A. I. LARKIN MEMORIAL CONFERENCE

June 24-28, 2007, Chernogolovka, Russia

Thank you for the invitation!

Vortices in high-temperature superconductors

G. Blatter

*Theoretische Physik, Eidgenössische Technische Hochschule Zürich-Hönggerberg, CH-8093 Zürich, Switzerland**
and Asea Brown Boveri, Corporate Research, CH-5405 Baden, Switzerland

M. V. Feigel'man

L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia
and The Weizmann Institute of Science, Rehovot 76100, Israel

V. B. Geshkenbein

Theoretische Physik, Eidgenössische Technische Hochschule Zürich-Hönggerberg, CH-8093 Zürich, Switzerland;
L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia;
and The Weizmann Institute of Science, Rehovot 76100, Israel

A. I. Larkin

L. D. Landau Institute for Theoretical Physics, 117940 Moscow, Russia
and The Weizmann Institute of Science, Rehovot 76100, Israel

V. M. Vinokur

Argonne National Laboratory, Argonne, Illinois 60439

Folgefonna Glacier , Norway

Thermo-magnetic instability of vortex matter in type II superconductors: Visualization by magneto-optical imaging

<u>Yuri Galperin</u>

Tom Henning Johansen

Superconductivity Group

University of Oslo, Norway

<u>Team:</u>

D. V. Shantsev

D. V. Denisov

A. L. Rakhmanov

J. I. Vestgården

V. Yurchenko

P. E. Goa

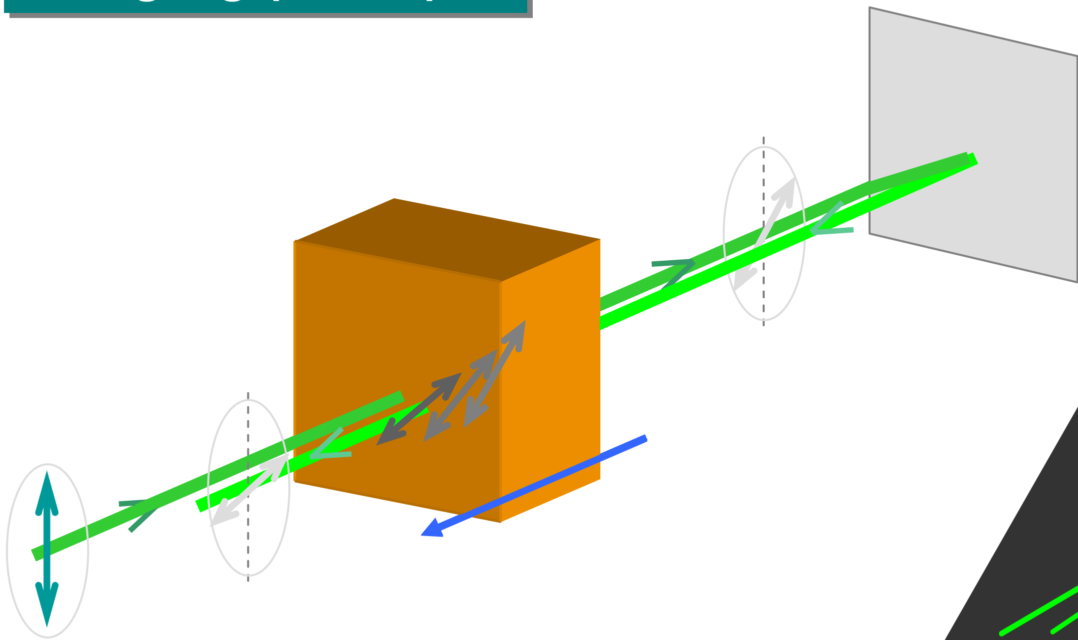
Å. A. F. Olsen

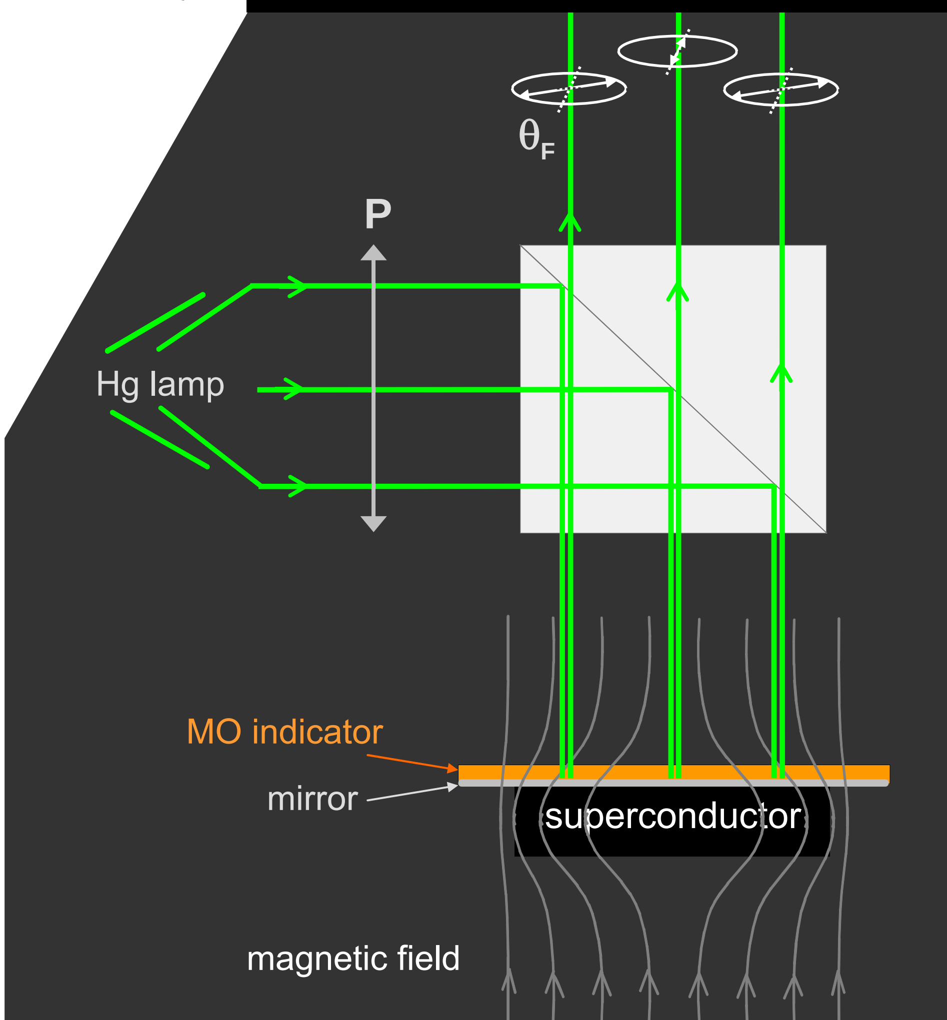
A. V. Bobyl

Outline

- Magneto-optical imaging
- Dendritic flux penetration – fingering instability
    - Experiment
    - Theory
    - Anisotropic critical current
    - Flux penetration in rings: A way to estimate local temperature
- Observation of individual vortices
    - Custom microscope
    - Vortex dynamics
- Interaction between magnetic domains in the indicator film and vortices
- Open questions and problems
- Conclusion

Imaging principle



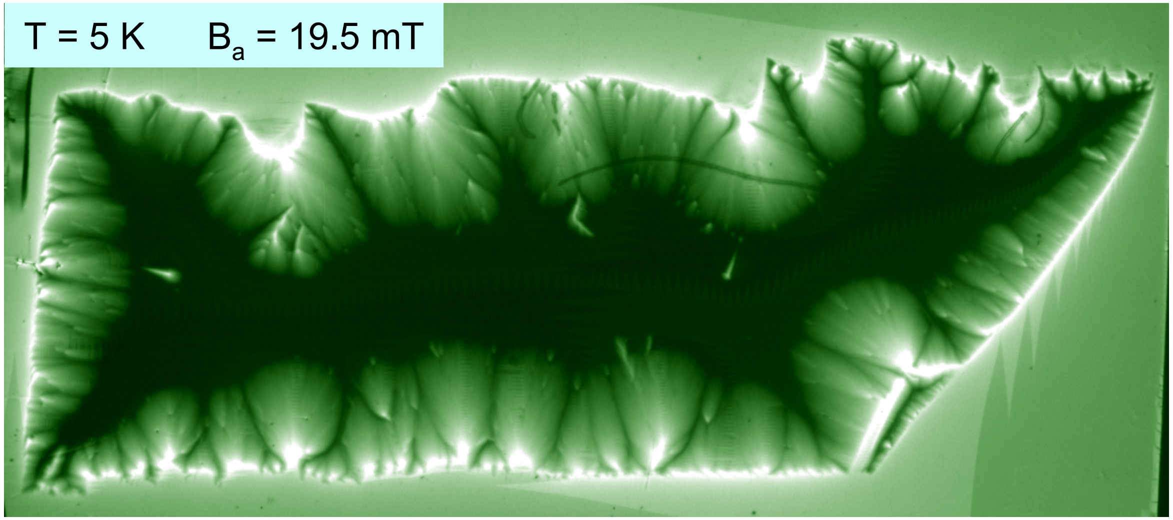


<u>Great help from ISP, Chernogolovka</u>

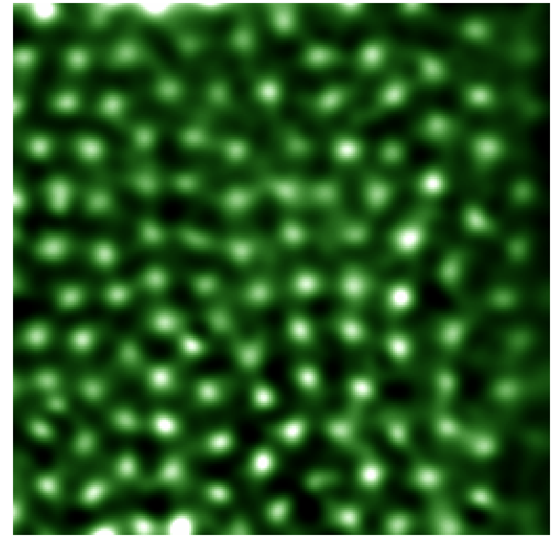
A. Polyanskii

L. Uspenskaya

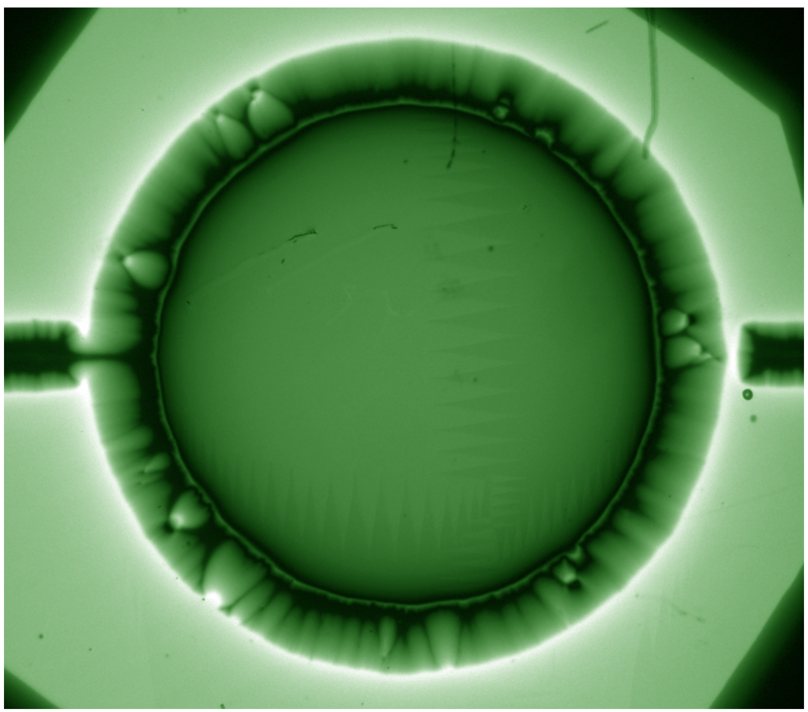
L. Vinnikov

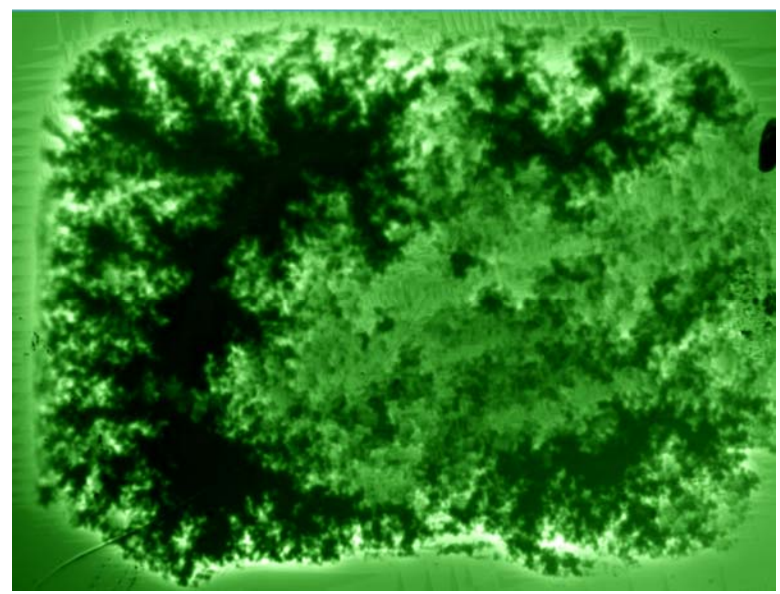


YBCO films



Vortex glass in NbSe





Outline

- Magneto-optical imaging
- Dendritic flux penetration – fingering instability
  - Experiment
  - Theory
  - Anisotropic critical current
  - Flux penetration in rings: A way to estimate local temperature
- Observation of individual vortices
  - Custom microscope
  - Vortex dynamics
- Interaction between magnetic domains in the indicator film and vortices
- Open questions and problems
- Conclusion

Motivation

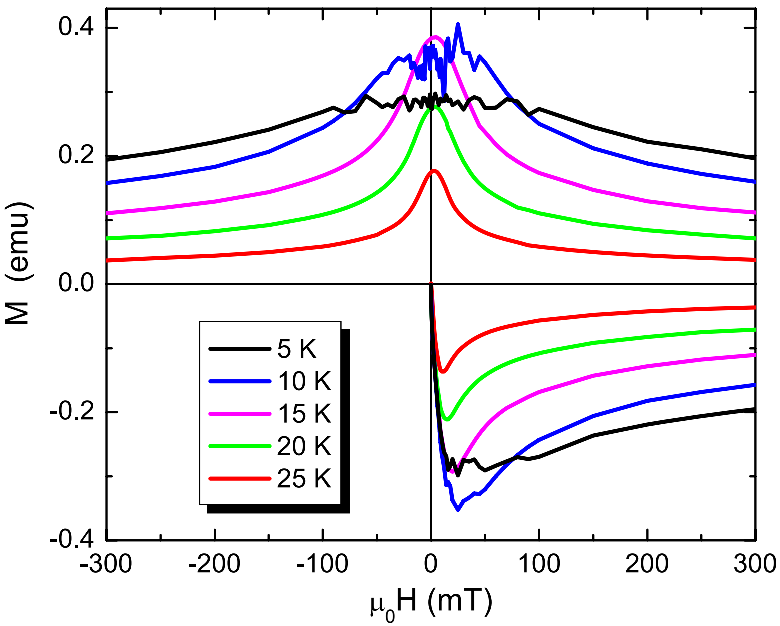
"Noisy" magnetization curves of thin films

- $\Delta M \sim$ ***0.01*** M
- ***many*** jumps
- occur at ***small*** field
- disappear at high T

There exists some effect limiting critical currents of thin films

MOI imaging showed dendritic flux penetration in the region of "noisy" magnetization curves

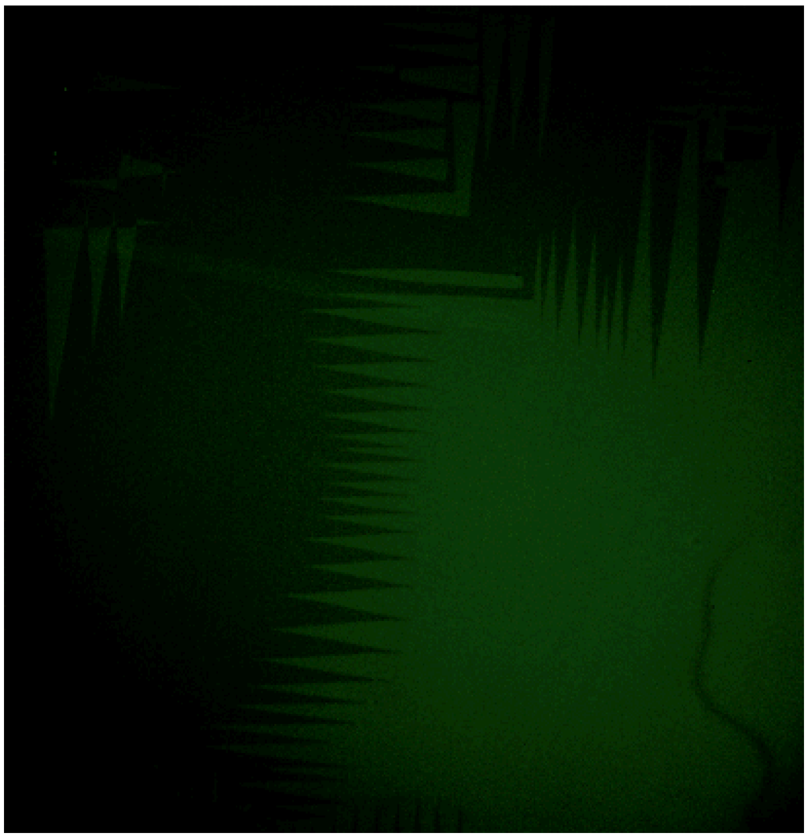
MgB_2 film



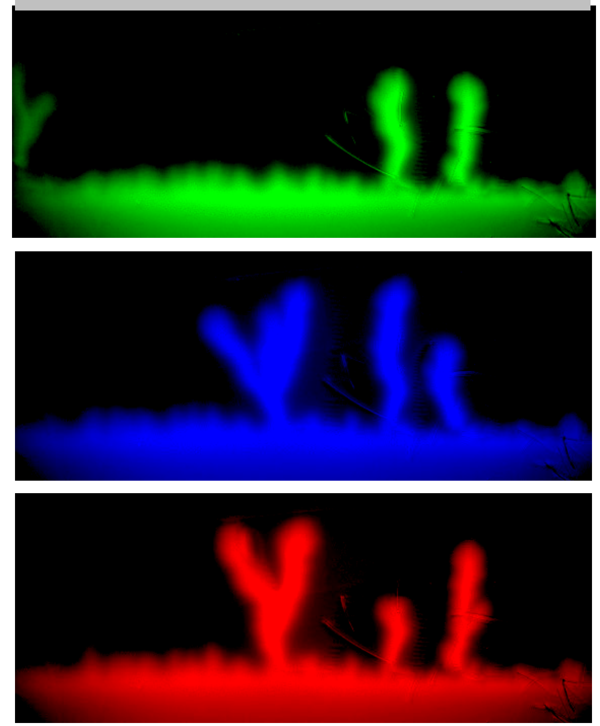
~~Sample inhomogeneities~~ OR Instability-driven

VIDEO ½-cycle

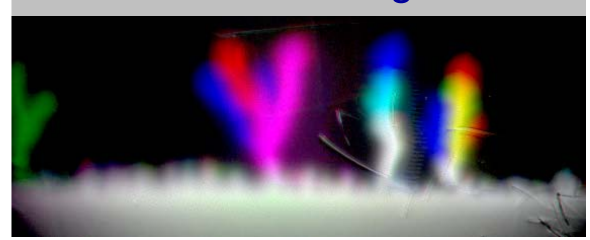
T = 3.5 K B_a^{max} = 68 mT



3 identical experiments
same part of sample



Sum of 3 images

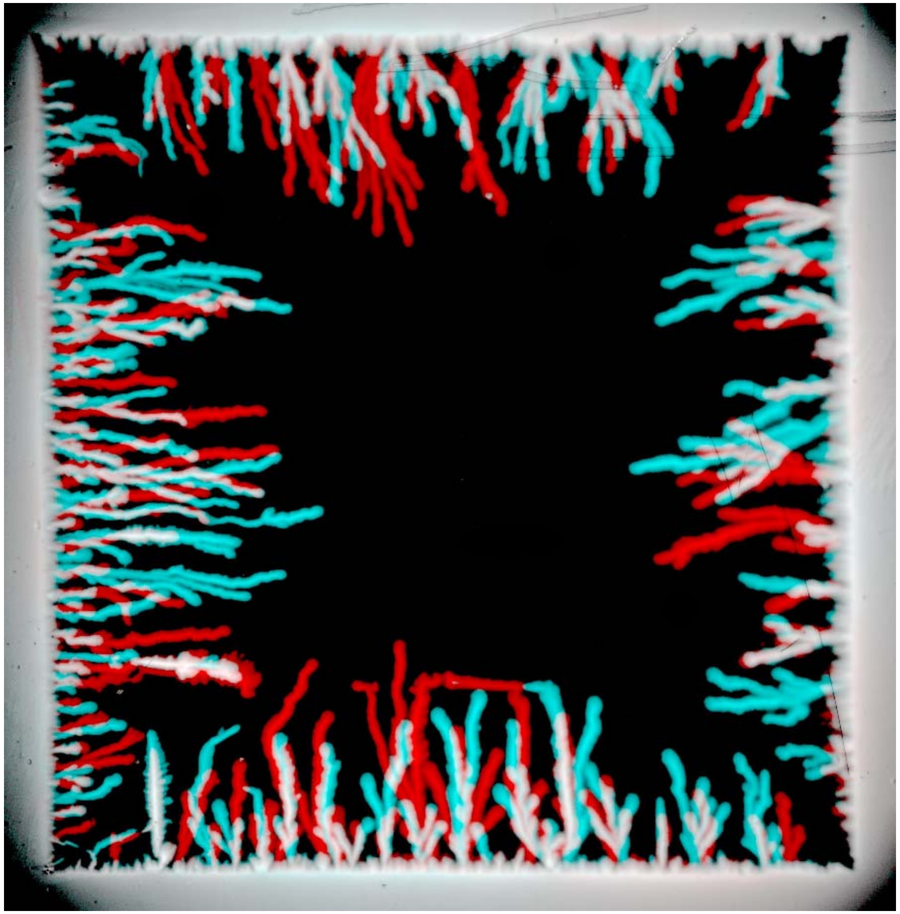


Global irreproducibility

2 repeated identical exp. runs

overlap

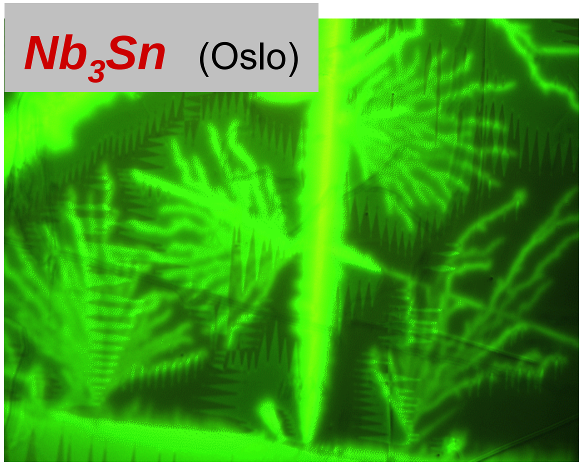
B_a = 25 mT



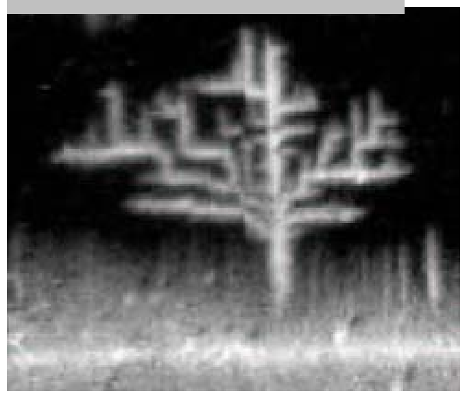
in “all” superconducting films

MgB_2 +

Nb_3Sn (Oslo)

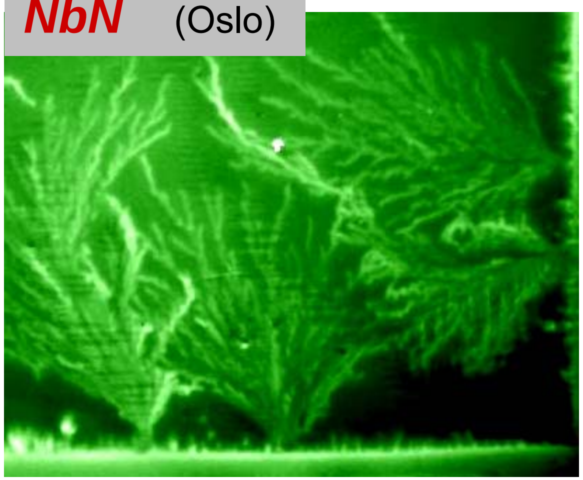


Pb (Menghini *et al.*)

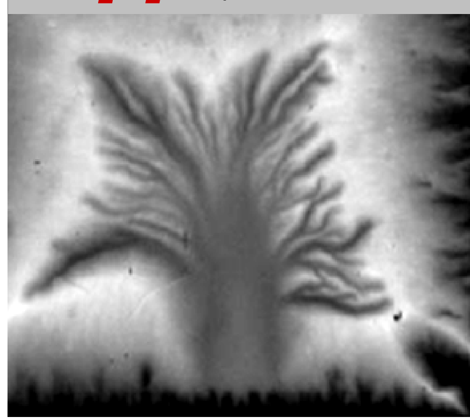


Nb (C.A. Duran *et al.*)

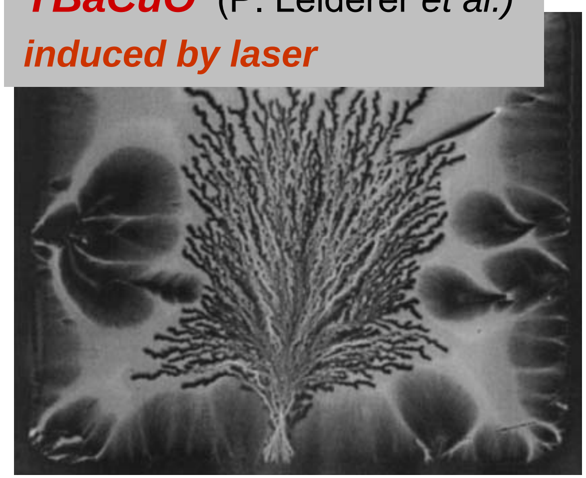
NbN (Oslo)



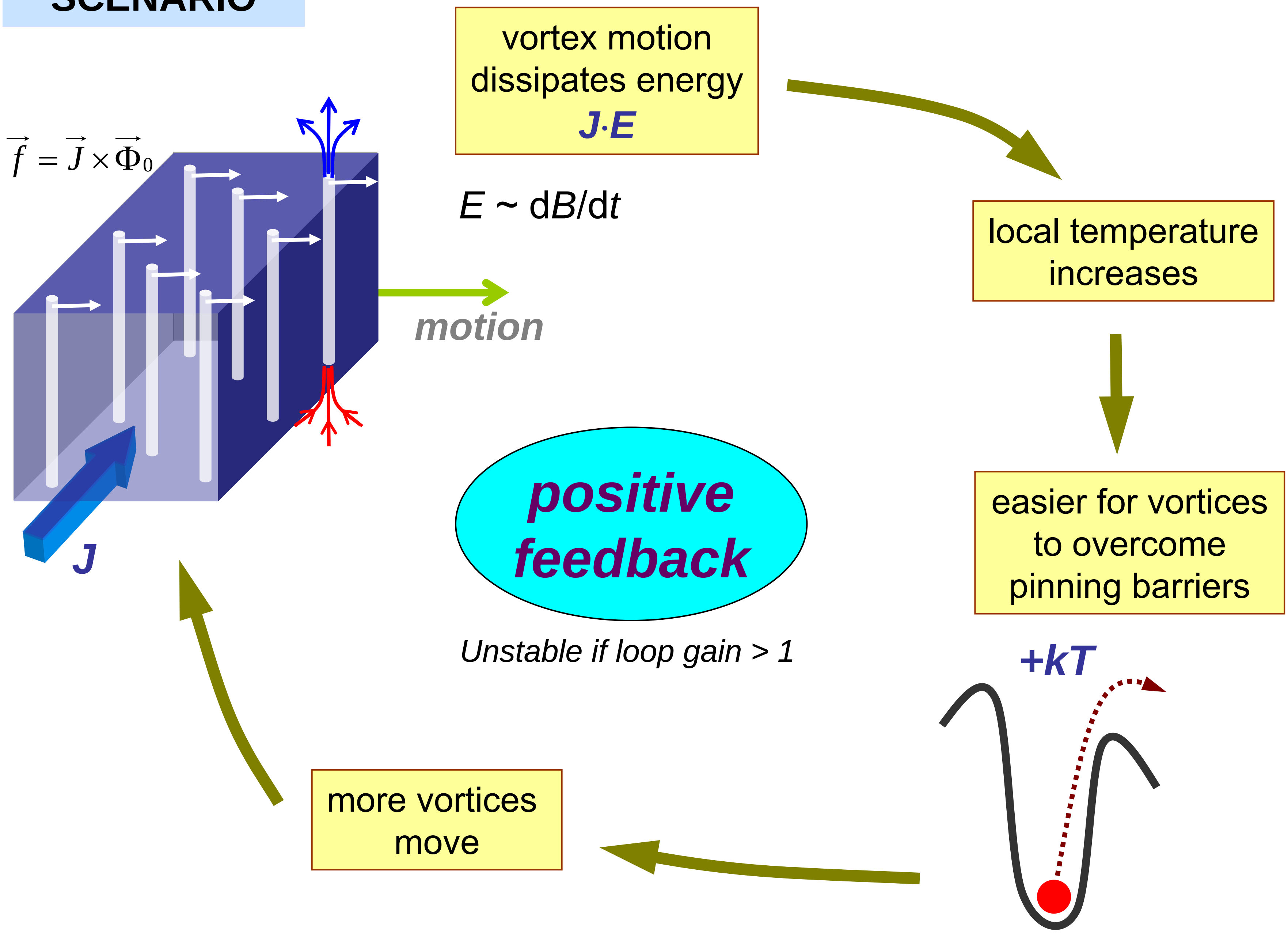
YNi_2B_2C (Wimbush *et al.*)



YBaCuO (P. Leiderer *et al.*)
induced by laser

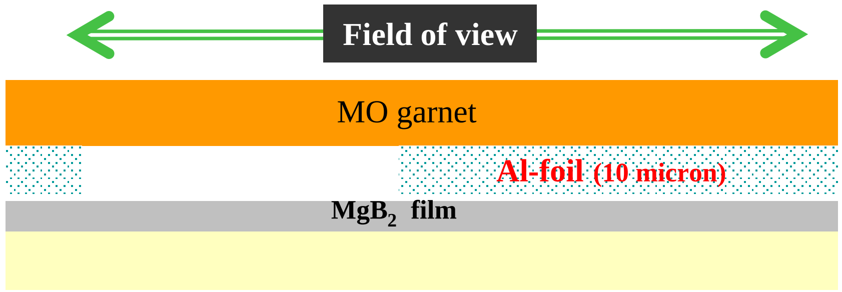


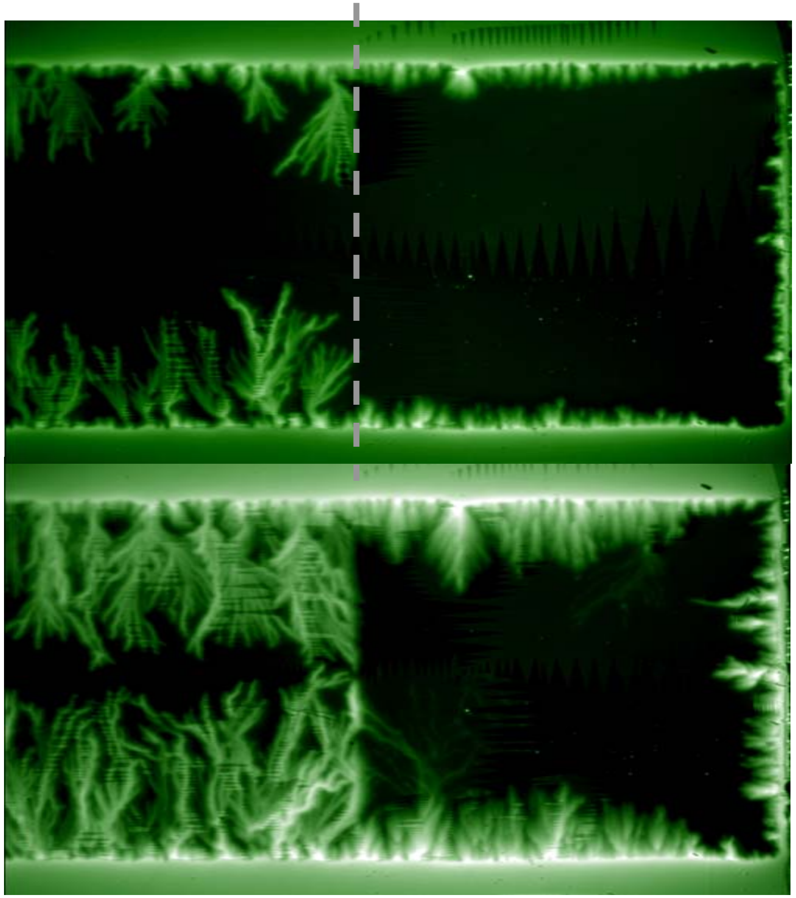
FLUX JUMP SCENARIO



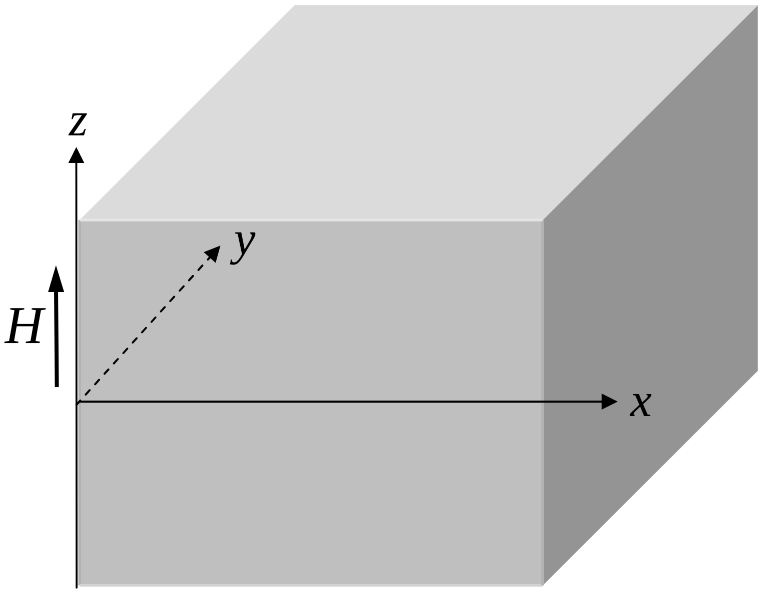
Thermo-magnetic instability: Experimental verification

Experimental verification by thermal shunting





What one would expect: Infinite slab

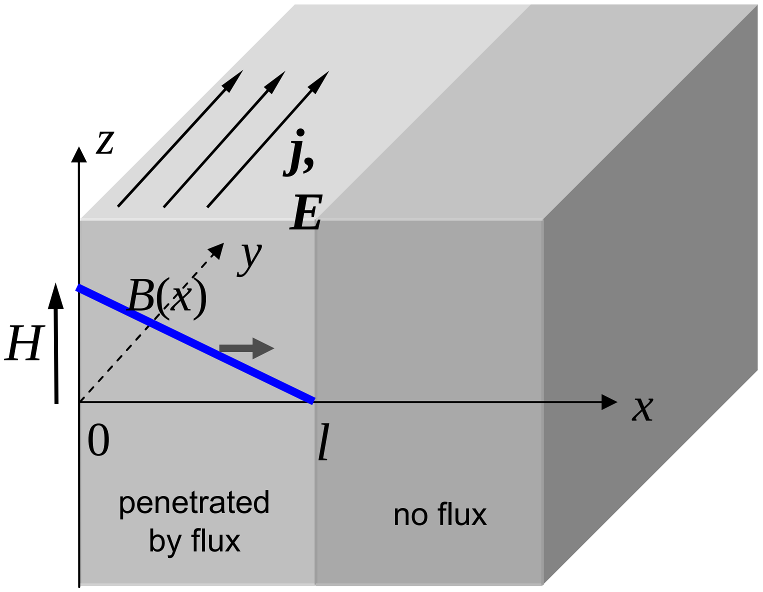


$$\begin{aligned} \mathrm{curl}\,\mathbf{B} &= \mu_0 \mathbf{j} \\ -\mathrm{curl}\,\mathbf{E} &= \dot{\mathbf{B}} \\ \mathbf{j}(\mathbf{r}) &= j_c(\mathbf{E}, \mathbf{B}, T) \end{aligned}$$

Stationary flux distribution

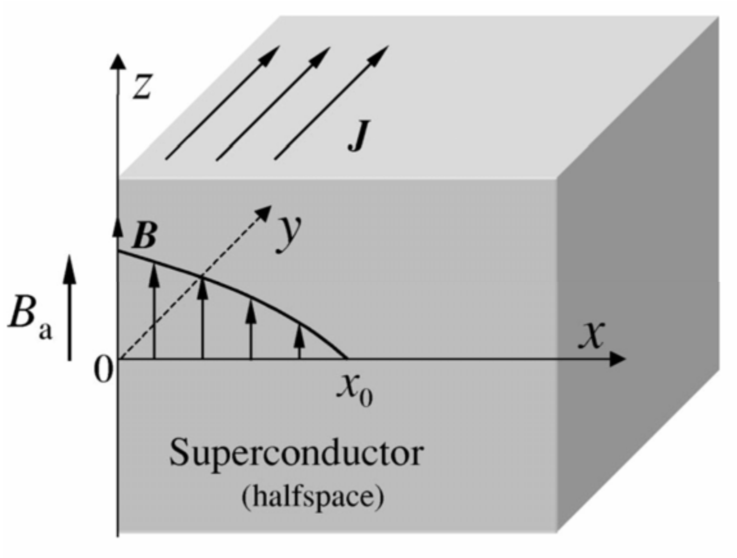
Bean's model

$$j(\mathbf{r}) = j_c(T)$$



Time-dependent flux distribution

$$\mathbf{j} = j_c(T)\, g(E)\, (\mathbf{E}/E)\,,$$
$$g(E) \propto E^{1/n}, \quad n \gg 1$$



Self-consistent solutions:

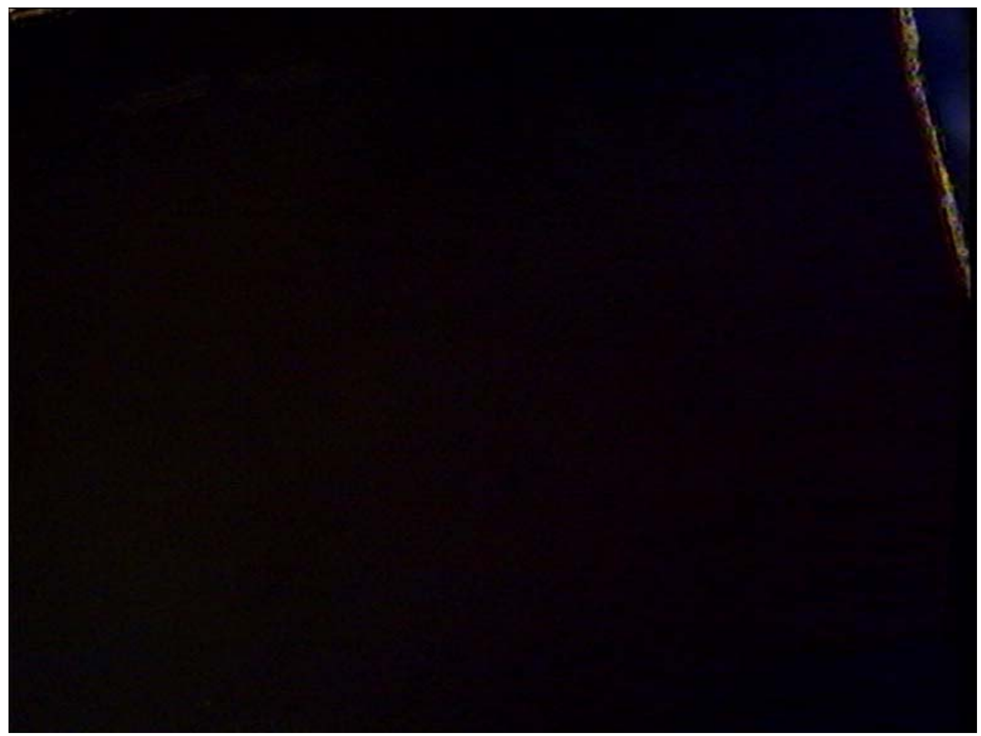
V. Vinokur, M. Feigel'man, and V. Geshkenbein, Phys. Rev. Lett. **67**, 915 (1991).

E.H. Brandt, Rep. Prog. Phys. **58**, 1465 (1995).

D. Shantsev, YG, T. Johansen, Phys. Rev. B 65, 184512 (2002)

Real time video:

YBCO, Cycle of magnetic field



Thermo-magnetic instability: Model

∞ ***slab*** in ***steady state*** (dH/dt > 0)

Thermal diffusion + Maxwell:

$$
\begin{aligned}
C(\partial T/\partial t) &= \kappa\nabla^2 T + \mathbf{jE} \\
\mathrm{curl}\,\mathbf{E} &= -\partial\mathbf{B}/\partial t\,, \\
\mathrm{curl}\,\mathbf{B} &= \mu_0\mathbf{j}
\end{aligned}
$$

E-*j* curve:

$$n \equiv \frac{\partial \ln E}{\partial \ln j} \gg 1 \qquad E \propto j^n$$

Add perturbation & Linearize

$$T + \delta T(x,y,t), \quad \mathbf{E} + \delta\mathbf{E}(x,y,t)$$

$$\delta T, \delta E \propto e^{\lambda t + ik_x x + ik_y y}$$

Solve dispersion equation and find $\lambda(\mathbf{k})$

Unstable if $\mathrm{Re}\,\lambda(k_x, k_y) > 0$

Fingering if $k_y \neq 0$

Find wave vectors for maximal increment

Solution for λ

Key parameter:

$$\tau = \frac{D_{\text{Thermal}}}{D_{\text{Magnet}}} = \frac{\kappa / C}{\partial E / \partial j \, \mu_0}$$

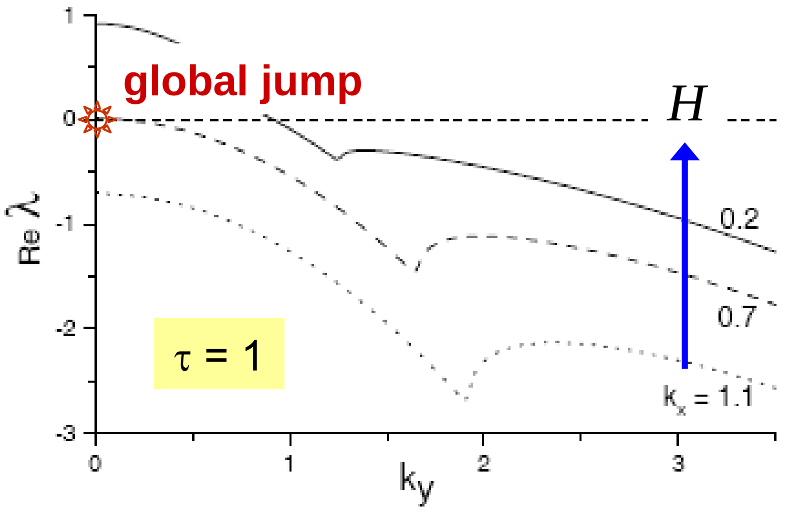
Global → Finger when

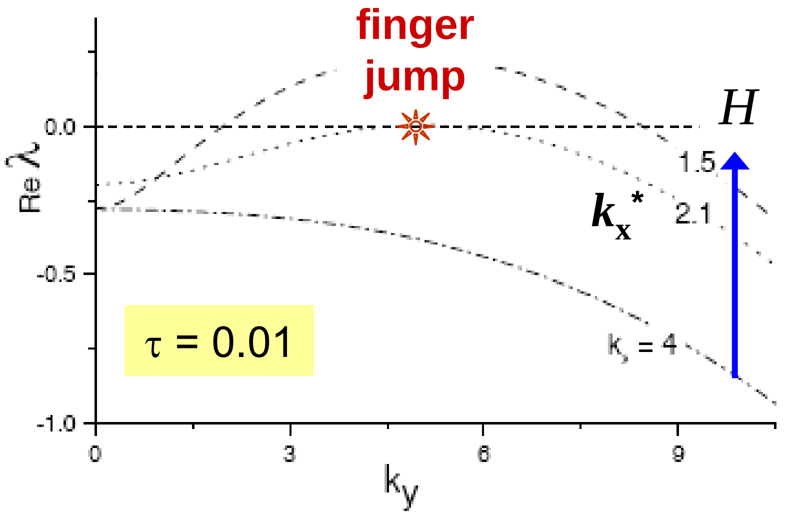
$$\tau \leq n^{-1} \qquad i.e. \qquad E > E_c = \mu_0 \, j_c \, \kappa / C$$

Finger jump will then occur at

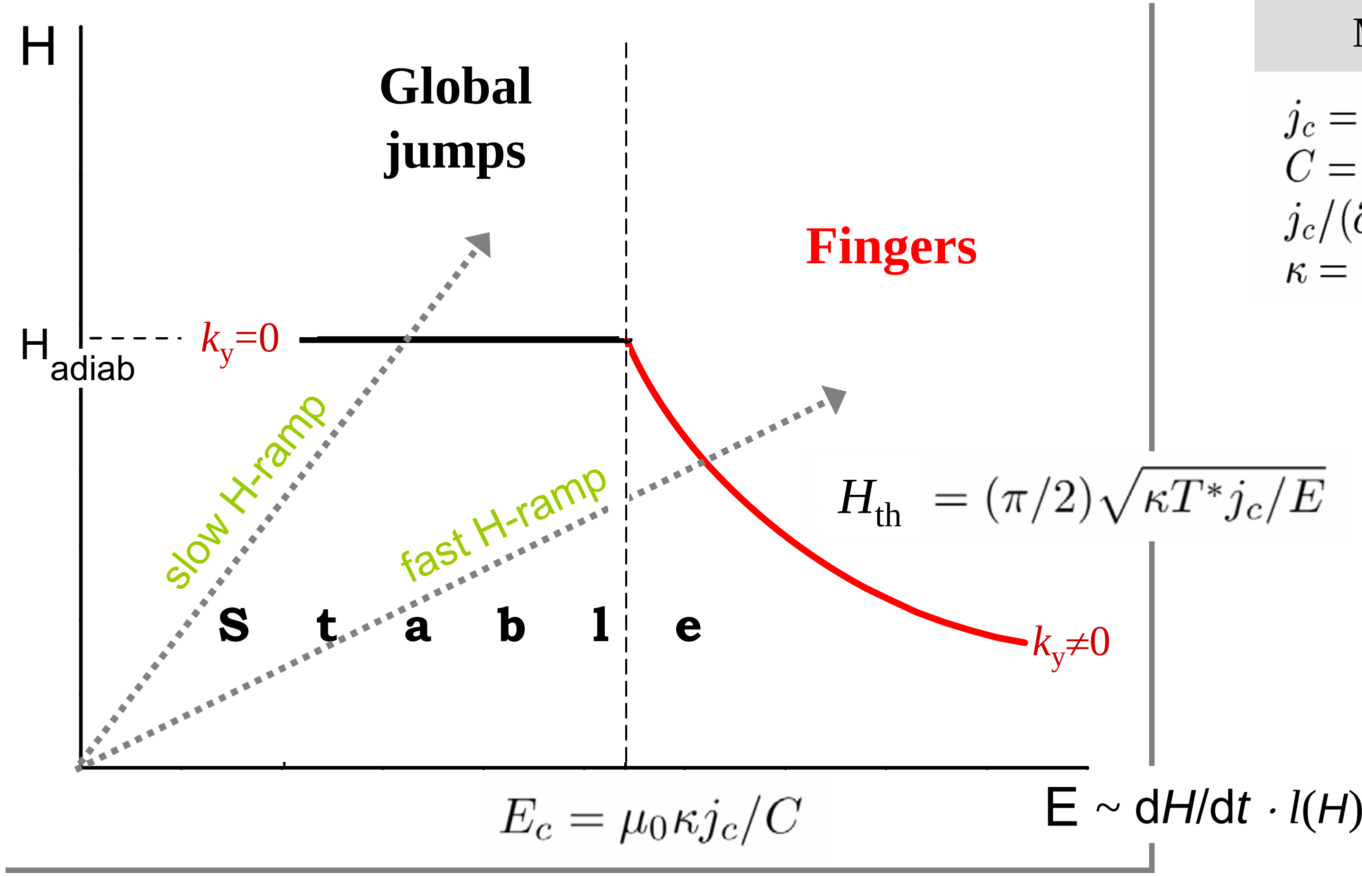
$$\boldsymbol{k_x}^* \quad \leftrightarrow \quad H = \frac{\pi}{2} \, j_c \sqrt{\frac{\kappa}{| \, j_c'(T) \, | \, E}}$$

n = 10





Stability diagram



MgB_2 parameters:

$j_c = 10^{10}$ A/m^2
$C = 10^3$ J/Km^3
$j_c/(\partial j_c/\partial T) \equiv T^* = 10$ K
$\kappa = 10^{-2}$ W/Km

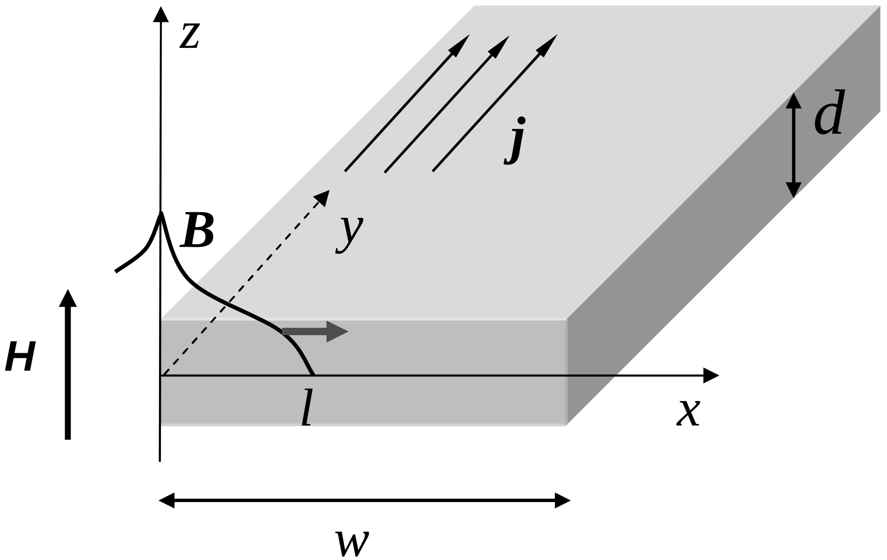
~ 0.1 V/m

need: μ_0 dH/dt ~ **1000 T/s**

Fingers ***not*** seen in bulks !

Films in perpendicular field

PRB **73** 014512 (2006)



Thermal diffusion + Maxwell

$$C(\partial T/\partial t) = \kappa \nabla^2 T + \mathbf{jE}$$
$$\text{curl } \mathbf{E} = -\partial \mathbf{B}/\partial t\,,$$

New:

Non-local electrodynamics

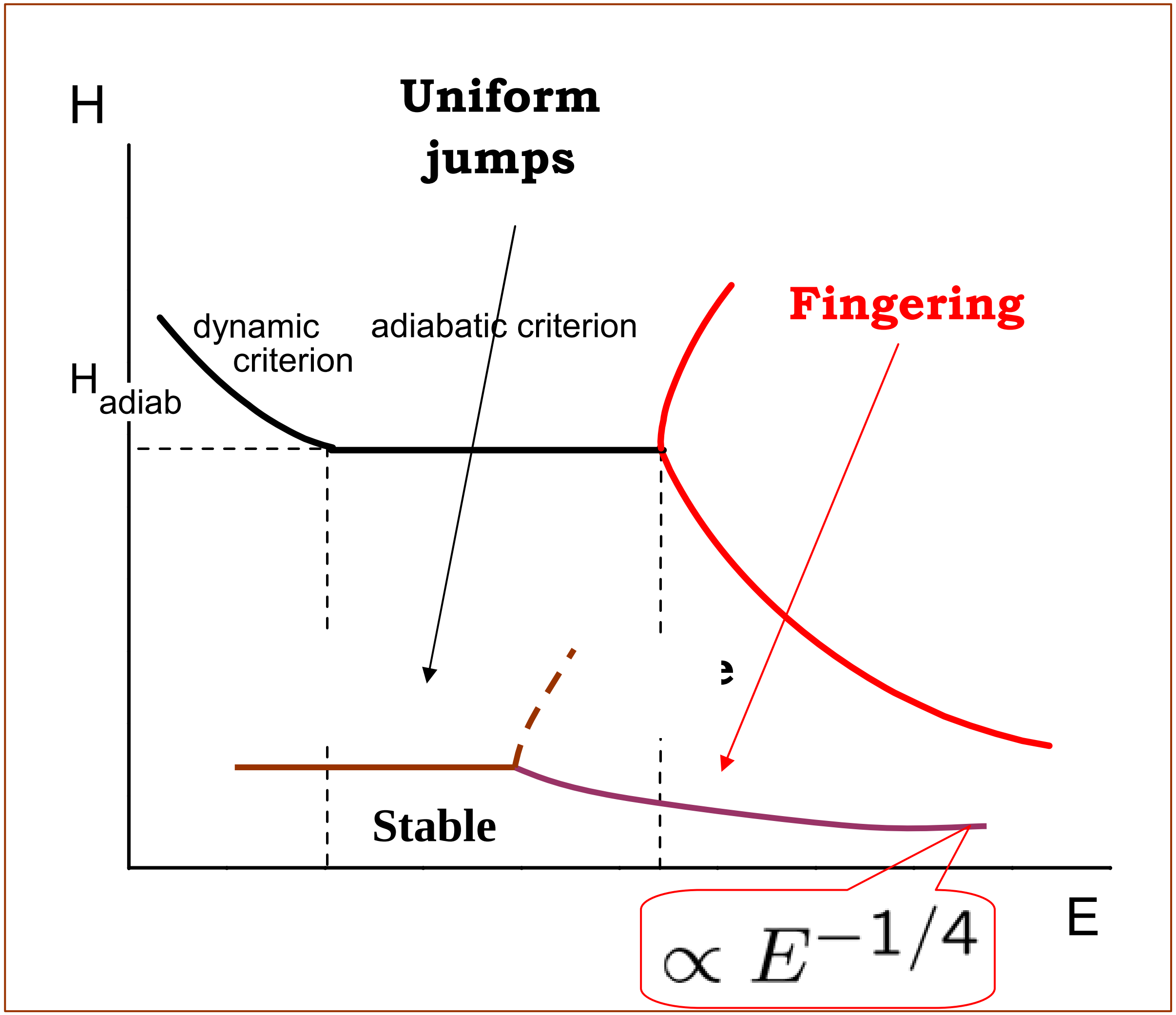
$$\mathbf{B}(\mathbf{r}) = \mu_0 \mathbf{H} + \frac{1}{4\pi} \int d^3 \mathbf{r}' \, \frac{\mathbf{j} \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3}$$

Heat removal into substrate

$$\kappa \nabla_z T = -h_0 (T - T_0),$$

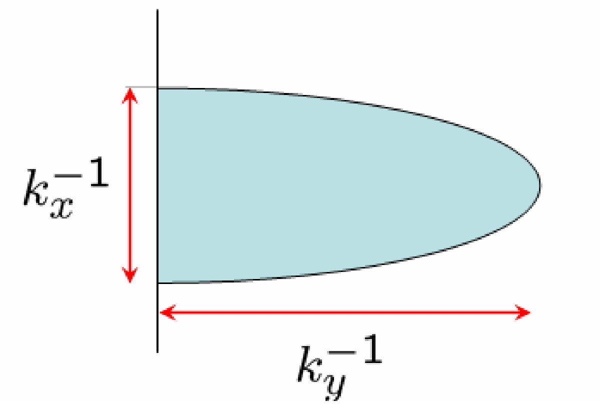
Linear expansion as before

see also Aranson *et al*. PRL **94** 037002 (2005)



Agrees with Aranson et al., Phys. Rev. Lett. **94**, 037002 (2005)

Important estimates



$$\frac{k_y}{k_x} = (2n)^{1/4}$$

$$j_c = 10^{10}\ \mathrm{A/m^2}$$
$$C = 10^3\ \mathrm{J/Km^3}$$
$$j_c/(\partial j_c/\partial T) \equiv T^* = 10\ \mathrm{K}$$
$$\kappa = 10^{-2}\ \mathrm{W/Km}$$
$$n = 30$$

$$k_y^{-1} \approx 3\ \mu\mathrm{m}$$
$$H_{\mathrm{adiab}} \approx 0.1\ \mathrm{T}$$

$$\lambda^{-1} \leq 1\mu\mathrm{s}$$
$$E_c \approx 0.1\ \mathrm{V/m}$$

Results of the calculation

First jump field:

$$\frac{H^{\text{film}}}{H^{\text{slab}}} \simeq \sqrt{\frac{d}{w}} \sim 0.01$$

Films:
far more
unstable

$$\mu_0 H^{\text{film}} \simeq 10 \text{ mT}$$

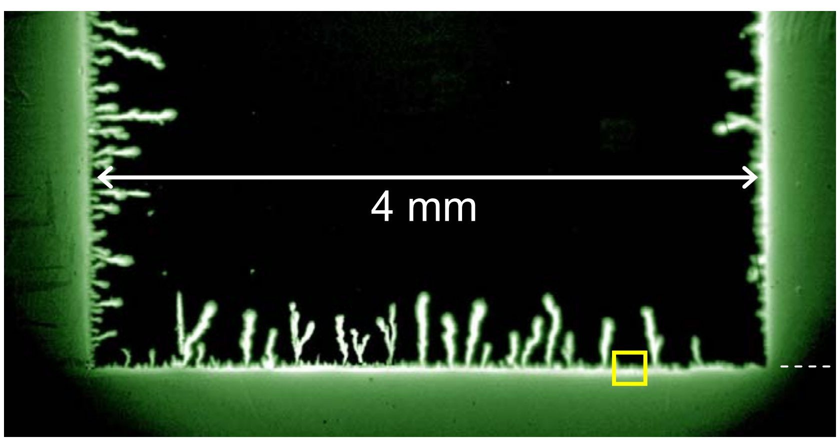
excellent agreement with our MOI experiments

$$\frac{E_c^{\text{film}}}{E_c^{\text{slab}}} \simeq \sqrt{\frac{\mu_0 j_c^2 d^2}{C T^*}} \sim 10^{-3}$$

Films:
far more
dendritic

But; E_c^{film} is still large

$\mu_0 \, dH/dt \sim 1$ T/s !



MgB_2 film

$T = 3.6$ K

Local E >> E_{ave}

Our linearized theory predicts

PRL **97** 077002 (2006)

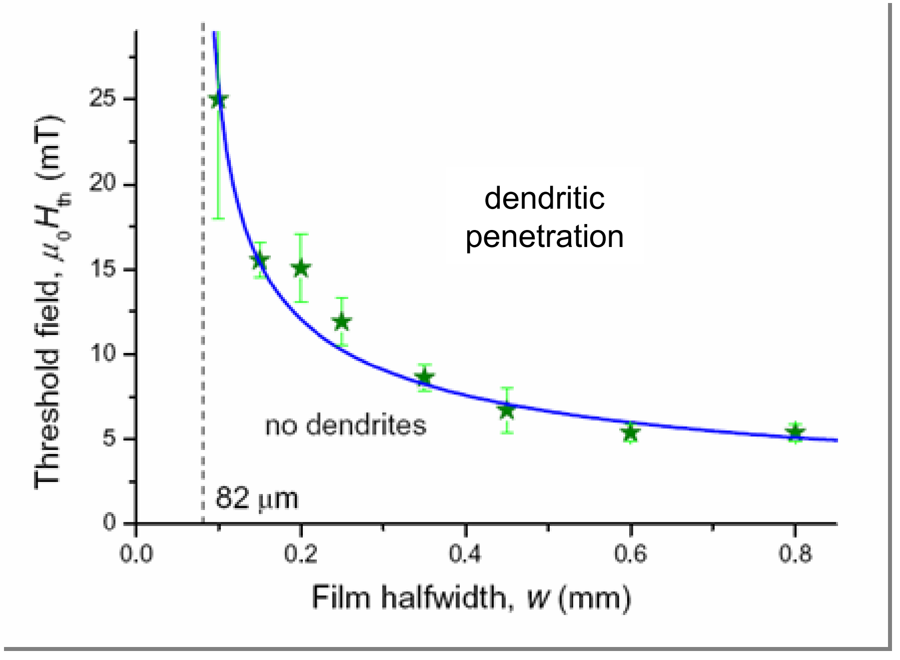
First dendrite comes at penetration depth

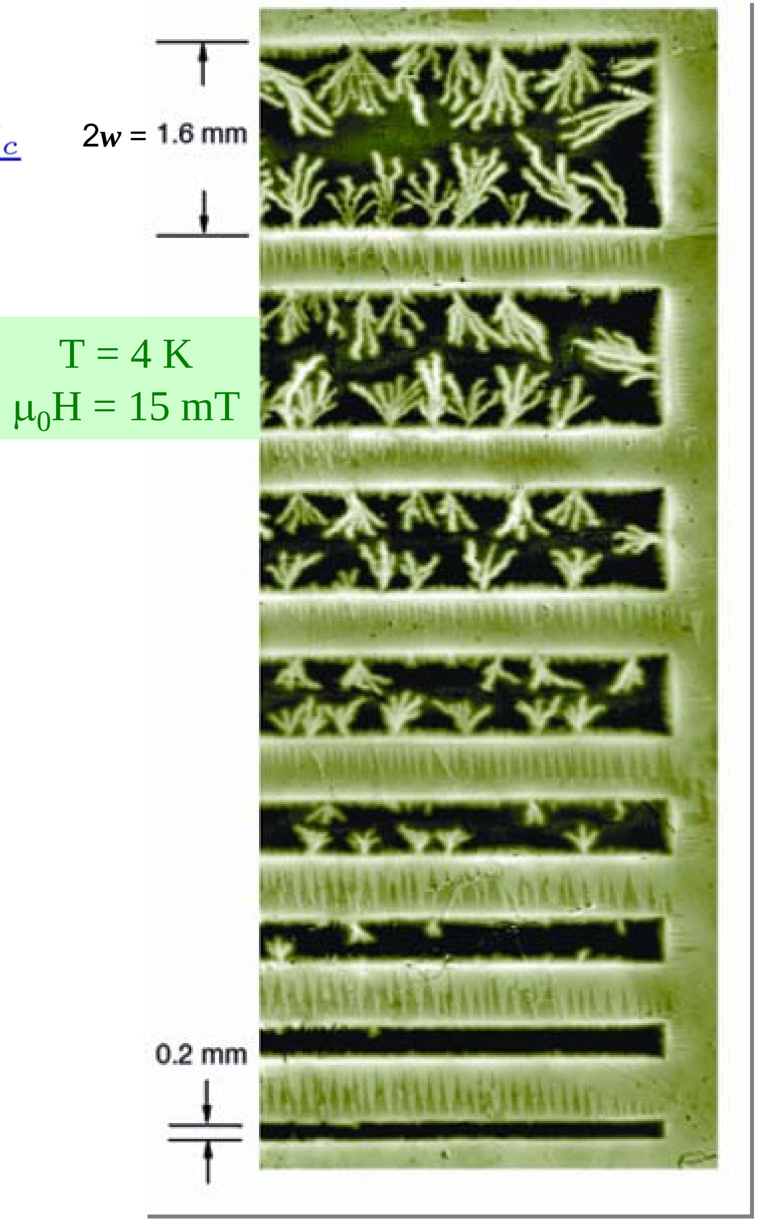
$$l_{th} = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)^{-1} \qquad \frac{1}{T^*} \equiv \frac{\partial \ln j_c}{\partial T}$$

…but only if $w > l_{th}$

If unstable, then

$$H_{th} = \frac{j_c d}{\pi} \operatorname{arccosh}\left(\frac{w}{w - l_{th}}\right)$$





T - dependence

PRL **97** 077002 (2006)

First dendrite comes at

$$l_{\rm th} = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)$$

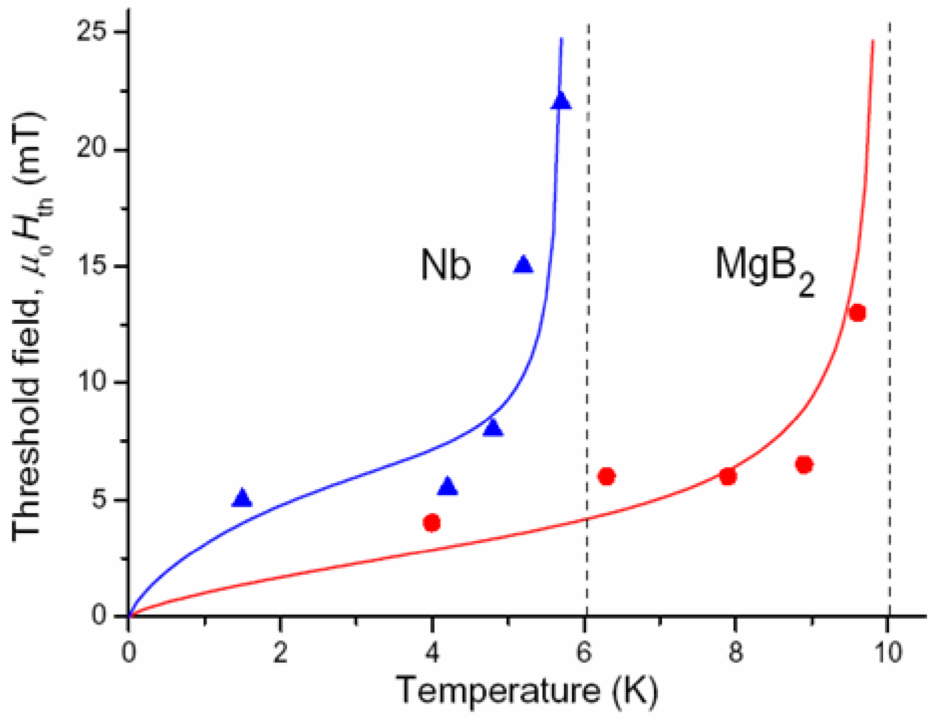
Assuming:

$$\kappa = \tilde{\kappa}\,(T/T_c)^3 \qquad j_c = j_{c0}(1 - T/T_c)$$

$$h_0 = \tilde{h}_0\,(T/T_c)^3 \qquad n = \tilde{n}(T_c/T - 1)$$

Threshold field:

$$H_{\rm th} = \frac{j_c d}{\pi}\text{arccosh}\left(\frac{w}{w - l_{\rm th}}\right)$$

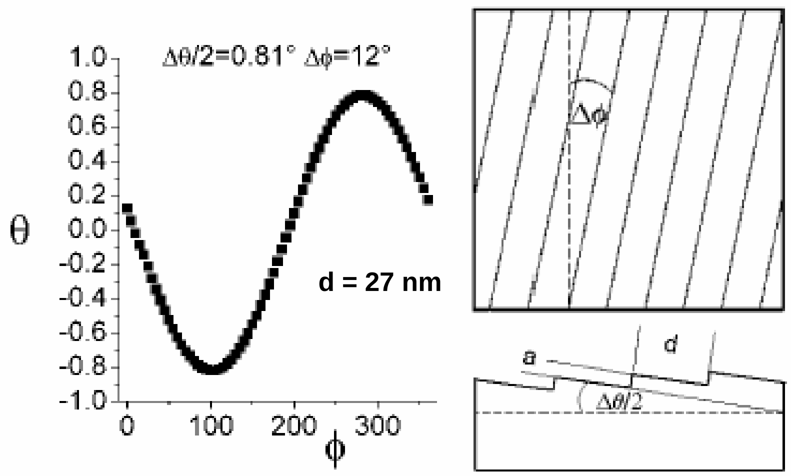


Nb data of Welling *et al.*
Physica C **411**, 11 (2004)

Anisotropic J_c

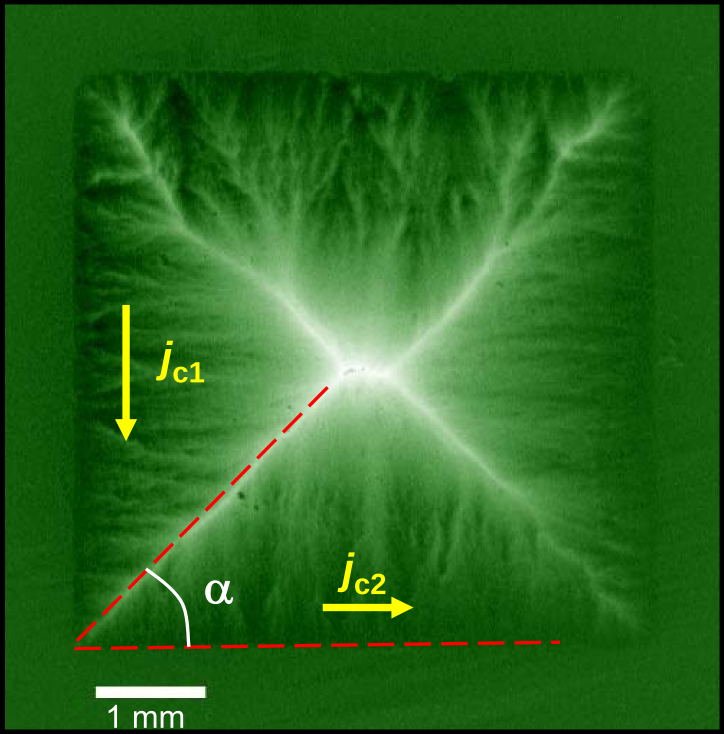
miscut Al_2O_3 substrate

X-ray:

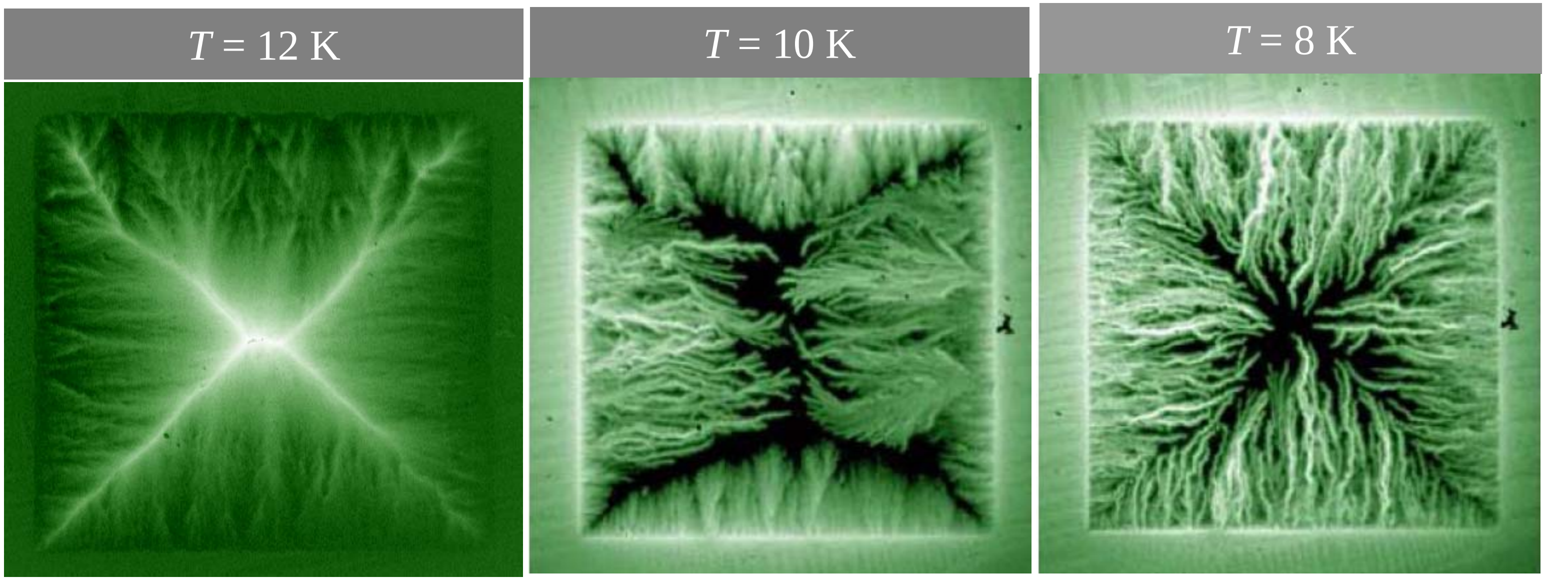


Square MgB_2 film

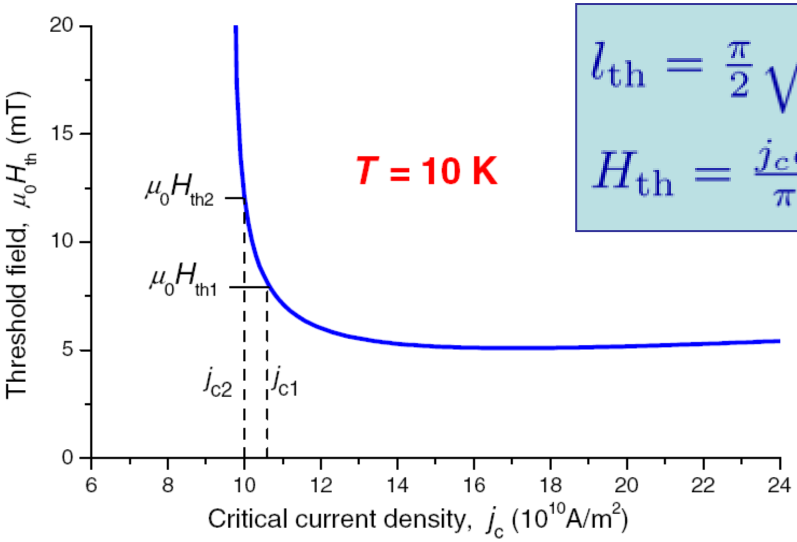
Remanent state, T = 12 K



$$\tan\alpha = \frac{j_{c1}}{j_{c2}} = 1.05$$

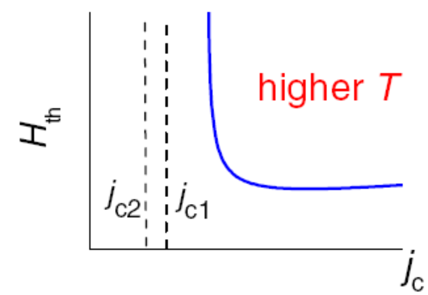


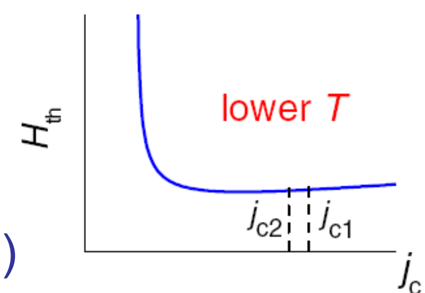
Explanation



$$l_{\rm th} = \frac{\pi}{2}\sqrt{\frac{\kappa T^*}{j_c E}}\left(1 - \sqrt{\frac{2h_0 T^*}{n d j_c E}}\right)$$

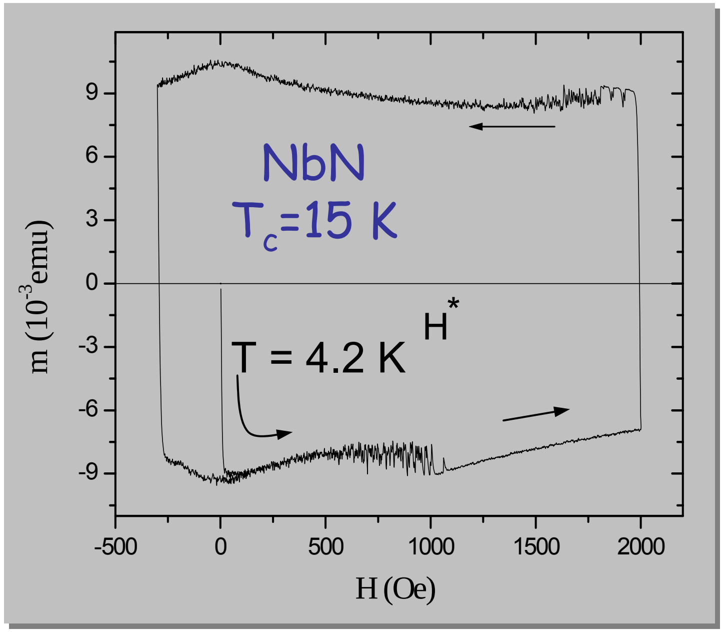
$$H_{\rm th} = \frac{j_c d}{\pi}\,\mathrm{arccosh}\left(\frac{w}{w - l_{\rm th}}\right)$$



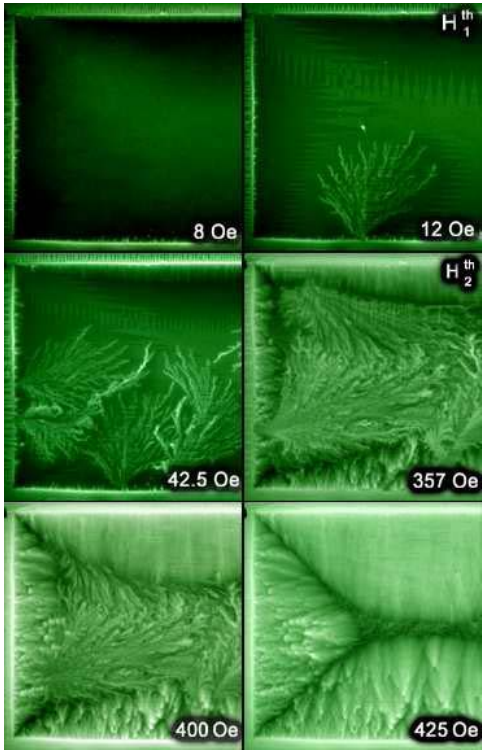


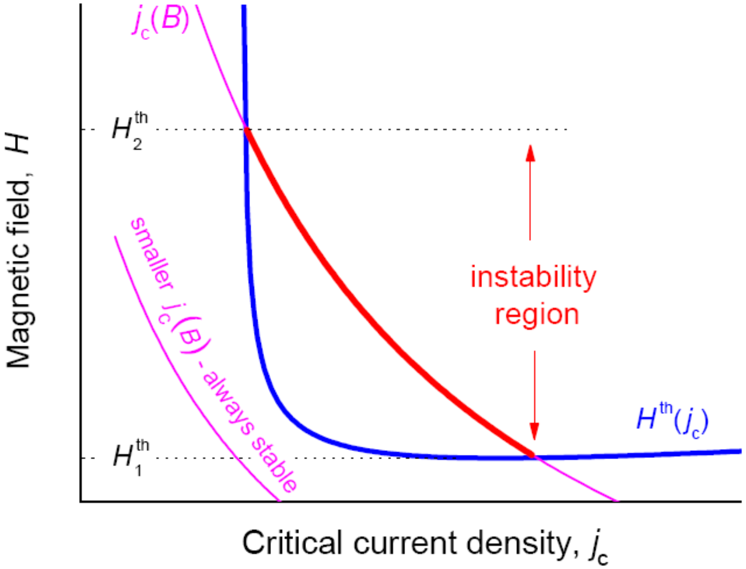
PRL **98,** 117001 (2007)

Reentrant behavior: Upper critical field



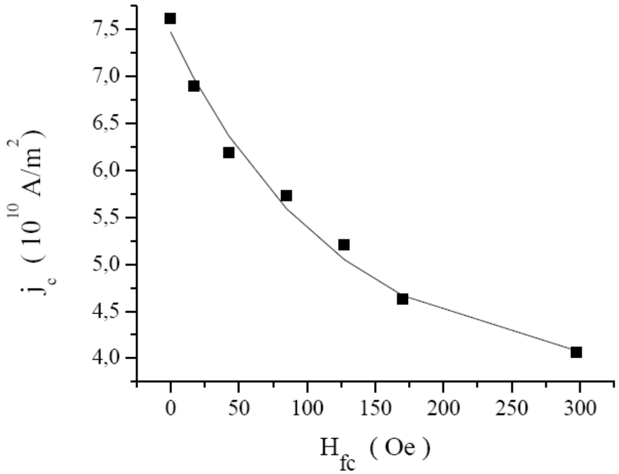
Dendritic instability exists in a finite domain of magnetic fields – there are both lower and upper critical fields



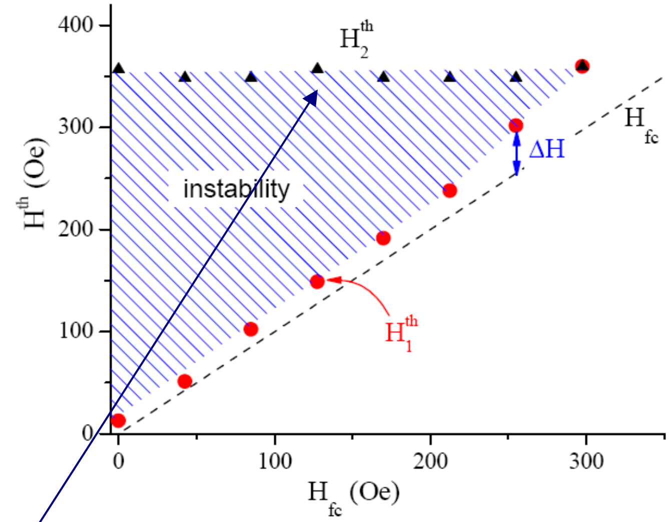


Explanation

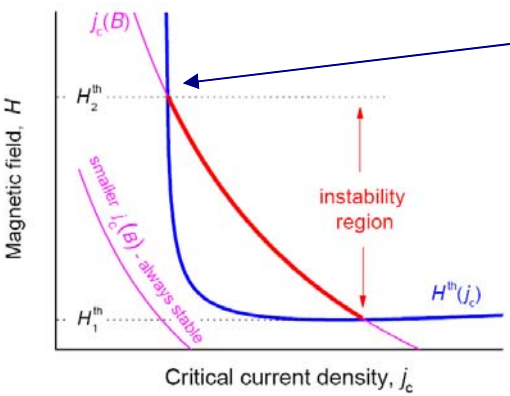
Verification



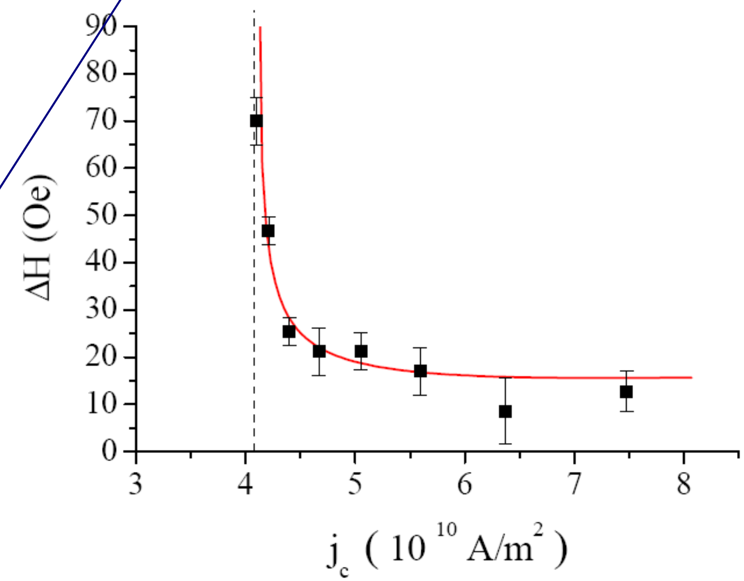
Direct measurements by MOI method at 4 K



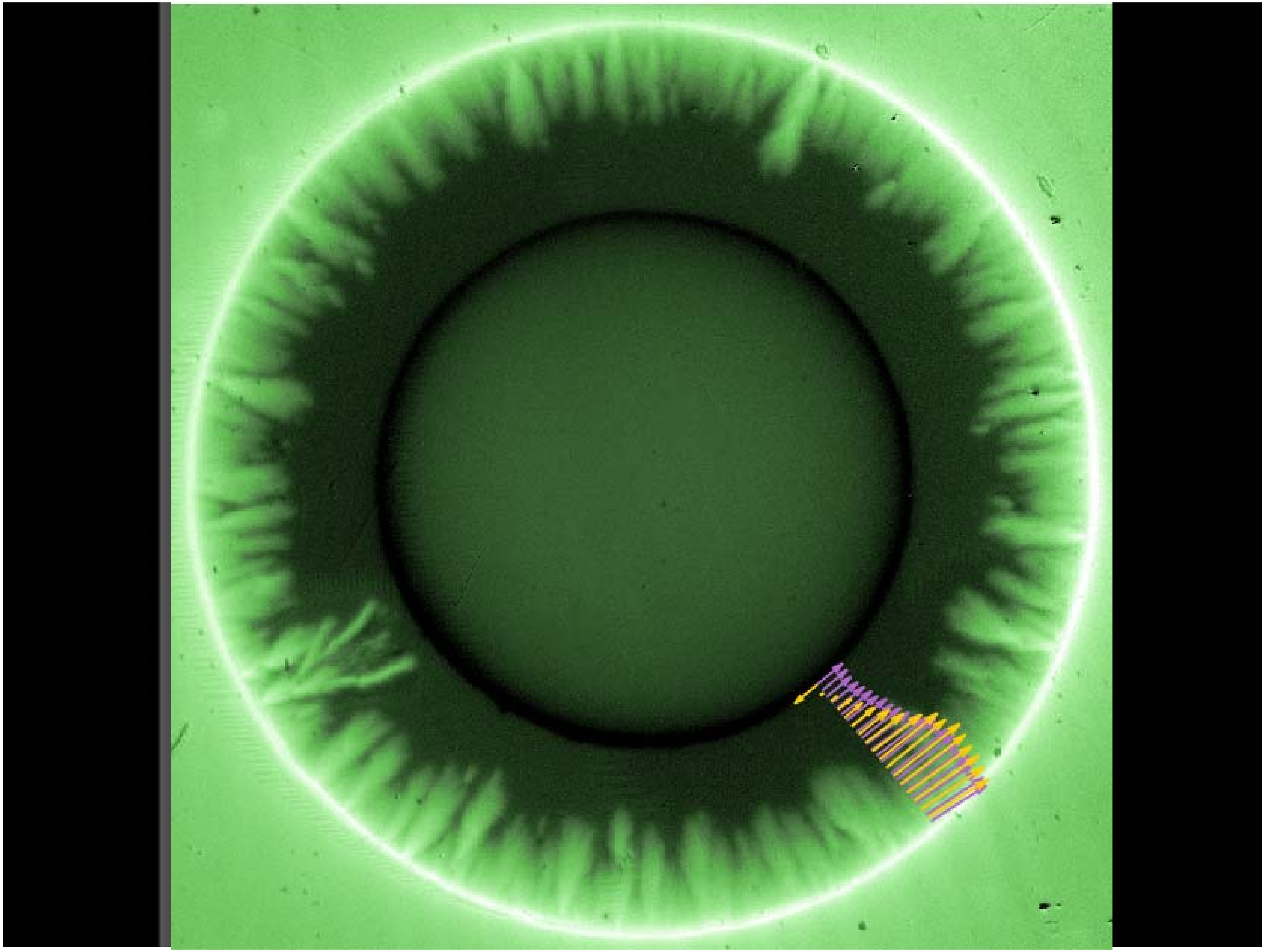
The difference $\Delta H = H_1^{\mathrm{th}} - H_{\mathrm{fc}}$ should correspond to onset of the dendritic instability



Very steep slope!



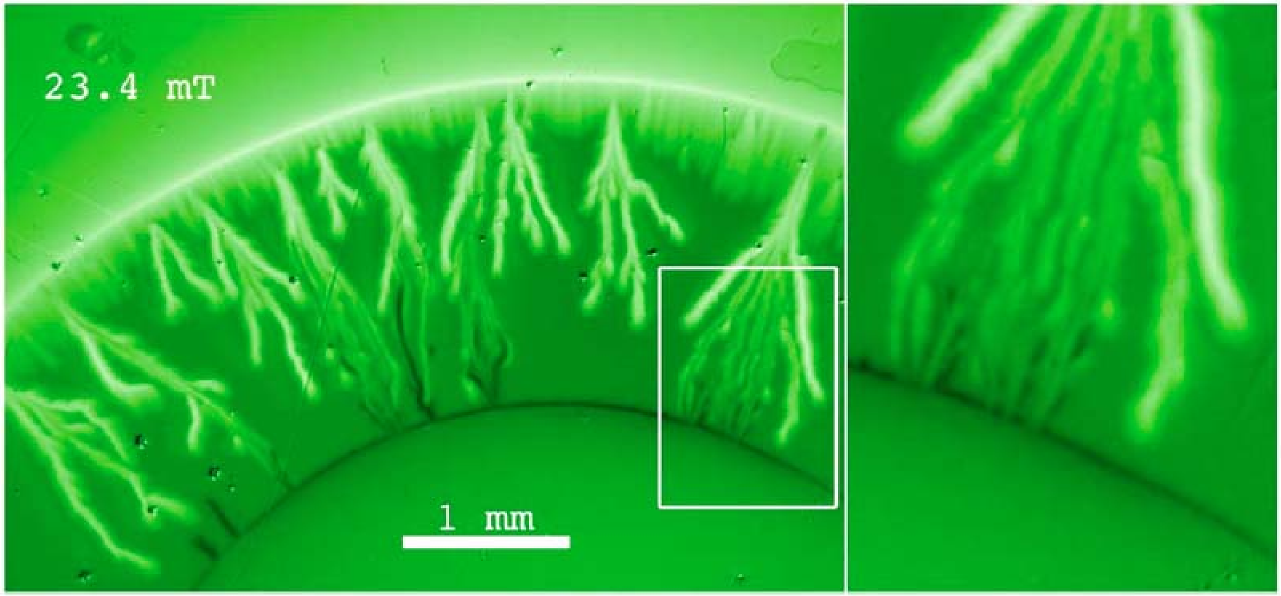
How to determine T without measuring T ?



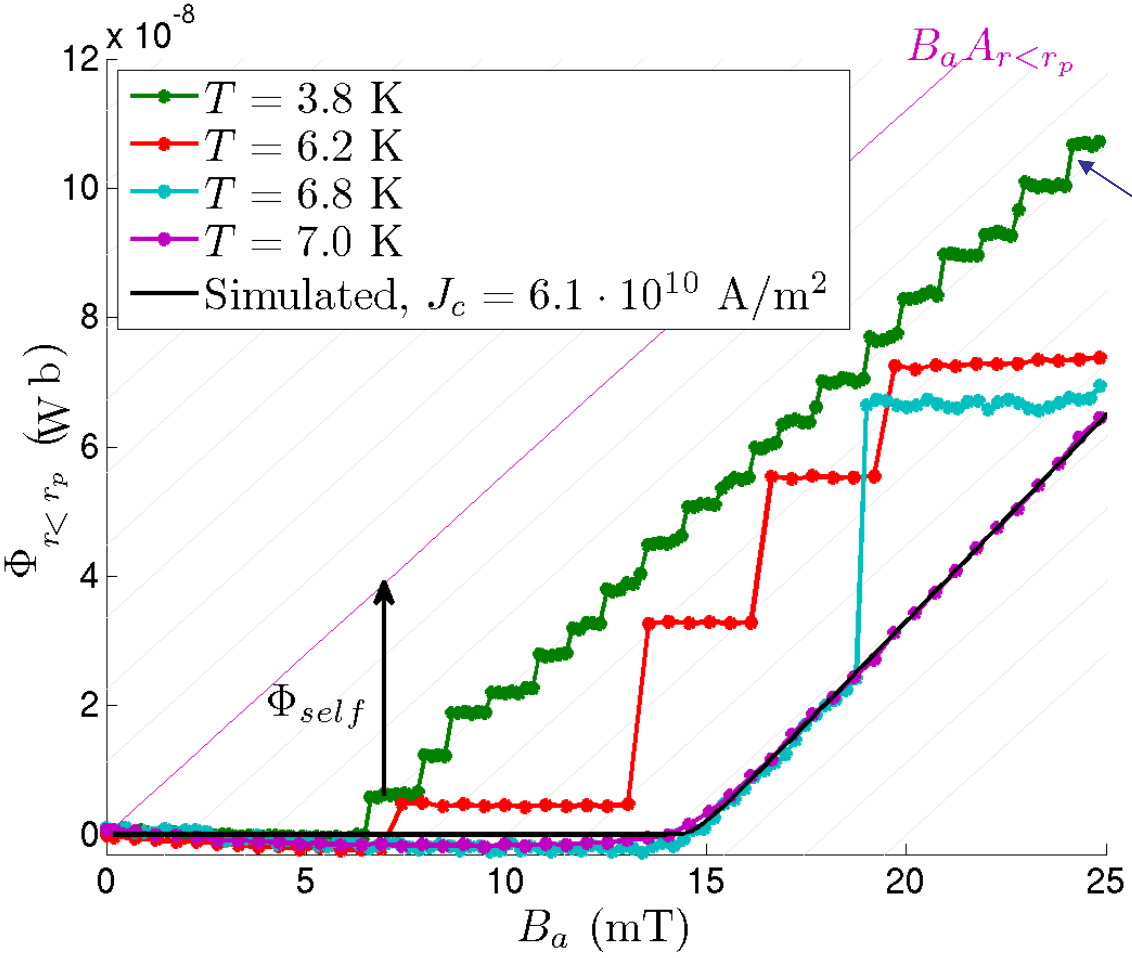
MgB_2 ring

Some avalanches perforate the ring:

they connect the outer and inner edges and can bring FLUX into the hole



Total magnetic flux in the ring versus applied field

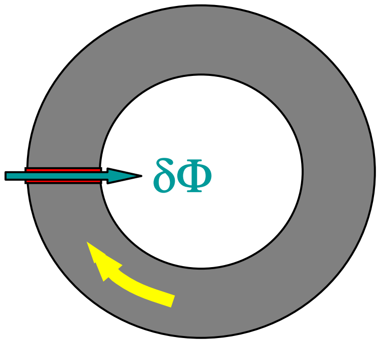


Every step is a perforating avalanche

$$L\frac{dI}{dt} + R(t)I = 0$$

$$c\frac{dT}{dt} = \rho J^2 - \frac{h}{d}(T - T_0)$$

Explanation



1. Quick perforation (10 ns) → heated resistive channel
2. Decrease of the current and injection of magnetic flux
3. Cooling and recovery

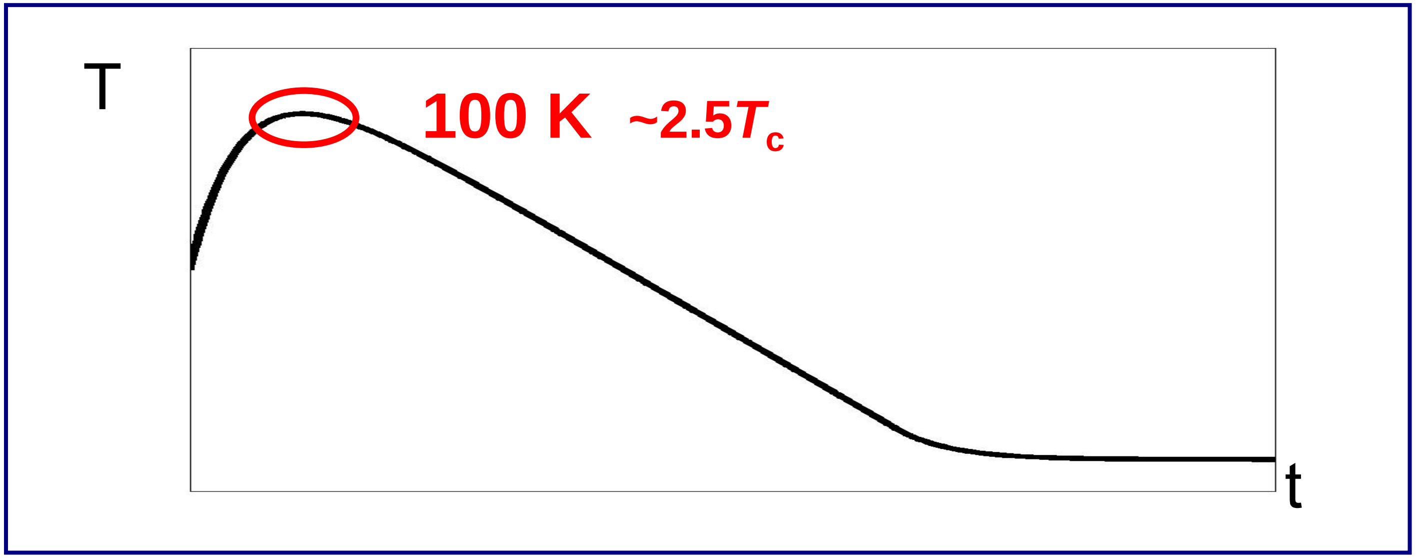
At the maximal temperature $\frac{dT}{dt} = 0$.

$$0 = \rho J^2 - \frac{h}{d}(T - T_0)$$

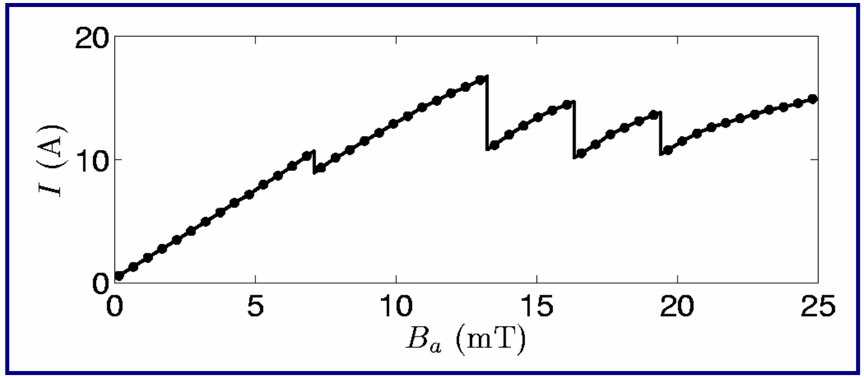
$$h(T) = h_0 (T/T_c)^3$$

$$\frac{\rho J^2 d T_c^{\,3}}{h_0} = T_{max}^{\,3}(T_{max} - T_0)$$

Temperature evolution in the heated channel:

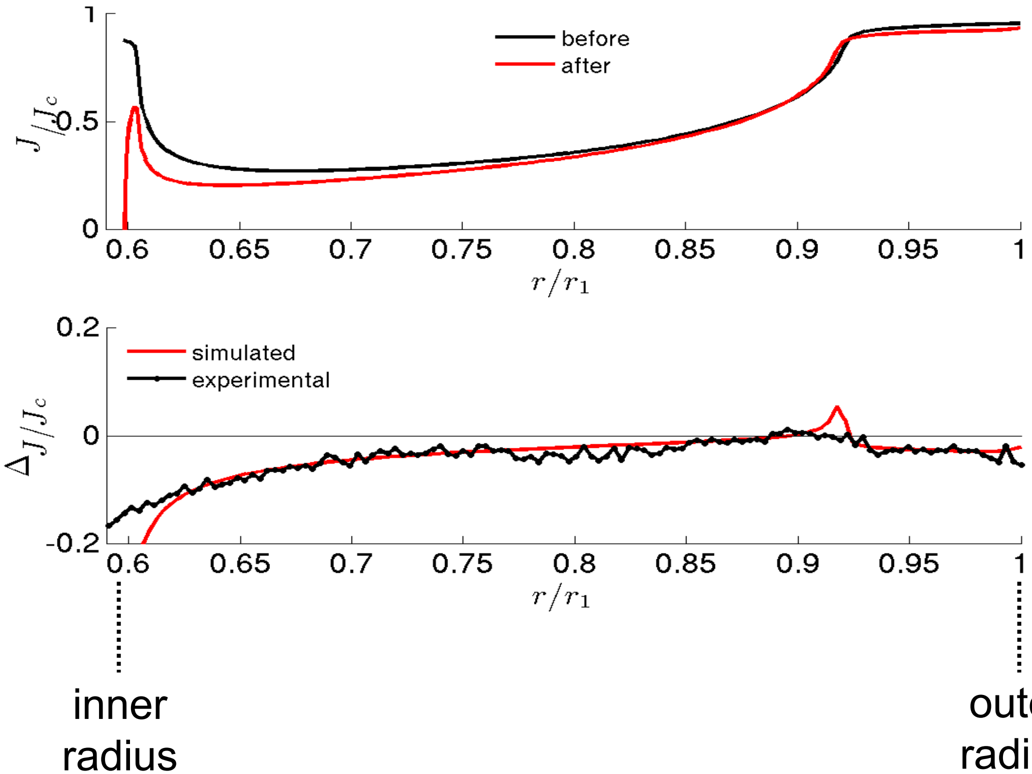


Simulations: Perforation reduces the total current in the ring by ~15%



Distribution of current density in the ring

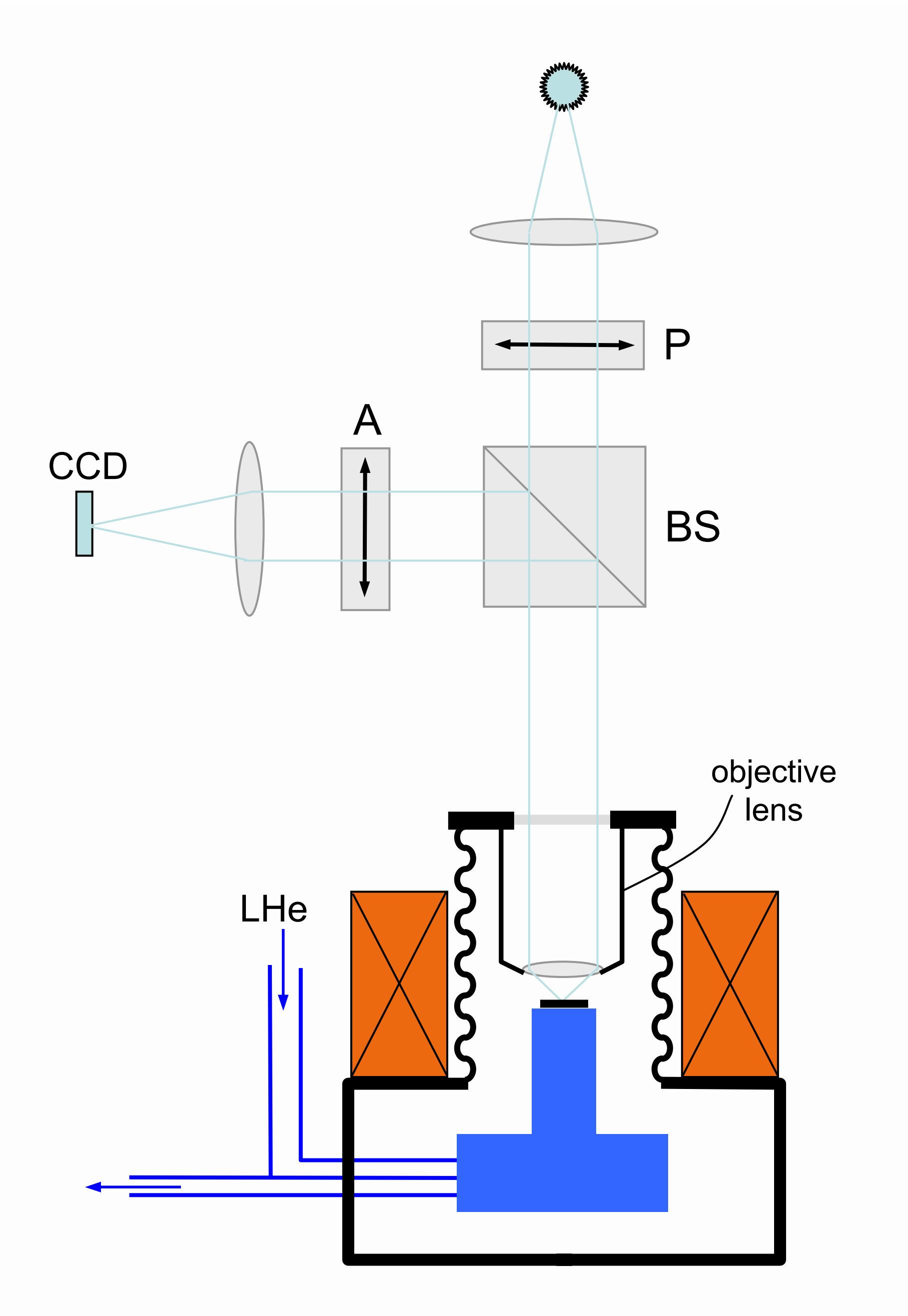
(calculated numerically following the method by Brandt)



Outline

- Magneto-optical imaging
- Dendritic flux penetration – fingering instability
  - Experiment
  - Theory
  - Anisotropic critical current
  - Flux penetration in rings: A way to estimate local temperature
- Observation of individual vortices
  - Custom microscope
  - Vortex dynamics
- Interaction between magnetic domains in the indicator film and vortices
- Open questions and problems
- Conclusion

Observation of single vortices

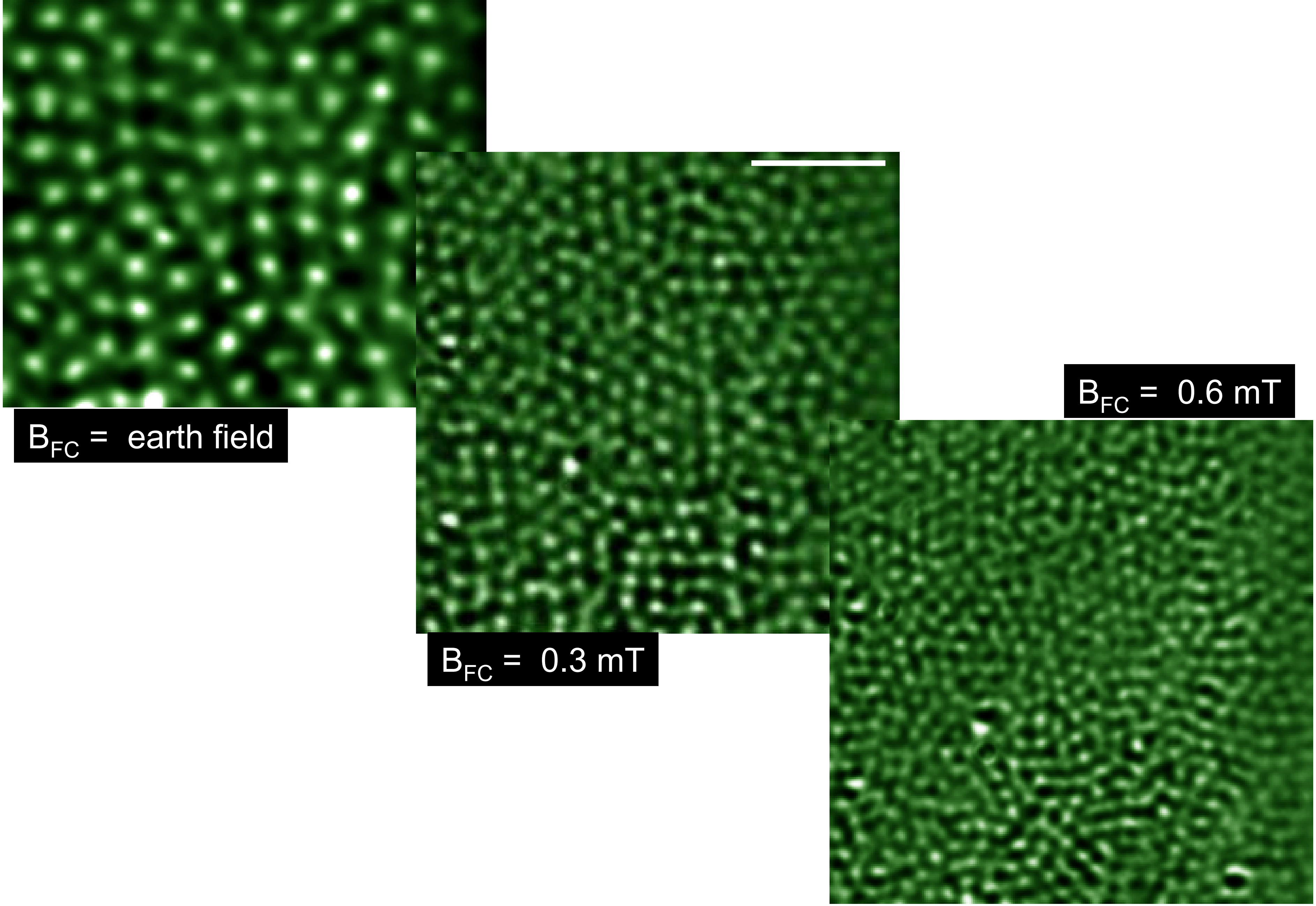


custom microscope

Special features:

- Glan-Taylor polarizers
- Smith beam splitter
- objective lens <u>inside</u> the cryostat
- Hi-res Cryostat (Oxford)

$NbSe_2$ field-cooled to 4.3 K

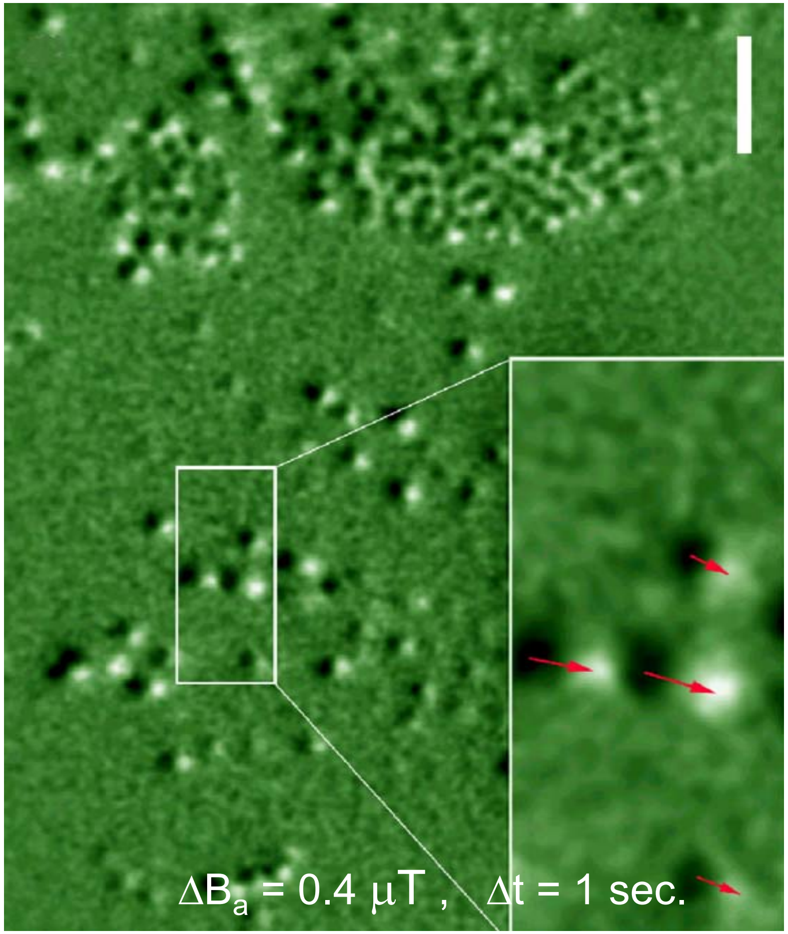


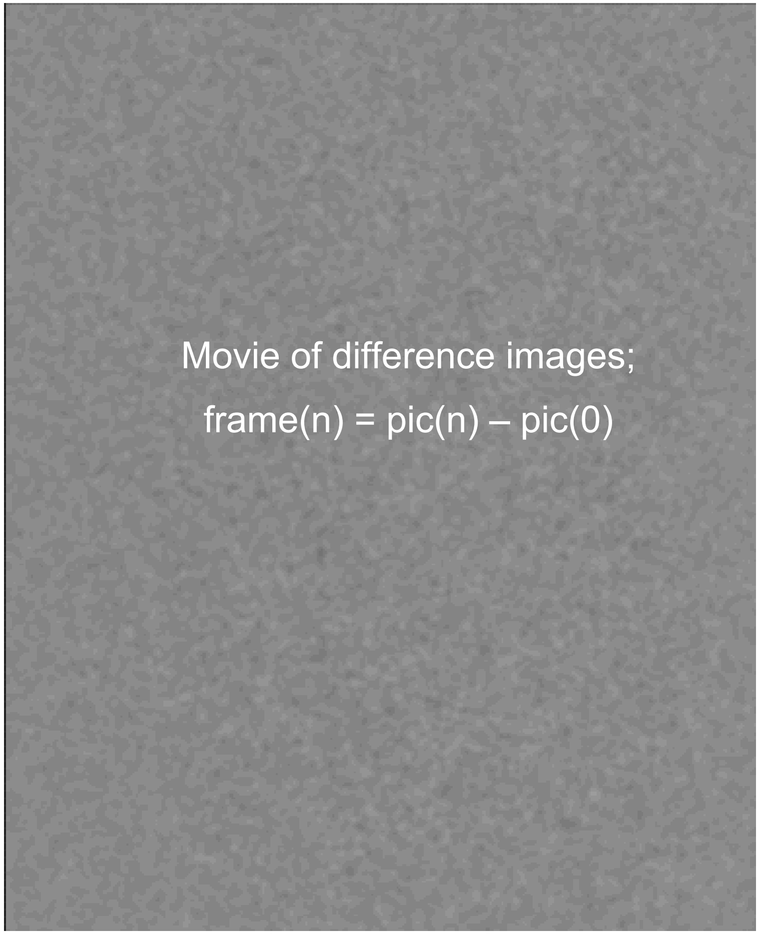
Vortex dynamics

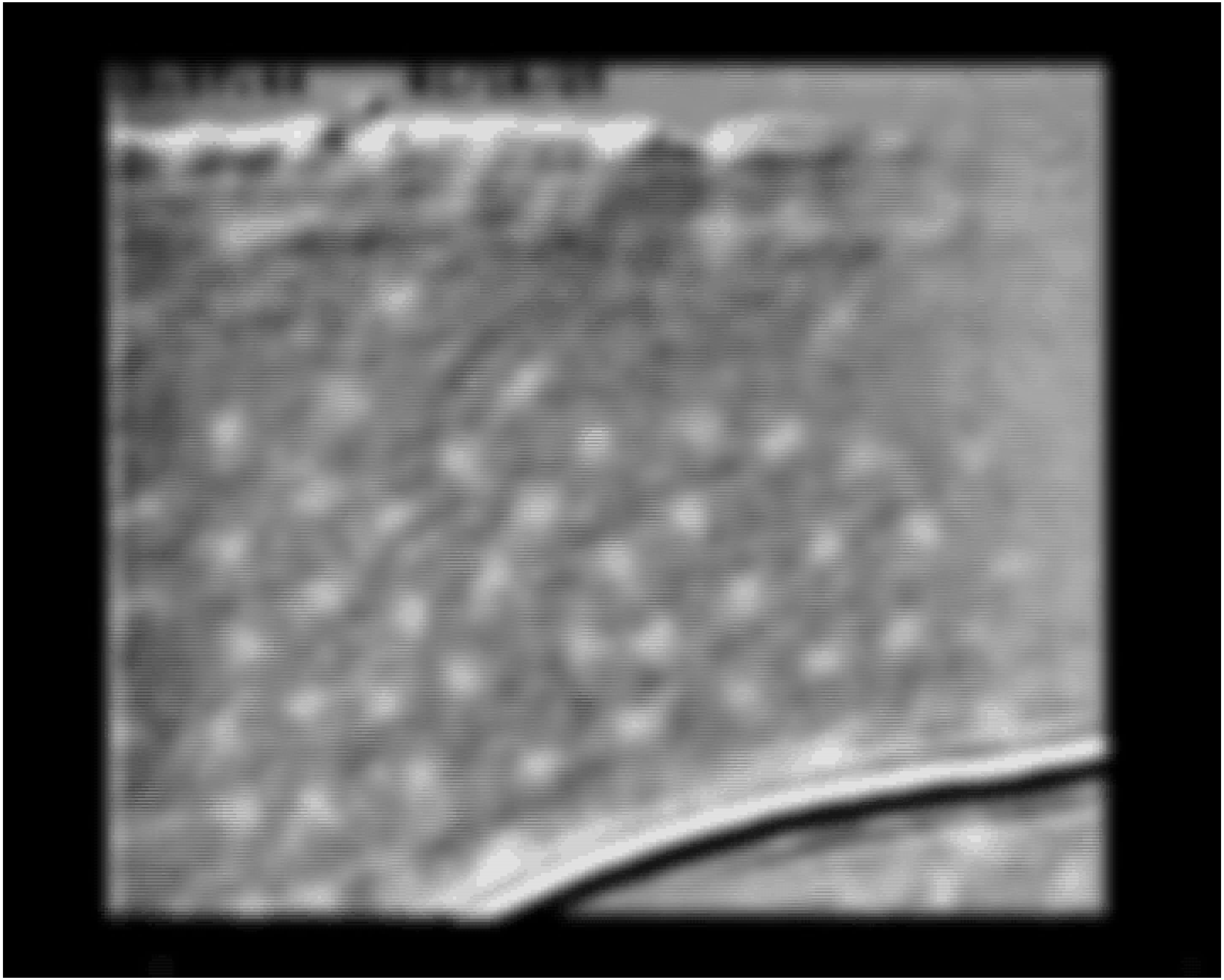
$NbSe_2$

cleaved single crystal   3×2×0.1 mm^3 ,

Tc= 7.2 K; FGF: 0.8 micron thick, no mirror

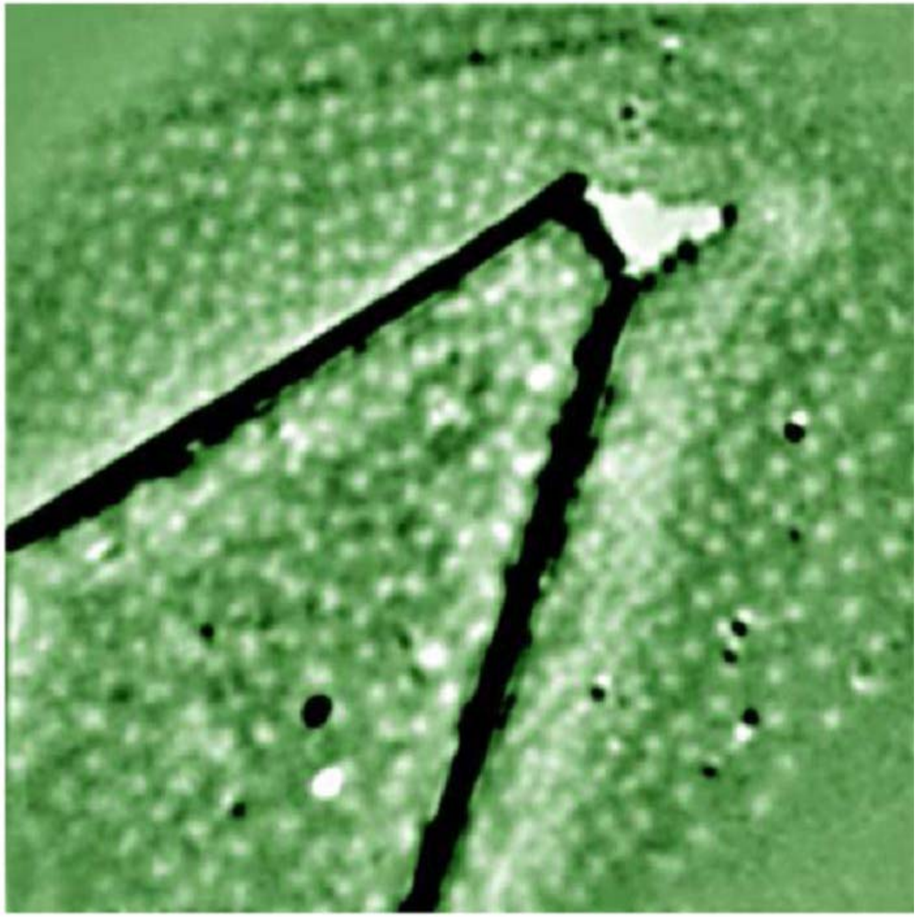




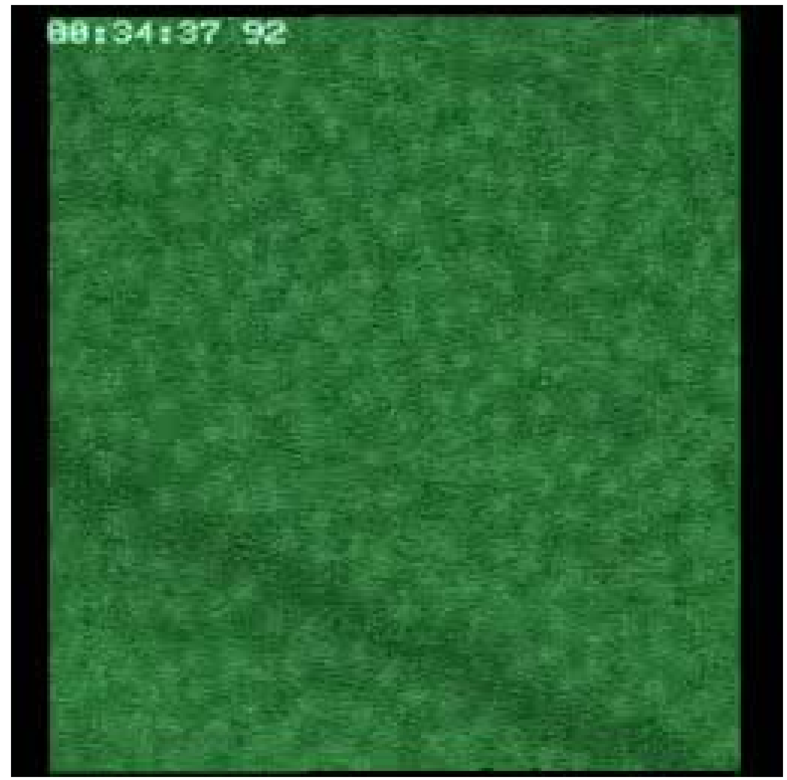


Outline

- Magneto-optical imaging
- Dendritic flux penetration – fingering instability
  - Experiment
  - Theory
  - Anisotropic critical current
  - Flux penetration in rings: A way to estimate local temperature
- Observation of individual vortices
  - Custom microscope
  - Vortex dynamics
- Interaction between magnetic domains in the indicator film and vortices
- Open questions and problems
- Conclusion

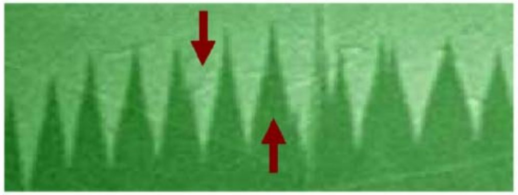


Bloch walls in the indicator films drag vortices



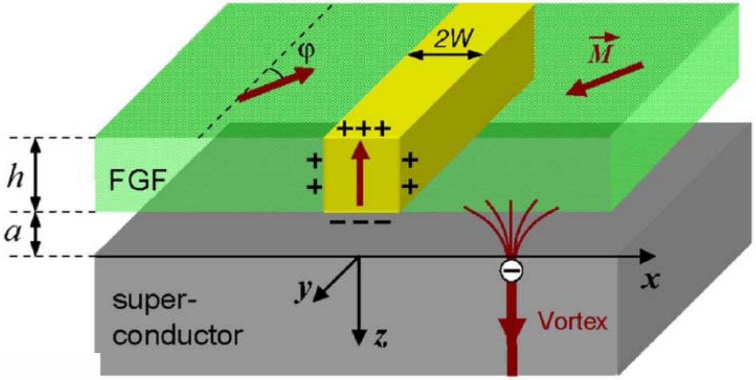
Magneto-optical image of the vortex distribution near a Bloch wall in a Bi-substituted lutetium iron garnet film placed on top of a superconducting $NbSe_2$ crystal.

Theory



x-component $$F^{vw} = F^{\perp} + F^{\parallel},$$

Contributions from perpendicular and parallel components of magnetization ***M***



Fourier components:

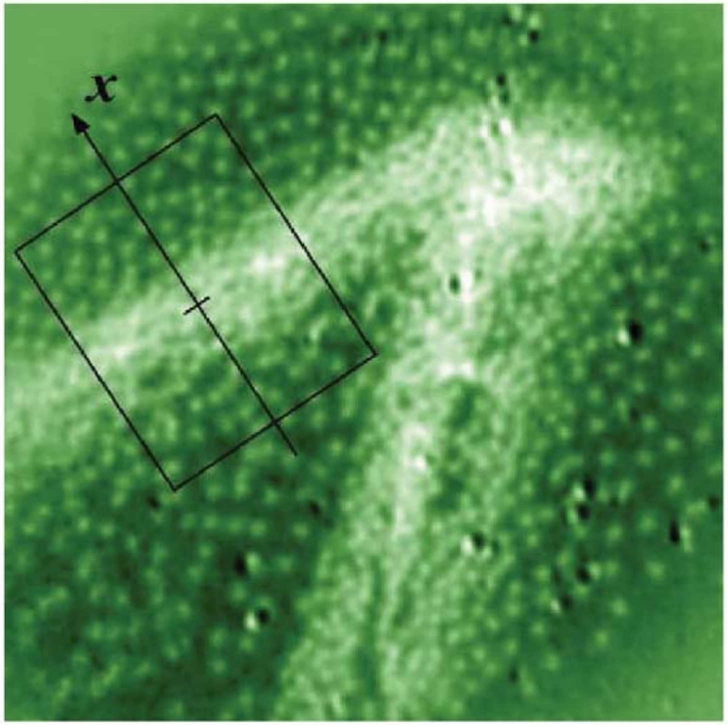
$$F_k^{\perp} = -4i\frac{M_s\Phi_0}{\lambda^2}\,\frac{1-e^{-|k|h}}{|k|\tau(\tau+|k|)}\,e^{-|k|a}\sin Wk,$$

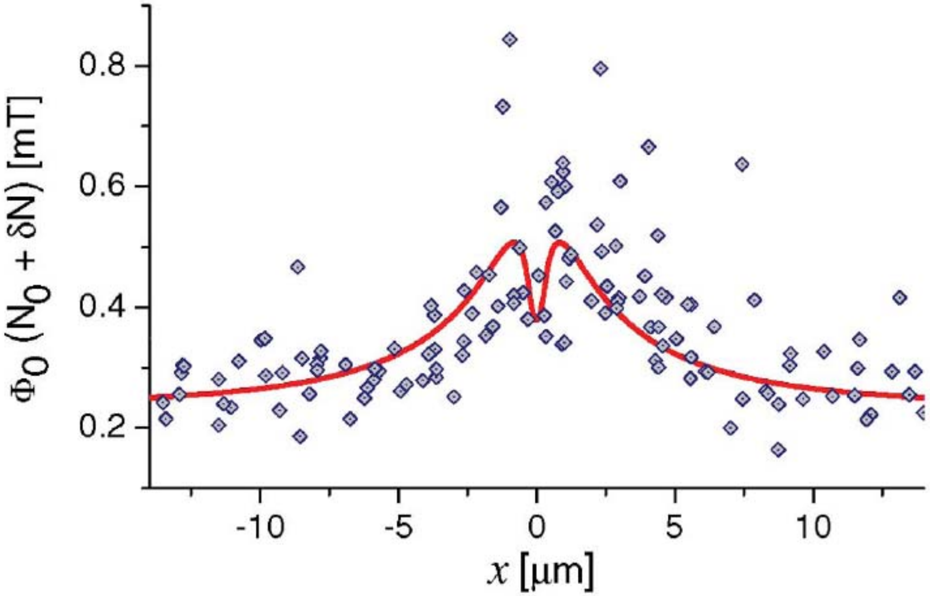
$$F_k^{\parallel} = 4i\frac{M_s\Phi_0}{\lambda^2}\,\frac{1-e^{-|k|h}}{k\tau(\tau+|k|)}\,e^{-|k|a}\cos Wk\sin\varphi,$$

$$\tau = \sqrt{\lambda^{-2}+k^2}$$

$F^{\parallel}$ is always attractive

$F^{\perp}$ is repulsive





Top:

Distribution of vortices formed in the presence of a Bloch wall.

The image was taken after the wall was removed by an in-plane field of the order of a few μT applied perpendicular to the indicated *x* axis.

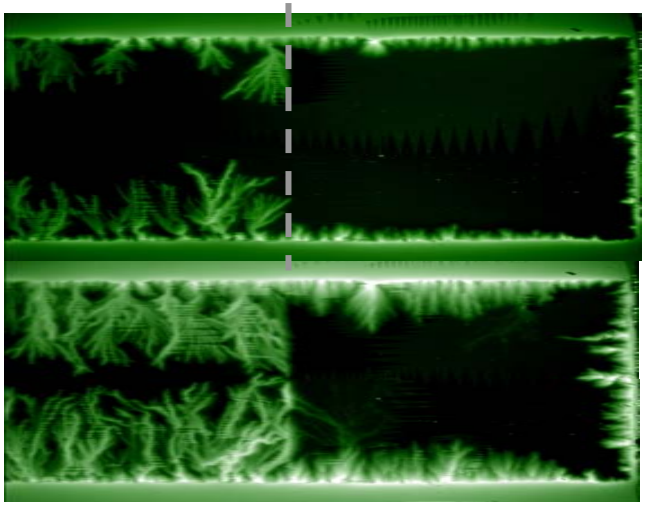
Bottom:

Vortex density obtained from the image (each symbol represents one vortex) together with the theoretical curve.

Outline

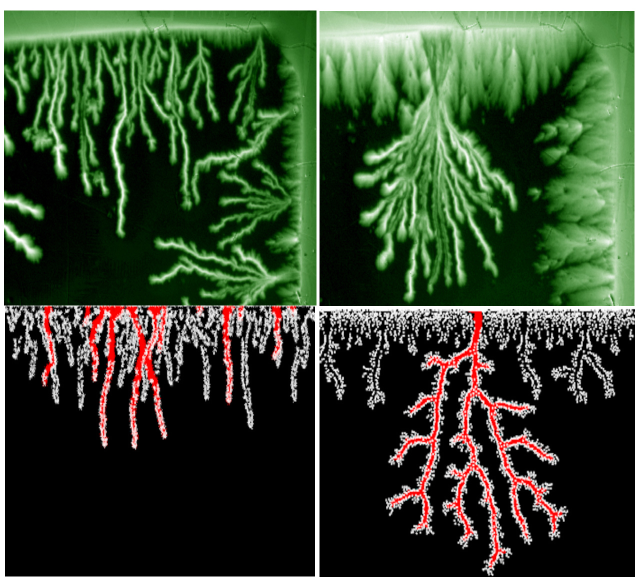
- Magneto-optical imaging
- Dendritic flux penetration – fingering instability
  - Experiment
  - Theory
  - Anisotropic critical current
  - Flux penetration in rings: A way to estimate local temperature
- Observation of individual vortices
  - Custom microscope
  - Vortex dynamics
- Interaction between magnetic domains in the indicator film and vortices
- Open questions and problems
- Conclusion

Thermal bypass or electromagnetic effects?



Mechanisms of branching

3.3 K



9.9 K

Nonlinear theory?

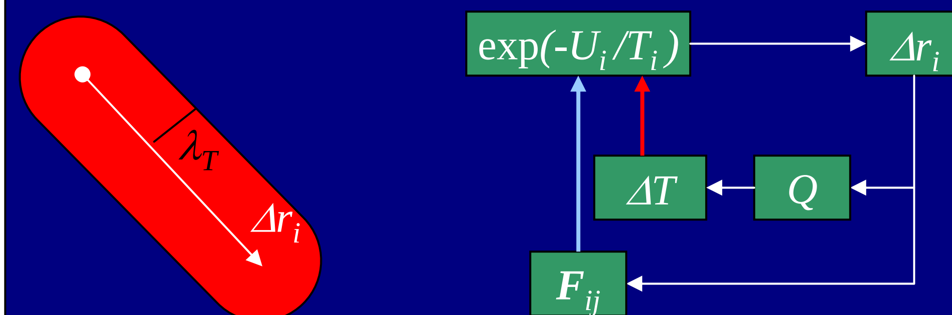
Simulations: $1/r^2$ - forces

1) Evaluate $P_i = \exp(-U_i/T_i)$

$$U_i = U_{pin} - \delta\,[\Sigma_j\,\mathbf{F}_{ij}(r_{ij}) + \mathbf{F}_M(r_i)]$$

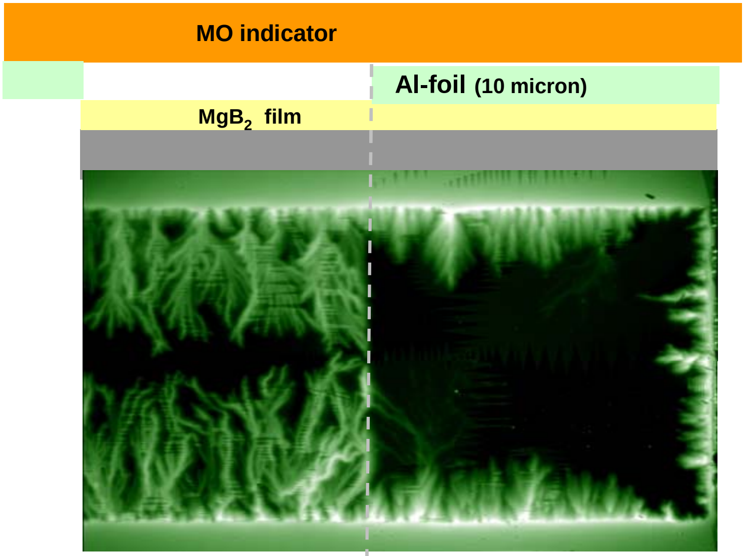
2) Displace $\Delta r_i \propto P_i$

3) $\Delta T = \Delta r_i\,F_i\,/c(T)$



Analytical nonlinear theory is absent.

Metal film suppresses thermo-magnetic instability

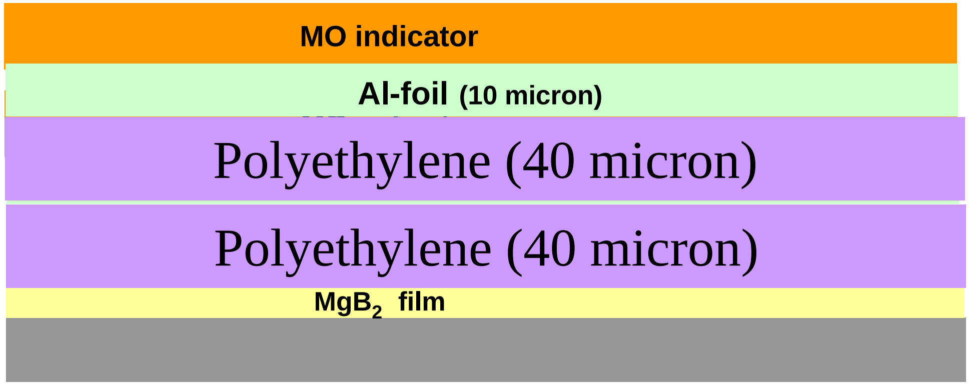


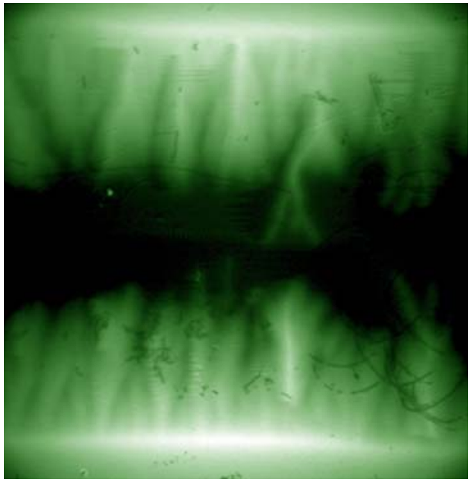
Physica C ***369***, *93 (2002)*

Heat removal (thermal contact)?

Electrodynamics? dB/dt => E => j

50% dendrites back

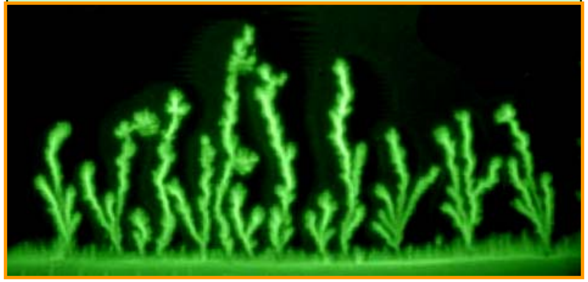


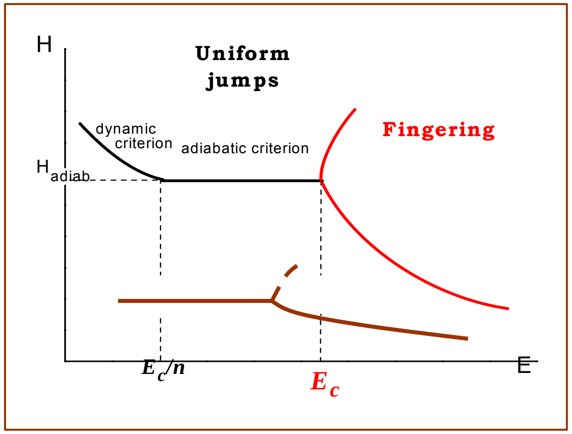


Poor thermal contact, but the instability is still suppressed

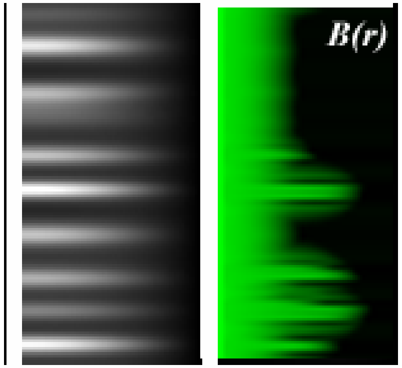
Conclusions

Fingering instability is observed experimentally



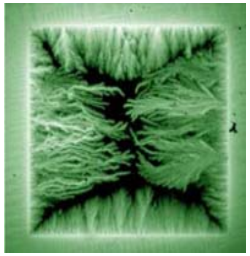


A linear theory based on the Maxwell and thermal diffusion equations is proposed. It predicts fingering for $E>E_c$, $H>H_f(E)$

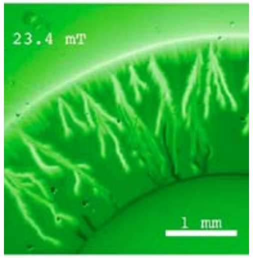


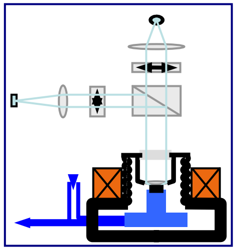
Numerics & simulations support analytical theory, show how the instability evolves beyond the linear regime

Dramatic role of anisotropy

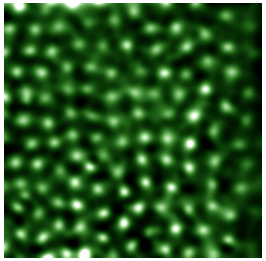


Multiply-connected samples

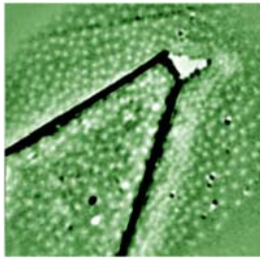




MOI of single vortices



Manipulation



More info:
http://www.fys.uio.no/super

Saltdasfjorden - Norway