How to determine the magnetic penetration depth in a superconducting film?

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Université de Liège

LABORATORY OF PHYSICS OF NANOSTRUCTURED MATERIALS

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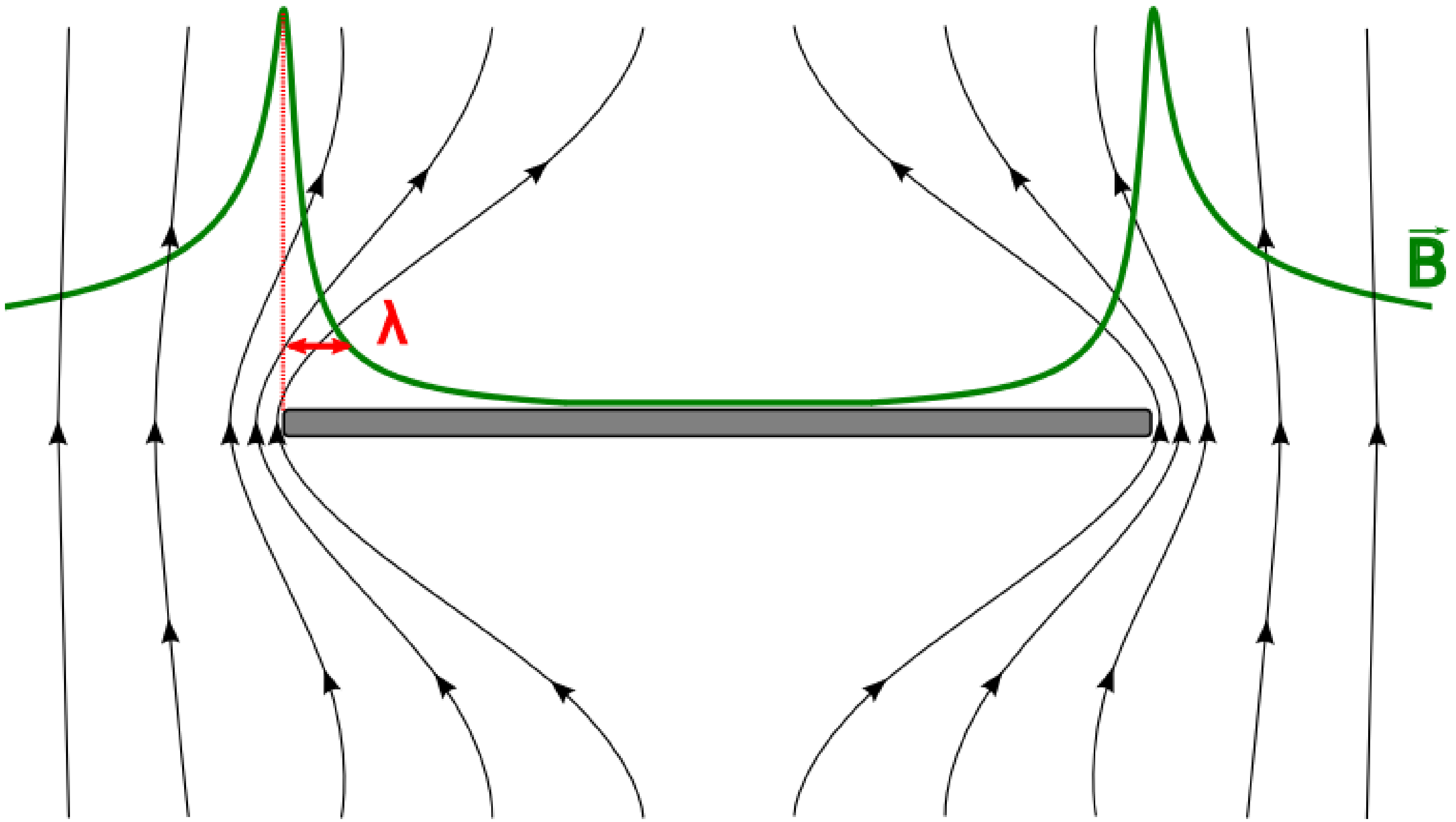
Why determine the magnetic penetration depth?

Characteristic distance for the field decay: λ



Lower critical field H_{c1}

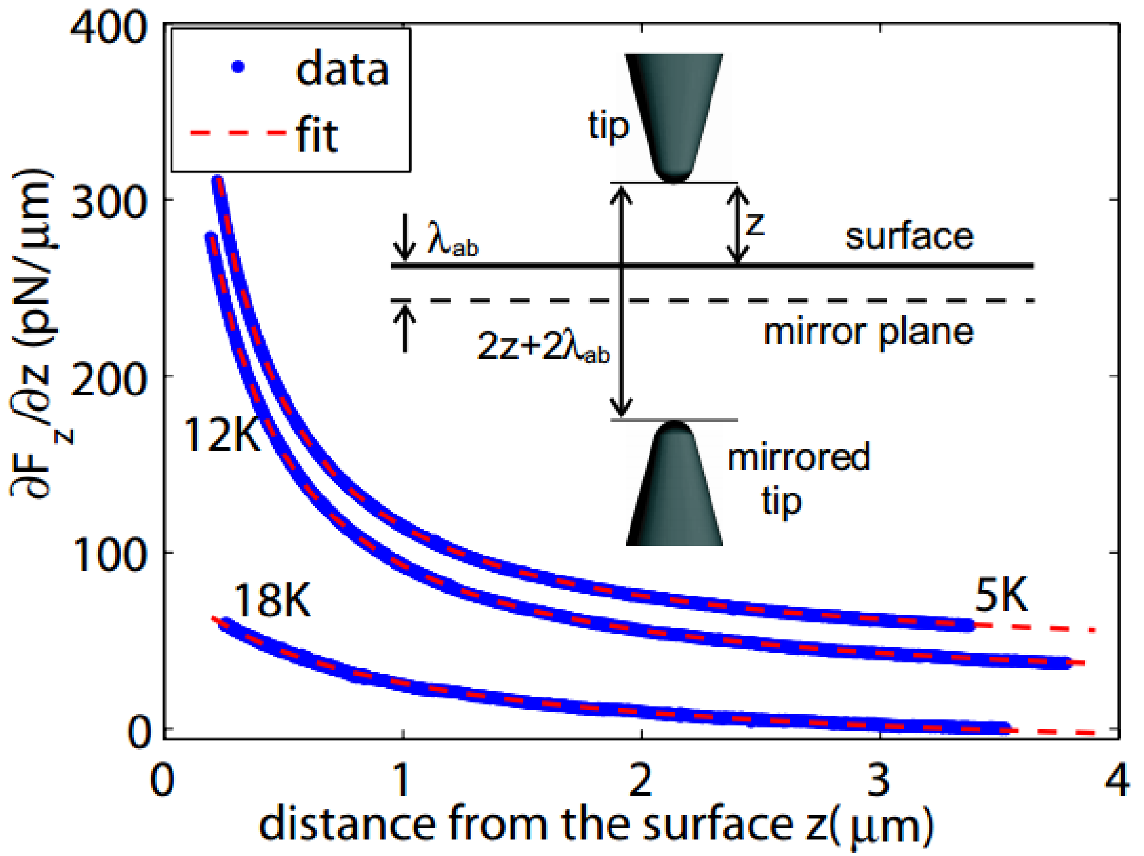
Critical depairing current J_c

Experimental techniques

Techniques grouped in two categories:

- Macroscopic response
- Local probing

Example: Meissner response

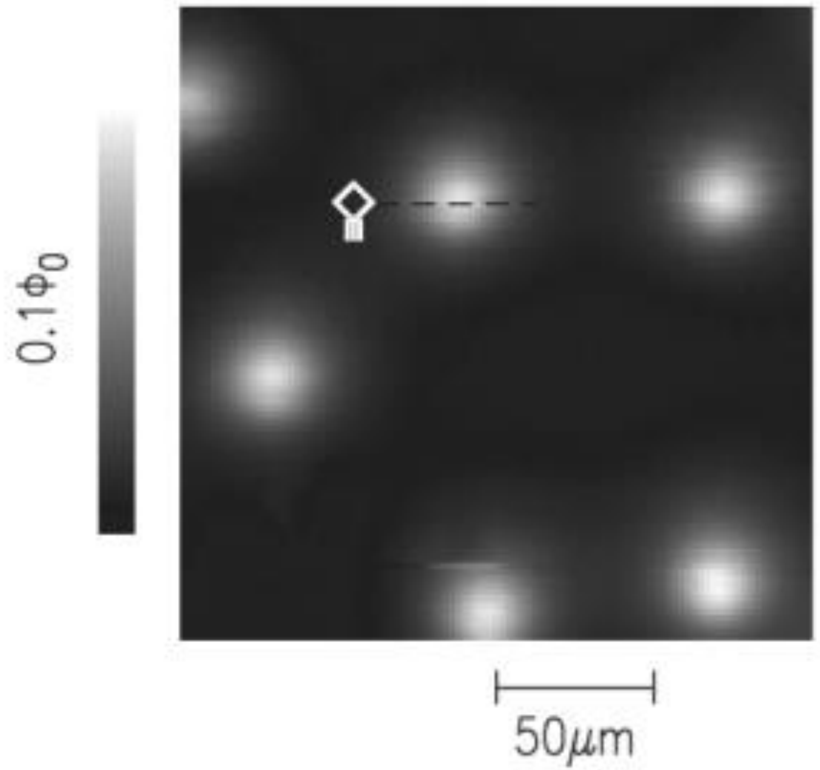


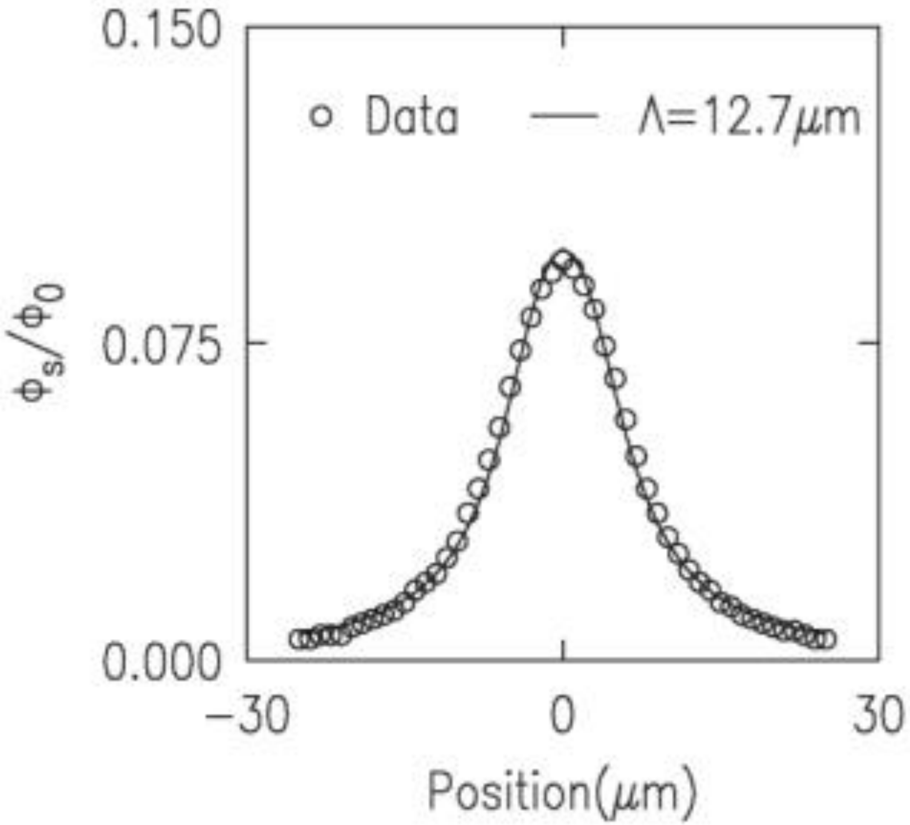
L. Luan *et al.*, Phys. Rev. B **81**, 100501 (2010)

J. Kim *et al.*, Phys. Rev. B **86**, 24501 (2012)

Experimental techniques

Example: vortex





J. R. Kirtley *et al.*, Supercond. Sci. Technol. **17**, 217 (2004)

Why a new microscopic technique to find λ?

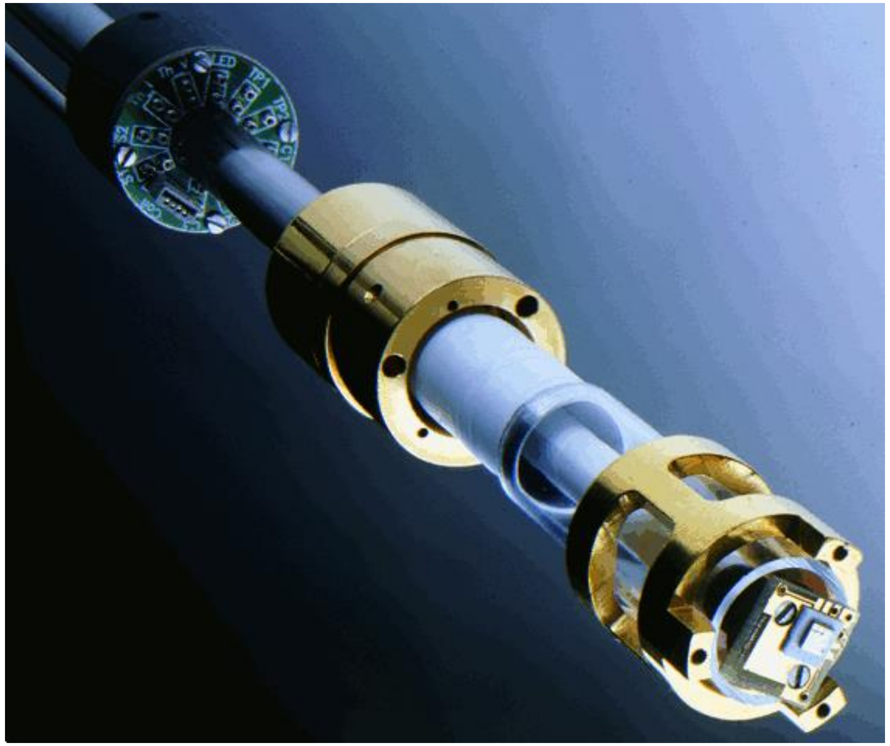
The previous models use $z + \lambda \longrightarrow$ calibration needed.

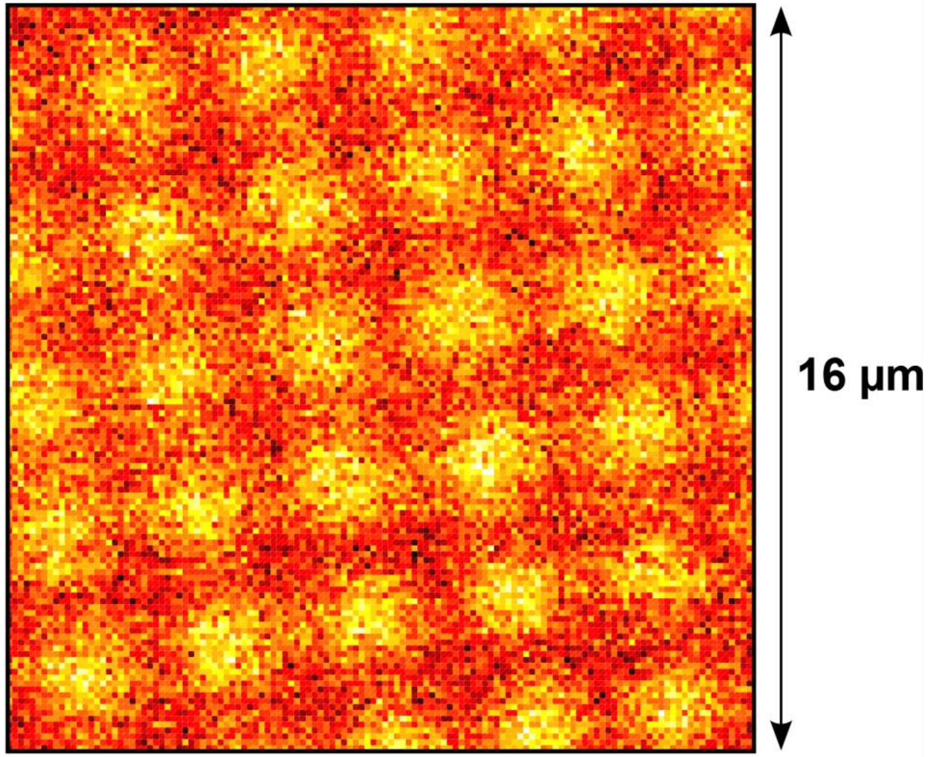
Goal: suppress the need for calibration and determine λ without knowledge of z

1. Experimental setup
2. Meissner state profile
3. Vortex profile

Scanning Hall probe microscopy

- Based on the Hall effect: measure $V_H \propto B_\perp$
- Non invasive, no contact with the surface



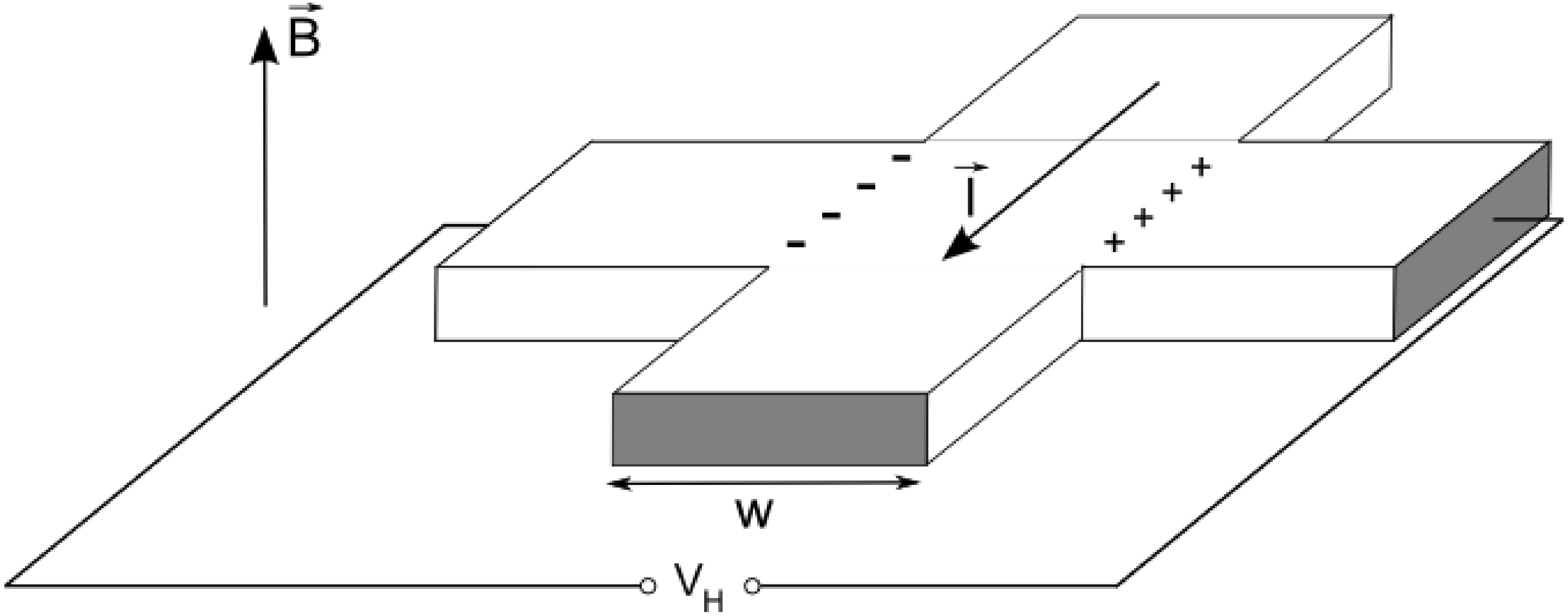


Performed at KU Leuven

2D images of $B_\perp$ close to the sample surface

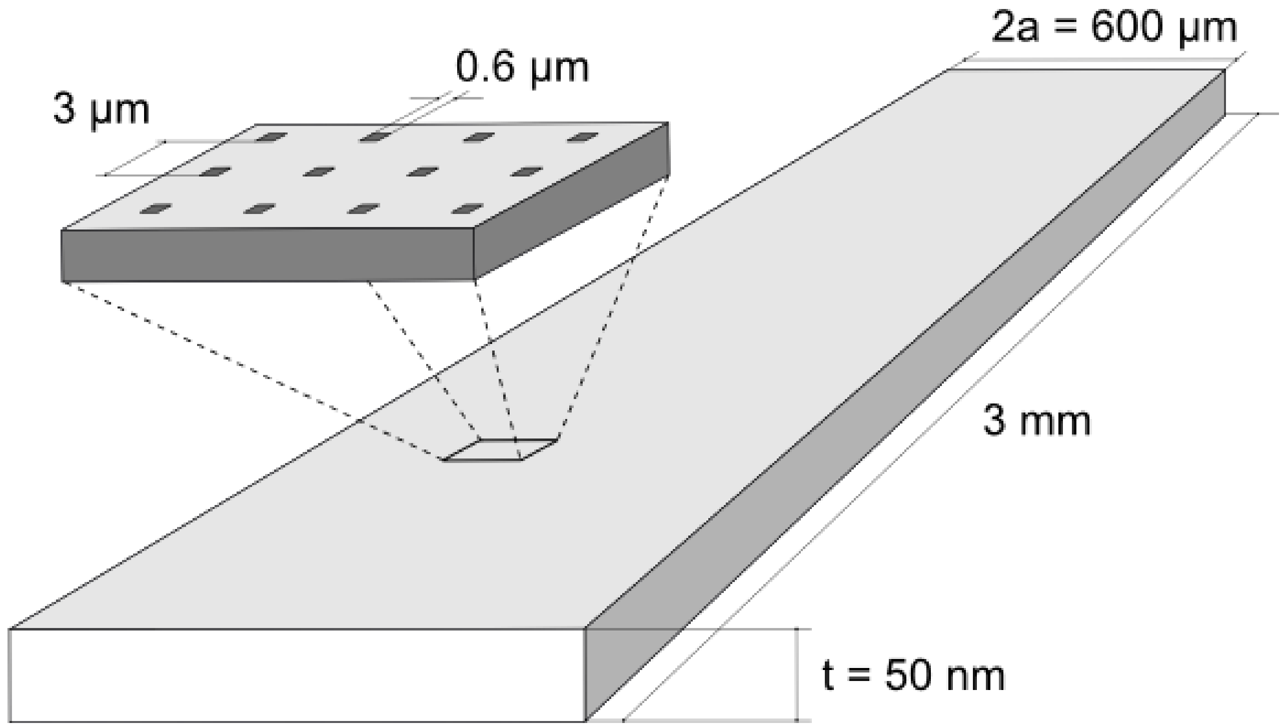
Hall probe design

Hall probe with active area $\sim 2w^2$



Sample: nanostructured Pb film

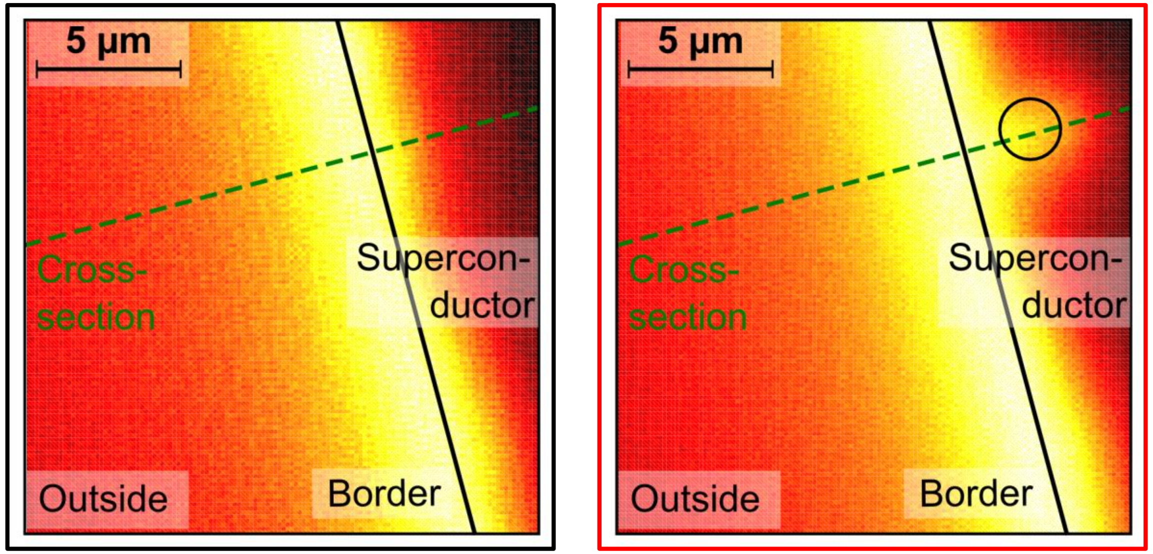
- Film: good knowledge of the geometry
- Pb: transition temperature $T_c = 7.2$ K

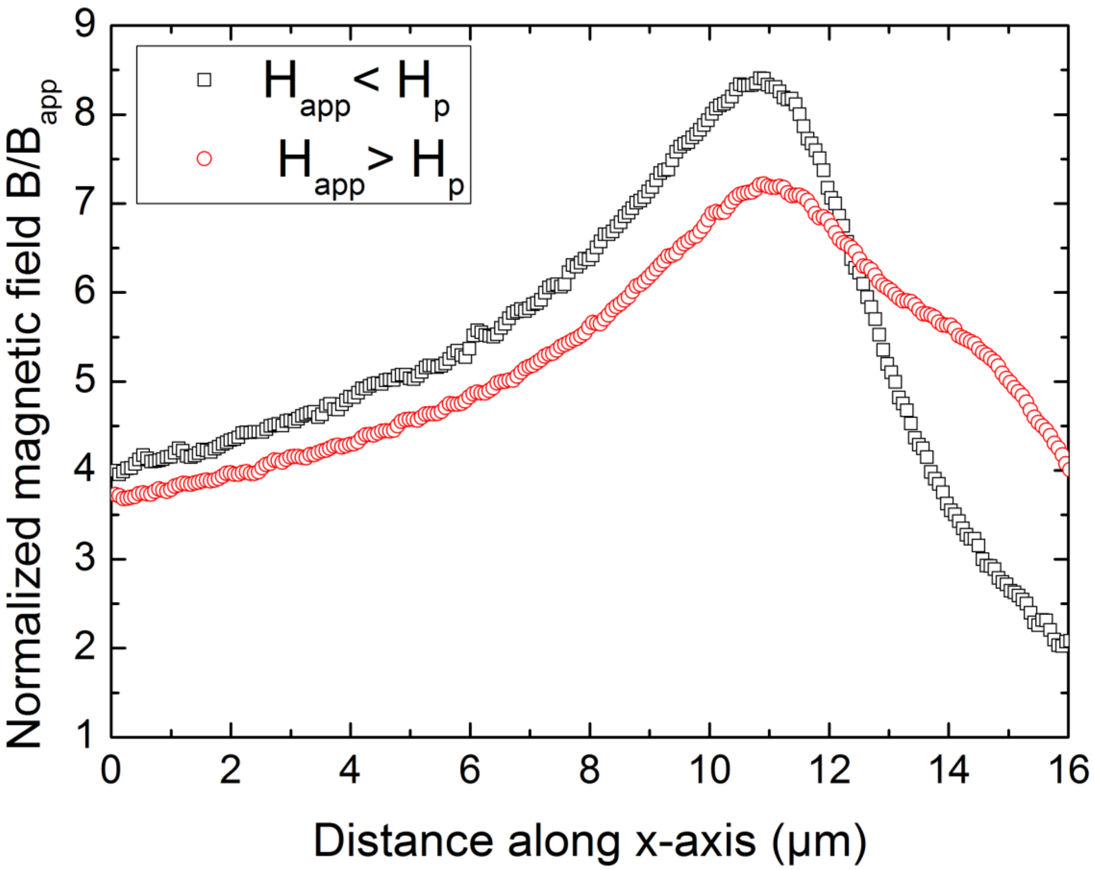


- Holes: detect first vortex entry

Field profile at the border

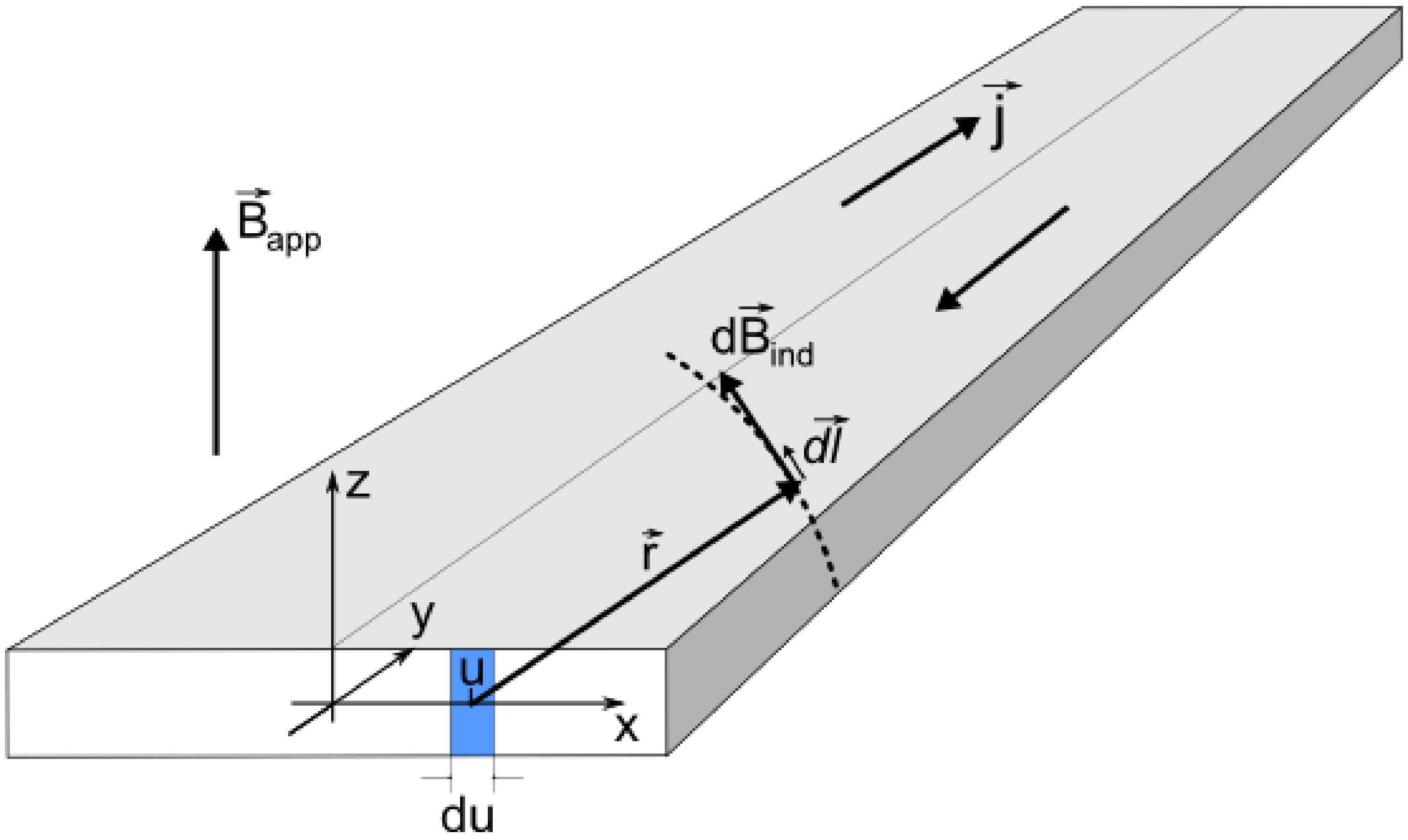
Zero field cooling to 4.2 K in $H_{\text{app}} < H_p$ ⟶ Meissner state.





Contributions to the measured magnetic field

- Applied field B_{app}
- Field B_{ind} induced by the screening currents $j(u)$



Expression of the magnetic field

- Thin rectangular strip:

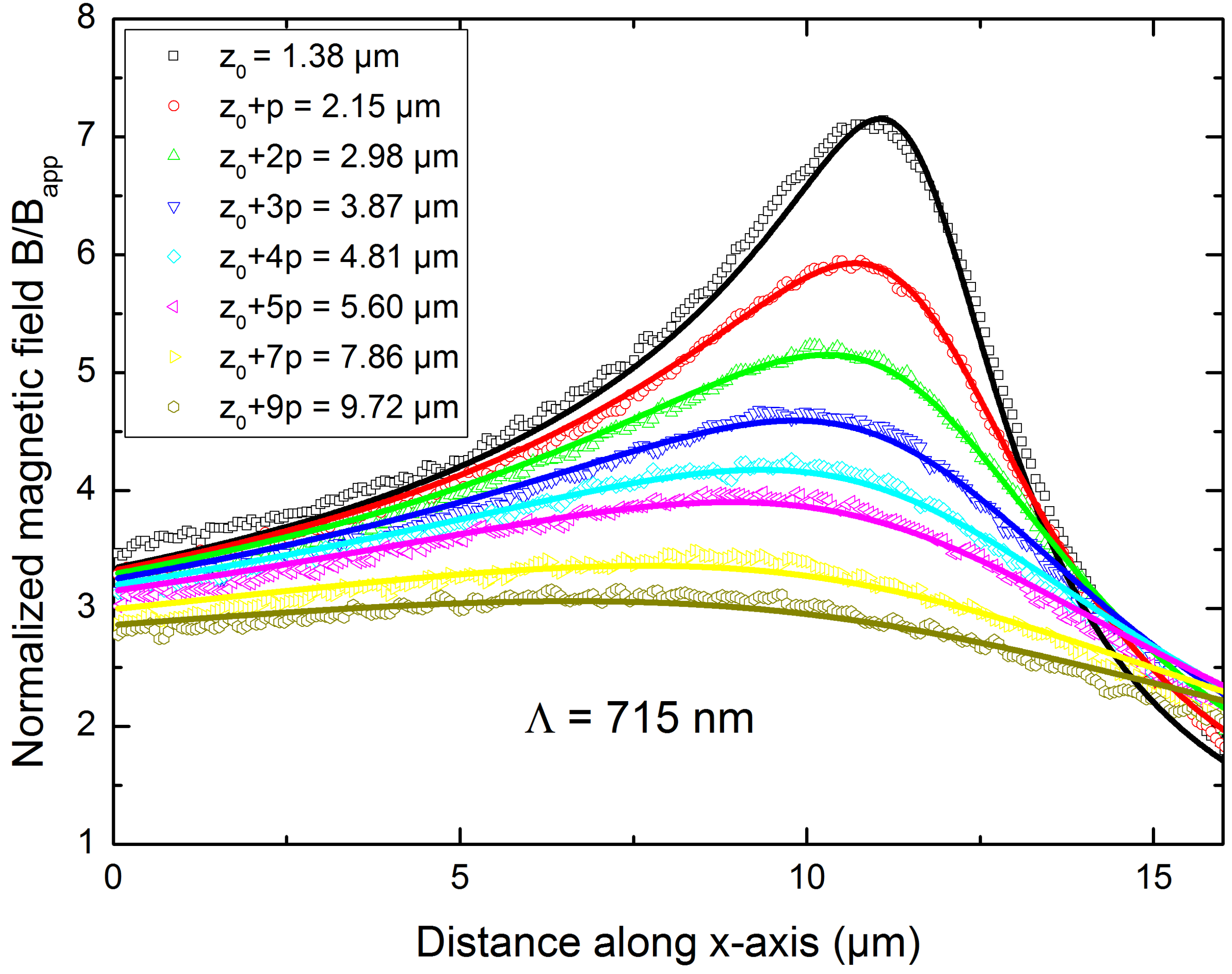
$$j(u) = \frac{2uB_{\text{app}}}{\mu_0\sqrt{(a^2 - u^2) + \frac{4a}{\pi}\Lambda}}$$

B. L. T. Plourde *et al.*, Phys. Rev. B **64**, 14503 (2001)

- Measured field (normalised):

$$\frac{B_z(x,z)}{B_{\text{app}}} = 1 + \frac{1}{\pi}\int_{-a}^{a} \frac{(x-u)udu}{((x-u)^2 + z^2)\sqrt{(a^2 - u^2) + \frac{4a}{\pi}\Lambda}}$$

Determination of the penetration depth λ



London penetration depth

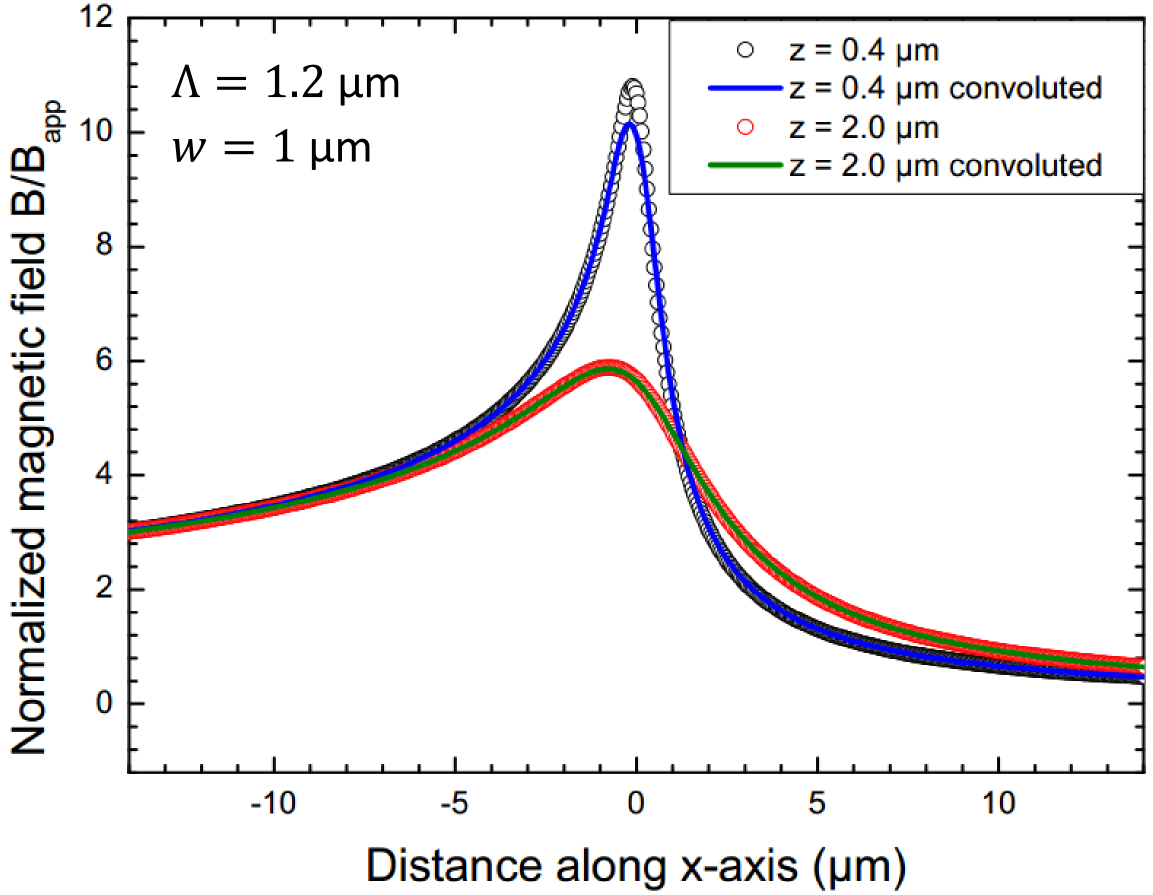
$$\lambda_{GL} = \underbrace{\left(0.64\sqrt{\frac{\xi_0}{l}}\right)^{-1}}_{\text{dirty limit}} \underbrace{\sqrt{1-\frac{4.2}{T_C}}}_{\text{temperature}} \underbrace{\sqrt{\Lambda \times t}}_{\text{thin film}} \simeq 89 \text{ nm}$$

- Applied field close to H_{c1}: screening less effective

  J. Gutierrez *et al.*, Phys. Rev. B **88**, 184504 (2013)

$$\lambda_L = \frac{\lambda_{GL}}{1.84} \simeq 48 \pm 11 \text{ nm}$$

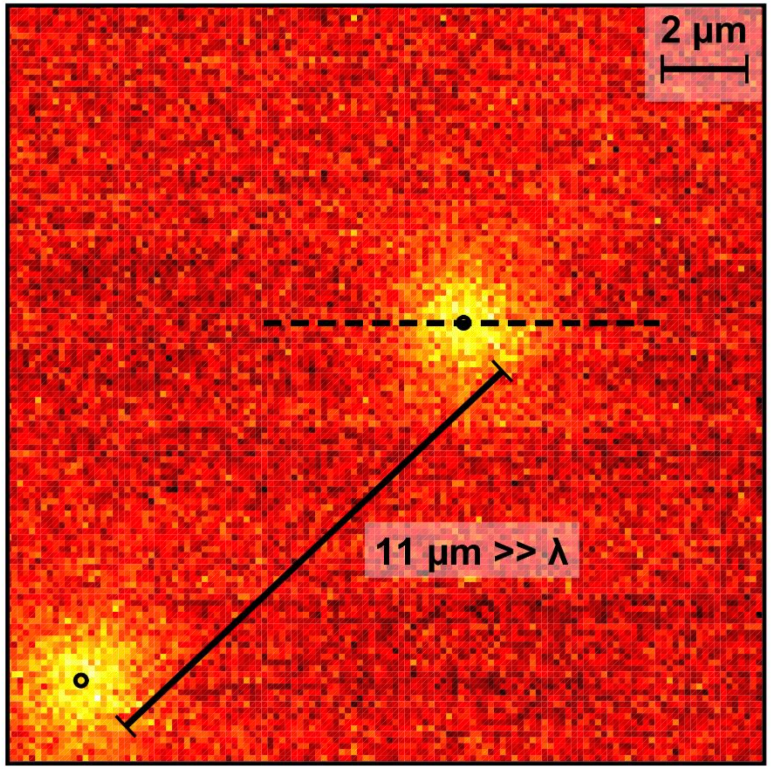
Negligible influence of the finite probe size

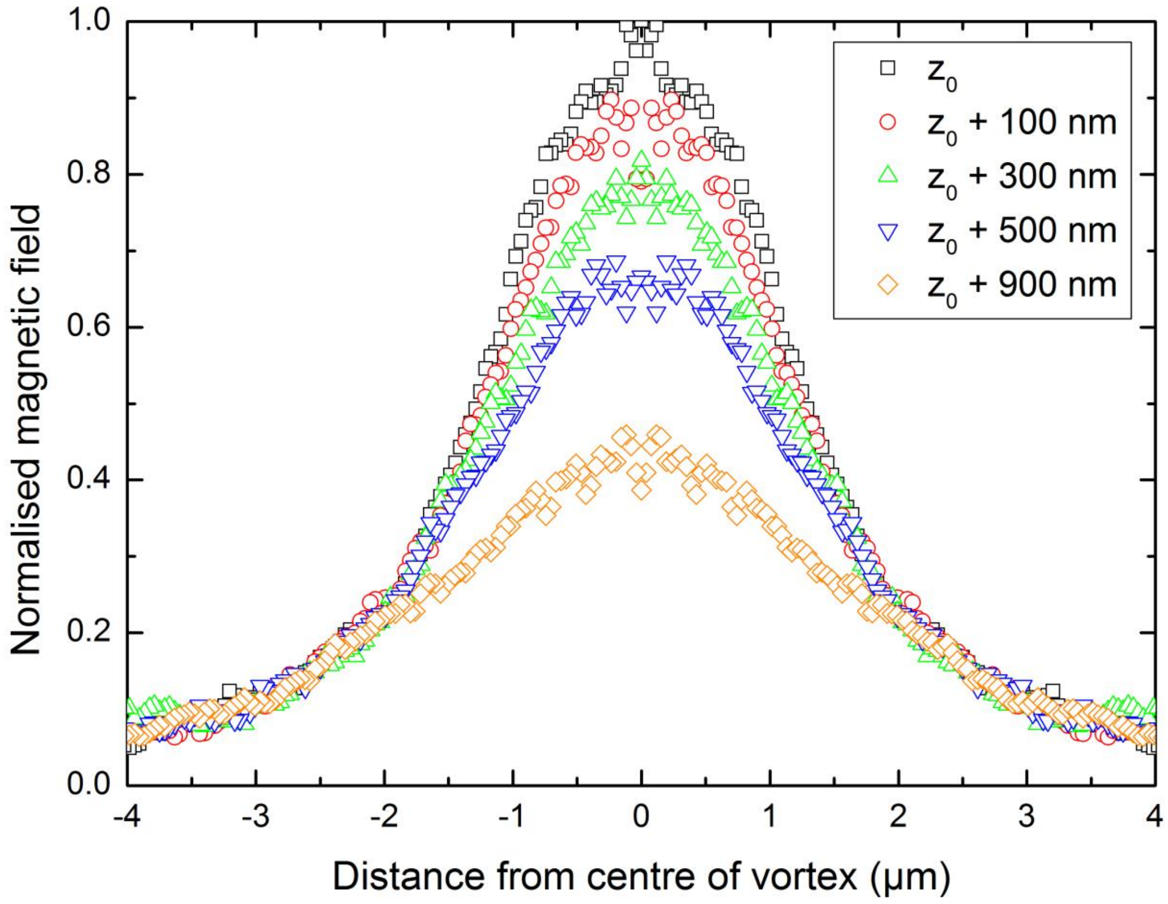


Negligible convolution effects for our scanning heights.

Field profile of an isolated vortex

Field cooling in $H_{\text{app}} \ll H_1$ (first matching field) ⟶ isolated vortex





Magnetic monopole model

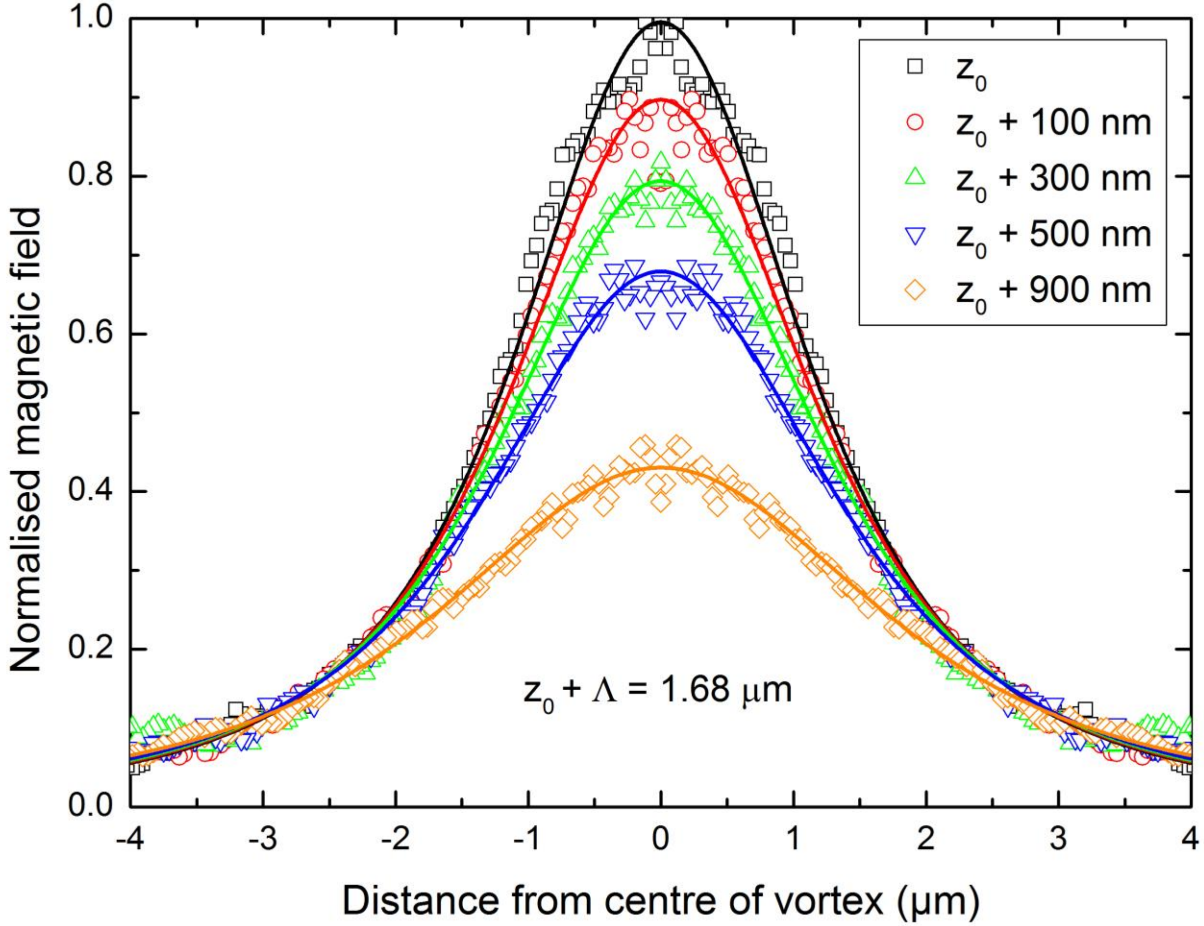
A vortex can be approximated by a magnetic monopole of charge $2\Phi_0$ located at a distance λ_{eff} below the surface:

$$B_z(\vec{r}) = \frac{\Phi_0}{2\pi} \frac{z + \lambda_{\mathrm{eff}}}{(r^2 + (z + \lambda_{\mathrm{eff}})^2)^{3/2}}$$

A. M. Chang *et al.*, Appl. Phys. Lett. **61**, 1974 (1992)

⟶ We will get values for $\mathrm{z} + \lambda_{\mathrm{eff}}$

Determination of the scanning height



By using $\lambda_{\text{eff}} = \Lambda$, we get $z_0 \approx 1\ \mu\text{m}$

Conclusions

- SHPM is used to map the magnetic field over a Pb film
- Meissner state at the border: theoretical model to determine
  - the magnetic penetration depth $\Lambda \longrightarrow \lambda_{\mathrm{L}} = 48$ nm (Pb)
  - the scanning height $z_0 \approx 1$ µm
- No significant corrections due to the Hall probe size
- Isolated vortex: the magnetic monopole model allows to extract the effective scanning height

For more information:

J. Brisbois *et al.*, J. Appl. Phys. **115**, 103906 (2014)