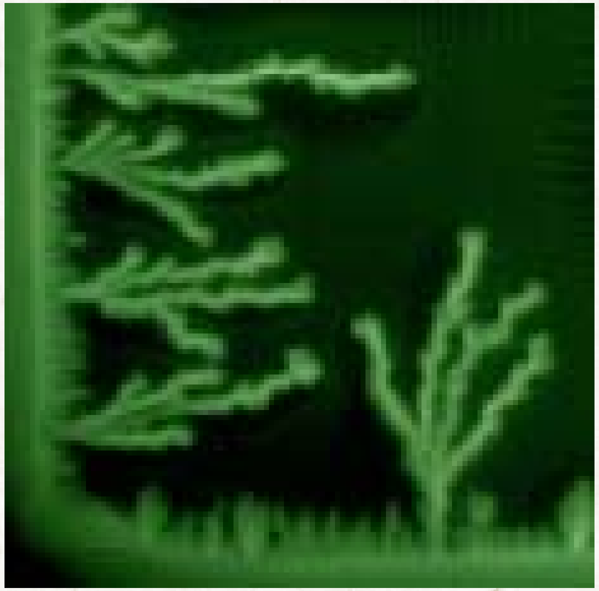
Magnetic avalanches in MgB_2 thin films



Sung-Ik Lee

Department of Physics,

Pohang University of Science and Technology

Collaborators

- Eun-Mi Choi, Hyun-Sook Lee, Byeongwon Kang, Won Nam Kang, H-G Lee and Sung-Ik Lee,
  Department of Physics, POSTECH
- Vitaliy V. Yurchenko, Å. A. F. Olsen, D. V. Shantsev, and T. H. Johansen
  Department of Physics, University of Oslo

Outlines

- Research objects
- Superconductivity of MgB_2
- What is Vortex avalanche?

  Introduction to the Magneto Optical imaging
- What has been studied?
- Magnetic avalanches MgB_2 thin films

  Au coating effect

  Size Effect

  Ring pattern: Vortex and Anti-vortex recombination

  with gold rim (width 100, 300, and 750㎛)
- Conclusions

Research objects

- The Critical Current Densities is anomalously high 10^7 A/cm^2 orders for the MgB_2 thin film:

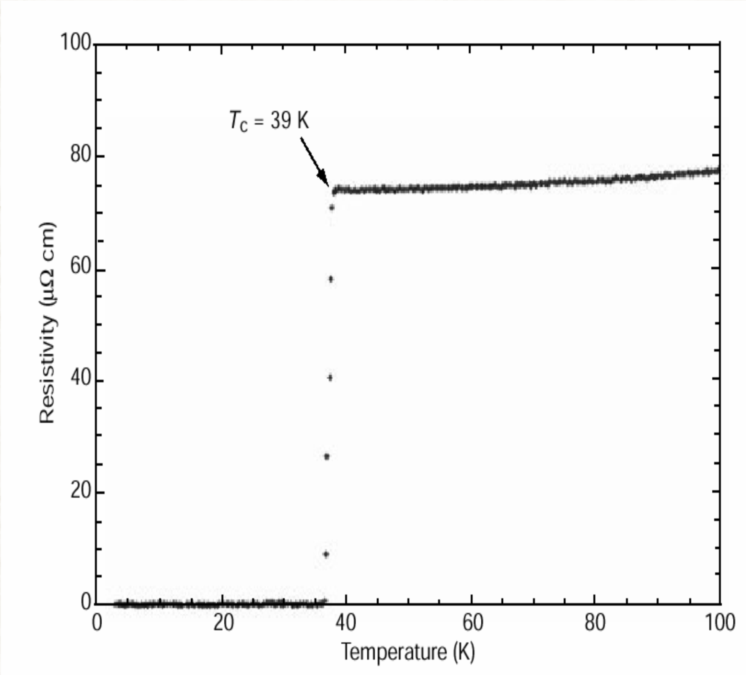
But vortex avalanche appears at low field and at low Temperature

- How to solve this problem?

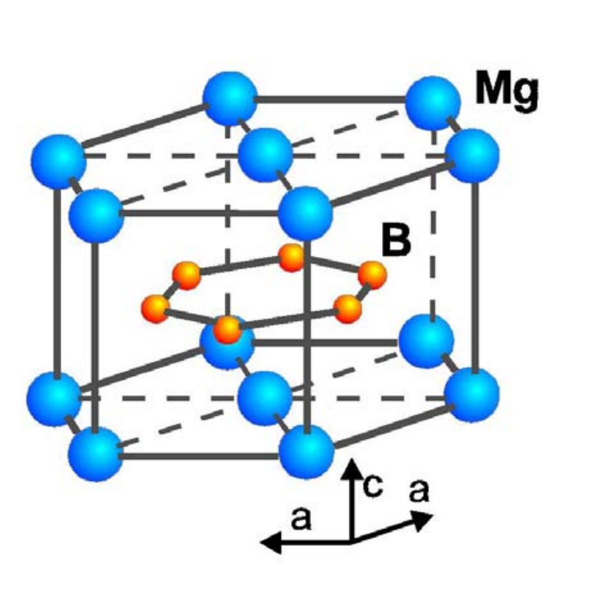
- Let's understand the origin of vortex avalanche!

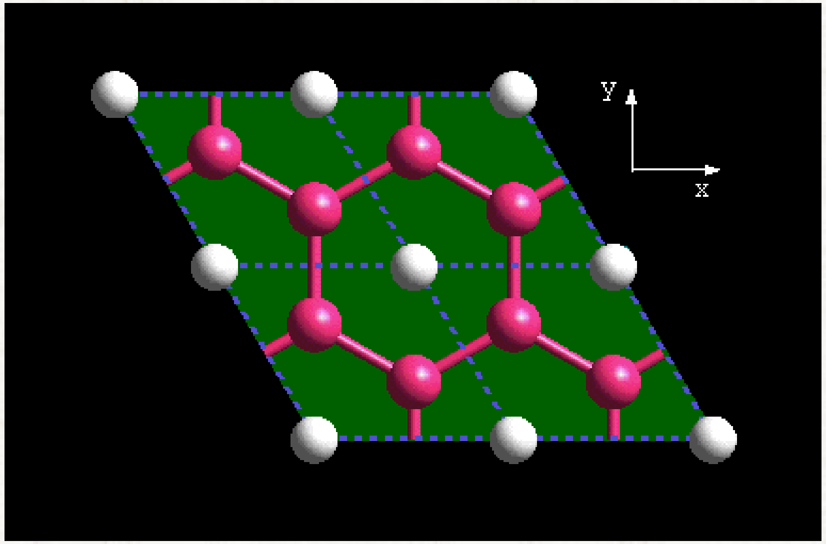
Thermo-magnetic instability?

MgB_2 – the overlooked superconductor
Synthesized 50 years ago
Commonly used in Chemistry Department
Superconductivity measured by Akimitsu, Japan



Crystal structures of MgB_2





Binary System

Is phonon mechanism the origin of Superconductivity-Yes

Isotope-effect : $Mg(^{11}B)_2$: T_c=39 K $Mg(^{10}B)_2$: T_c=40 K

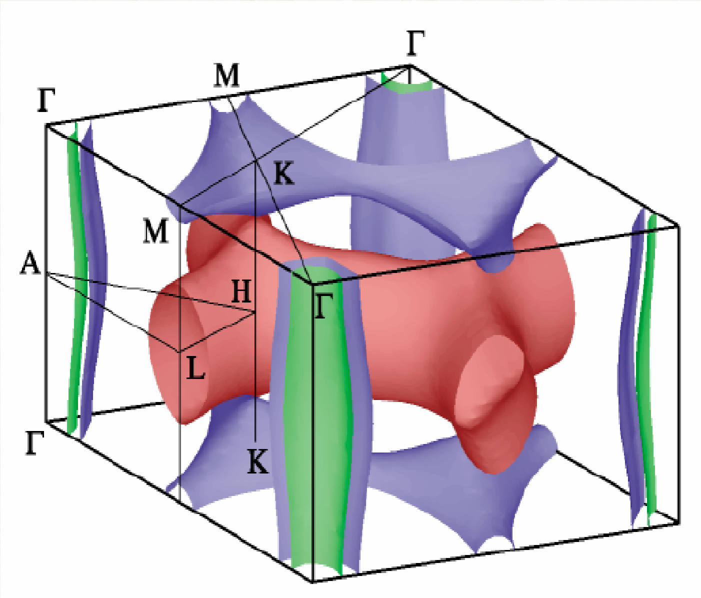
no indication of magnetic interactions

High T_c is understandable

$$T_c = 1.13\omega_c e^{-1/VN(0)}$$

Do we understand superconductivity of this materials?
No!
New Phenomena-Two gap superconductivity

Electronic and Gap structure



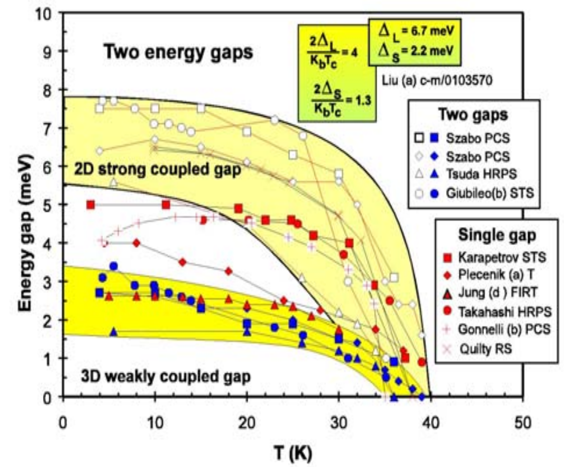
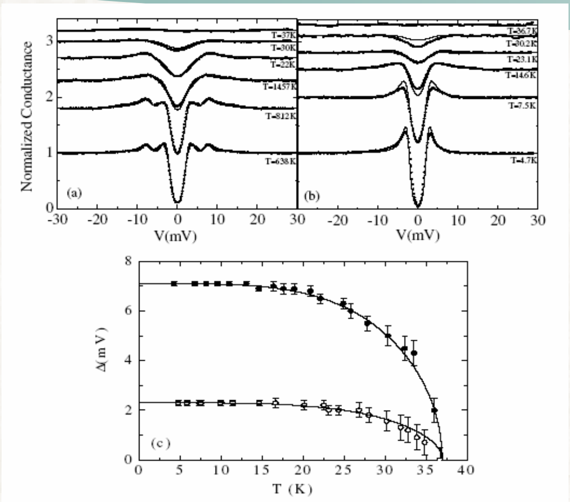


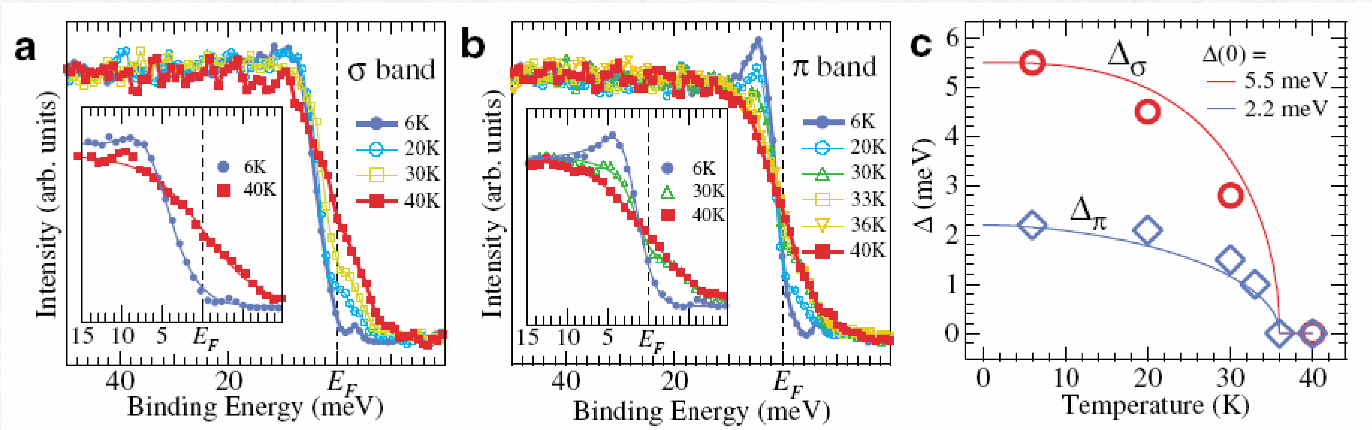
Figure 35. Energy gap dependence on temperature obtained from point contact spectroscopy (PCS), high-resolution photoemission spectroscopy (HRPS), scanning tunneling spectroscopy (STS), tunneling (T), far-infrared transmission (FIRT), Raman spectroscopy (RS) experiments. Data are taken from references [Szabo], [Tsuda], [Giubileo (b)], [Karapetrov], [Plecenik (a)], [Jung (d)], [Takahashi], [Laube], [Gonnelli (b)], [Quilty].

Two gaps ?   All of the superconducting properties are affected by this two gap nature. These include Static and Dynamic Properties.

Example of two-gap nature



Iavarone +Sung-Ik Lee.
PRL. **89**, 187002 (2002)

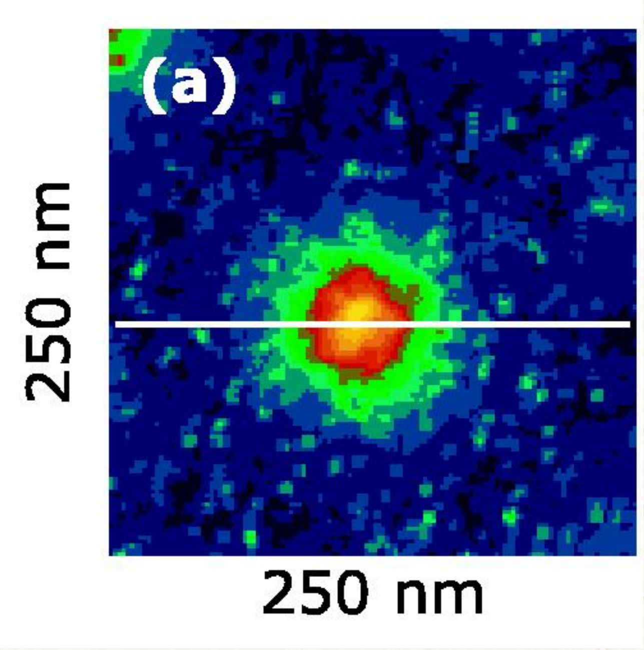


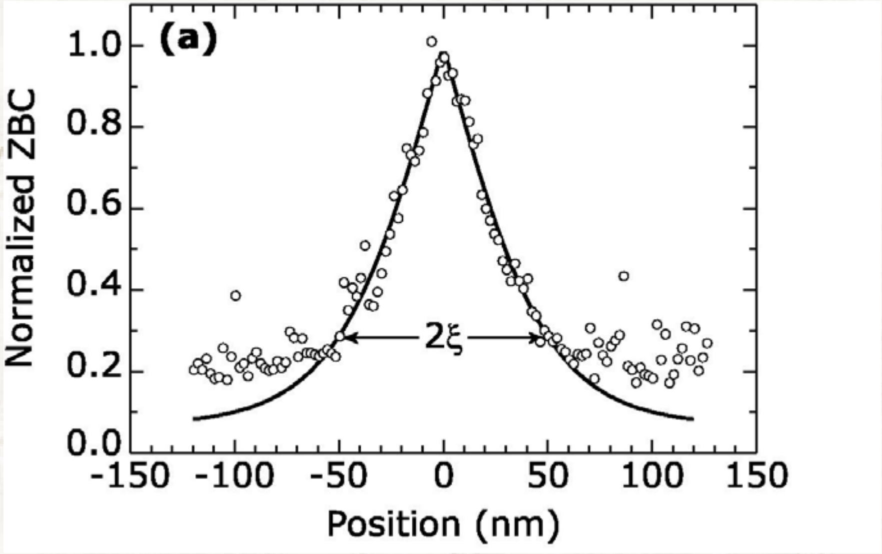
Photoemission. Tsuda *et al*. PRL **91**, 127001 (2003)

STM measurements with field in c-axis direction

$$H_{c2}^{c}(T=0\mathrm{K})=3.1\mathrm{T} \Rightarrow \xi \approx 10\mathrm{nm}$$

Size of the vortex core: $\xi \approx 50\mathrm{nm}$

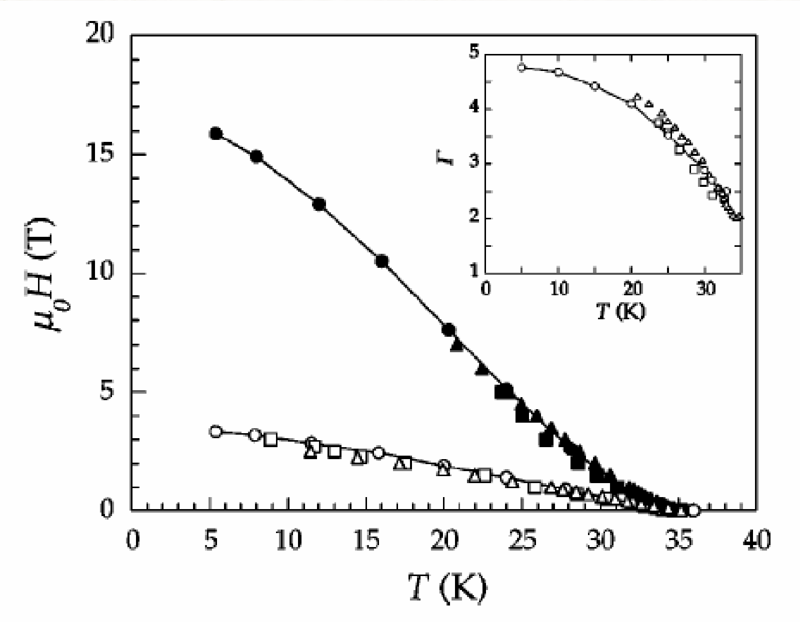




Eskildsen et al, PRL 89, 187003 (2002)

H_{c2} - clean limit

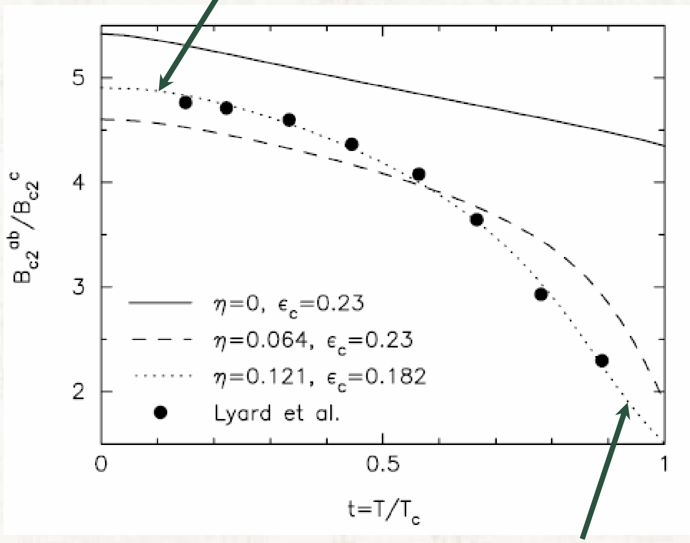
Argonne National Lab + Postech



$H_{c2}^{\perp}(0) \approx 3.5$ T

$H_{c2}^{\parallel}(0) \approx 15$ T

σ band control here



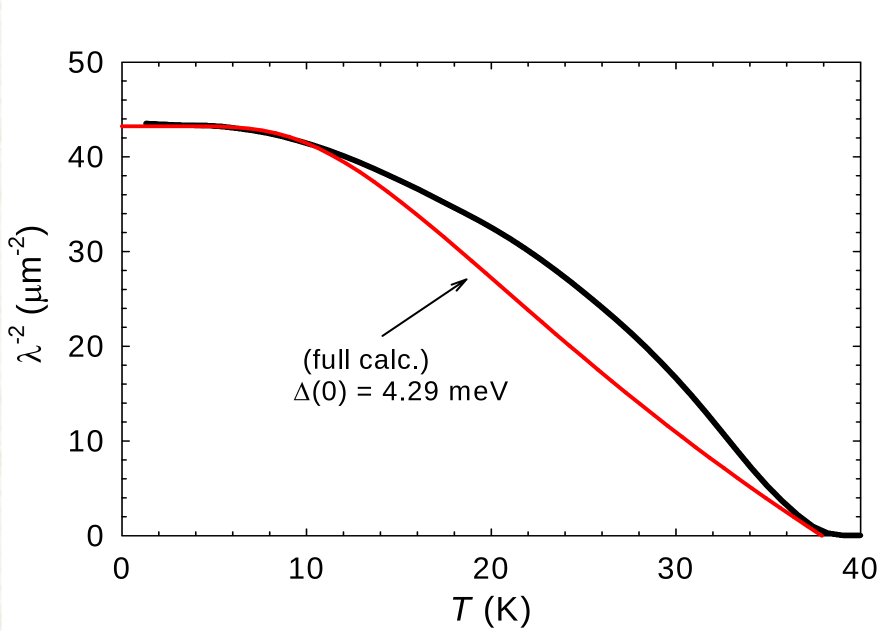
π band is important here

Full BCS Calculation Assuming Single Gap

Lemberger & Sung-Ik Lee

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = 1 - 2\int_{\Delta}^{\infty}\left(-\frac{\partial f}{\partial E}\right)D(E)dE$$

D(E) : quasiparticle density of states
f : Fermi function

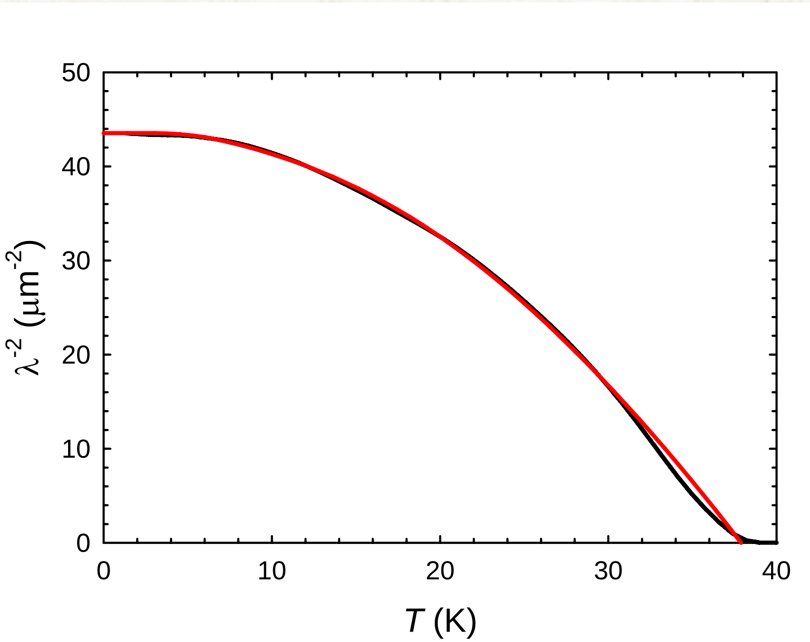


Full BCS Calculation Assuming Double Gap

Lemberger & Sung-Ik Lee

$$\frac{\lambda^{-2}(T)}{\lambda^{-2}(0)} = 1 - 2\left[c_1 \int_{\Delta_S}^{\infty} \left(-\frac{\partial f}{\partial E}\right) D_S(E)dE + c_2 \int_{\Delta_L}^{\infty} \left(-\frac{\partial f}{\partial E}\right) D_L(E)dE\right]$$

c_1 (c_2) : contribution of small (large) gap to r_s



$\Delta_S(0) = 2.61 \pm 0.41$ meV

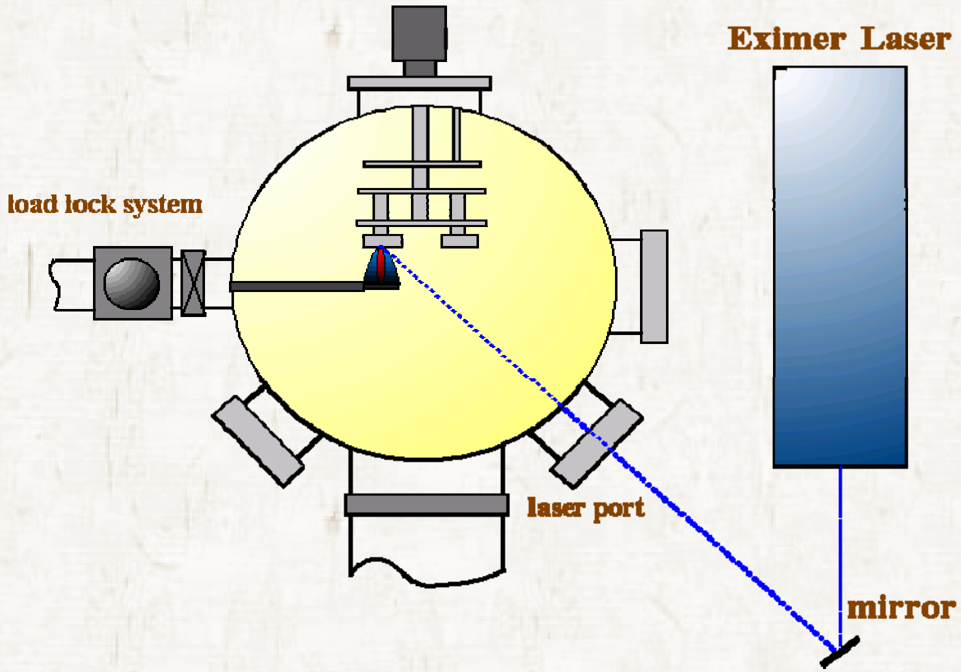
$\Delta_L(0) = 6.50 \pm 0.33$ meV

$c_1 = 0.21 \pm 0.06$

$c_2 = 1 - c_1$

Fabrication of MgB_2 thin films

Growth of the precursor B films by PLD

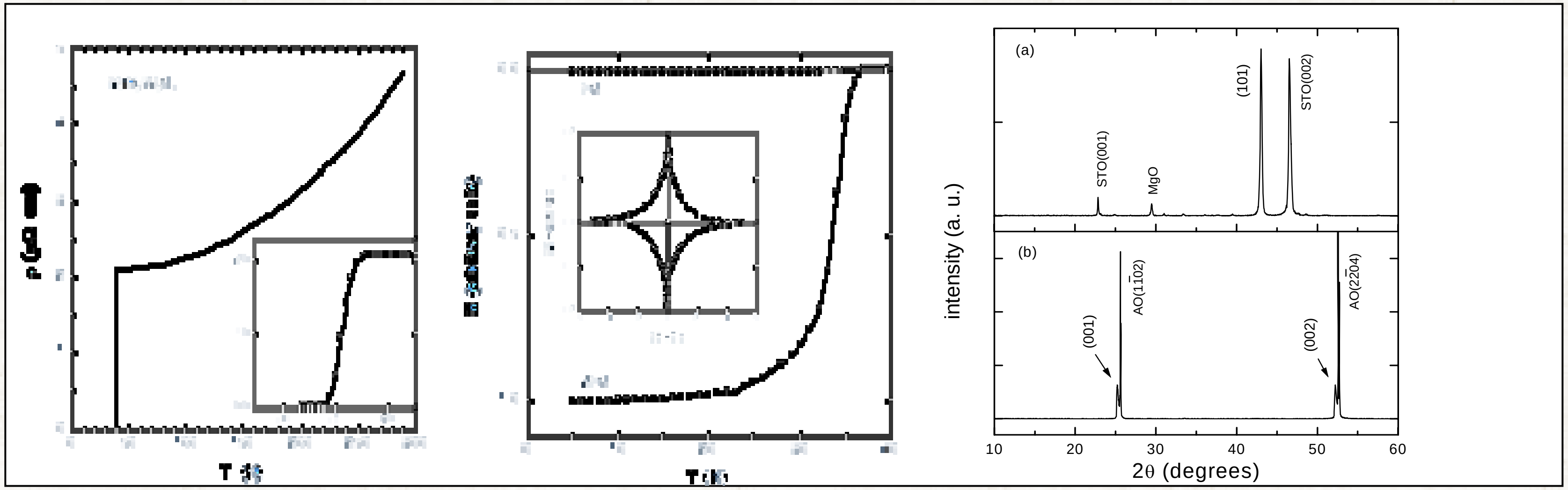


MgB_2 thin films with T_c of 39 K

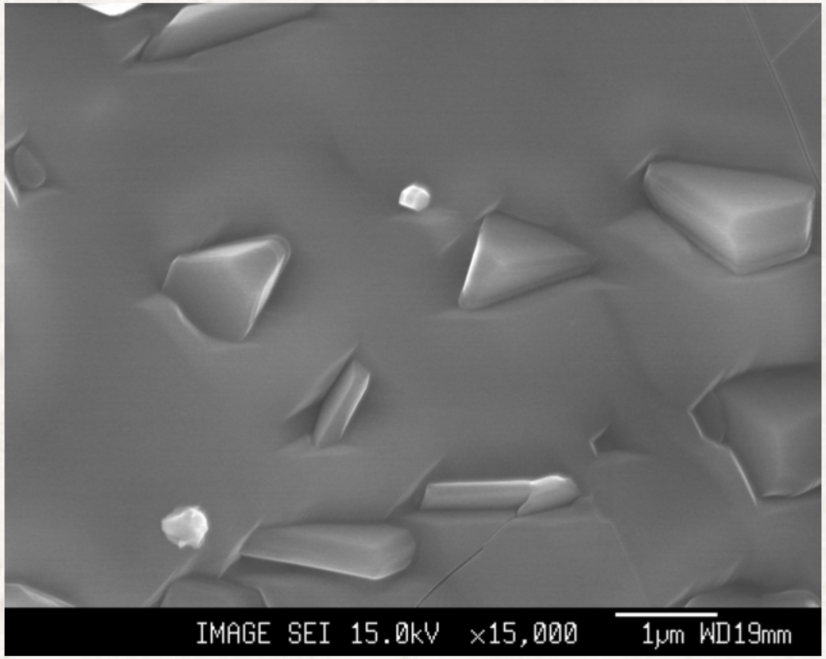
– T_c = 39 K

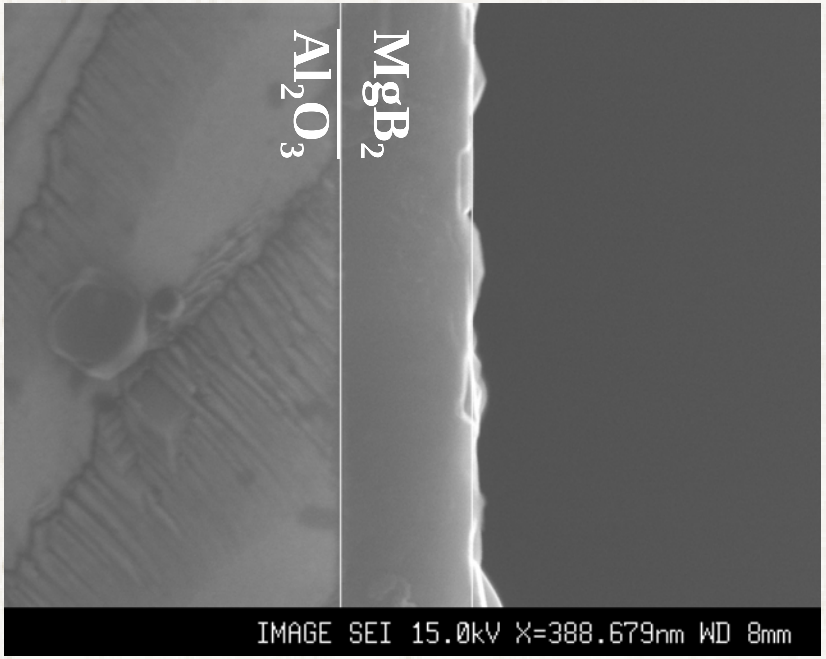
- J_c ~ 20 MA/cm^2 @ 15 K and 0 T
- Critical Current Density-World Record
- Highly c-axis oriented thin films
- Science 292, 1521 (2001), PRL 87, 087002 (2001)

POSTECH

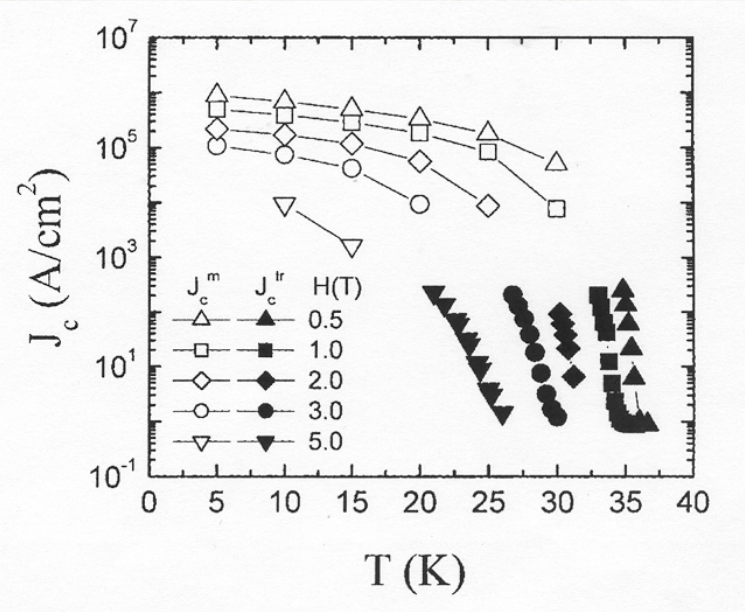


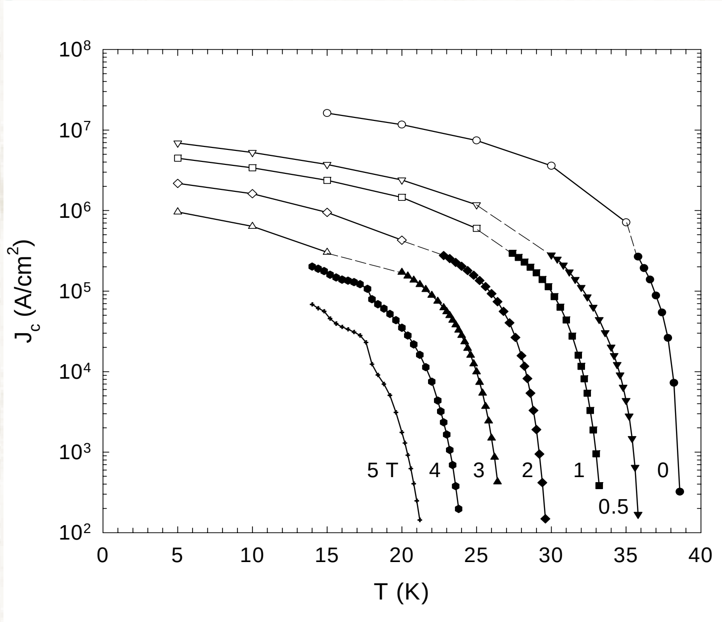
SEM pictures of MgB_2 Thin Films





Critical current density





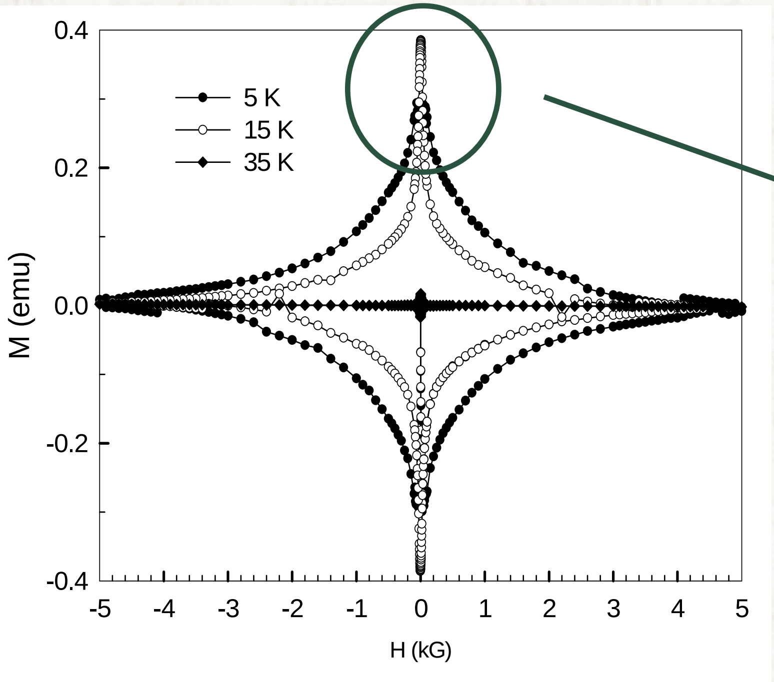
For bulk sample

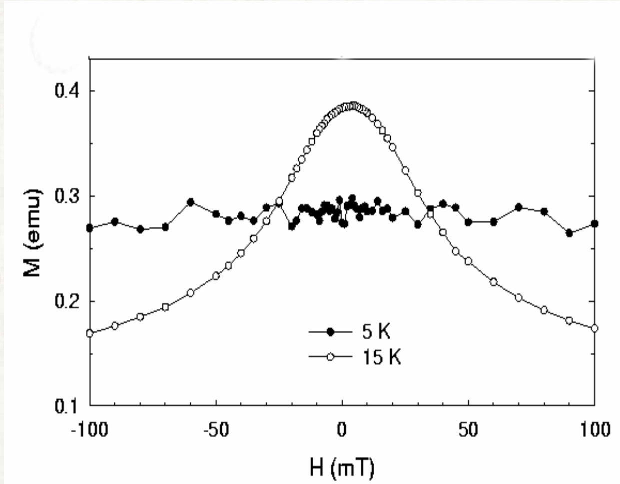
For single crystal
at 500 Oe
Jc ~ 1.5 x 10^5A/cm^2 at 5 K

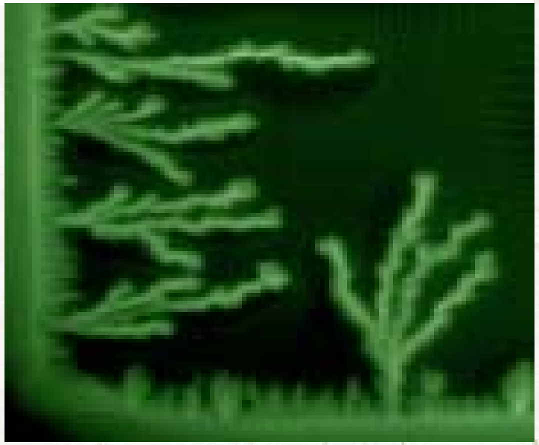
For thin film

at *H* = 0 T
Jc **~ 40 MA/cm^2 at 5 K**
16 MA/cm^2 at 15 K
0.1 MA/cm^2 at 37 K

Problems for Critical Current Densities

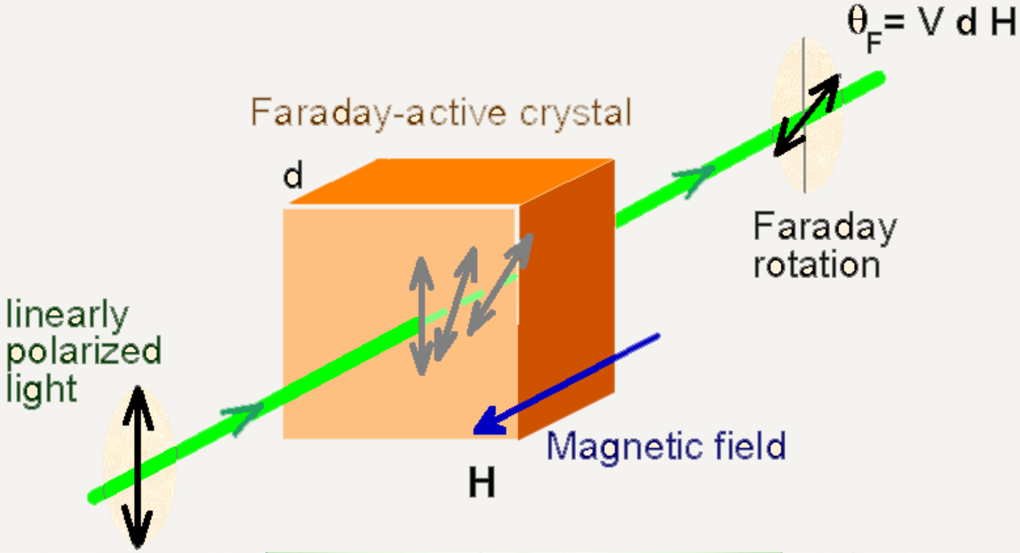


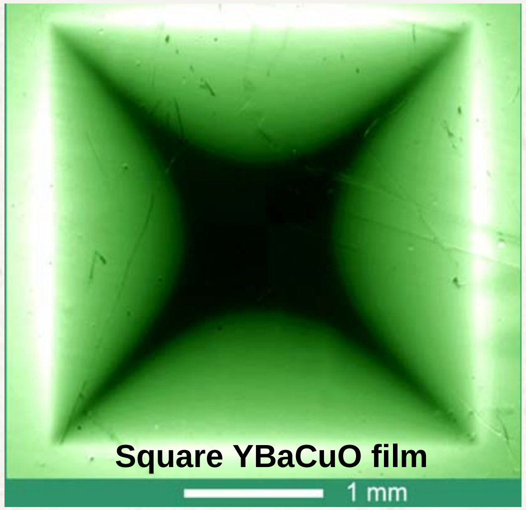




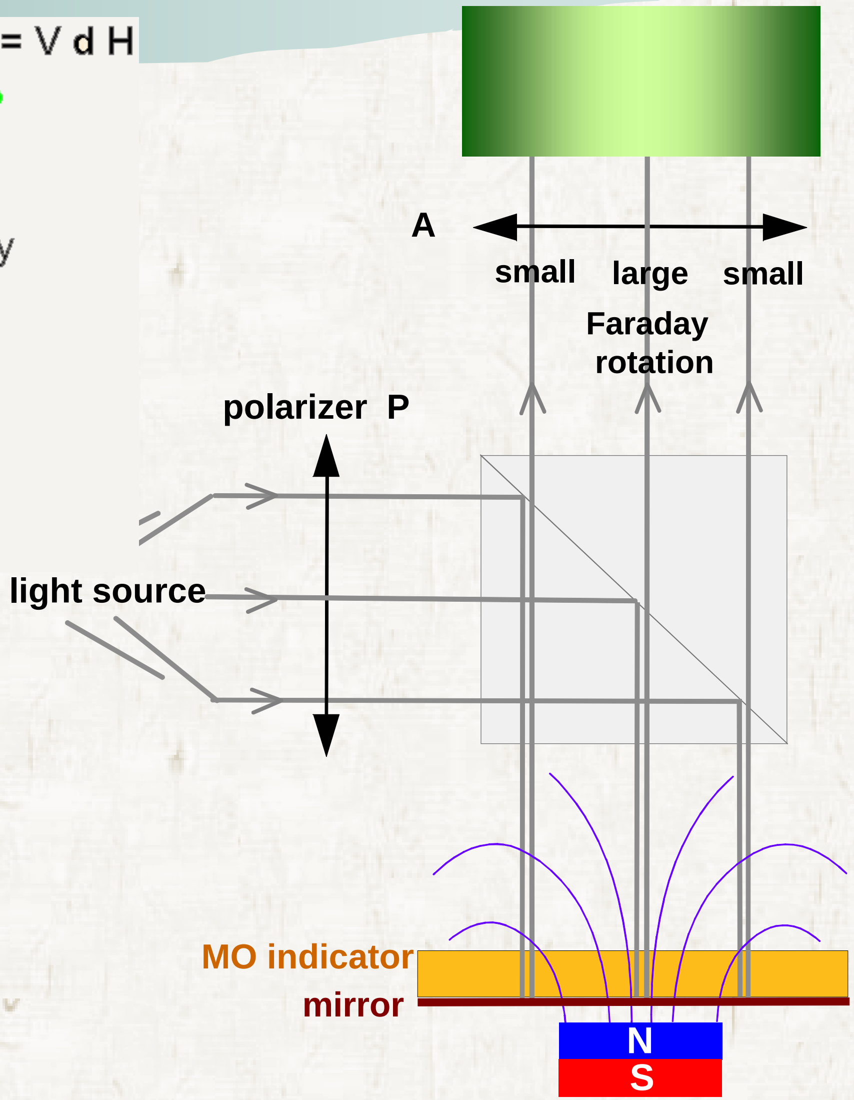
Flux jumps or Flux noise in *M-H* loop
⟶ vortex avalanche phenomenon

Magneto-optical Imaging





Square YBaCuO film



Vortex Avalanche in MgB_2 Thin Film

- Why thin film of MgB_2?

- Low Thermal Conductivity, Low Specific Heat, High Critical density, Thin film

- How to cure?

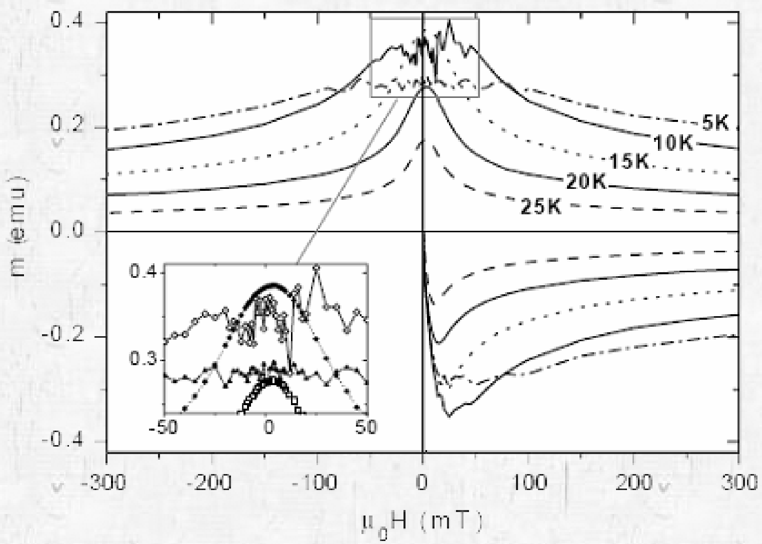
  Increase the thermal conductivity by gold deposition on MgB_2 thin film

  Reduce the size of thin film

Vortex avalanches in MgB_2 thin film

MO images

Magnetic Hysteresis (*M-H*) Loop

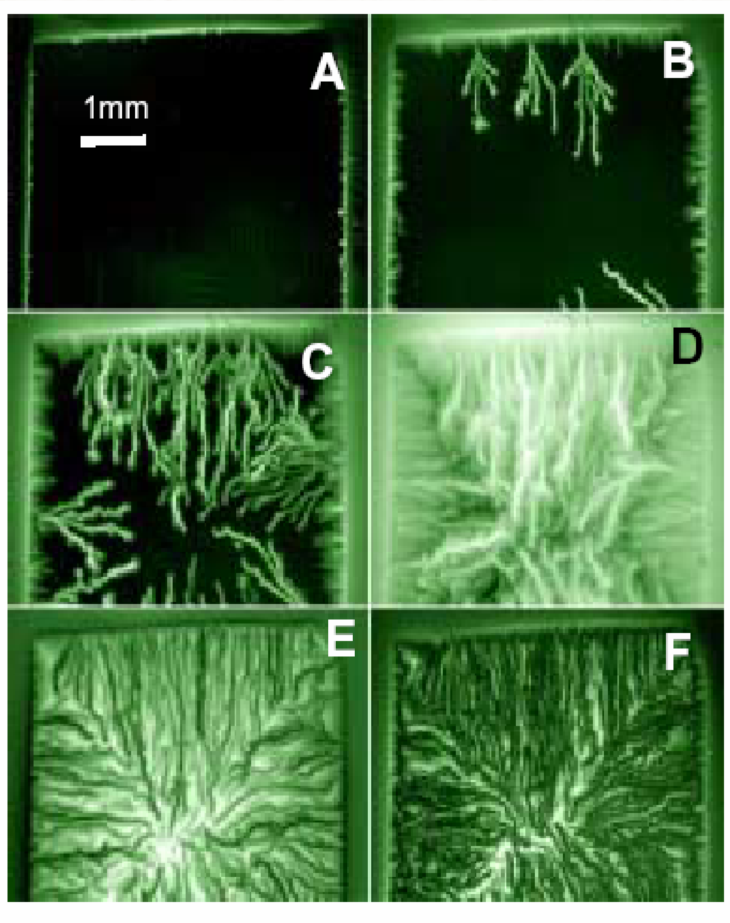


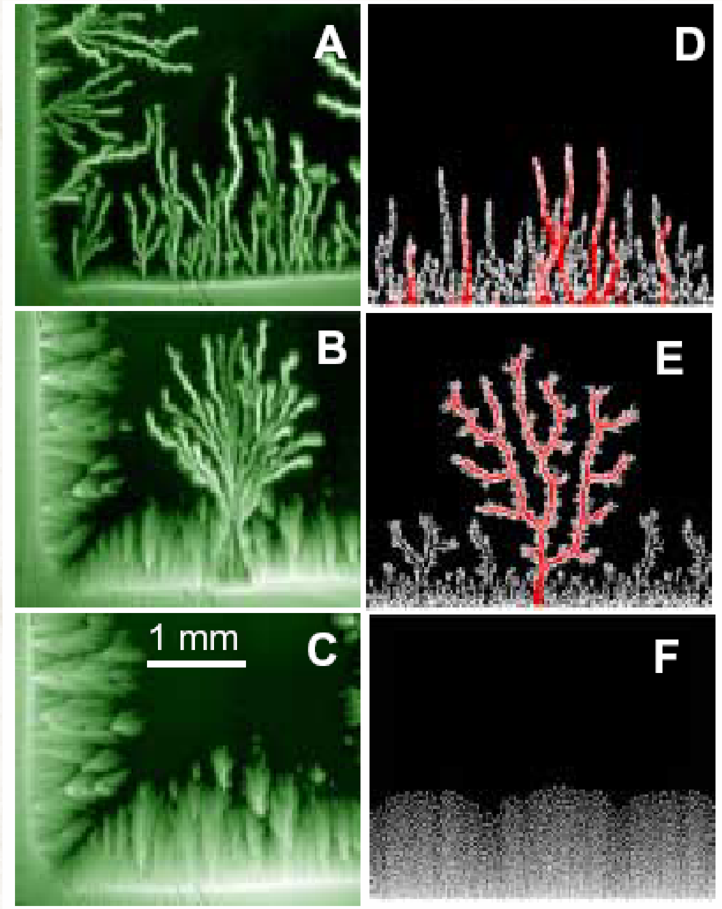
Field increases from zero up to 35 mT , 3K

http://www.fys.uio.no/super/movies.html

Magneto Optics Image of the vortex Penetration

U of Oslo & Postech





Current-induced dendritic magnetic instability in MgB_2 films

U of Oslo & Postech

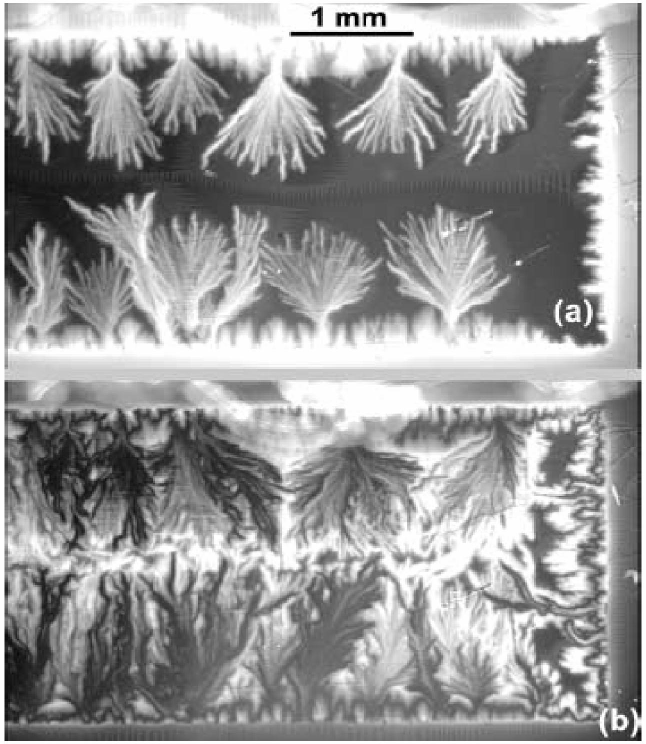
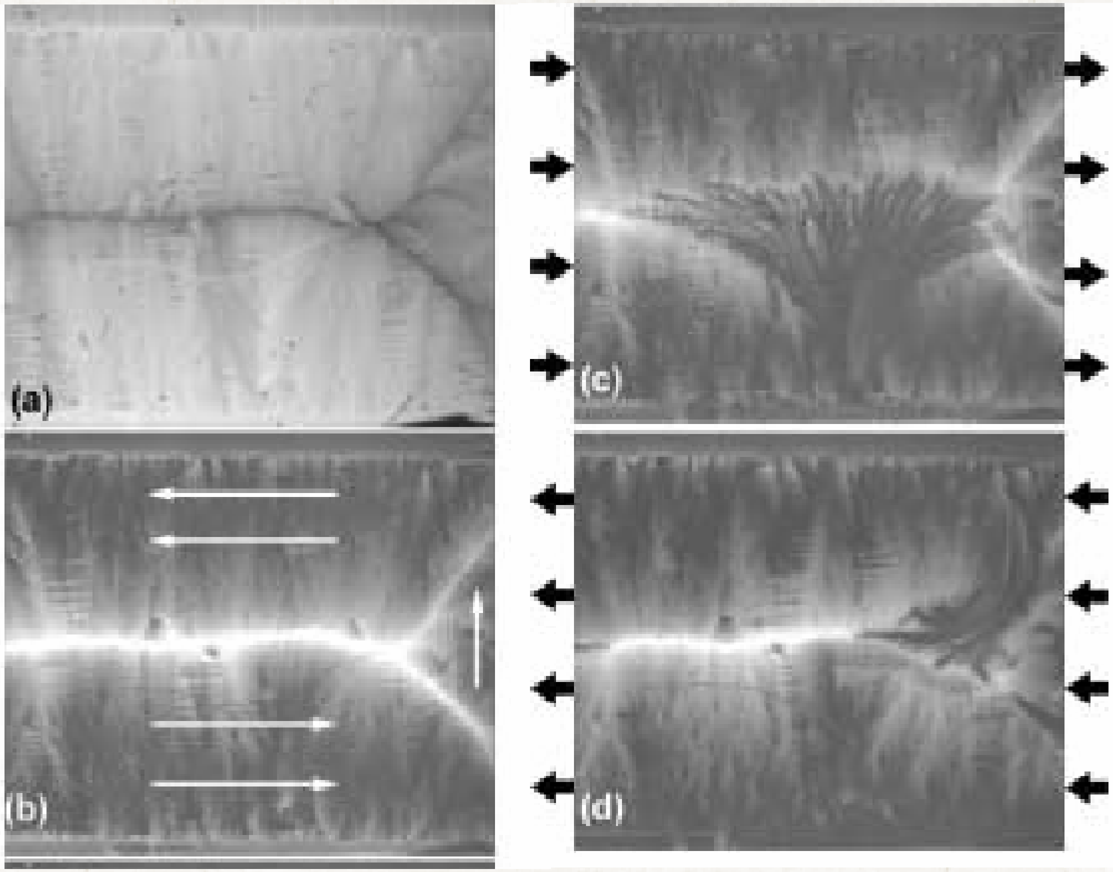
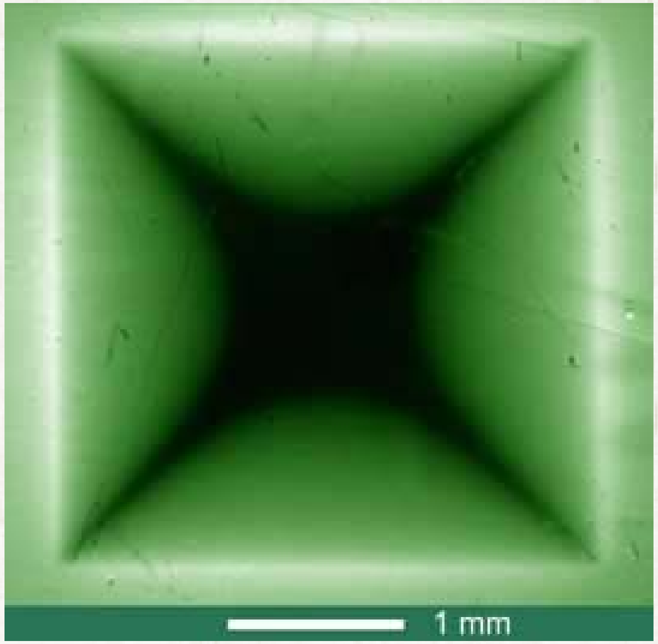


FIG. 1. Magneto-optical images of the flux distribution in a rectangular strip of MgB_2 thin film at 3.5 K. The image brightness represents the magnitude of the local flux density.



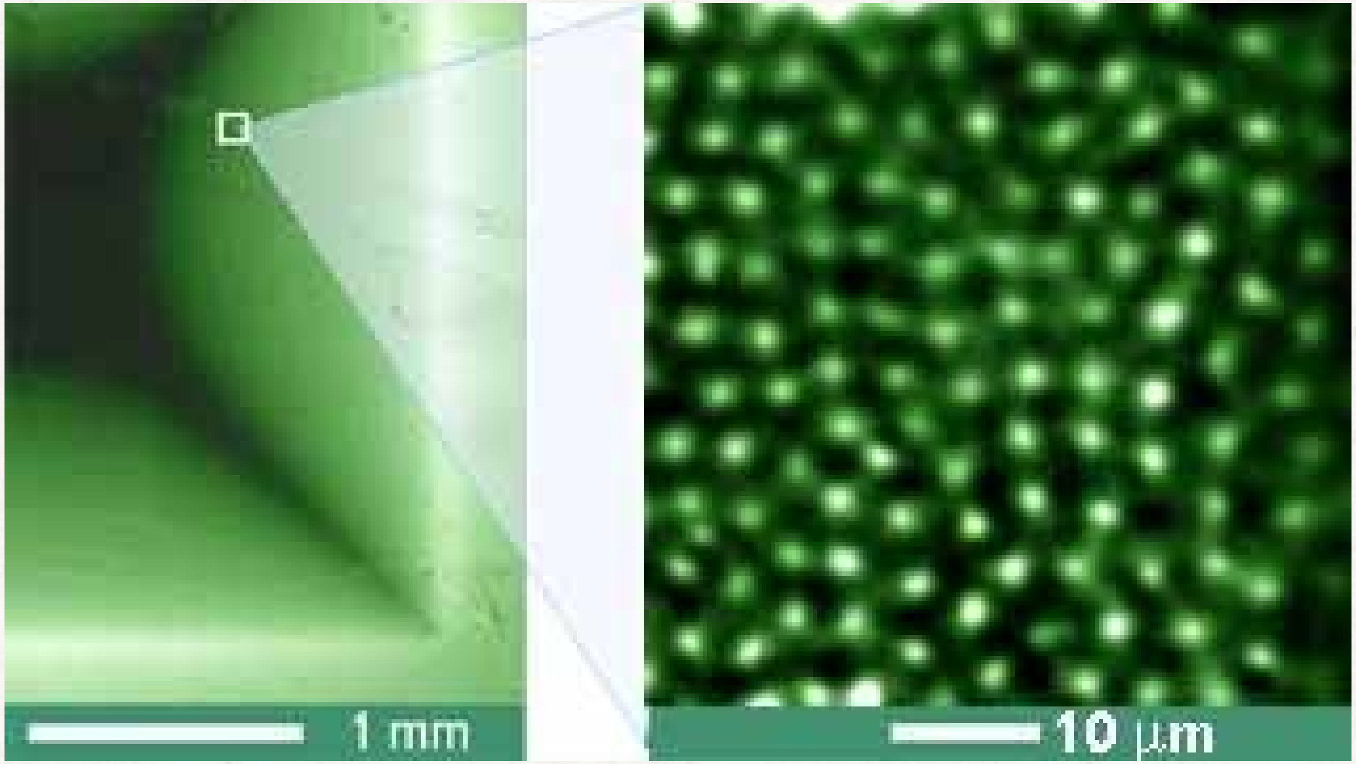
Observation of critical state

YBCO film



Homepage : http://www.fys.uio.no/super/mo/index.html#obcrstate

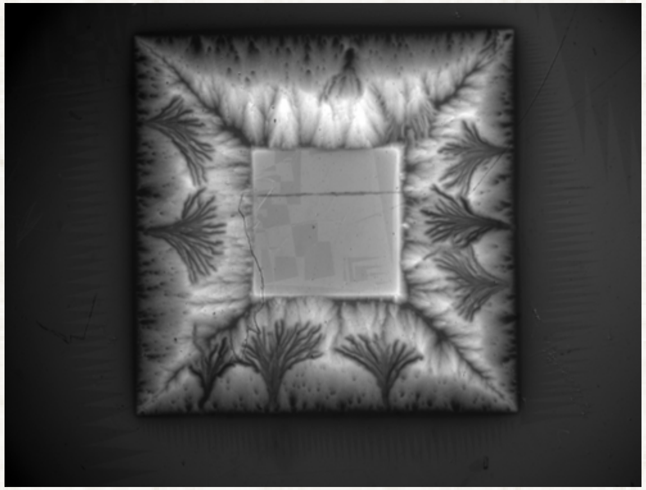
Resolving of individual vortices

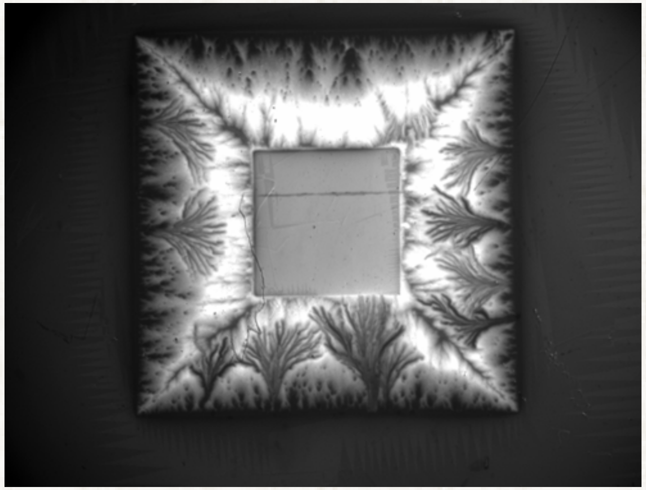


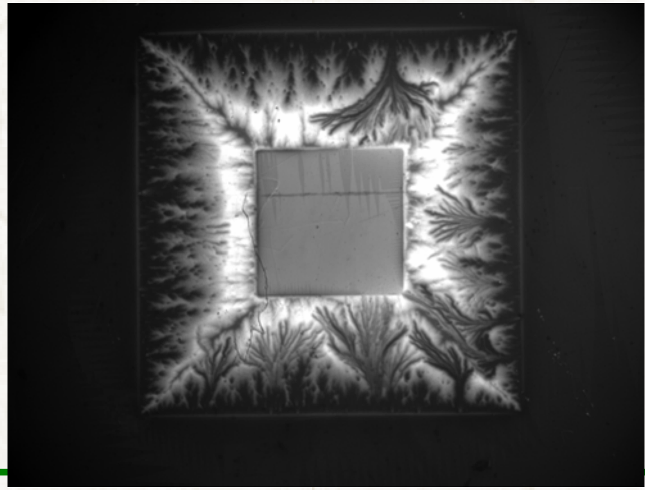
Homepage : http://www.fys.uio.no/super/mo/#mo-principle

Square pattern of MgB_2 thin film

At 3.4K, decreasing applied field







Remnant state

Simulation of Vortex avalanche
Maxwell equation coupled to heat diffusion

PRL. 28(2005) 037002 I. S. Aranson *et. al.*

$$C\partial_t T = \nabla\kappa\nabla T - (T - T_0)h/d + \mathbf{JE}(J,T), \quad (1)$$

$$\partial_t \mathbf{B} = -\nabla\times\mathbf{E}(J,T), \qquad \nabla\times\mathbf{H} = \mathbf{J}\delta(z), \quad (2)$$

A thin film strip: width w, length L, thickness $d \ll w$,

H_0 : xy plane perpendicular to the magnetic filed

$\mathbf{B}(\mathbf{r},t)$: Magnetic induction

$T(\mathbf{r},t)$: Temperature

$C(T)$: Heat capacity $\kappa(T)$: Thermal conductivity

$h(T,T_0)$: Heat transfer coefficient to the coolant or substrate

$\mathbf{E} = \mathbf{J}E(J,T)/J$: Electric field

$$E = (J - J_C)\rho_F \quad \text{for} \quad J > J_C$$

$$E = E_C \exp(J - J_C)/J_1 \quad \text{for} \quad J < J_C$$

Experiment

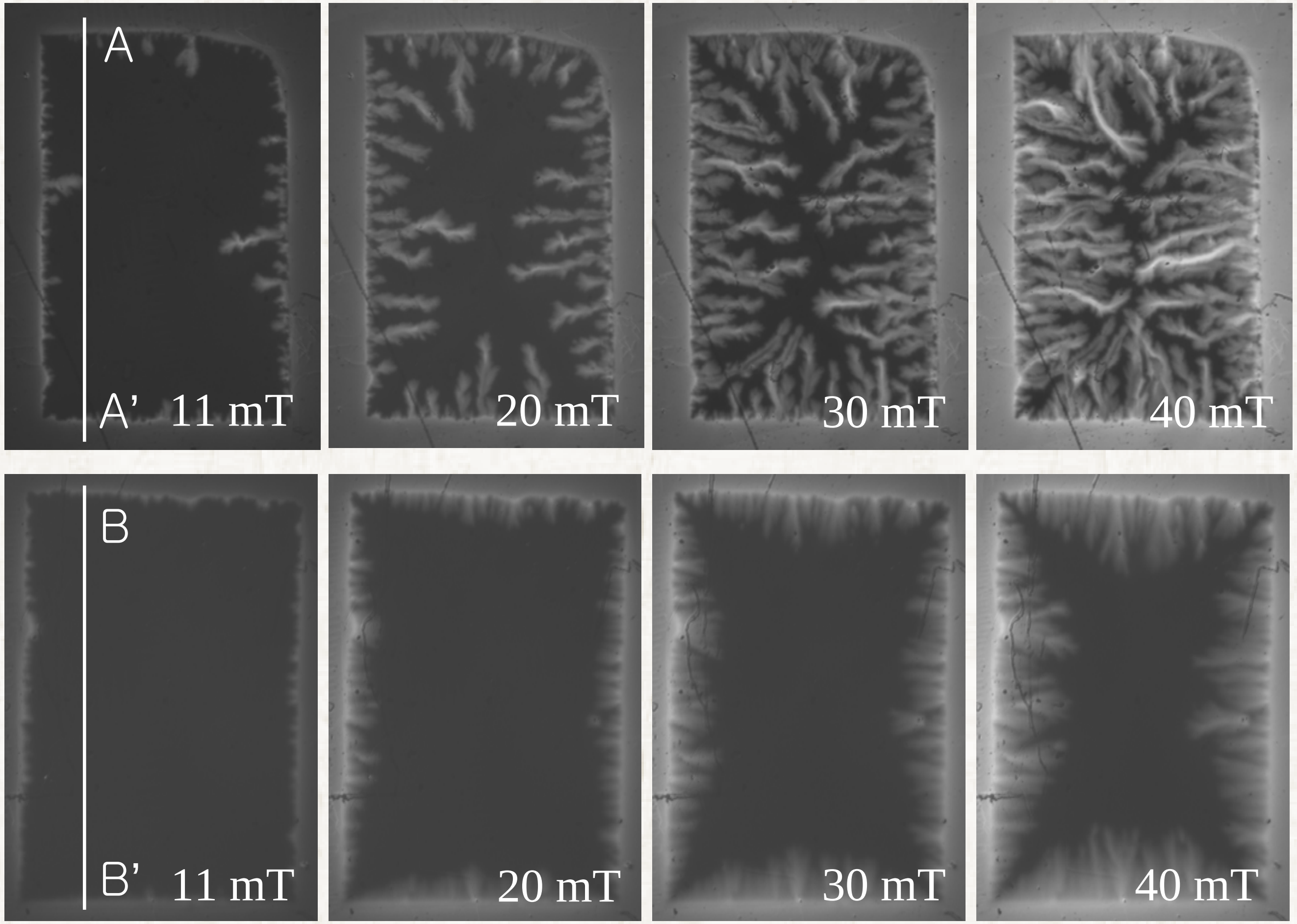
Magnetic avalanches in MgB_2 thin films with and without a deposited Au layer

Measurements of vortex avalanche

- The Magneto Optical Imaging (MOI) temperature : 3.8 K
  field sweep rate : 2 mT/sec

- The Magnetization Measurements
  measuring *M-H* loop using SQUID

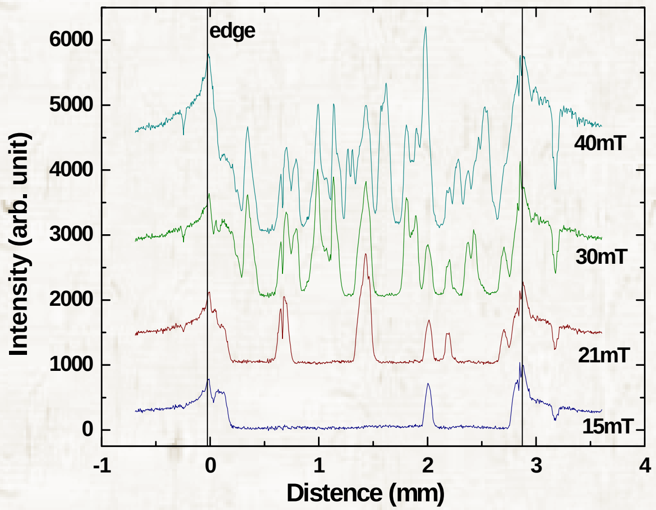
The Au coating effect on MO



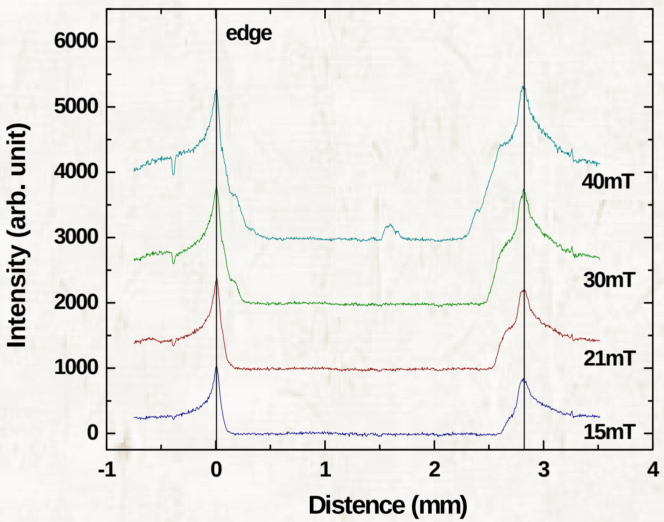
0 μm

2.55 μm

Profiles of Flux density



0 μm



2.55 μm

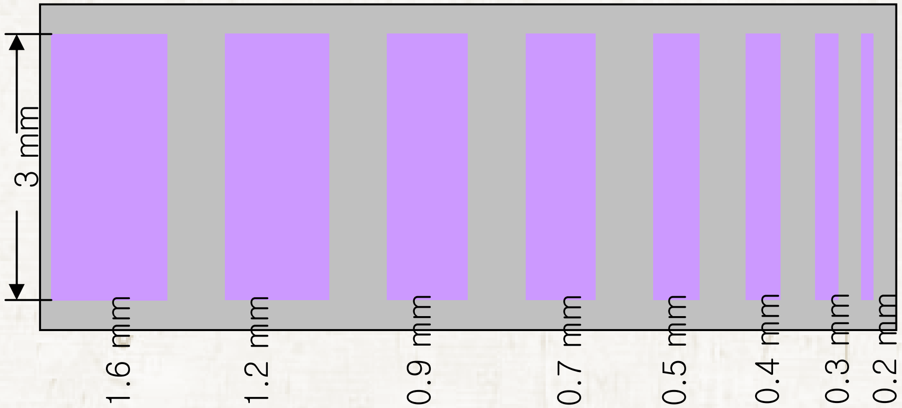
Experiment

Magnetic avalanches in MgB_2 thin films with different width

Sample preparation and Measurements

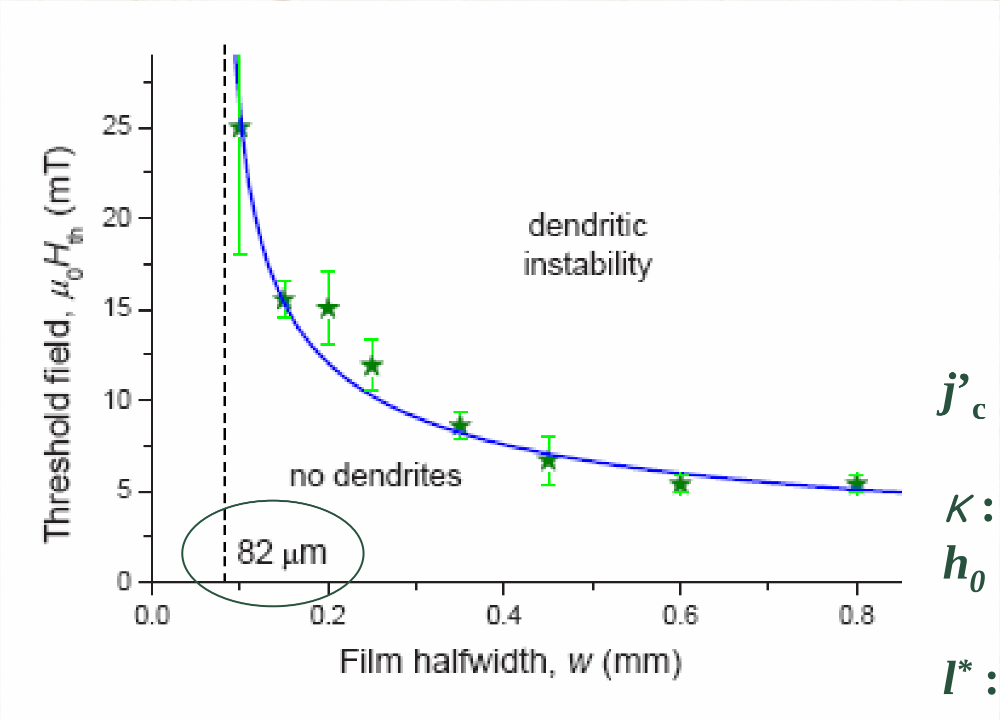
- Sample Preparation
  using photo lithography

- The Magneto Optical Imaging (MOI) temperature : 3.8 K
  field sweep rate : 2 mT/sec



Threshold magnetic field of the dendritic instability in MgB_2 thin film

Symbol : experimental data
Line : theoretical fit



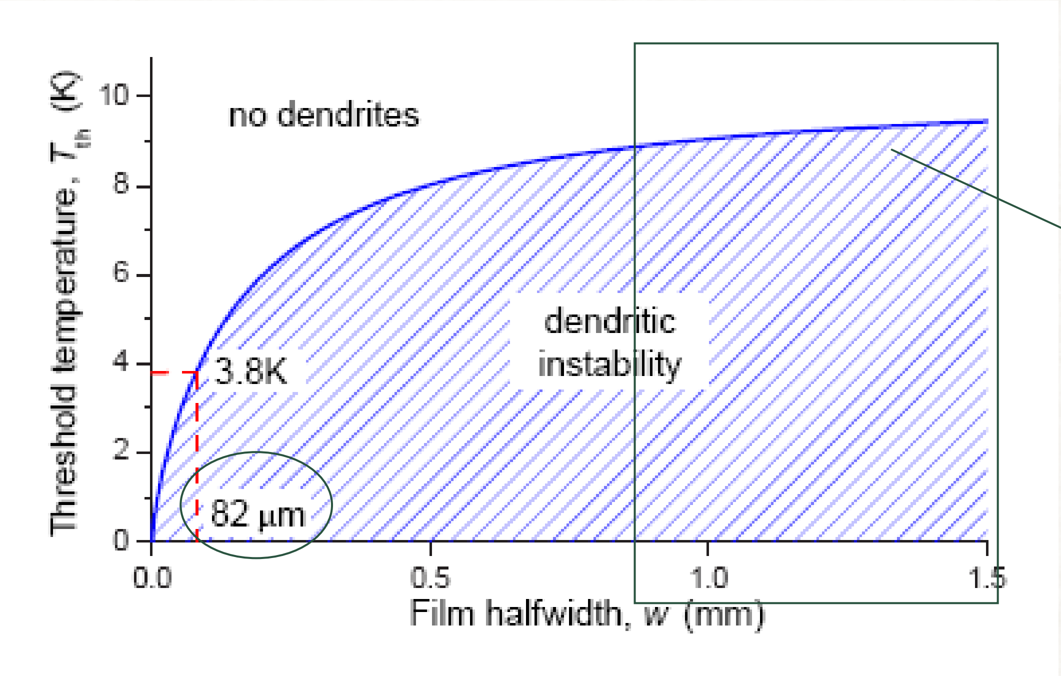
$$H_{th} = \frac{j_c d}{\pi} \operatorname{arccosh}\left(\frac{w}{w - l^*}\right)$$

$$l^* = \frac{\pi}{2}\sqrt{\frac{\kappa}{|j'_c| E}}\left(1 - \sqrt{\frac{2h_0}{nd|j'_c|E}}\right)^{-1}$$

$$j_c = j_{c0}(1 - T/T_c), n = \tilde{n}(T_c/T - 1)$$

j'_c : temperature derivative of the critical current density
κ : thermal conductivity
h_0 : coefficient of heat transfer to the substrate
l^* : threshold flux penetration depth
n : dimensionless quantity

Theoretical dependence of the threshold temperature (T_{th}) on the MgB_2 film width



Saturation of T_{th}(w) dependence

→

threshold temperature for wide MgB_2 films : around 10K

Experiment

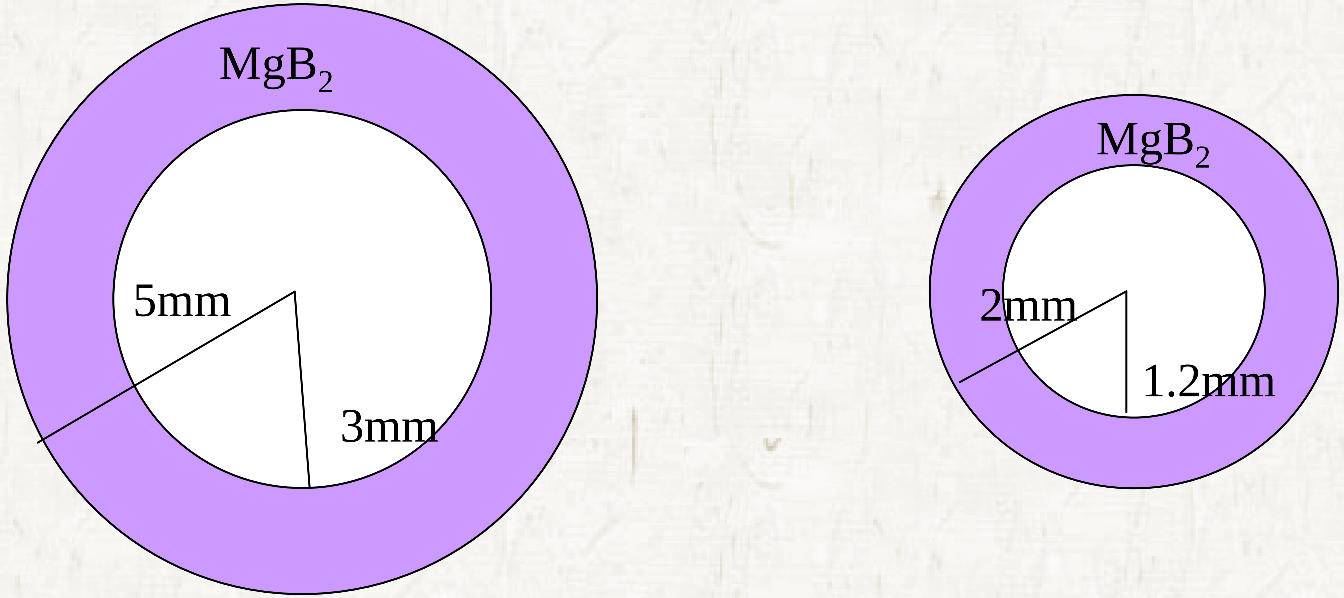
Magnetic avalanches in MgB_2 thin films ring patterned

Why ring patterned samples?

- Vortex Profiles for various type configuration

- Will be used in
  SQUID (Ring-type Pattern)
  Magnetic bearings,
  High-field permanent magnets

Sample preparation

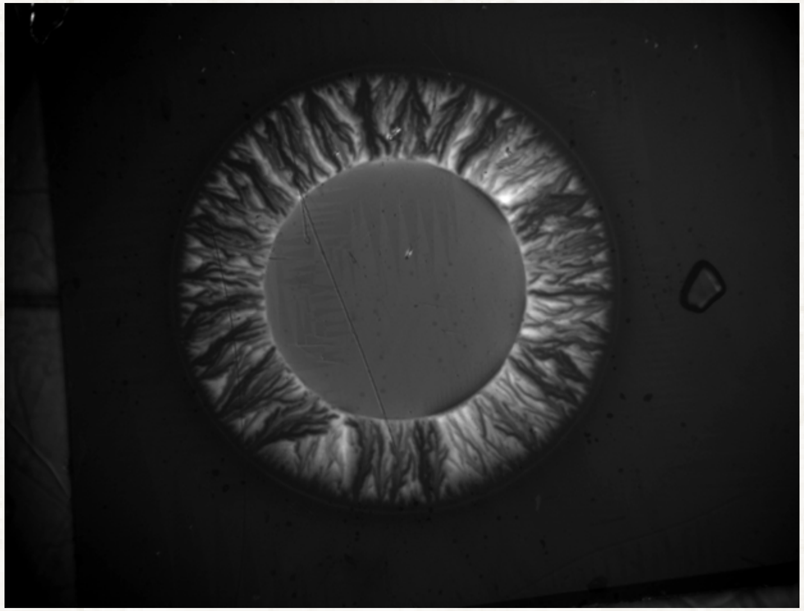


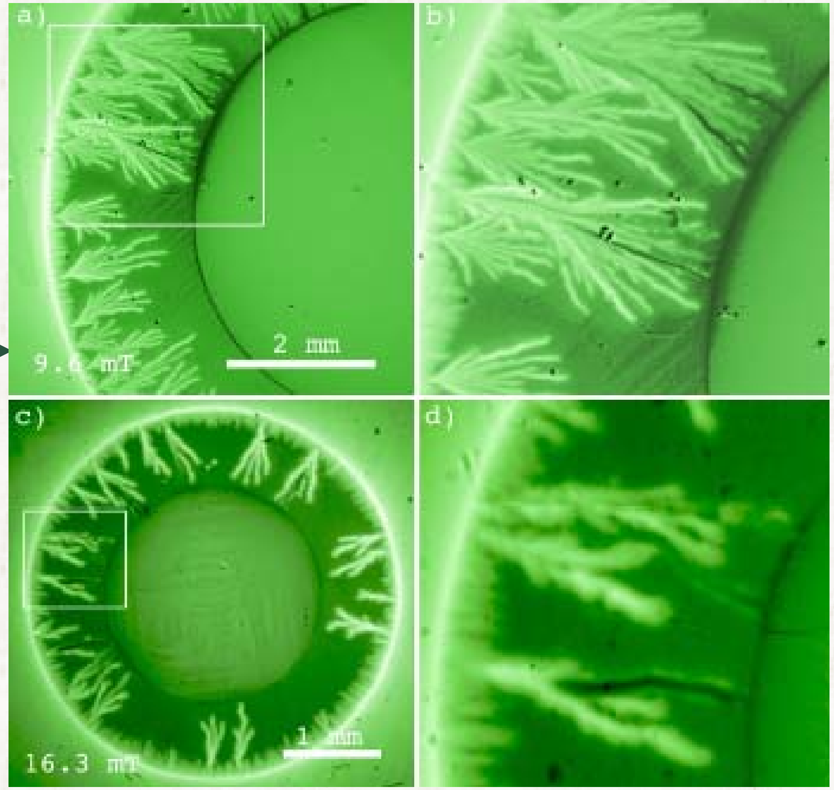
Ring 1

Ring 2

The thickness of film : 500nm
Film fabrication : two-step method using PLD
Pattern : using photolithography

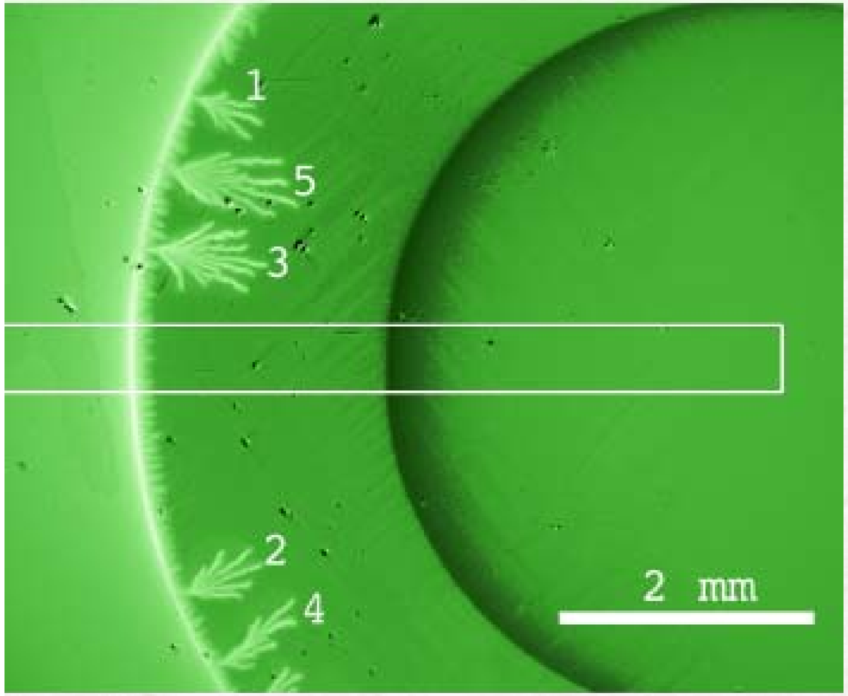
Dendrites of opposite polarity in MgB_2 ring

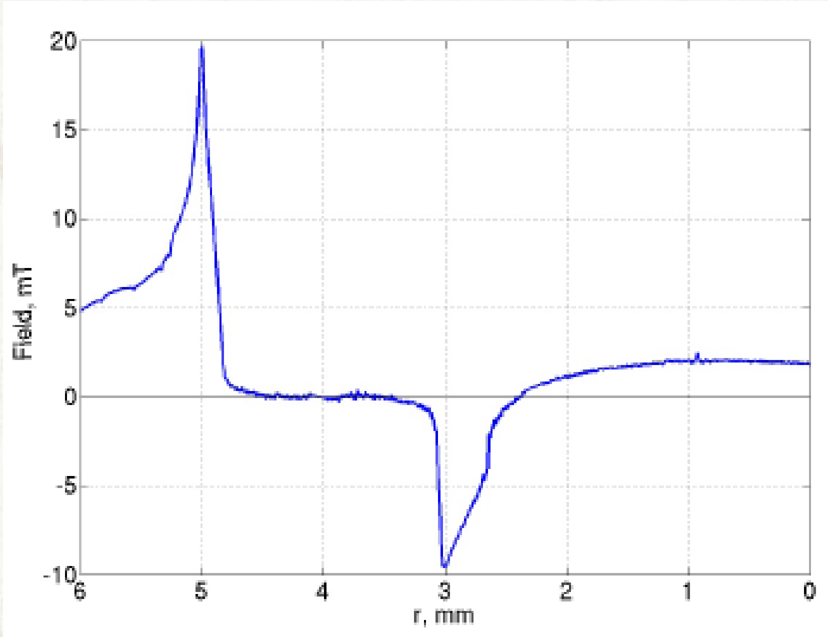




(a) and (b) : ring 1
(c) and (d) : ring 2

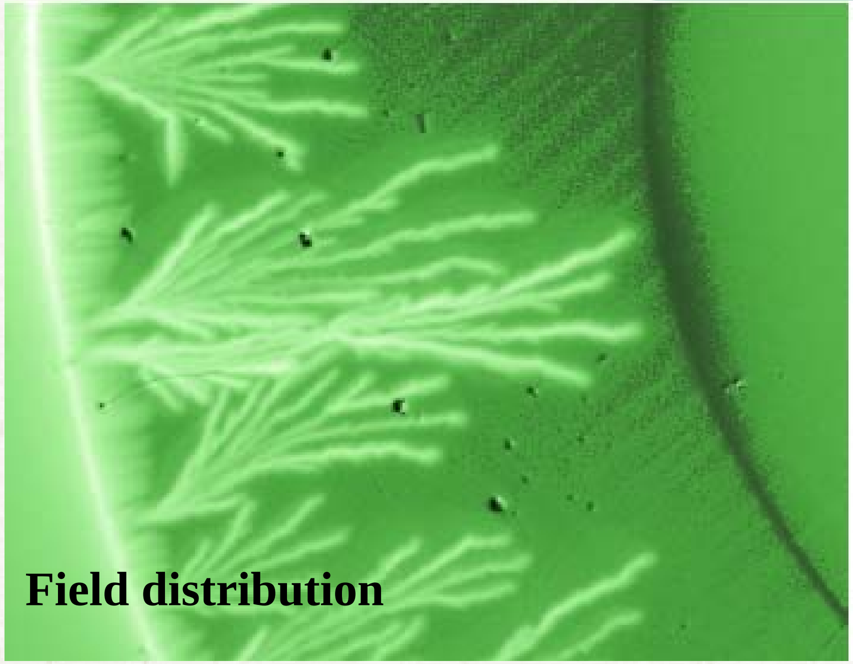
The flux distribution at B=3.6mT

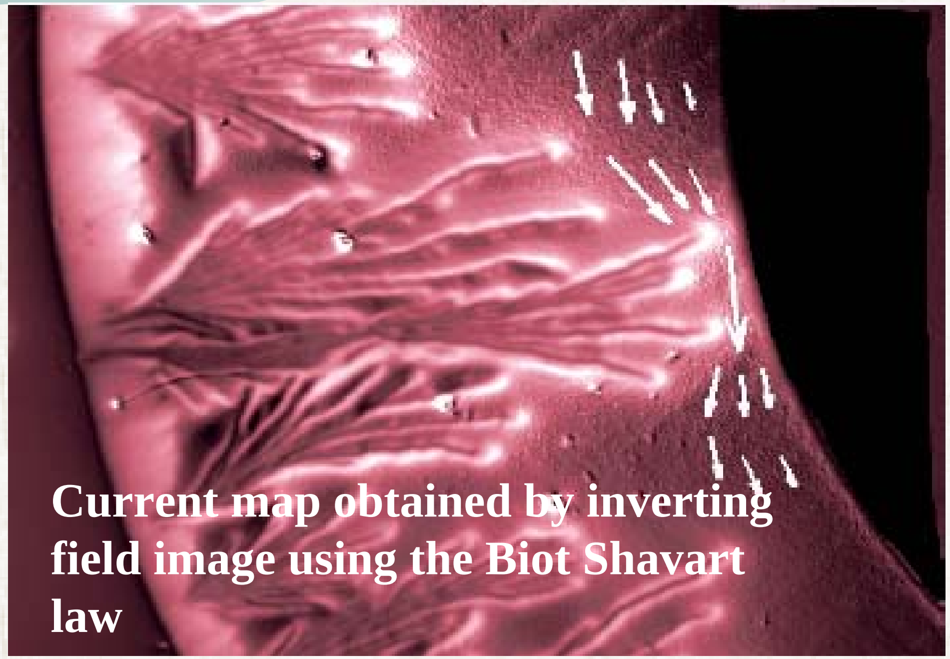




Generation of a strong filed in opposite direction at the inner edge:
: Super current is flowing to generate the stray field

Mechanism of formation of anti-dendrites



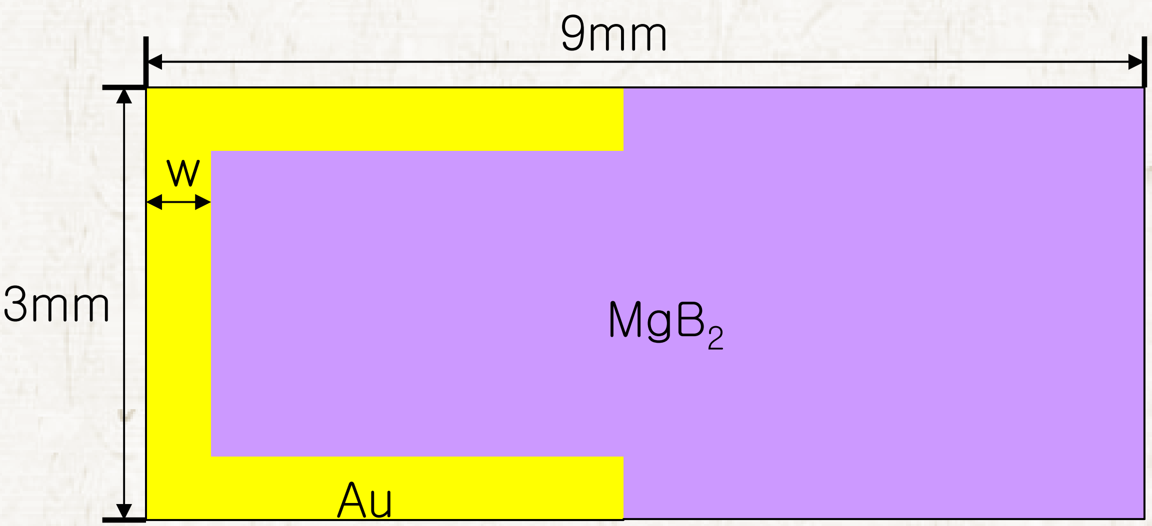


1) When a bright dendrite come close to the inner edge, the negative field there is locally enhanced
2) Heat dissipation associated with the bright dendrite tip, which facilities the growth of an anti-dendrites

Experiment

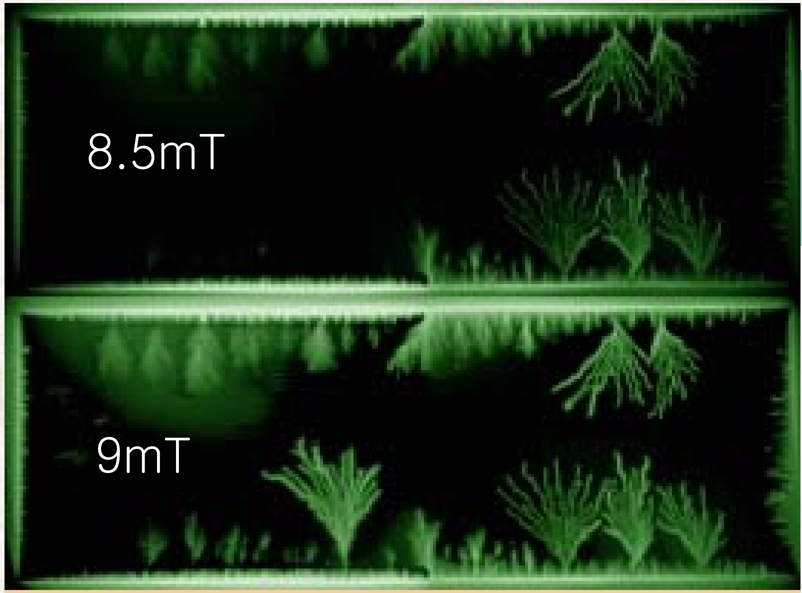
Magnetic avalanches in MgB_2 thin films with gold rim (width 100, 300, and 750 ㎛)

Sample preparation

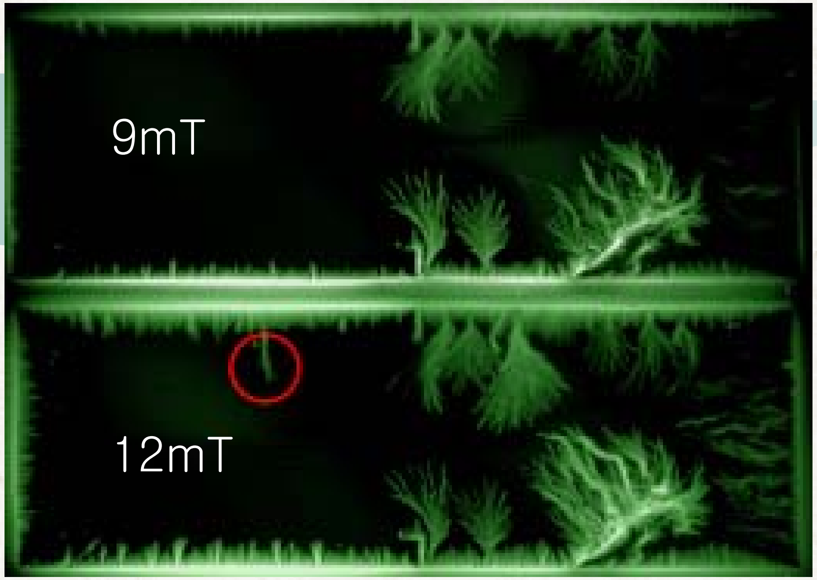


Sample	w, ㎛
A	100
B	300
C	750

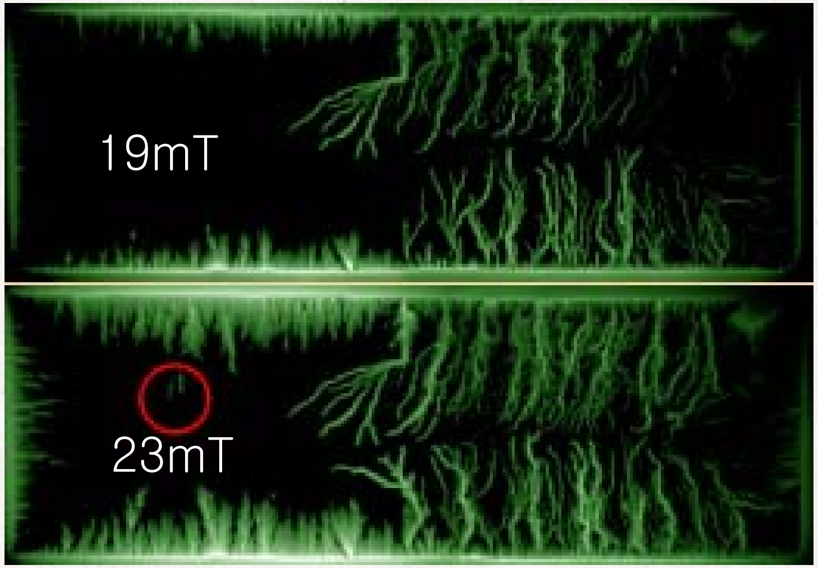
The thickness of film : 400nm
Film fabrication : two-step method using PLD
Pattern : using photolithography



100 ㎛



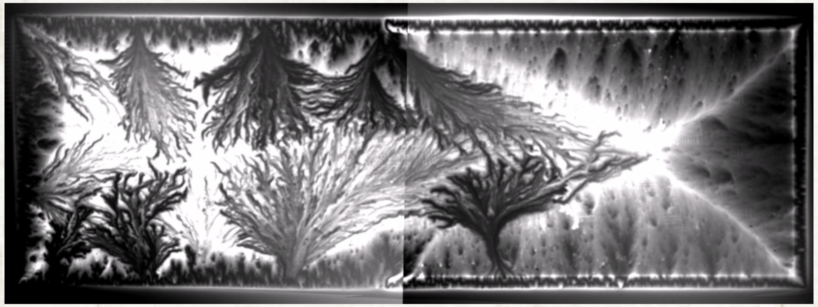
300 ㎛



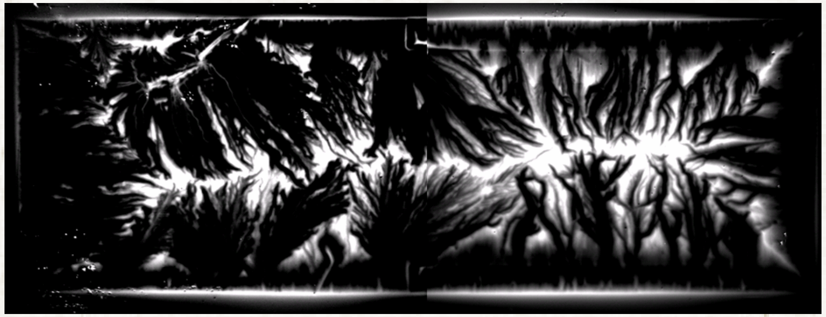
750 ㎛

Figure 2

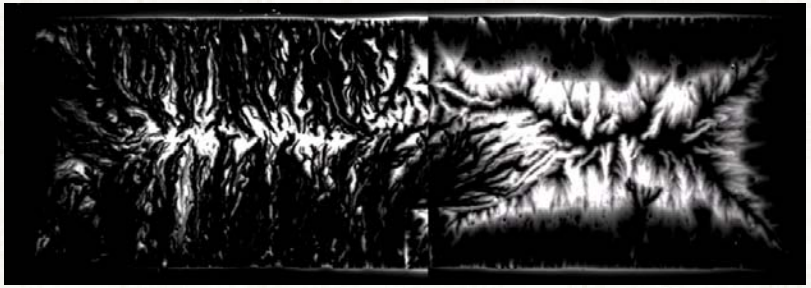
Remnant State



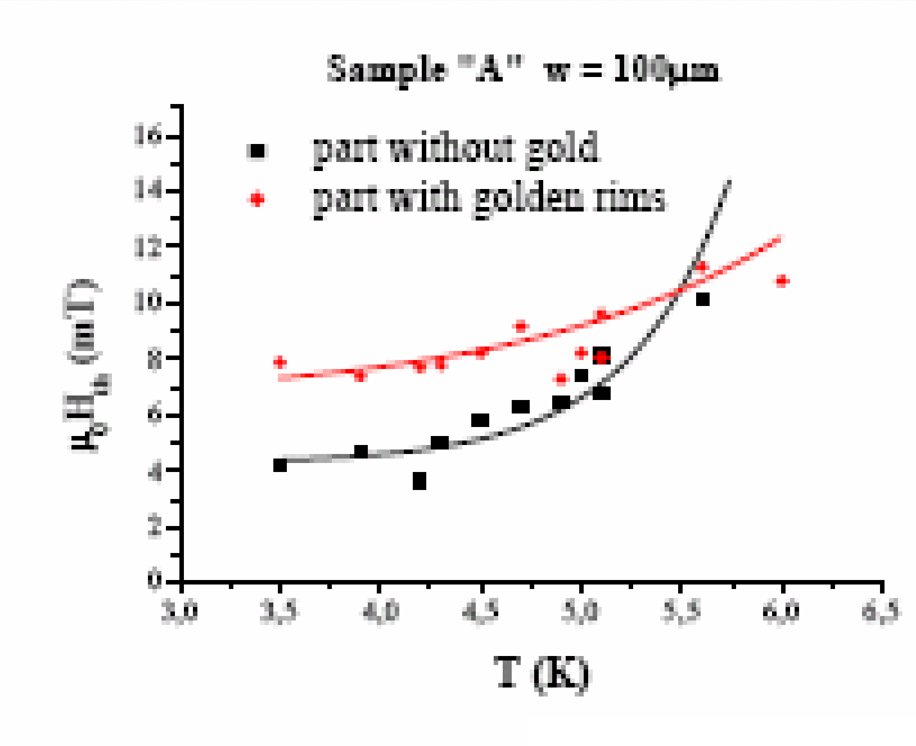
100㎛

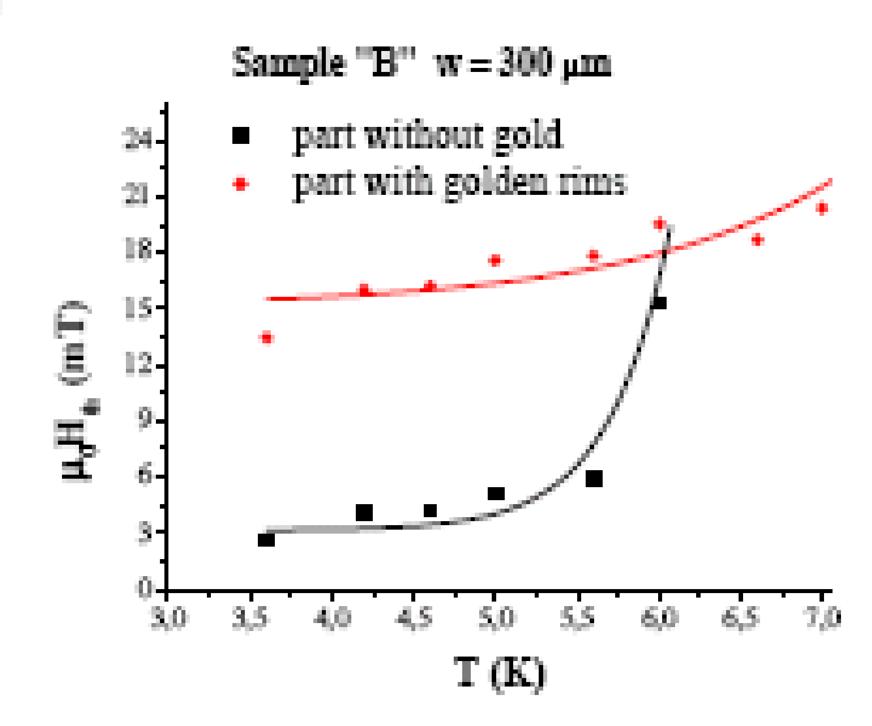


300㎛



750㎛


Sample "A" w = 100μm
part without gold
part with golden rims
μ0Hth (mT)
T (K)


Sample "B" w = 300 μm
part without gold
part with golden rims
μ0Hth (mT)
T (K)

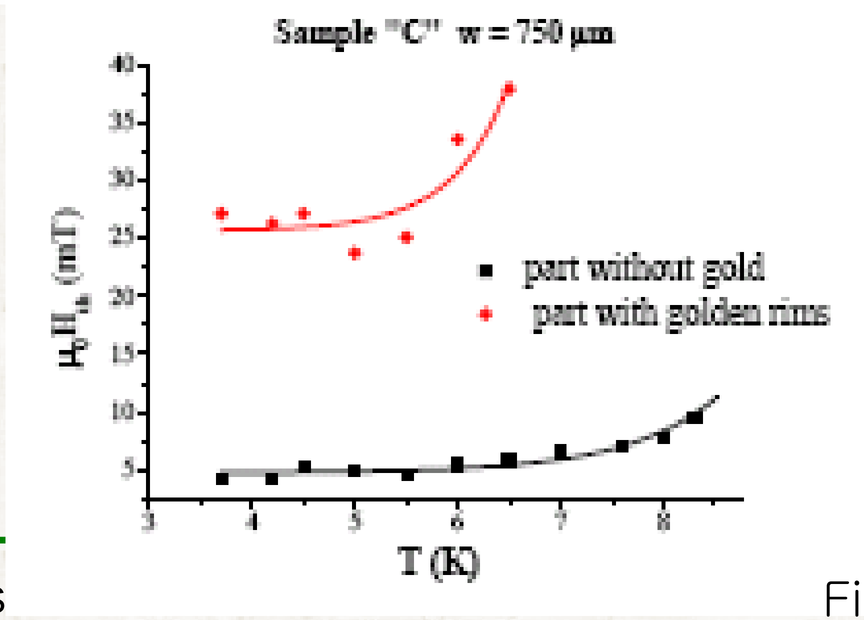

Sample "C" w = 750 μm
part without gold
part with golden rims
μ0Hth (mT)
T (K)

Figure 4

Conclusions I

- Observe Vortex Avalanche in MgB_2
- Suppress the vortex avalanche by gold deposition on MgB_2- Restore the superconducting critical current density
- Avoid the dendritic instability by reduce the size of thin film
- The dendritic instability is from thermo-magnetic origin
- Observe the dendrites of anti-vortices in the ring patterned MgB_2 thin film.

Conclusions II

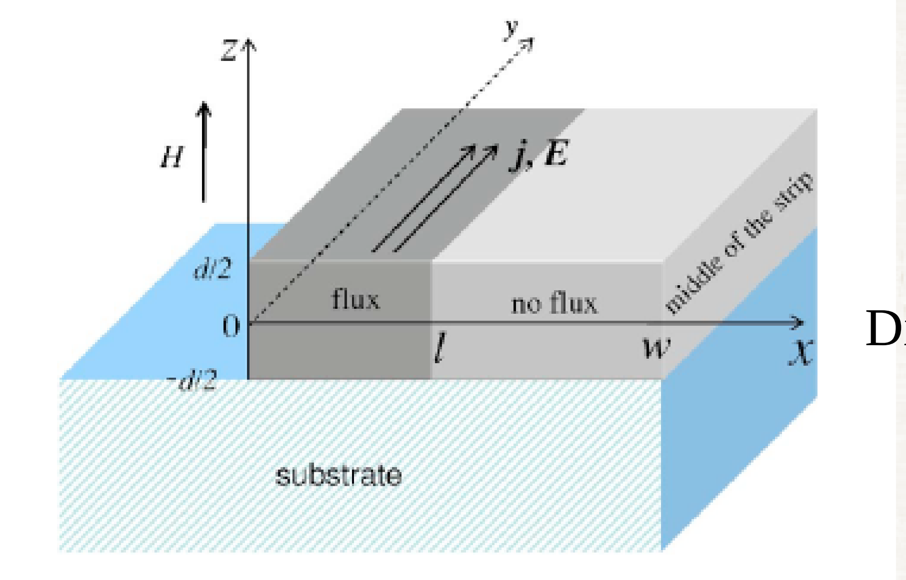
- Study the vortex avalanche in MgB_2 thin films with gold rim
  - a substantial increase of the threshold field $\boldsymbol{H_{th}}$, i.e. the field of the first dendrite
  - Suppression of dendritic instabilities inside the golden rims, i. e. the dendrites nucleate on the inner edge of the gold rims

Different dendrites grown in three parts of the sample shows different thermo magnetic instabilities

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*

Model and basic equation



$$C\partial_t T = \nabla^2 T + \mathbf{JE}(J,T)$$

$$\partial_t \mathbf{B} = -\nabla \times \mathbf{E}(J,T), \quad \nabla \times \mathbf{H} = \mathbf{J} \;\; (\nabla \times \mathbf{B} = \mu_0 \mathbf{J})$$

$$\mathbf{J} = J_c(T) g(E)(\mathbf{E}/E) \rightarrow J \approx J_c(T)$$

B : determined in the region 0<x<*l*

Dimensionless parameters

$$n(E) \equiv \partial \ln E / \partial \ln J \approx J_c / \sigma E >> 1$$

$$(\sigma(E) \equiv \partial J / \partial E) \rightarrow E \propto J^n$$

$$\tau \equiv \mu_0 \kappa \sigma / C$$

τ : the ratio of thermal and magnetic diffusion coefficients

smaller → slower heat diffuse

→ more unstable superconductor

→ formation of instability-induced nonuniform structures

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*

- **Perturbation analysis**

  - Assumptions : $d \le \lambda_L << \sqrt{dw}\,,\ \lambda_{eff} << l << w \quad (\lambda_{eff} = \lambda_L^2 / d)$
  - Linearized dimensionless equations

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

$$\delta\mathbf{J} = (\frac{\partial j_c}{\partial T}\delta T + \sigma\delta E_y)\frac{\mathbf{E}}{E} + J_c\frac{\delta\mathbf{E}_x}{E}$$

$$\delta T = T^*\theta\exp(\lambda t/t_0 + ik_x\xi + ik_y\eta)$$

$$\delta E_{x,y} = E\varepsilon_{x,y}\exp(\lambda t/t_0 + ik_x\xi + ik_y\eta)$$

$$\delta J_{x,y} = J_c i_{x,y}\exp(\lambda t/t_0 + ik_x\xi + ik_y\eta)$$

Θ, ε, and i : z-dependent

dimensionless Fourier amplitude

$$\xi = x/a,\ \eta = y/a,\ \varsigma = z/a$$

$$a = (\sqrt{CT^*/\mu_0 J_c^2})$$

adiabatic length

$$T^* = -(\partial \ln J_c / \partial T)^{-1}$$

$$t_0 = \sigma CT^*/J_c^2 = \mu_0\sigma a^2$$

magnetic diffusion time

$$i_x = \varepsilon_x,\ i_y = -\theta + n^{-1}\varepsilon_y,\ \mathbf{k}\times[\mathbf{k}\times\varepsilon] = \lambda n\mathbf{i},\quad \lambda\theta = \tau(-k_y^2\theta + \frac{\partial^2\theta}{\partial\varsigma^2}) + (i_y + \varepsilon_y)/n$$

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*

- **Perturbation analysis**

  - Boundary condition

    assumptions : heat exchange follows the Newton cooling law

$$\kappa\nabla(T+\delta T) = -h_0(T+\delta T - T_0)$$

Θ, ε and **i** : perturbations averaged over the film thickness

at the film edge (ξ=0) : $\delta J_x = 0,\ \delta E_x = 0$

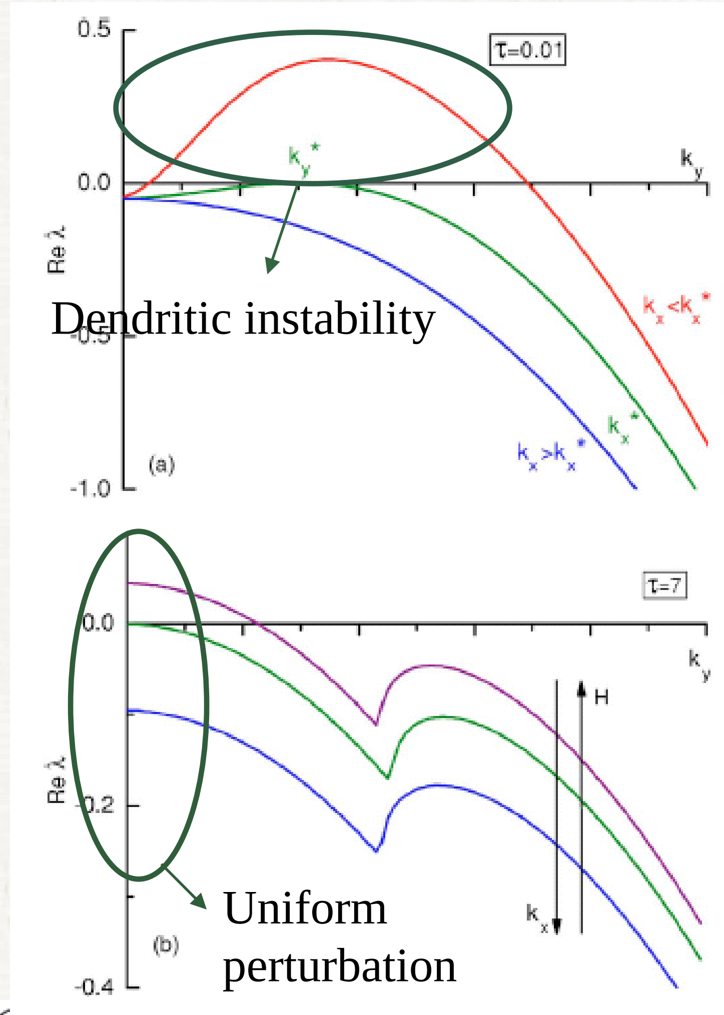
at the flux front (ξ=l/a) : $\delta J_y = \delta E_y = \delta T = 0$

→ Fourier expansions for x and y components of electric field perturbation contain only sin($k_x\xi$) and cos sin($k_x\xi$)

→ $k_x = (\pi a / 2l)(2s+1),\ s = 0, 1, 2, \ldots$: magnetic field dependent

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*



Dispersion relation for λ(*k_x*,*k_y*)

$$A_1\lambda^2 + A_2\lambda + A_3 = 0.$$

$$A_1 = n\gamma\alpha, \quad A_2 = k_y^2(1+\tau A_1) + nk_x^2 + A_1(h\tau - 1),$$

$$A_3 = k_y^4\tau + nk_x^2k_y^2\tau + nk_x^2(h\tau + 1/n) + k_y^2(h\tau - 1).$$

Re λ (dimensionless instability increment)
>0 : exponential growth of perturbation

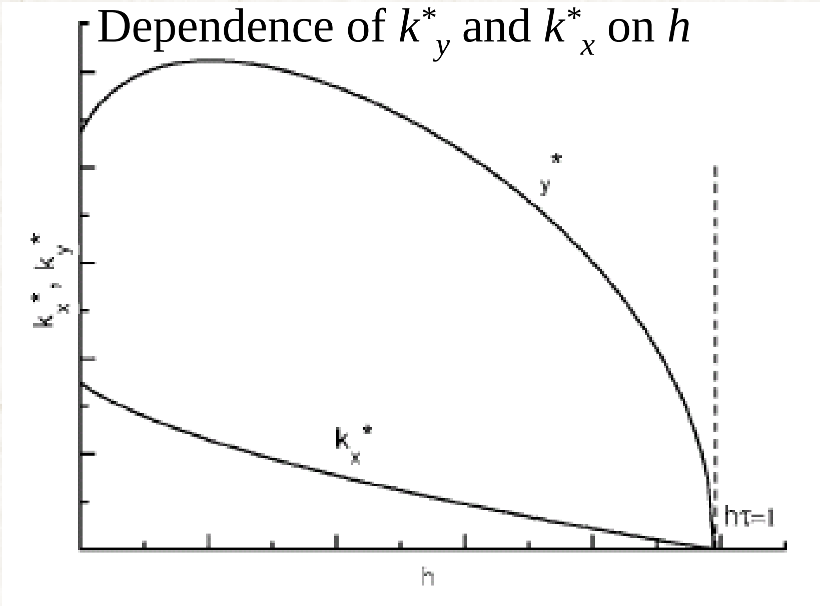
Critical k^*_x: applied magnetic field
k^*_y: spatial scale of instability

$$k_x^* = (\sqrt{n+1} - \sqrt{nh\tau})/n\sqrt{\tau},$$

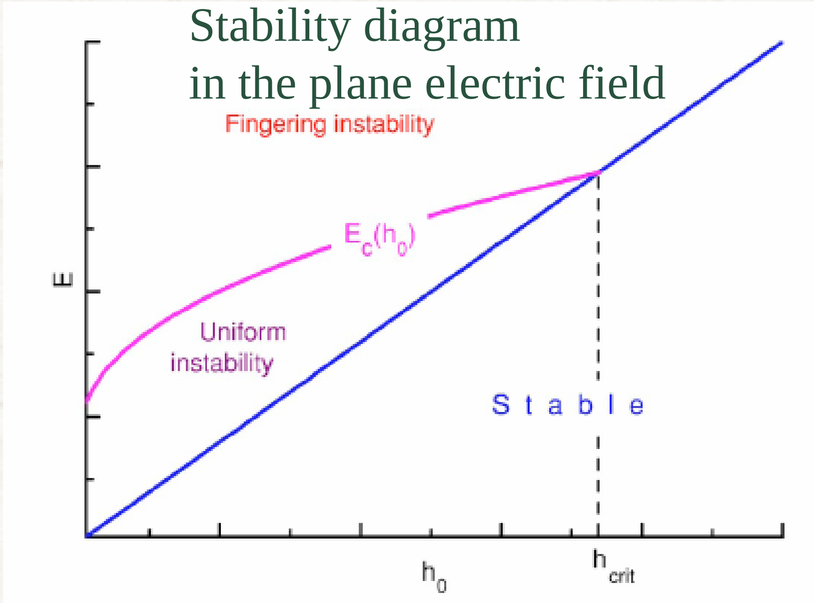
$$k_y^* = [\sqrt{nh\tau+1}(\sqrt{n+1} - \sqrt{nh\tau+1})]^{1/2}/\sqrt{n\tau}.$$

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*



n=20, τ=0.01, α=0.00 1



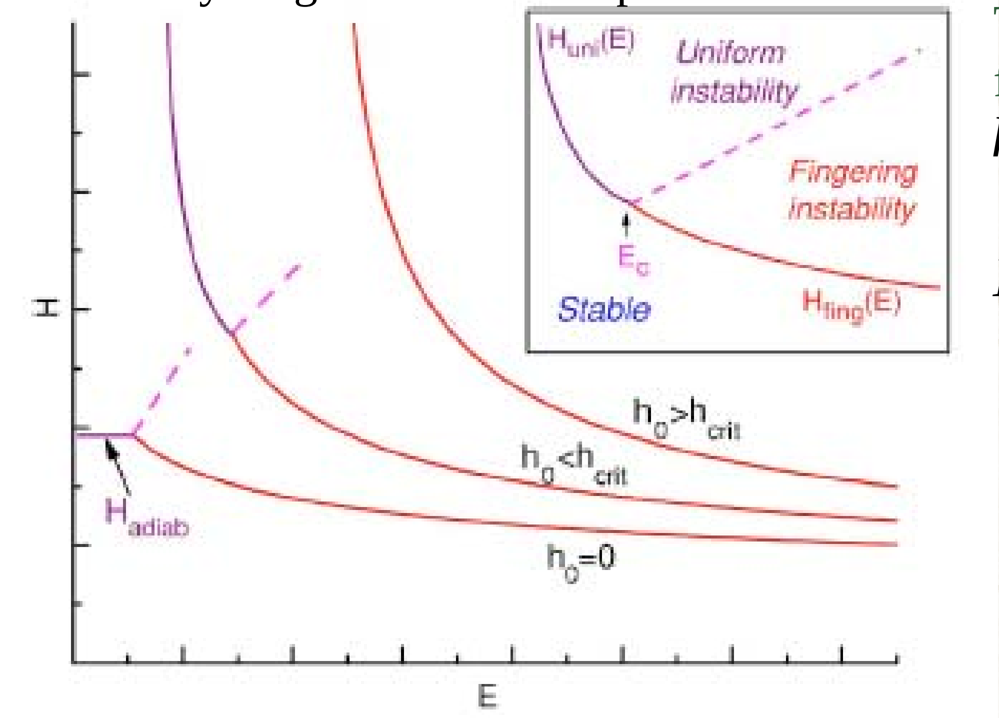
1-$h\tau$>0 for n=30 and α=0.001

$$E_c(0) = \frac{\gamma^2 \mu_0^2 J^3 \kappa}{\pi^2 C^2 T^*} d^2, \; E_c(h_{crit}) = 4E_c(0)$$

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*

Stability diagram in the *H*-*E* plane



Threshold magnetic field for the fingering instability

$$h << 1/\tau,\ n >> 1$$

$$H_{fing} = \left(\frac{J_c d^2}{\pi w}\sqrt{\frac{\kappa T^* J_c}{E}}\right)^{1/2}$$

Dendritic and uniform flux jumps in superconducting films

PRB. 73(2006) 014512 D. V. Denisov *et. al.*

- Thin film vs. bulk

- background electric field in the superconductor

$$\frac{E_c(0)}{E_c^{slab}} = \frac{\gamma^2}{\pi^2}\frac{d^2 J_c^2 \mu_0}{CT^*}$$

thin strip : $E_c \approx 4 \times 10^{-4}$ v/m, slab : : $E^{slab}{}_c \approx 0.1$ v/m

- threshold magnetic field

$$\frac{H_{fing}}{H_{fing}^{slab}} = \frac{\sqrt{2}}{\pi}\frac{d}{\sqrt{wl^*}} \qquad (l^* = (\pi/2)\sqrt{\kappa T^* / J_c E})$$

l^* : flux penetration depth

$l^* >> d$