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Invited presentation WT-27-INV given at ISS 2015 in Funabori, Tokyo, Japan, November 16 to 18th, 2015.

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# Current Flow in Polycrystalline Iron-Based Superconductors Assessed by Scanning Hall Probe Microscopy

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ISS2015, Tokyo, November $17^{th}$

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# Outline

- Motivation
  - Asymmetry of magnetization loops
  - Hysteresis in field dependence of $J_c$ (transport measurements)
  - Common explanation
- Experimental
  - Samples (polycrystalline Ba-122)
  - Scanning Hall probe microscopy
  - Inter- and intra-granular currents
- Model: Josephson coupled grains
- Comparison with data
- Conclusions

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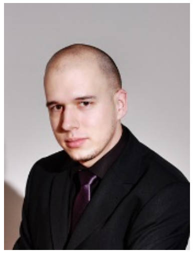
# Acknowledgments

Johannes Hecher



Thomas Baumgartner

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Super Iron
FP7-NMP-2011-Eu-Japan

Exploring the potential
of Iron-based Superconductors

COOPERATION

FWF

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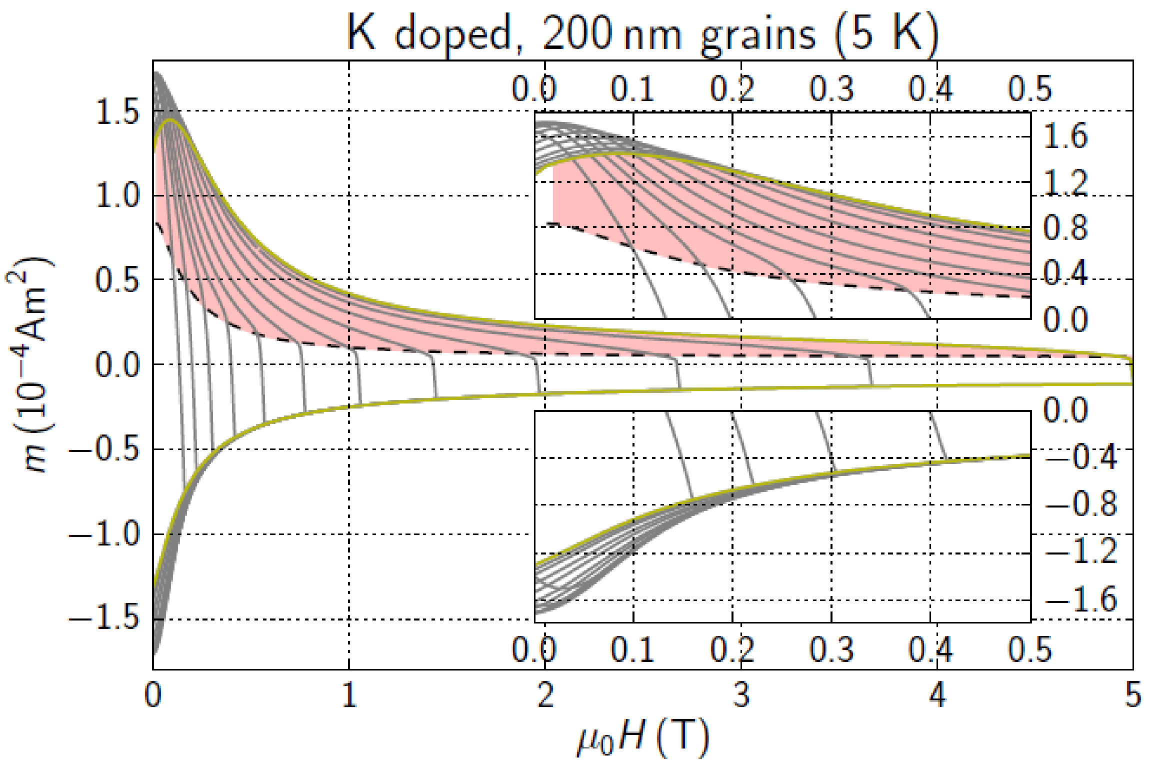
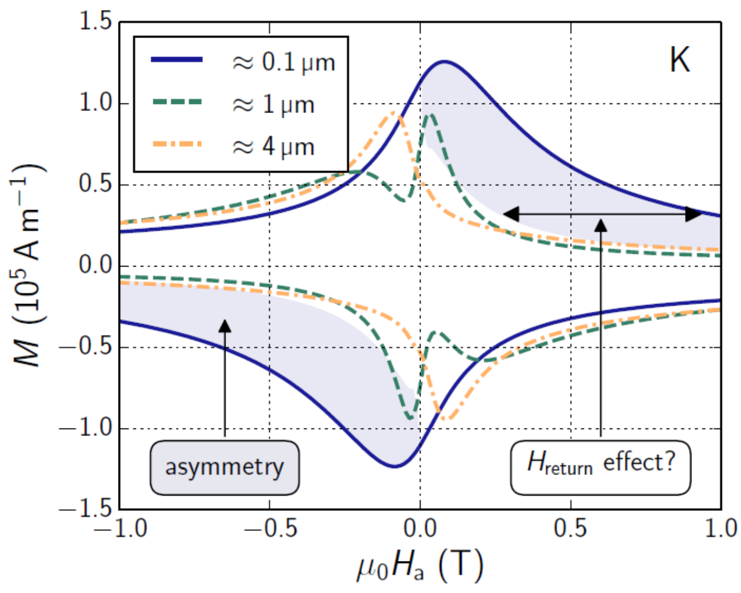
# Asymmetry of magnetization loops



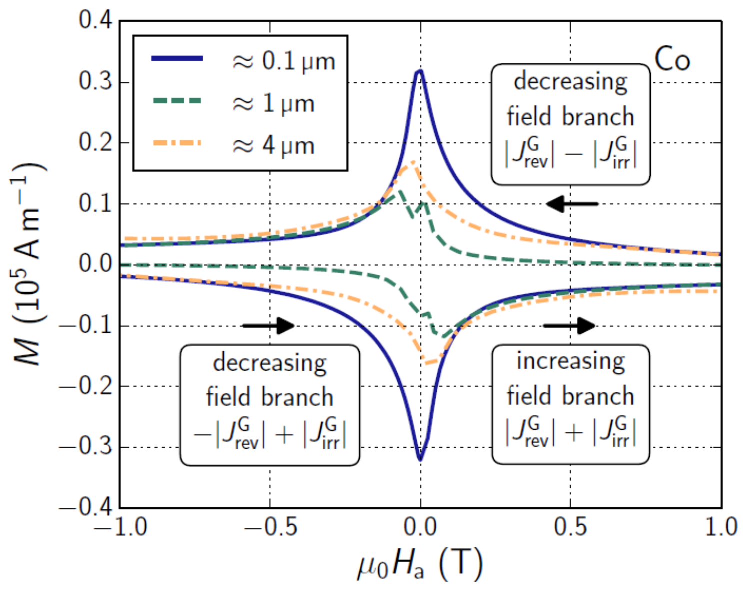

- Higher macroscopic currents in decreasing fields than in increasing fields
- K- and Co-doped Ba-122

# Influence of grain size

K-doped Ba-122




Co-doped Ba-122




- Submicron sized grains: peak at decreasing fields (intergranular currents)
- "Large grains": peak at increasing fields (intra-granular currents)
- Medium sized grains: both peaks

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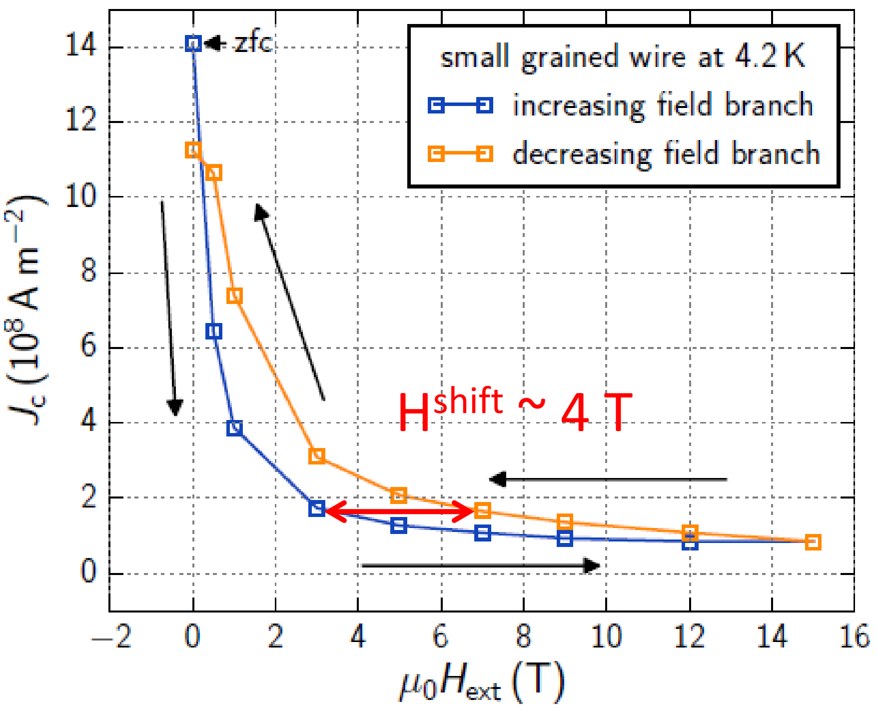
# Hysteresis in transport measurements

K-doped Ba-122 wire



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# Common explanation: return field

- Return fields of the grains: $H^{return}$
- $J_c$ is determined by the field at the grain boundaries
- $H^{return}$ adds or subtracts from the applied field:

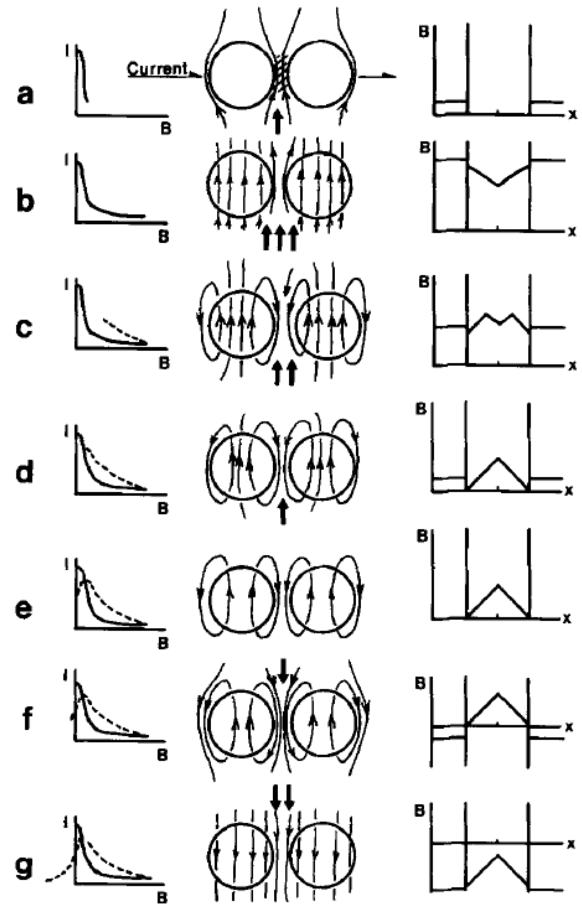
$$H^{shift} = 2H^{return}$$

**Ba-122 wire:**

$\mu_0 H^{return} = \sim 2$ T
$J^{grain} \sim H^{return}/r = |r \sim 100\ \text{nm}| = 2\times10^{9}\ \text{A/cm}^2 > J_d$

Corresponding field gradient would be easily visible in our SHPM experiments, but is absent.

**This explanation can be ruled out in our case!**




J. E. Evetts and B. A. Glowacki
Cryogenics 28 (1988) 641

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# EXPERIMENTAL

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# Samples

**$Ba_{0.6}K_{0.4}Fe_2As_2$**

Applied Superconductivity Center

Florida State University

Hot isostatic pressure (HIP)

- 600-1120 °C
- 10-20 h
- Grain sizes $s_0$ ~ 100 nm, 1 µm, 3 µm
- $J_c$(sf, 5 K) ~ 10, 1, $1 \cdot 10^4$ $Acm^{-2}$

**$Ba(Fe_{0.92}Co_{0.08})_2As_2$**

University of Tokyo

Ambient pressure

- 500-1100 °C
- 24-240 h
- Grain sizes $s_0$ ~ 100 nm, 1 µm, 3 µm
- $J_c$(sf, 5 K) ~ 5, 0.5, $1 \cdot 10^4$ $Acm^{-2}$

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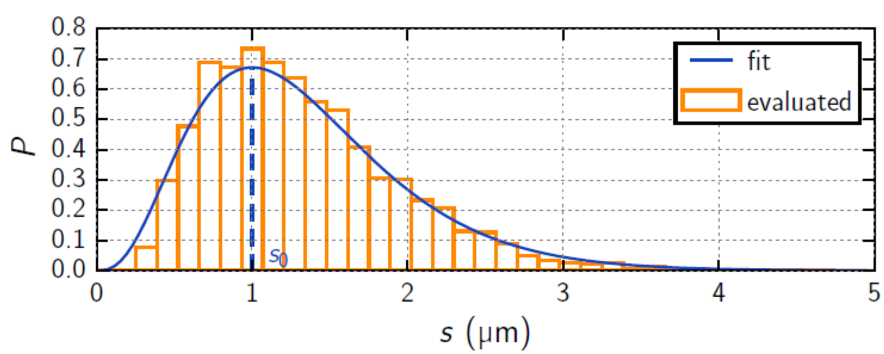
Grain size distribution:

$$P(s, s_0) = \frac{s^3}{2s_0^4} e^{-\frac{3s}{s_0}}$$

$s_0$.......grain "radius"

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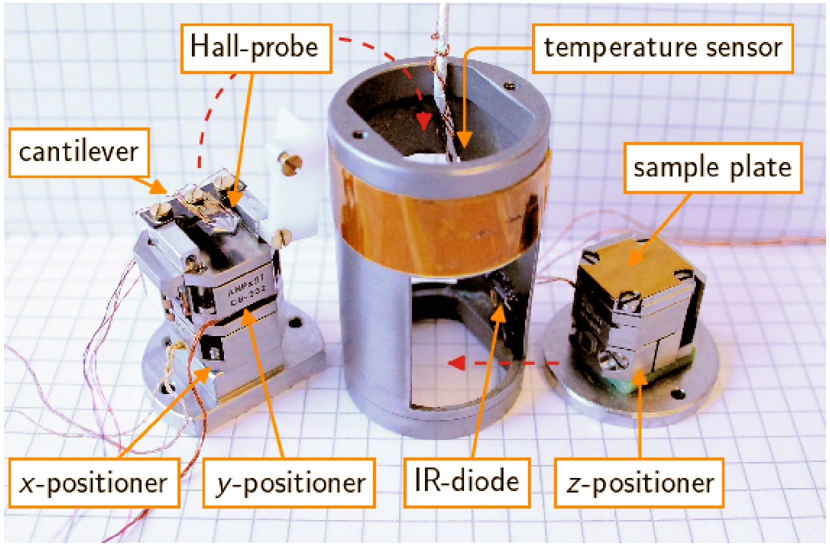
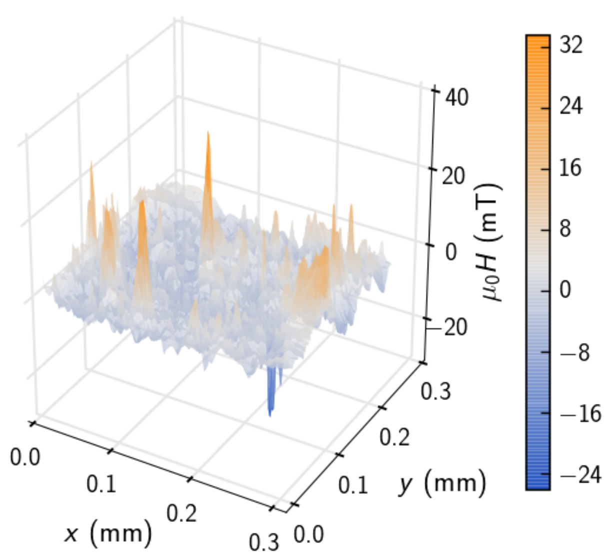
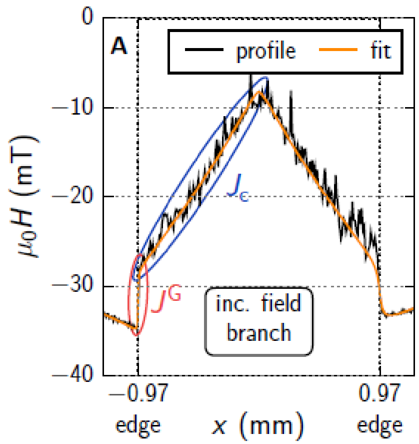
# Scanning Hall Probe Microscope (SHPM)

- Helium gas flow cryostat: 3-150 K
- 8 T superconducting magnet
- Scan range: 3×3 mm$^2$
- Spatial resolution: 2 µm

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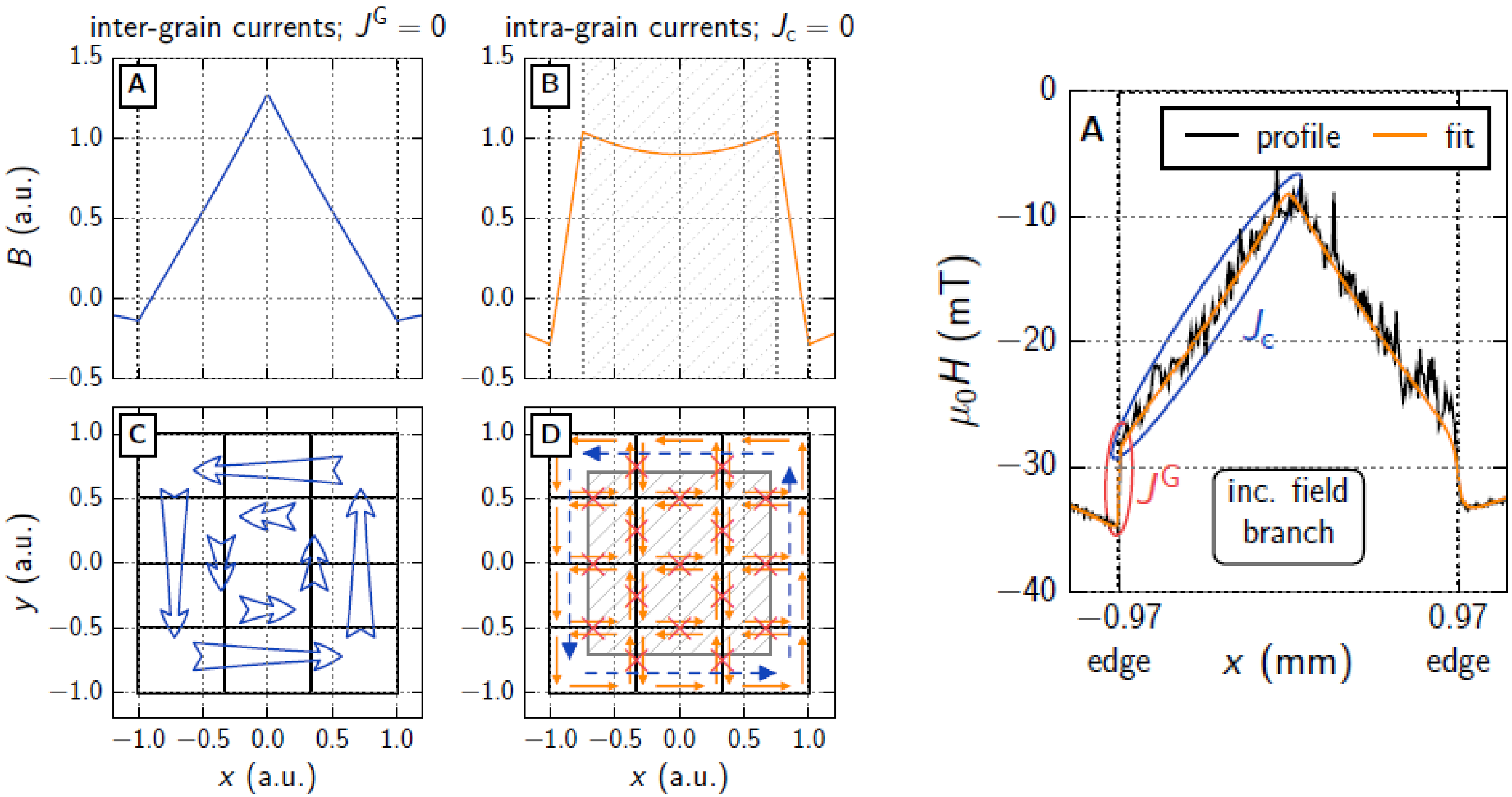
# Derivation of inter- and intra-granular current densities

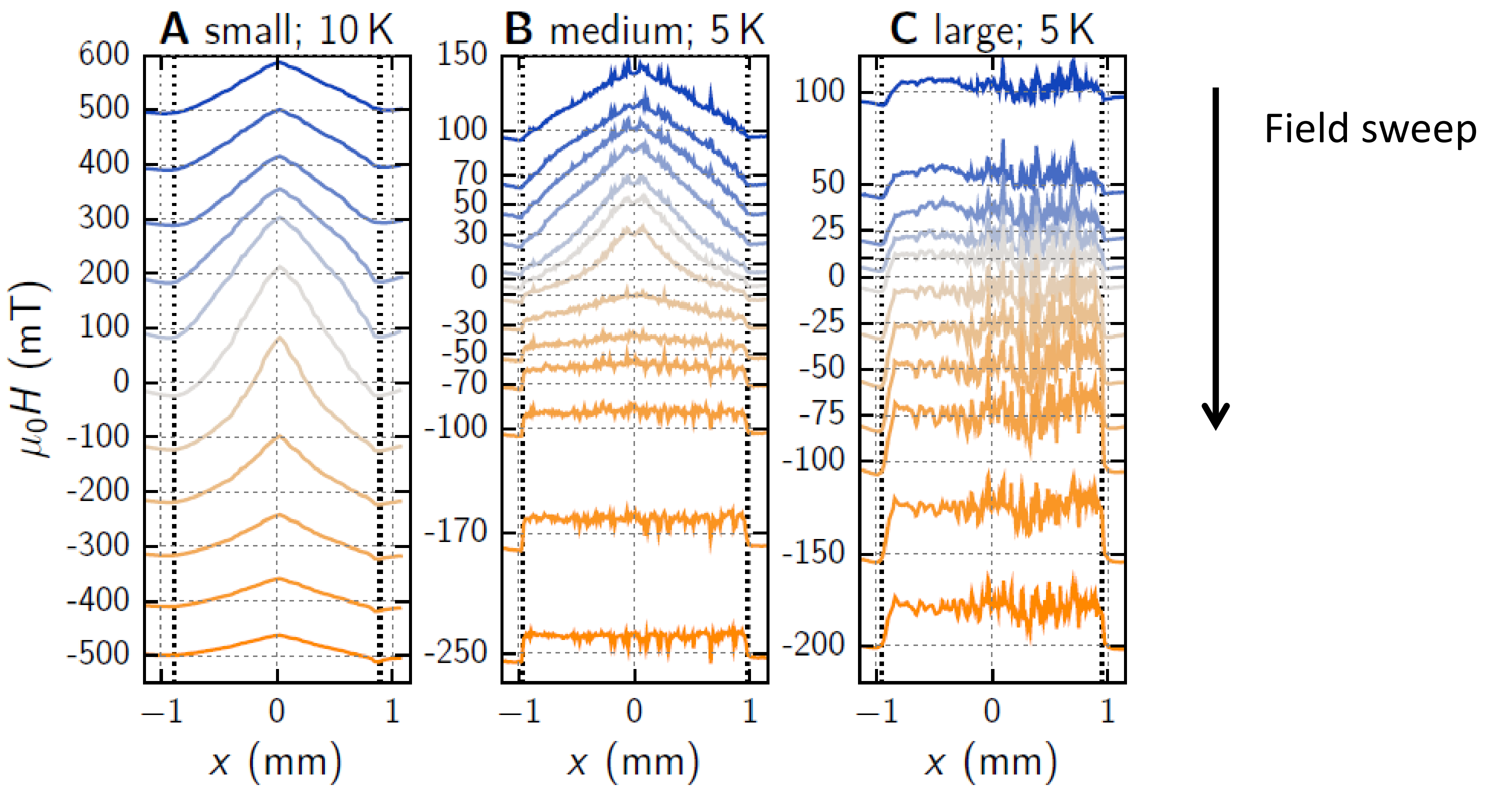



**Average** global (inter-granular) and local (intra-granular) critical current densities can be derived simultaneously.

# RESULTS

# Field profiles at different applied fields

**K-doped Ba-122**




Inter-grain currents

both

Intra-grain currents

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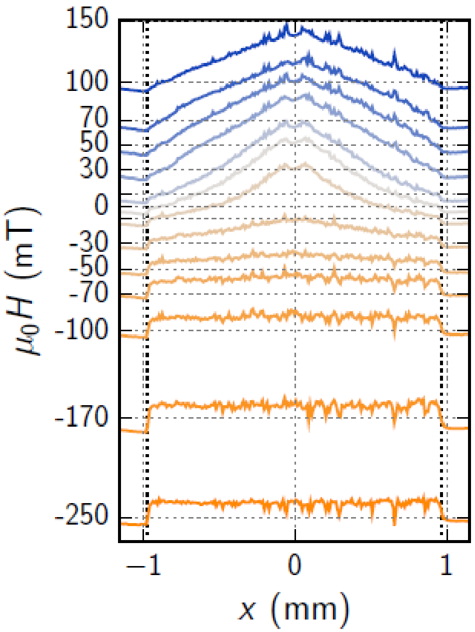
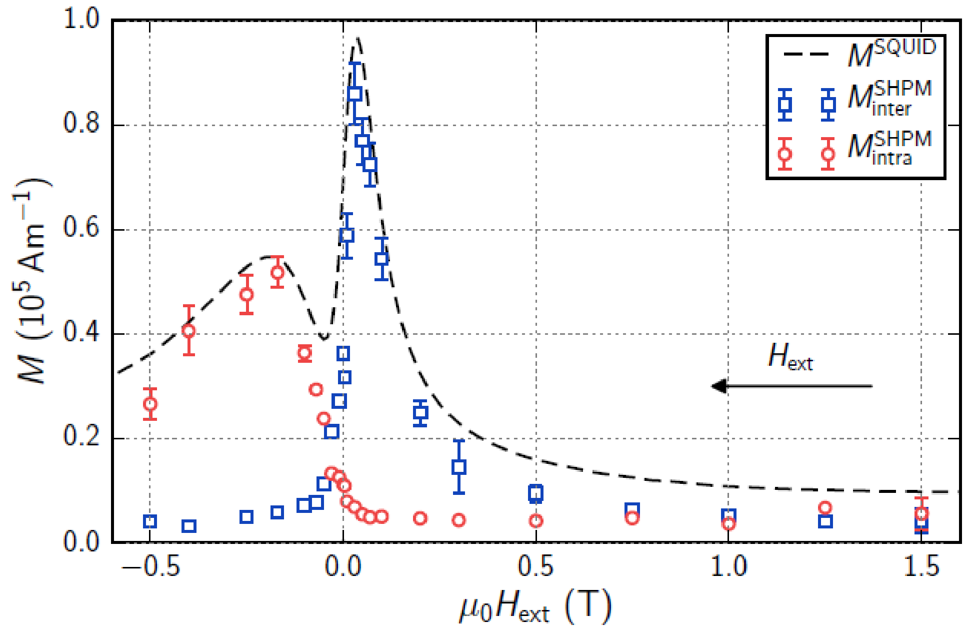
# Separation of inter- and intra-granular contributions




Field profiles




Magnetization

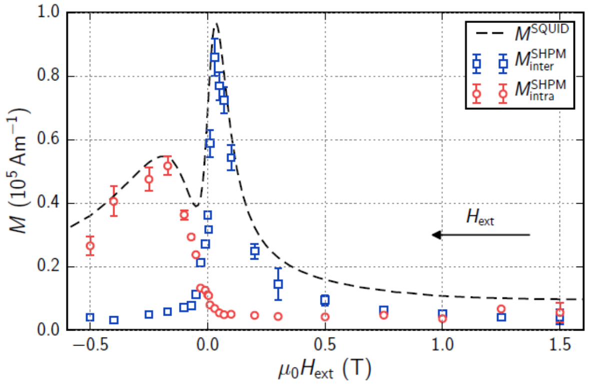
Evaluation of current densities → calculation of magnetization

**Anti-correlated behavior of inter- and intra-grain currents**

# MODEL

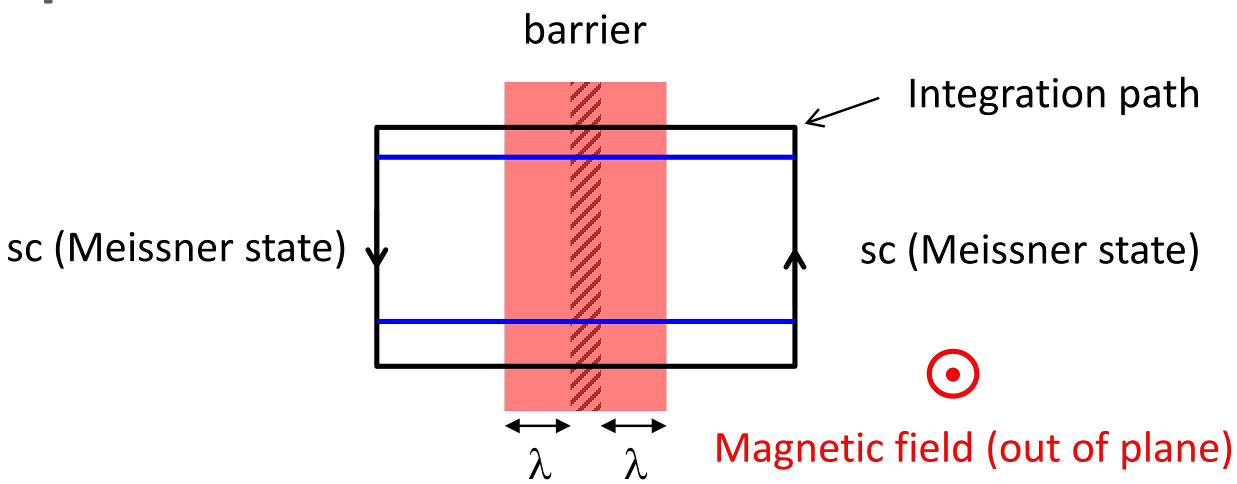
# Model assumptions

- Josephson coupled grains
  - Only weak links (density of low angle grain boundaries (strong links) below the percolation threshold)
- Averaging over the grain size distribution
  - Average Josephson current density depends on the junction width
- Reversible and irreversible currents add within the grains
  - Reversible currents: equilibrium magnetization
  - Irreversible currents: flux pinning
  - They add/subtract on the in-/decreasing field branch




corresponding magnetization

# Josephson Junctions



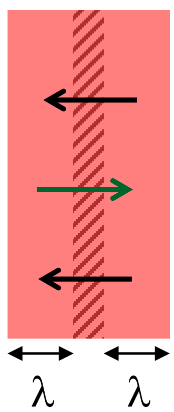

$$\nabla\varphi = \frac{2m_e}{\hbar e n_e} J_s + \frac{2e}{\hbar} A$$

**Path integral:** $\Delta\varphi = \frac{2m_e}{\hbar e n_e} \oint J_s d\vec{r} + \frac{2e}{\hbar} \phi = 2\pi n$

Has to be fulfilled for all possible paths!

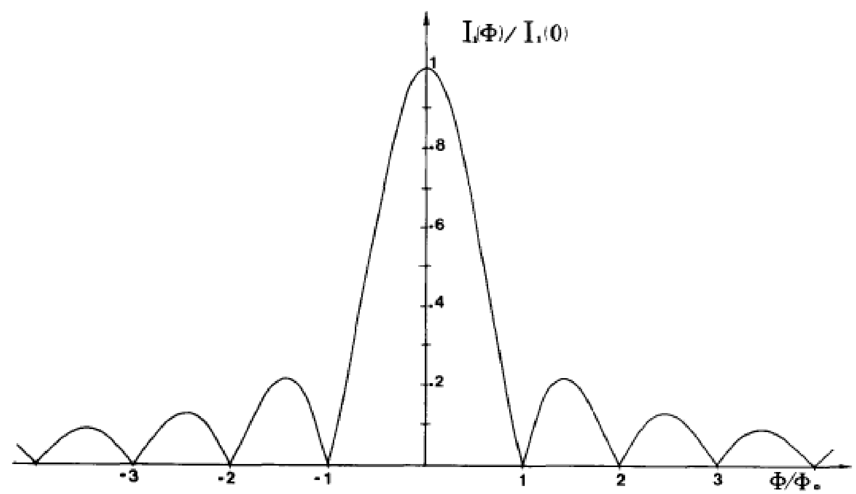
$\varphi$…phase of superconducting wave function

# Josephson Junctions

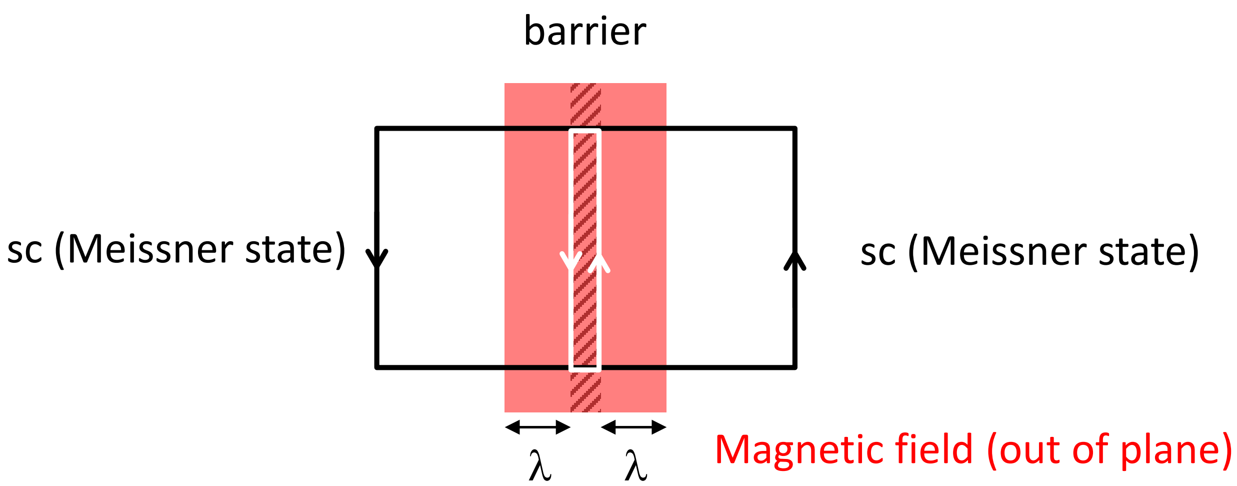



- Currents flowing in different direction (partly) compensate each other.
- Fraunhofer pattern
- $I_B \propto B^{-1}$

$$I_B \propto \left| \frac{\sin \pi \frac{\phi}{\phi_0}}{\pi \frac{\phi}{\phi_0}} \right|$$




# Alternative description: Surface currents




Path integral: $\Delta\varphi = \frac{2m_e}{\hbar e n_e}\oint J_s d\vec{r} + \frac{2e}{\hbar}\phi = 2\pi n$

Phase shift is determined by the surface currents at boundary!

**Advantage: Not restricted to Meissner state/currents**

Motivated by ideas of D´yachenko et al., e.g. Physica C 213 (1993) 167

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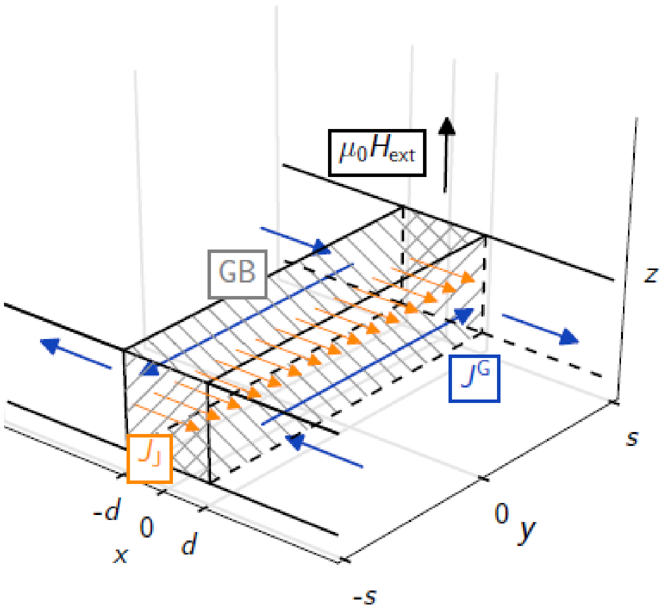
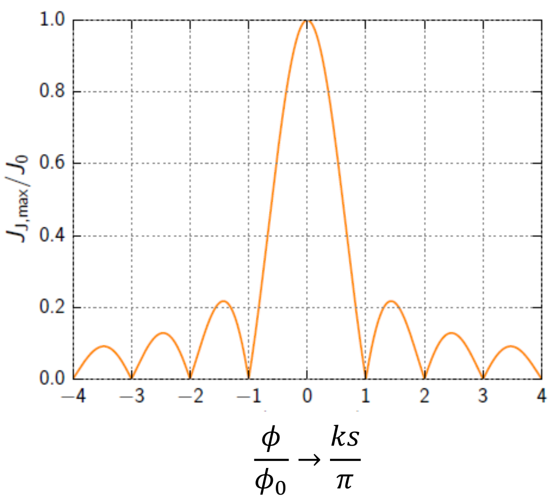
# Average current density across junction (grain boundary)

$$I \propto \left| \frac{\sin \frac{\phi}{\phi_0}}{\frac{\phi}{\phi_0}} \right| \rightarrow J(B) = J_0 \frac{\sin(k(B)s)}{k(B)s}$$

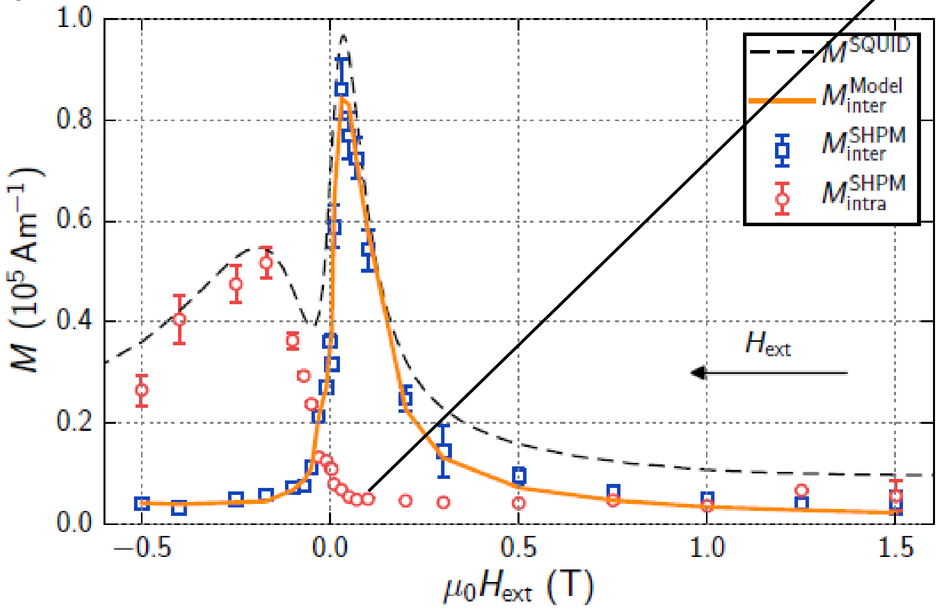
$$k(B) = \frac{4\pi\mu_0}{\phi_0}\left(\lambda^2 J^G(B) + \frac{d}{\mu_0}B\right)$$

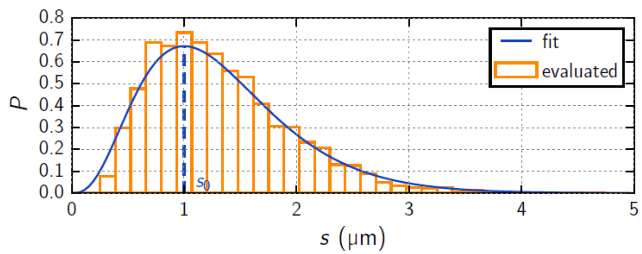


# Fit to experimental data

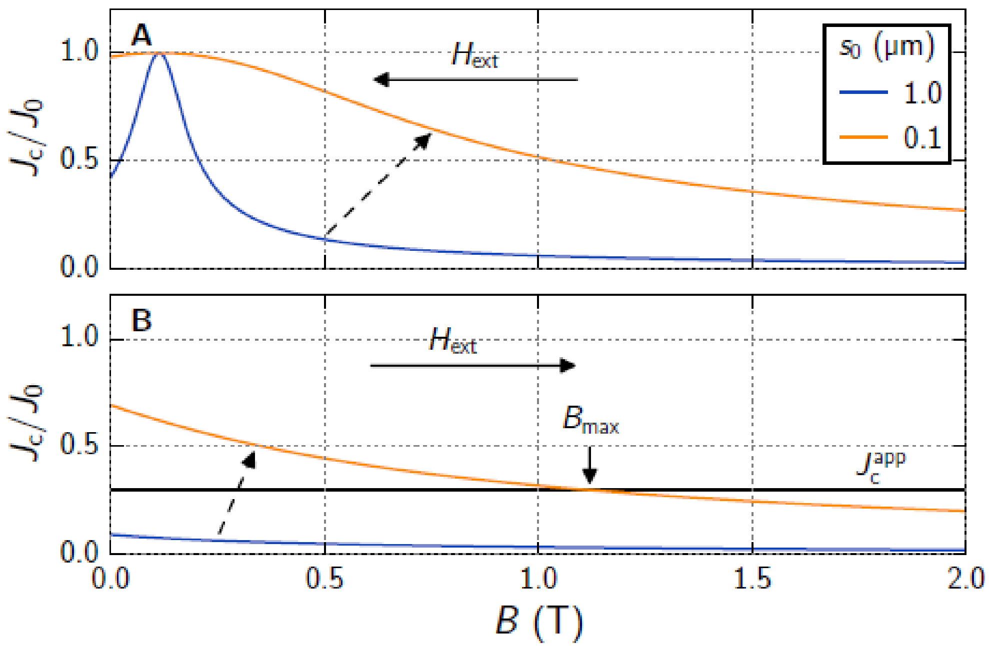
$$J_c = J_0 \int_0^\infty \frac{\sin(k(B)s)}{k(B)s} P(s, s_0) \mathrm{d}s \qquad k(B) = \frac{4\pi\mu_0}{\phi_0}\left(\lambda^2 J^G(B) + \frac{d}{\mu_0} B\right)$$

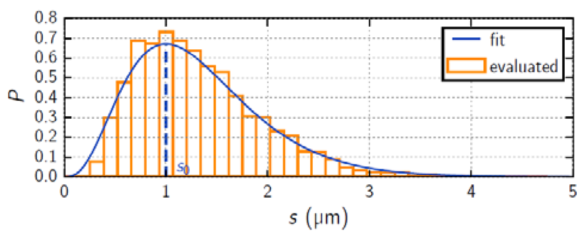



Fit parameters: $J_0 = (1.9 \pm 0.4) \times 10^4$ Acm$^{-2}$
$\lambda = 180 \pm 20$ nm
$d = 2.7 \pm 0.7$ nm

# Small grains favor high in-field currents




$$J_c = J_0 \int_0^\infty \frac{\sin(k(B)s)}{k(B)s} P(s, s_0) \mathrm{d}s$$

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# Conclusions

- Grain boundary physics dominates the critical currents in untextured polycrystalline Ba-122.
- A grain refinement reduces the field dependence of $J_c$.
  - $J_c$ of the order of 0.1 MA/cm$^2$ @ 4.2K 10 T seems possible for nanosized grains (20 nm).
- Intra-granular currents reduce the macroscopic currents.
  - Pinning should **not** be very strong.
  - Magnetic history effects on the critical currents
  - Asymmetric hysteresis loops