The Paramagnetic Meissner Effect in Josephson Junction Arrays

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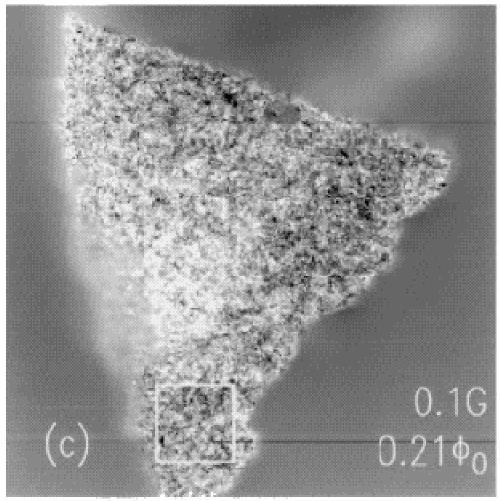
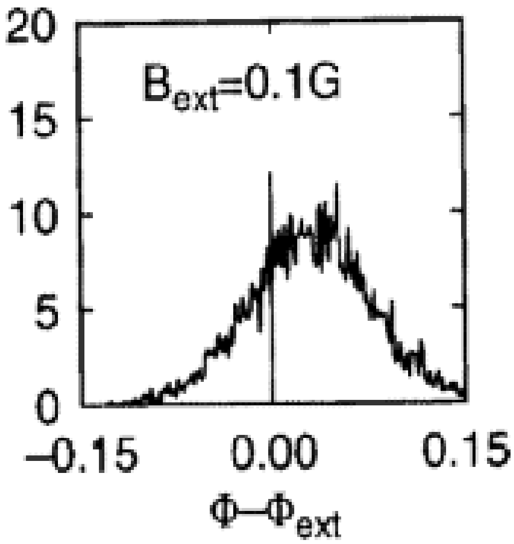
Support: AFOSR Grant F49620-98-1-0072,
Center for Superconductivity Research, UMD

Outline

- Paramagnetic Meissner effect.
- Arrays.
- Bulk susceptibility.
- Single-loop model.
- Scanning SQUID measurements.
- Single loop revisited.
- Possible explanations.

Field cooled BSCCO[1,2]





[1]W. Braunisch *et al*. PRL **68** 1908 (1992)
[2]J. R. Kirtley *et al.* J. Phys.: Cond. Mat. **10** L97 (1998)
[3]A. K. Geim *et al*. Nature. **396** 144 (1998)
[4]D. J. Thompson *et al* PRL **75** 529 (1995)
[5]P. Kostic *et al*. PRB **53** 791 (1996)

π-junctions in d-wave ceramics?

PME observations

Nb - D.J. Thompson *et al*. PRL **75** 529 (1995)
P. Kostic *et al*. PRB **53** 791 (1996)

Al - A.K. Geim *et al*. Nature **396** 144 (1998)

BSCCO - W. Braunisch *et al*. PRL **68** 1908 (1992)
J.R. Kirtley *et al*. J. Phys: Cond Mat. **10** L97 (1998)

YBCO - S. Reidling *et al*. PRB **49** 13283 (1994)

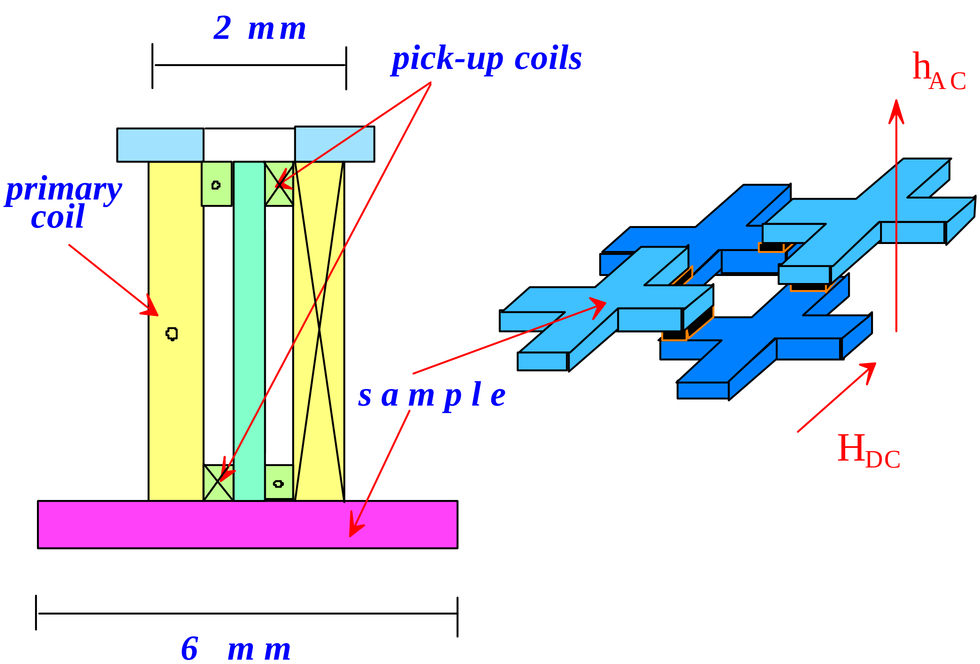
NCCO - G. S. Okram *et al*. J. Phys:Cond Mat. **9** L525 (1997)

HgCCO - U. Onbasli *et al*. Phys. Stat. Sol. B **194** 371 (1996)

Proposed causes

- π-junctions
- Surface effects
- Random pinning
- Non-equilibrium

Bulk susceptibility

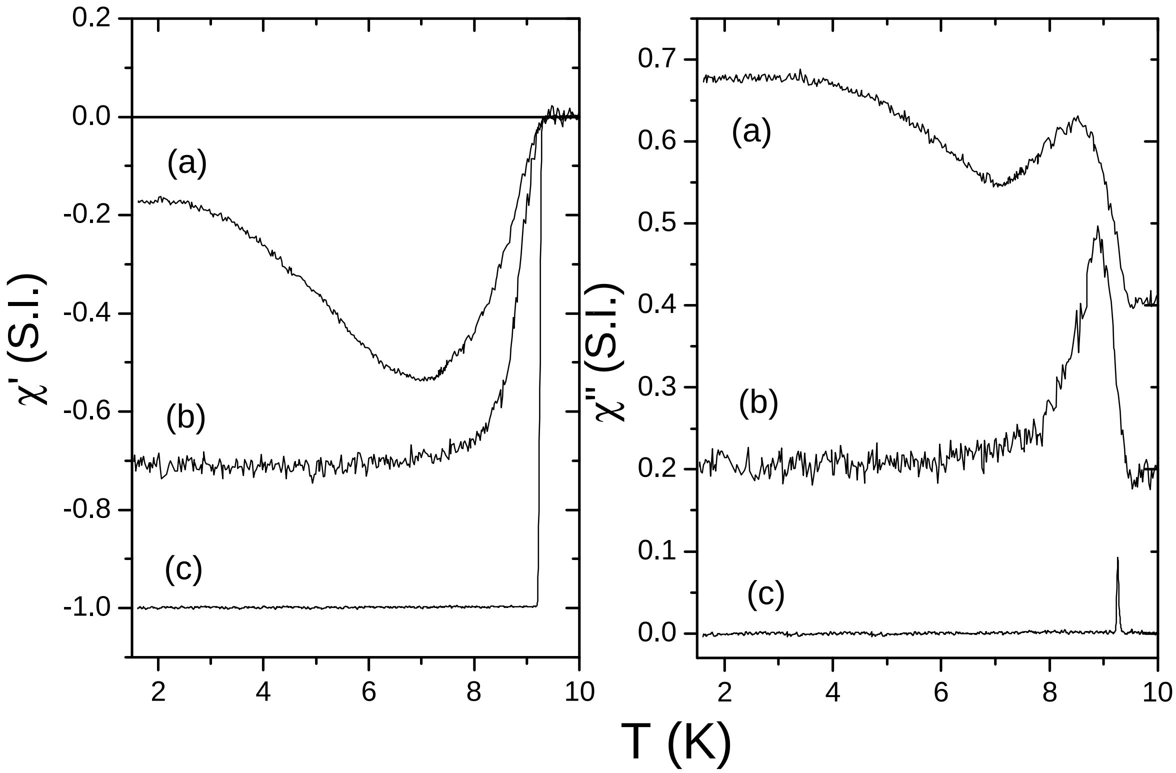


$$H_{EXT} = h_{AC}\cos(\omega t)$$

$$M(t) = h_{AC}\,\Sigma[\chi'_m \cos(m\omega t) + \chi''_m \sin(m\omega t)]$$

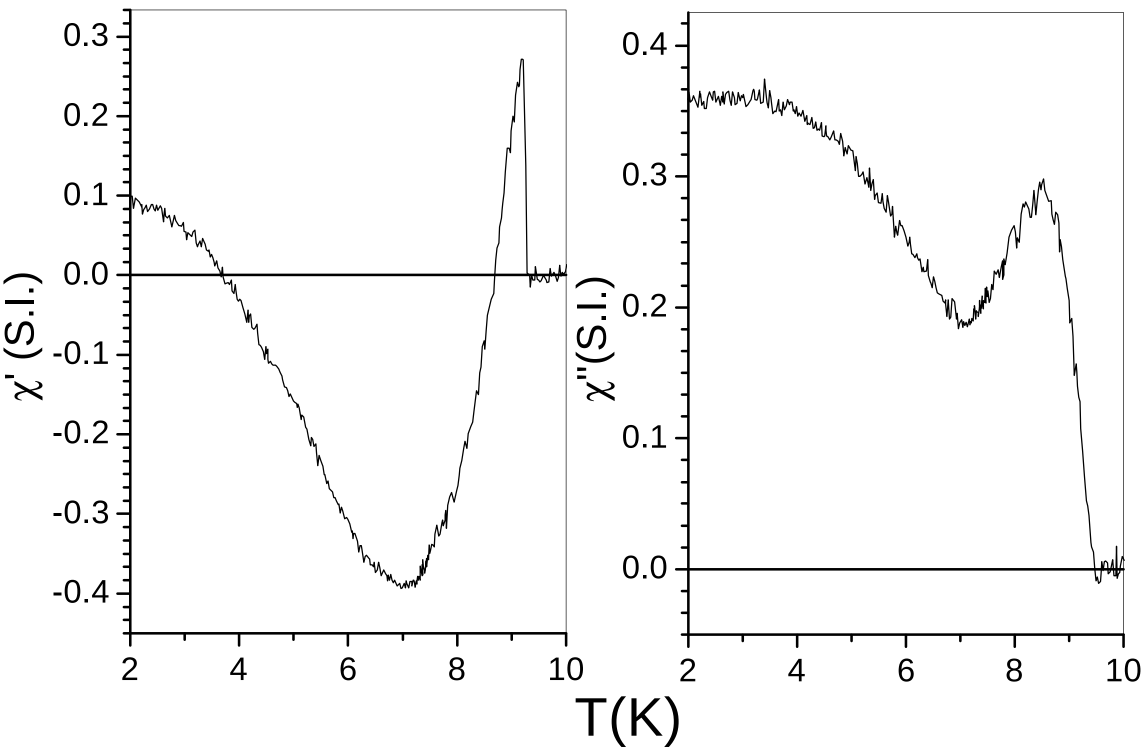
$$M_1(t) = h_{AC}[\chi'_1 \cos(\omega t) + \chi''_1 \sin(\omega t)]$$

Data



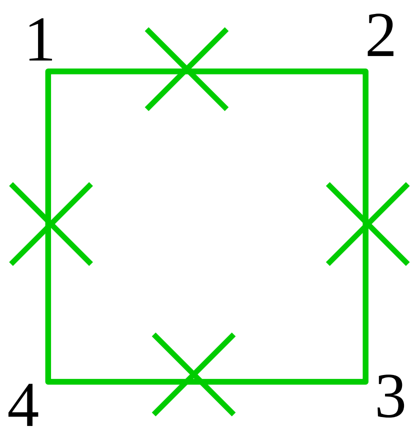
(a) h_{AC}=96 mOe, array.
(b) h_{AC}= 7 mOe, array.
(c) h_{AC}=10 mOe, Nb film

Data, loops only



(Nb background subtracted)

Single-loop simulation



$$H_{EXT} = h_{AC} \cos(\omega t)$$

$$\Phi_{TOT} = \Phi_{EXT} + LI$$

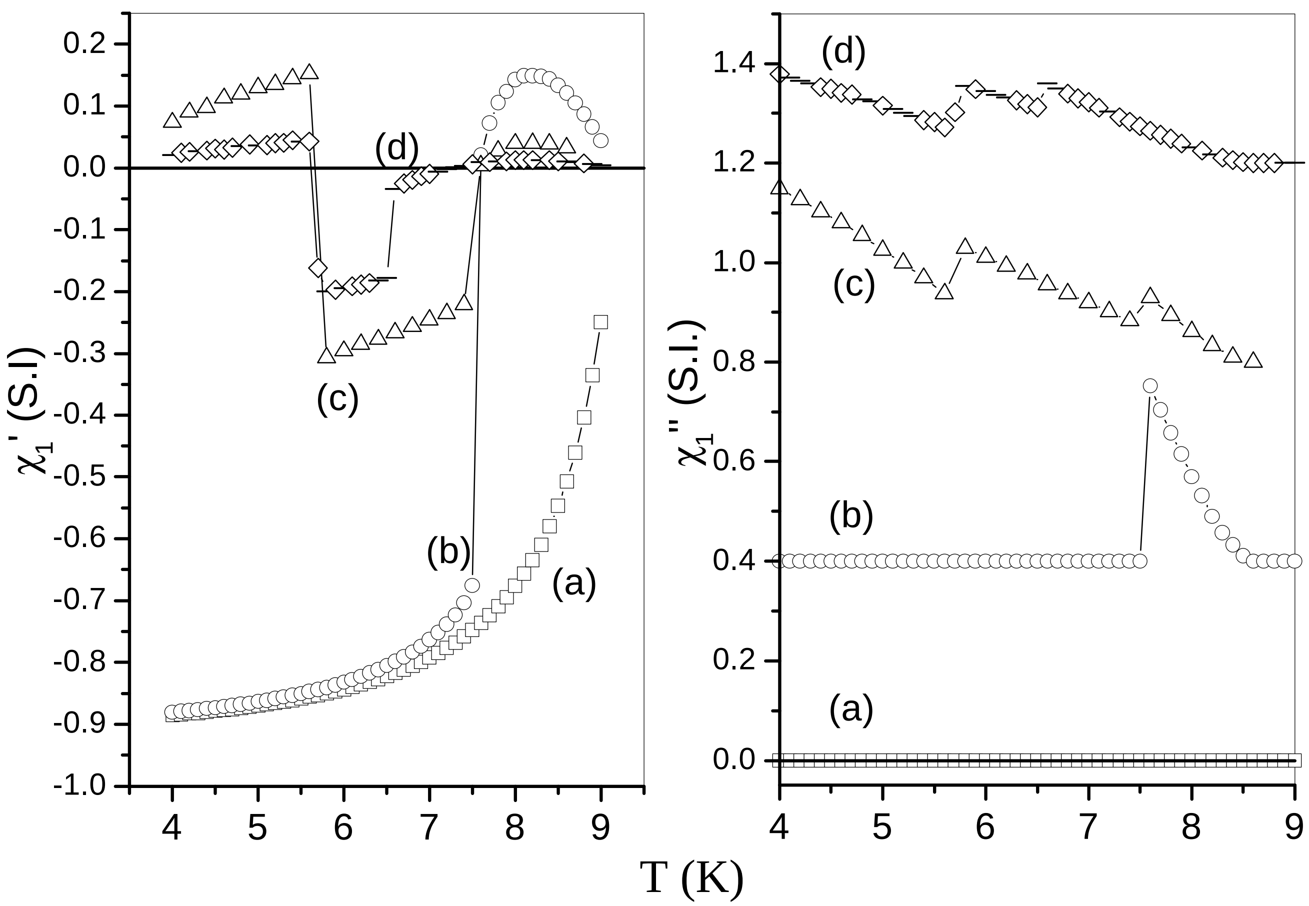
$$I = I_C \sin \gamma_{ij} + \frac{\Phi_O}{2\pi R}\frac{d\gamma_{ij}}{dt} + \frac{\Phi_O C}{2\pi}\frac{d^2\gamma_{ij}}{dt^2}$$

$$M = \frac{LI}{\mu_o a^2}$$

$$M(t) = h_{AC} \Sigma[\chi'_m \cos(m\omega t) + \chi''_m \sin(m\omega t)]$$

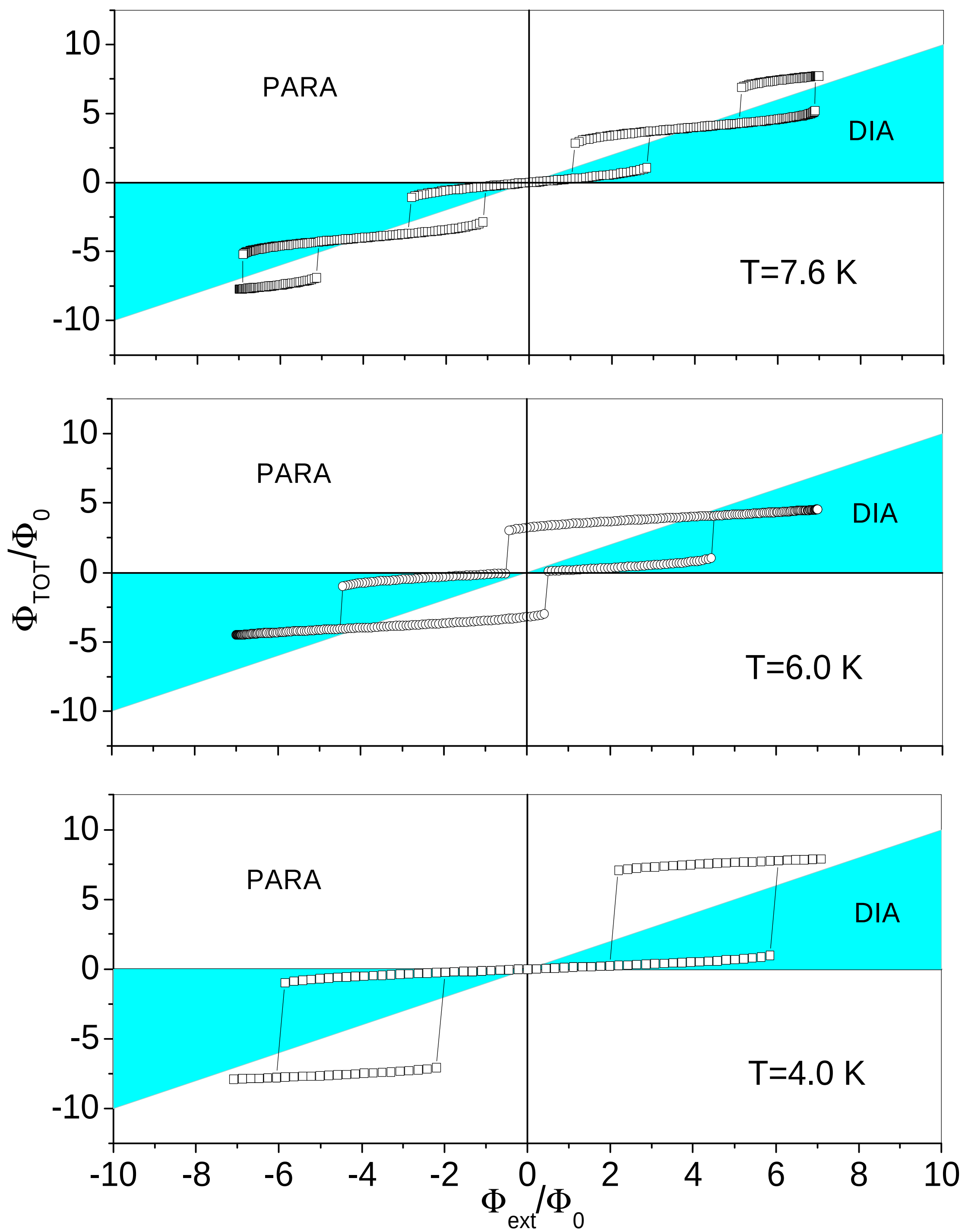
$$M_1(t) = h_{AC}[\chi'_1 \cos(\omega t) + \chi''_1 \sin(\omega t)]$$

Single-loop simulation



(a) h_{AC}= 5 mOe, loop.
(b) h_{AC}= 29 mOe, loop.
(c) h_{AC}= 69 mOe, loop.
(c) h_{AC}= 118 mOe, loop.

Single-loop simulation

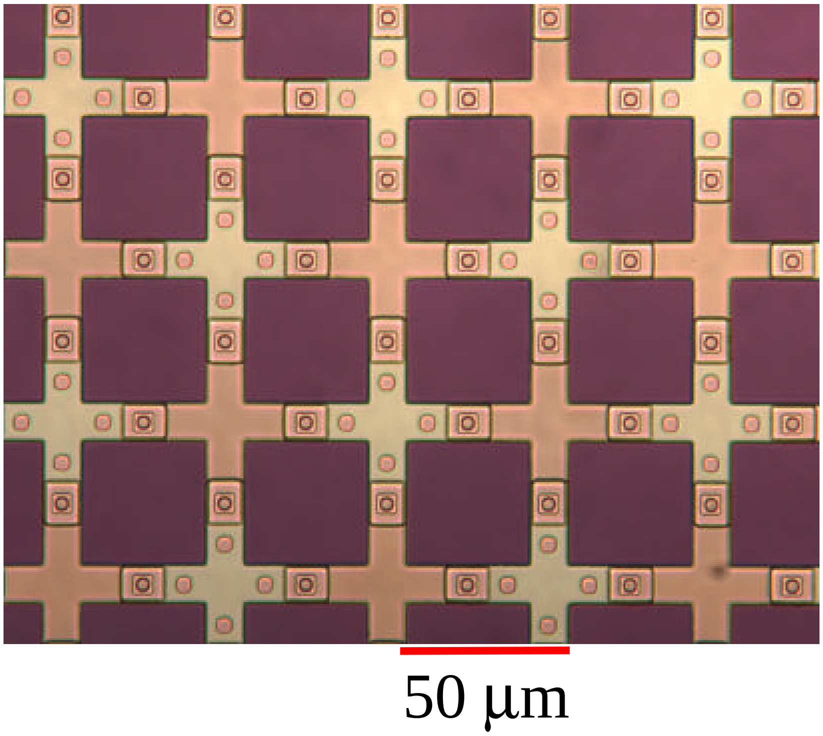


Susceptibility summary

- Nb-AlOx-Nb arrays are paramagnetic
- No π junctions
- Little disorder
- Single-loop: paramagnetic and diamagnetic states
- Is single-loop model enough?

C. Auletta *et al.*; Physica C **235-240**, 3315 (1994); Phys. Rev. B **51**, 12844 (1995).
F. M. Araujo-Moreira *et al.*, Phys. Rev. Lett. **78**, 4625 (1997); P. Barbara *et al.*, Phys. Rev. B **60**, 7489 (1999).

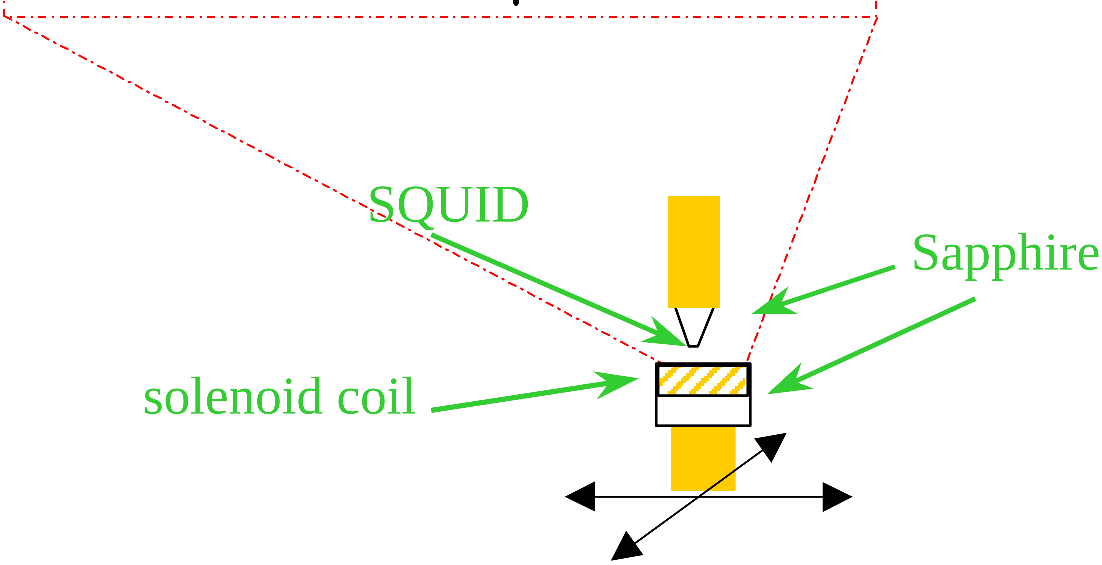
Scanning SQUID Experiment



Unshunted Array
Nb - AlOx -Nb

30 x 100 junctions

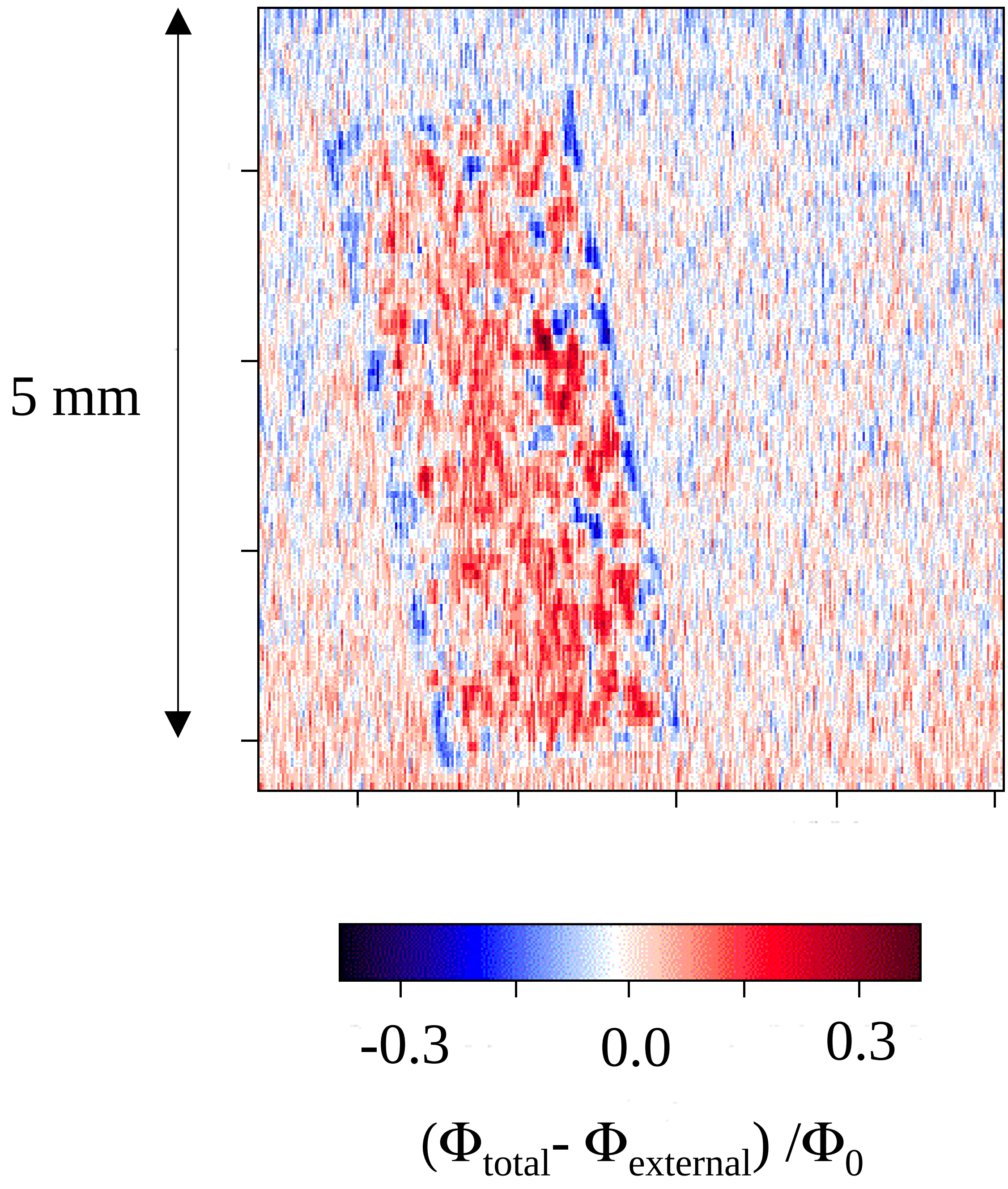
$$b_l = \frac{2pLI_c}{\Phi_0} = 30$$



Sample is field cooled
Measured with field turned on

Paramagnetic Image of JJ Array

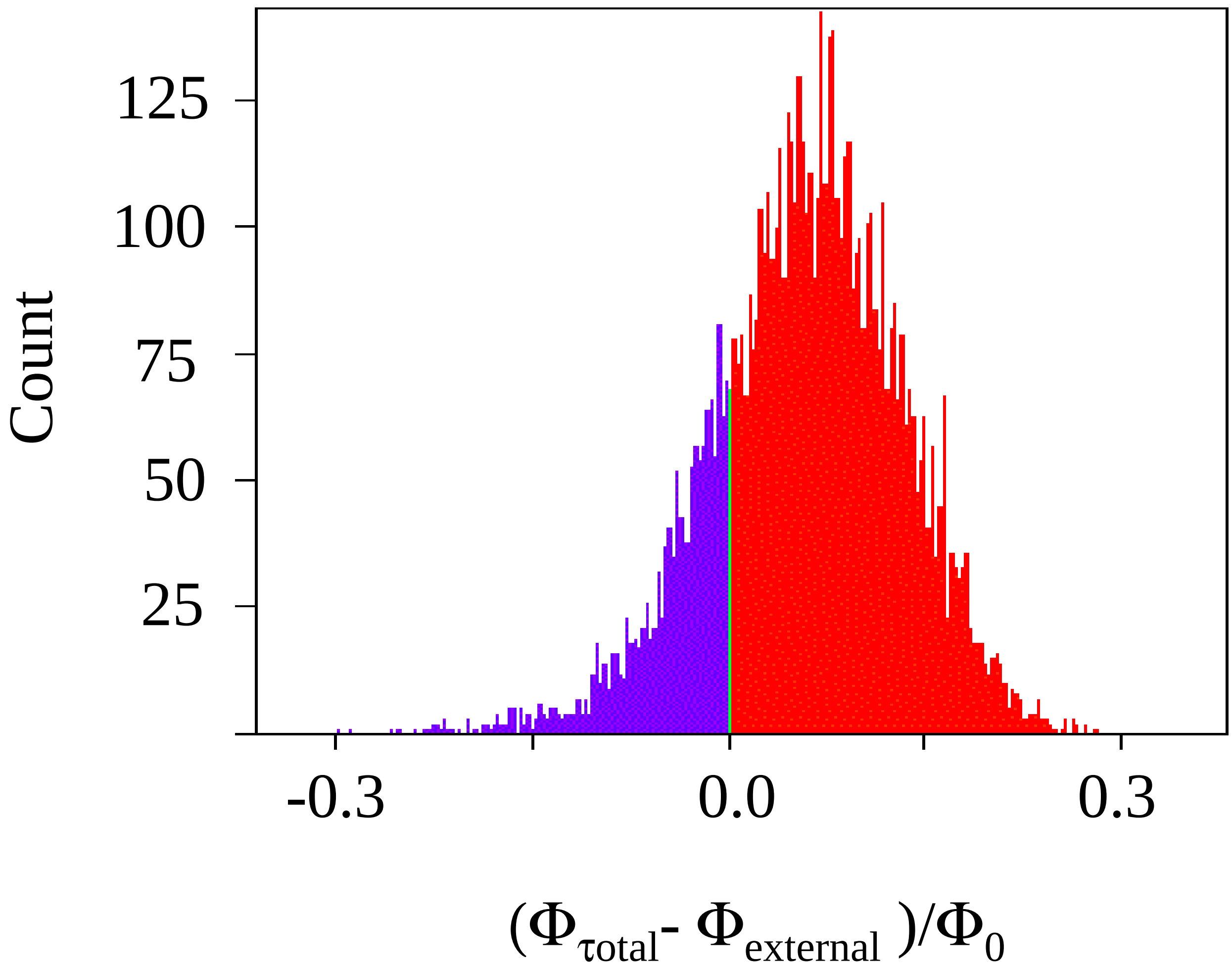
$\Phi_{external}$=4.8Φ_0

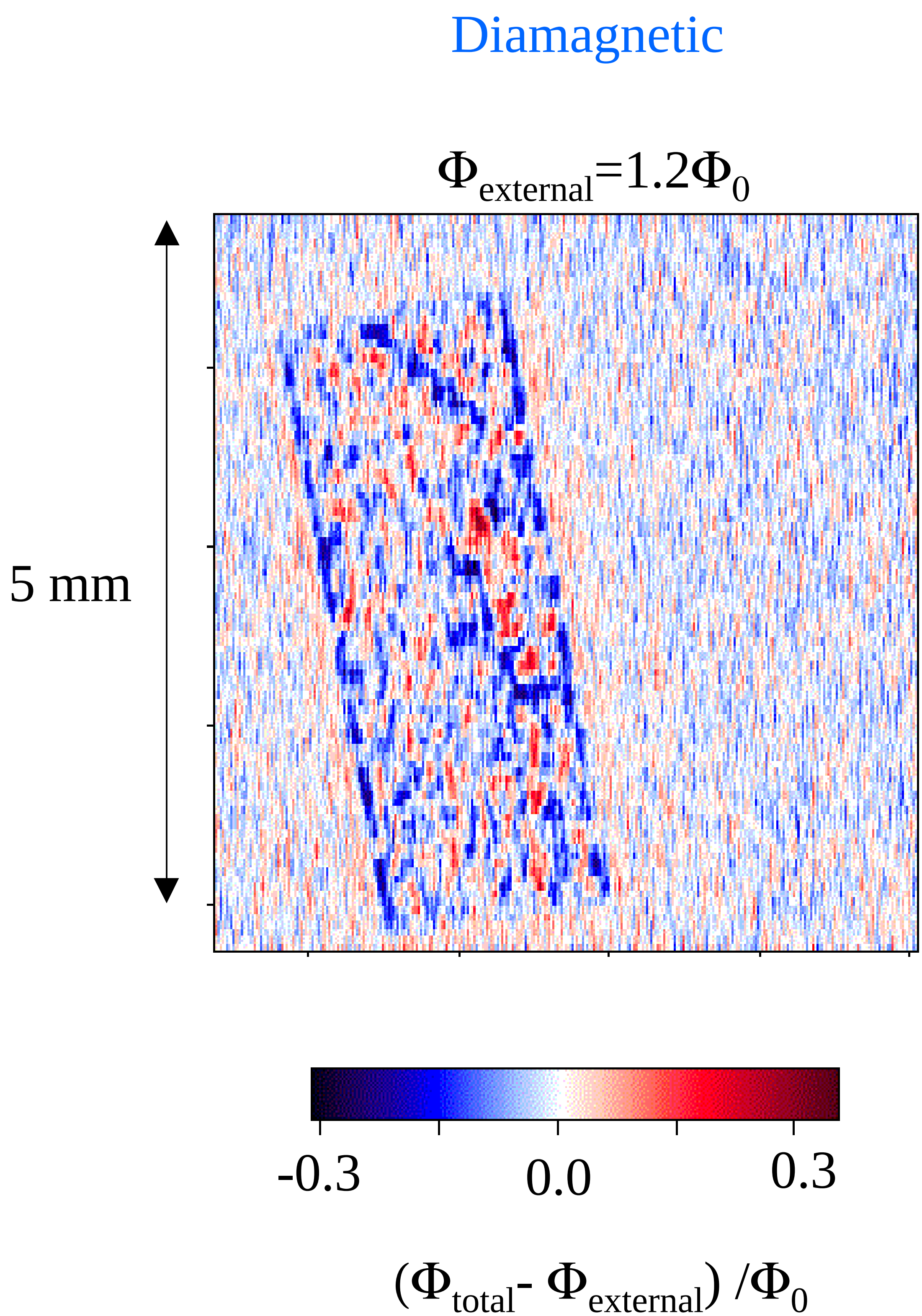


$$M = B - H$$

Histogram of Flux Values for JJ Array

$\Phi_{external} = 4.8\Phi_0$

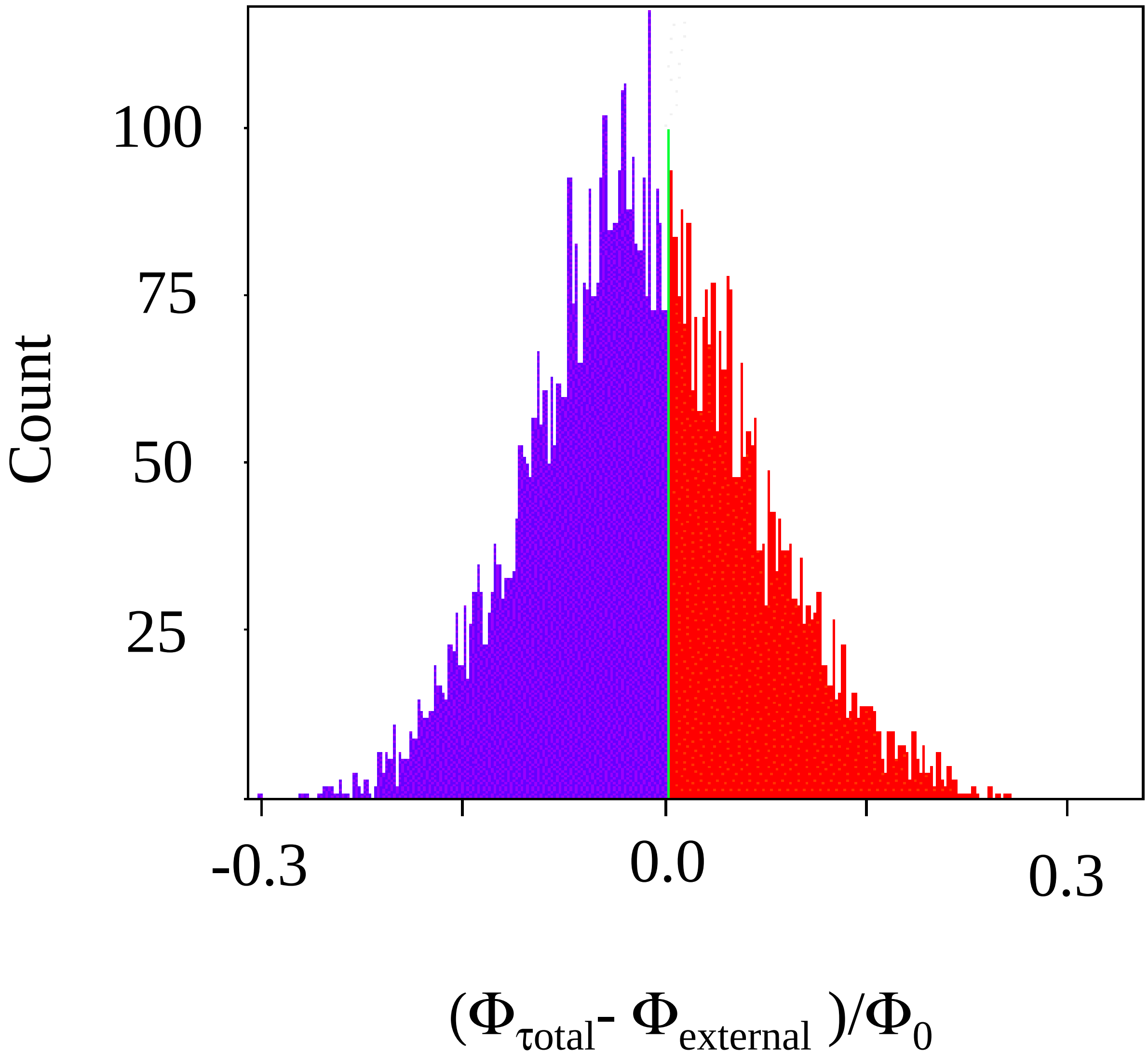




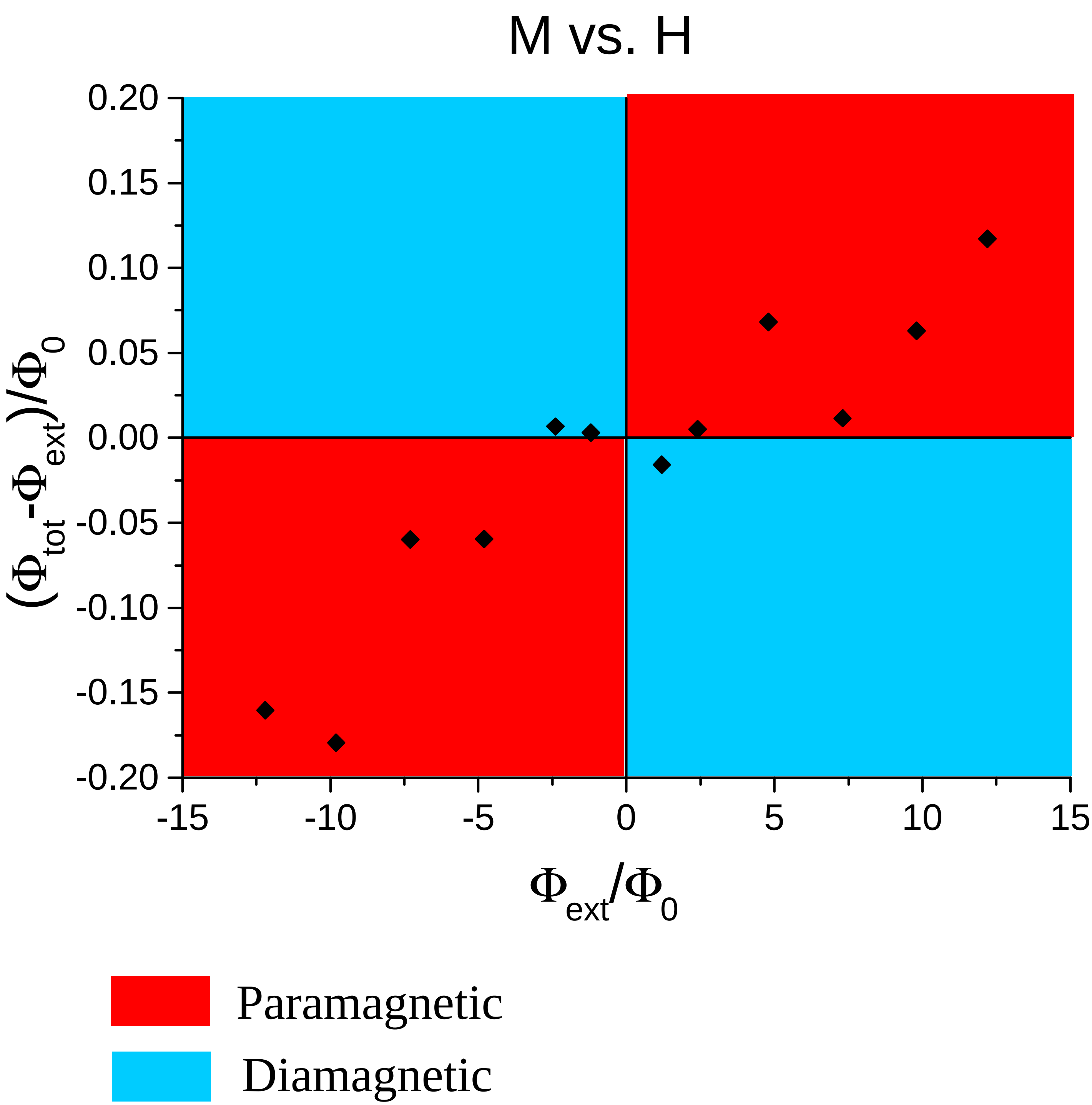
Diamagnetic
$\Phi_{external}=1.2\Phi_0$
5 mm
-0.3
0.0
0.3
$(\Phi_{total}-\Phi_{external})/\Phi_0$

Histogram of Flux Values for JJ Array

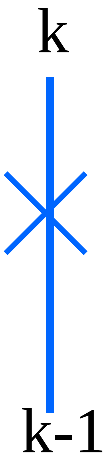
$\Phi_{external}=1.2\Phi_0$



Array Exhibits Paramagnetism For Some Cooling Fields!

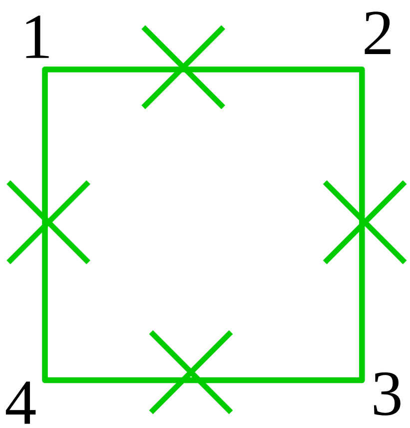


Four Junction Loop



$$I = I_c \sin g$$

$$g_i = q_k - q_{k-1} - \frac{2p}{\Phi_0}\int_k^{k-1} A \cdot dl$$



L = self- inductance of loop

$$\sum_i g_i = 2pn - \frac{2p}{\Phi_0}\Phi_{total}$$

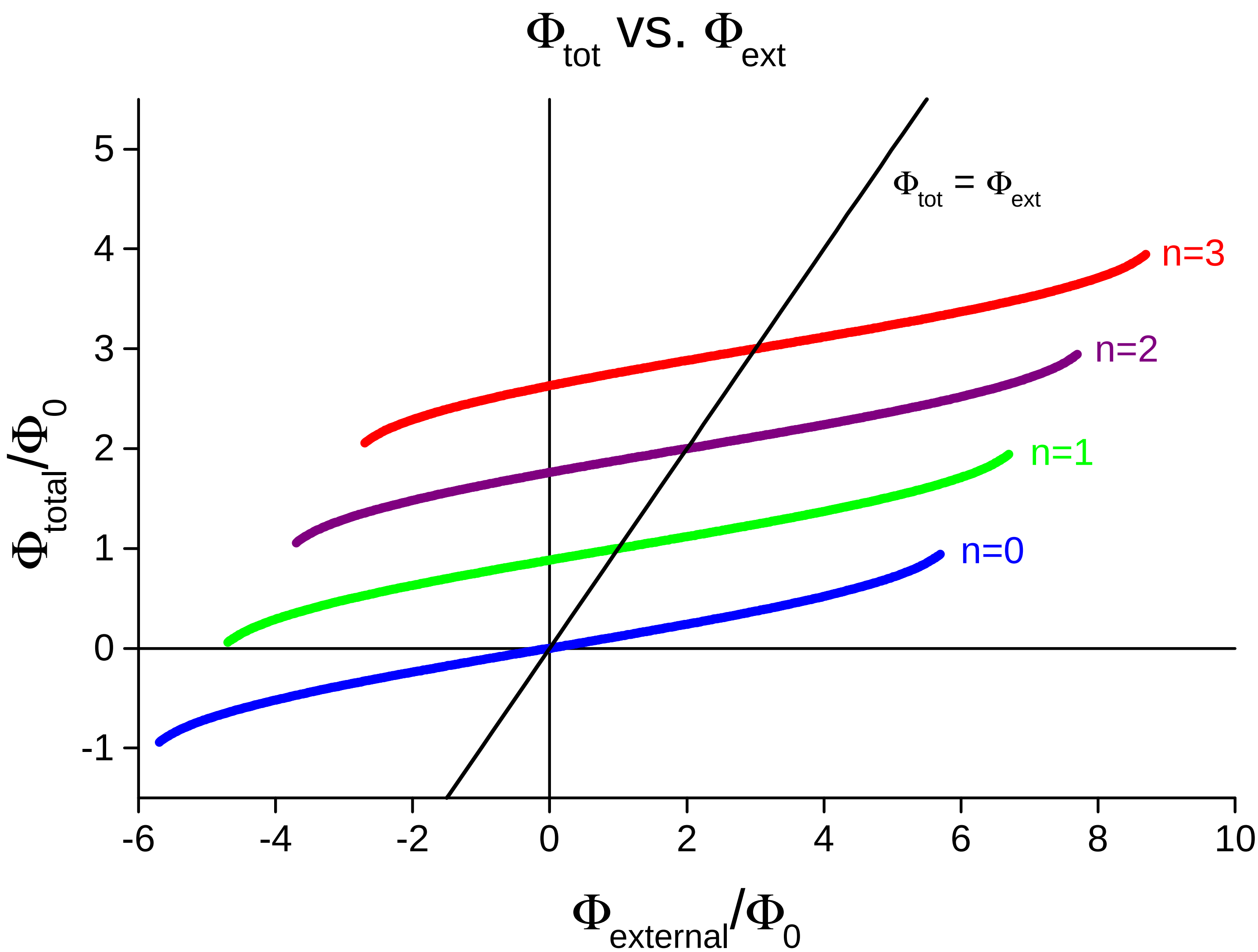
$$\Phi_{total} = \Phi_{external} + LI$$

By symmetry: $g_1 = g_2 = g_3 = g_4 = g_i$

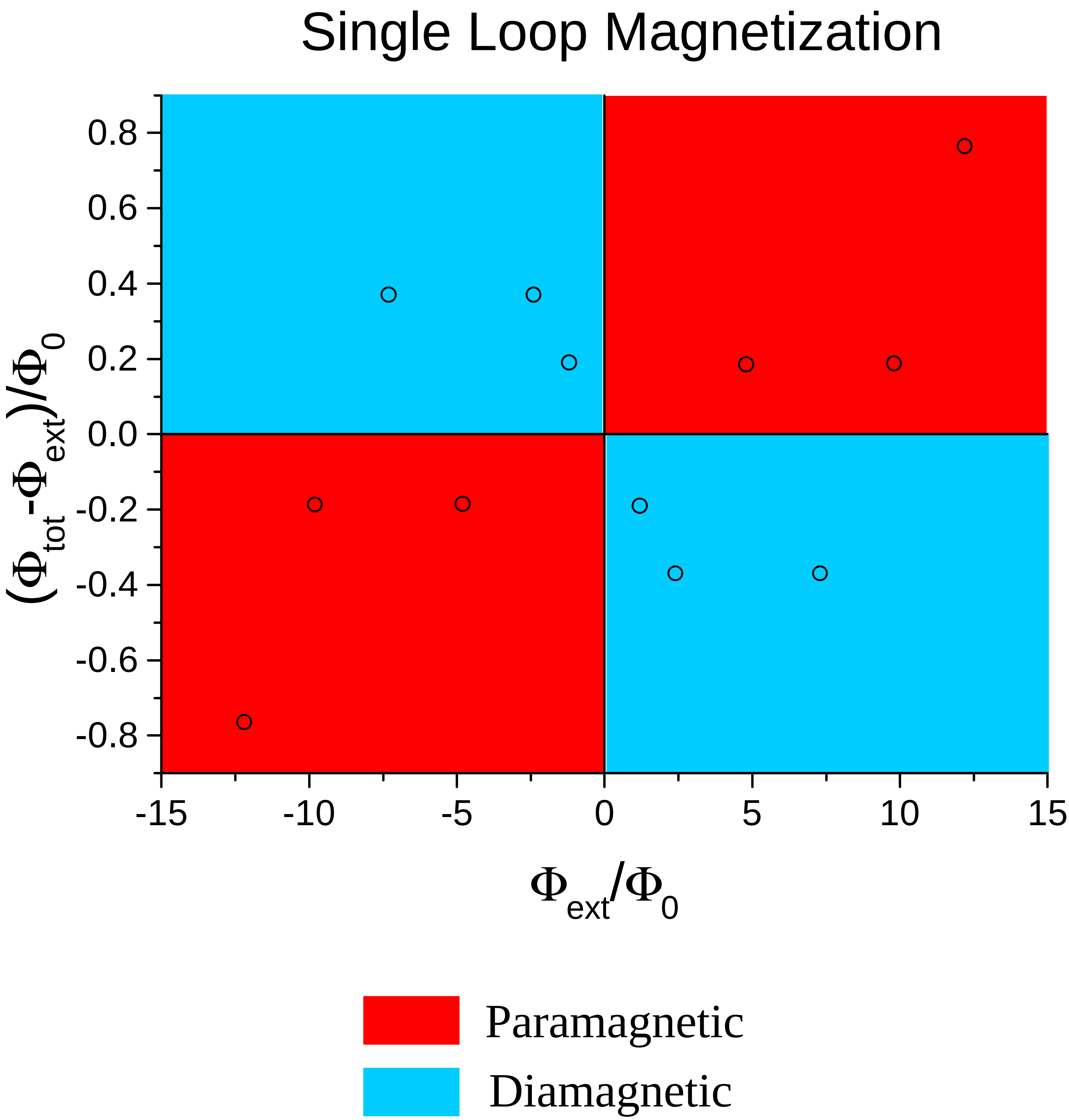
$$g_i = \frac{p}{2}n - \frac{p}{2}\frac{\Phi_{total}}{\Phi_0}$$

$$\frac{\Phi_{tot}}{\Phi_0} = \frac{\Phi_{ext}}{\Phi_0} + \frac{LI_c}{\Phi_0}\sin\left(\frac{p}{2}n - \frac{p}{2}\frac{\Phi_{tot}}{\Phi_0}\right)$$

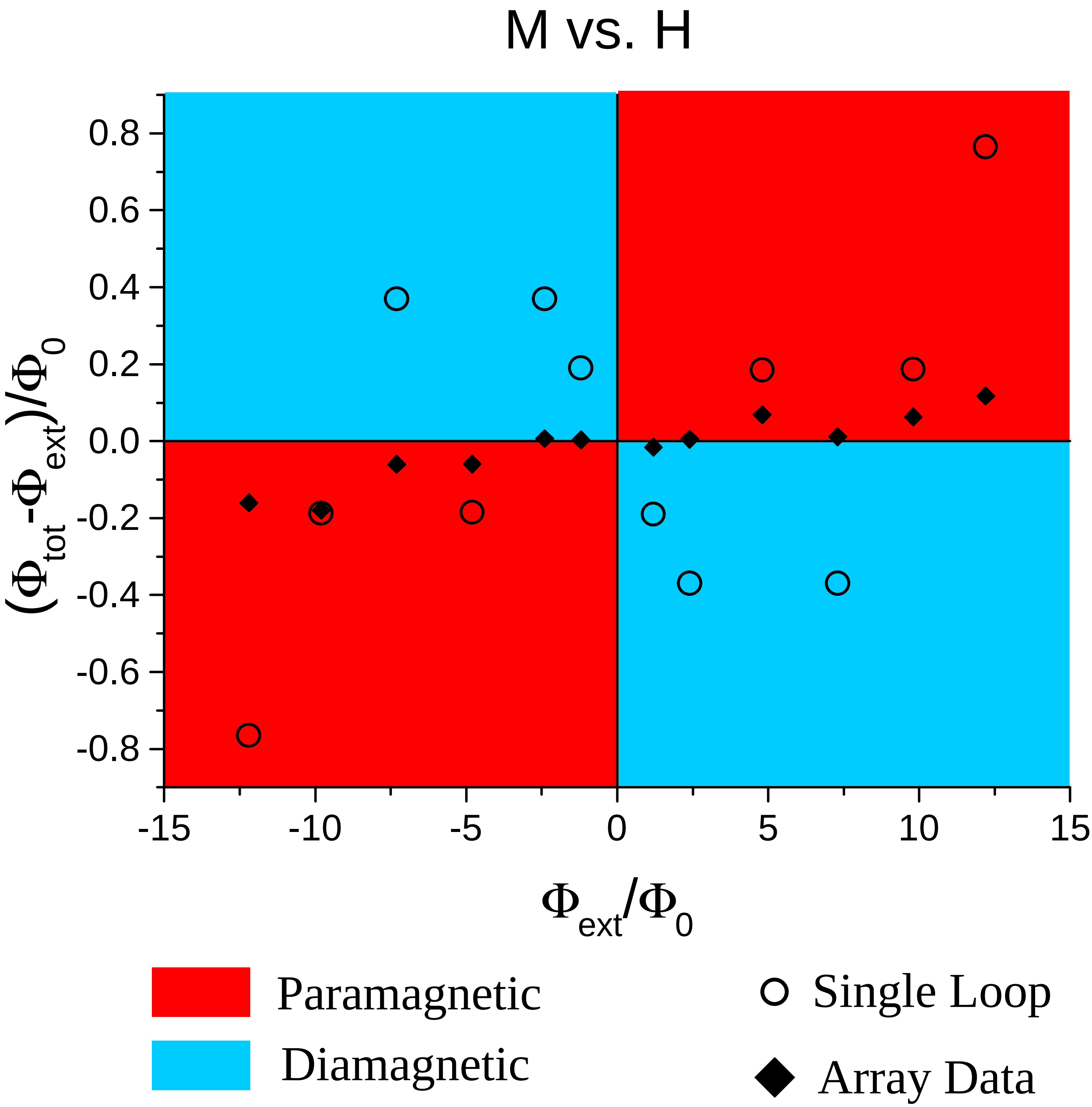
Four Junction Loop



$$\frac{\Phi_{tot}}{\Phi_0} = \frac{\Phi_{ext}}{\Phi_0} + \frac{LI_c}{\Phi_0}\sin\left(\frac{p}{2}n - \frac{p}{2}\frac{\Phi_{tot}}{\Phi_0}\right)$$

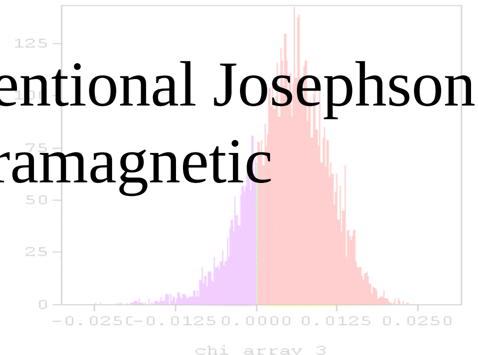


Single Loop Magnetization
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
$(\Phi_{tot}-\Phi_{ext})/\Phi_0$
-15
-10
-5
0
5
10
15
Φ_{ext}/Φ_0
Paramagnetic
Diamagnetic

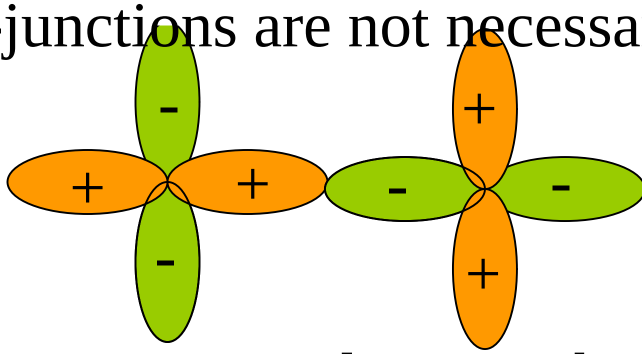

M vs. H
$(\Phi_{tot}-\Phi_{ext})/\Phi_0$
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-15
-10
-5
0
5
10
15
Φ_{ext}/Φ_0
Paramagnetic
Diamagnetic
Single Loop
Array Data

Conclusions

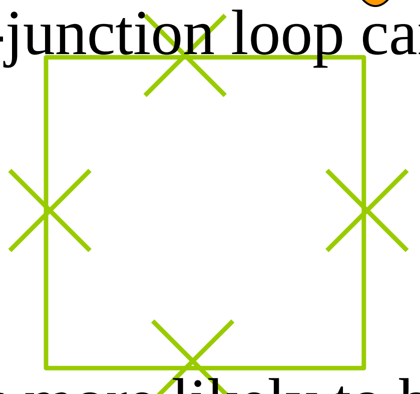
Conventional Josephson junction arrays can be paramagnetic



π-junctions are not necessary for paramagnetism



The 4-junction loop can be paramagnetic



Arrays more likely to be paramagnetic than diamagnetic; single loop nearly equally likely.

What are the differences with π-junction arrays?