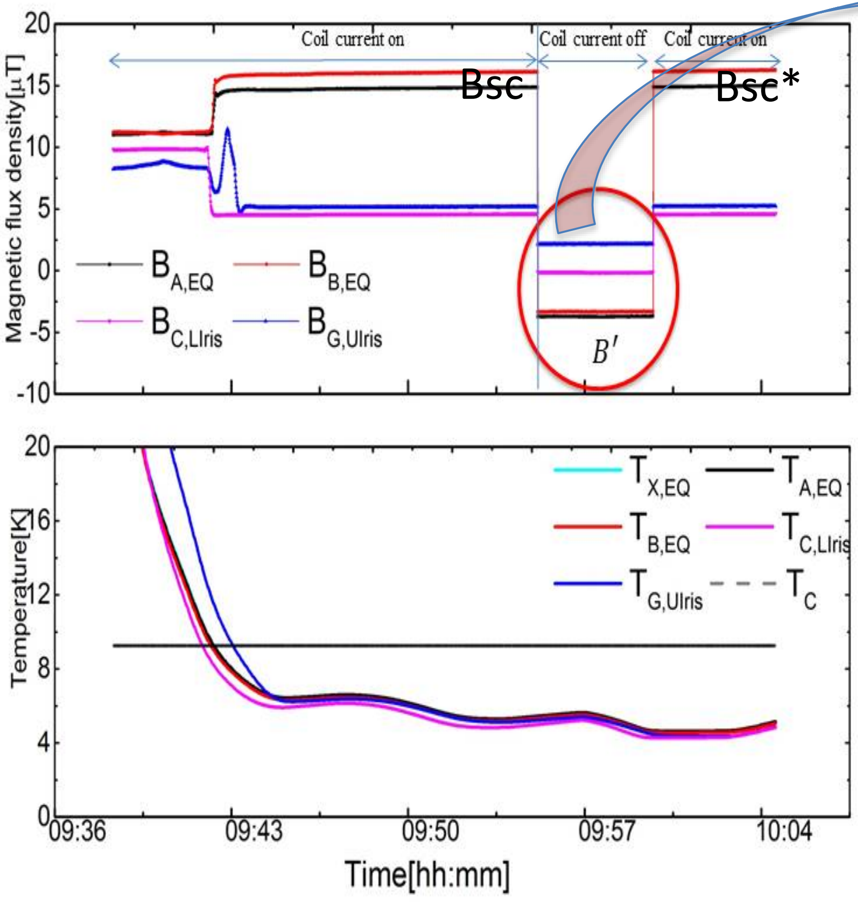



Fig.2. Responses of magnetometer to cavity cool-down process

**B′ in this work is $B_{left}$ in Method C**

- A step-wise jump in the measured flux density was clearly recoded by the magnetometers attached to the equator and lower iris.
- The flux densities stayed more or less at static after the jump was completed while the coil excitation current being still maintained.
- The difference between Bsc and Bsc* in is less than 3%.

# Effect of Switching Coil Current OFF and Back ON

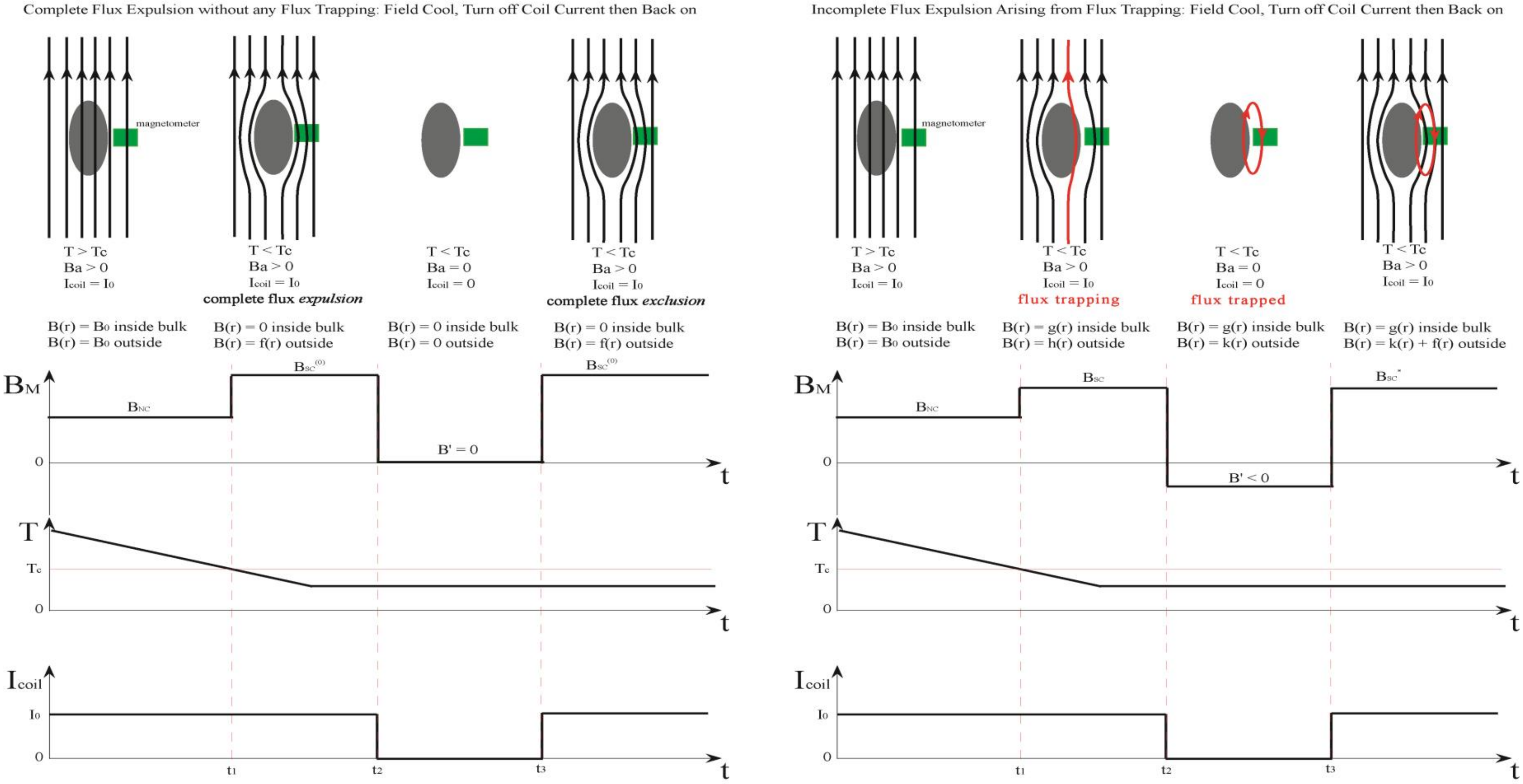
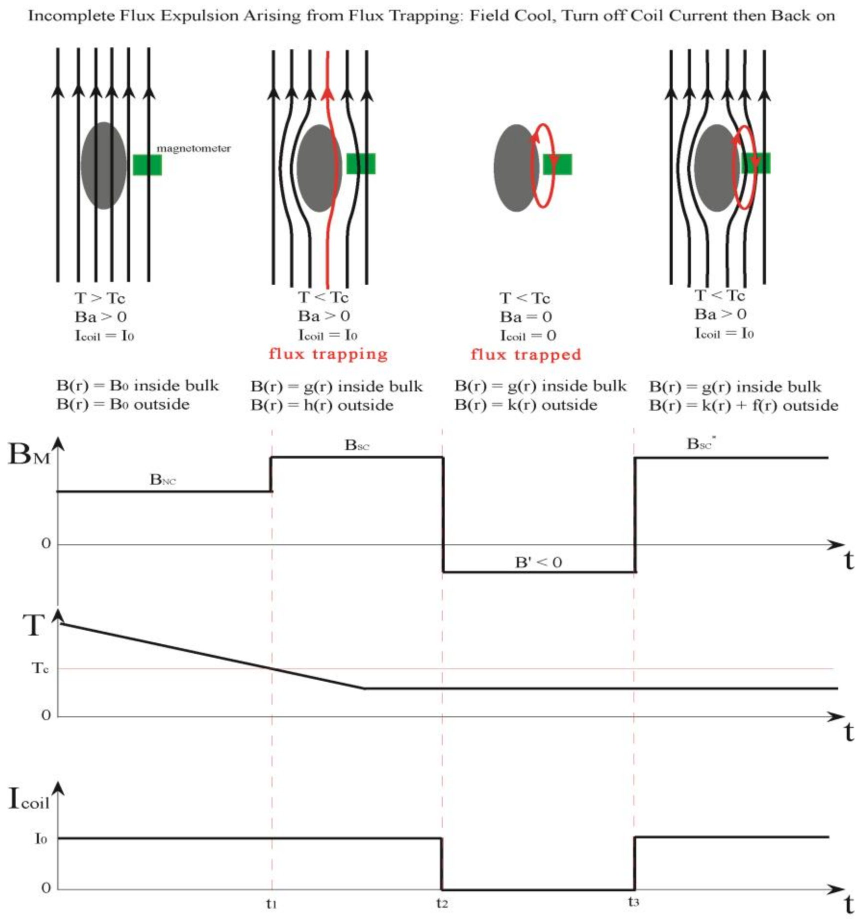



Fig. 3 The sketches of magnetic flux line distribution over a superconductor volume during a cooldown process with an applied magnetic field. **Complete flux expulsion(left) and incomplete flux expulsion(right)**

# Finding B’ without Turning Off Coil Current




A conjecture based on the principle of field superposition

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

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

# Experimental Verification of Conjecture

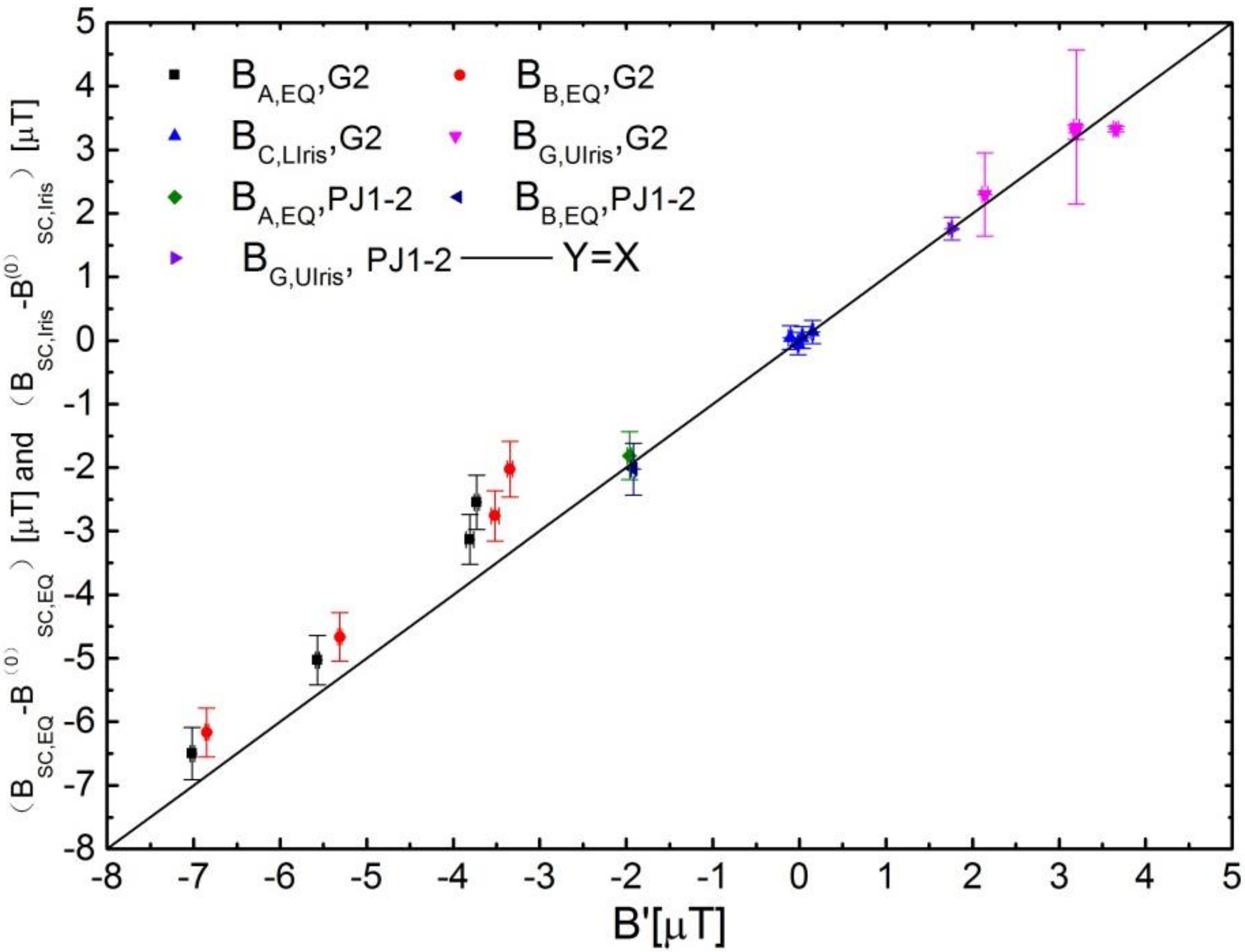
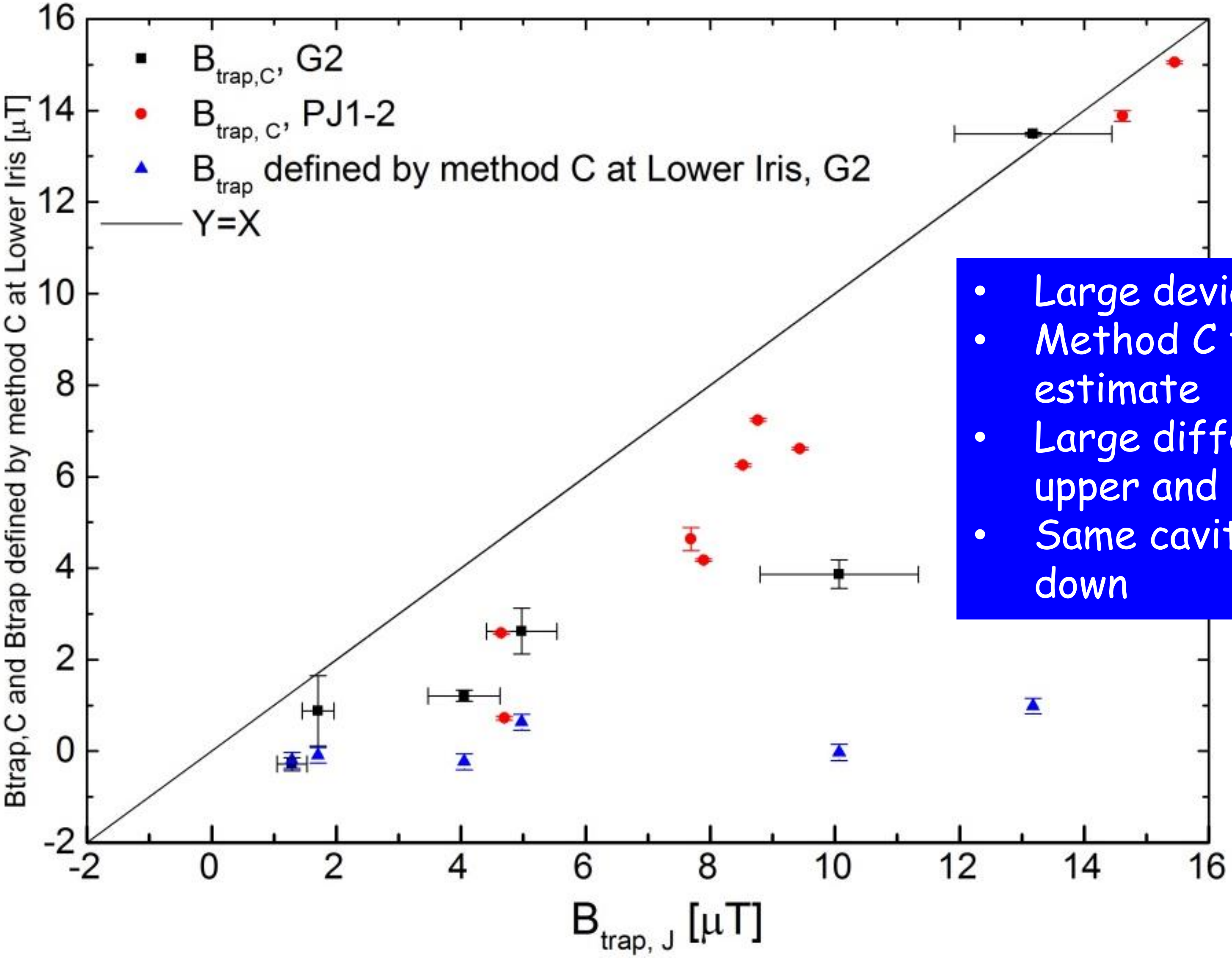



Fig.4. The correlation between the calculated and measured $B'_{Eq/Iris}$

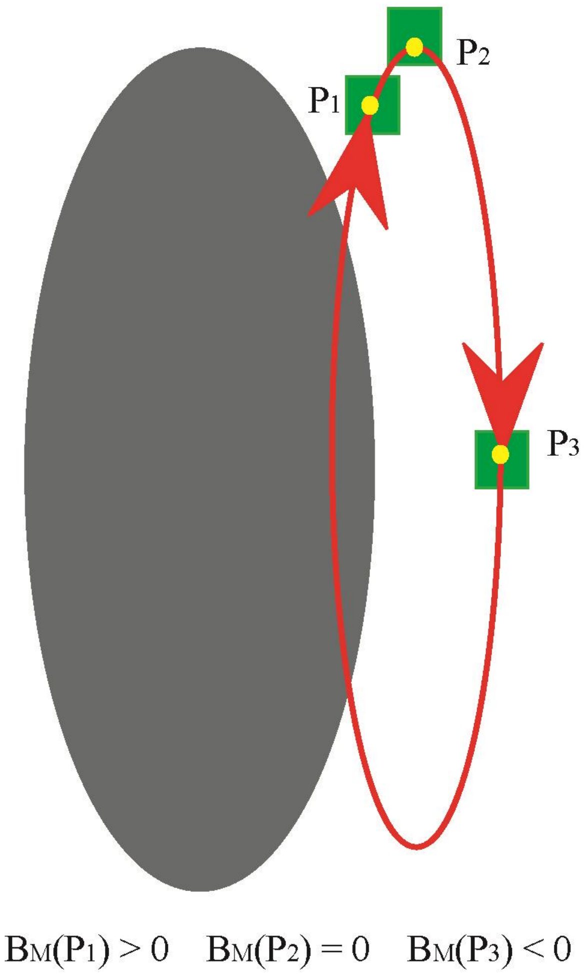
# Comparing Method J with Method C




- Large deviation
- Method C tends to under estimate
- Large difference between upper and lower iris
- Same cavity same cool down

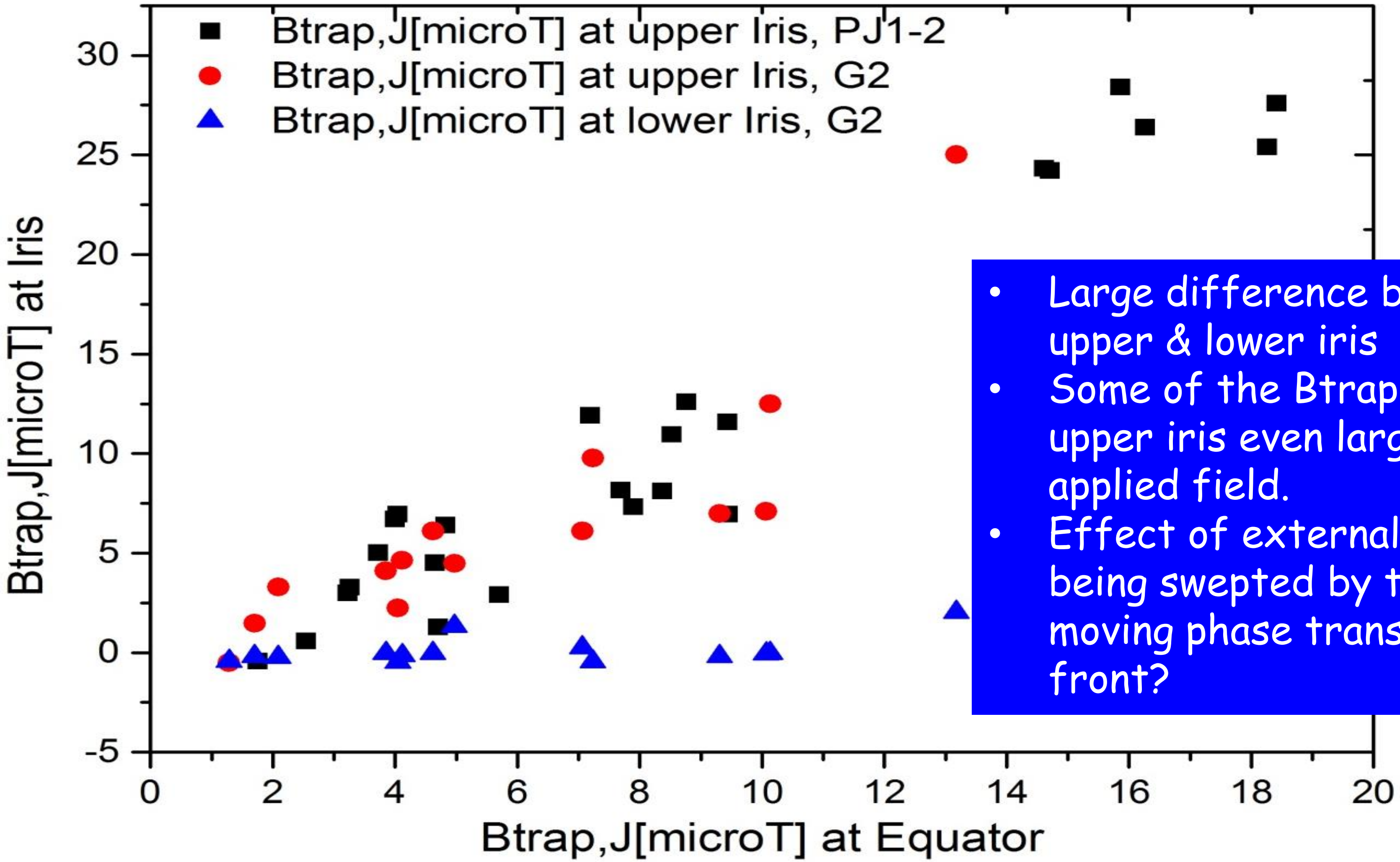
# Understanding Deviation Between Method J and Method C

Varability of Measured Local Flux Density outside of a Supercoductor with Trapped Flux




- B′ (or $B_{left}$ ) expected to be sensitive to location of probe
- Observed variability between values measured by probes at lower and upper iris may be a result of this effect.

# $B_{trap}$ Method J: Iris vs Equator




- Large difference between upper & lower iris
- Some of the Btrap at upper iris even larger than applied field.
- Effect of external field being swepted by the moving phase transition front?

# Conclusion

- Three methods for trapped flux measurements experimentally crossed checked.
- A conjecture brought forward, based on field superposition principle, experimentally. It permits determination of $B_{left}$ defined in method C though two measured quantities defined in Method J: $B_{left} = \mathrm{B}_{\mathrm{sc,iris}} - \mathrm{B}^{(0)}_{\mathrm{SC,iris}}$.
- Method J and method F are found consistent within 3%.
- Method C appears to be problematic
  - It tends to under estimate by a large margin, as compared to method F.
  - Using it, large difference is observed between trapped flux measured at upper and lower iris.
- Unification of three methods partial success.
  - One possible way to improve this situation is to couple the measurement effort with numerical simulation effort.
  - Identify sensitive locations for placing probes.
  - Orientation-resolved measurements should be very helpful.