*Torino – 27 Febbraio 2006*

# *Il Campo Magnetico si può vedere:*
# auto-organizzazione di
# Pattern Magnetico in Sistemi Complessi

INFN-NASTRI project

INFN-DISCOLI project

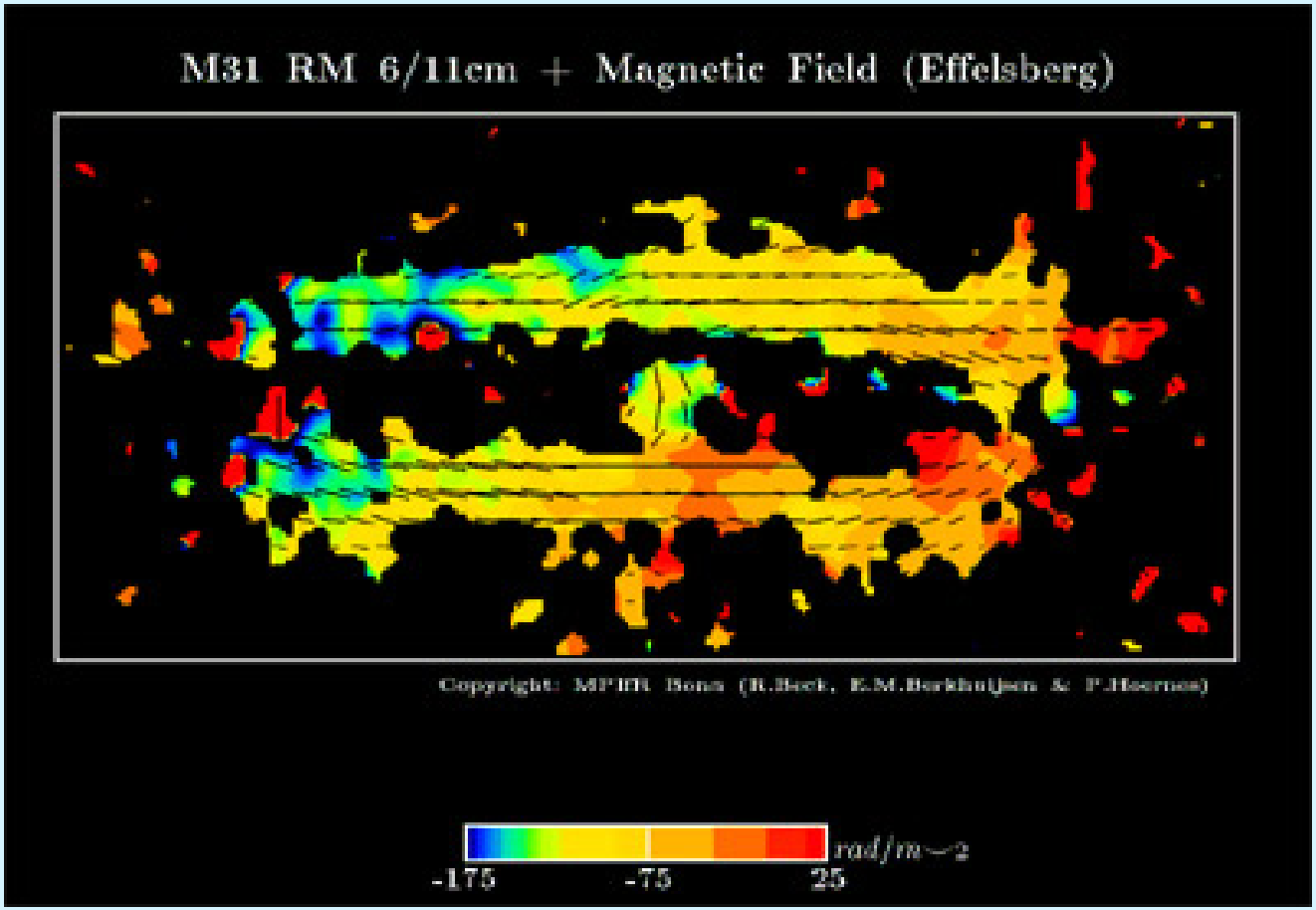
*Enrica Mezzetti, Bruno Minetti, Roberto Gerbaldo, Gianluca Ghigo, Laura Gozzelino, Francesco Laviano*

Dipartimento di Fisica, Politecnico di Torino

# Outline

1. Real-Time Visualization of the Magnetic Field Distribution
   - Magneto-Optical Imaging (MOI) technique overview: parallel measurement of the local magnetic field for any flat material
   - Observation of Magnetic Patterns in Magnetic Materials
   - Visualization of the Complex Magnetic Pattern in Superconductors makes possible a *direct comparison with other physical systems*
2. Probing and Controlling Self-organized Criticality in Superconductors: the NASTRI project
3. Functional Nanostructuring of Superconductors by High Energy Heavy Ion Irradiation: the DISCOLI project

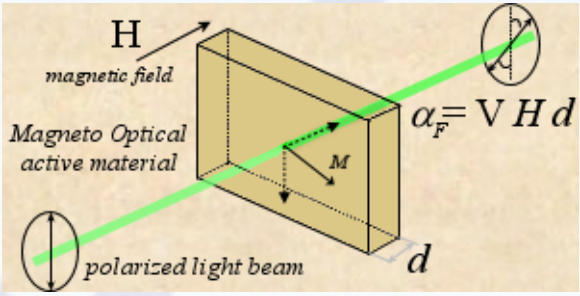
# Visualization of the Magnetic Field Distribution



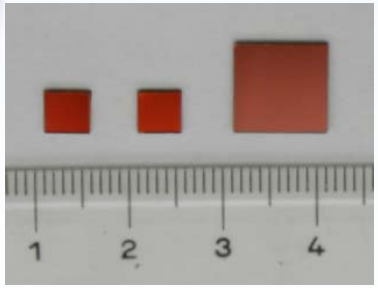

An Aitoff projection of the celestial sphere in Galactic coordinates, showing recently compiled sample of 1203 rotation measures (RMs). Closed circles represent positive RMs, while open circles correspond to negative RMs, in both cases the diameter of a circle proportional to the magnitude of its RM. The 887 blue sources represent RMs toward extragalactic sources, while the 316 red sources indicate RMs of radio pulsars. The SKA will be able to measure in excess of ten million RMs, spaced at less than an arcminute between sources. Figure courtesy of Jo-Anne Brown.

# MOI principle:

- **Faraday effect** (light intensity = local magnetic flux density)



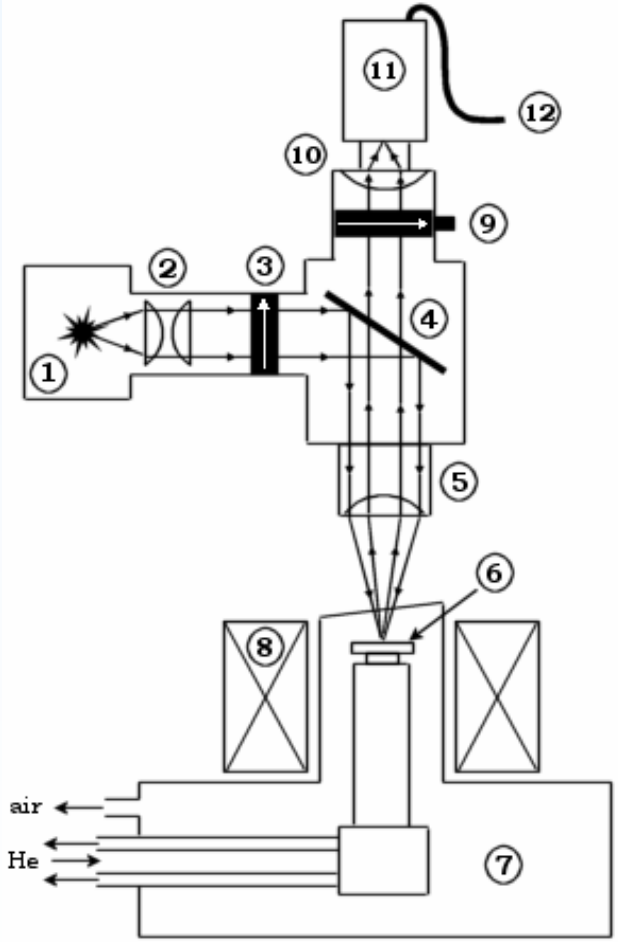

- **Ferromagnetic indicator film** (BIG) for measurement of opaque samples

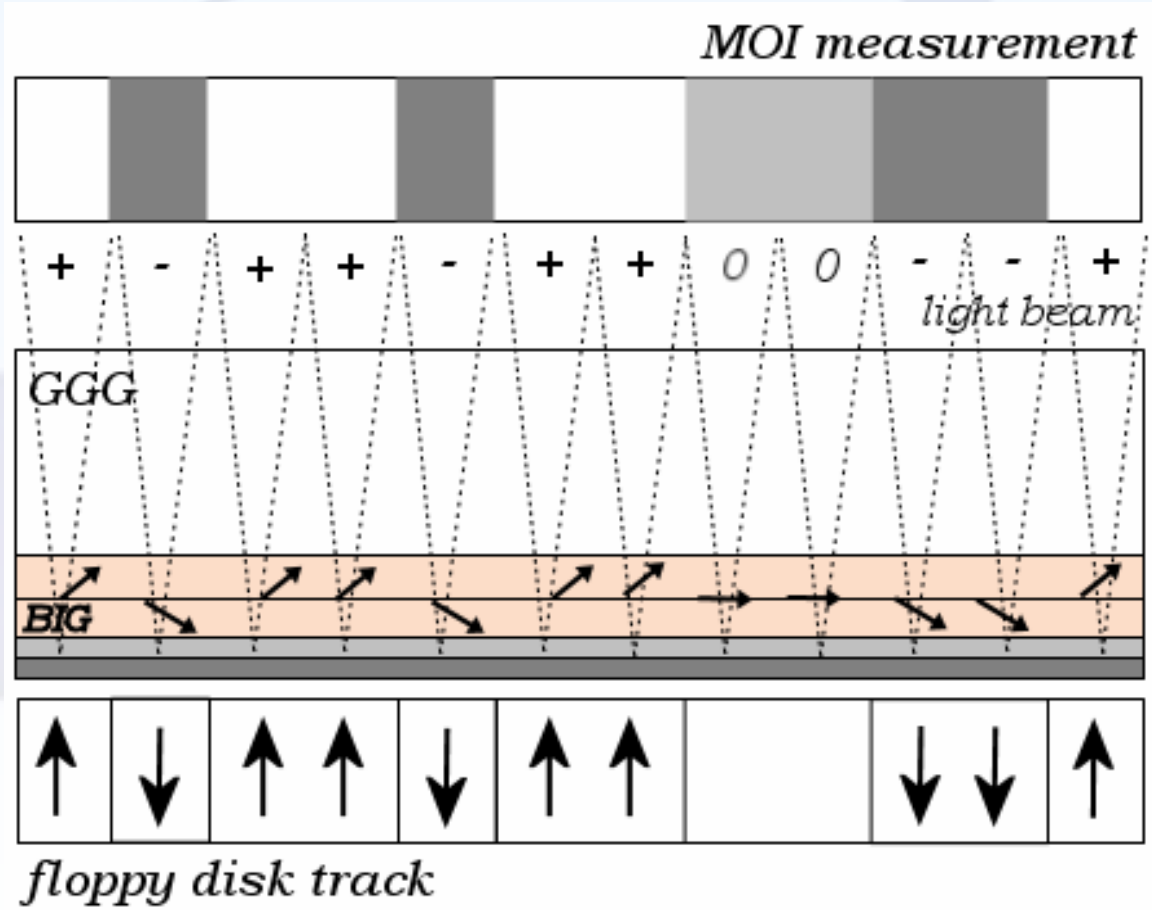



- MOI **example: commercial 3.5” Floppy disk**

# MOI Experimental Set-up

## (LIMADEL – Department of Physics – Politecnico di Torino)



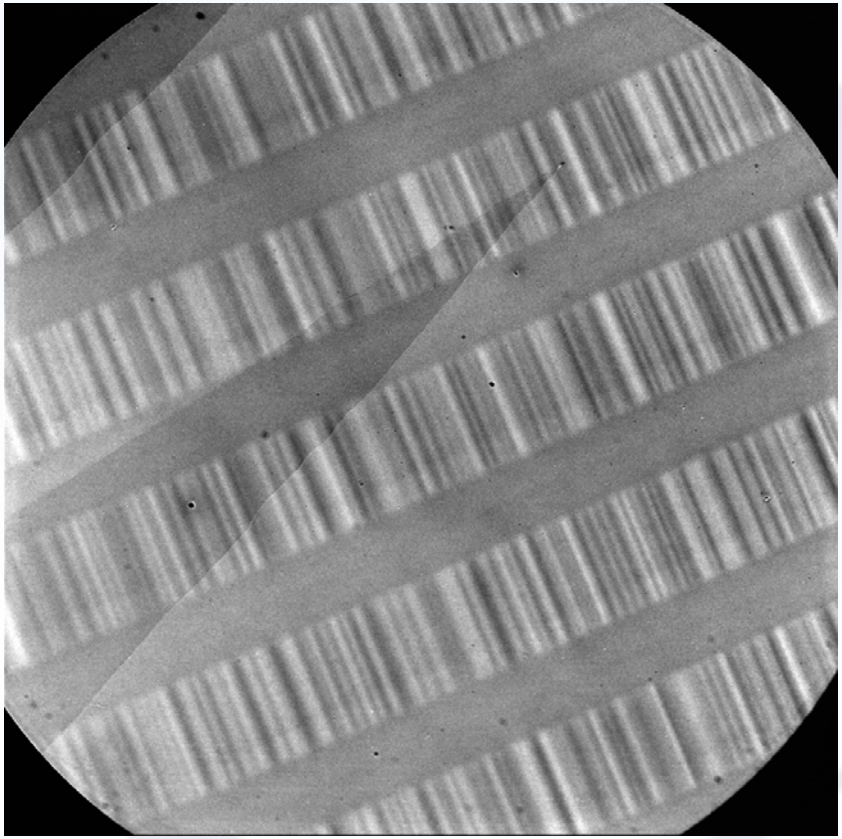



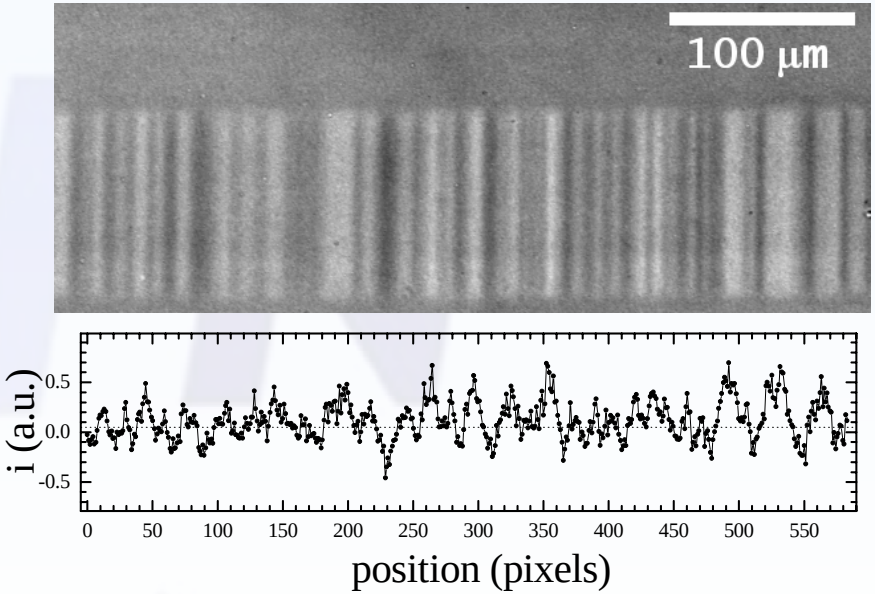

Scheme of the experimental set-up. The light beam, from the Hg lamp (1), is collimated by a bi-convex lens (2) before passing through a polariser (3). After the exciting filter (not drawn), the light hits a beam-splitter (4) and is focused by the objective lens (5) onto the indicator surface (6). The magneto-optical active media is put inside the cryostat, eventually over non-active samples (7). An external magnet (8), cooled with water, generates a uniform magnetic field in the direction perpendicular to the indicator plane. The refracted light passes through the lens (5), the beam-splitter (4) and the rotating analyser (9), before being focalised by the camera lens (10) and captured in the CCD matrix of the video-camera (11). A personal computer (12-not drawn) picks up the digital signal of the camera and elaborates it.

# Direct Visualization of the Magnetic Field:

## commercial 3.5” Floppy disk

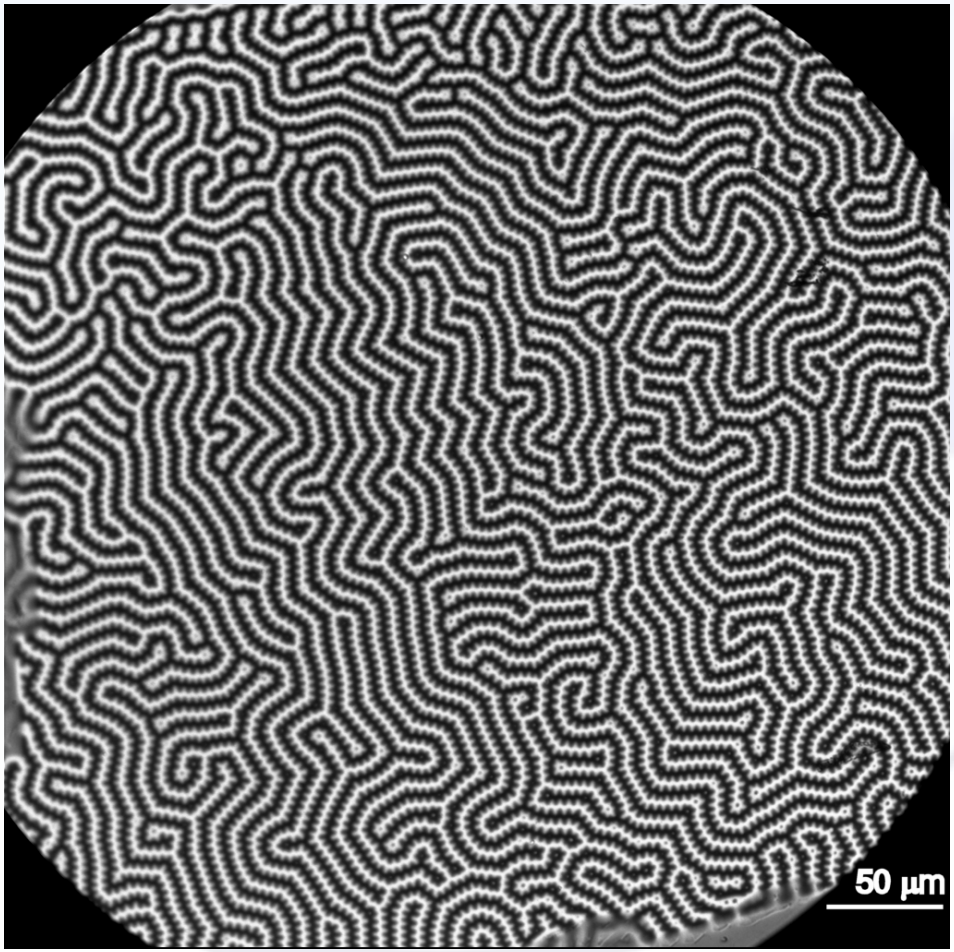
*“As taken” MOI Frame*

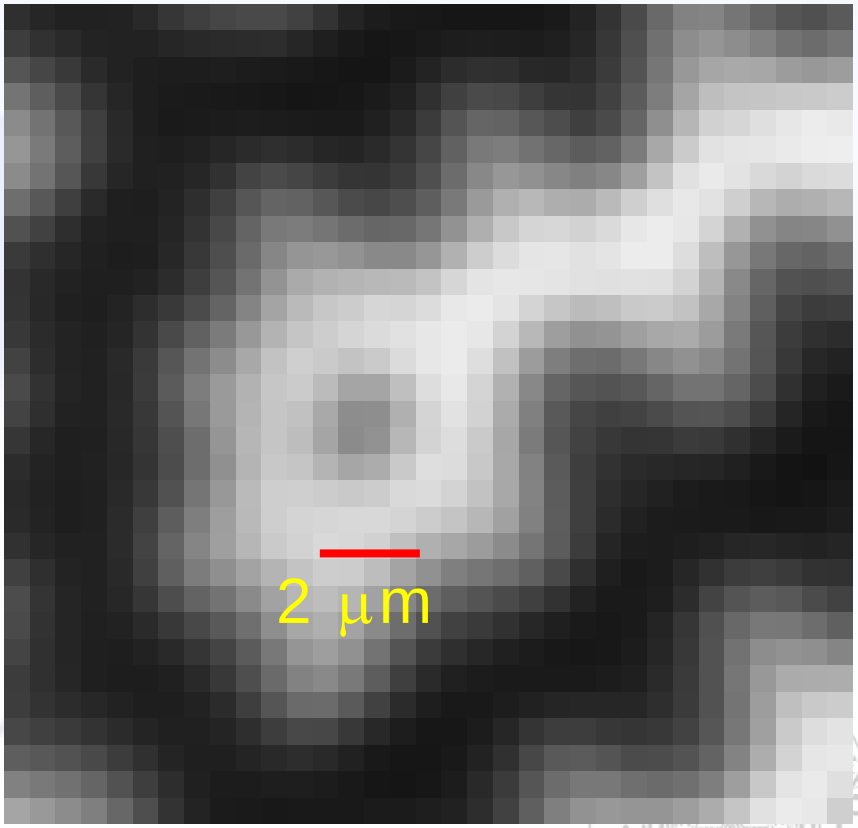





*MOI* = **Direct Optical Read-out of a Magnetic Pattern**

# MOI of "Maze-pattern" in BFO ($BaFe_{12}O_{19}$), *ferrite single crystal*




*MOI zoom*

# Comparison with MOI *pioneering work*

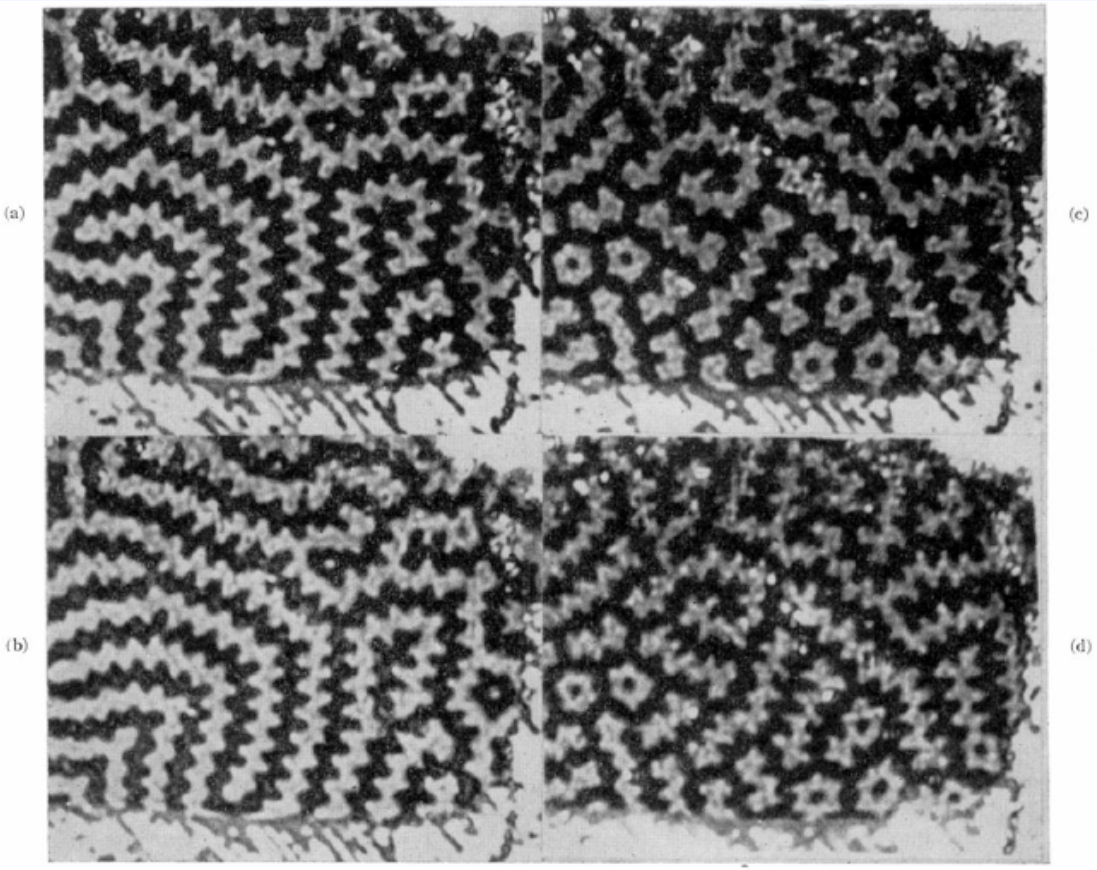
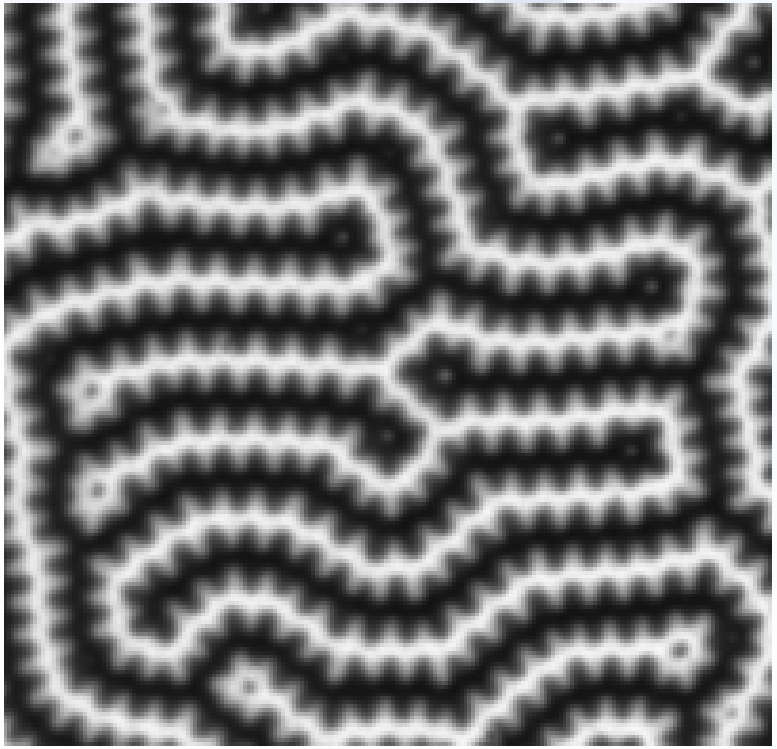



FIG. 1. (a) Original domain pattern on BiMn grain. (b) Same area after 15 000-oe field applied parallel with the surface. (c) Same field applied perpendicular to surface and (d) after cooling to 77.3°K for one minute. 2500×.

(Kerr-imaging of BiMn from B. W. Roberts and C. P. Bean, Phys. Rev., **96** (1954) 1494)



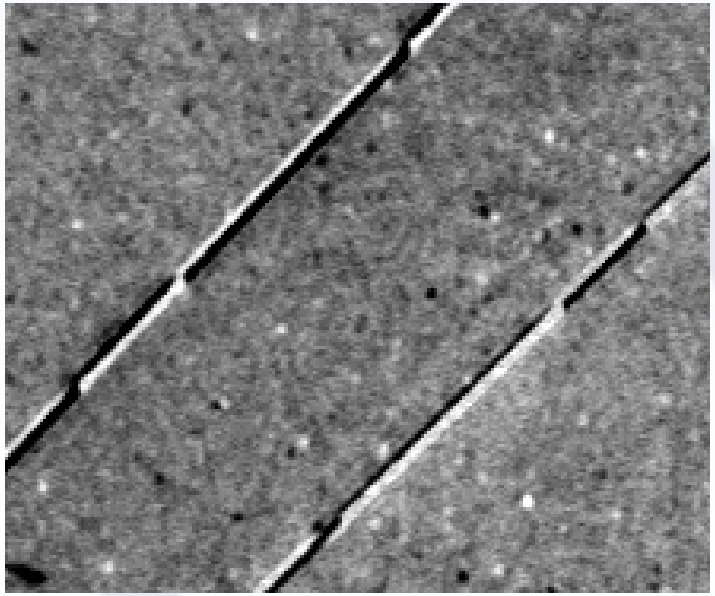
*MOI – 400X*

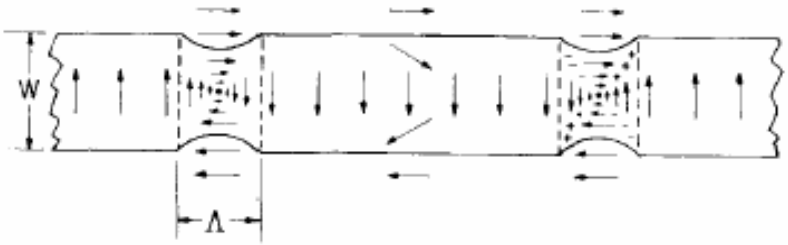
*Spatial resolution 400 nm*

# MOI of Domain-Walls in Garnet films

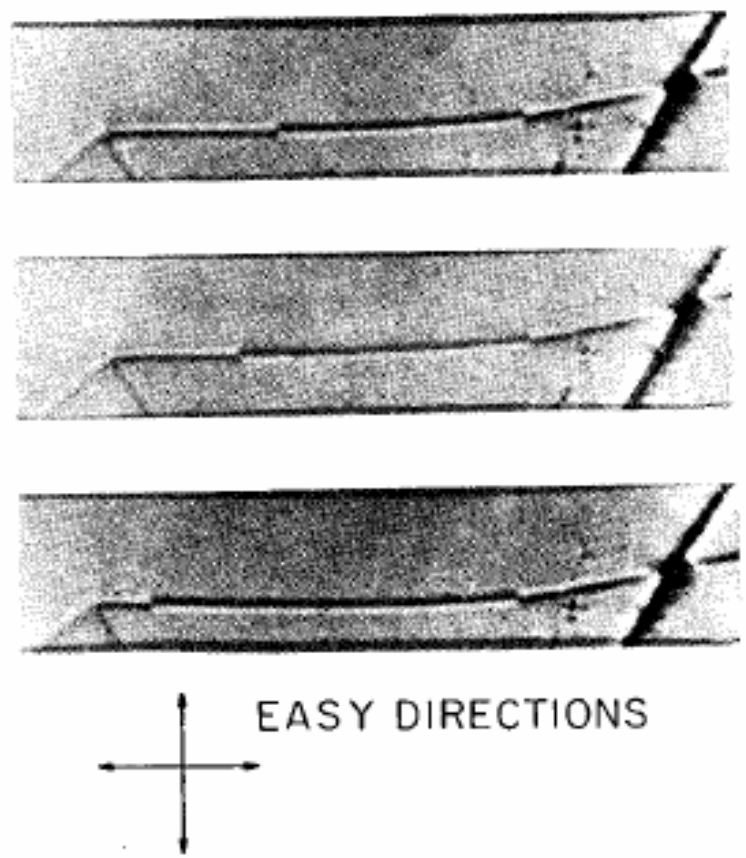
## Line transition in 180° Néel wall

BIG



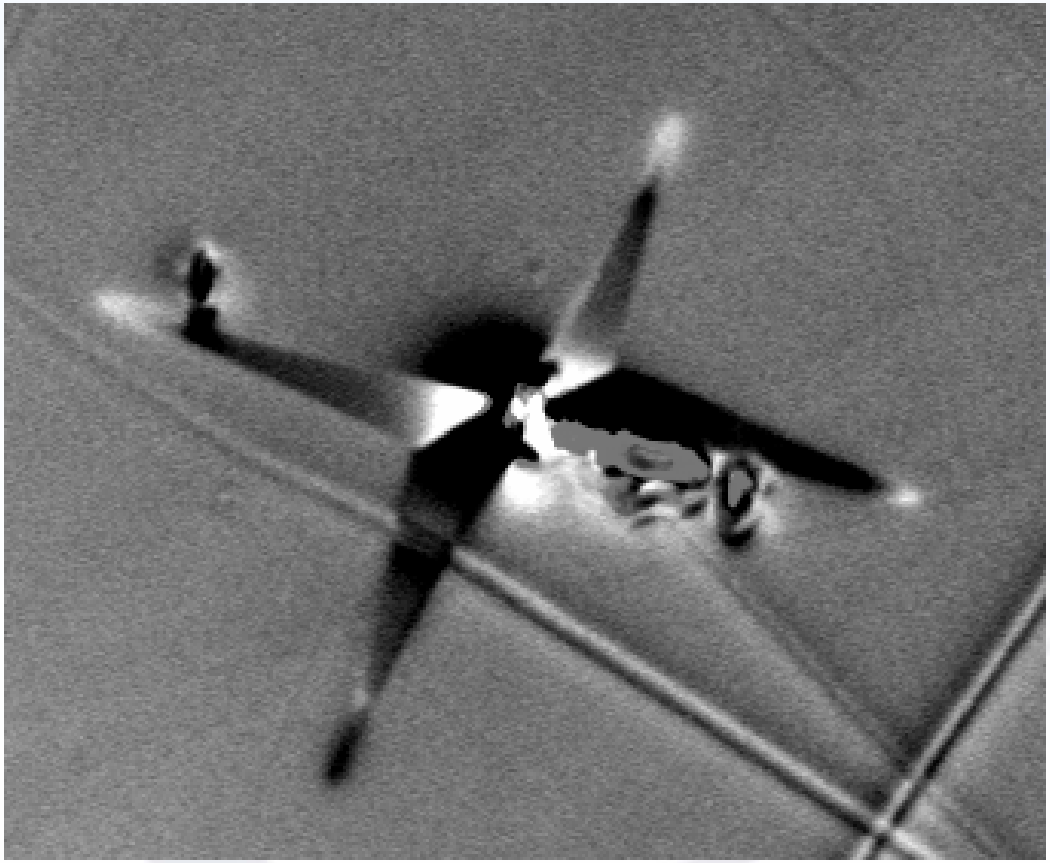



**SmTmCaGe** (M. H. Kryder et al., JAP **53** (1982) 5810)

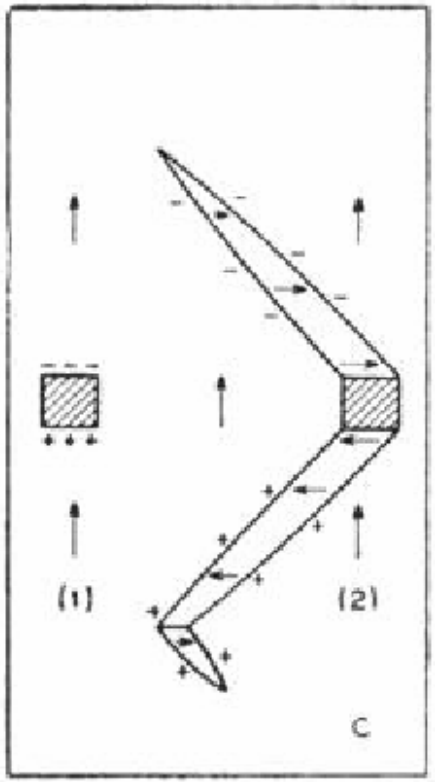


# MOI of Domain-Walls in Garnet films

## Néel-Tip wall (BIG)



(L. Néel, J. de phys. [8] **5**, (1944) 241)



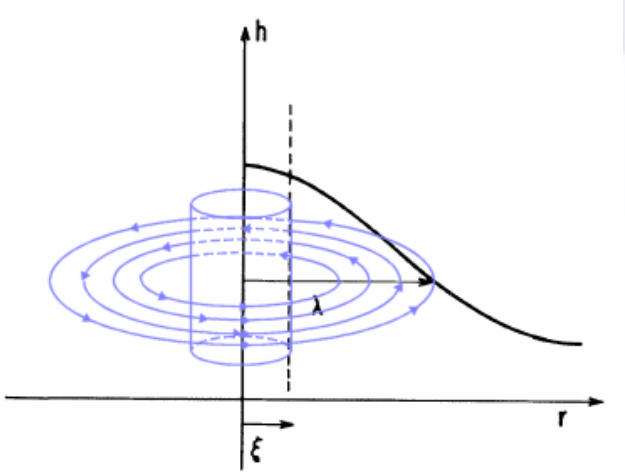
# MOI of Superconducting Materials

***Type I*** *Superconductivity:*

Complete expulsion of the external magnetic field, after zero field cooling = ***Perfect diamagnetism***

***Type II*** *Superconductivity:*

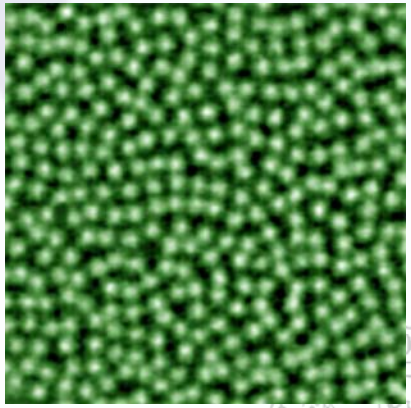
Nucleation of topologic singularities carrying single magnetic flux quanta (***vortices*** or ***fluxons***)




***Characteristic lengths of the Vortex magnetic structure:***

•*Nonsuperconducting Core of 2ξ size* (that is about the size of the super-charge carriers)

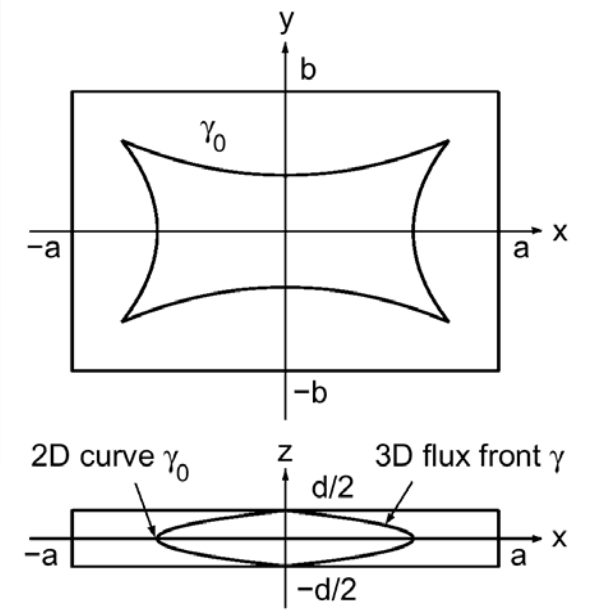
•*Supercurrent loop decaying over the λ length scale*

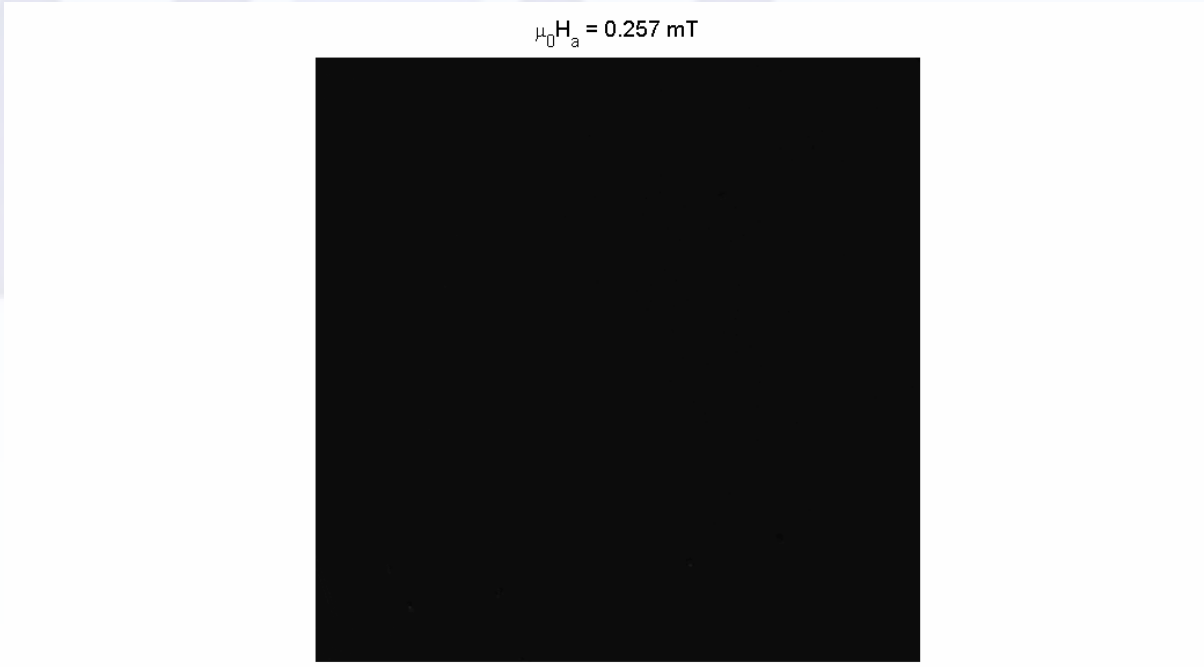


(MOI from P. E. Goa, H. Hauglin, M. Baziljevich, E. Il'yashenko, P. L. Gammel and T. H. Johansen, Supercond. Scie. Technol., **14** (2001) 729)

# *The Magnetic State of a Type II Superconductor is generated by the Complex Dynamics of the Vortex Population*

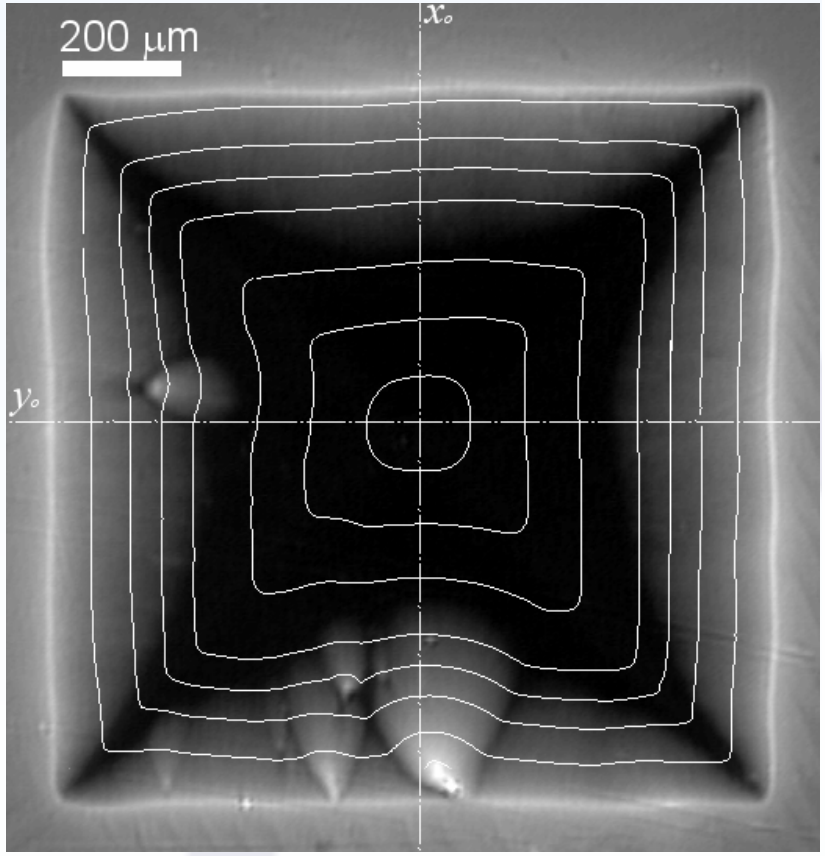
- **the vortices are nucleated from the edges** and move inside the sample under the interaction with the ***Lorentz forces*** (coming from the screening supercurrents) and with the ***structural defects***

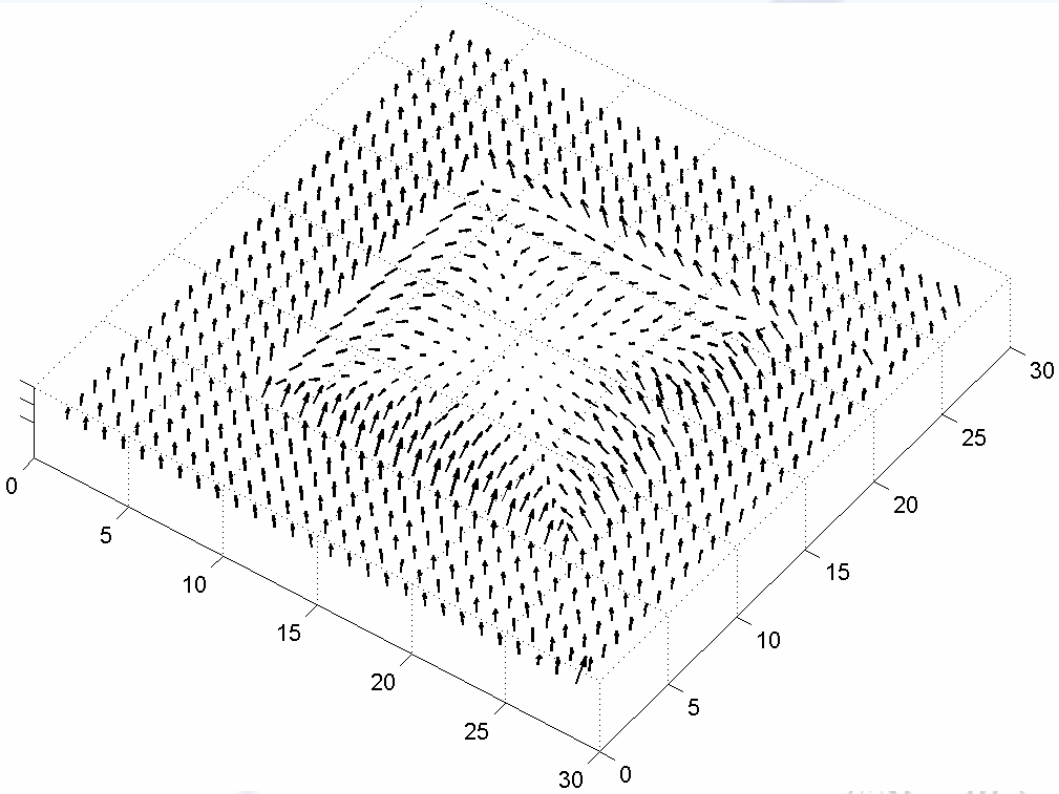



(from G. P. Mikitik and E. H. Brandt, Phys. Rev. B **62**, (2000) 6800)

# MOI of Superconducting Materials: Quantitative Analysis




F. Laviano, D. Botta, A. Chiodoni, R. Gerbaldo, G. Ghigo, L. Gozzelino, S. Zannella and E. Mezzetti, Supercond. Sci. Technol., **16** (2003) 71

F. Laviano, D. Botta, A. Chiodoni, R. Gerbaldo, G. Ghigo, L. Gozzelino, and E. Mezzetti, Phys. Rev. B **68**, 014507 (2003).

## INFN-NASTRI *Project*

# Probing the Nonlinearity and Long-range interaction of the Vortex Matter

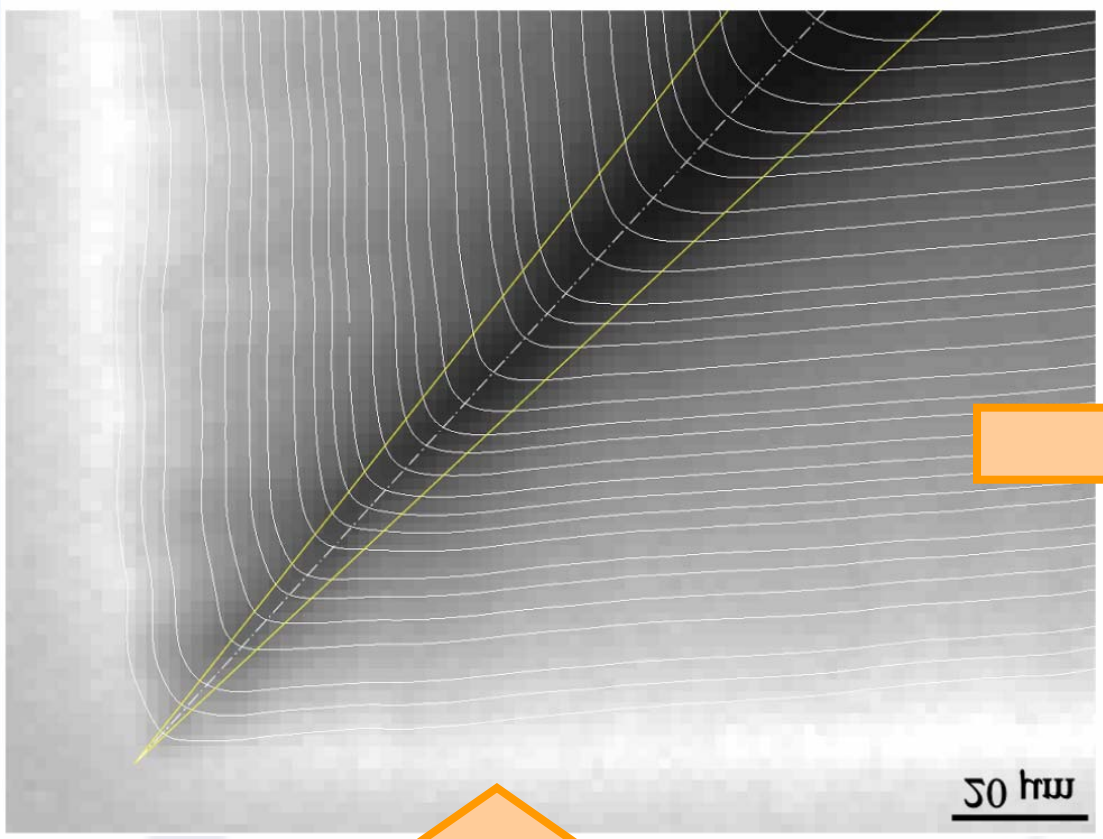
**Nonlinearity of the Vortex critical state (strong nonlinearity of the E and J relation)**

A. Gurevich and J. McDonald, Phys. Rev. Lett. **81**, 2546 (1998);
A. Gurevich and M. Friesen, Phys. Rev. B **62**, 4004 (2000)

**Long-range interaction** of Vortices and Screening currents and **Nonlocal screening** in a Superconducting film: *the Meissner currents flow in the whole superconducting volume*

E.H. Brandt, Phys. Rev. B **64** (2001) 024505

# Discontinuity lines



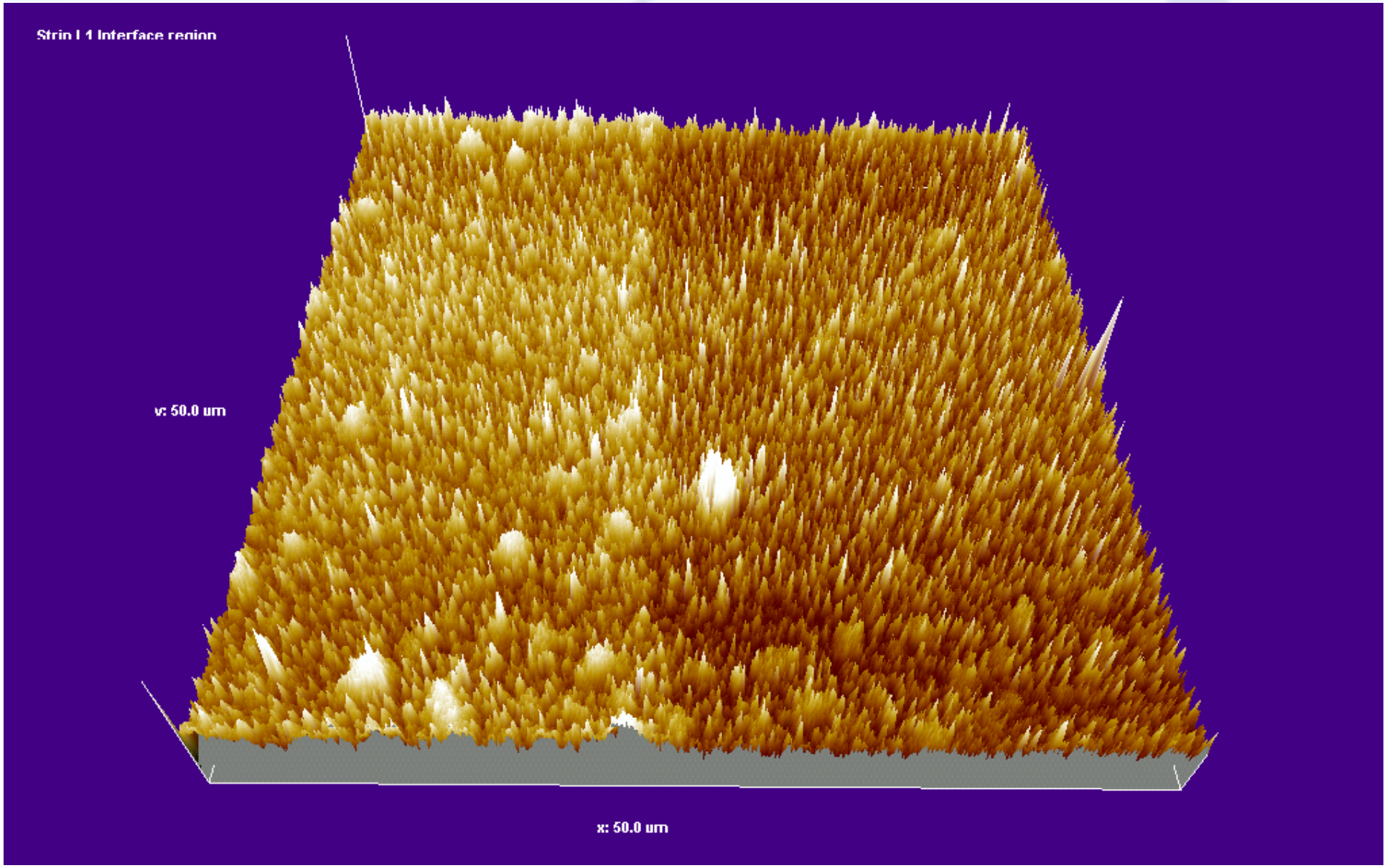

***Discontinuity lines*** locally testify the strong ***nonlinear charge current flow***, like in a ***charged plasma***.

$\boldsymbol{J}$

*Direction of the supercurent flow*

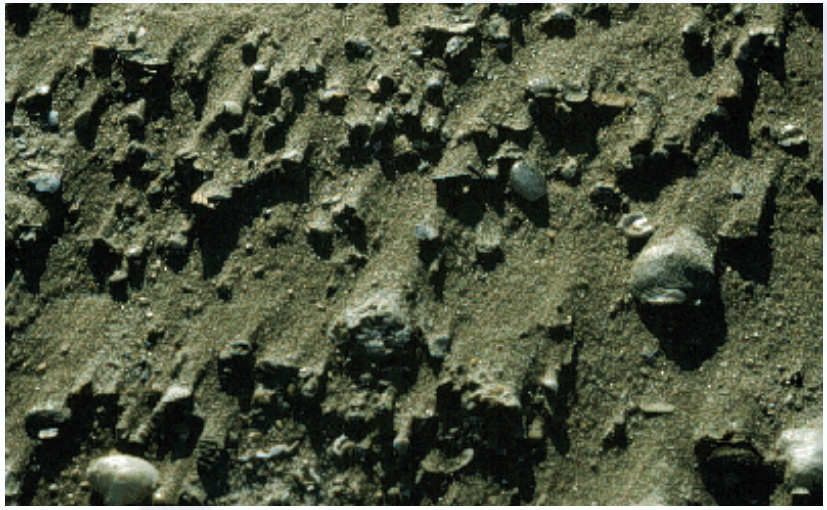
# INFN-NASTRI *Project*: *Nanostructuring by means of High Energy Heavy Ion Irradiation*

## *INFN-LNL and INFN-LNS*



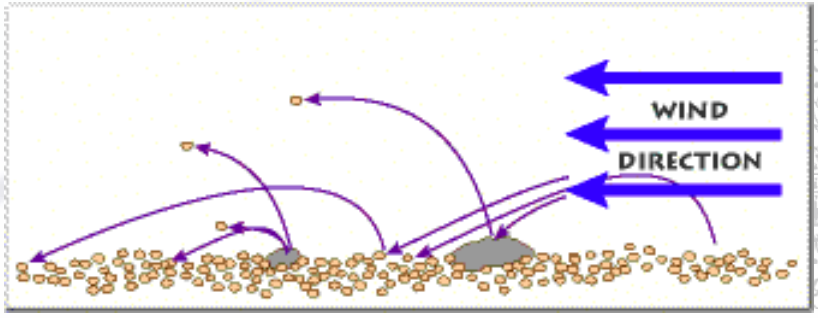
# INFN-NASTRI *Project*: Long-range disturbance and Collective behaviour

*Irrelevance of the Microscopic details*: Pattern formation of sand in desert

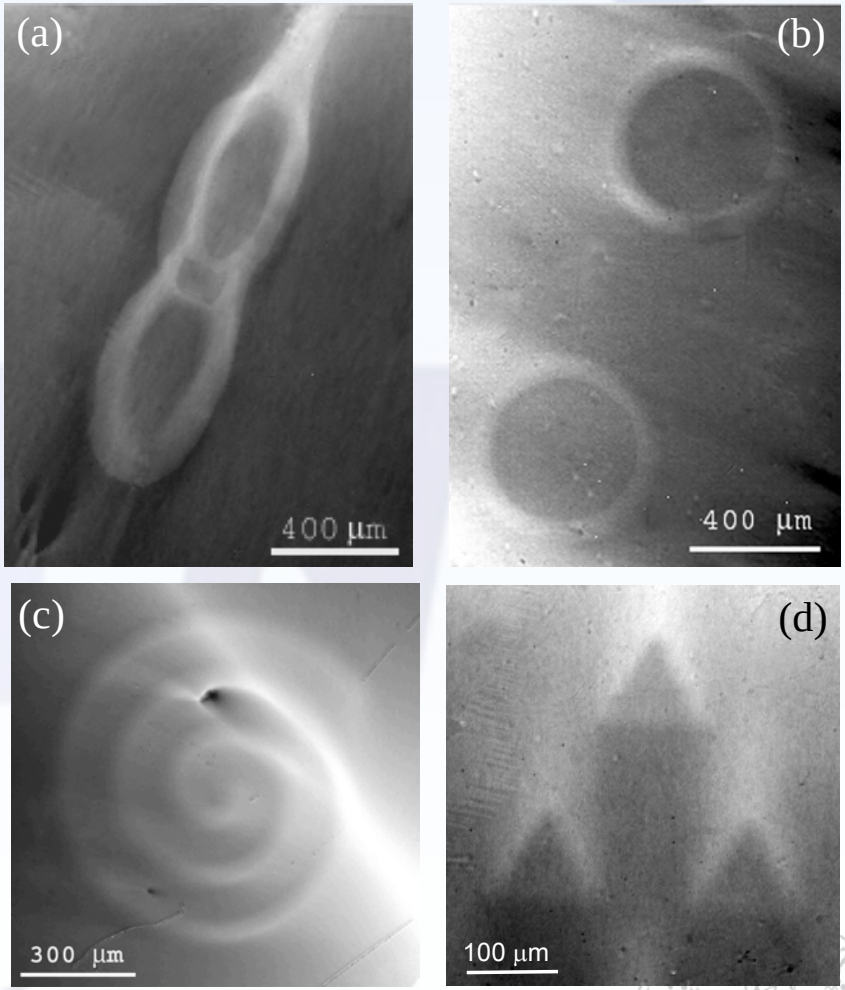


***Saltation process:***

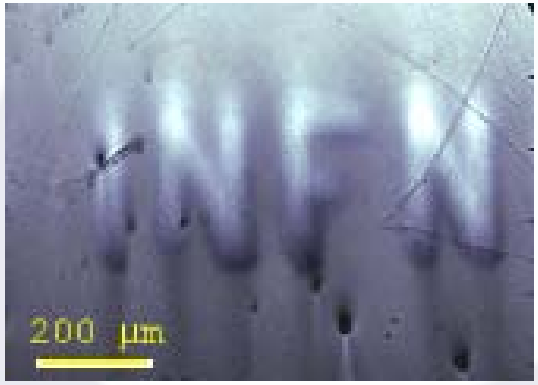
*Ventifacs and Wind shadows*



# INFN-NASTRI *Project*: Pattern formation




Nanostructured areas in superconductors can model the pattern formation on a macroscopic (global) length scale

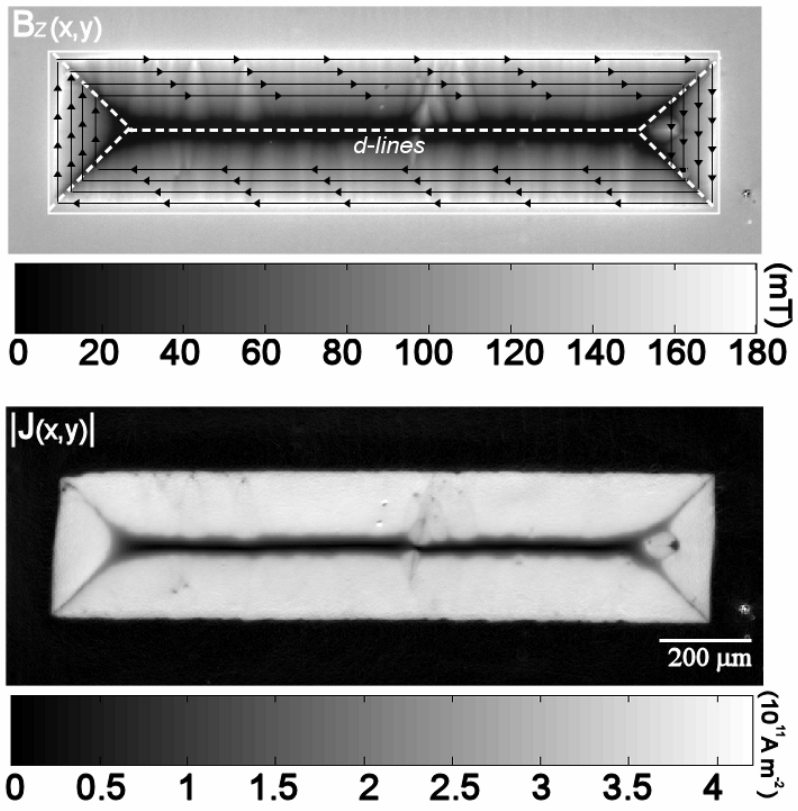


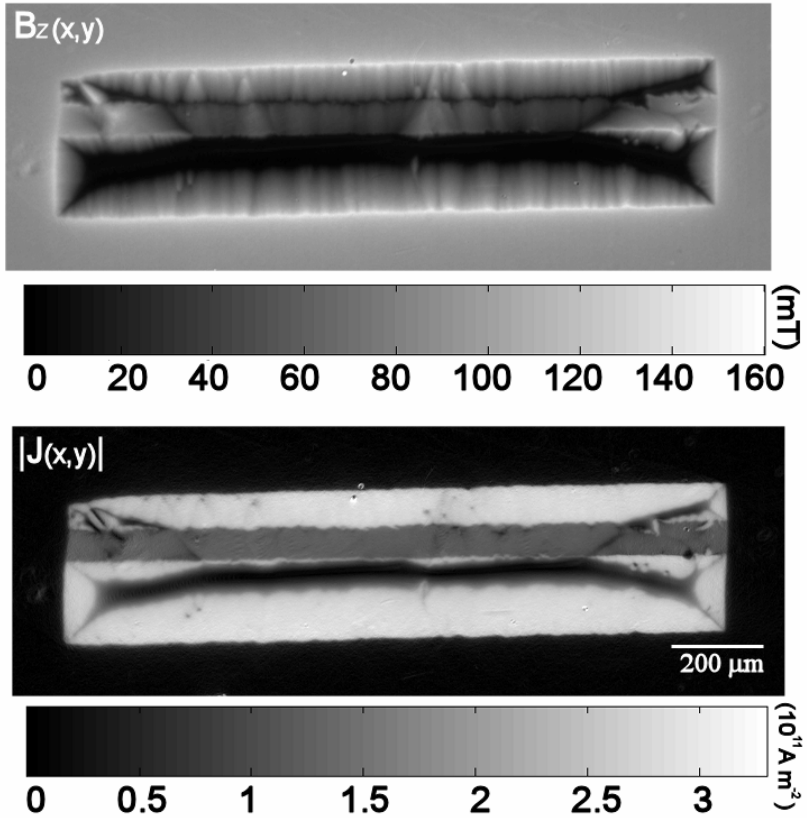

The images were taken at T = 50 K in remnant state after a field cooling in a magnetic field of 80 mT.

Rovelli, A; Amato, A; Botta, D.; Chiodoni, A.; Gerbaldo, R.; Ghigo, G.; Gozzelino, L.; Laviano, F.; Minetti, B.; Mezzetti, E., NIMB **240** (2005) 842

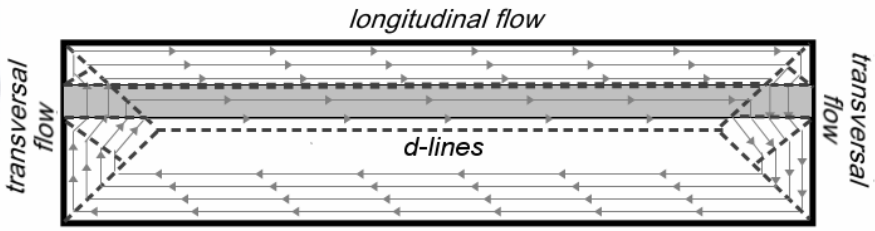
# INFN-NASTRI *Project*: *Local Nanostructuring*

***Confined High-energy Heavy-ion Irradiation as a tool to control the Vortex Matter***



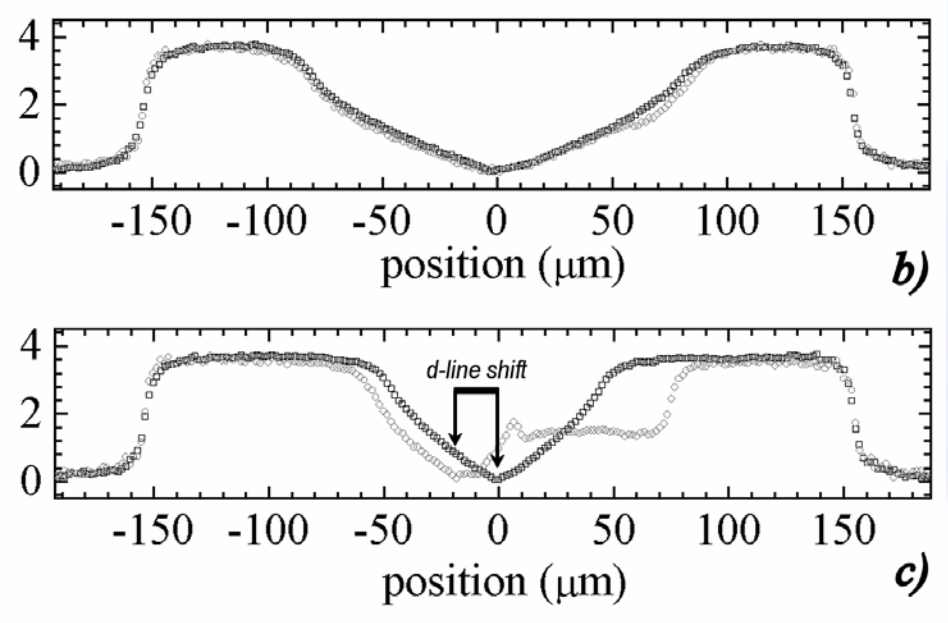

YBCO, T= 4.13 K and $\mu_0 H_{app}$= 117.3 mT

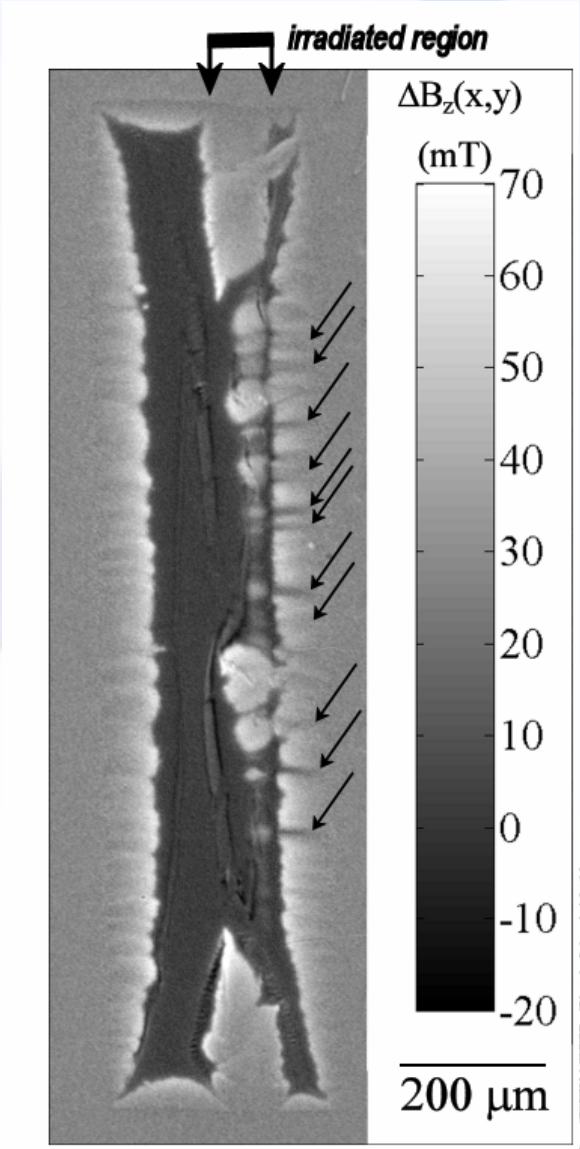



http://arxiv.org/abs/cond-mat/0309609

# INFN-NASTRI *Project*: Observation of Pattern Transitions in the Vortex Matter

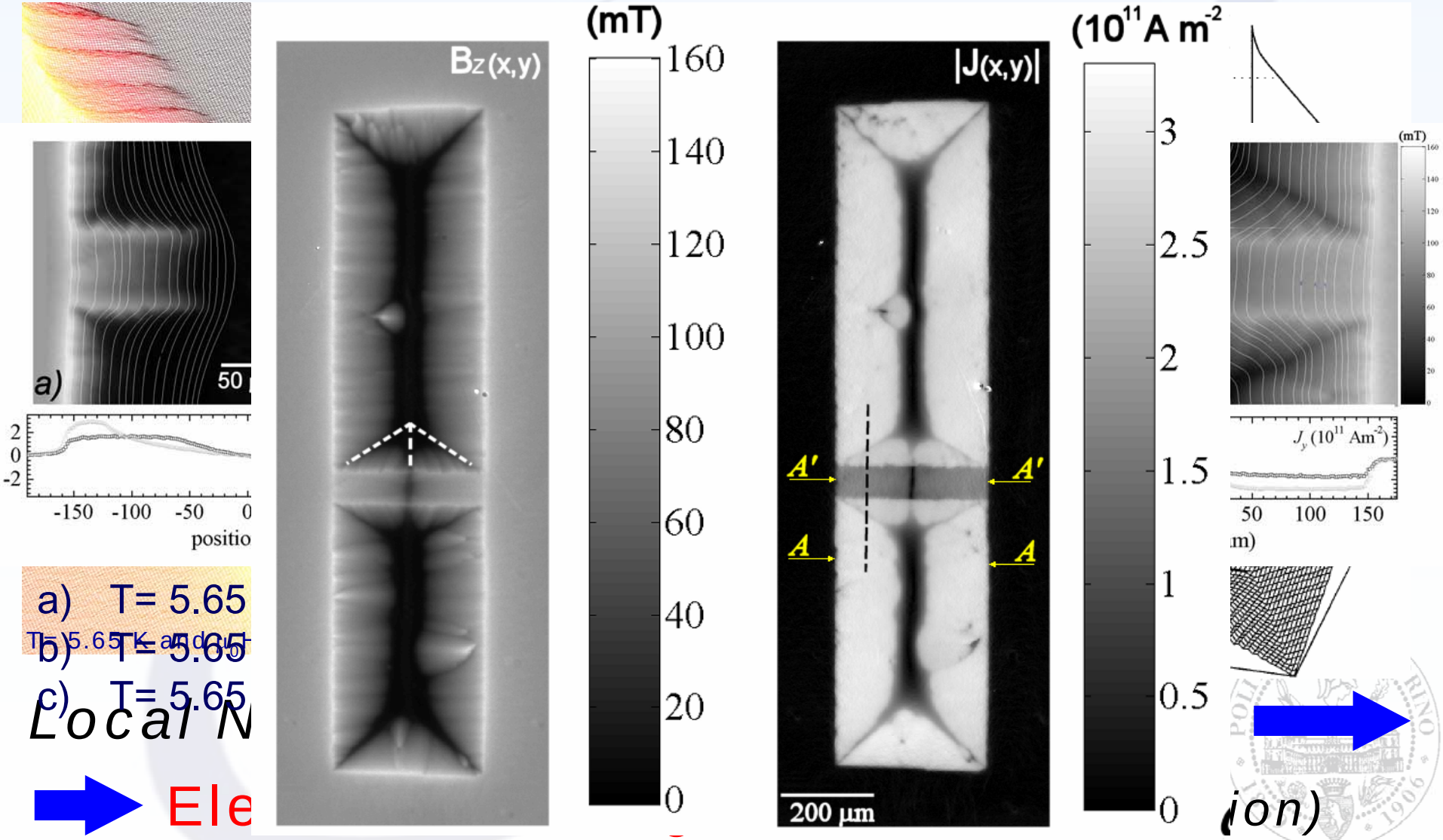
***re-distribution of the supercurrent in the whole sample***




A pattern transition occurs in the nanostructured region after vortices overcame the interface

# INFN-DISCOLI *Project*: Functionalization of the High Energy Heavy Ion Irradiation on Superconductors




a) T= 5.65

b) T= 5.65

c) T= 5.65

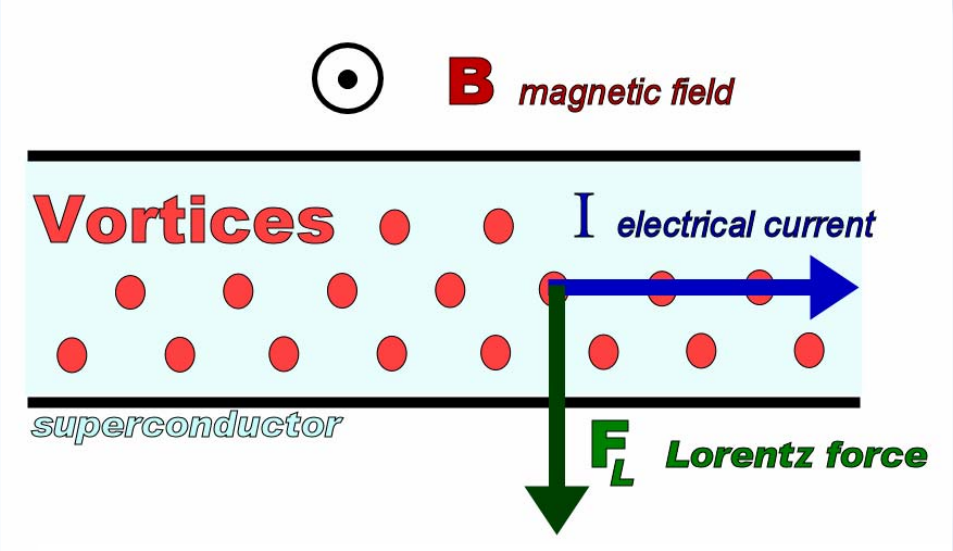
T= 5.65 K and 0.5

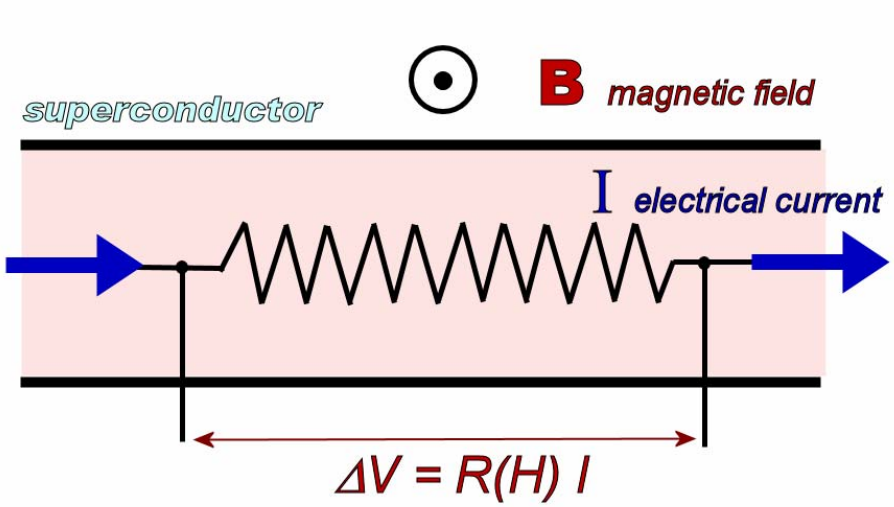
*Local N*

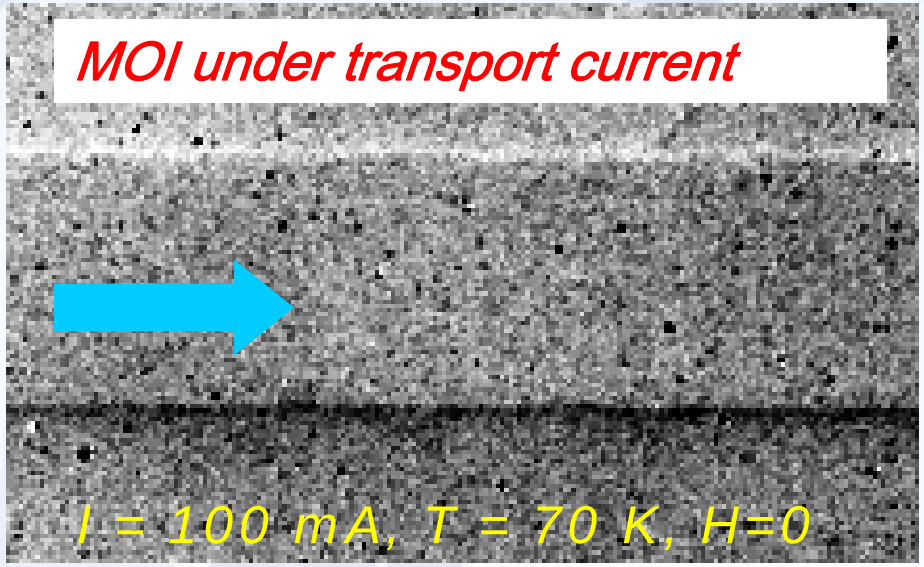
Ele

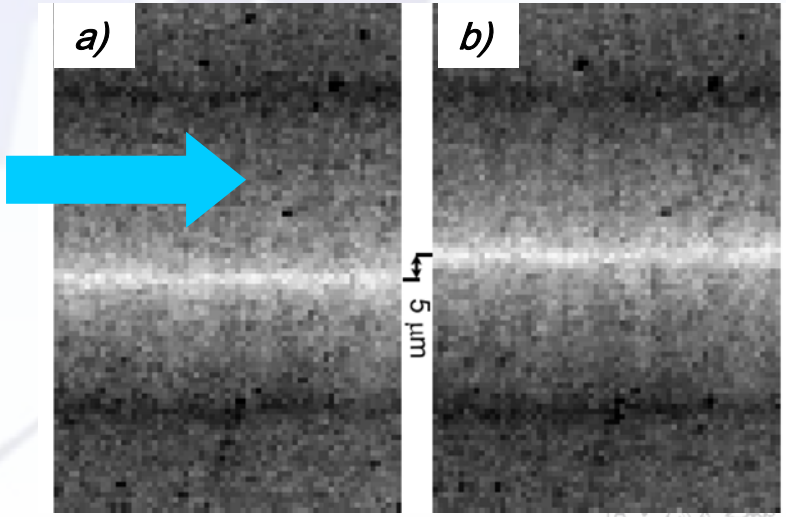
*ion)*

# DISCOLI Device: *working principle*



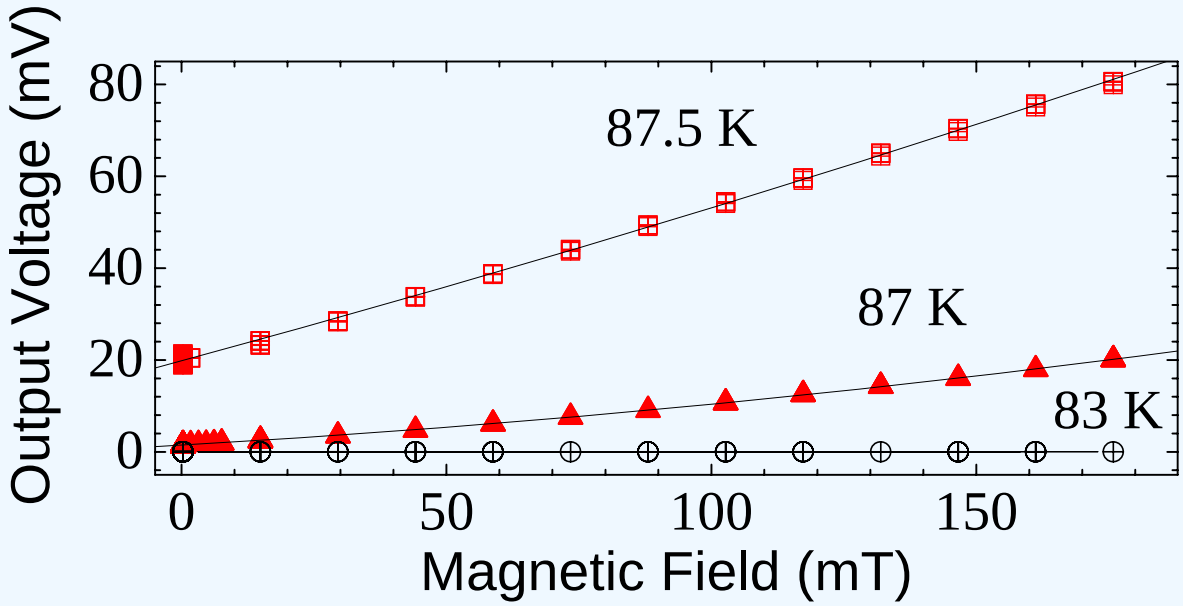



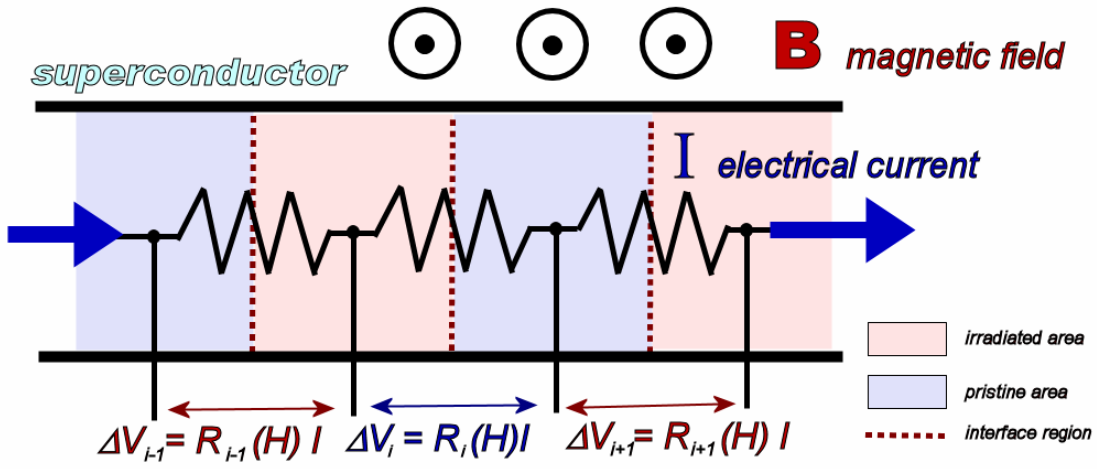



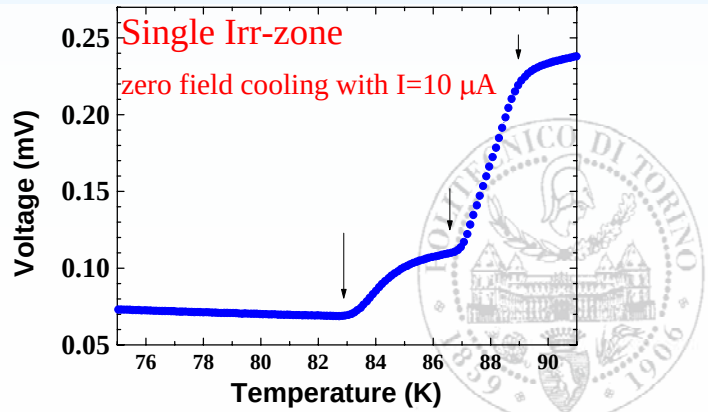

transport current after H= 600 Oe *(T= 70K)*.

*a) I=50 mA; b) I=0 A*

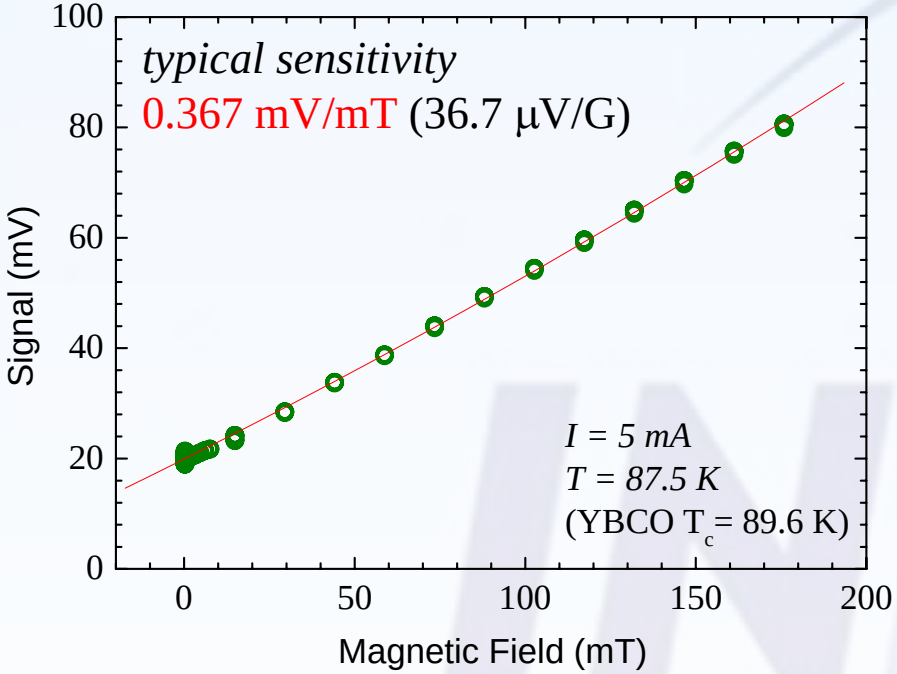
# DISCOLI Device: *idea for* electromagnetic disturbance localization and read-out

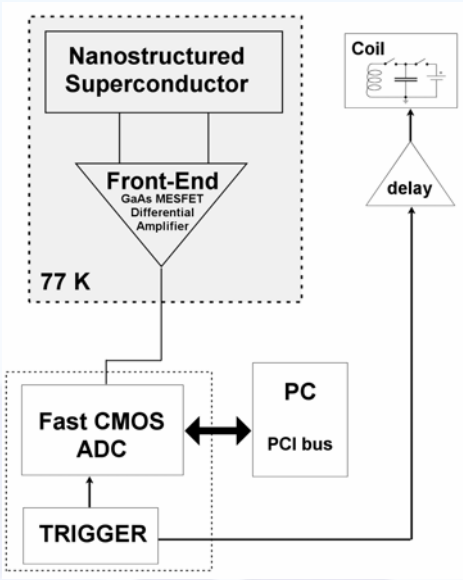


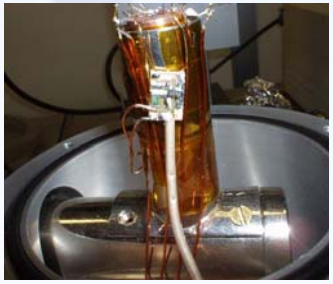



# DISCOLI Device: Performance

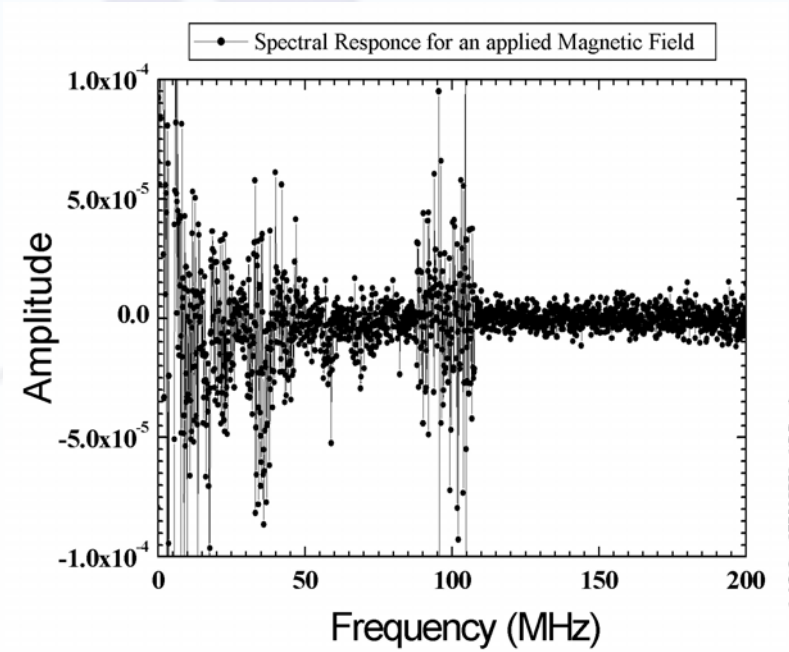


*Magneto-resistive device, figures of merit:*

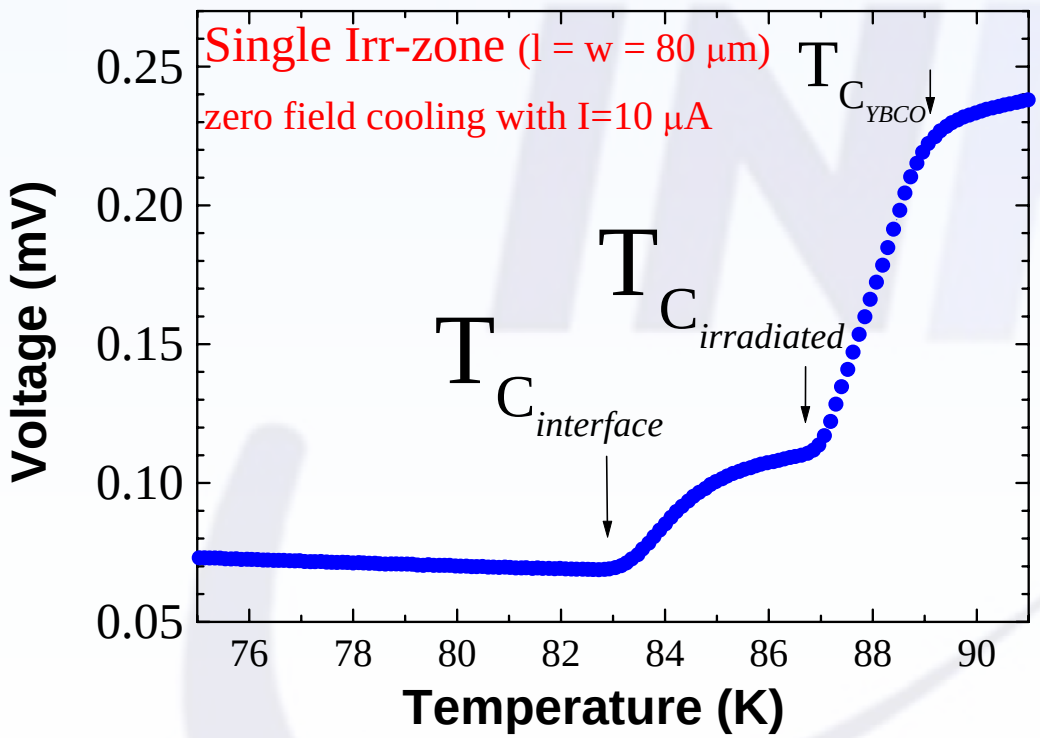
- Electrical power consumption < 1 mW
- Cheap cryogenic environment (>77 K)
- Time responce 10 ns
- Sensitivity > 35 μV/G
- *Saturation field not reached at 4 T*



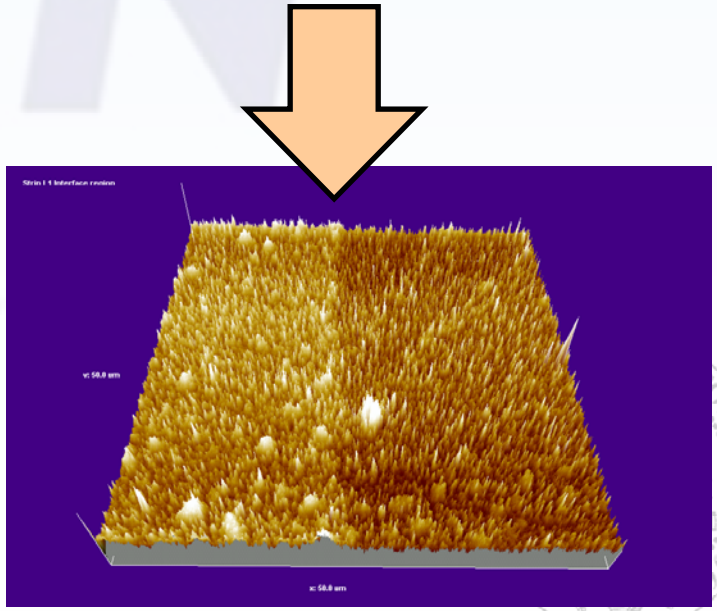
# Interfaces

The interfaces produced by the confined High Energy Heavy Ion Irradiation show Josephson-like behaviour

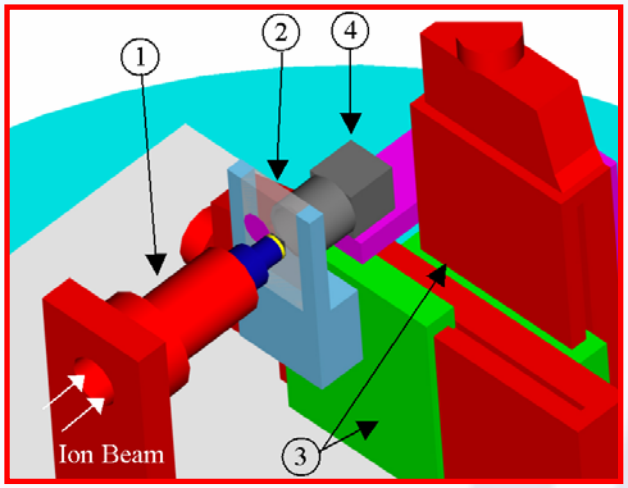
Multiple superconducting transitions occur: *SNS – SS'S*




High $T_c$ Superconductor
Planar SS'S Josephson Junction

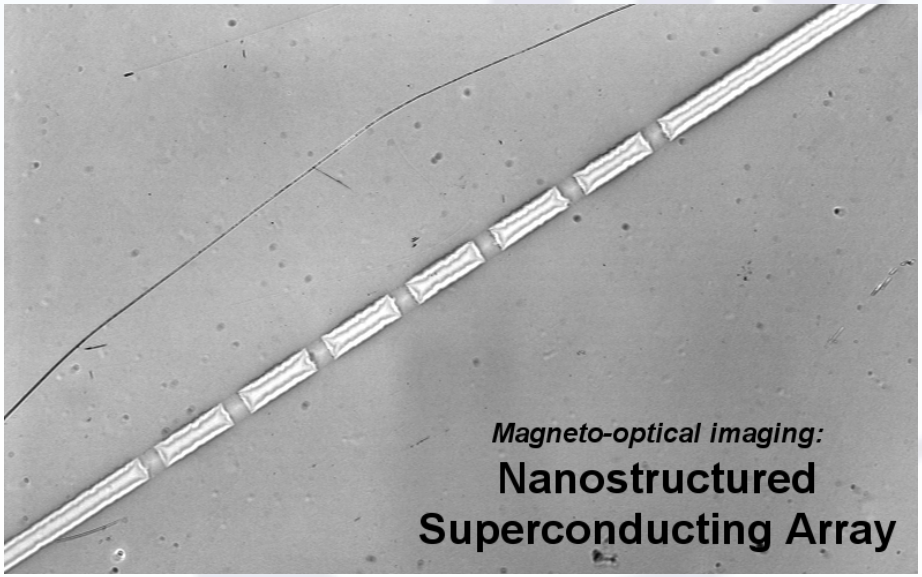


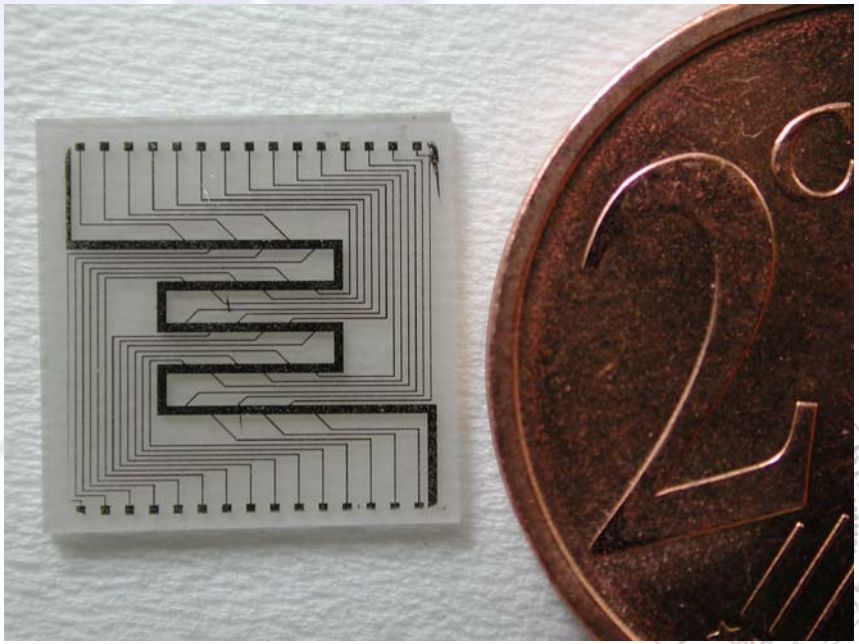
# Bi-dimensional DISCOLI Device




High-Energy Heavy-Ion lithography facility made in the framework of the INFN-DISCOLI project for producing arbitrary geometries of the irradiated area by a micro-confined beam

(1) Faraday cup and collimator with a pinhole micrometric aperture
(2) sample holder with scintillating screen and sample
(3) linear stages
(4) CCD camera.



# Conclusions

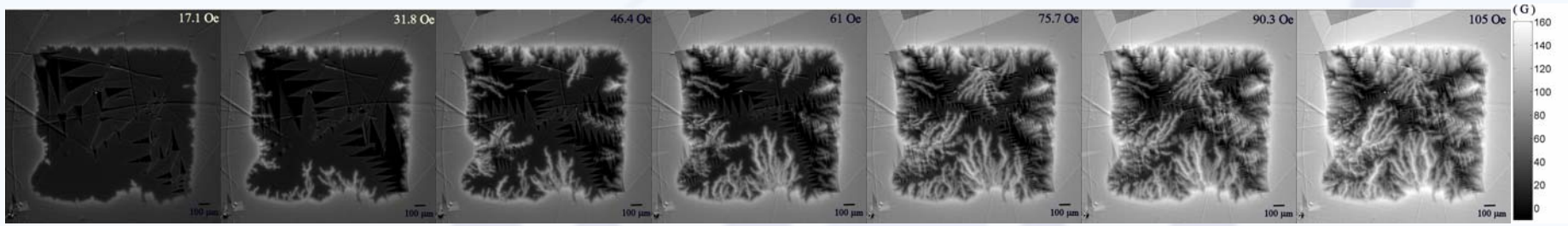
- Real-time visualization by Magneto-Optical imaging extends the knowledge about the magnetic field forces:
  1. MOI visualization unveils the complex phenomenology of the observed materials from the microscopic details up to the collective behaviour;
  2. MOI visualization allows observing the local electromagnetic responce of functionalized materials and checking device reliability.

- DISCOLI device allows us to **detect magnetic field perturbations** on the *micrometer scale* and on the *nanosecond time*, up to fields of several Tesla.

- DISCOLI project achievements leads to the developent of matrices of electromagnetic devices, probing the magnetic quanta on nanosecond time.

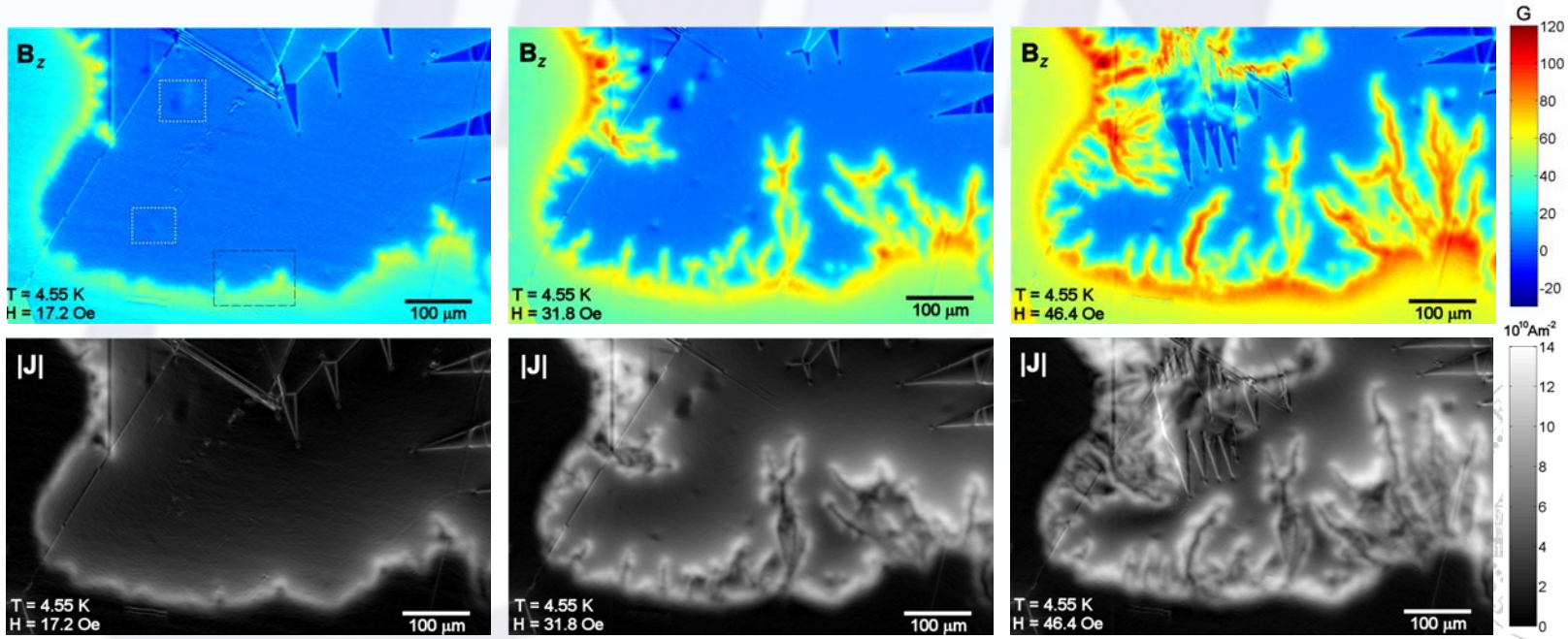
# Thanks to Everybody!!!

# MOI of Self-organized Vortex Patterns



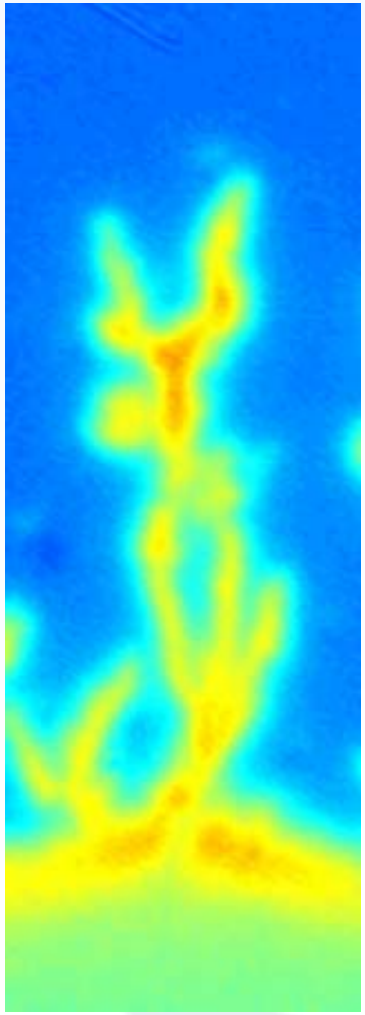

$MgB_2$ film from C. Ferdeghini, INFM-LAMIA, Genova

Presented at the NATO Advanced Workshop on Magneto-optical Imaging, Øystese, Norway (Published by Kluver)

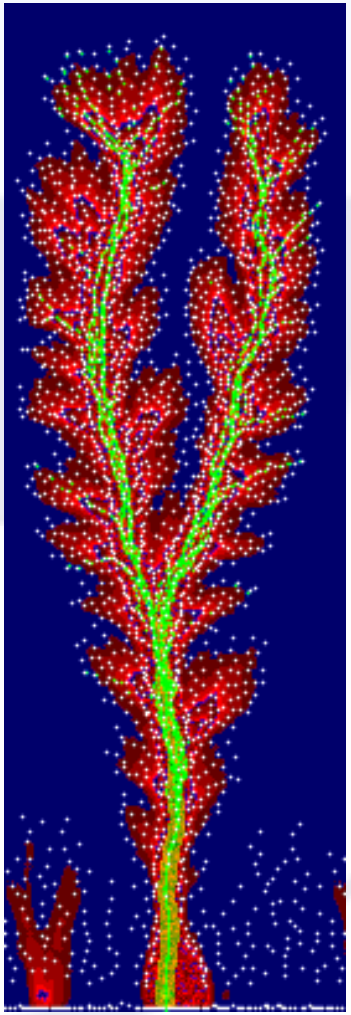


# MOI of Self-organized Vortex Patterns

MOI Zoom



Simulation



Fractal pattern of the *dendritic instability*:

Self-similarity, branching and scaling

*Biological systems*

*Earthquakes*

*Material Fractures*

# Conclusions 2

- MOI allows one to *really see the real-time magnetic field distribution* over a surface with sub-micron resolution
- Detailed imaging of magnetic patterns in crystalline materials opens new ways for studying condensed-matter phenomena and *pattern formation in complex systems*

**Thanks to everybody!!!!!**

# MOI of Magnetic Domains and Domain-Walls

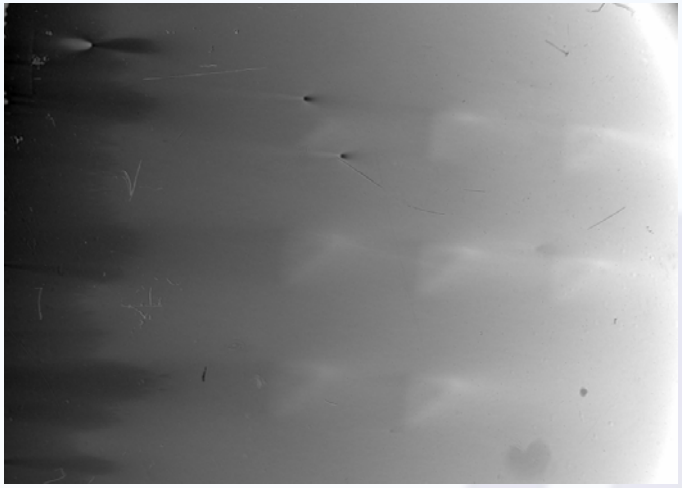
Direct visualization of the microscopic magnetic structure in the whole material:

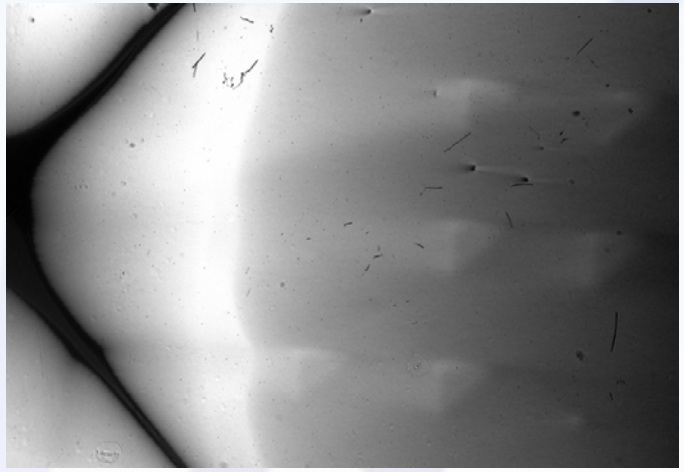
- Different length-scales
- Fractal pattern

Branching on different scales shows *self-organization* of ferromagnetic domains and domain-walls

# INFN-NASTRI *Project*: Long-range disturbance and Collective behaviour

Rovelli, A; Amato, A; Botta, D.; Chiodoni, A.; Gerbaldo, R.; Ghigo, G.; Gozzelino, L.; Laviano, F.; Minetti, B.; Mezzetti, E., NIMB **240** (2005) 842

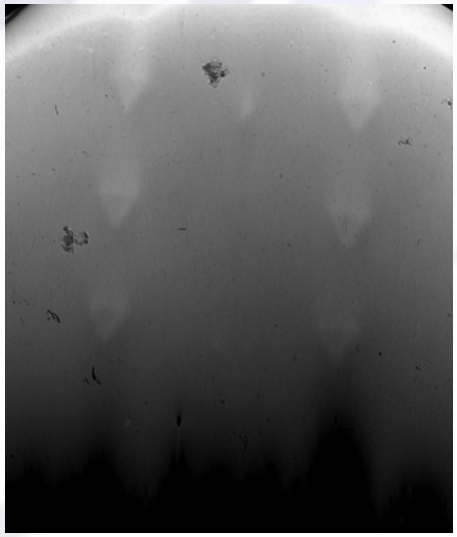




Array of nanostructured micro-areas:

Long range disturbance in the Vortex Matter

MOI of YBCO square film (1 cm x 1 cm)



*Collective behaviour emerges up to the macroscopic length scale*

*Long-range interaction and nonlinearity are essential ingredients for the complex pattern formation*