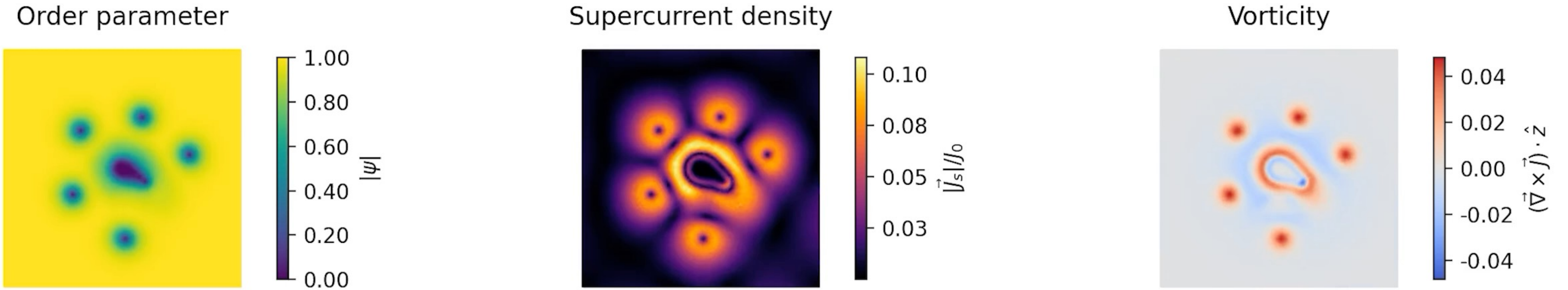
Vortex dynamics induced by scanning SQUID susceptometry



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APS March Meeting 2023, Las Vegas, NV, Session K27, 2023.03.07

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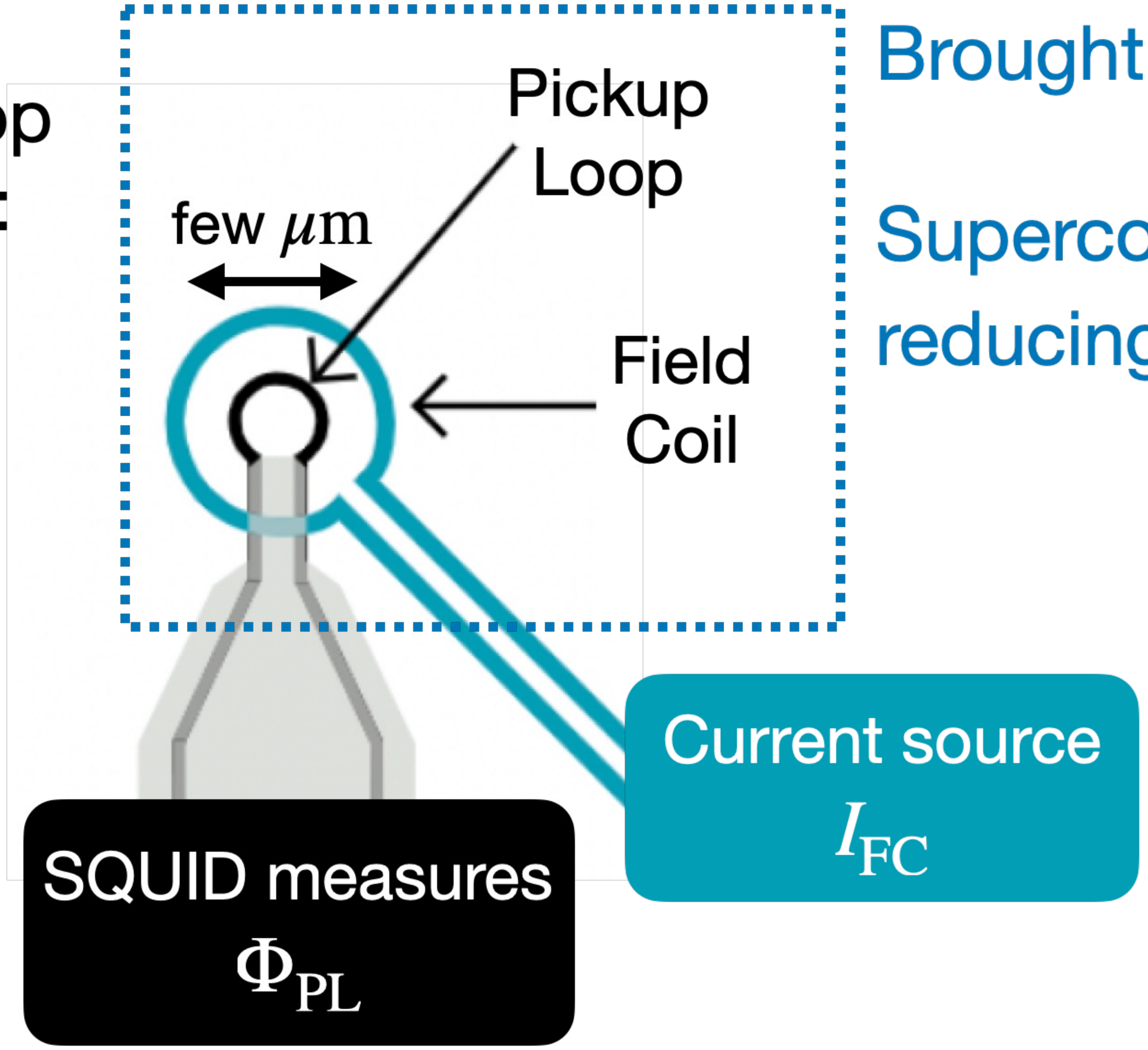
Scanning SQUID susceptometers measure the **local magnetic response** of superconductors

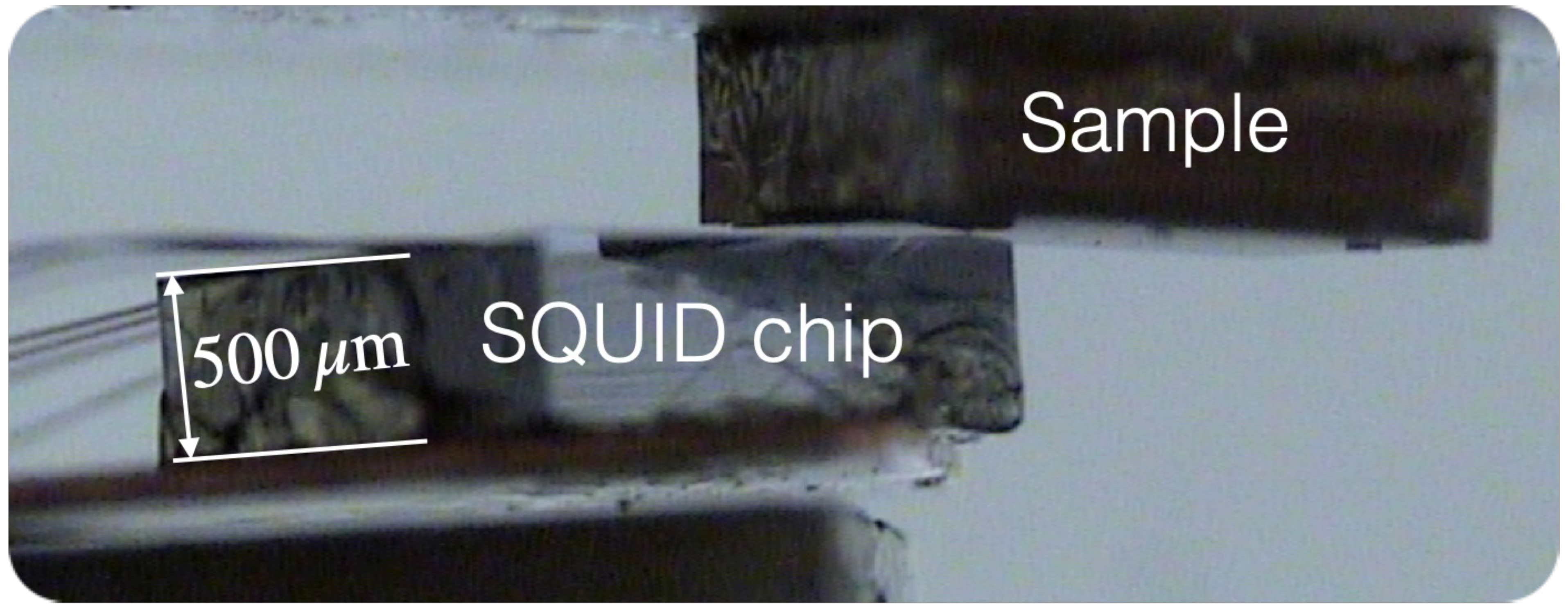
Field coil-pickup loop mutual inductance:

$$M = \Phi_{PL}/I_{FC}$$



Brought close to sample surface.

Superconducting sample screens applied field, reducing M.



Rev. Sci. Instrum. **72**, 2361 (2001)
Rev. Sci. Instrum. **79**, 053704 (2008)
Phys. Rev. B **85**, 224518 (2012)
Rev. Sci. Instrum. **87**, 093702 (2016)

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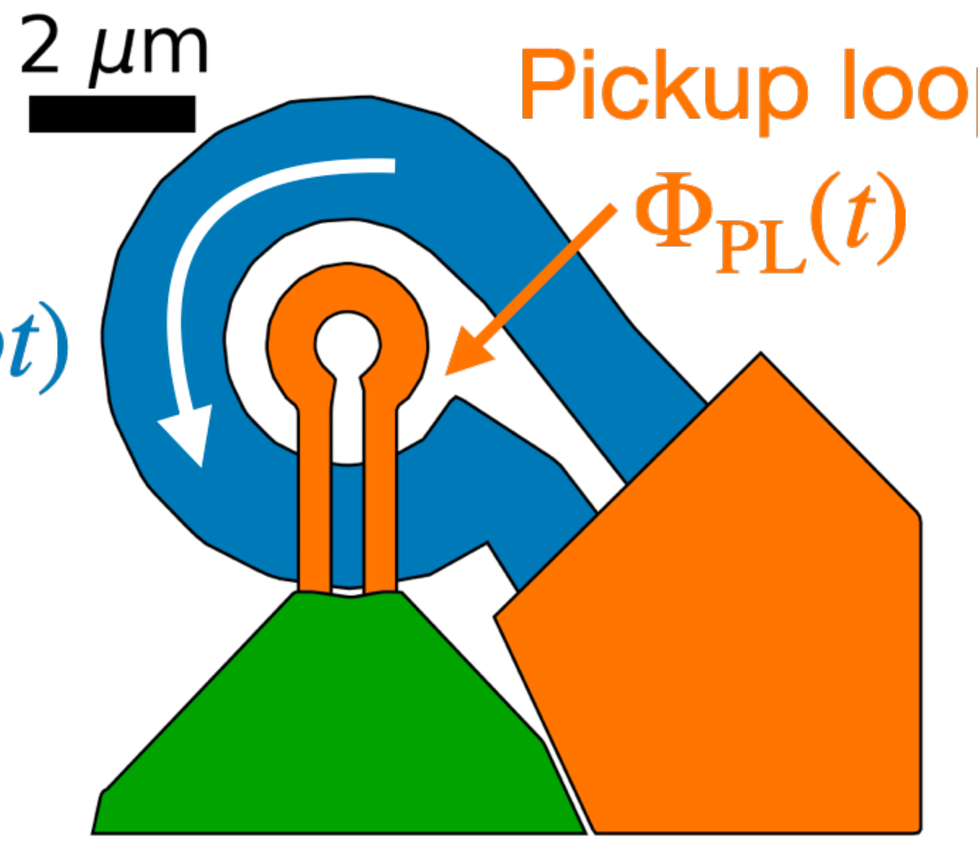
Low frequency AC magnetic response



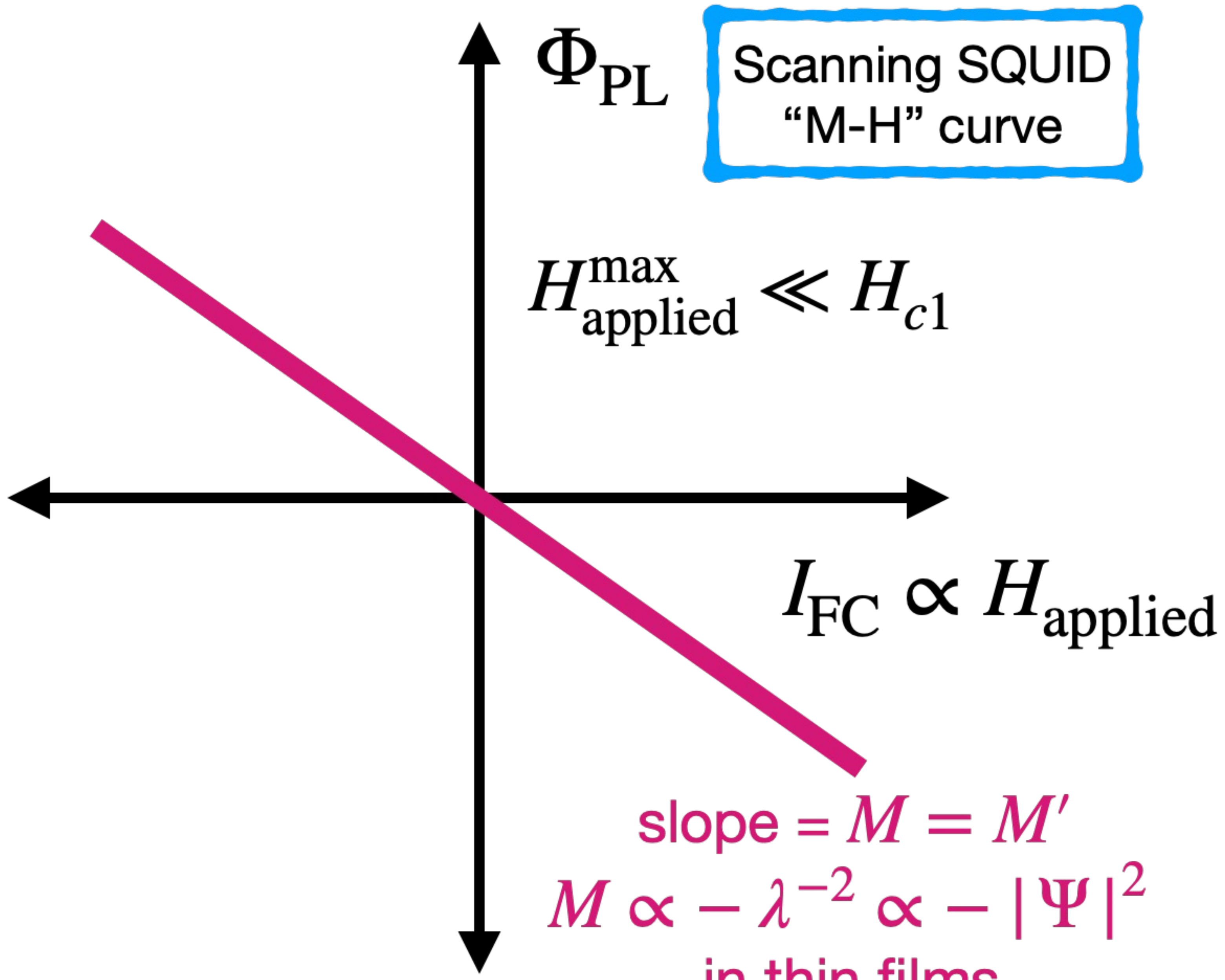
Demodulated magnetic response

$$M = \frac{\sqrt{2}}{I_{FC,pk}} \int \Phi_{PL}(t) e^{-i\omega t} dt = M' + iM''$$

$M' = \mathrm{Re}(M) \rightarrow$ superfluid

$M'' = \mathrm{Im}(M) \rightarrow$ dissipative

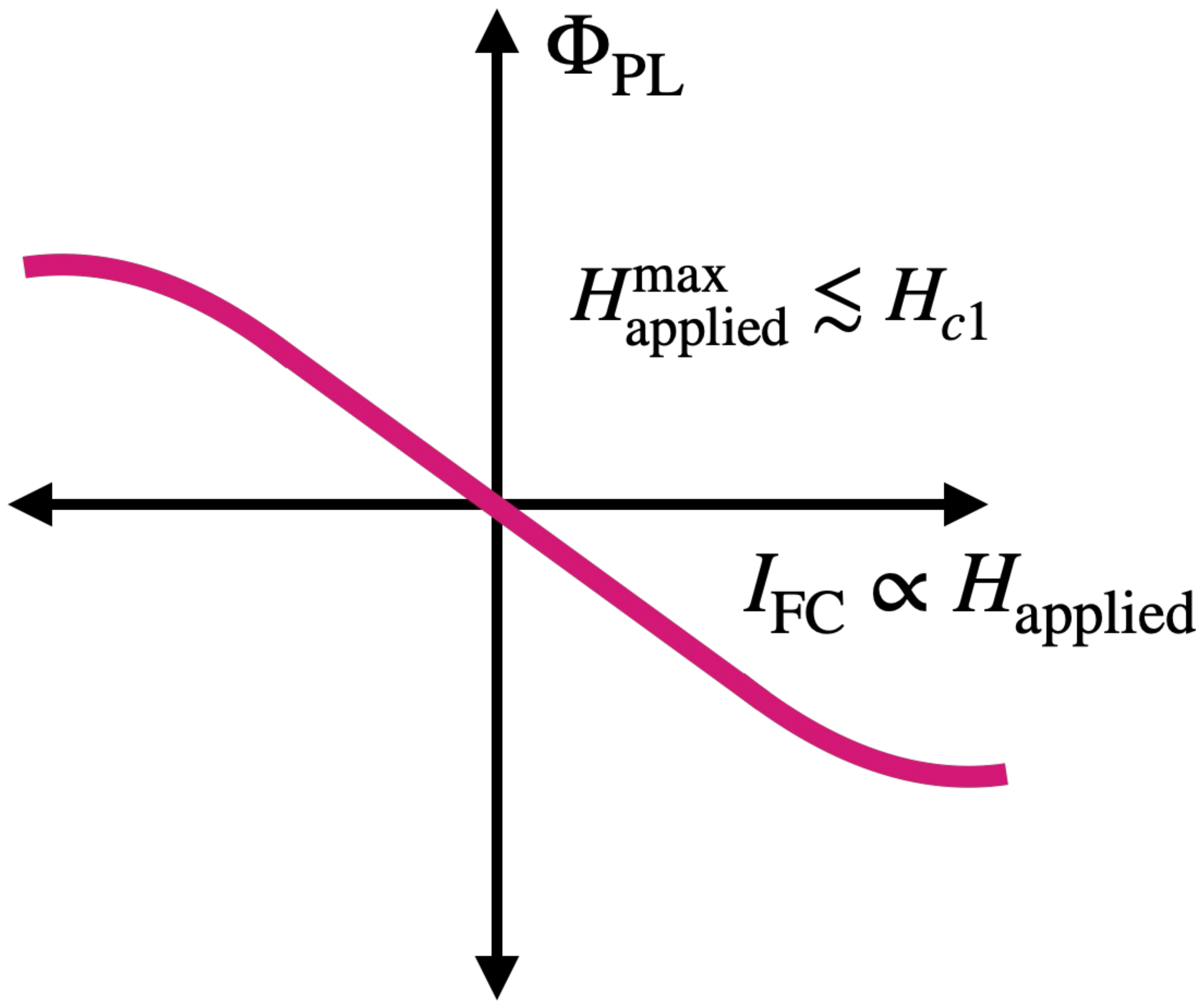
Scanning SQUID "M-H" curve

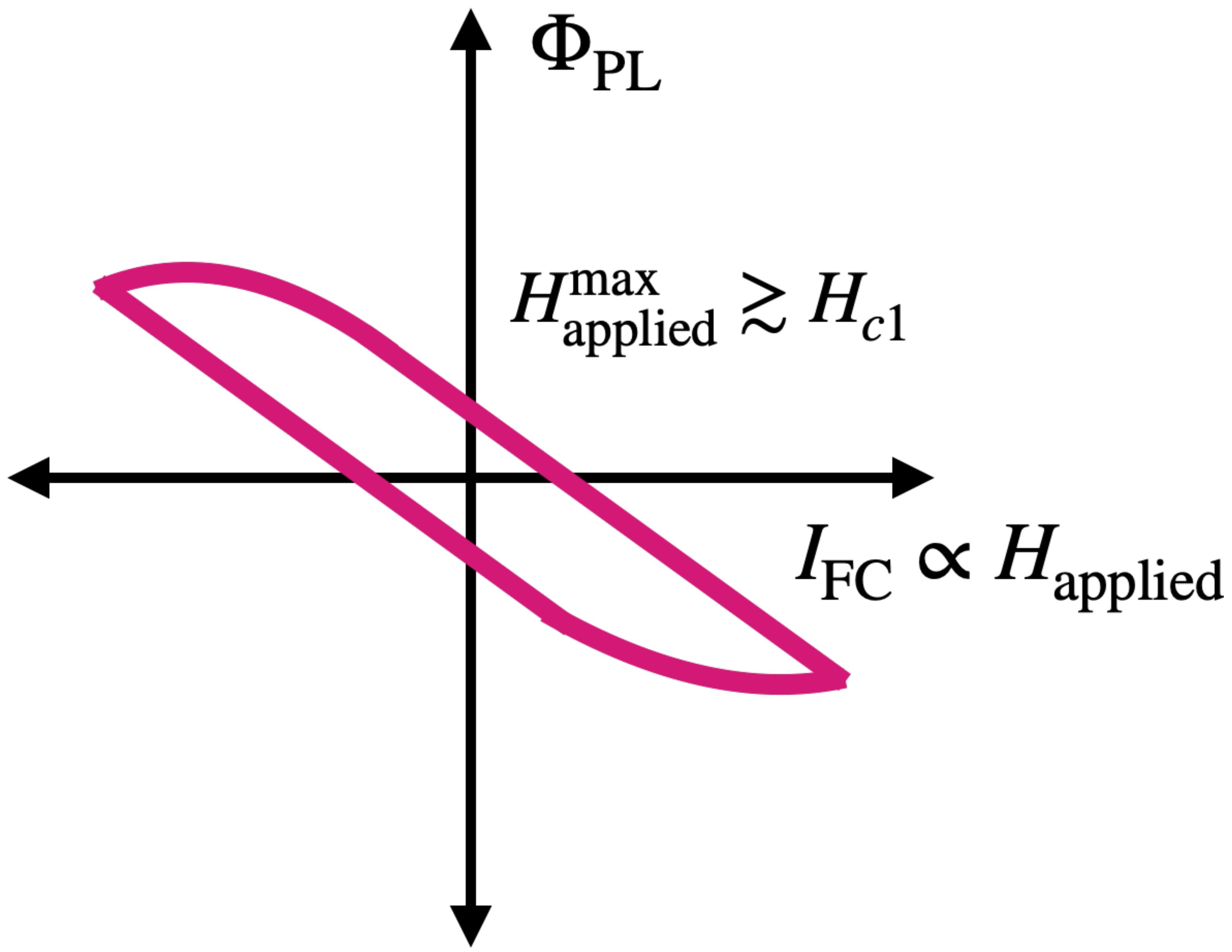


slope $= M = M'$

$M \propto -\lambda^{-2} \propto -|\Psi|^2$

in thin films



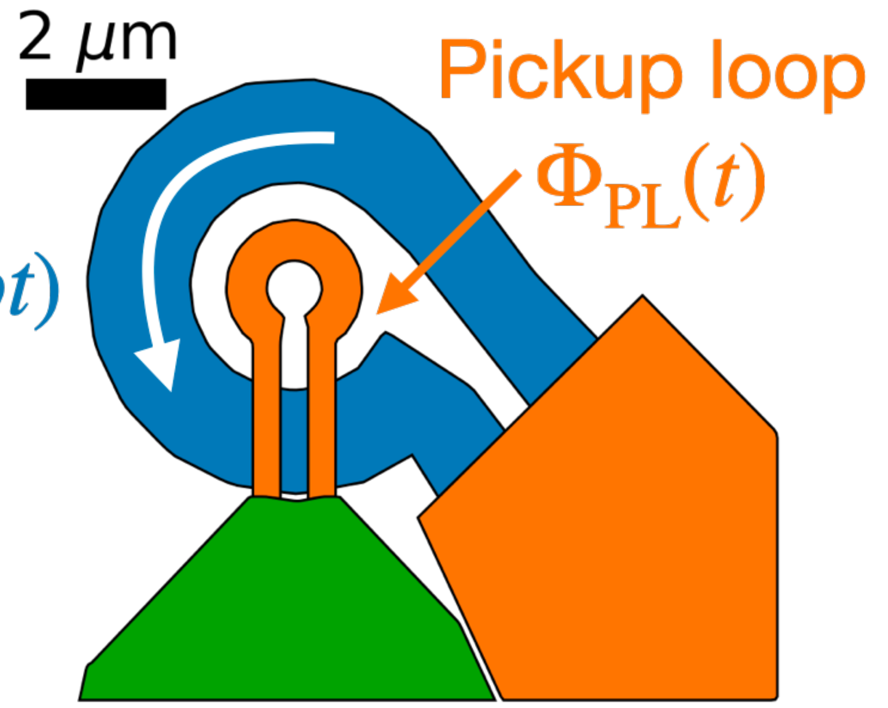


Linear, non-hysteretic
(London)
$M'' = 0$

Non-linear, non-hysteretic
(suppressed $|\Psi|^2$)
$M'' = 0$

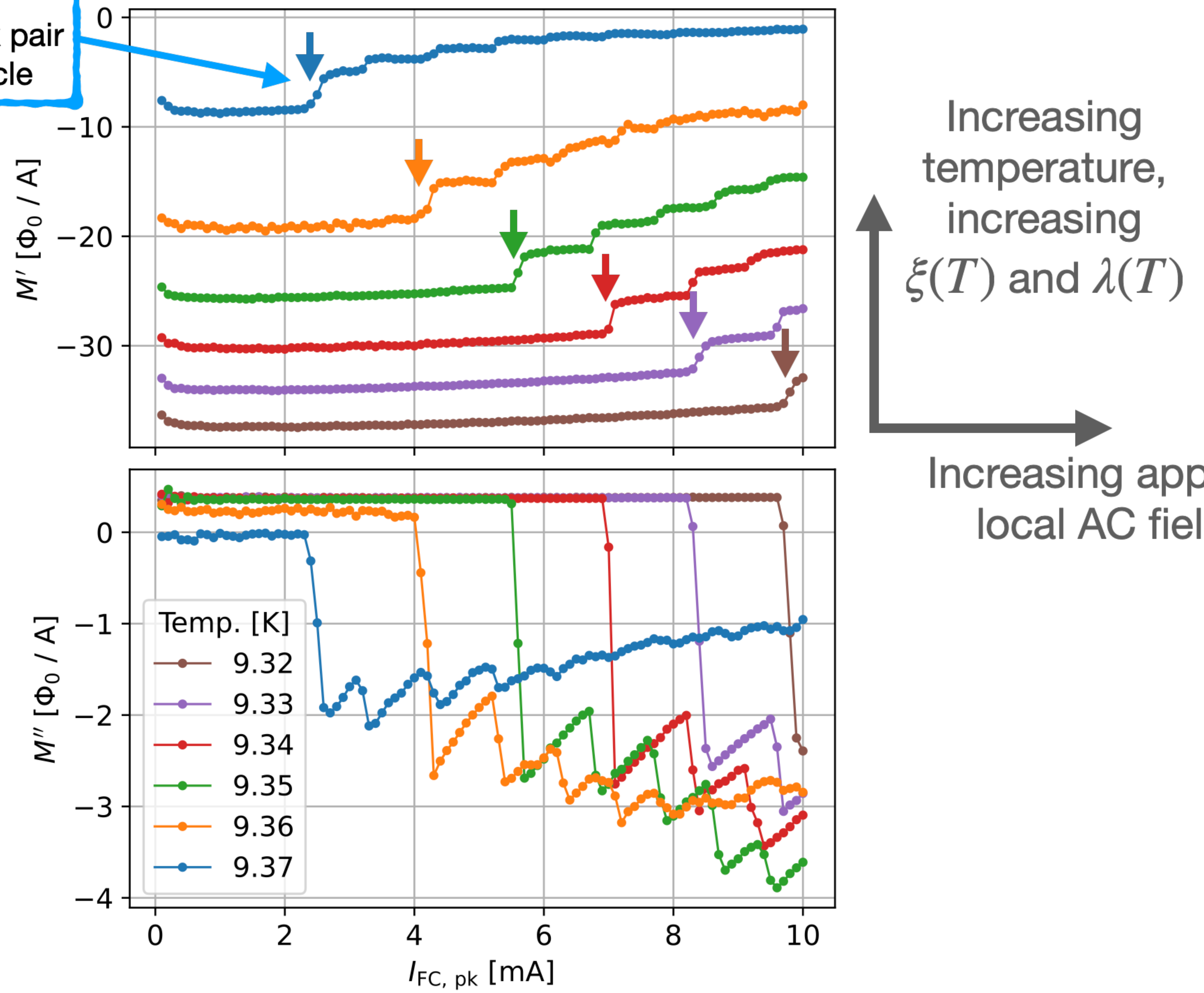
Non-linear, hysteretic
(vortex motion)
$M'' \neq 0$

M encodes "fingerprints" of few-vortex dynamics in niobium thin film near T_c



M vs. $I_{FC,pk}$

1 induced vortex-antivortex pair per half AC cycle



$M' = \mathrm{Re}(M) \rightarrow$ superfluid
$M'' = \mathrm{Im}(M) \rightarrow$ dissipative

Measurements: Eli Mueller

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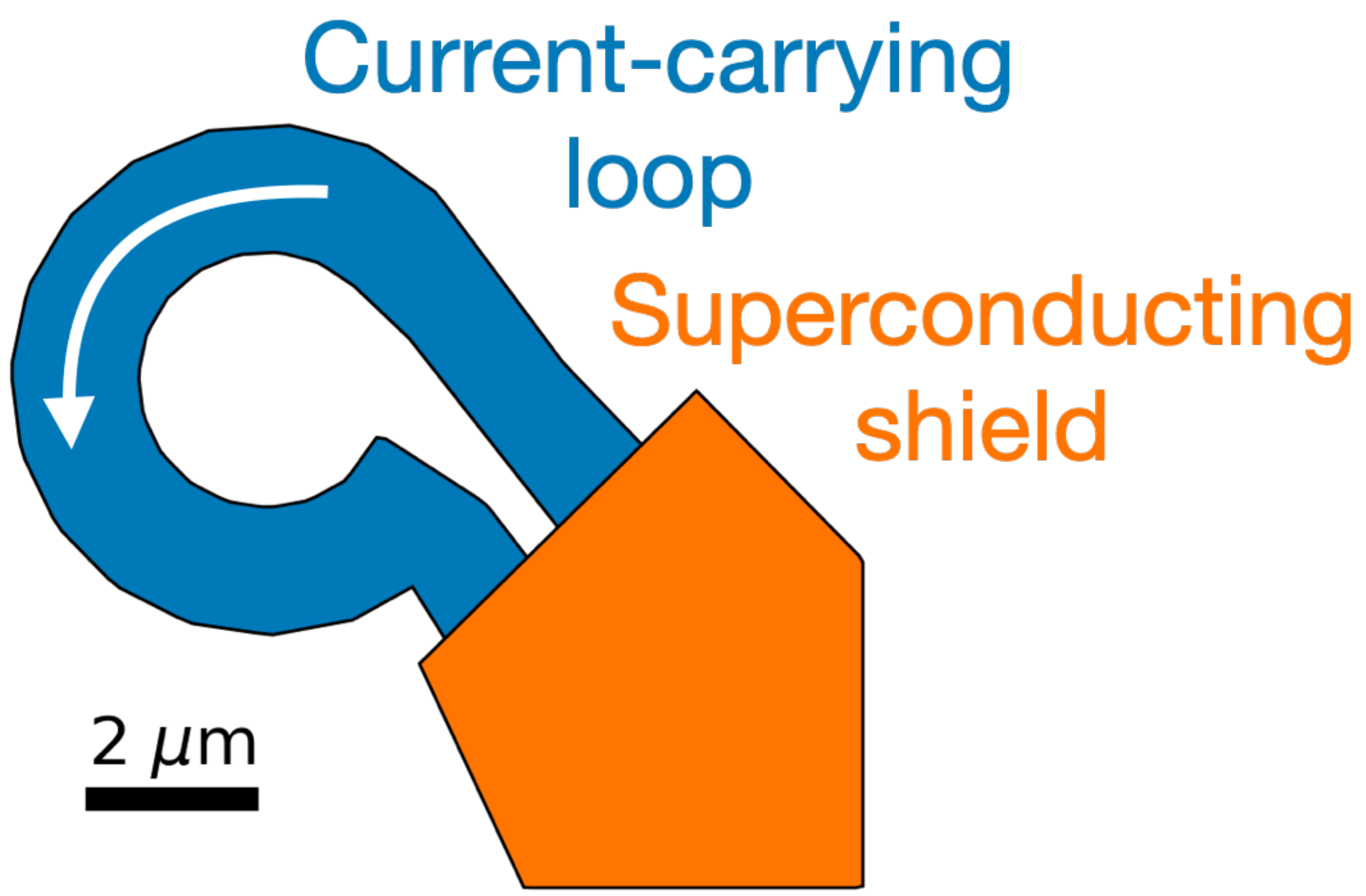
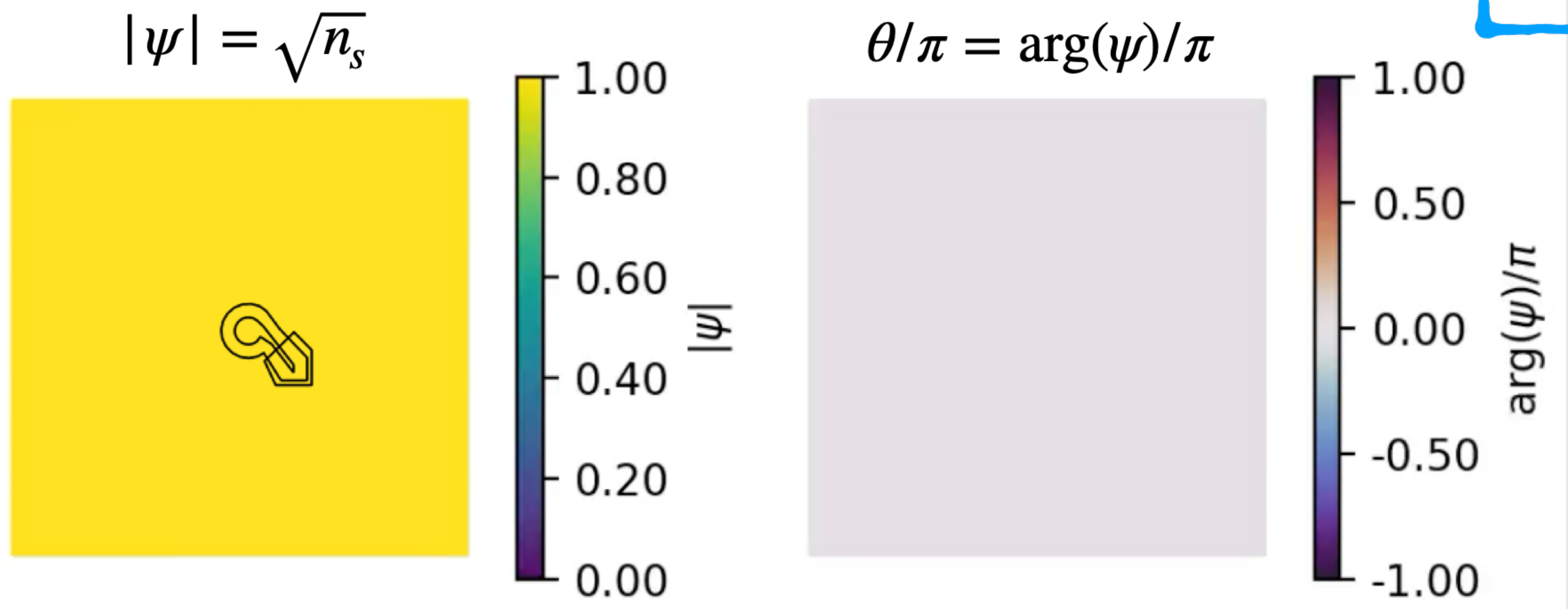
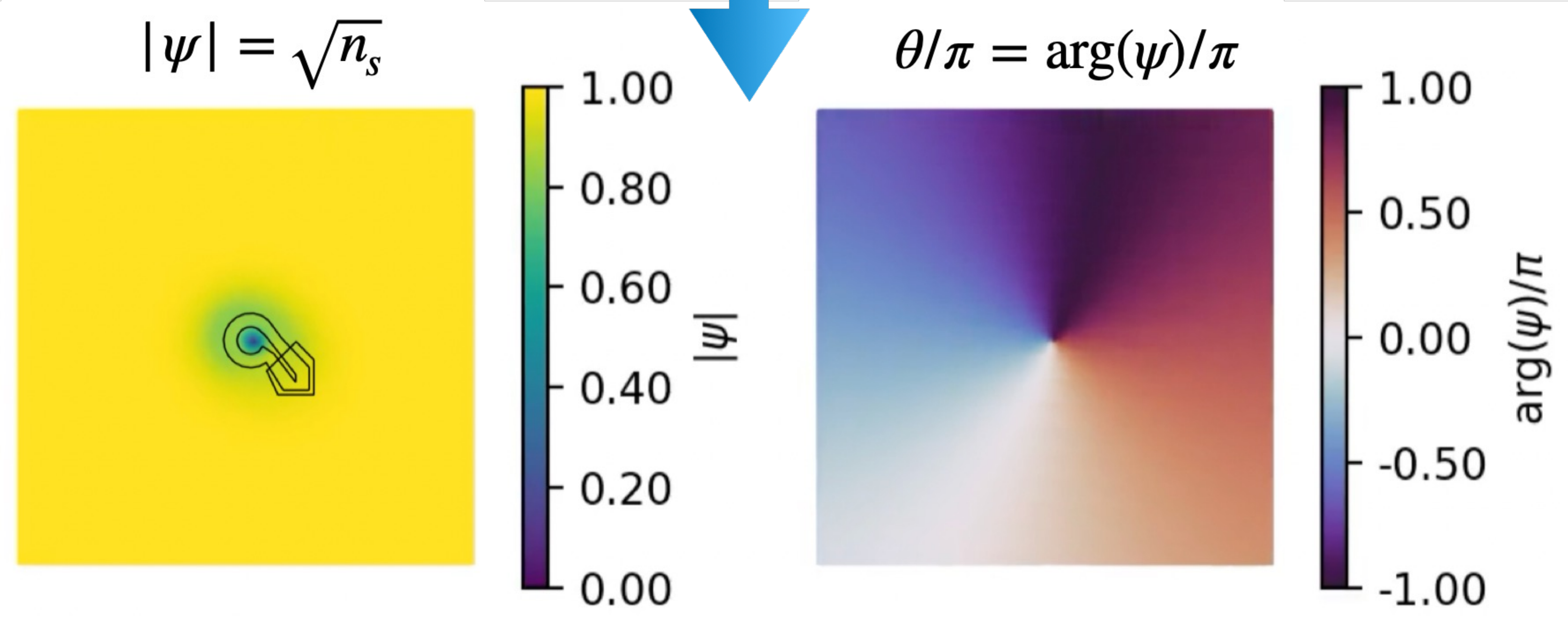
How to generate vortices with a local magnetic source?



H_{applied} at edge ≈ 0



$$\oint_{\text{edge}} \nabla\theta \cdot \mathbf{dr} = 0$$



$$\oint_{\text{edge}} \nabla\theta \cdot \mathbf{dr} = 2\pi$$

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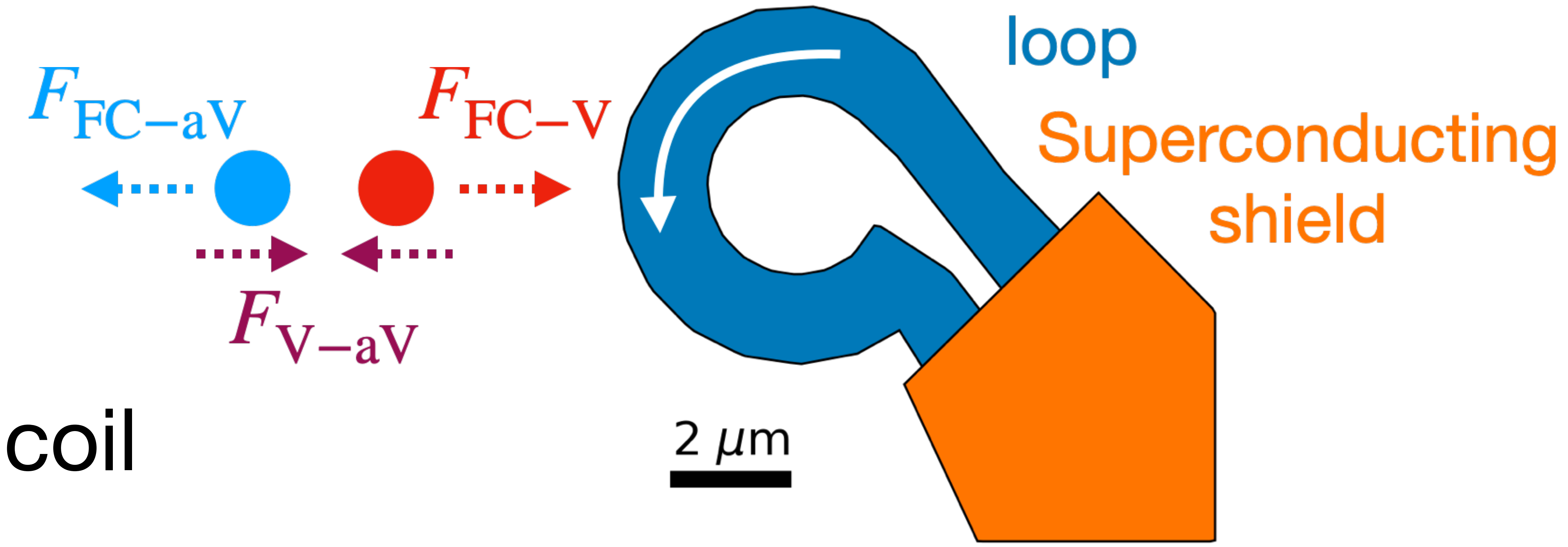
SQUID field coil can generate a single vortex-antivortex pair in a thin film

- Vortex pulled toward center of field coil, antivortex pushed away from center of field coil
- Antivortex exits the film or becomes pinned/annihilated far from the SQUID



This process is analogous to a phase slip in a 1D superconducting wire.

2D time-dependent Ginzburg-Landau (TDGL) simulation, $\xi = 0.9\mu\mathrm{m}, \lambda = 1.35\mu\mathrm{m}, I_{\mathrm{FC}} = 2.5\mathrm{mA}$

Simulation method: arXiv:2302.03812 (2023) [and references therein]; py-tdgl.readthedocs.io

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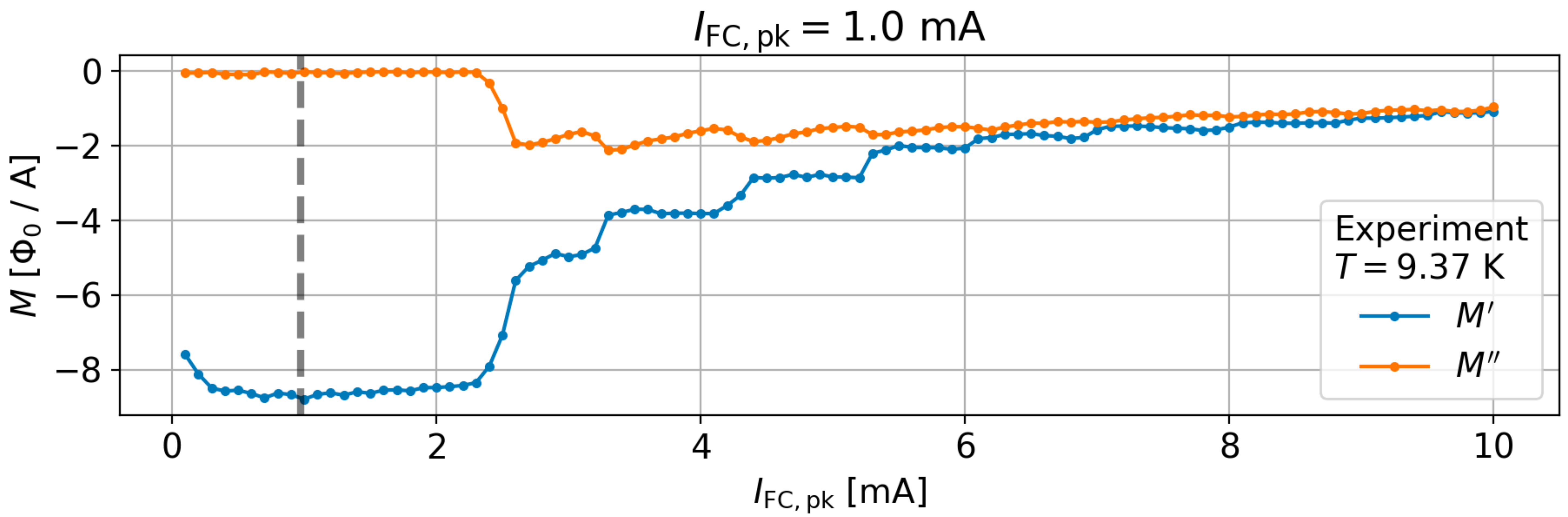
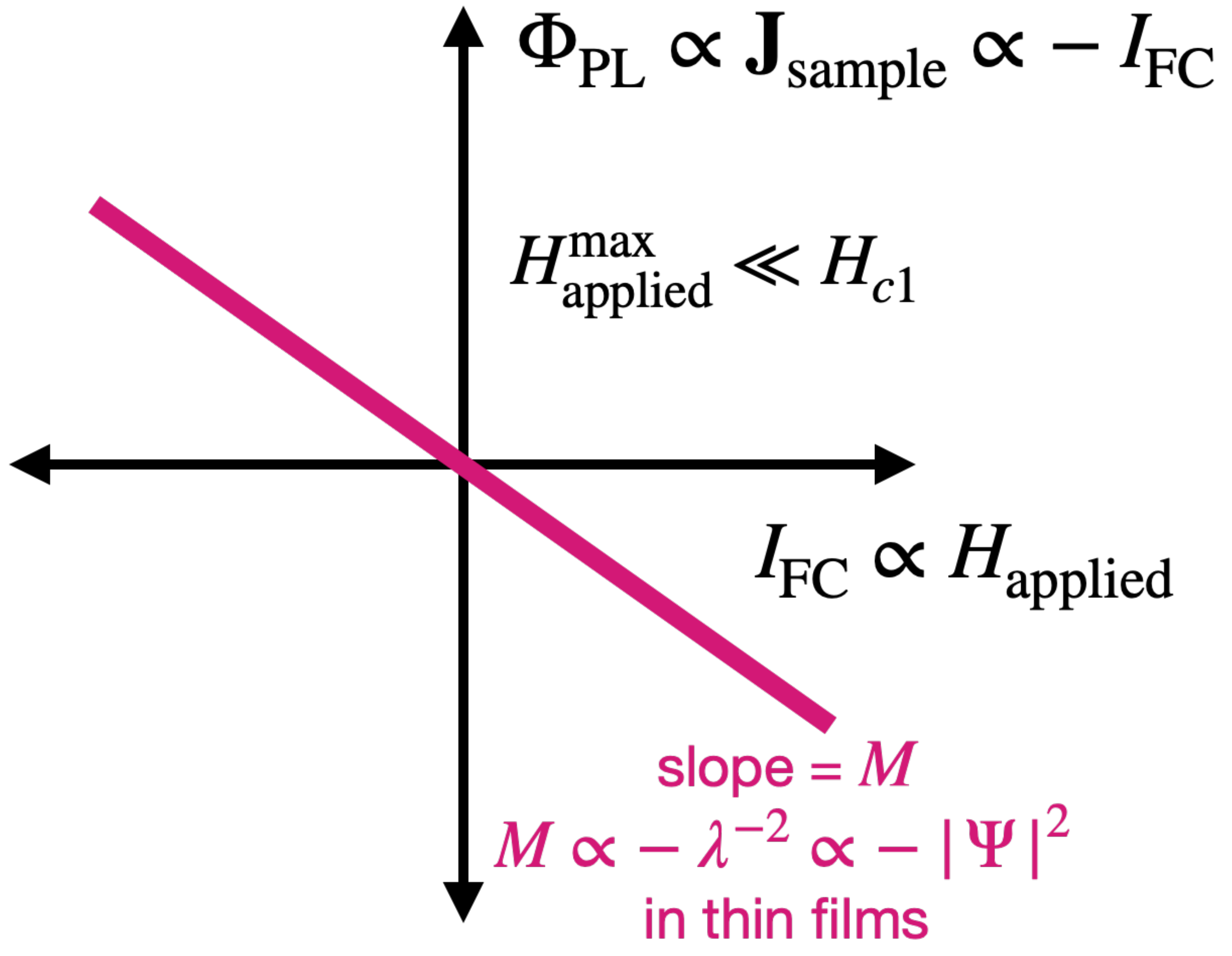
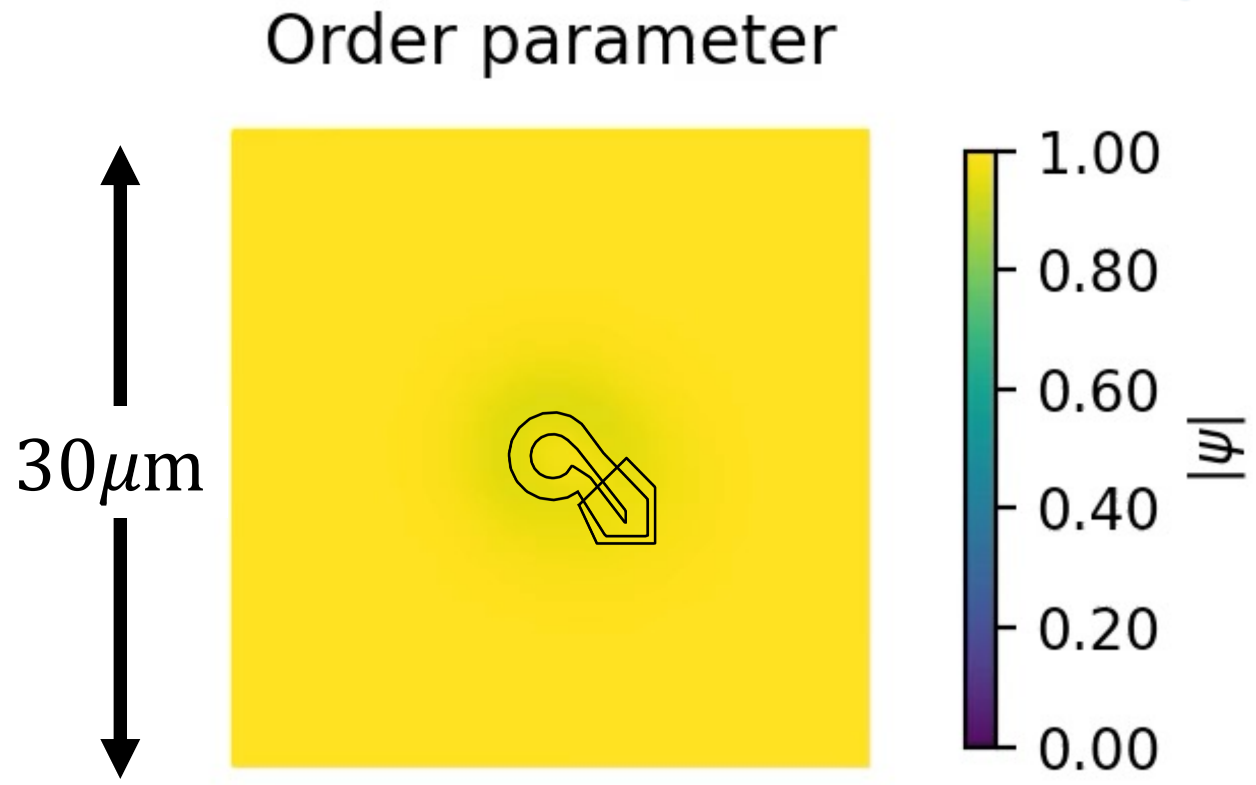
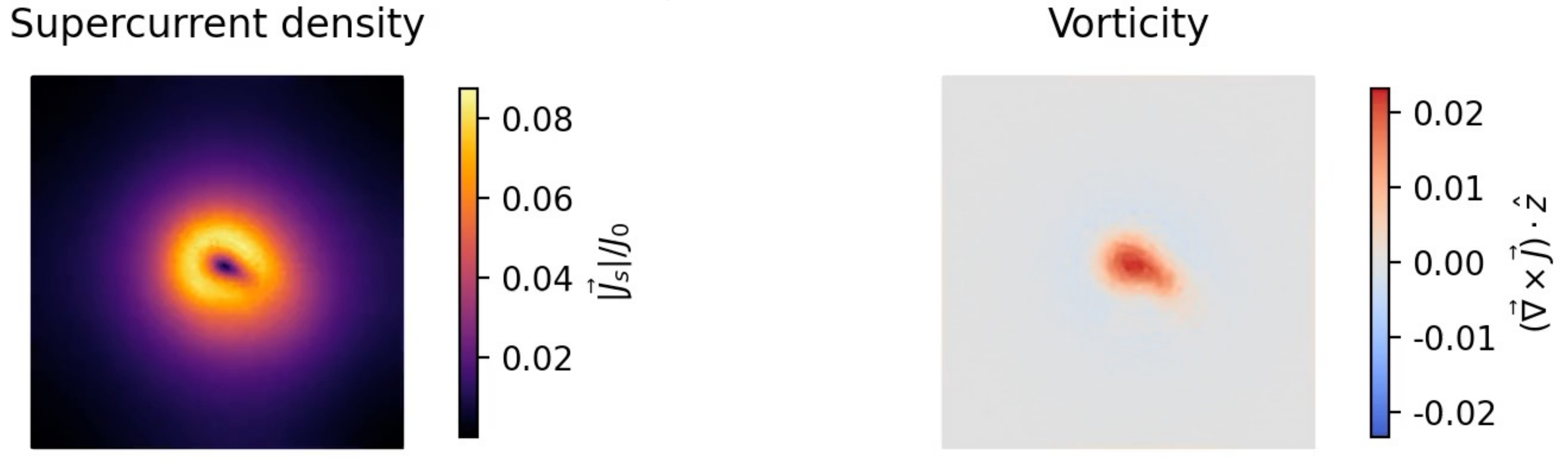
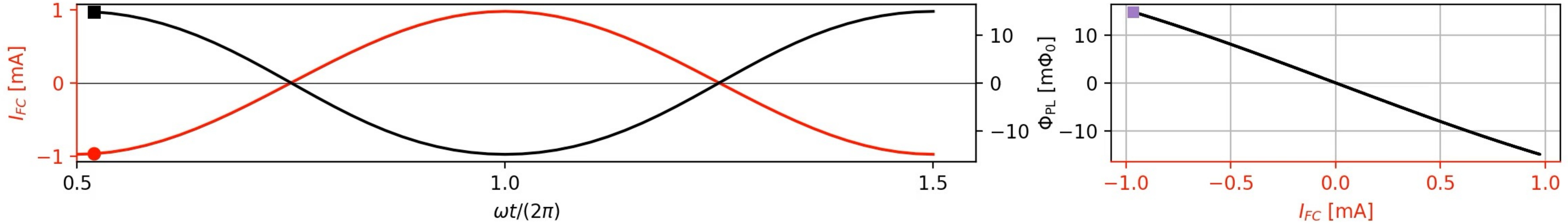




Linear, non-hysteretic diamagnetic response.







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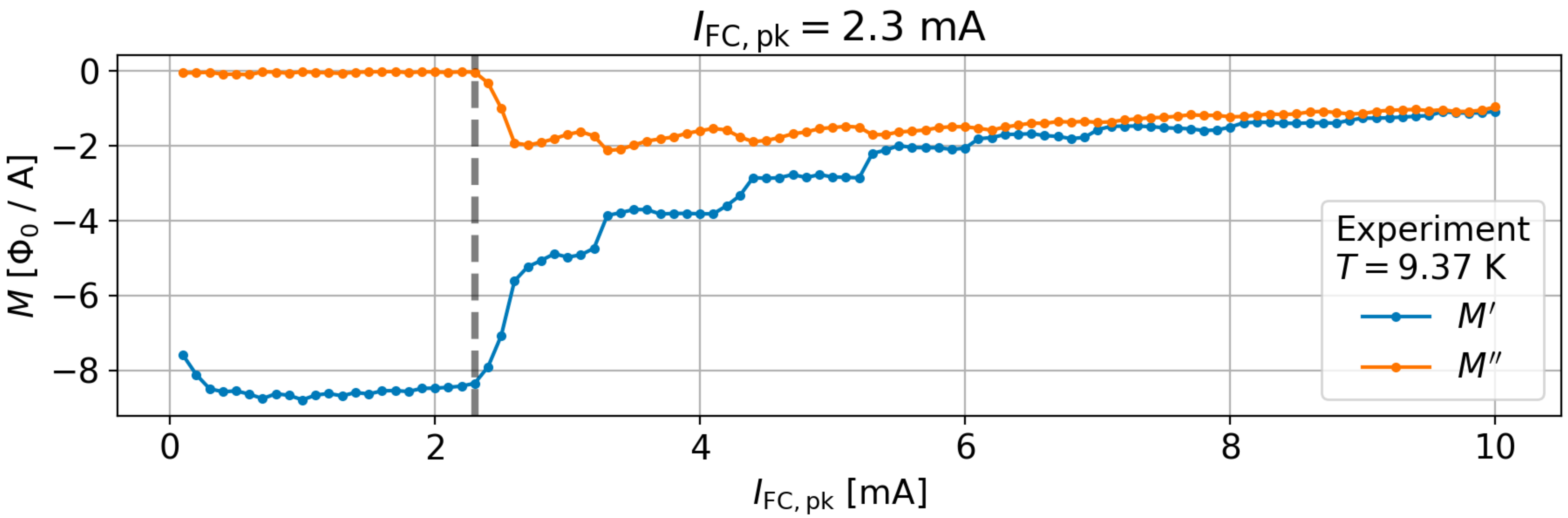
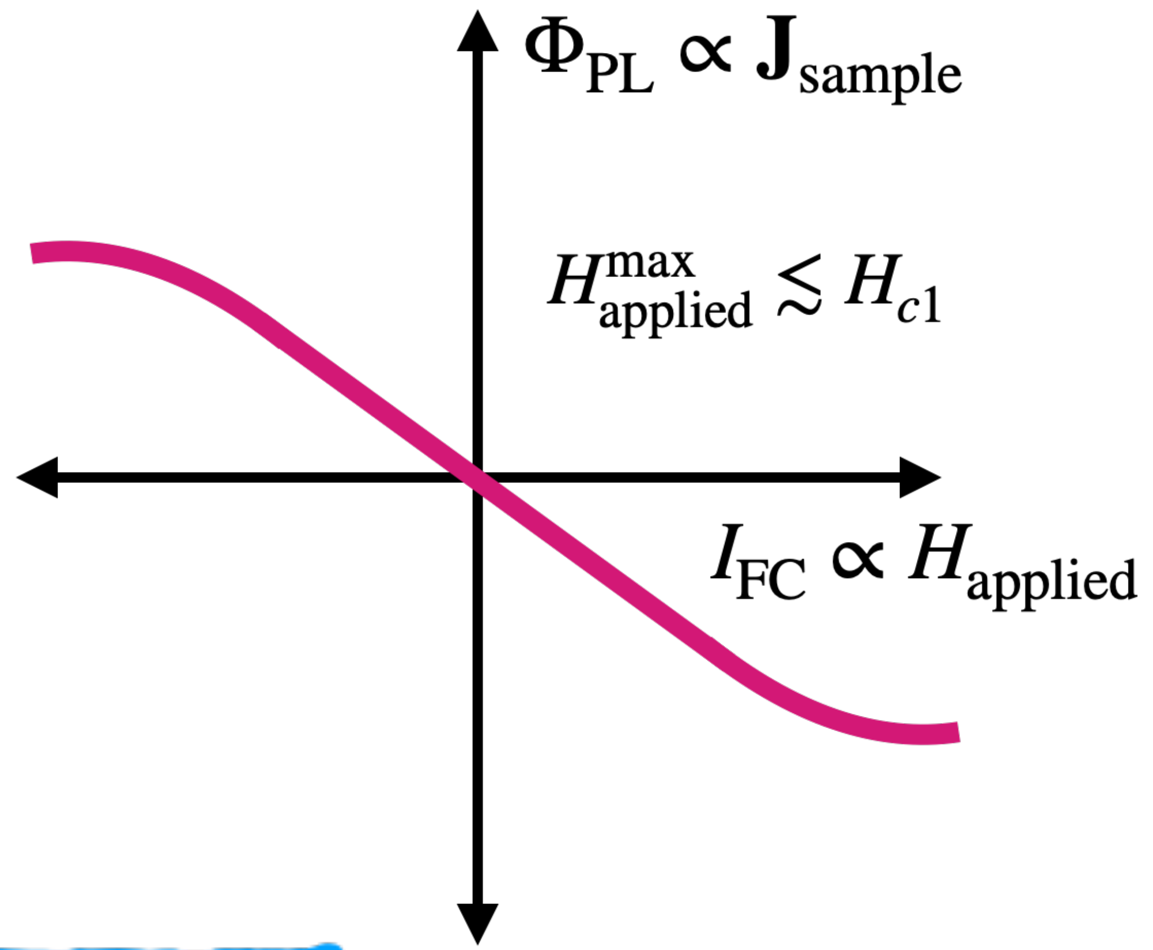
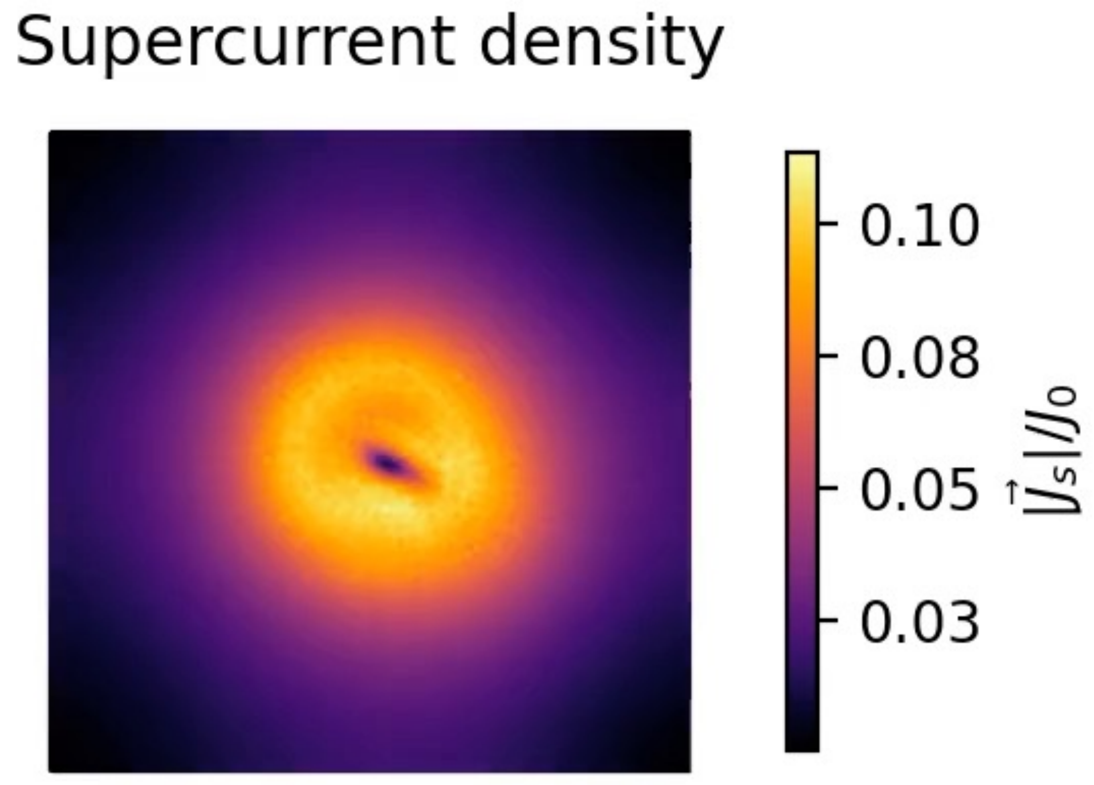
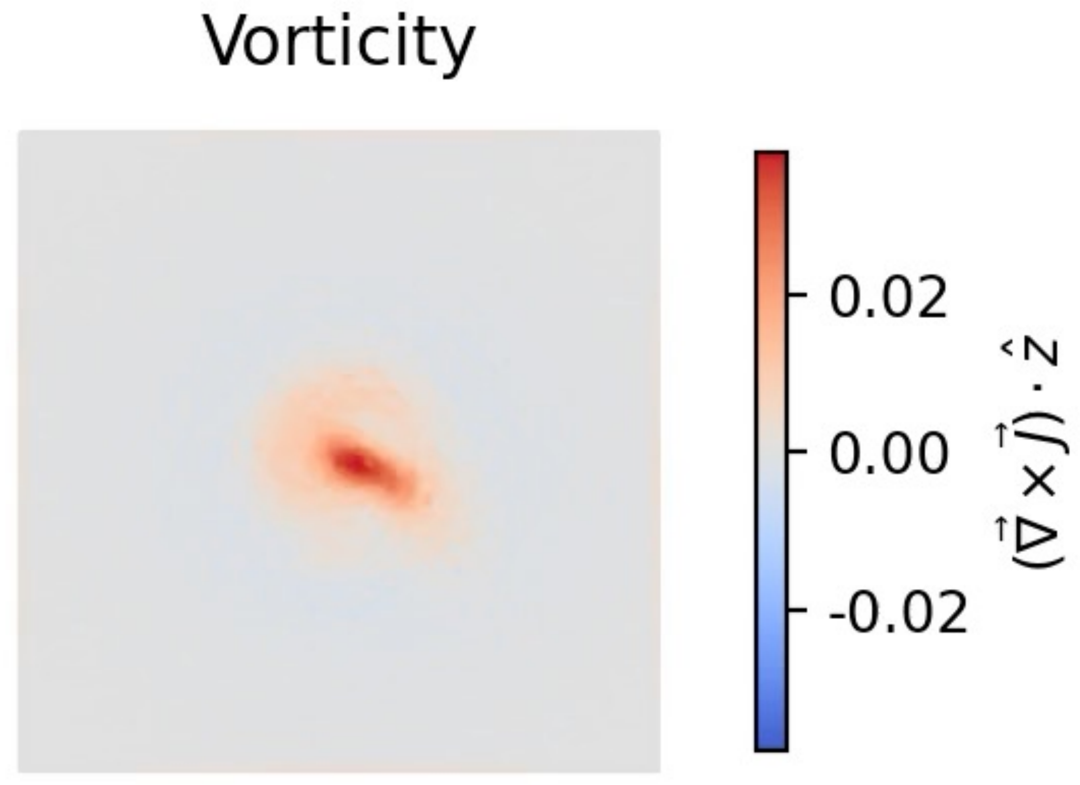
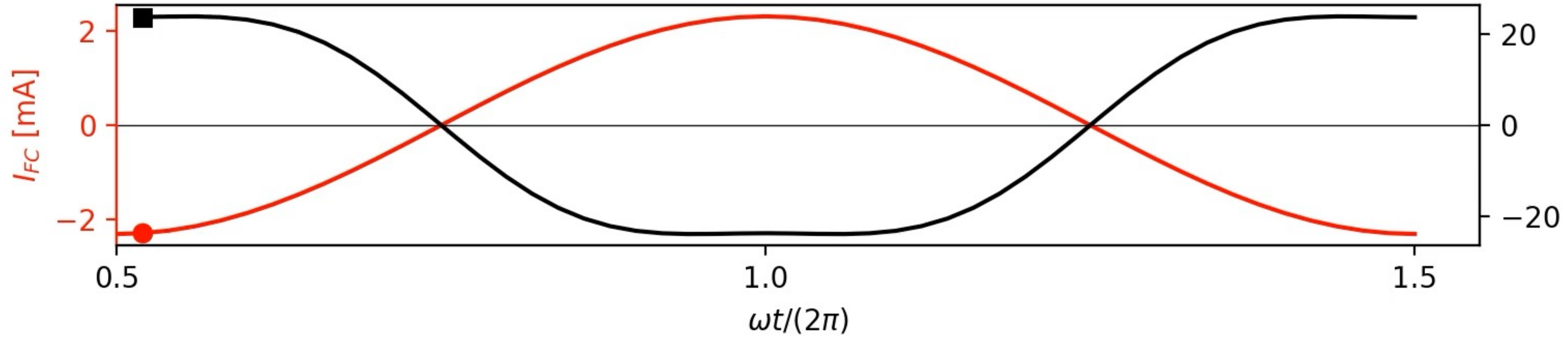


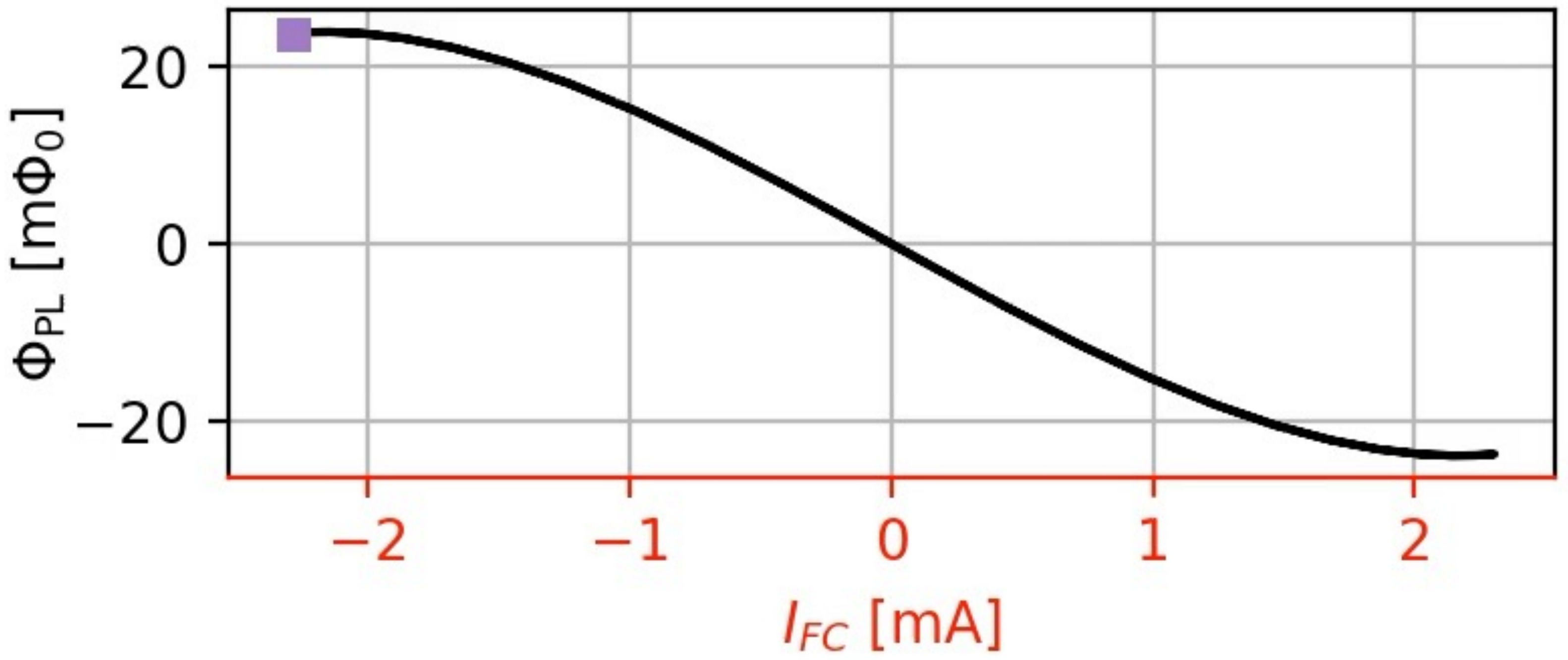


Non-linear, non-hysteretic diamagnetic response due to suppressed superfluid density.









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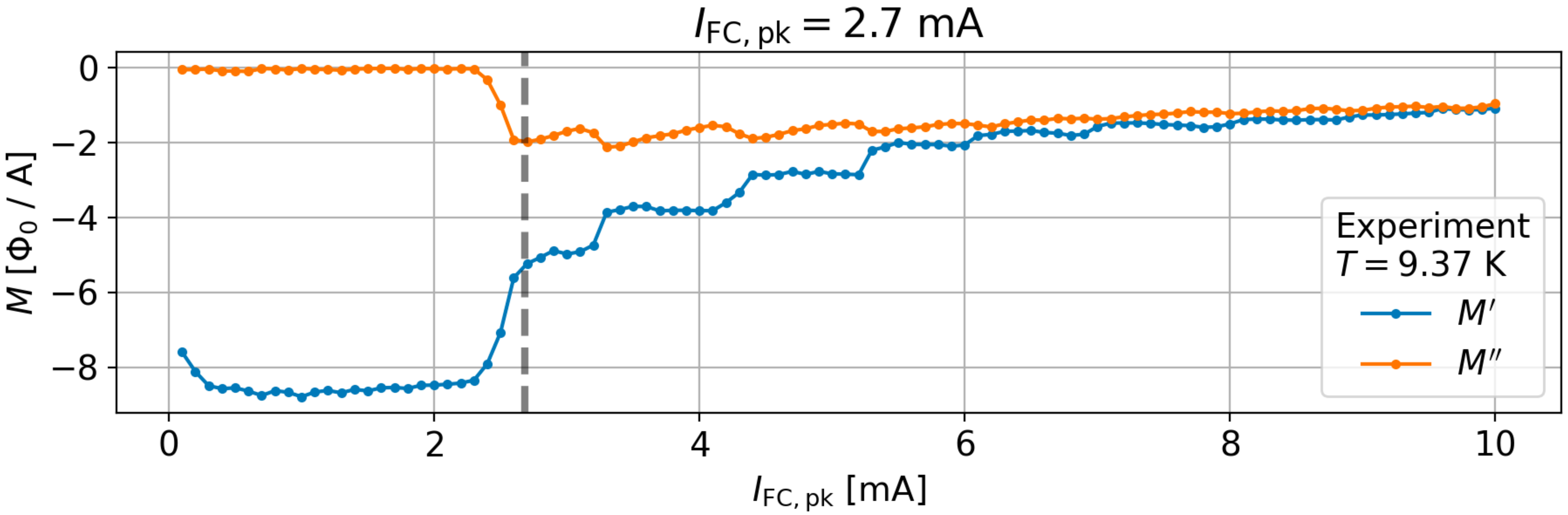
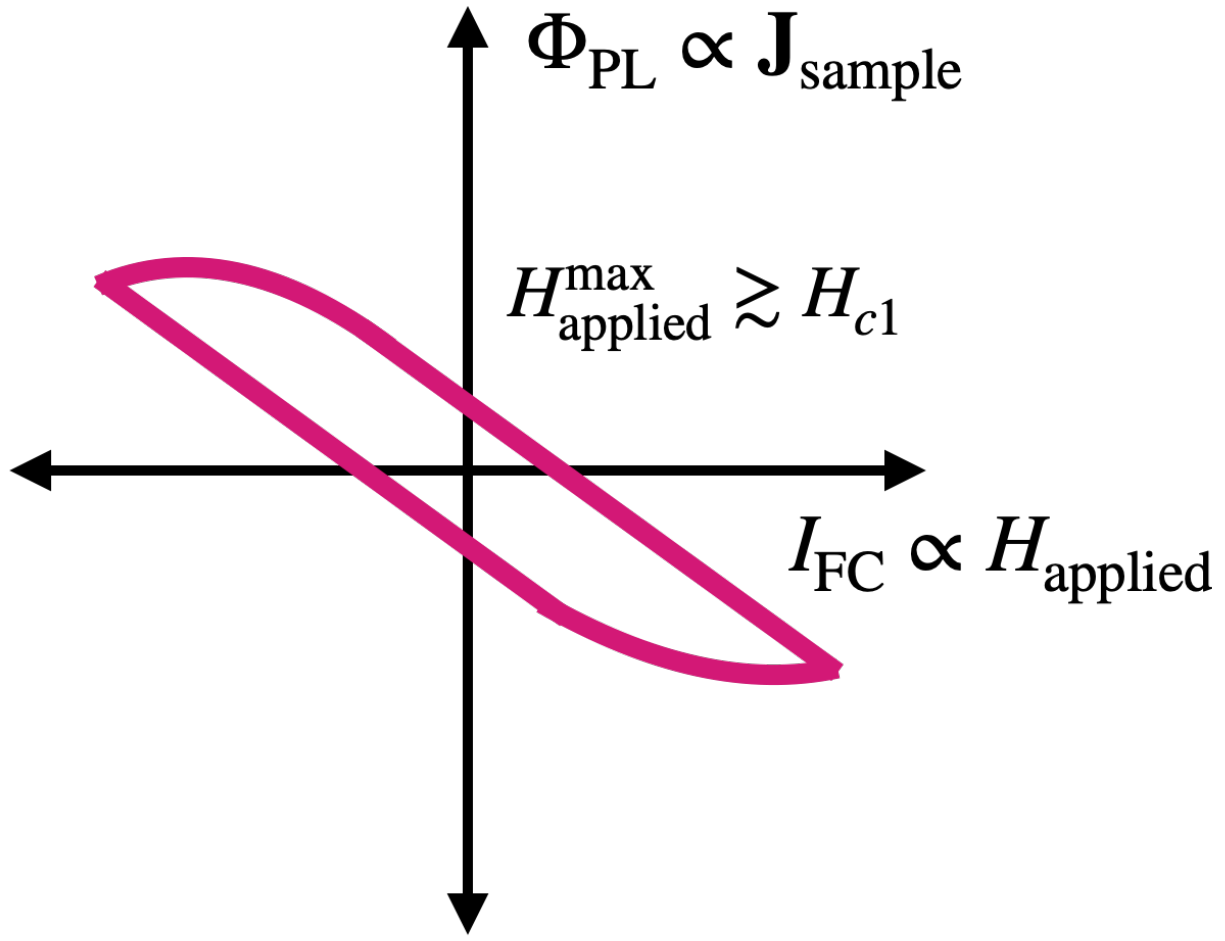
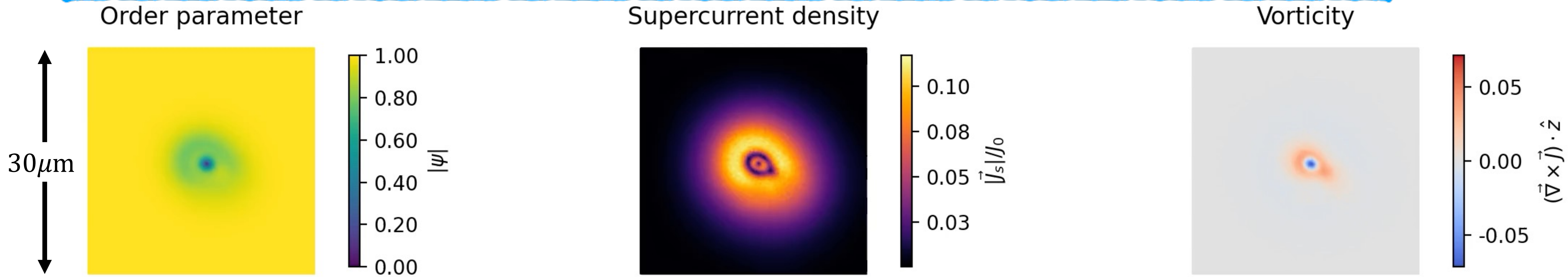
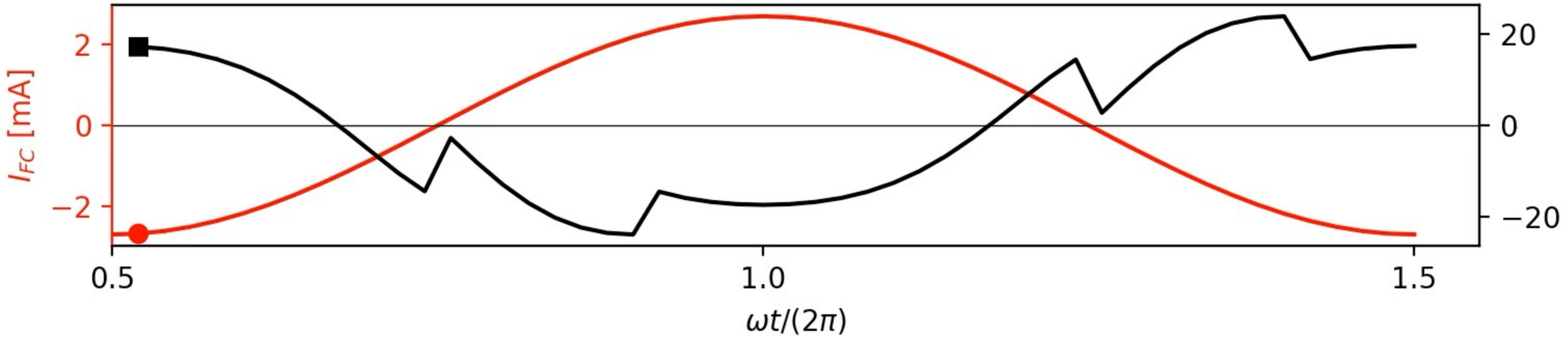
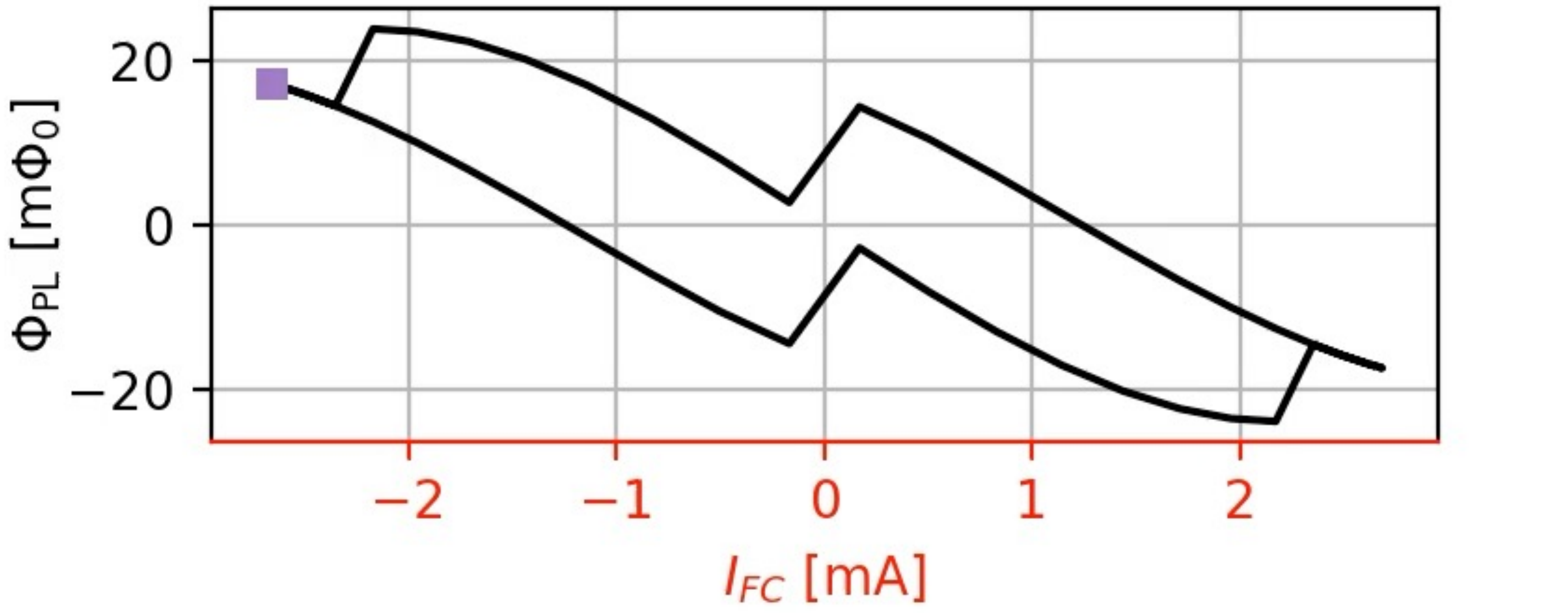


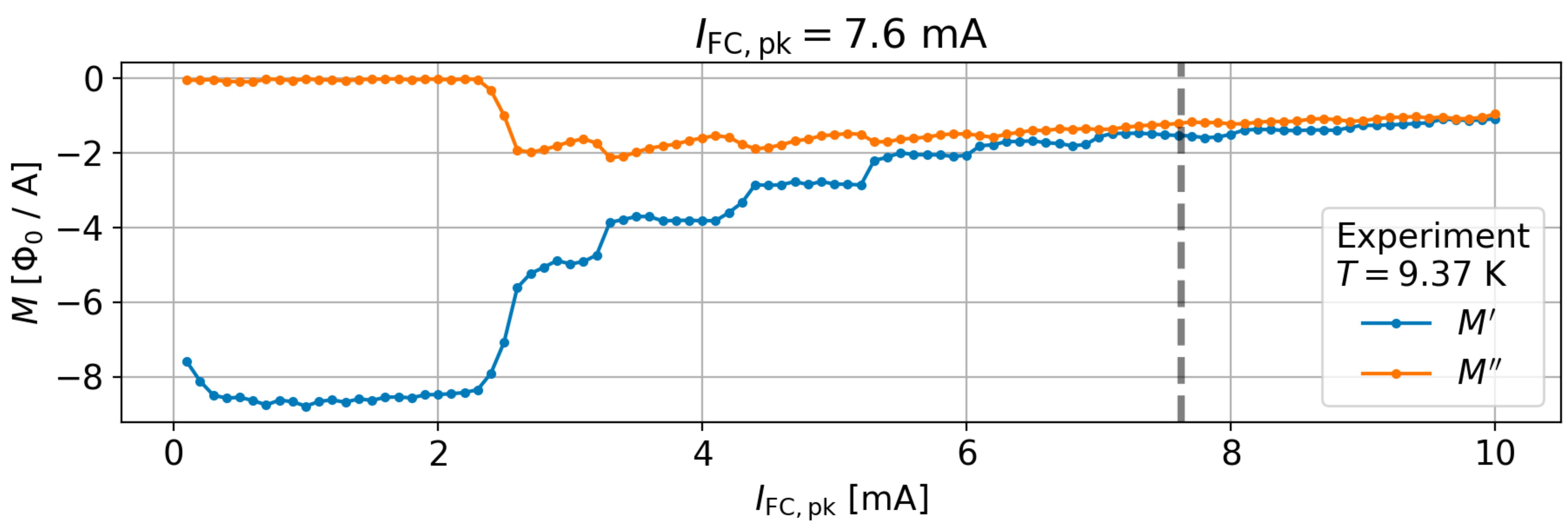


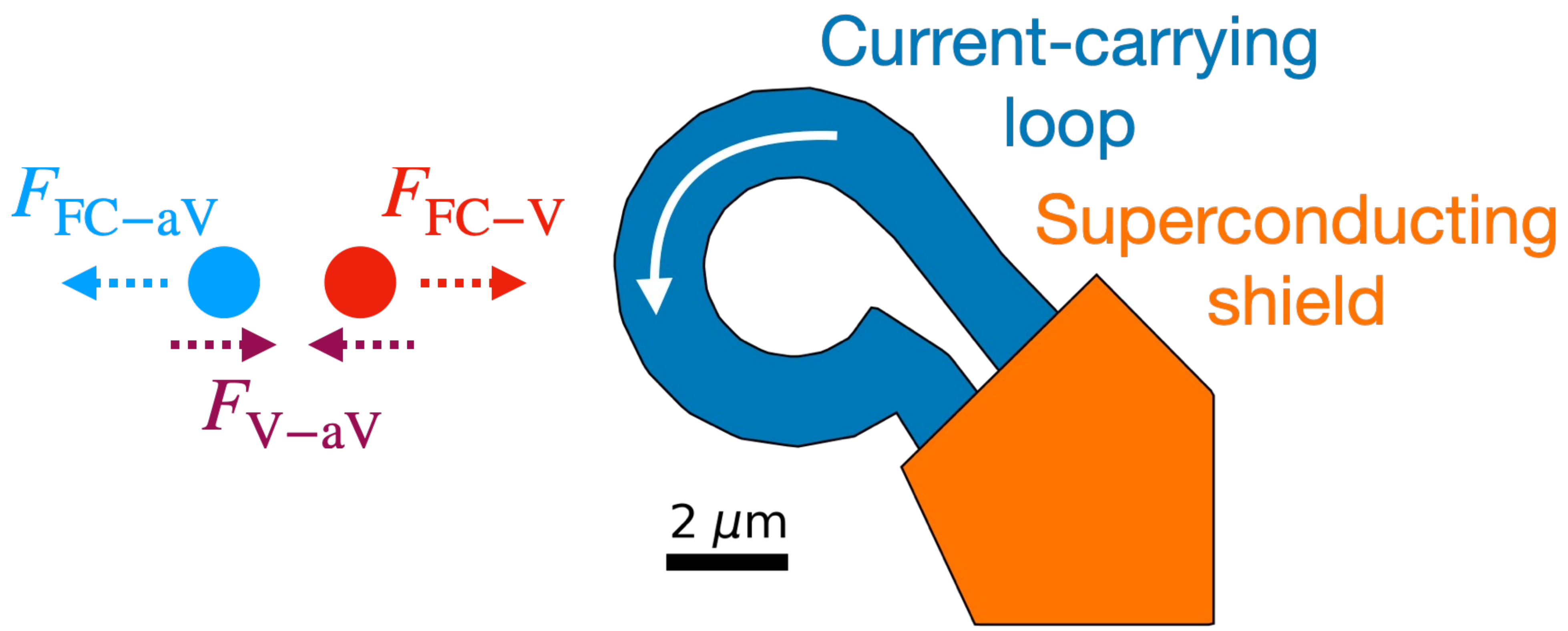
Non-linear, hysteretic response. One V-aV pair induced each half AC cycle; aV pinned far from SQUID.





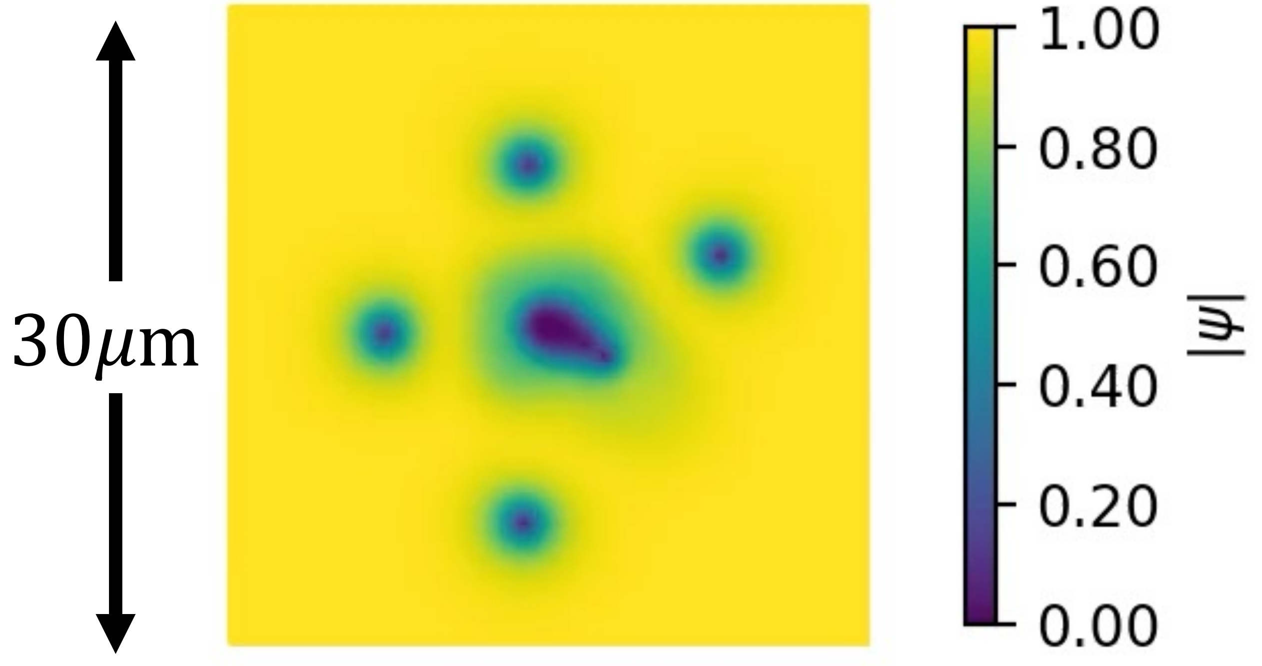




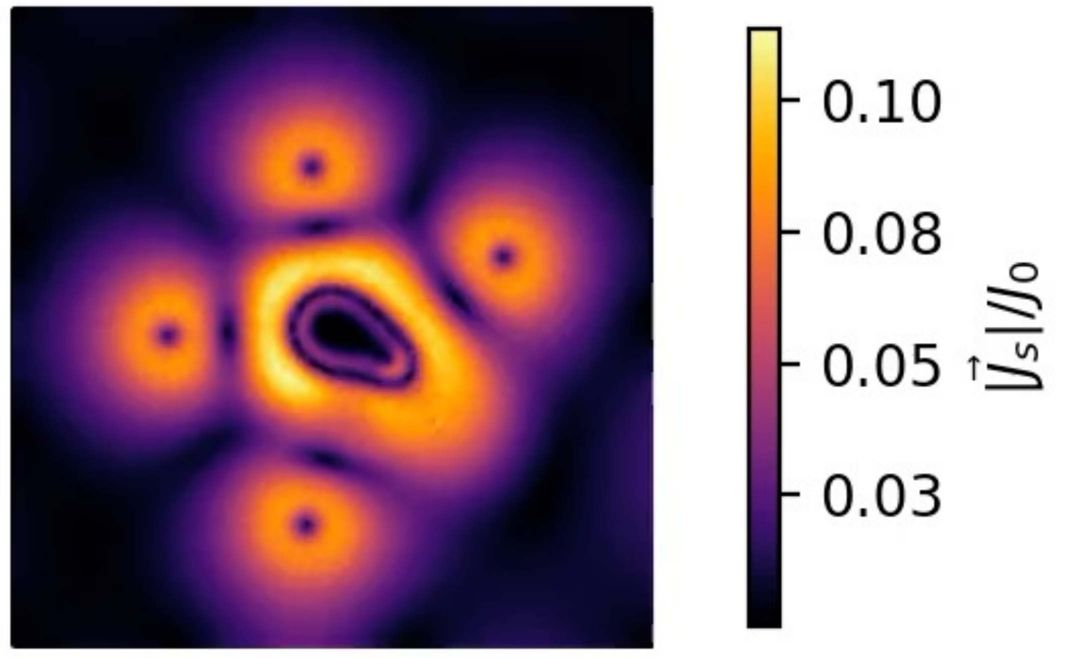


Non-linear, hysteretic response. Many V-aV pairs induced each half AC cycle; some aV pinned far from SQUID.

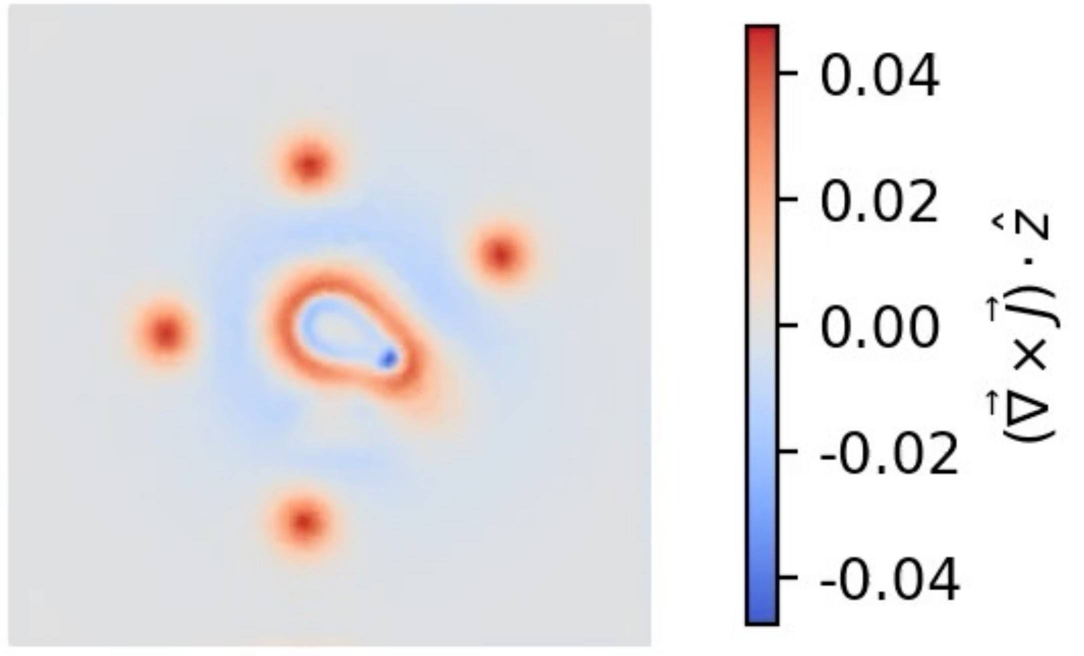
Order parameter

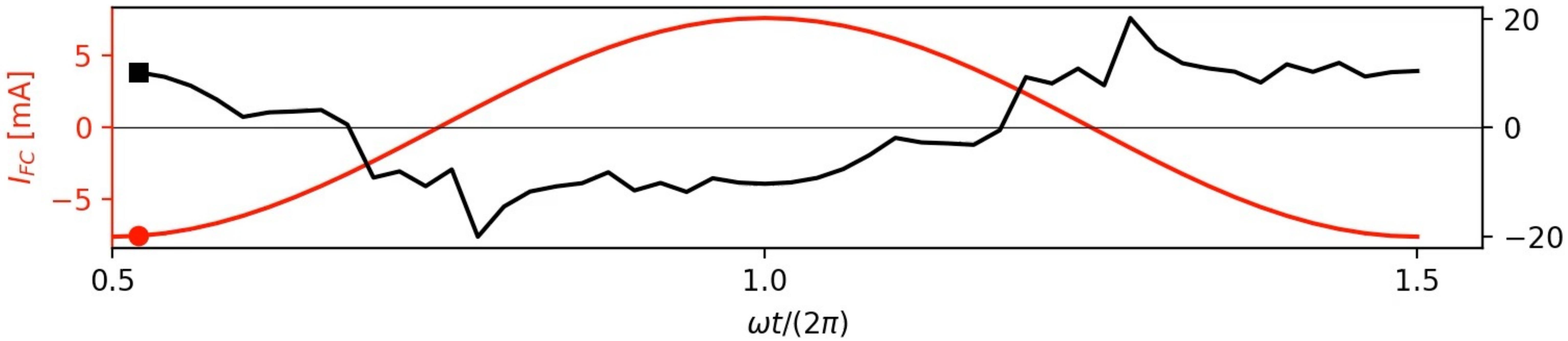


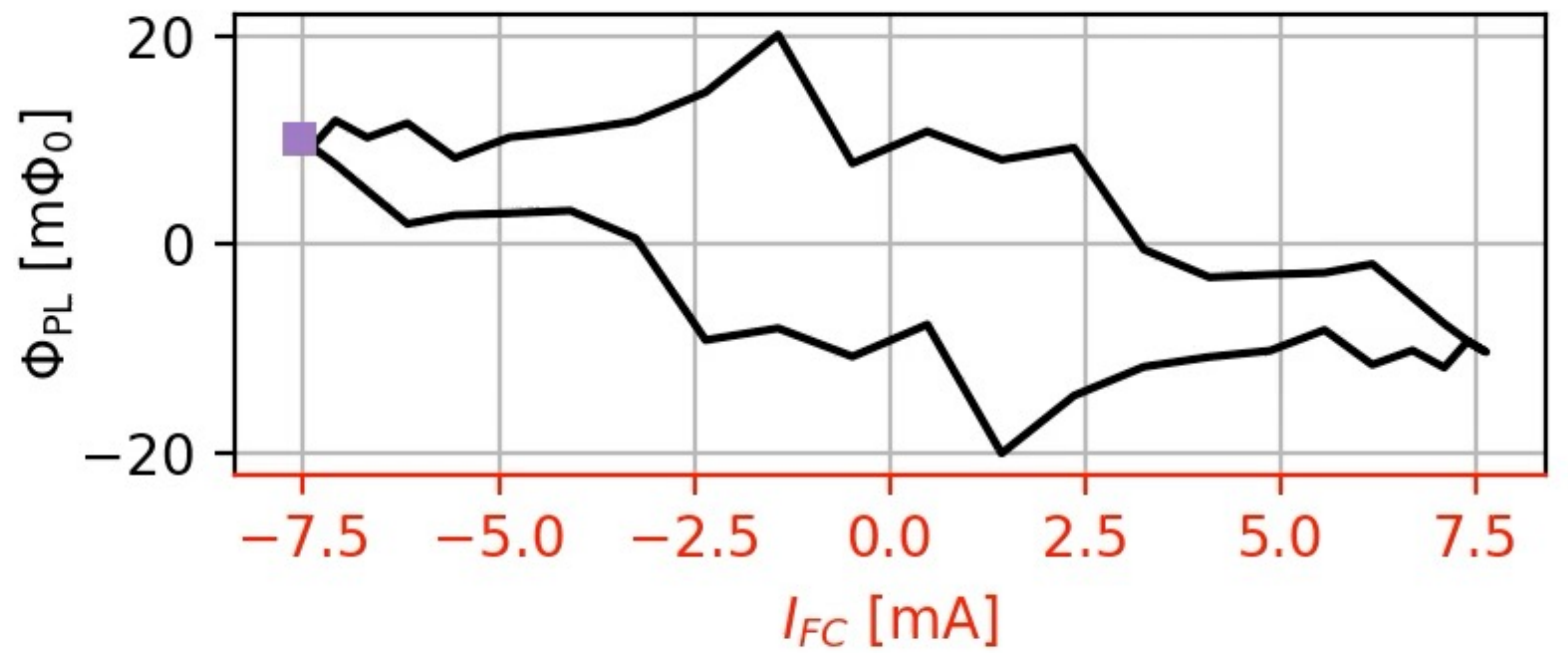
Supercurrent density



Vorticity

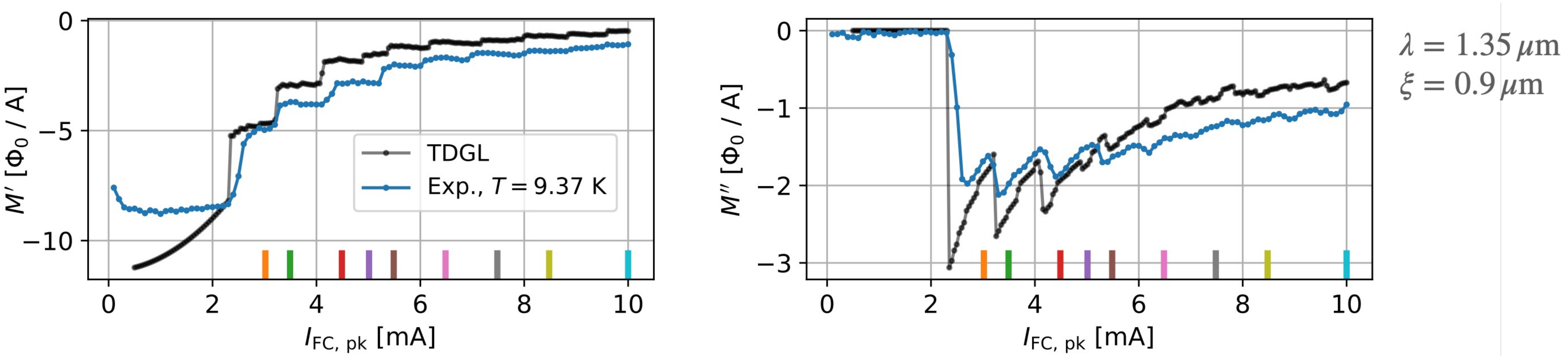






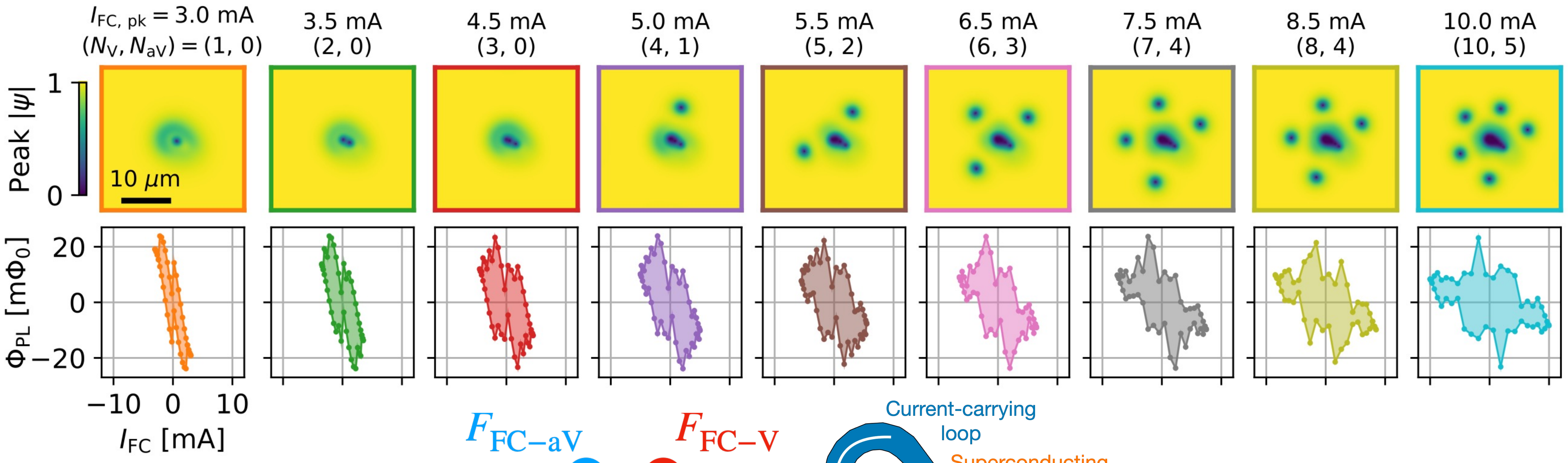
Simulation captures the observed demodulated magnetic response

Demodulated mutual inductance signal

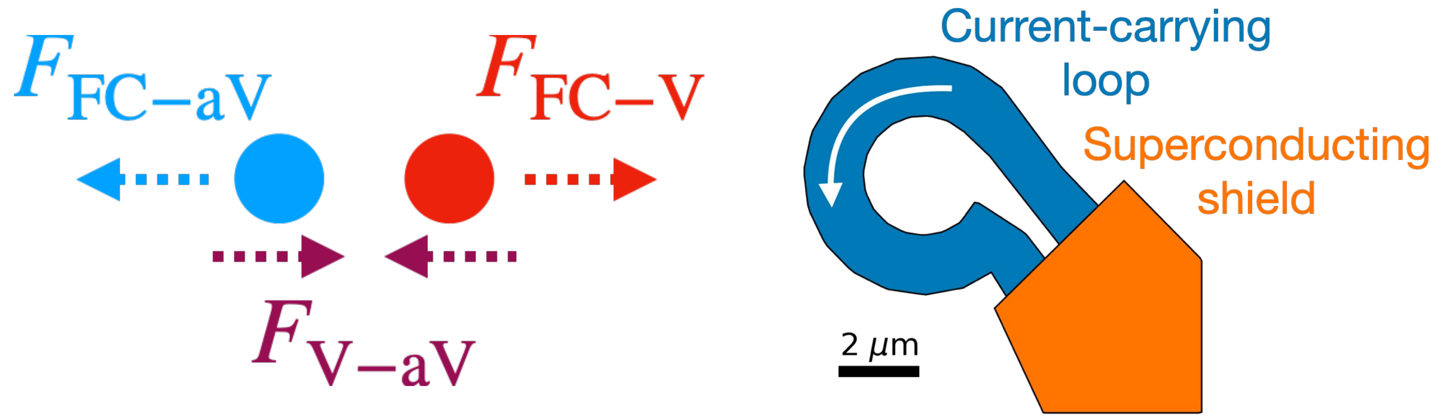


Vortex configurations

Hysteresis loops



Area of hysteresis loop ∝ energy dissipated per cycle



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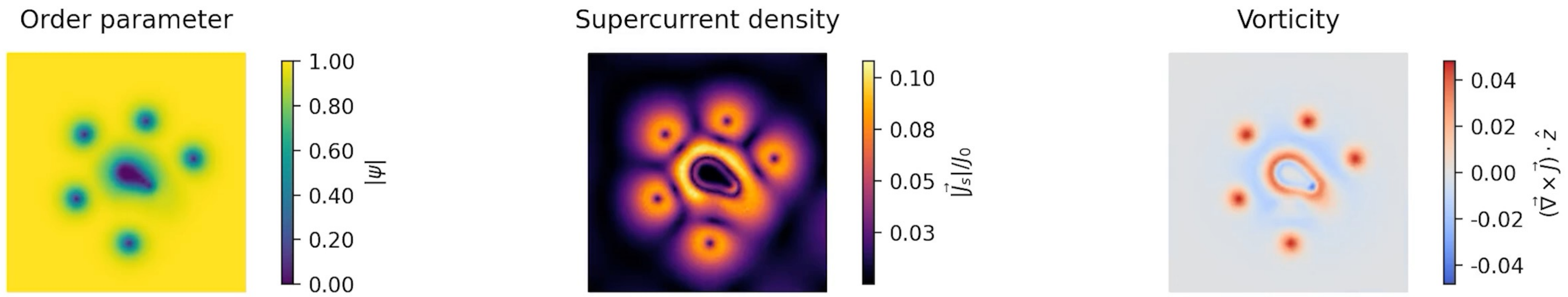

- Scanning SQUID susceptometry + TDGL modeling enables local studies of vortex dynamics resolved at the single-vortex level
- Local approach is complementary to global AC susceptibility and transport, which can be dominated by the surface barrier
- Can be easily extended to study inhomogeneous 2D superconductors, engineered pinning, etc.

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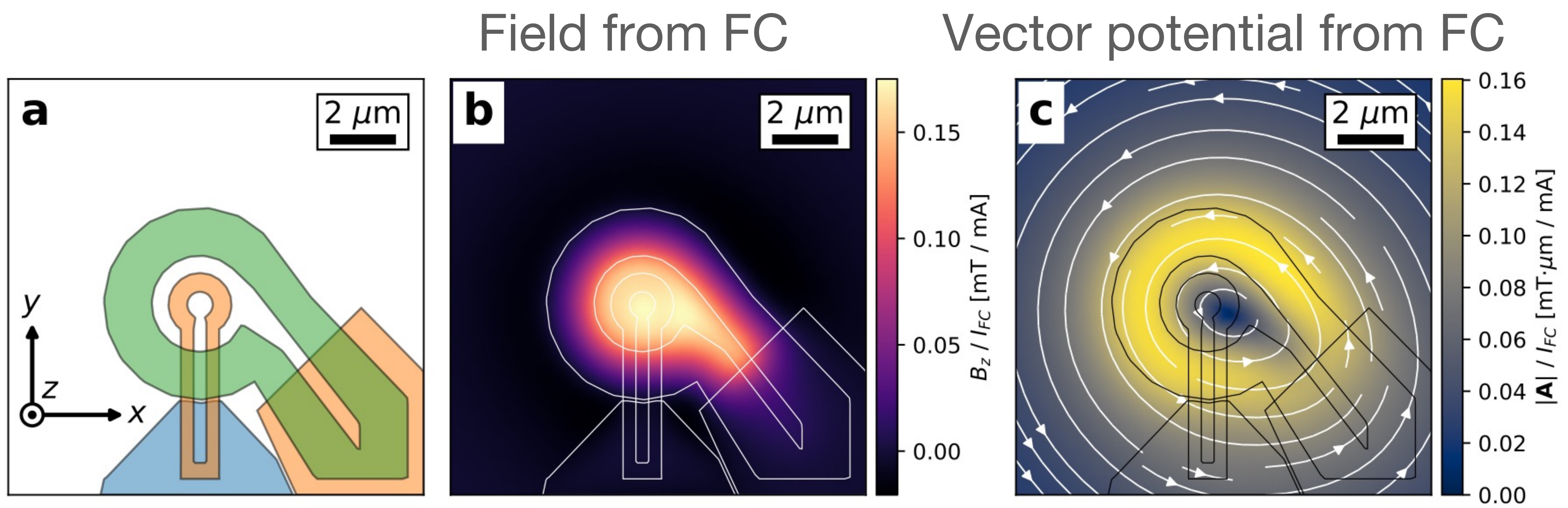
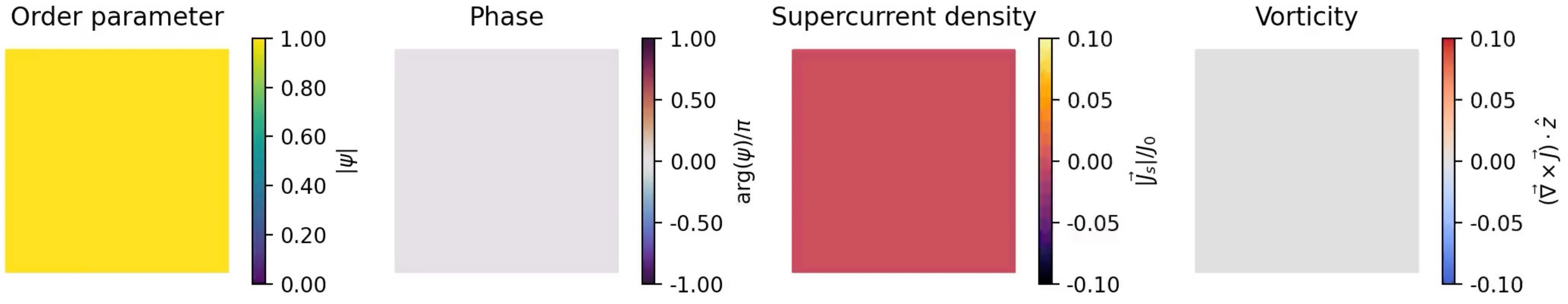
Ingredients for modeling vortex dynamics induced by SQUID susceptometry



Comp. Phys. Comm. **280**, 108464 (2022), superscreen.readthedocs.io



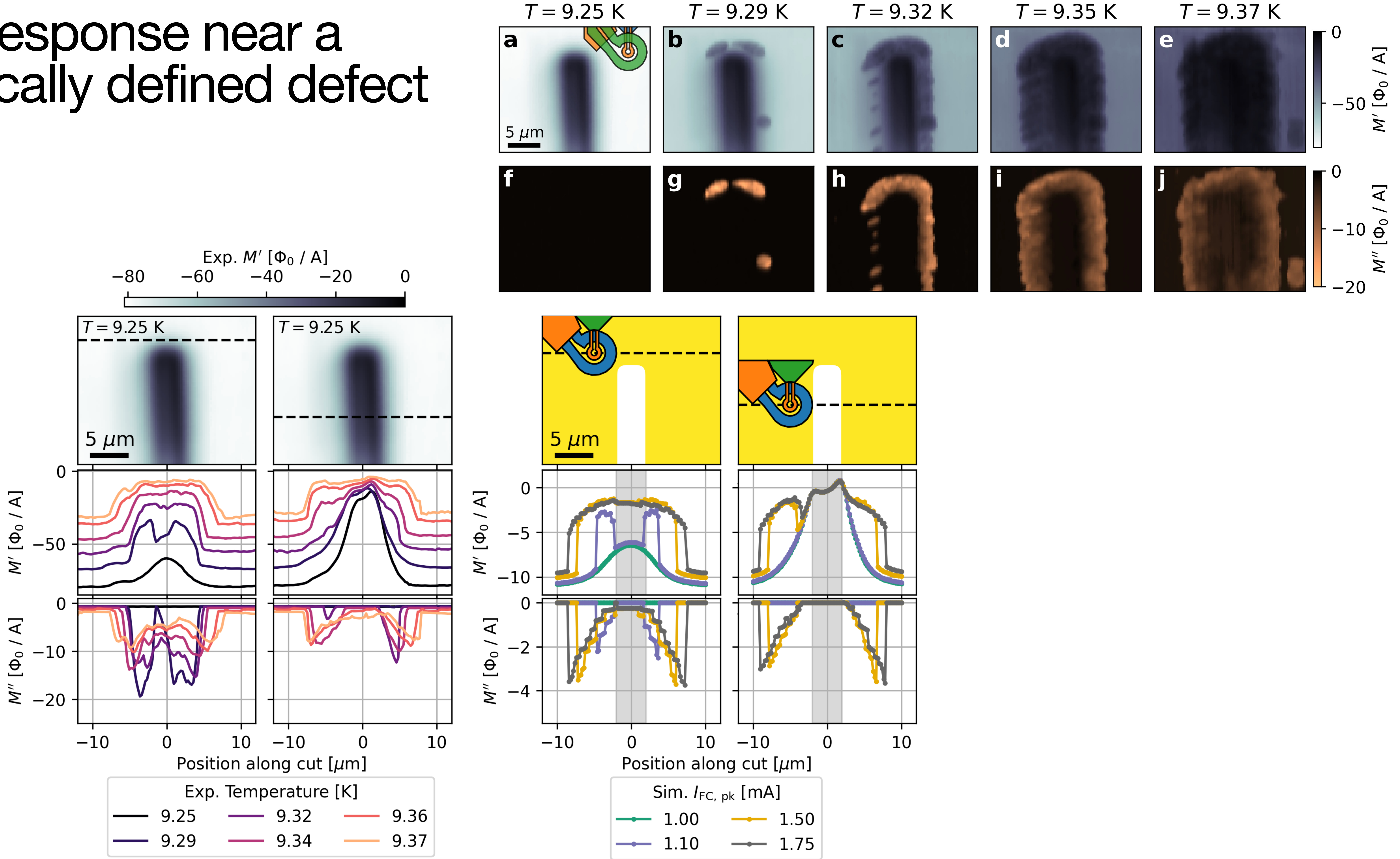
arXiv:2302.03812 (2023); py-tdgl.readthedocs.io

1. Model field applied to sample by SQUID for a given I_{FC}
2. Model sample response to applied field
3. Calculate the flux that the SQUID sees, Φ_{PL}, due to $\mathbf{J}_s$ in the sample
4. Demodulate $\Phi_{\mathrm{PL}}(t)$ over a full AC cycle to get $M = M' + iM''$

Demodulated magnetic response

$$M = \frac{\sqrt{2}}{I_{\mathrm{FC,pk}}}\int \Phi_{\mathrm{PL}}(t)e^{-i\omega t}\mathrm{d}t = M' + iM''$$

Magnetic response near a lithographically defined defect



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pyTDGL: Time-dependent Ginzburg Landau in Python

pypi v0.2.1 | build passing | docs passing | codecov 91% | license MIT | code style black

DOI 10.5281/zenodo.7618841

arXiv:2302.03812 (2023); py-tdgl.readthedocs.io

$$\frac{u}{\sqrt{1+\gamma^2|\psi|^2}}\left(\frac{\partial}{\partial t}+i\mu+\frac{\gamma^2}{2}\frac{\partial|\psi|^2}{\partial t}\right)\psi=(\epsilon-|\psi|^2)\psi+(\nabla-i\mathbf{A})^2\psi$$

$$\nabla^2\mu=\nabla\cdot\mathrm{Im}[\psi^*(\nabla-i\mathbf{A})\psi]=\nabla\cdot\mathbf{J}_s$$

$\psi(\mathbf{r},t)$: Complex order parameter

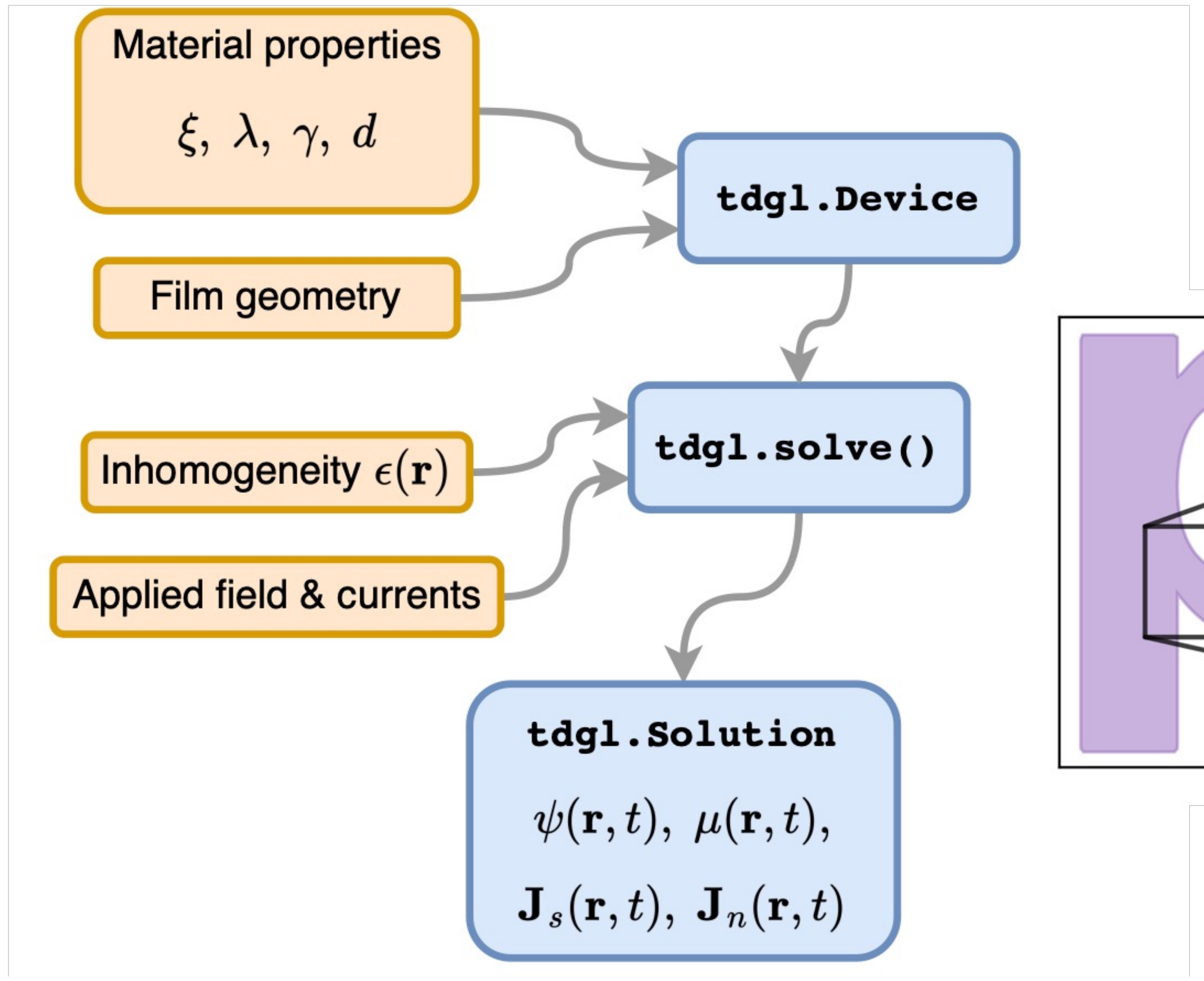
$\mu(\mathbf{r},t)$: Electric scalar potential

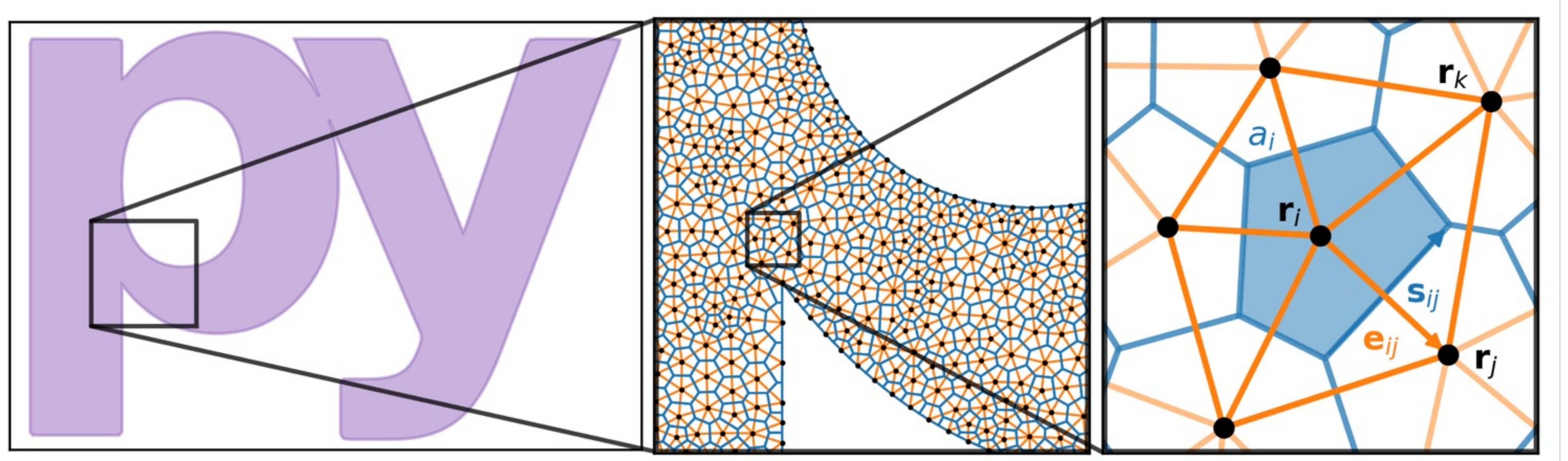
$\mathbf{J}_s(\mathbf{r},t)$: Supercurrent density

$\mathbf{J}_n(\mathbf{r},t)=\nabla\mu$: Normal current density

$\epsilon(\mathbf{r})=T_c(\mathbf{r})/T-1$: Local critical temperature

$\gamma\propto\tau_E\Delta_0$: Inelastic scattering (vortex viscosity)





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Computer Physics Communications
Volume 280, November 2022, 108464

SuperScreen: An open-source package for simulating the magnetic response of two-dimensional superconducting devices ☆, ☆☆

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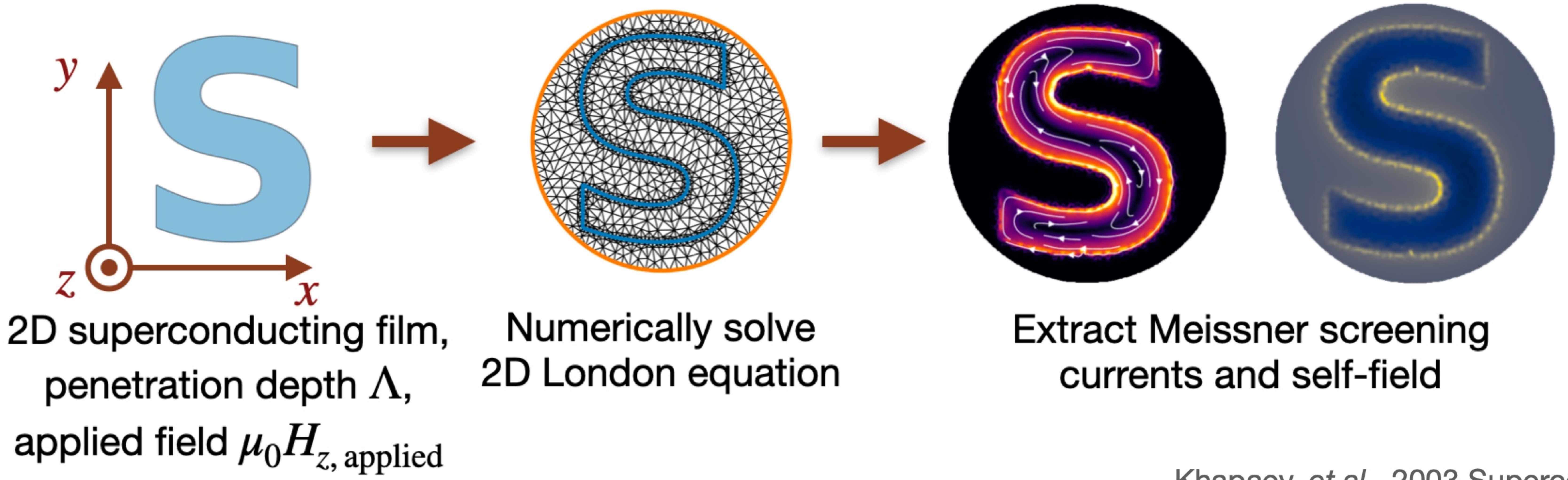
arXiv:2203.13388 (2022), superscreen.readthedocs.io



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