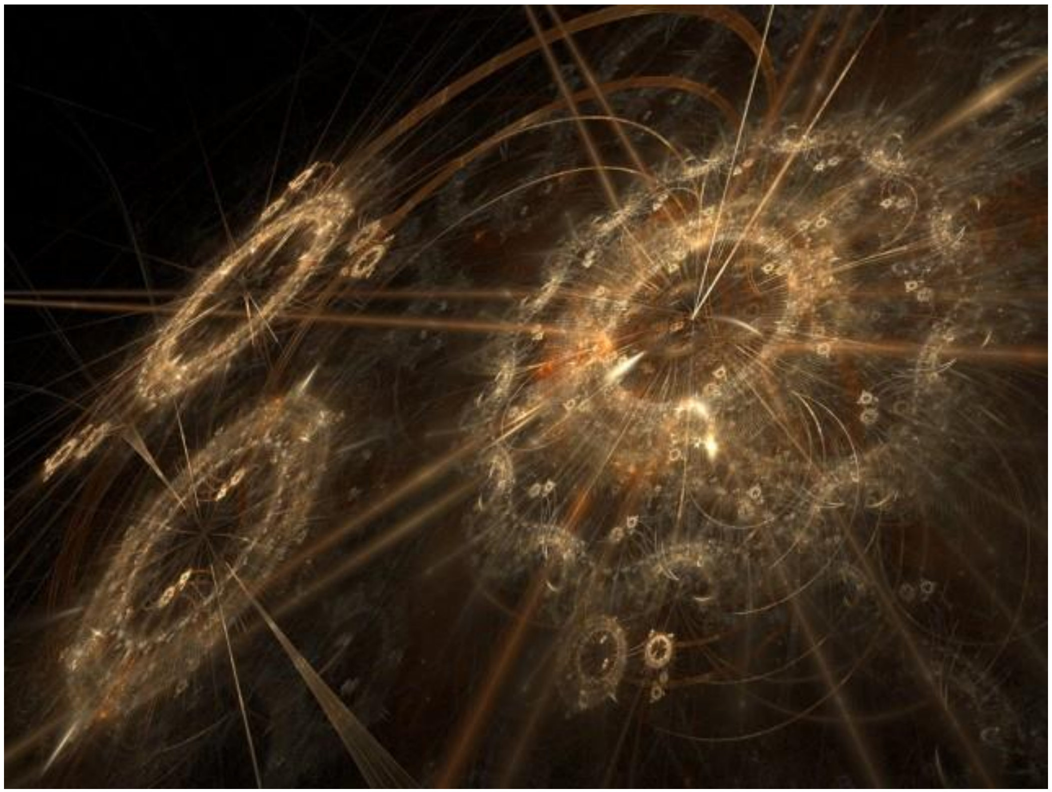
Critical phenomena in superconductors: dendritic flux instabilities against Bean critical state.

P. Mikheenko

Department of Physics, University of Oslo, P.O. Box 1048 Blindern, 0316 Oslo, Norway

Superconductivity in cosmology

The link between superconductivity and black holes



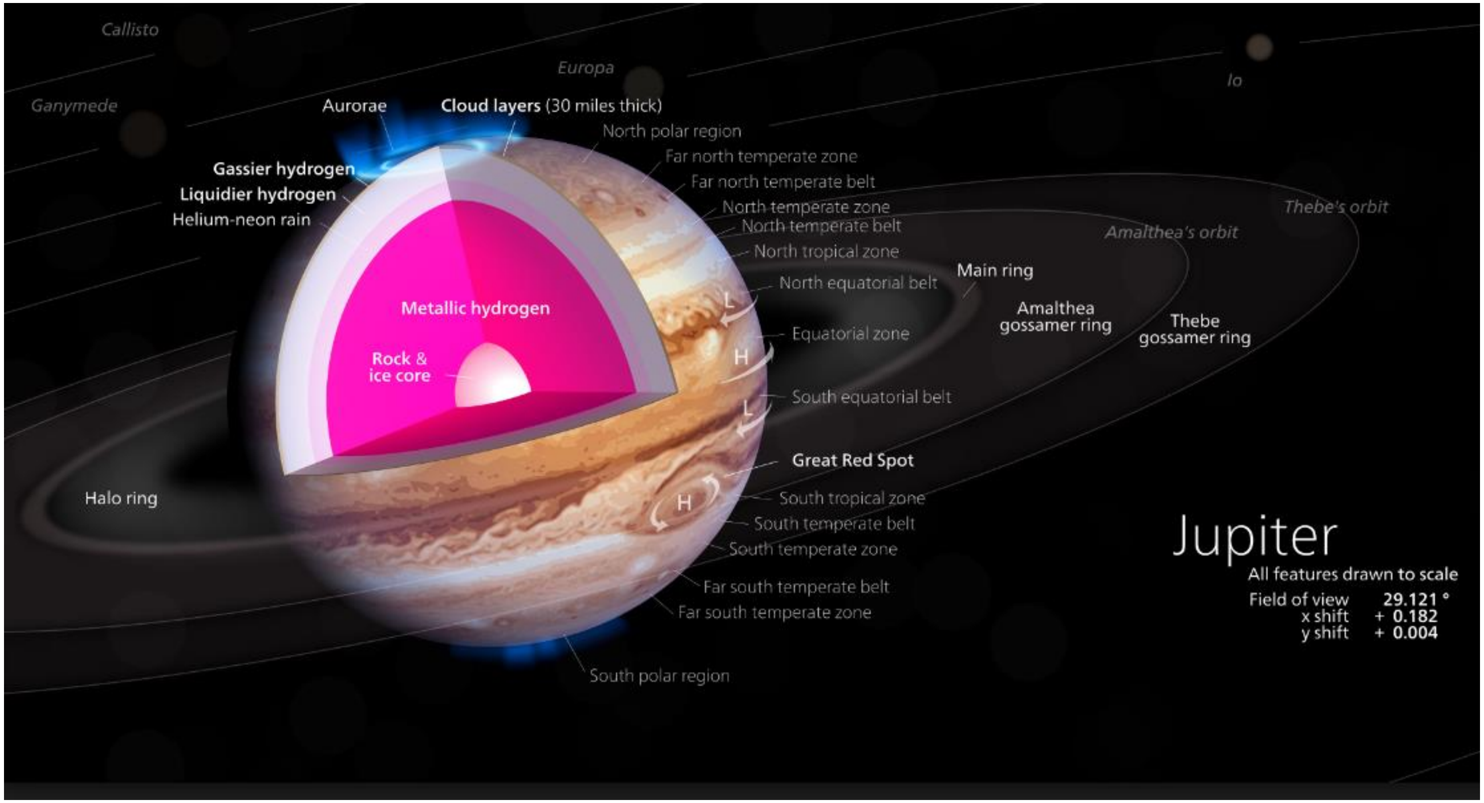
"Clockwork Dreams" by NitroX72

An electron thrown into superconductor disappears immediately, in a similar way to what happens to an object which falls into a black hole. The descriptions in terms of quantum fields (without gravity), such as the ones describing the interactions of the electrons in the superconductor, are equivalent to some quantum gravitational theory descriptions in an exotic higher dimensional space-time.

http://mappingignorance.org/2015/06/10/the-link-between-superconductivity-and-black-holes/

Superconductivity in cosmology

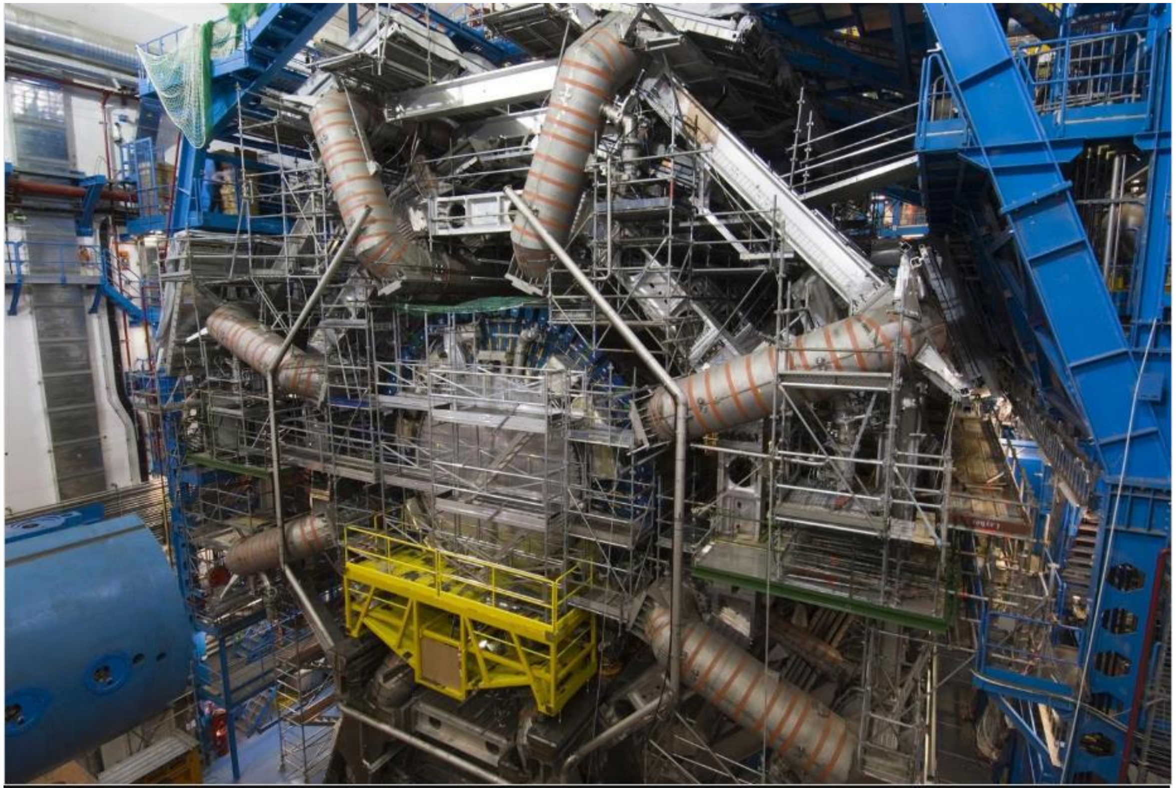
'Somewhat more interesting is the possibility of the superconductivity of metallic hydrogen in the depths of large planets — Jupiter and Saturn': V.L. Ginzburg.



https://www.extremetech.com/extreme/220962-new-hydrogen-discovery-could-help-make-room-temperature-superconductors-a-reality

UiO : University of Oslo

Superconductivity in relativistic heavy ion collisions



The magnet system on the ATLAS detector includes eight huge superconducting magnets (grey tubes) arranged in a torus around the LHC beam pipe (Image: CERN)

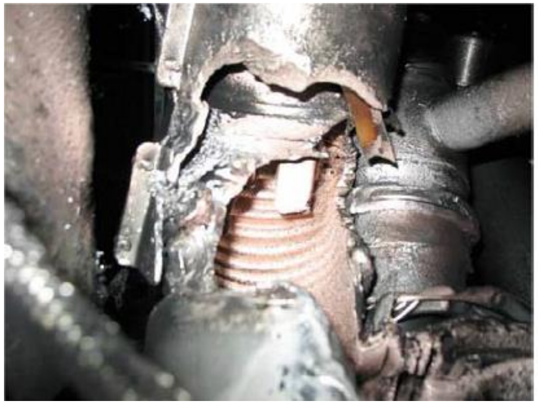
The Large Hadron Collider (LHC) is currently operating at the energy of 6.5 TeV per beam. At this energy, the trillions of particles circle the collider's 27-kilometre tunnel 11,245 times per second. The magnet system on the ATLAS detector includes eight huge superconducting magnets (grey tubes) arranged in a torus around the LHC beam pipe (Image: CERN).

All the magnets on the LHC are superconducting. There are 1232 main dipoles, each 15 metres long and weighing in at 35 tonnes. If normal magnets were used in the 27 km-long LHC instead of superconducting magnets, the accelerator would have to be 120 kilometres long to reach the same energy.

Superconductivity and Large Hadron Collider

All the magnets on the LHC are superconducting. There are 1232 main dipoles, each 15 metres long and weighing in at 35 tonnes. If normal magnets were used in the 27 km-long LHC instead of superconducting magnets, the accelerator would have to be 120 kilometres long to reach the same energy.

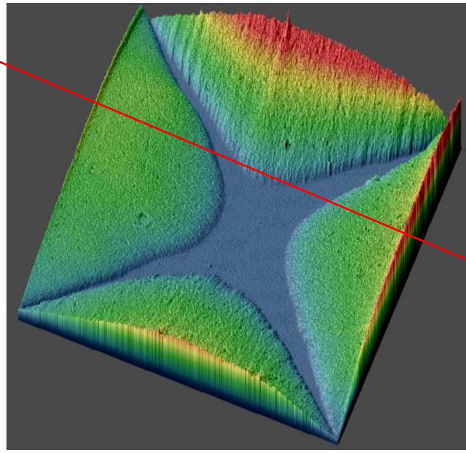
Thermal runaway on Large Hadron Collider

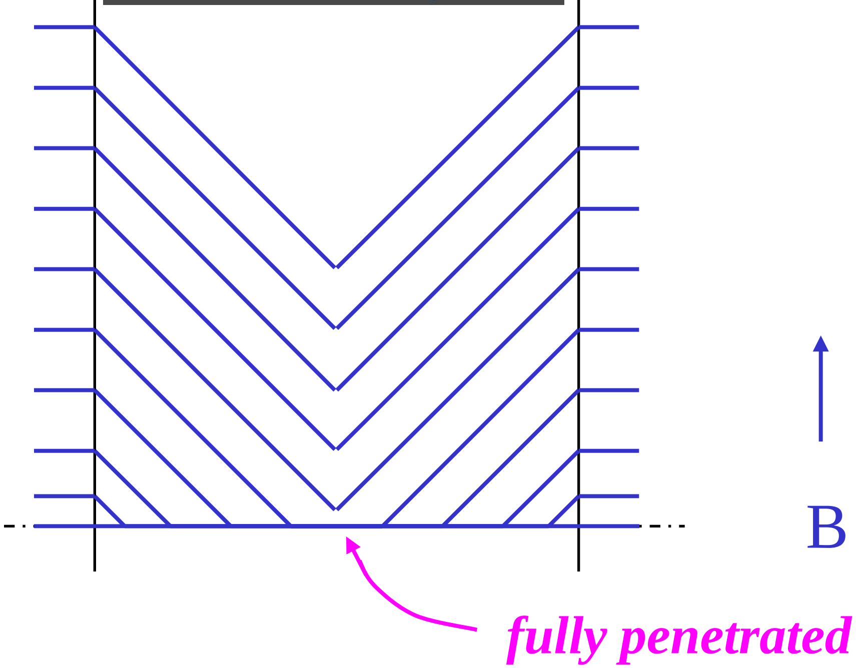


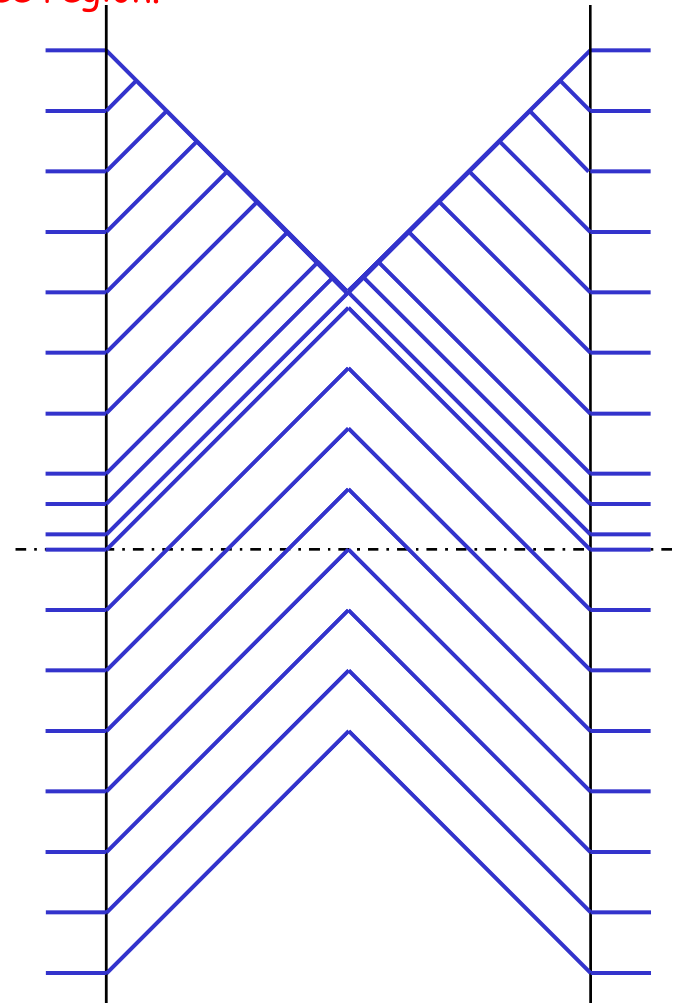
On 19 September 2008, during powering tests of the main dipole circuit in sector 3-4 of the LHC, an electrical fault occurred producing an electrical arc and resulting in mechanical and electrical damage, release of helium from the magnet cold mass and contamination of the insulation and beam vacuum enclosures. Proper safety procedures were in force and no one was put at risk, but material damage is important, eventually affecting some 700 m of the 3.3 km length of the sector.

Bean critical state model

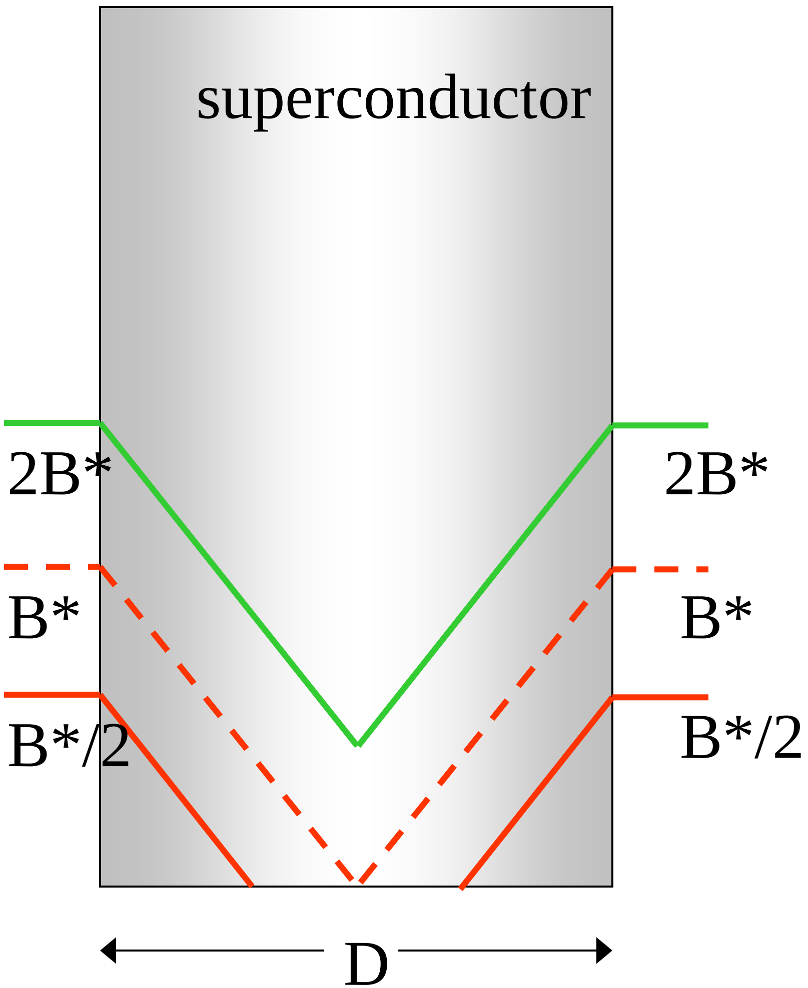
Magnetic field penetrates to or 'exit' from the sample with constant gradient and current equal to critical current. There is no current in flux-free region.

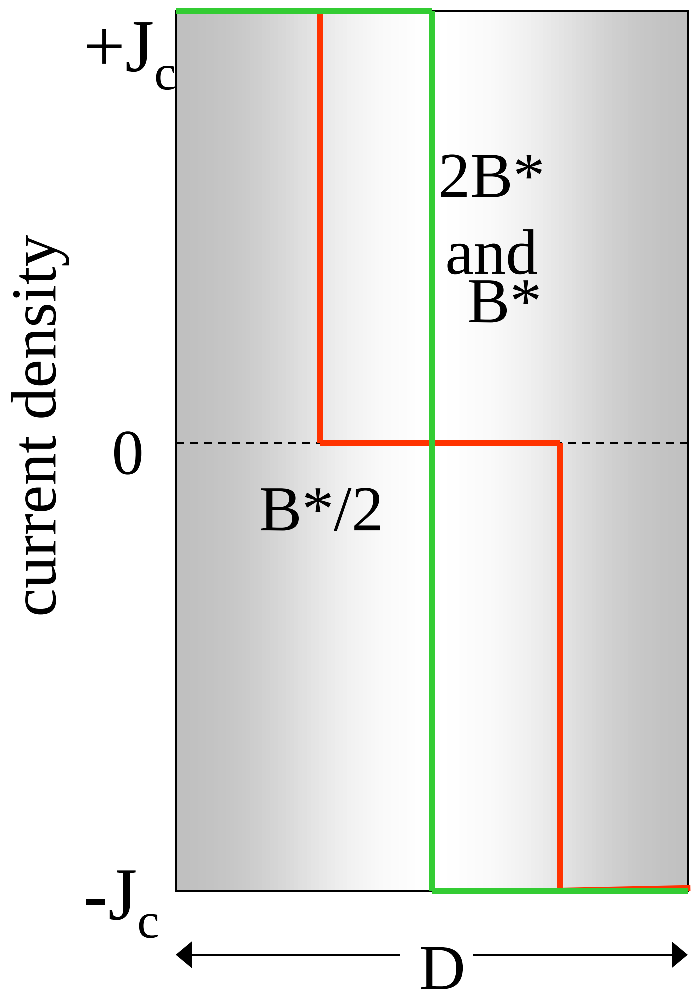






Meissner effect: current distribution

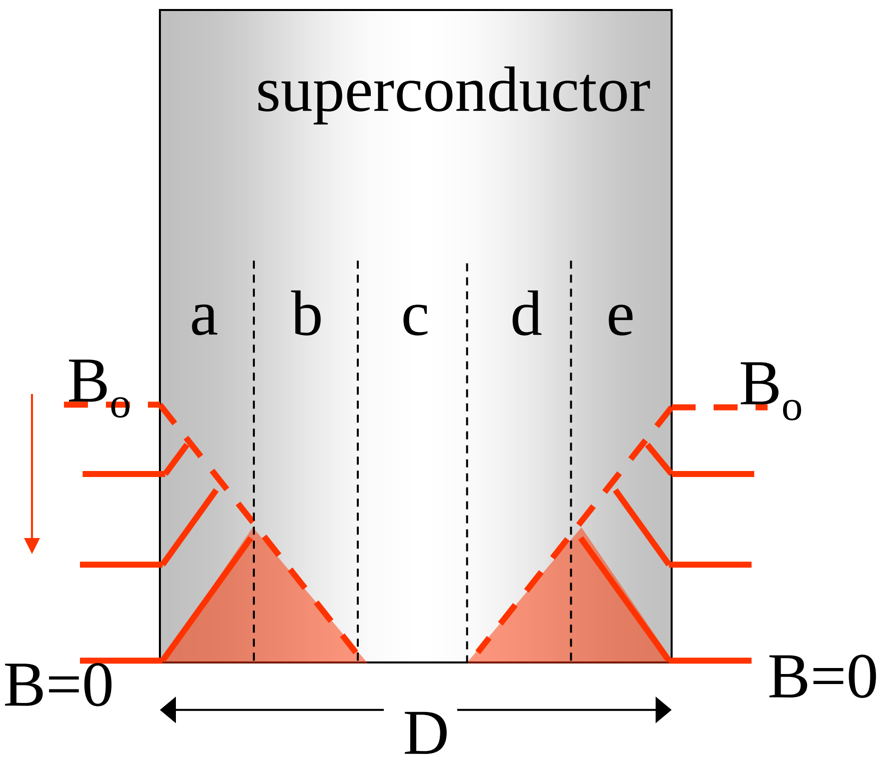


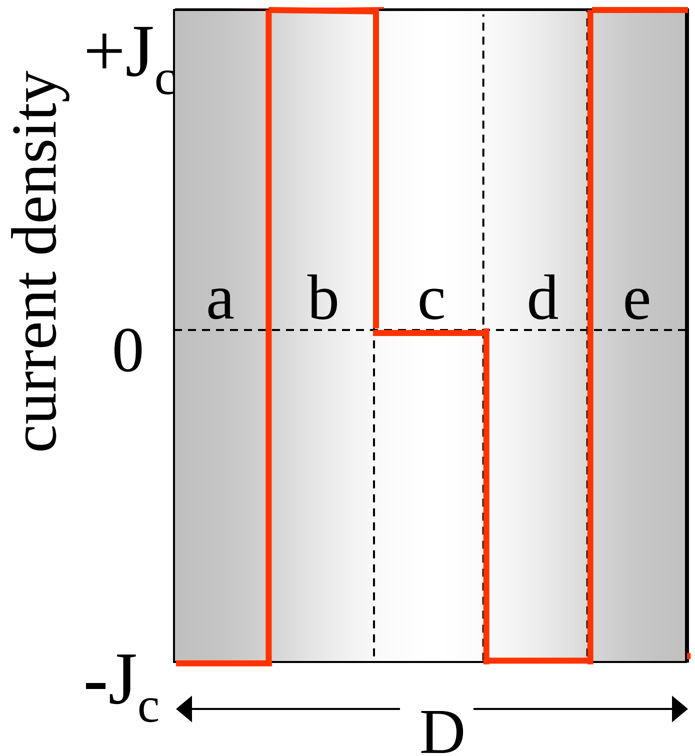


Meissner effect: field decrease

First increasing B to a value B_o then reducing B to zero again

Because the flux density gradient must remain constant, *flux is trapped* inside the superconducting sample, even at B=0



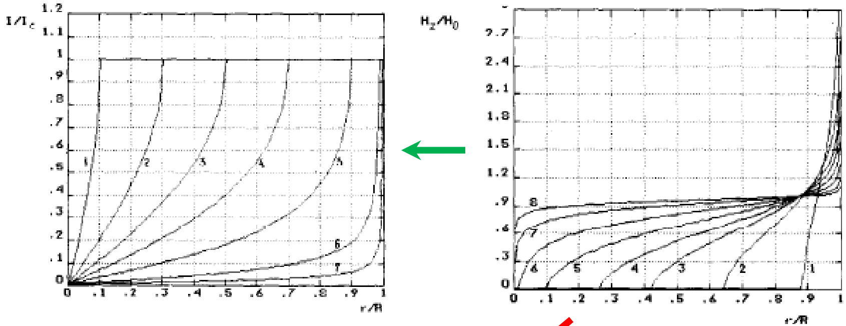


Bean critical state: thin films

Inductance measurements of HTSC films with high critical currents

P.N. Mikheenko and Yu.E. Kuzovlev

Physica C 204 (1993) 229–236
North-Holland

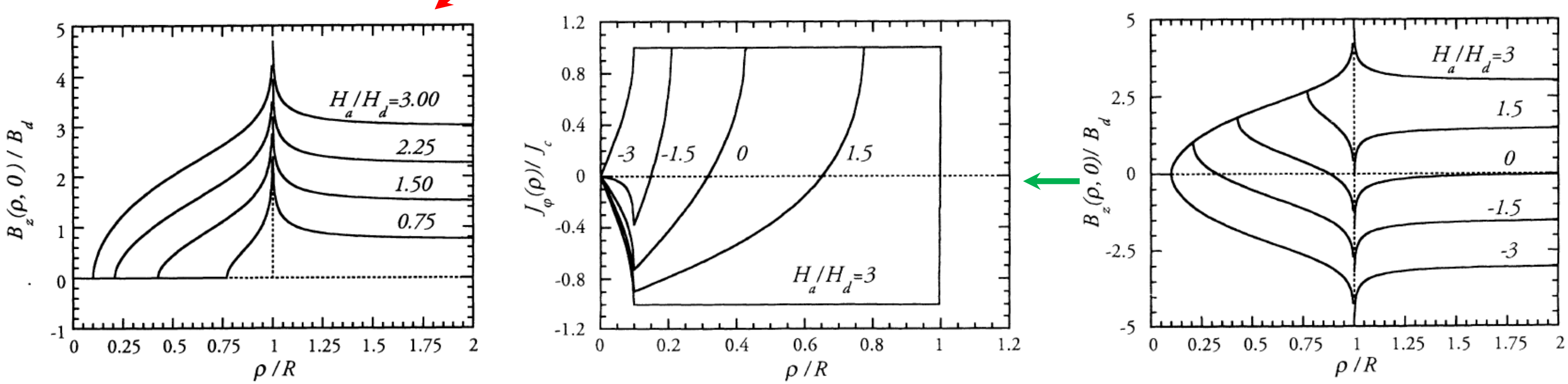


PHYSICAL REVIEW B VOLUME 50, NUMBER 13 1 OCTOBER 1994-I

Hysteretic ac losses and susceptibility of thin superconducting disks

John R. Clem and Alvaro Sanchez

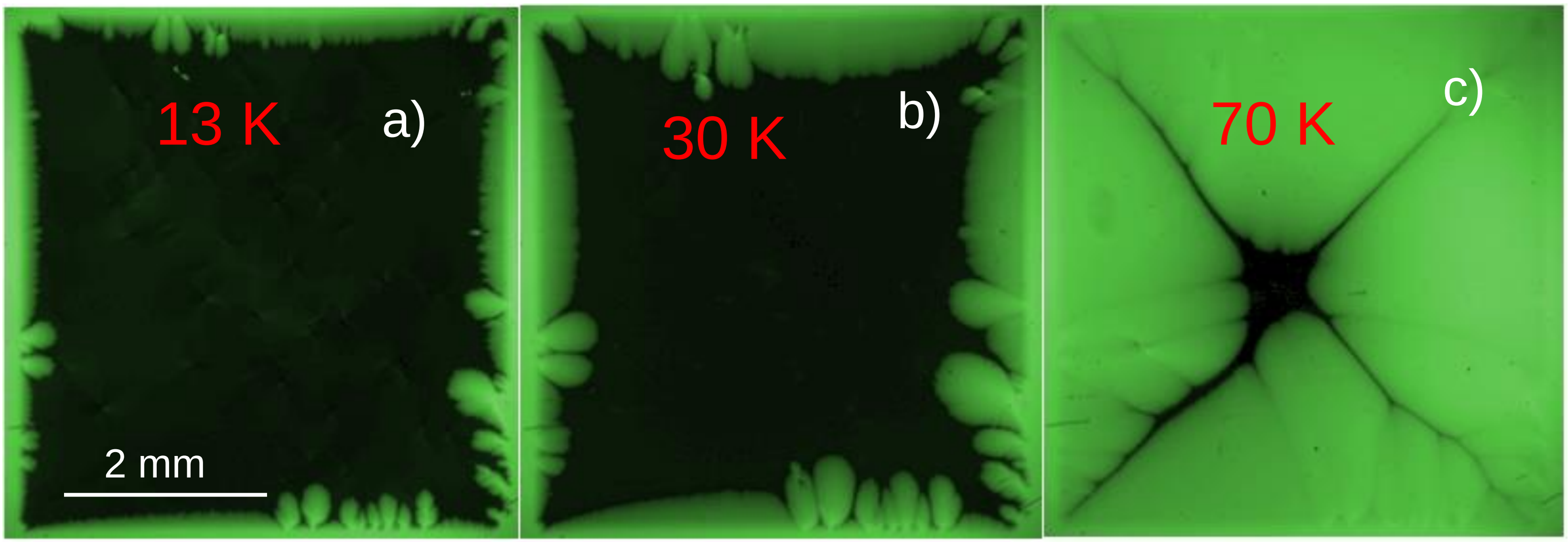
An important theoretical advance recently has been made by Mikheenko and Kuzovlev,[4] who showed how to apply the critical-state theory to thin superconducting disks. This work has been extended (and corrected) by Zhu *et al.*[5] The latter paper contains the basic information that is needed to calculate the hysteretic ac losses in a thin superconducting disk, as well as related properties such as the complex ac susceptibility.



Magnetic field penetrates to or 'exit' from the sample with a varying gradient. Current is equal to critical current in region with magnetic flux. There is current in flux-free region.

UiO : University of Oslo

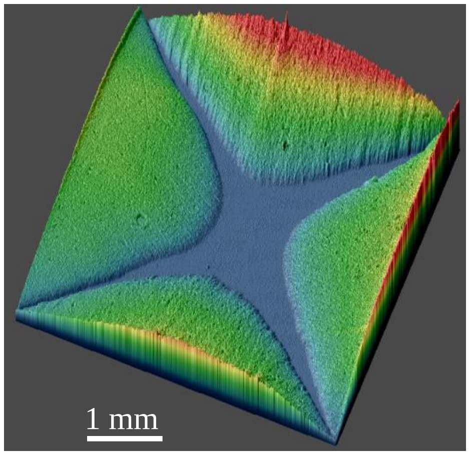
Magneto-optical imaging of $YBa_2Cu_3O_x$ thin films



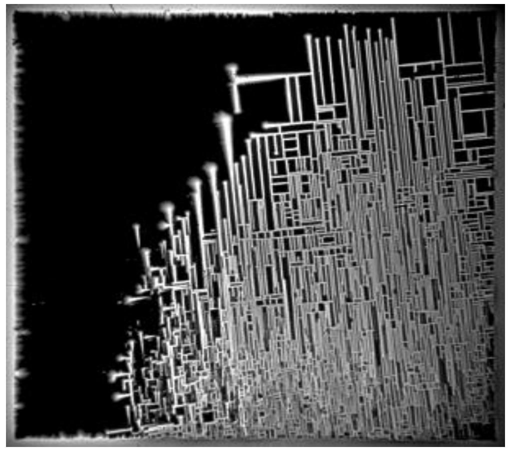
Magneto-optical image of an YBCO film at magnetic field of 85 mT and temperature of 13 K (a), 30 K (b) and 70 K (c).

P. Mikheenko, V-S Dang, Y Y Tse, M M Awang Kechik, P Paturi, H Huhtinen, Y Wang, A Sarkar, J S Abell and A Crisan, Supercond. Sci. Technol. **23**, 125007 (2010).

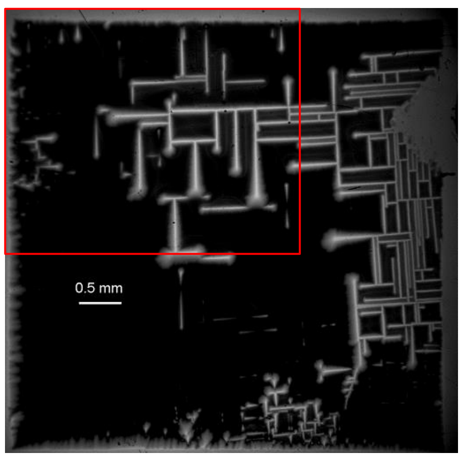
Magnetic flux penetration in superconducting films



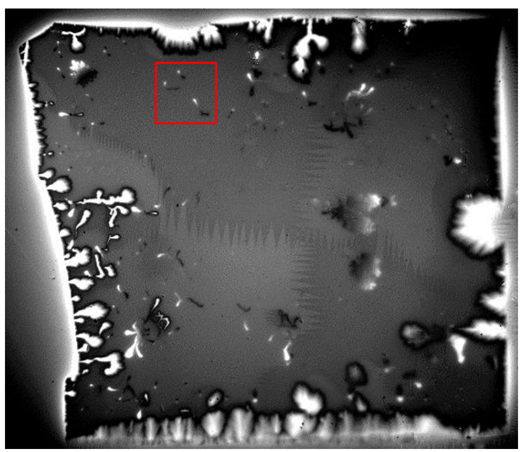
T = 70 K, ideal YBCO



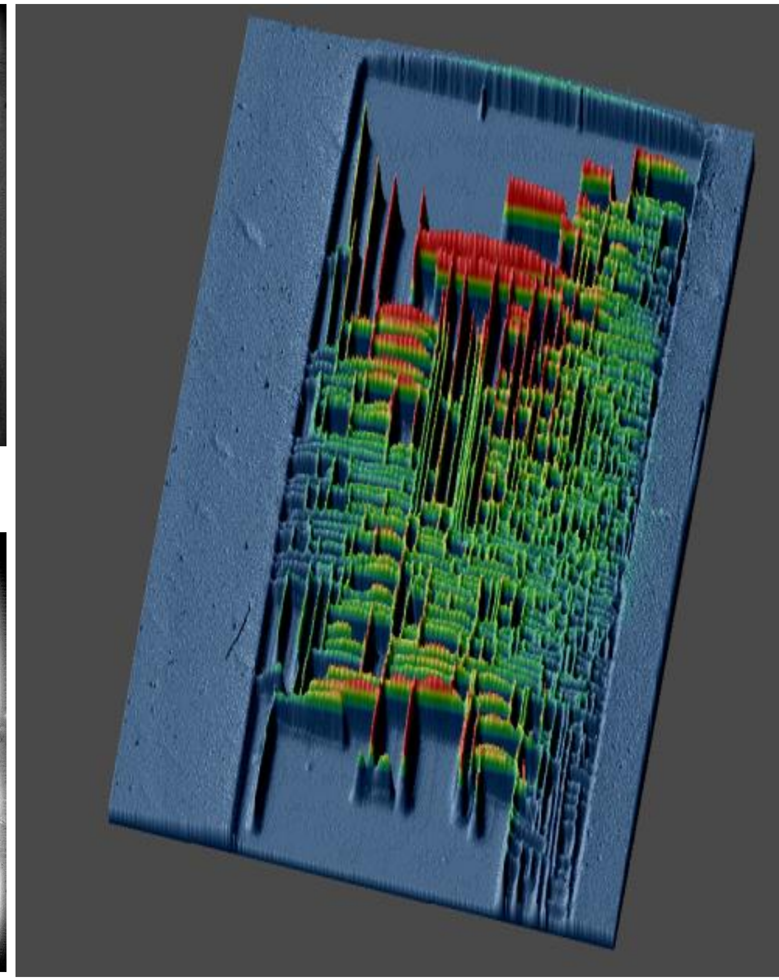
T = 4 K, YBCO



T = 4 K , YBCO



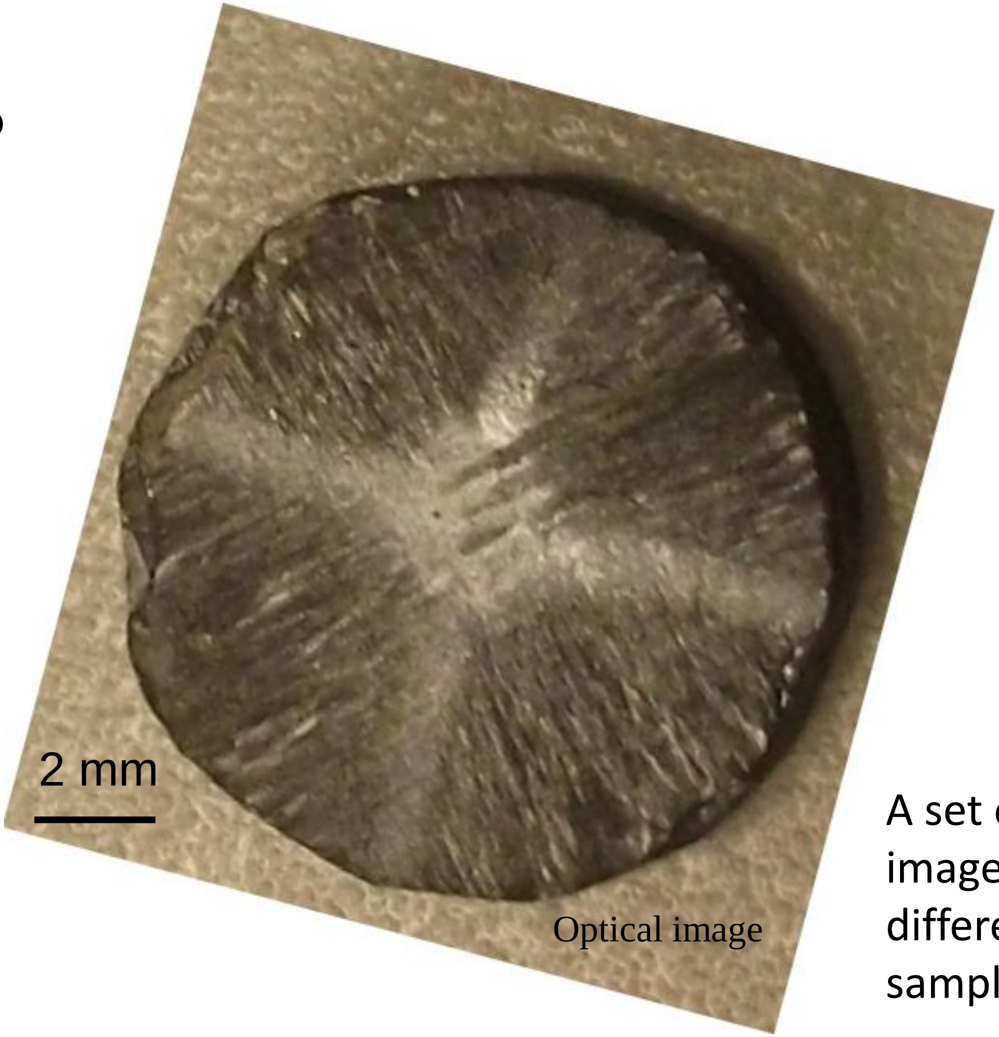
T = 4 K , MgB_2



T = 20 K , YBCO

Trapped magnetic flux in melt grown $YBa_2Cu_3O_x$

The sample was zero field cooled to 79 K. At this temperature magnetic field of 85 mT was applied and than removed.

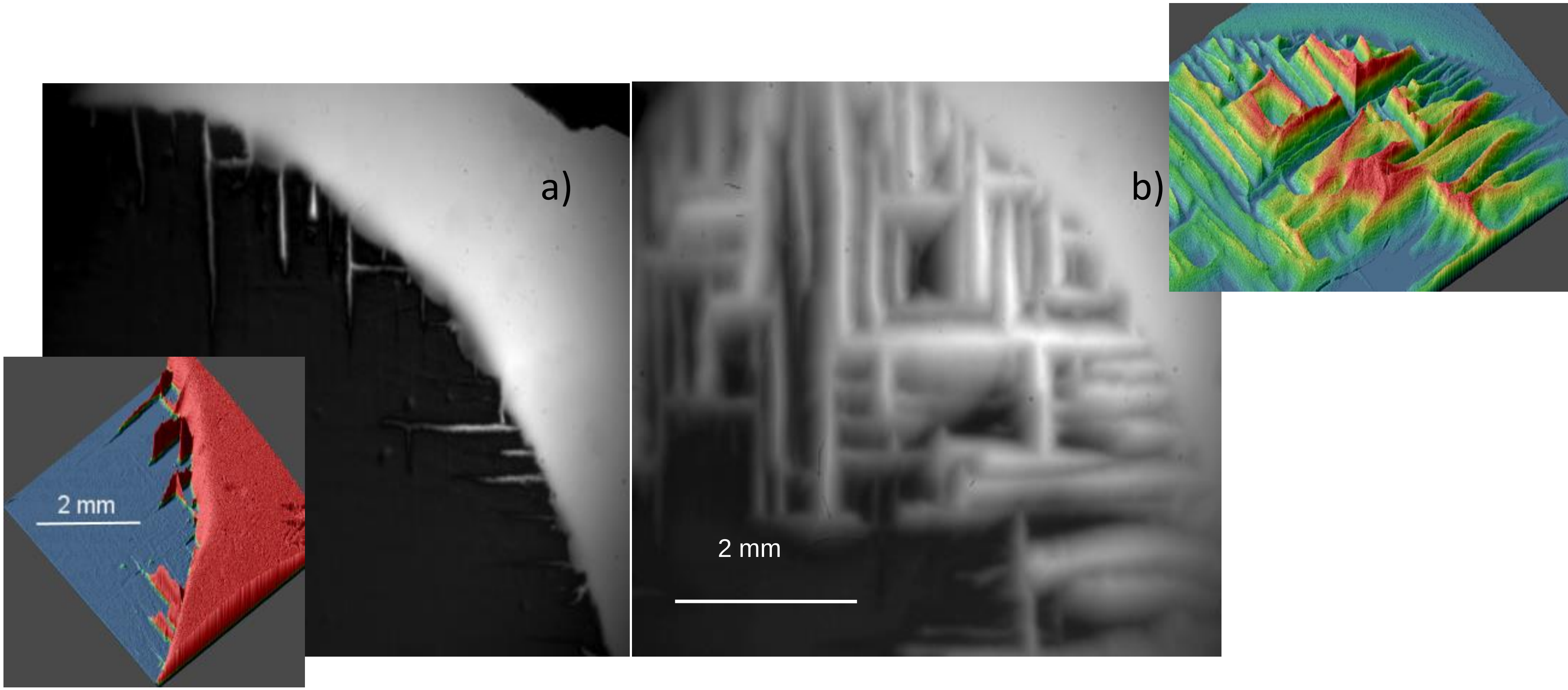


Optical image

A set of magneto-optical images was recorded at different positions in the sample.

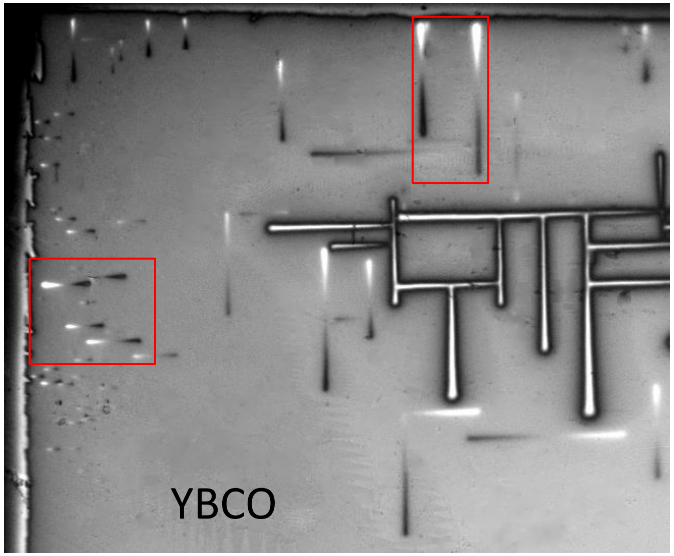
UiO : University of Oslo

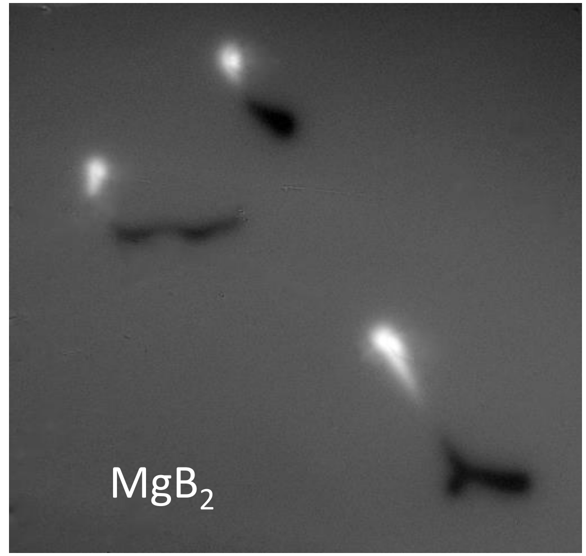
Magneto-optical imaging of bulk $YBa_2Cu_3O_x$

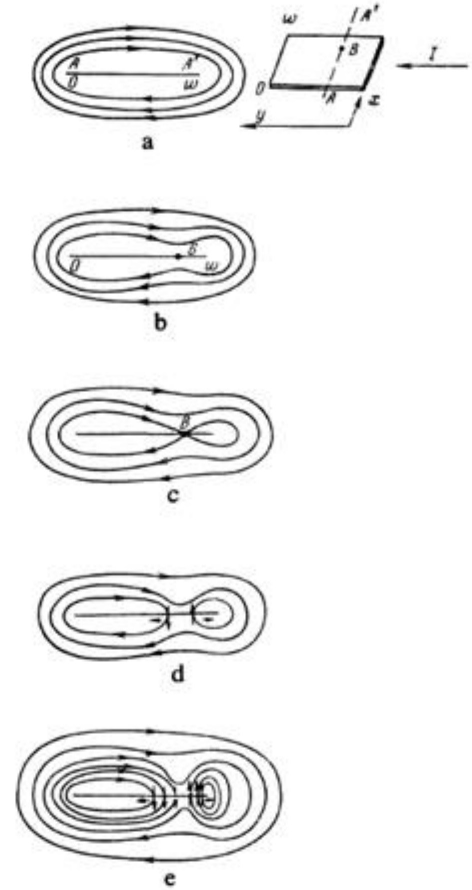


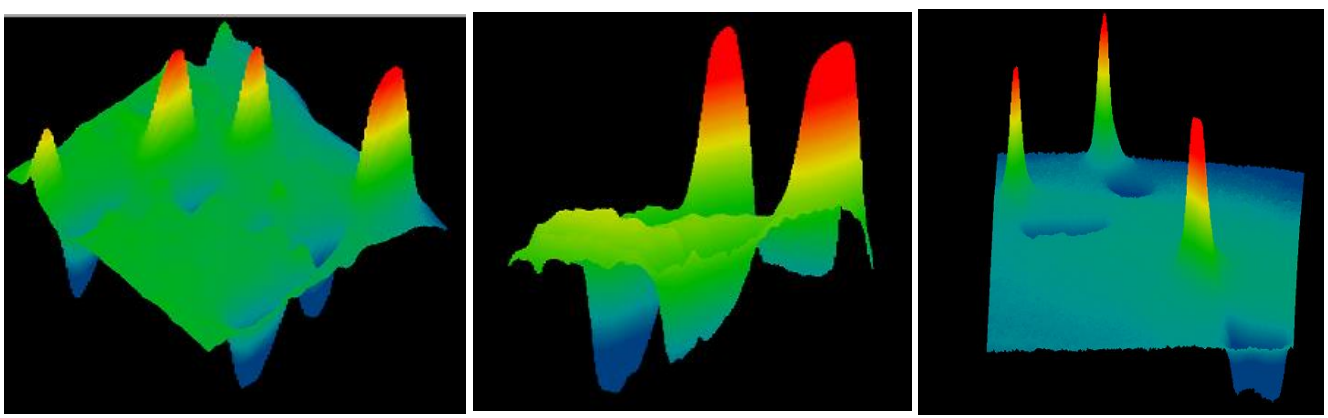
Magneto-optical image of flux penetration into a melt-grown bulk YBCO at magnetic field of 85 mT and temperatures of 20 K (a) and 77.3 K (b), respectively. The screening of the magnetic flux is considerably better at liquid hydrogen (a) than at liquid nitrogen (b) temperature.

Magnetic flux penetration on intrinsic defects



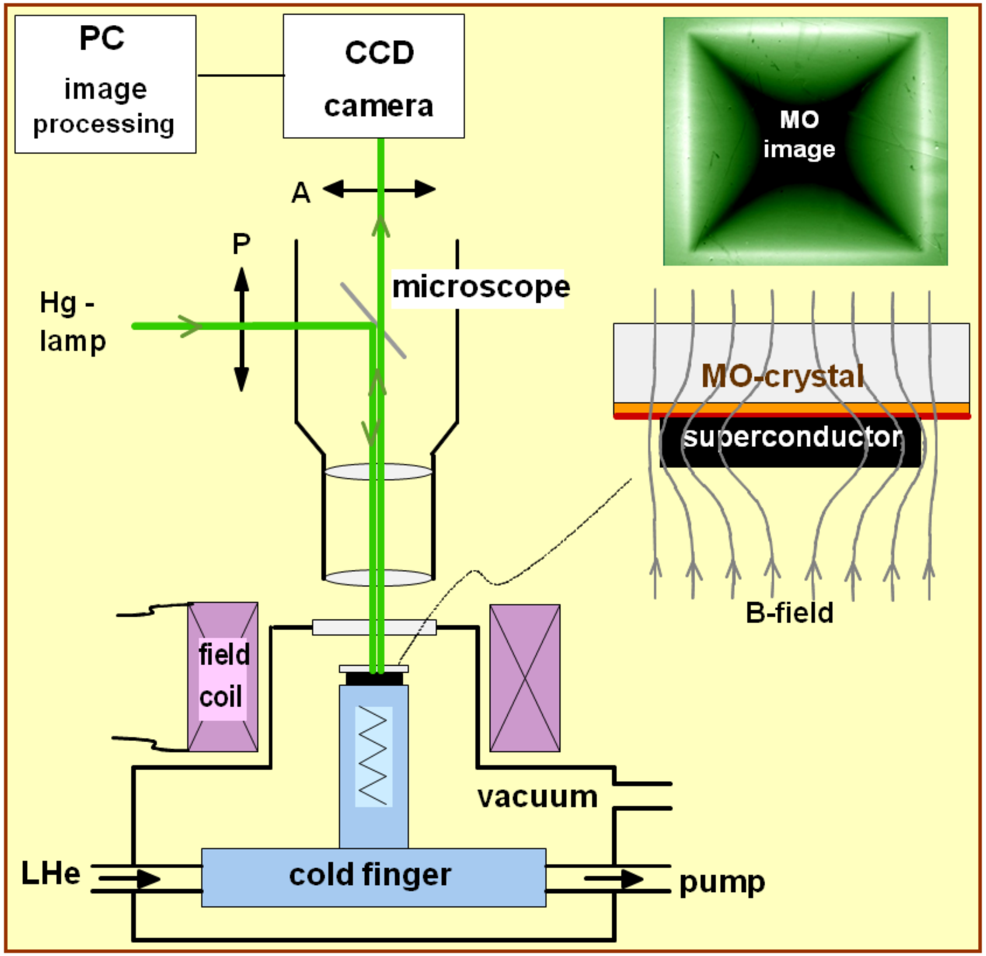






Yu. M. Ivanchenko and P. N. Mikheenko, New mechanism of penetration of vortices into current-saturated superconducting films, Zh. Eksp. Teor. Fiz. 85,2116-2127 (1983)

Faraday effect and magneto-optical imaging

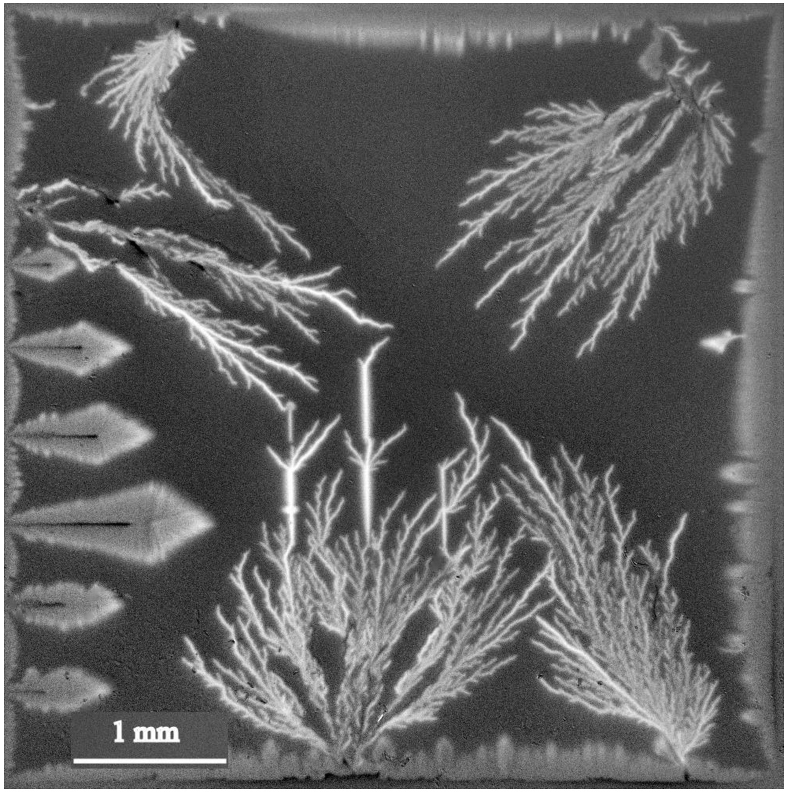


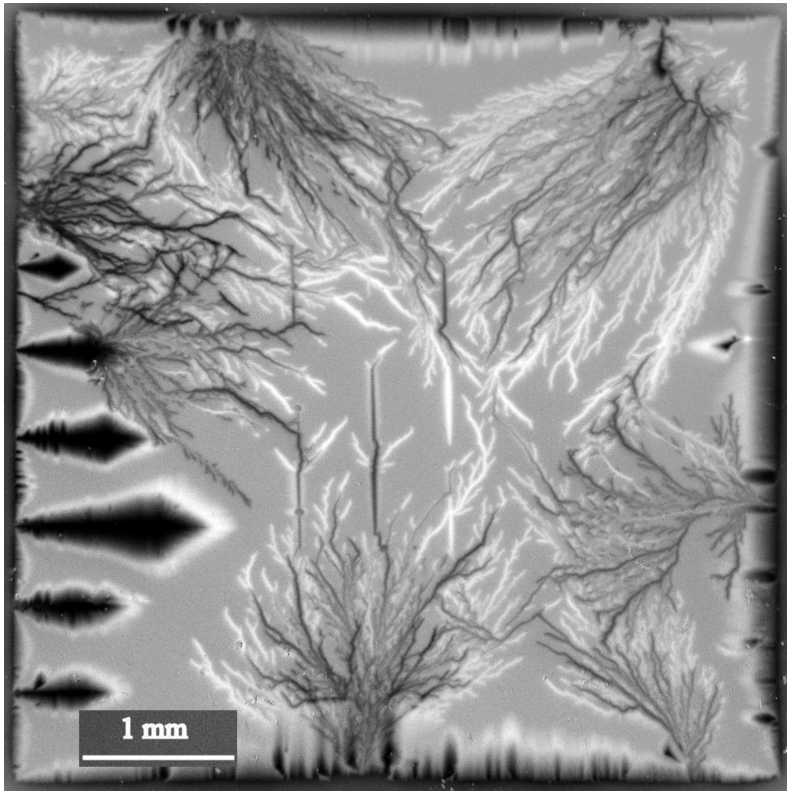
Michael Faraday, 1842, by Thomas Phillips

The Faraday effect is a rotation of the polarization of light in presence of magnetic field. The effect was discovered by Michael Faraday in 1845.

https://en.wikipedia.org/wiki/Michael_Faraday

Dendritic flux penetration in Nb films





Dendrites and antidendrites in superconducting Nb films at T = 4 K.

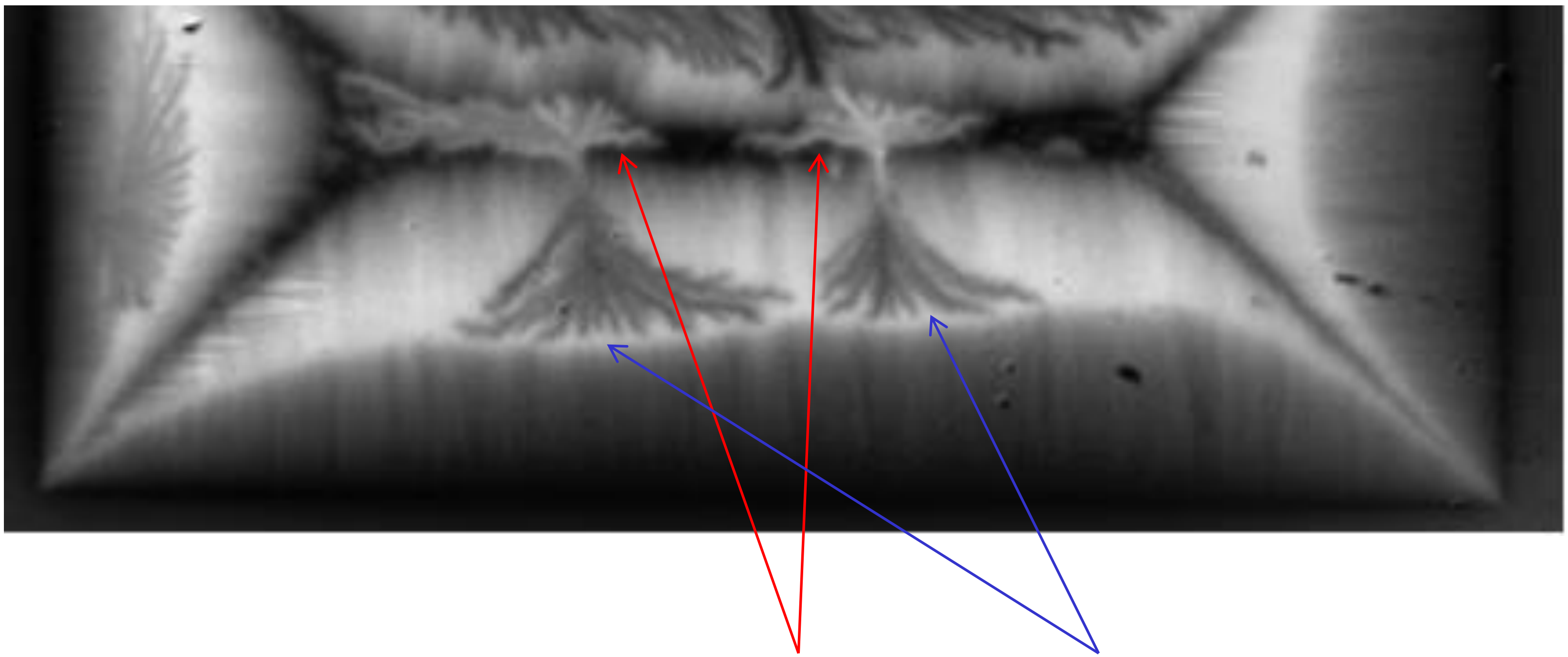
Dendrites in stones

https://www.google.co.uk/search?q=dendrites+in+stones&source=lnms&tbm=isch&sa=X&ved=0ahUKEwivkJWAirHTAhWKiCwKHWTbCQIQ_AUIBigB&biw=1920&bih=1073#imgrc=97qTtIzp8DQZ0M:&spf=199

https://www.google.co.uk/search?q=dendrites+in+stones&source=lnms&tbm=isch&sa=X&ved=0ahUKEwivkJWAirHTAhWKiCwKHWTbCQIQ_AUIBigB&biw=1920&bih=1073#imgrc=HPXRHstxgj-FpM:&spf=226

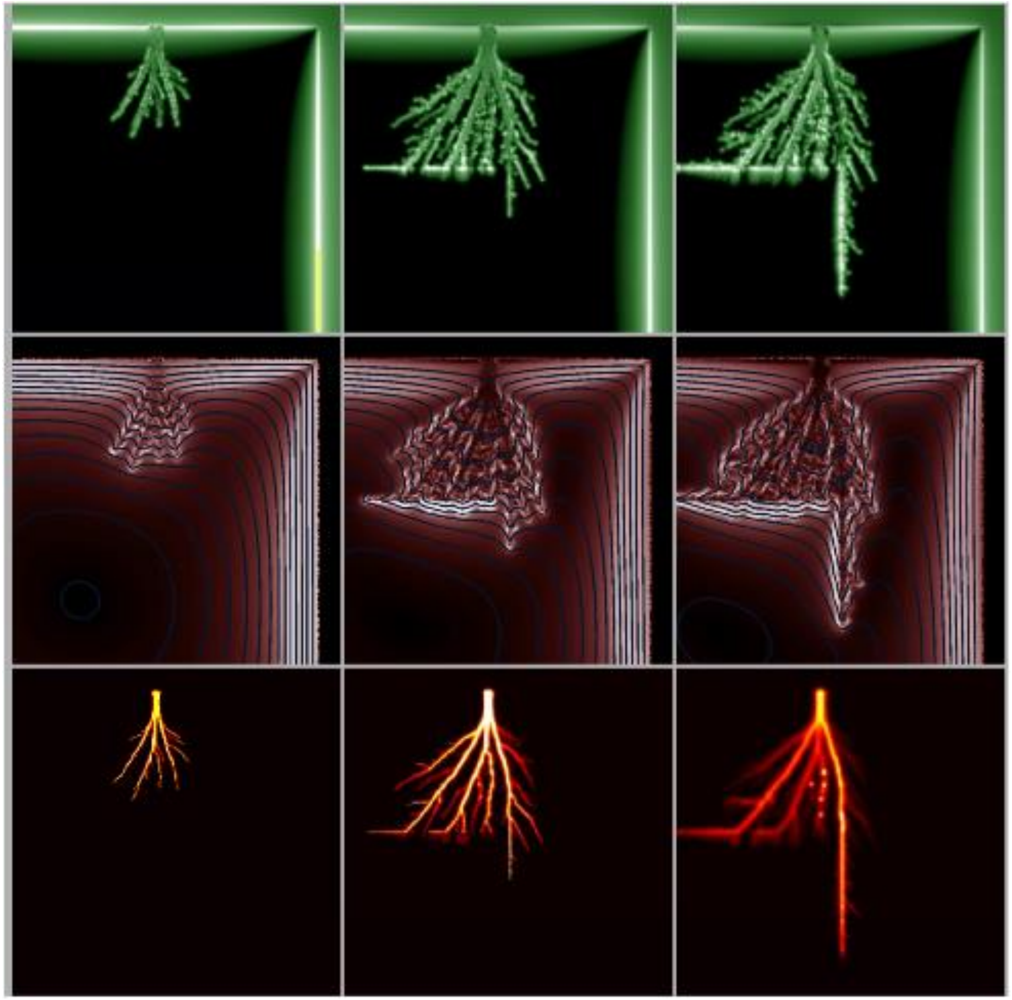
https://www.google.co.uk/search?q=dendrites+in+stones&source=lnms&tbm=isch&sa=X&ved=0ahUKEwivkJWAirHTAhWKiCwKHWTbCQIQ_AUIBigB&biw=1920&bih=1073#imgrc=1oVYYYvcwdnF4M:&spf=235

Flux-antiflux avalanches in NbN films



Simultaneous excitation of dendrites and anti-dendrites in superconducting NbN 1.5 x 3 mm film at T = 4 K.

Distribution of magnetic flux, current and temperature

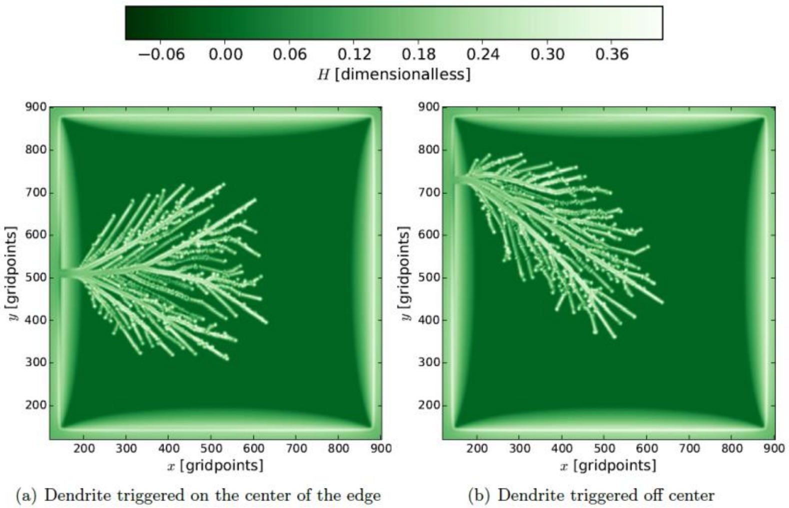


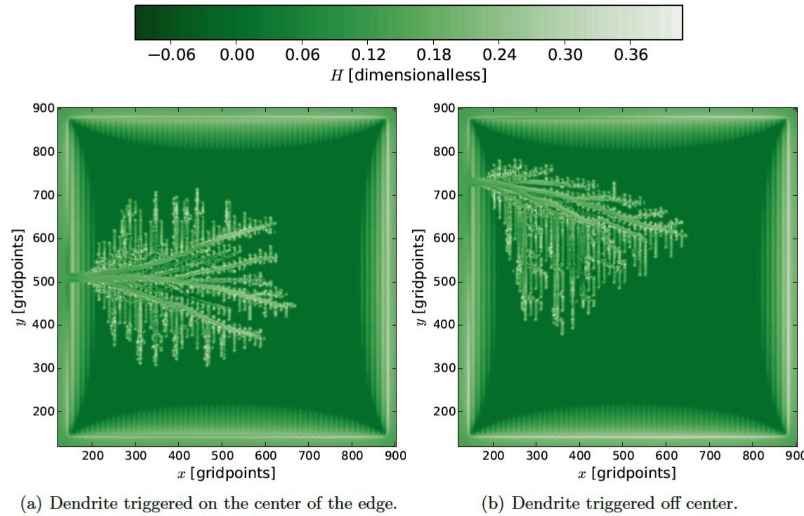
Flux density map on different stages of dendrite penetration into superconducting sample.

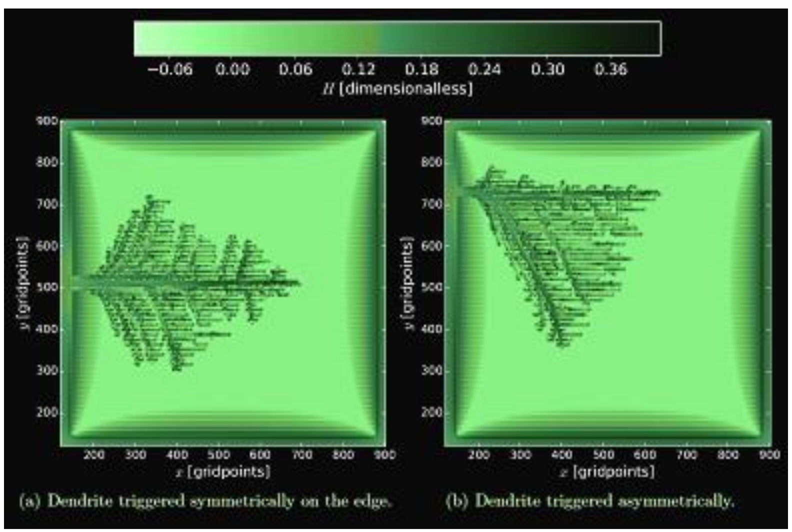
Distribution of electrical current on different stages of dendrite penetration into the sample.

Distribution of temperature during dendrite penetration into the sample. The sample can be overheated above critical temperature.

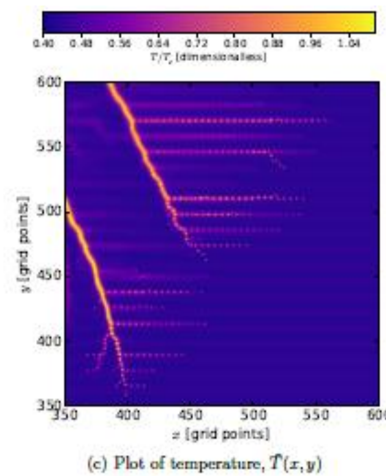
Dendritic avalanches in films with modulated critical current density







Art of making a perfect Christmas tree

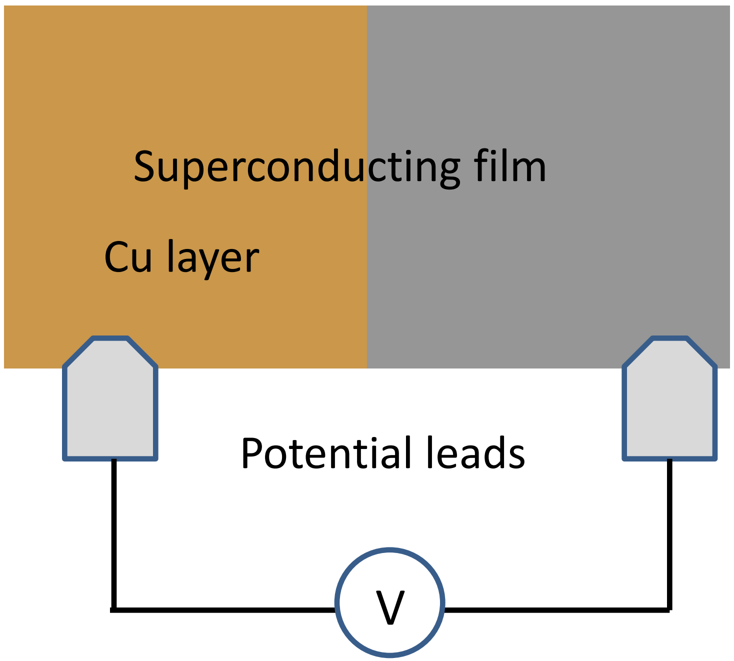


Gorse bush

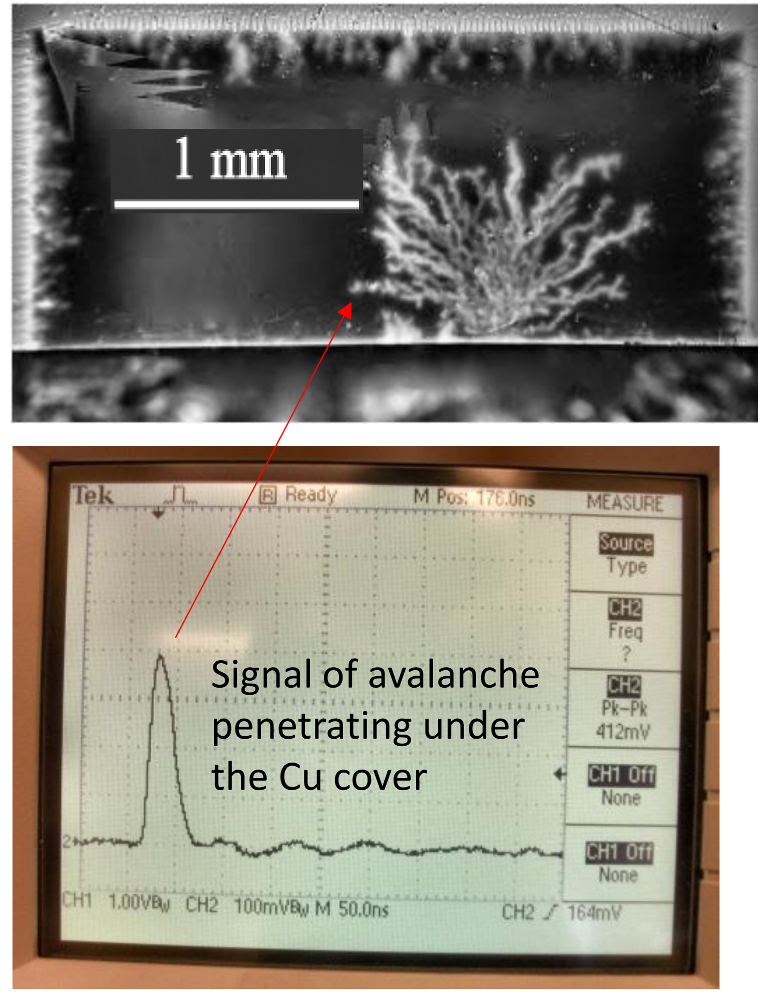
Comparison of dendrites in a sample with uniform J_{c0} to the dendrites in the sample with weak channels, in which $J_{c1} = 3/4J_{c0}$.

Pulse measurements of dendritic avalanches

The voltage peak appears when avalanche strikes under Cu pad.

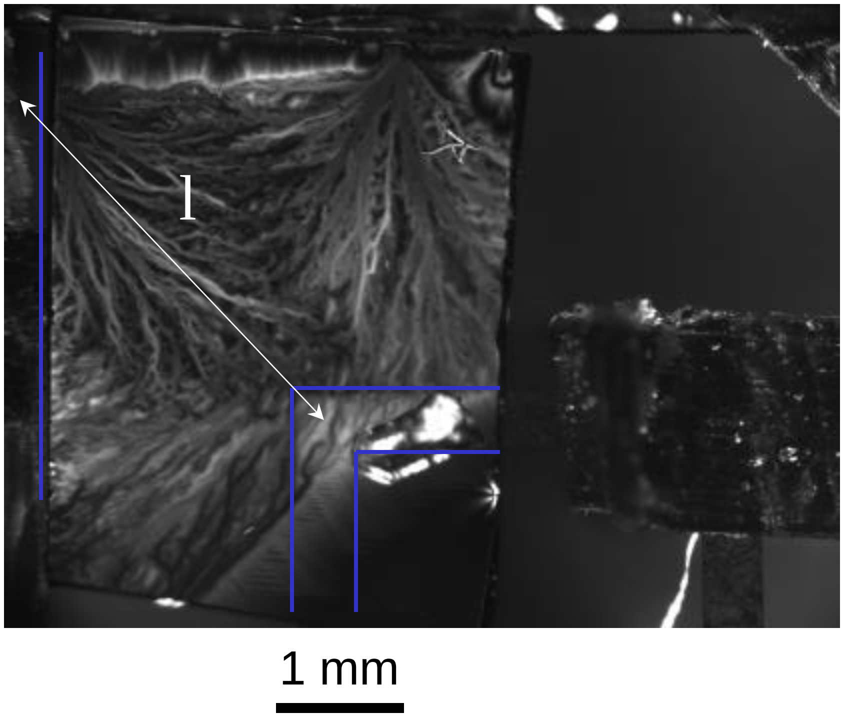


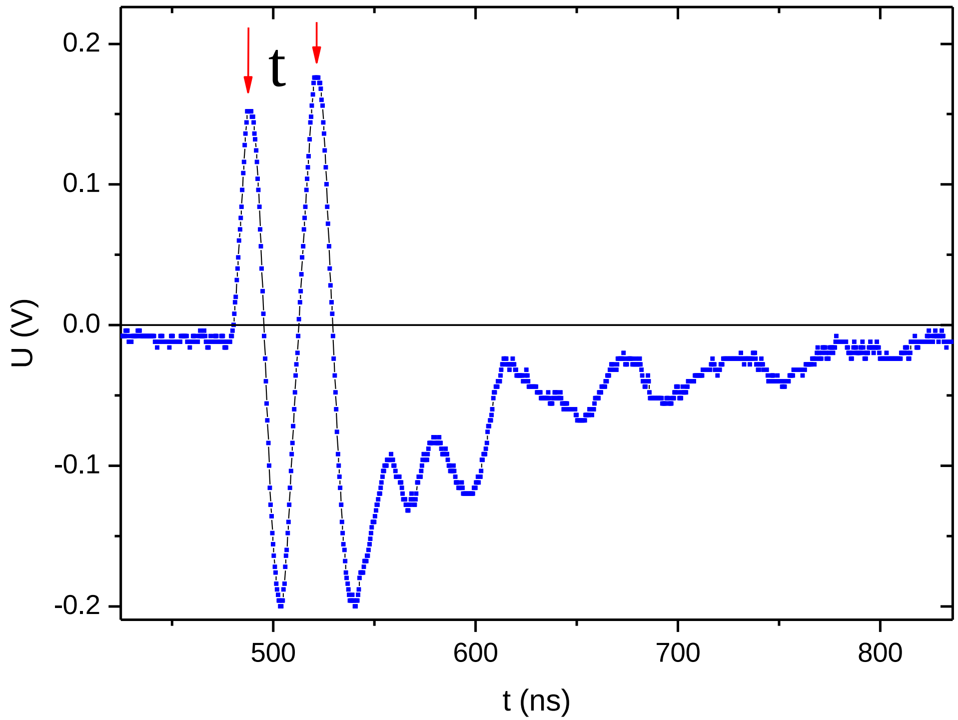
Voltmeter with nanoseconds resolution



P. Mikheenko et al., Appl. Phys. Lett. **102**, 022601 (2013).

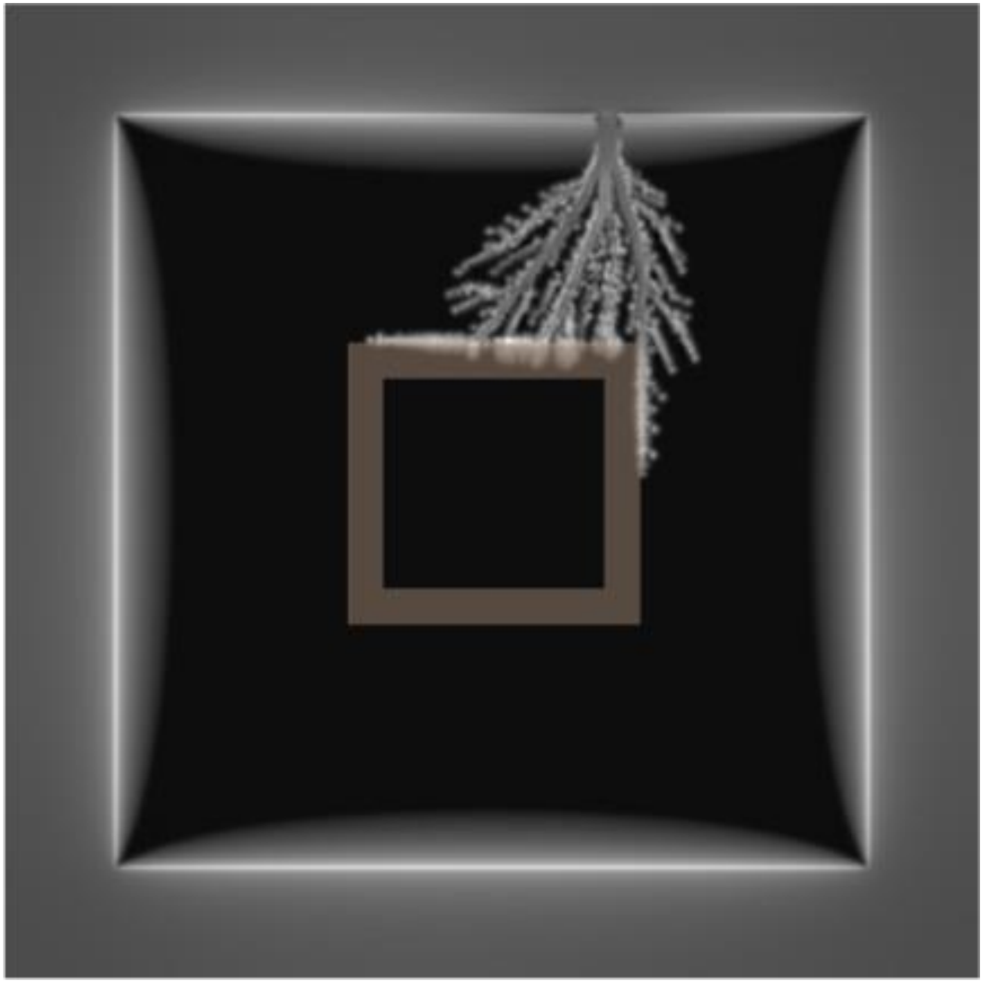
Measuring speed of dendritic flux avalanches





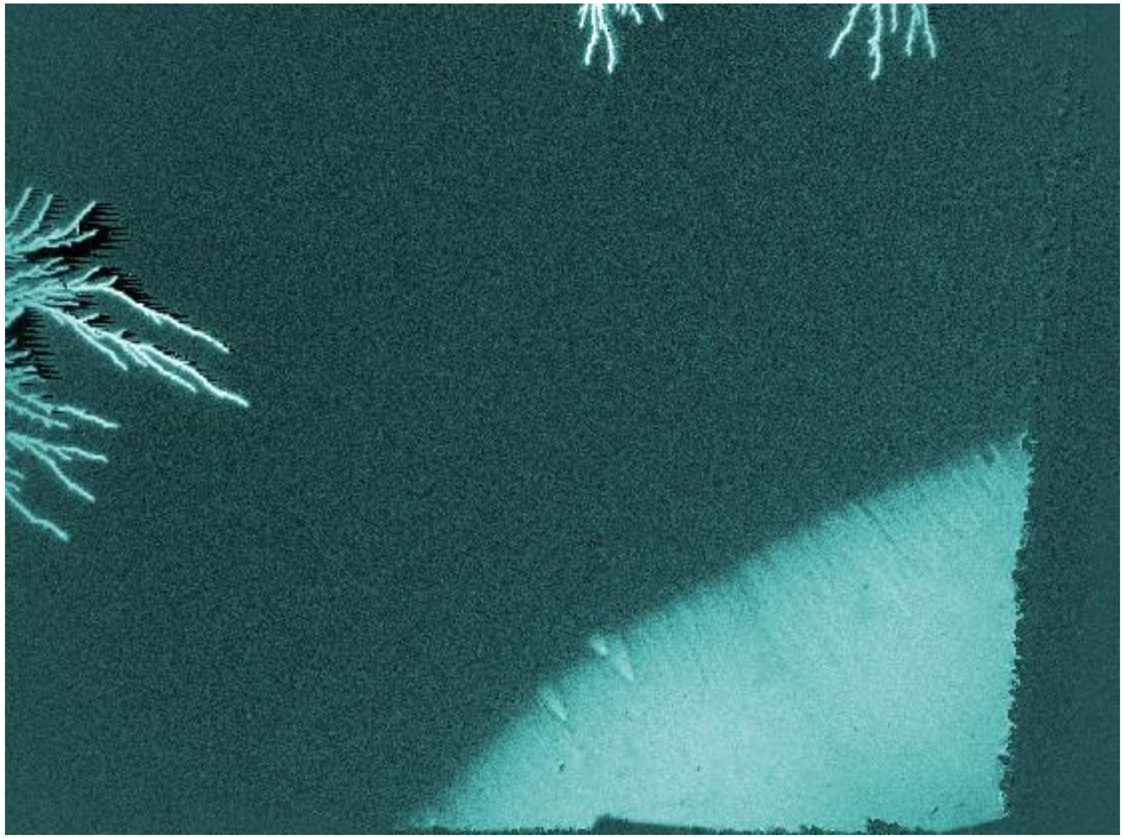
v = l/t = 73 km/s

Screening of dendritic flux avalanches: numerical simulations



A conductive layer deposited on or applied to superconductor can be used to protect a particular area from the invasion of avalanches.

Imaging with MOI a non-magnetic layer

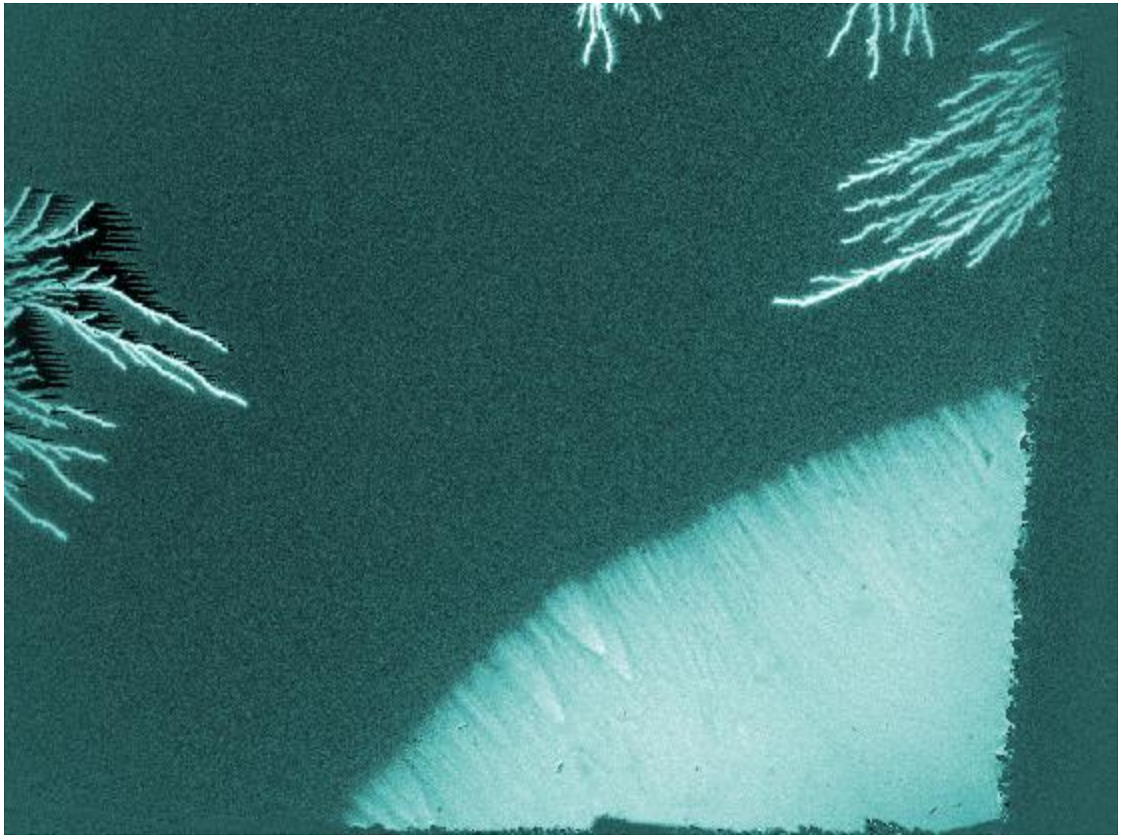


1 mm

T = 3.7 K

H = 1.53 mT

Imaging with MOI a non-magnetic layer

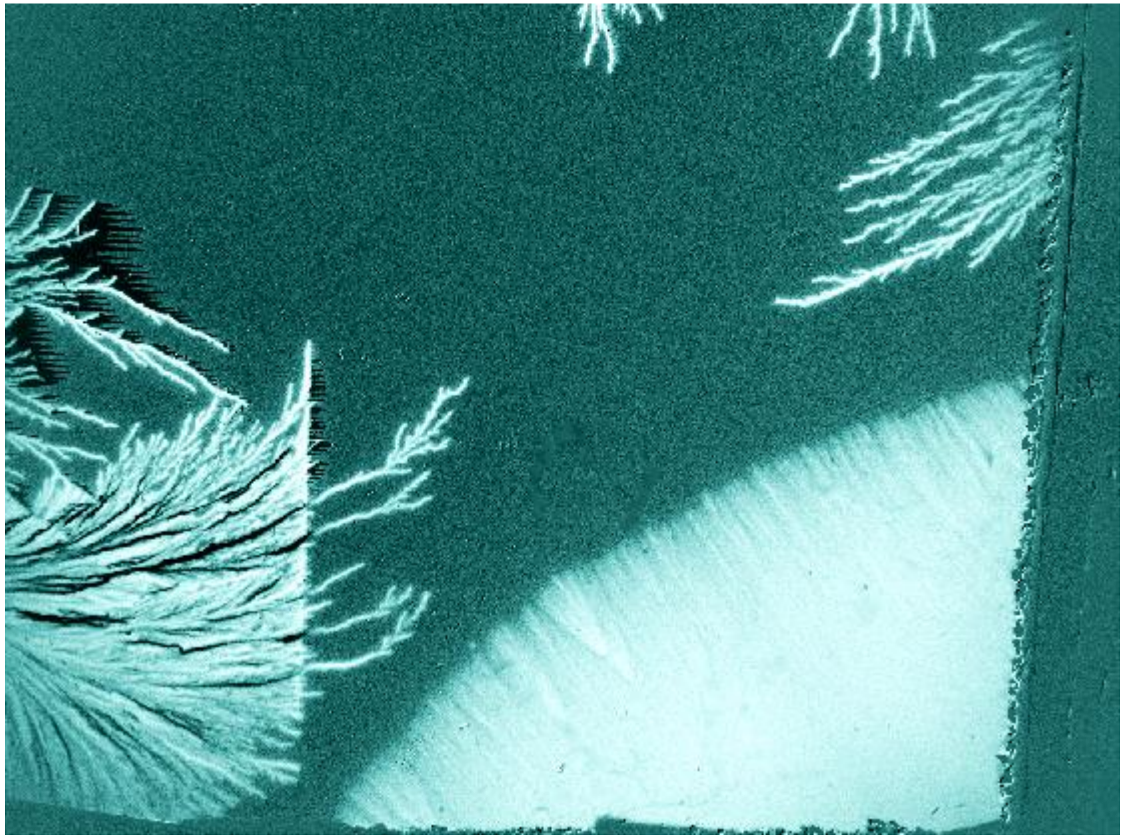


1 mm

T = 3.7 K

H = 2.04 mT

Imaging with MOI a non-magnetic layer

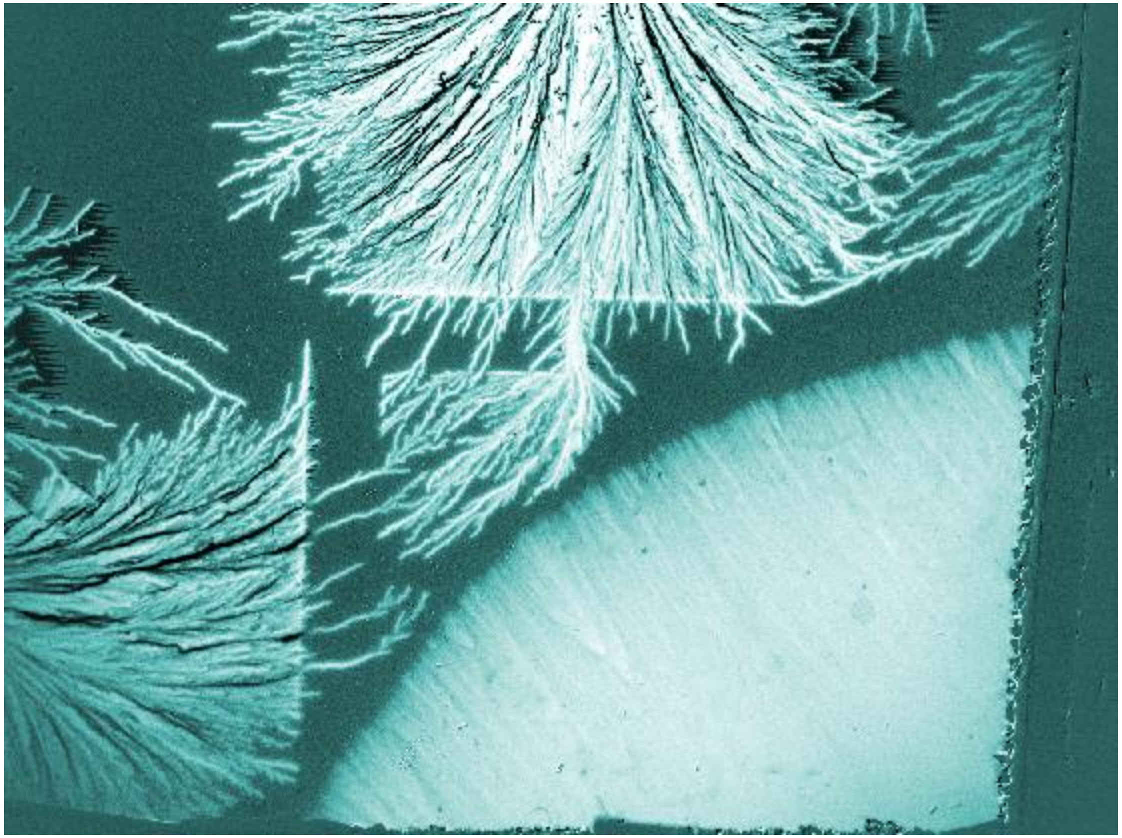


1 mm

T = 3.7 K

H = 2.38 mT

Imaging with MOI a non-magnetic layer

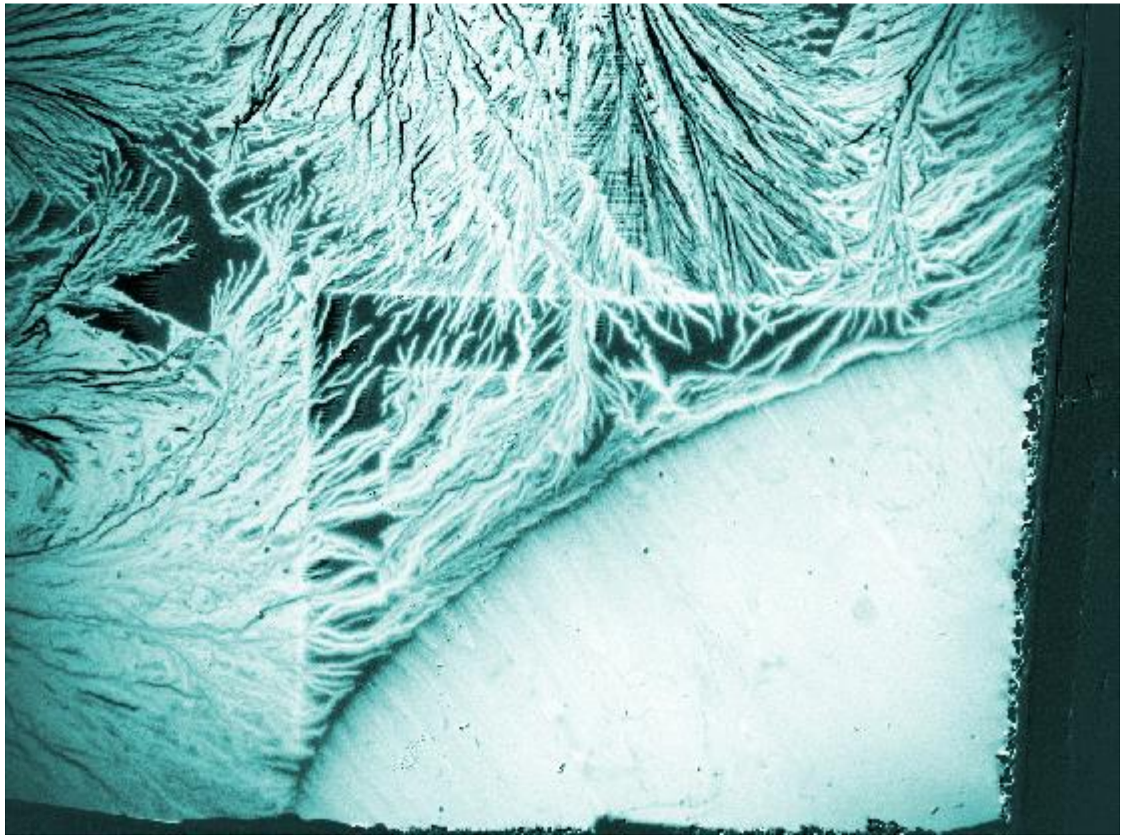


1 mm

T = 3.7 K

H = 3.06 mT

Imaging with MOI a non-magnetic layer

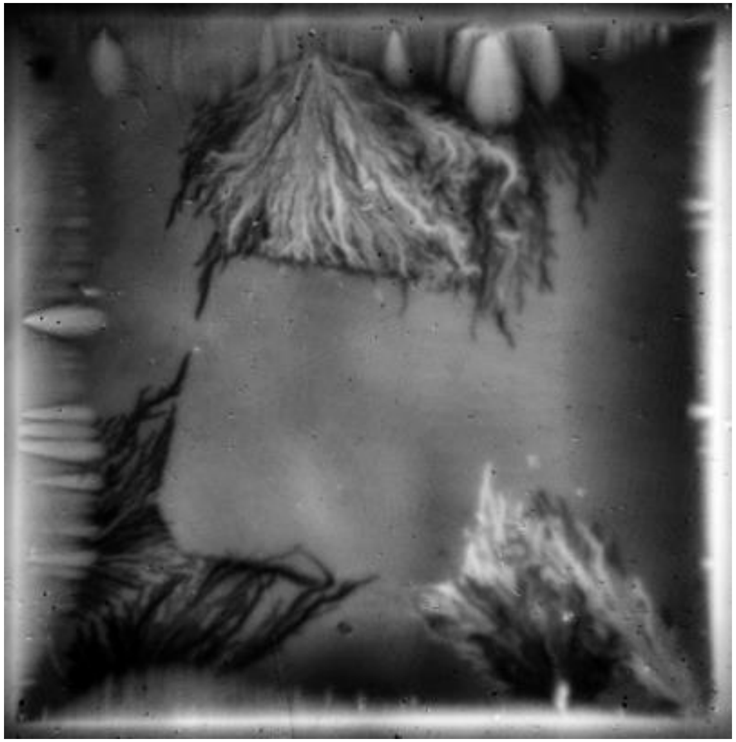


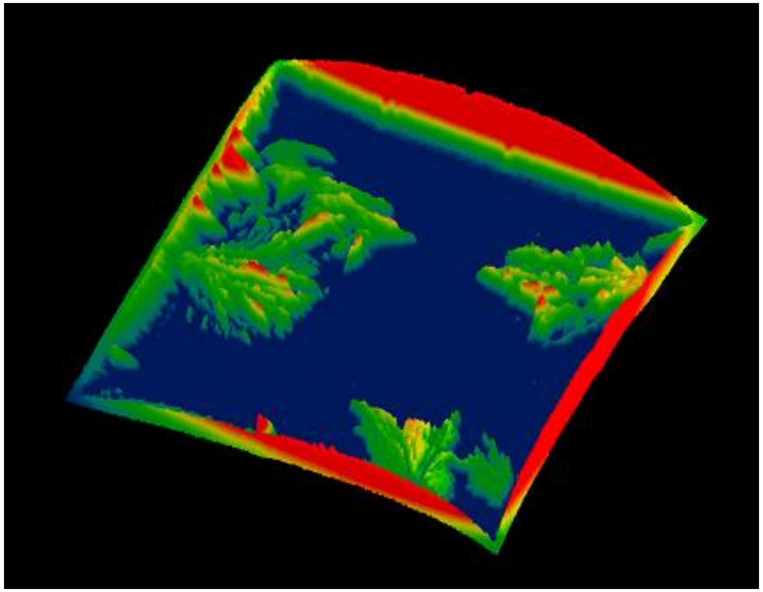
1 mm

T = 3.7 K

H = 5.61 mT

Protection of electronic equipment from dendritic avalanches



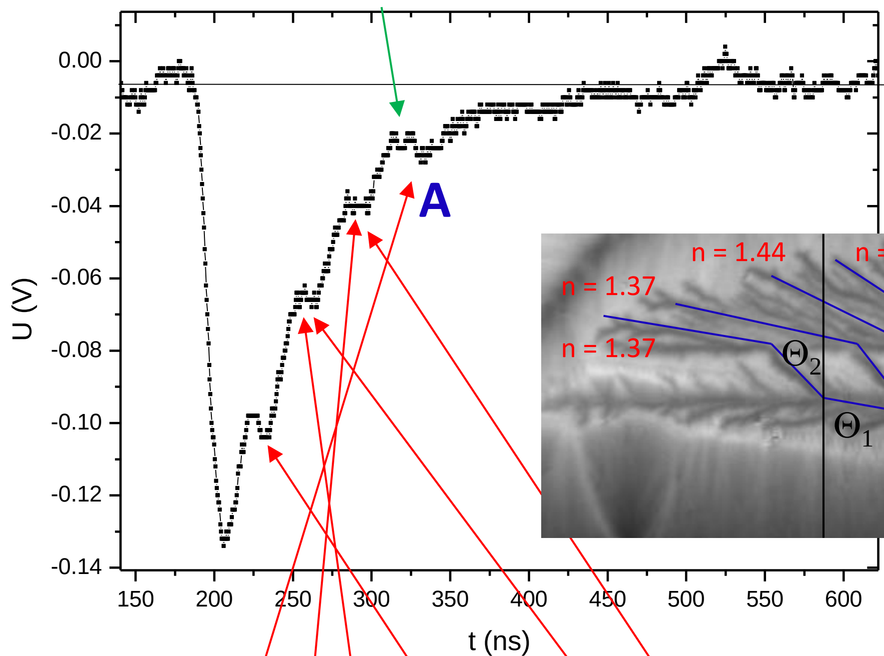


Distribution of magnetic flux in 5mm x 5 mm NbN superconducting film at 4 K.

A conductive layer effectively protects an area of the film from the avalanche. Only the fast motion of flux could be screened.

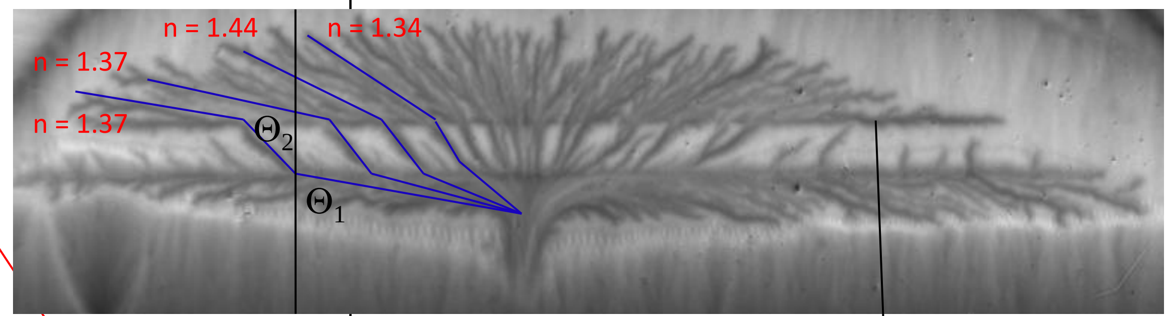
P. Mikheenko et al., AIP Advances 6, 032304 (2016).

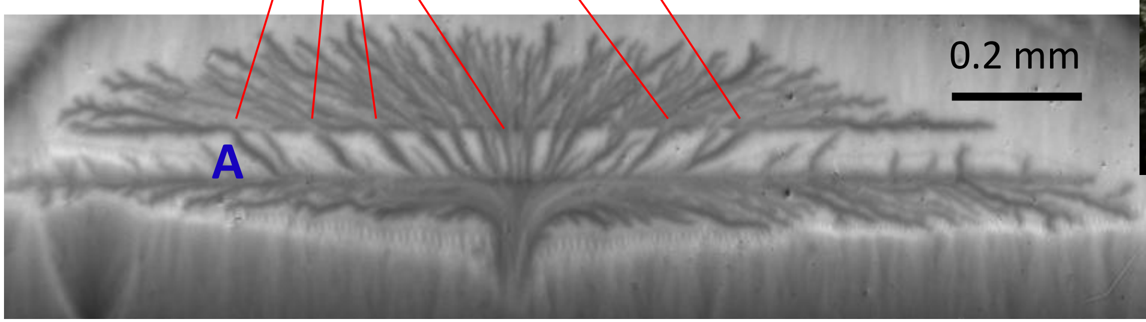
Geometrical optics of dendritic flux avalanches

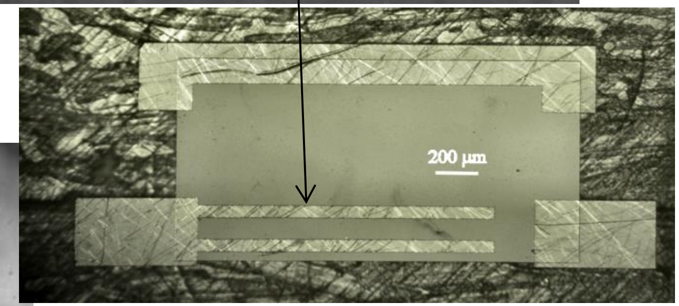


Snells law $$\frac{\sin(\Theta_1)}{\sin(\Theta_2)} = \frac{n_2}{n_1}$$

v_{CuNbN} = 8.2 km/s and v_{NbN} = 11.5 km/s

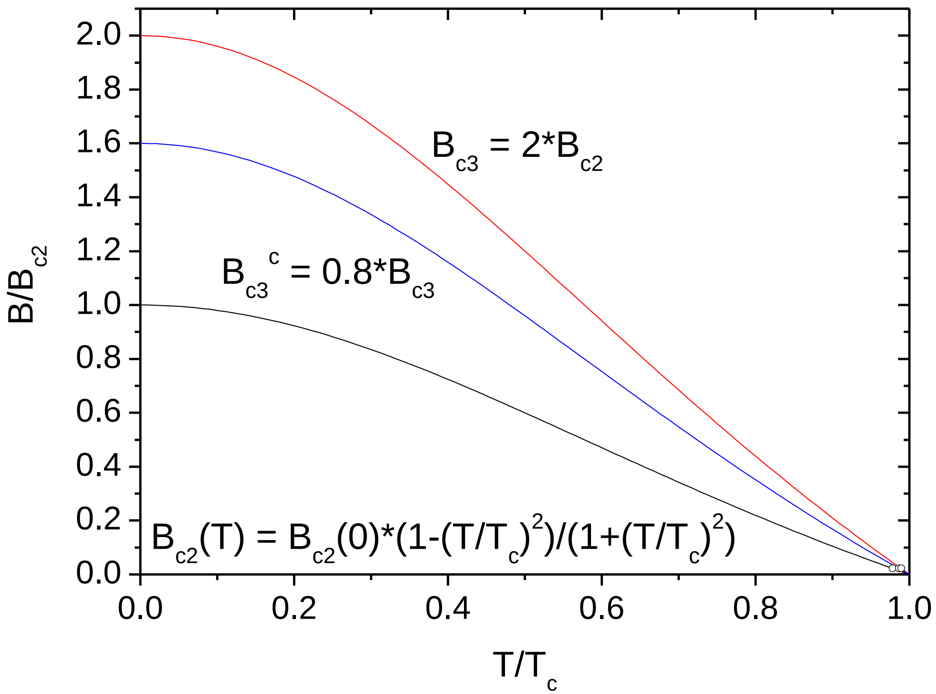






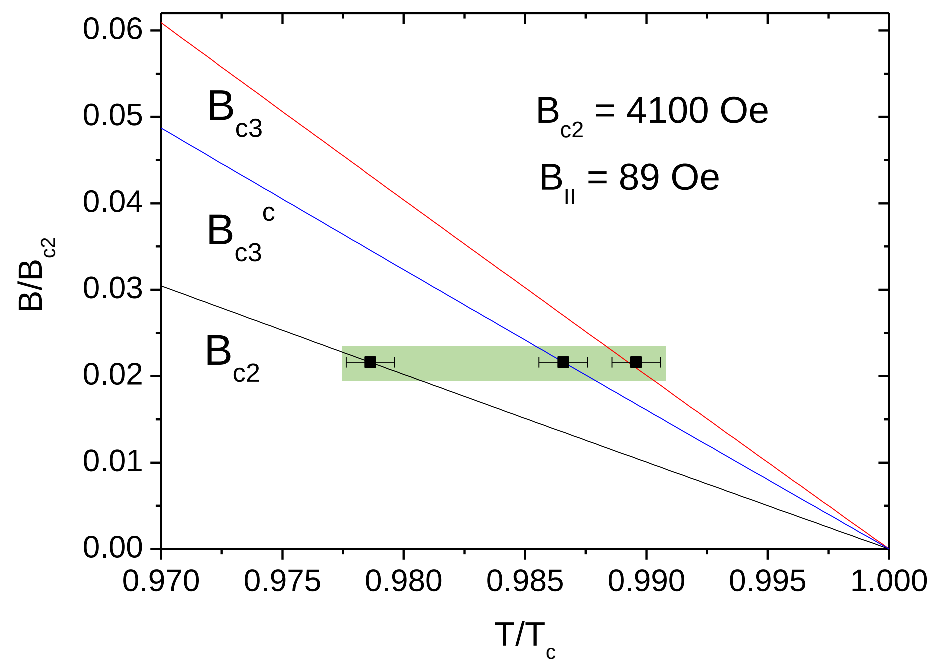
P. Mikheenko et al., **Phys. Rev. B 91,** 060507(R) (**2015**).

Surface superconducting state in Nb single crystal



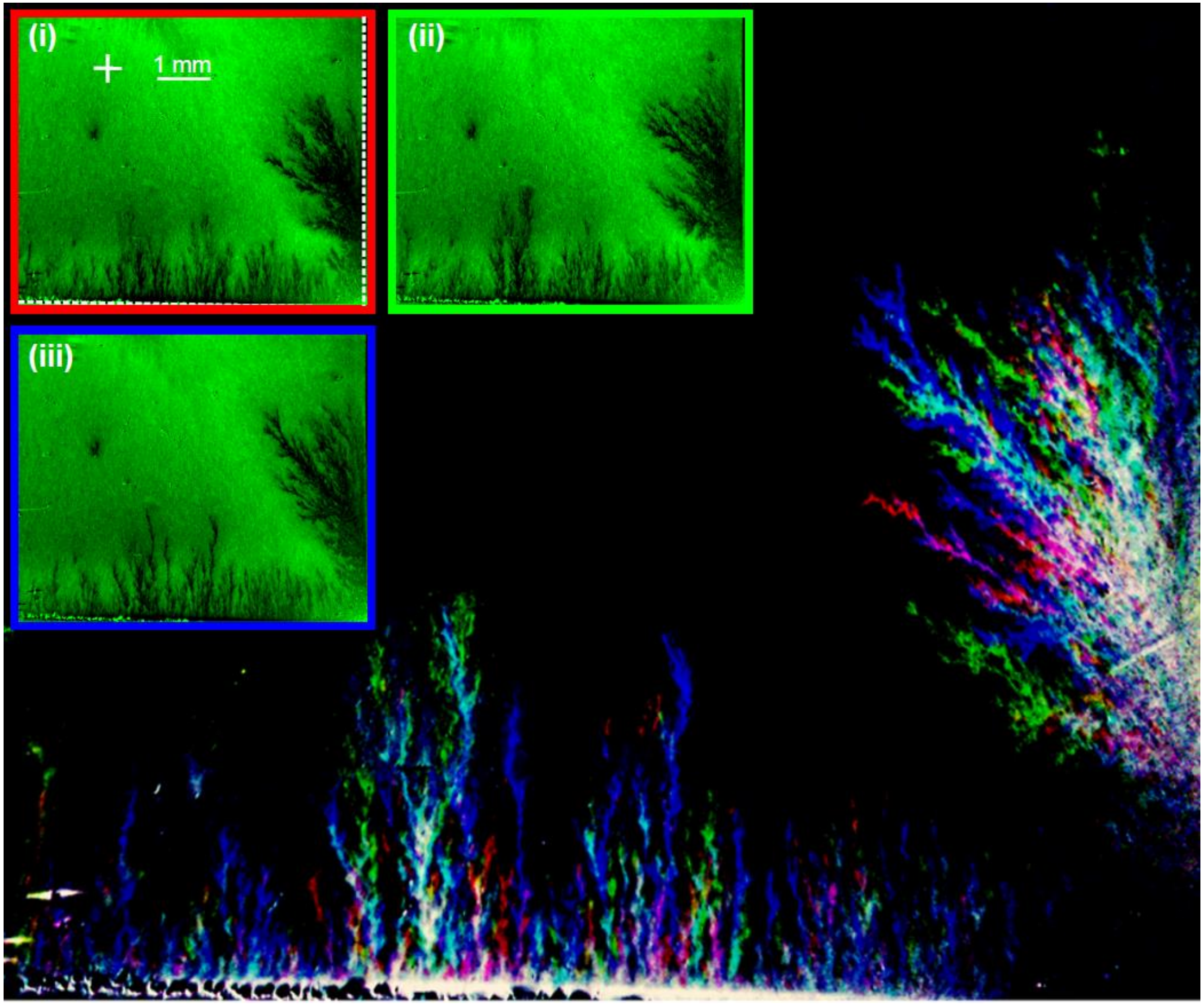
$T_c = 9.25$ K

Phase diagram of Nb



Imaging conditions for superconducting Nb single crystal.

Magnetic flux penetration in Nb single crystal



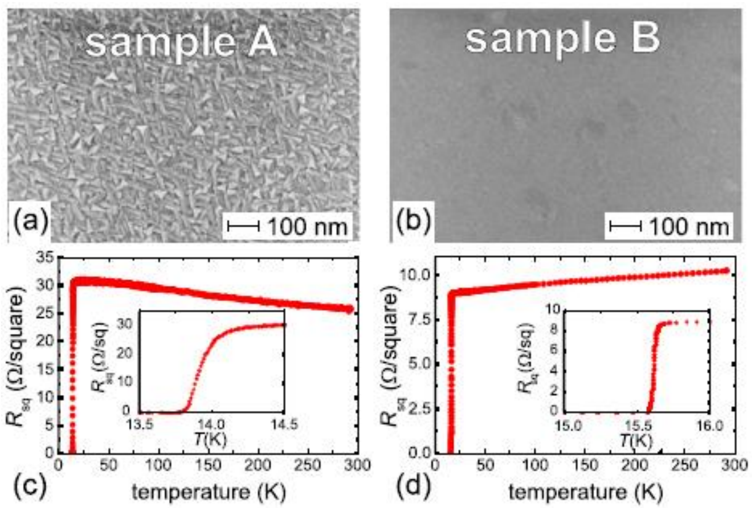
UiO : University of Oslo

Nanoscale origin of dendritic avalanches

Thermo-magnetic stability of superconducting films controlled by nano-morphology

V. V. Yurchenko, , K. Ilin, J. M. Meckbach, M. Siegel, A. J. Qviller, Y. M. Galperin, and T. H. Johansen

Appl. Phys. Lett. **102**, 252601 (2013);



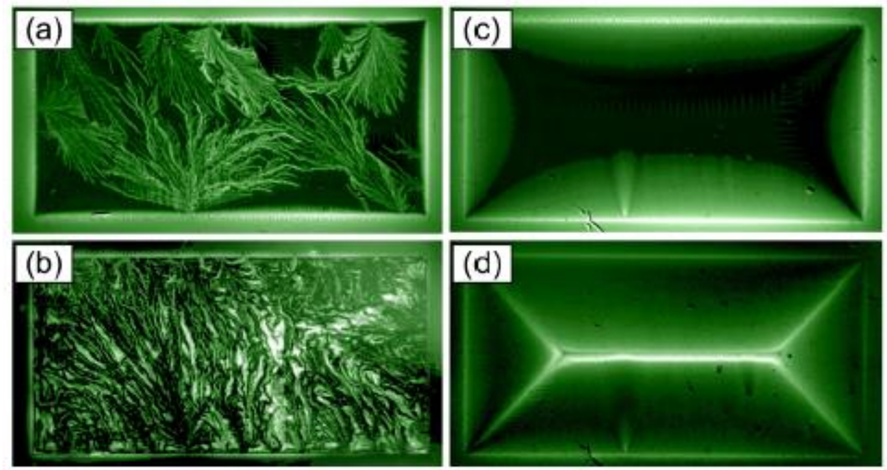


TABLE I. Comparison of characteristic measures for sample A and sample B.

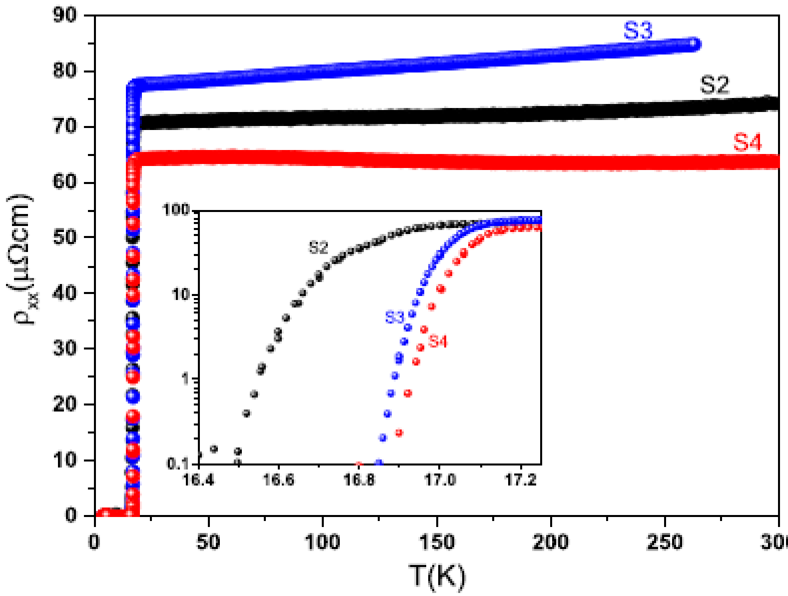
Film	d (nm)	T_c (K)	ΔT_c (K)	$-\frac{dB_{c2}}{dT}$ (T/K)	D (cm^2/s)	$\frac{R(300\,K)}{R(25\,K)}$	$B_{c2}(0)$ (T)	ρ (25 K) ($\mu\Omega$ cm)
Sample A	170	13.7	0.2	4.5	0.24	0.84	61.3	533
Sample B	175	15.5	0.04	1.7	0.64	1.13	25.6	166

Nanoscale origin of dendritic avalanches

Supercond. Sci. Technol. 29 (2016) 105011 (5pp) doi:10.1088/0953-2048/29/10/105011

Superconducting properties of very high quality NbN thin films grown by high temperature chemical vapor deposition. D Hazra et al.

Samples	Substrate	a Å	f factor	R_H (10^{-3} $\mu\Omega$cm T^{-1})	ρ_{xx} ($\mu\Omega$cm)	RRR	T_c (K)	ΔT_c (K)	$\left.\frac{dB_{c2}}{dT}\right\|_{T=T_c}$ (T K^{-1})
S2	$Al_2O_3(11\bar{2}0)$	4.436	0.92	5.6	70.0	1.05	16.80	0.55	0.96
S3	AlN (0001)	4.434	0.99	6.9	76.6	1.11	17.02	0.32	0.99
S4	$Al_2O_3(0001)$	4.427	0.98	5.0	62.8	1.0	17.06	0.32	0.96



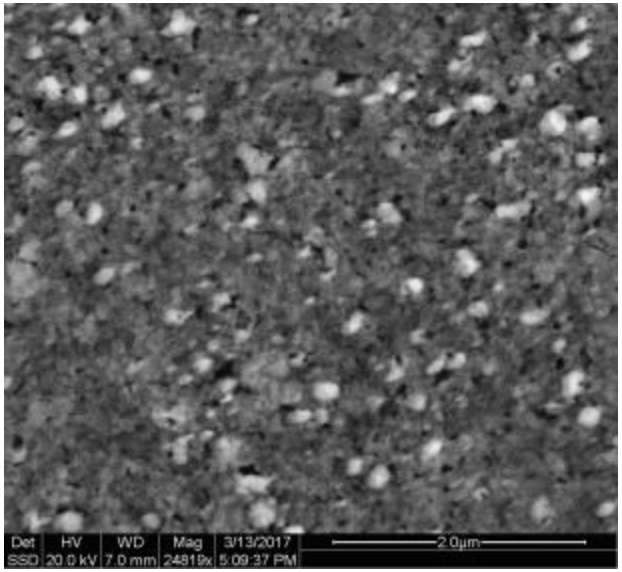
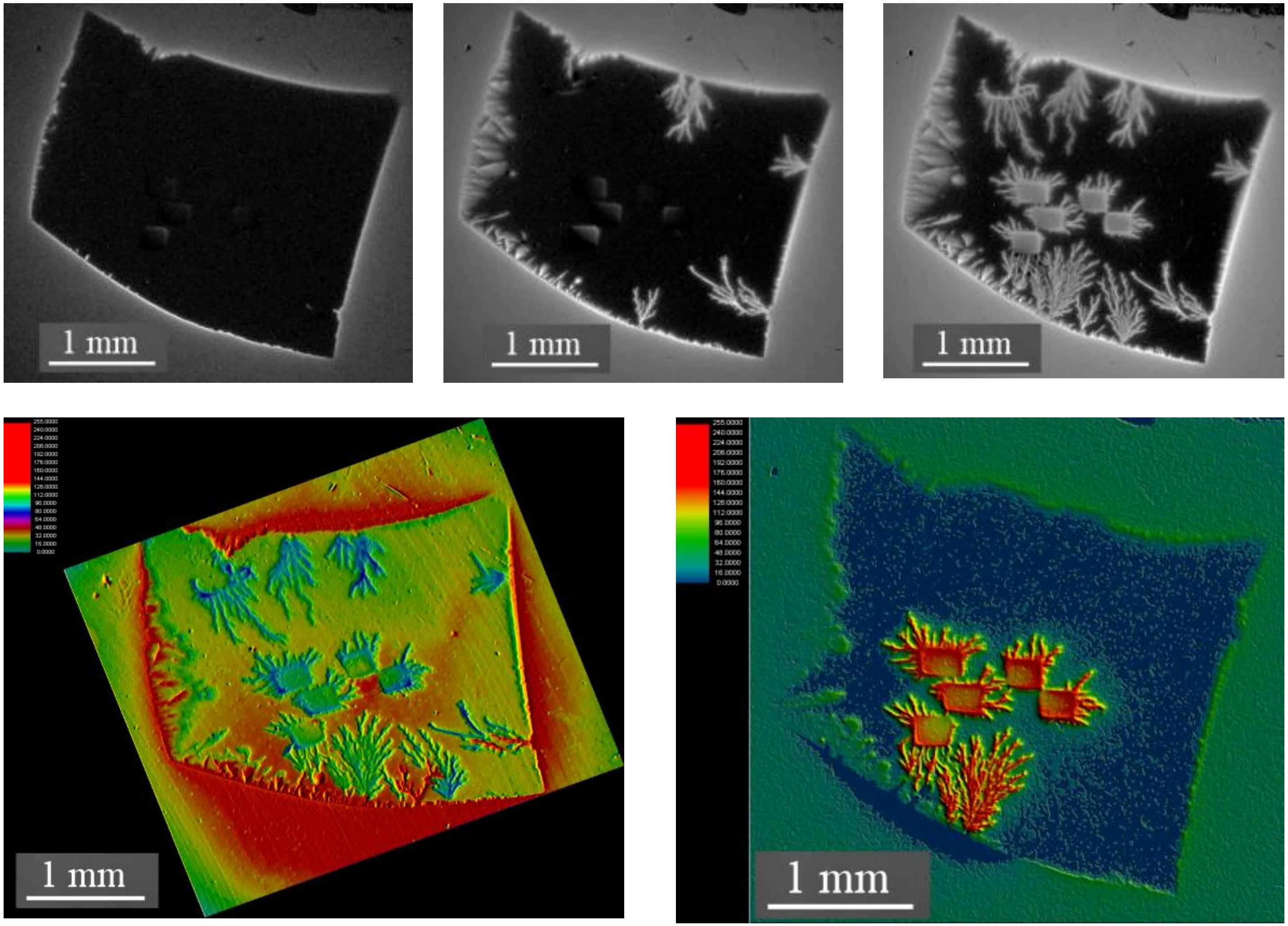


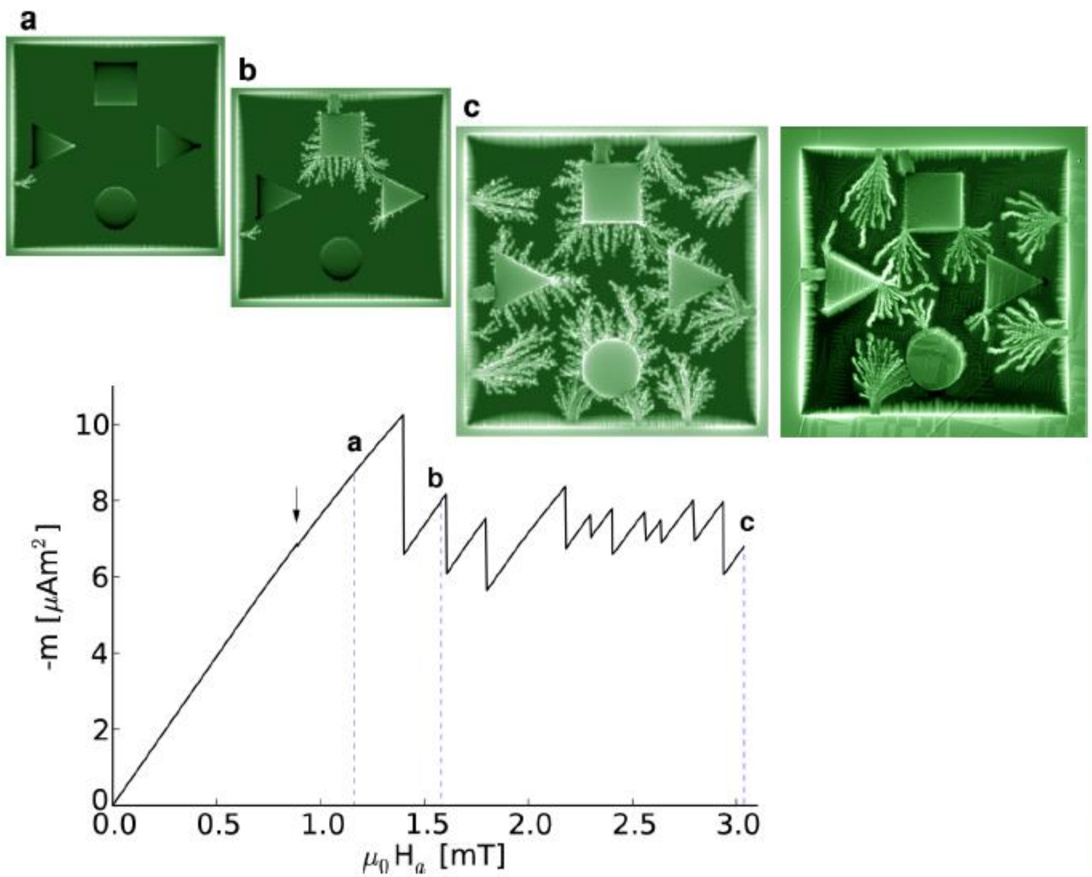
Image: T.H. Qureishy

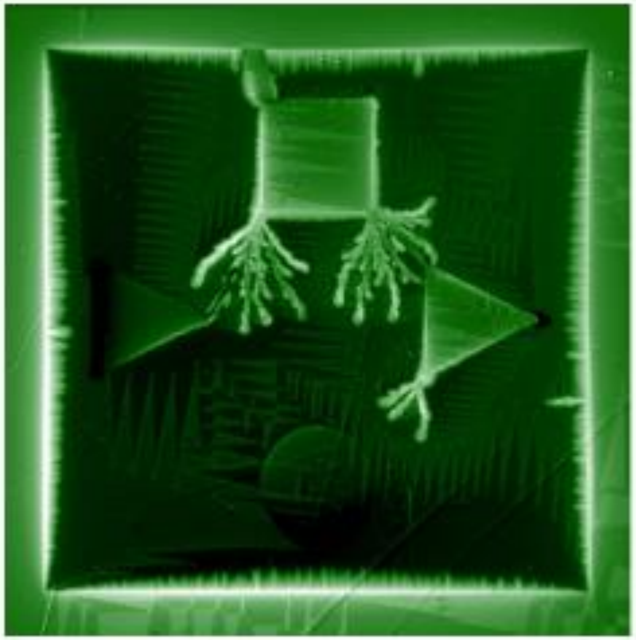
Nanoscale origin of dendritic avalanches



Cascade excitation of dendritic avalanches

J. I. Vestgården, F. Colauto, A. M. H. de Andrade, A. A. M. Oliveira, W. A. Ortiz, and T. H. Johansen, **Cascade dynamics of thermomagnetic avalanches in superconducting films with holes,** PHYSICAL REVIEW B **92**, 144510 (2015)





Conclusions

- In superconductors with strong pinning, a critical state develops, in which electrical current reaches its critical value in the regions where magnetic flux penetrates the superconductor. A good approximation to describe this process in bulk superconductors is the Bean model, in which critical current is proportional to the gradient of magnetic field.

- Bean critical state could be disrupted by thermo-magnetic instabilities, during which a large amount of energy is released in the form of heat. In thin-film superconductors, thermo-magnetic instabilities appear in the form of dendritic flux avalanches

- Magneto-optical imaging (MOI) is a powerful technique that allows direct optical imaging of Bean critical state and dendritic flux avalanches.

- Dendritic avalanches show a variety of unusual effects. There exists a delicate balance between the realization of Bean critical state and appearance of dendritic flux instabilities.

- The behaviour of dendritic flux avalanches can be controlled by modifying properties of superconducting films.