UiO : University of Oslo

UNIVERSITY OF BIRMINGHAM

Introduction to superconductivity

P. Mikheenko

Department of Physics, University of Oslo, P.O. Box 1048, Blindern, 0316 Oslo, Norway
University of Birmingham, Birmingham B15 2TT, UK

15-26 May 2017 Oslo, Norway

Superconductivity in relativistic heavy ion collisions

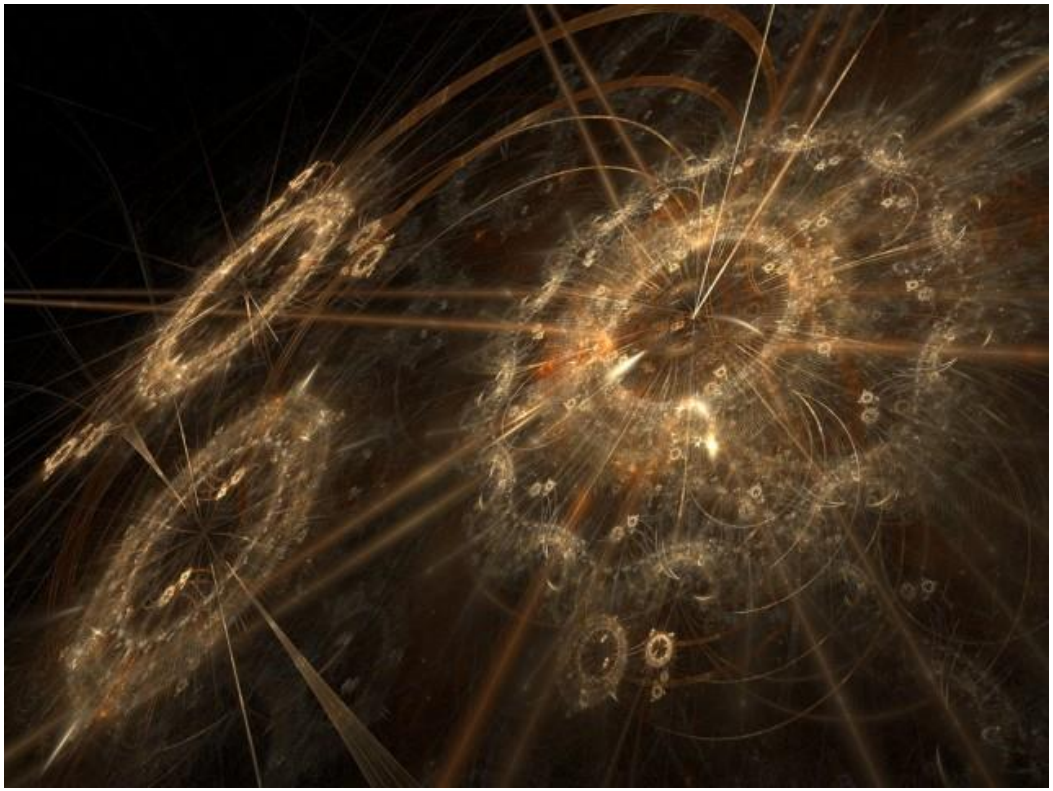
The magnet system on the ATLAS detector includes eight huge superconducting magnets (grey tubes) arranged in a torus around the LHC beam pipe (Image: CERN)

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 in cosmology

The link between superconductivity and black holes



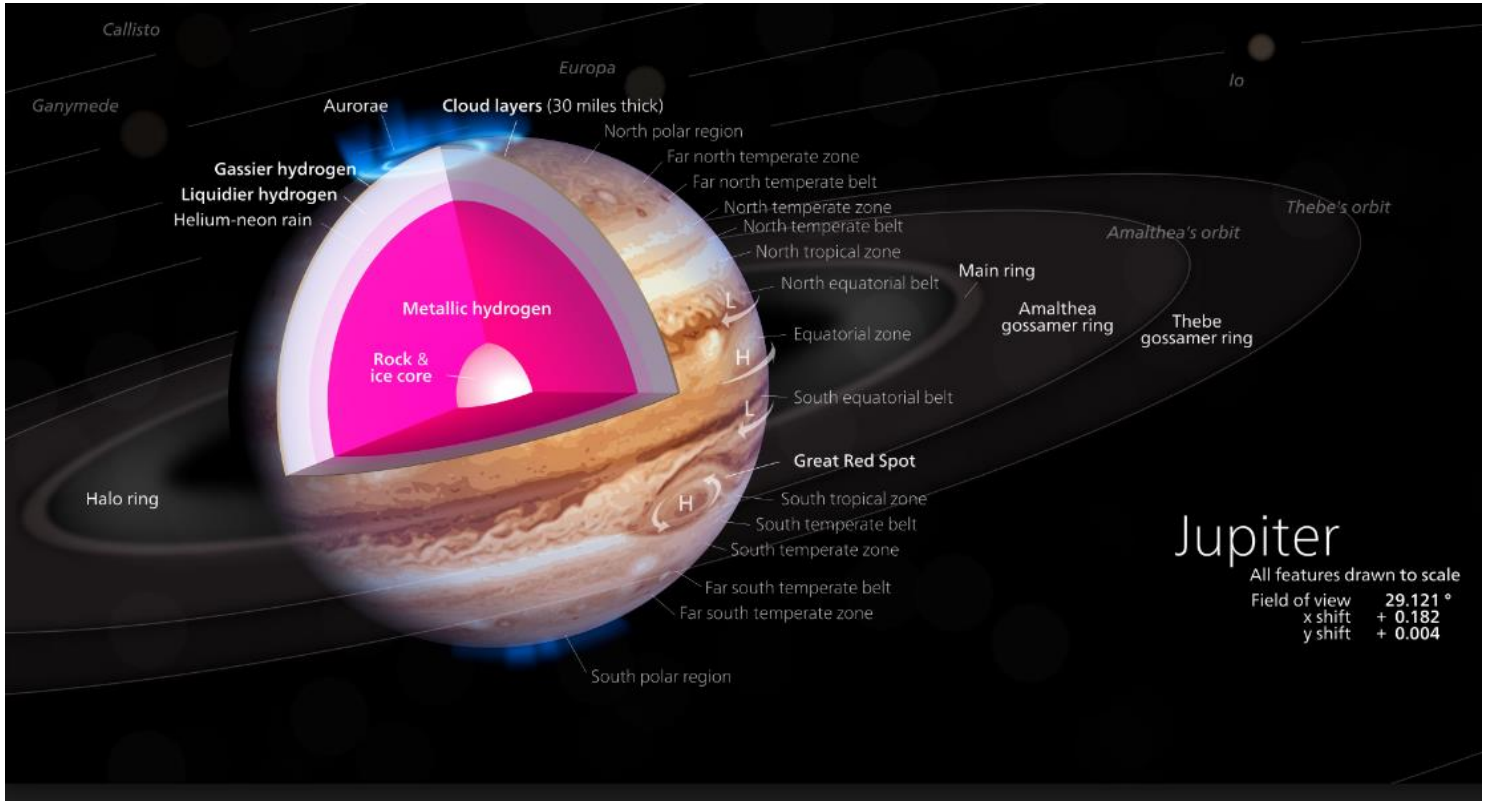
"Clockwork Dreams" by NitroX72

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/

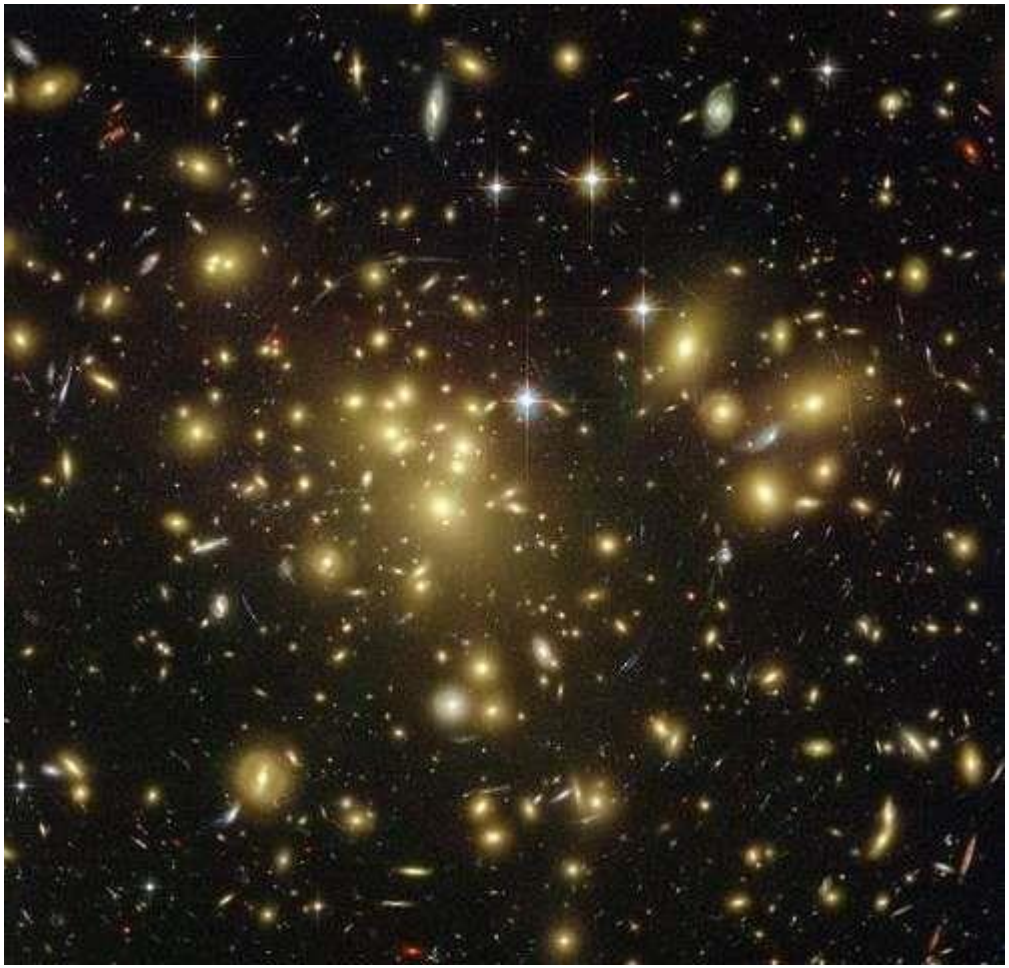
Superconductivity in cosmology

'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

Superconductivity and dark matter



Superconductors could detect superlight dark matter.

The dark matter particles that are thought to be constantly flowing through the Earth will scatter off a free electron in the superconductor. If a dark matter particle has enough energy to pull an electron above the material's band gap, it will break the Cooper pair. A second device (a calorimeter) measures the heat energy deposited in the absorber, providing direct evidence of the dark matter particle.

Yonit Hochberg, Yue Zhao, and Kathryn M. Zurek. "Superconducting Detectors for Superlight Dark Matter." Physical Review Letters. DOI: 10.1103/PhysRevLett.116.011301

https://phys.org/news/2016-02-superconductors-superlight-dark.html

Superconductivity in cancer therapy

Making cancer treatment more accessible:
Alexey Radovinsky, Joe Minervini, Phil Michael, and Leslie Bromberg of the Plasma Science and Fusion Center MIT collaborates on a smaller, lighter delivery system for proton-beam radiotherapy.

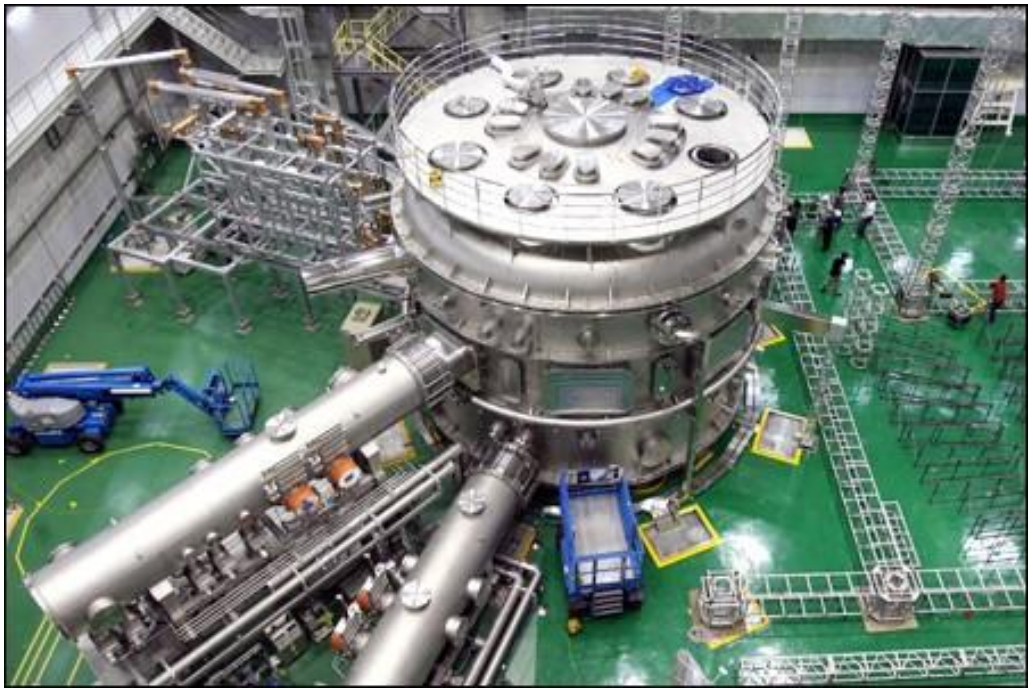
Joseph Minervini: “Using superconductivity in a cyclotron design can reduce its mass an order of magnitude from conventional, resistive magnet machines,”

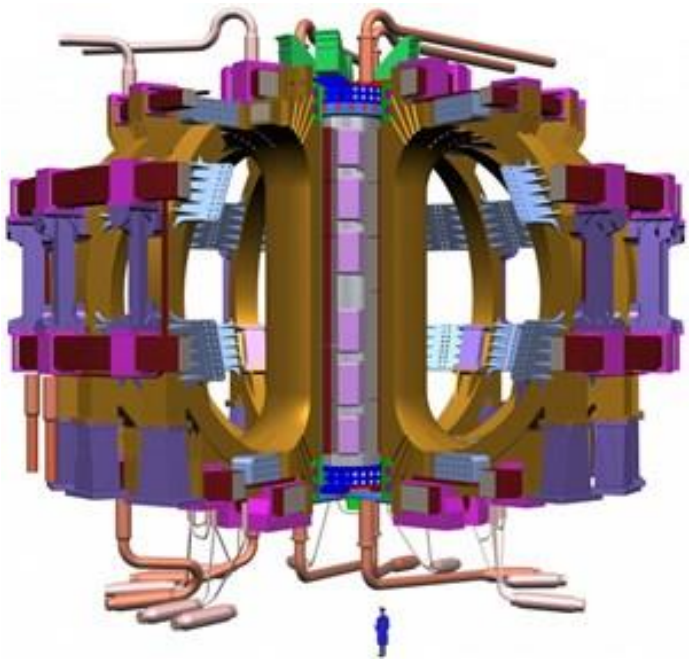
http://thesilicongraybeard.blogspot.no/2015/07/techy-tuesday-using-superconductors-to.html
http://news.mit.edu/2015/making-cancer-treatment-more-accessible-0604

Primary energy solution: thermonuclear energy, ITER?

‘ITER (International Thermonuclear Experimental Reactor, and is also Latin for "the way") is an international nuclear fusion research and engineering megaproject, which will be the world's largest magnetic confinement plasma physics experiment.’

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

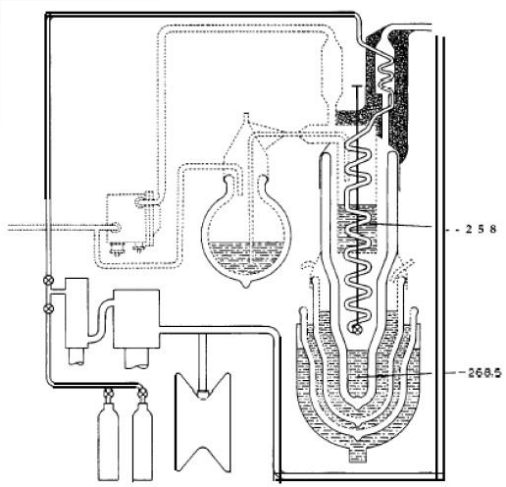


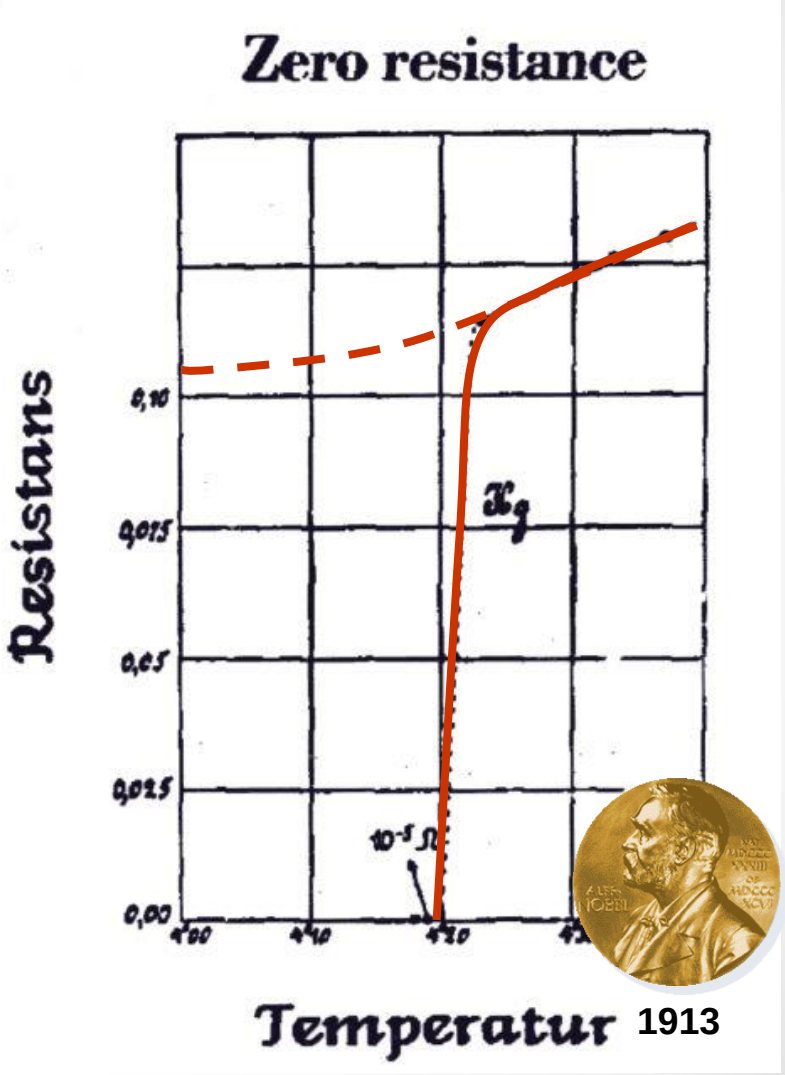


‘Without superconductivity, ITER would go from being a "net energy positive" machine to a "net energy negative" machine.’

https://www.iter.org/newsline/146/408

Discovery of Superconductivity





1913

- Discovered by **Kamerlingh Onnes** in 1911 during first low temperature measurements to liquefy helium
- Whilst measuring the resistivity of “pure” Hg he noticed that the electrical resistance dropped to zero at 4.2K
- In 1912 he found that the resistive state is restored in a magnetic field or at high transport currents

The superconducting elements

Transition temperatures (K)
Critical magnetic fields at absolute zero (mT)

Li	Be 0.026											B	C	N	O	F	Ne
Na	Mg											Al 1.14 10	Si	P	S	Cl	Ar
K	Ca	Sc	Ti 0.39	V 5.38	Cr	Fe	Ni	Cu	Zn 0.875 5.3	Ga 1.091 5.1	Ge	As	Se	Br	Kr
Rb	Sr	Y					Pd	Ag	Cd 0.56 3	In 3.4 29.3	Sn 3.72 30	Sb	Te	I	Xe
Cs	Ba	La 6.0 110				Re 1.4 20	Os 0.655 16.5	Ir 0.14 1.9	Pt	Au	Hg 4.153 41	Tl 2.39 17	Pb 7.19 80	Bi	Po	At	Rn

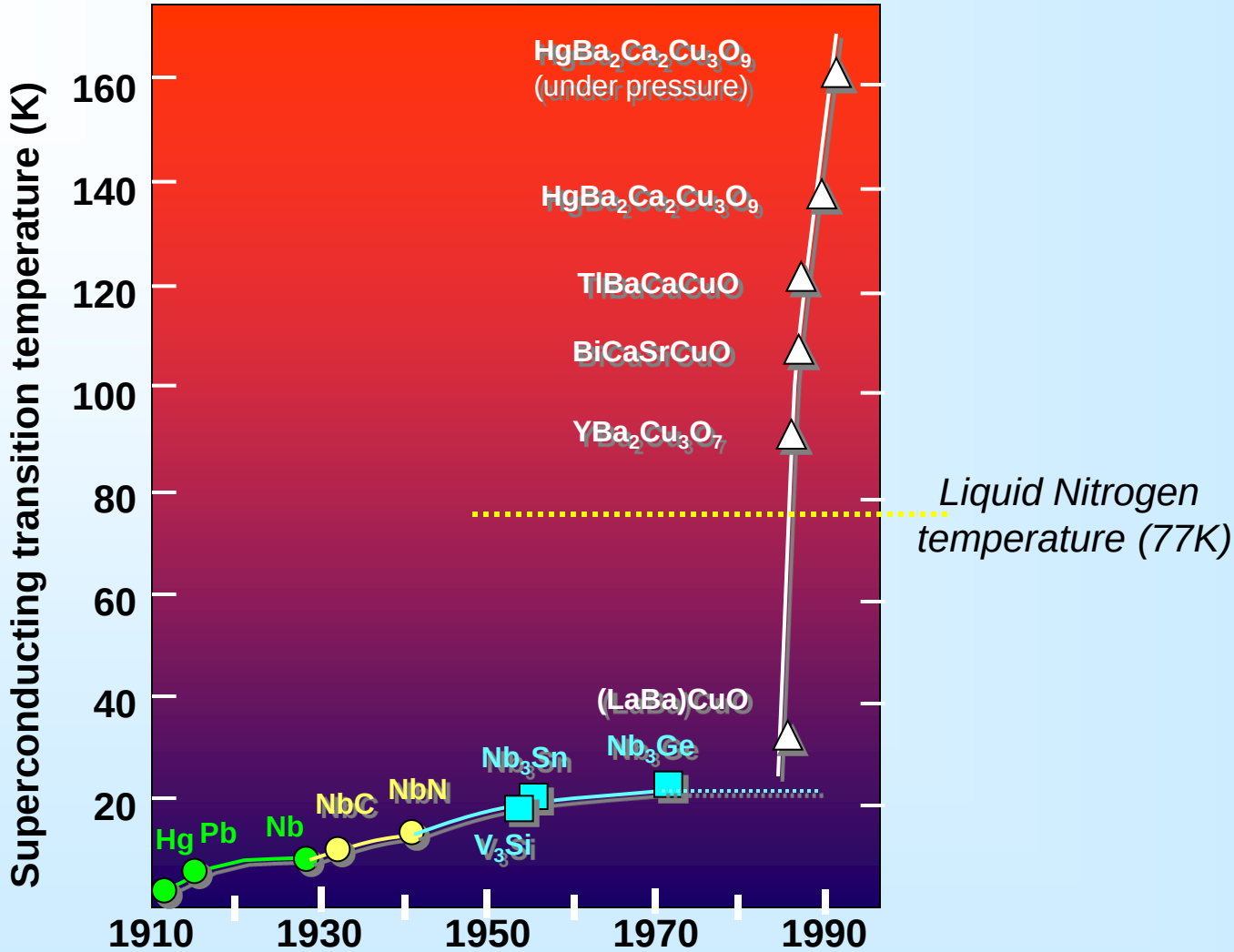
Fe (iron)
T_c=1K
(at 20GPa)

Nb (Niobium)
T_c=9K
H_c=0.2T

- Transition temperatures (K) and critical fields are generally low
- Metals with the highest conductivities are not superconductors
- The magnetic 3d elements are not superconducting

...or so we thought until 2001

Superconductivity in alloys and oxides

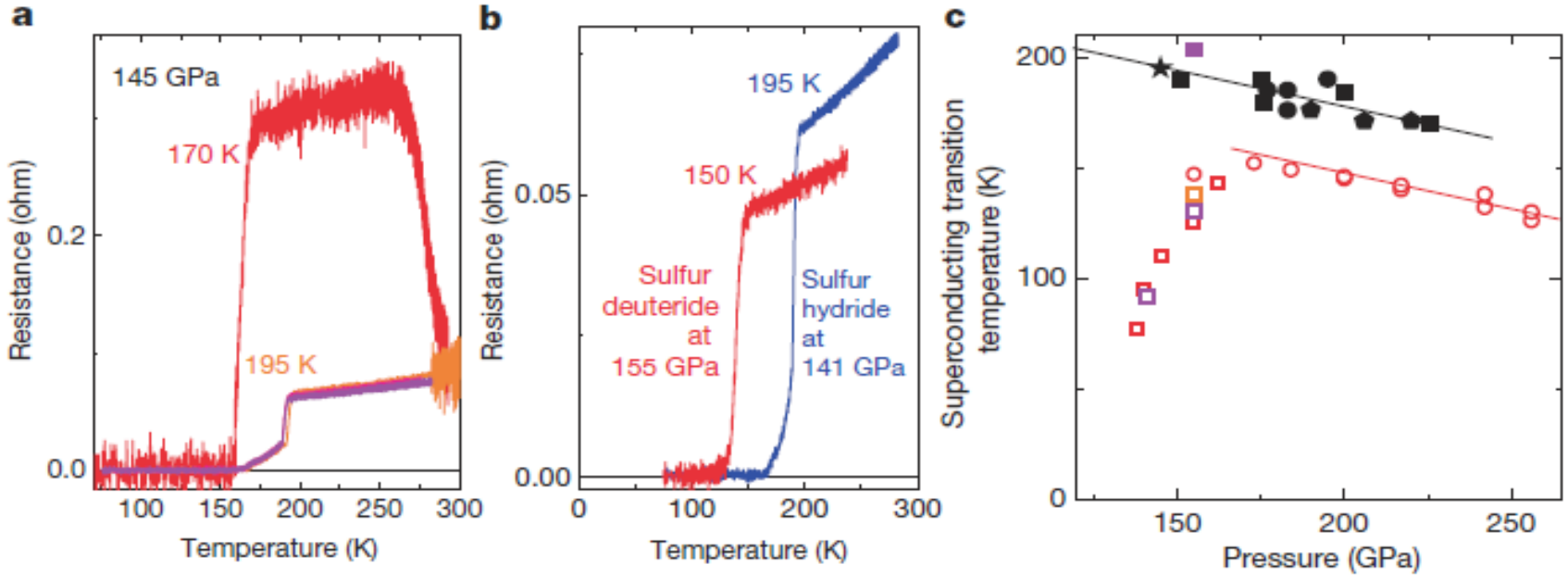


Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

doi:10.1038/nature14964 2015

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

[1]Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany. [2]Institut für Anorganische Chemie und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, 55099 Mainz, Germany.

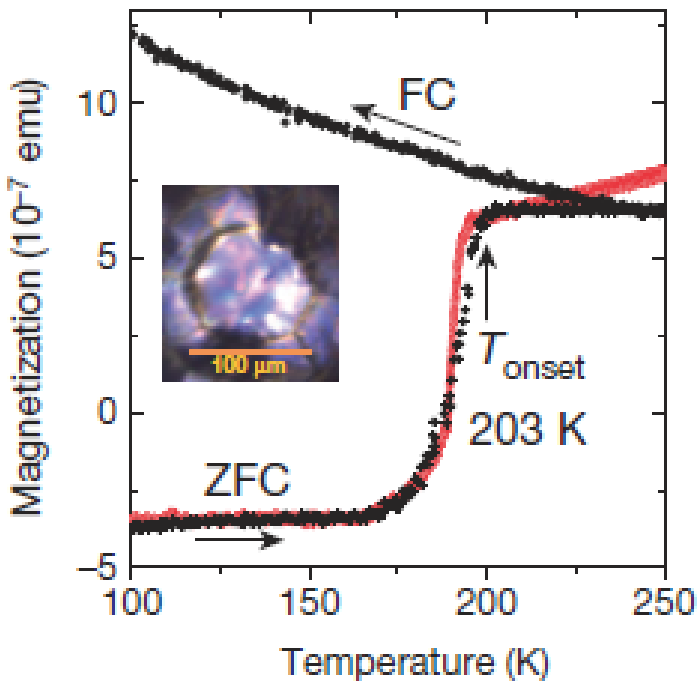


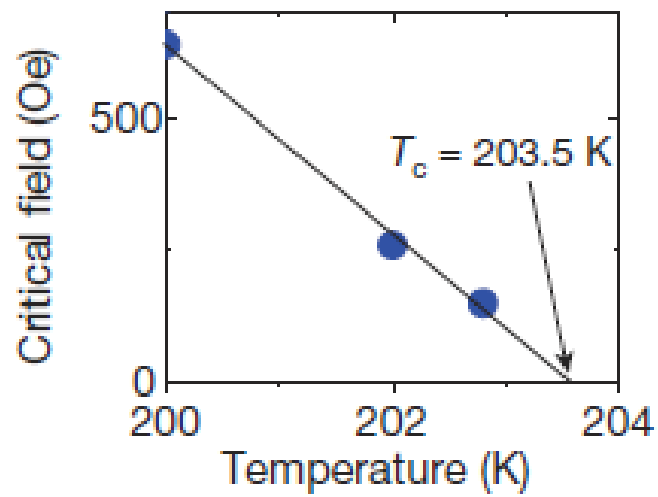
Conventional superconductivity at 203 kelvin at high pressures in the sulfur hydride system

doi:10.1038/nature14964 2015

A. P. Drozdov[1]*, M. I. Eremets[1]*, I. A. Troyan[1], V. Ksenofontov[2] & S. I. Shylin[2]

[1]Max-Planck-Institut für Chemie, Hahn-Meitner-Weg 1, 55128 Mainz, Germany. [2]Institut für Anorganische Chemie und Analytische Chemie, Johannes Gutenberg-Universität Mainz, Staudingerweg 9, 55099 Mainz, Germany.





General properties

- Zero resistance (*Kammerlingh-Onnes, 1911*) at $T < T_c$. The temperature T_c is called the *critical* one.

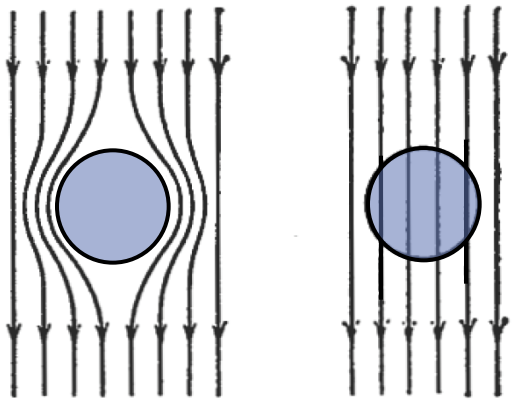
- Superconductivity can be destroyed also by an external magnetic field H_c which is also called the *critical* one (*Kammerlingh-Onnes, 1914*). Empirically,

$$H_c(T) = H_c(0)\left[1 - (T/T_c)^2\right] .$$

- If the superconductivity is destroyed by a current the critical current is just the one which produces the field H_c at the surface (the *Silsby rule*).

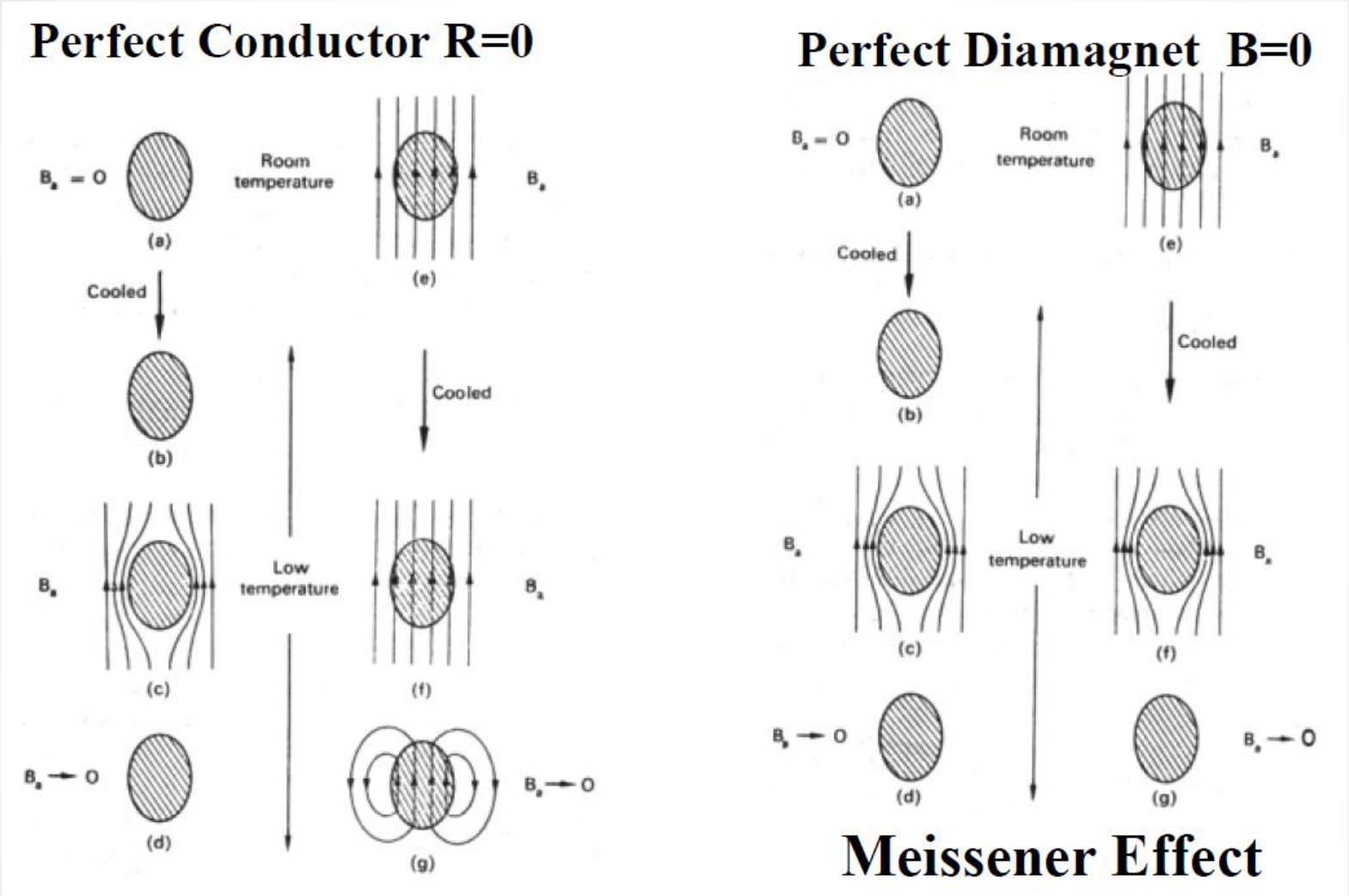
- The *Meissner-Ochsenfeld effect* (1933)

Magnetic field does not penetrate superconductor



Only for long samples!

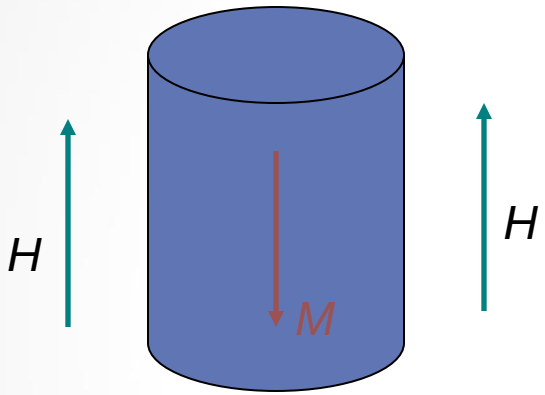
Meissner effect



Ideal conductor!

Ideal diamagnet!

Type I superconductors: Magnetization curve

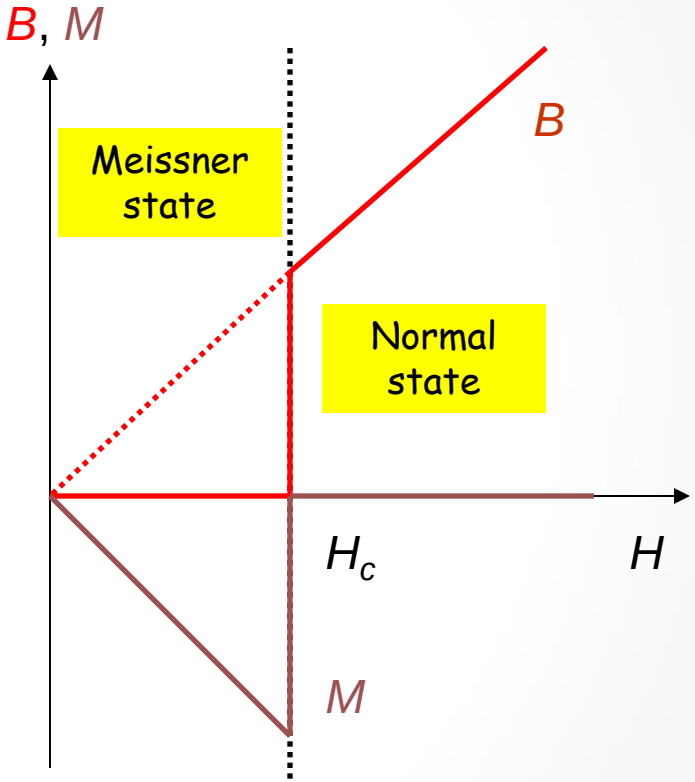


SI: $B/\mu_0 = H + M$

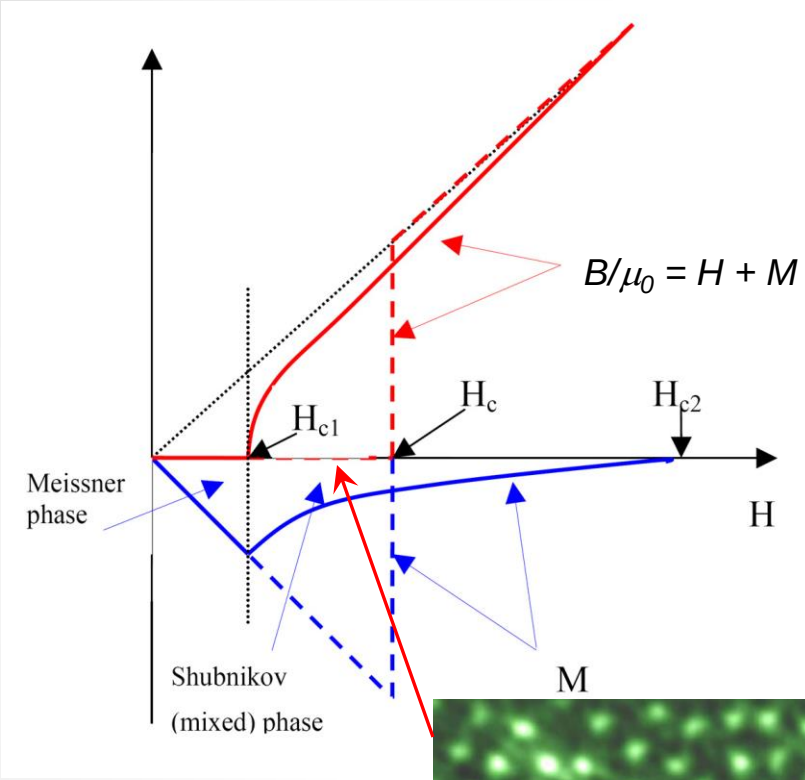
H – magnetic field strength

M – magnetization

B – magnetic induction



Type II superconductors



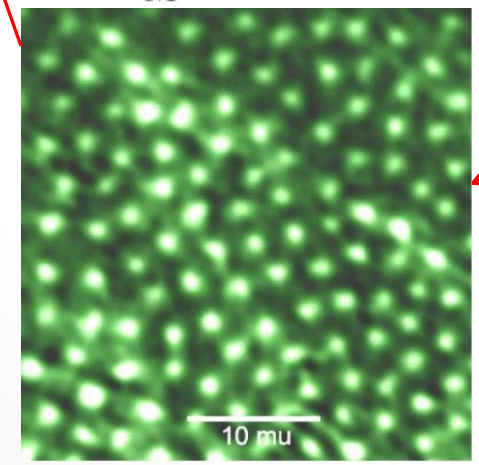
Dashed lines – type I superconductor

Solid lines – type II superconductor

In type II superconductors the Meissner effect in incomplete in the region

$$H_{c1} < H < H_{c2}$$

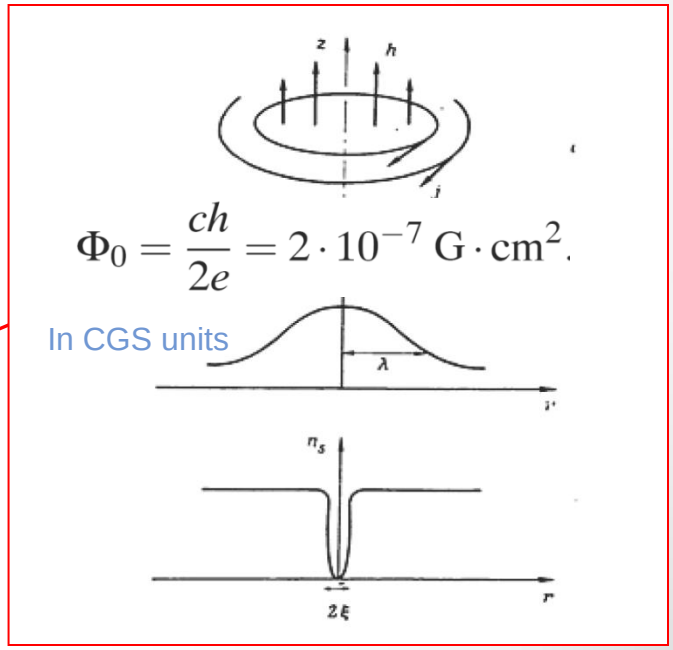
$\Phi_0 = h/(2e) \approx 2.067833758(46)\times10^{-15}$ Wb

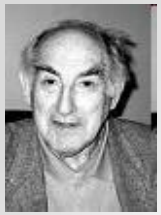


Vortex lattice

A. A. Abrikosov

2003



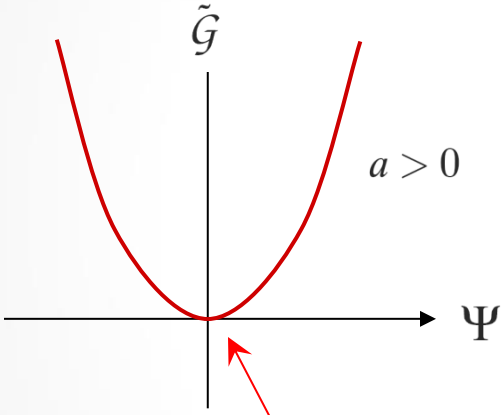


Ginzburg-Landau Theory (1950)

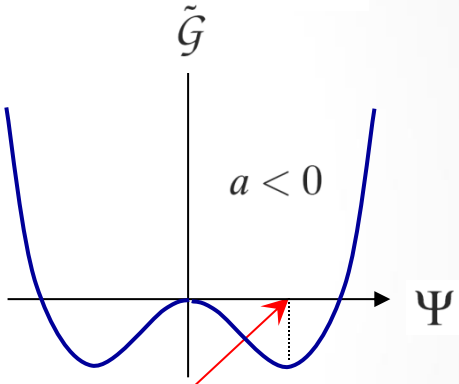
2003

Order parameter

$$|\Psi|^2 \ll 1 \quad \Rightarrow \quad \mathcal{G}_s = \mathcal{G}_n + a|\Psi|^2 + \frac{b}{2}|\Psi|^4 + \cdots .$$



$$\tilde{\mathcal{G}} \equiv \mathcal{G}_s - \mathcal{G}_n$$



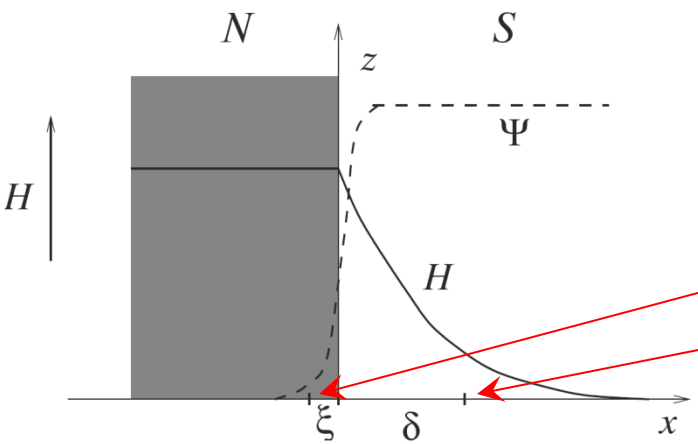
1962

a should change the sign at the transition point

Introduce $\tau = \frac{T - T_c}{T_c}$. Near T_c, $|\tau| \ll 1$: $a = \alpha\tau$, $\alpha > 0$.

$$\boxed{\begin{array}{lll} \Psi = 0 & \text{at} & T > T_c, \\ |\Psi|^2 = -(\alpha/b)\tau = |\Psi_0|^2 & \text{at} & T < T_c \end{array}}$$

N-S interface



$$\Psi = \tanh \frac{x}{\xi\sqrt{2}}$$

$\xi = \lambda/k$ ➡ *the coherence length.*

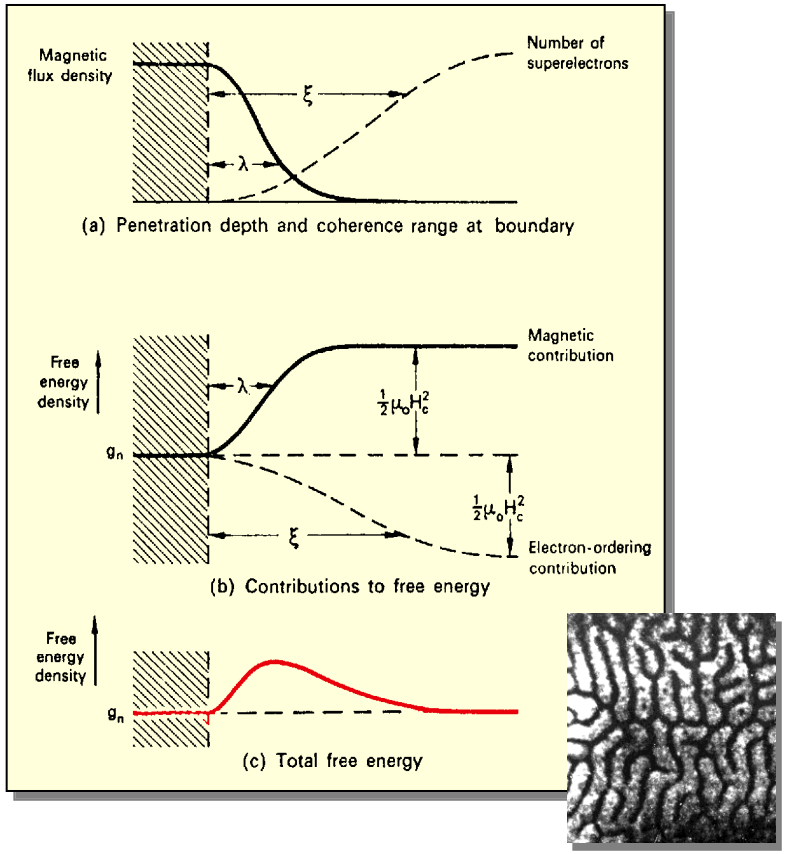
δ is just the London penetration depth near T_c.

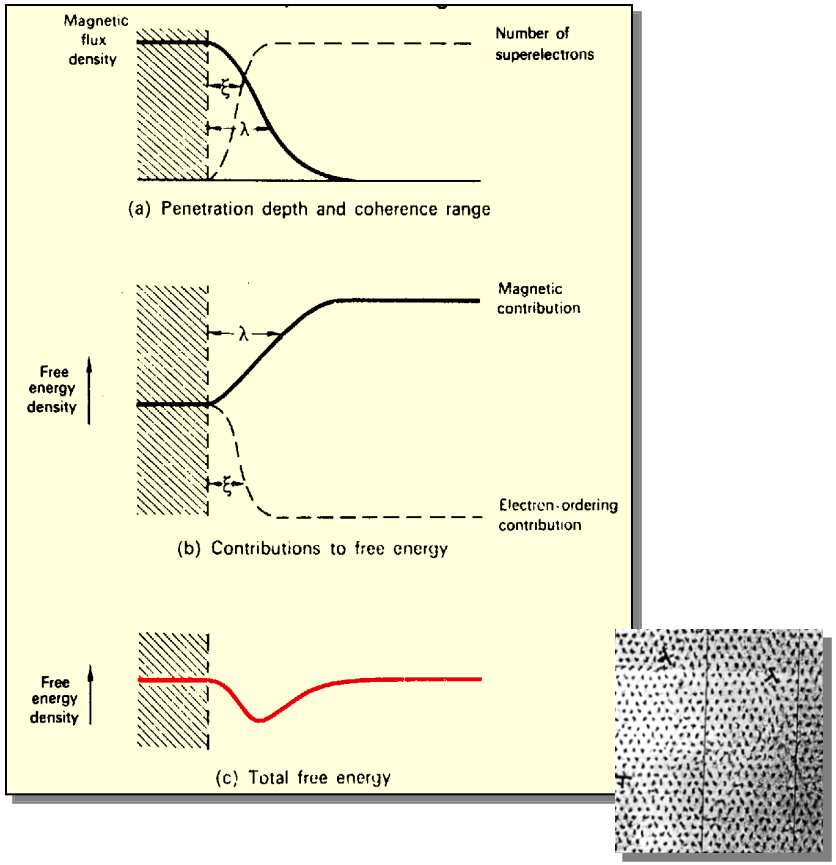
Surface energy:

$$\sigma_{ns} = \begin{cases} > 0, & \kappa < 1/\sqrt{2} \\ = 0, & \kappa = 1/\sqrt{2} \\ < 0, & \kappa > 1/\sqrt{2}, \end{cases} \qquad \kappa = \frac{\lambda}{\xi}$$

Depending on GL parameter k there is a tendency either to create, or not to create new surfaces

Two types of superconductors





(Abrikosov lattice, 1952)

Surface energy is positive:

Type I superconductivity

Surface energy is negative:

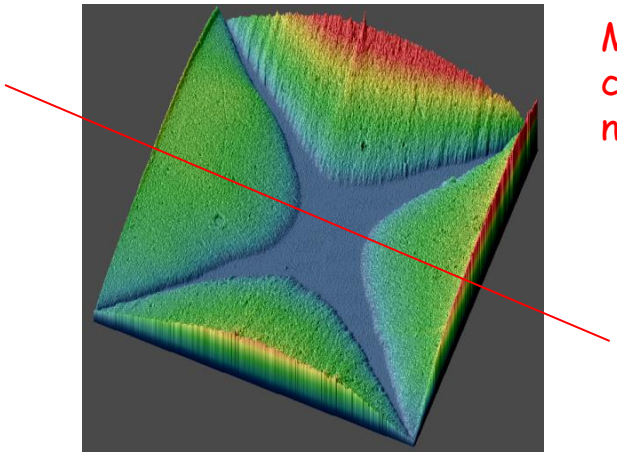
Type II superconductivity

Characteristic parameters of superconductors

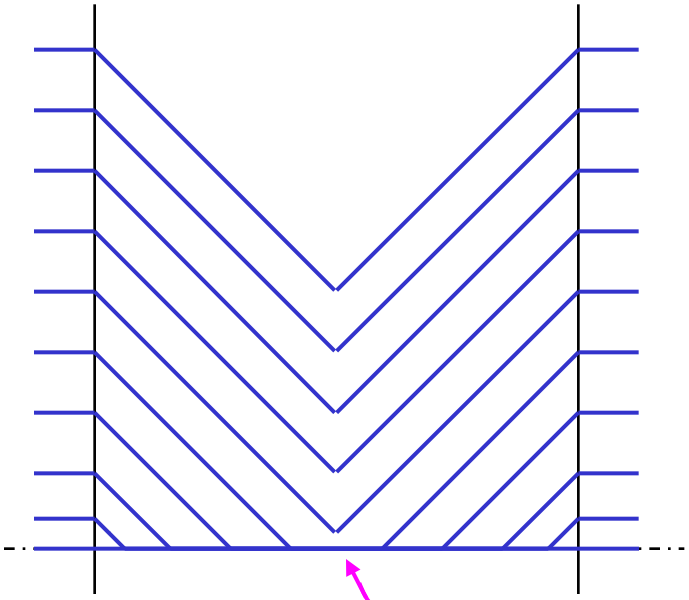
Superconductor	T_c (K)	$\lambda(0)$ (Å)	$\xi(0)$ (Å)	$H_{c2}(T)$
Nb	9.2	450	380	0.2
NbTi	9.5	1600	50	14
NbN	16	2000	50	16
Nb_3Sn	18.4	800	35	24
Nb_3Ge	23	-	35	38
$Ba_{0.6}K_{0.4}BiO_3$	31	2200	35	32
MgB_2	39	850	37	39
UPt_3	0.5	7800	200	2.8
UBe_{13}	0.9	3600	170	8
URu_2Si_2	1.2	-	130	8
$CeIrIn_5$	0.4	5300	250	1.0
$CeCoIn_5$	2.3	-	80	11.9
$TmNi_2B_2C$	11	800	150	10
$LuNi_2B_2C$	16	760	70	7
K_3C_{60}	19.5	~4800	35	~30
Rb_3C_{60}	30	~4200	30	~55
$YBa_2Cu_3O_7$	93	1450	13	150
$HgBa_2Ca_2Cu_3O_{10}$	135	1770	13	190

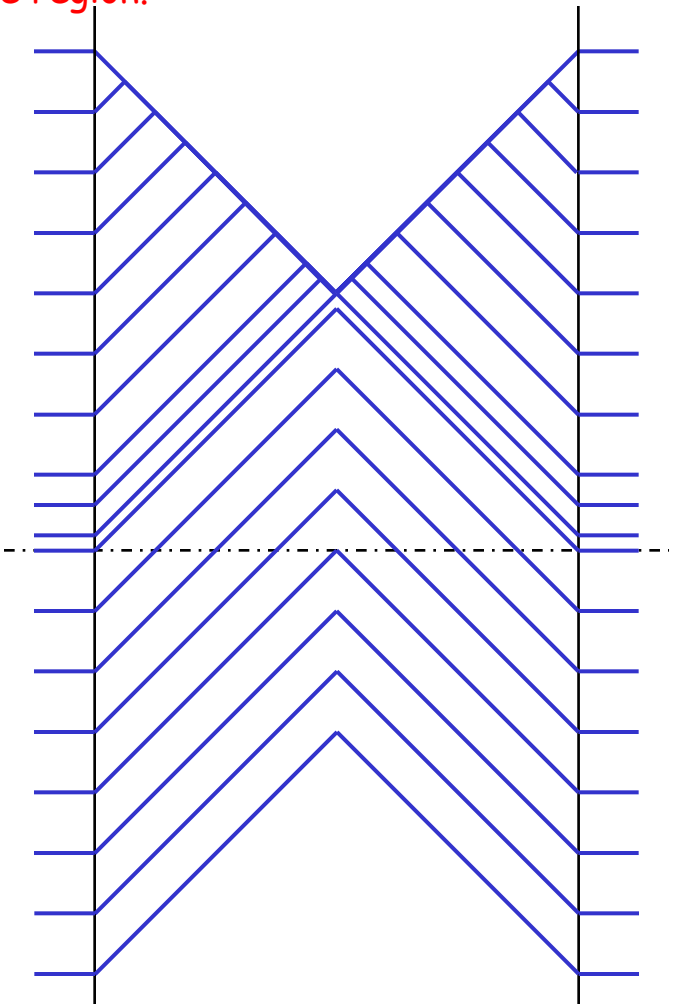
Critical temperature T_c, the penetration depth λ (0), the Cooper-pair size $\xi(0)$ and the upper critical magnetic field H_{c2} for type-II superconductors (for layered compounds, the in-plane values are given)

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.



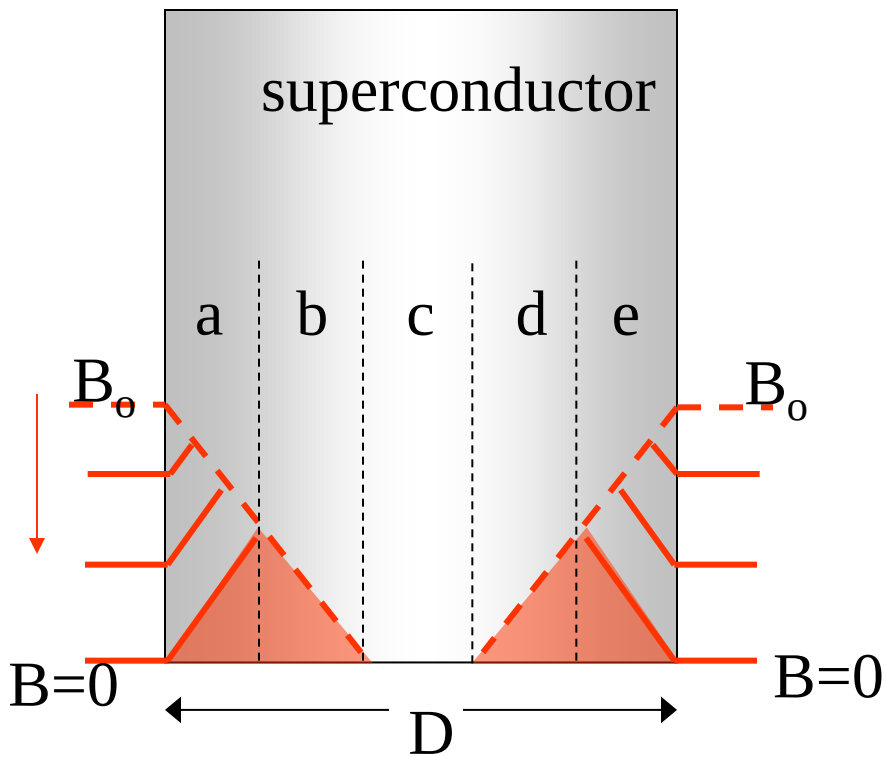


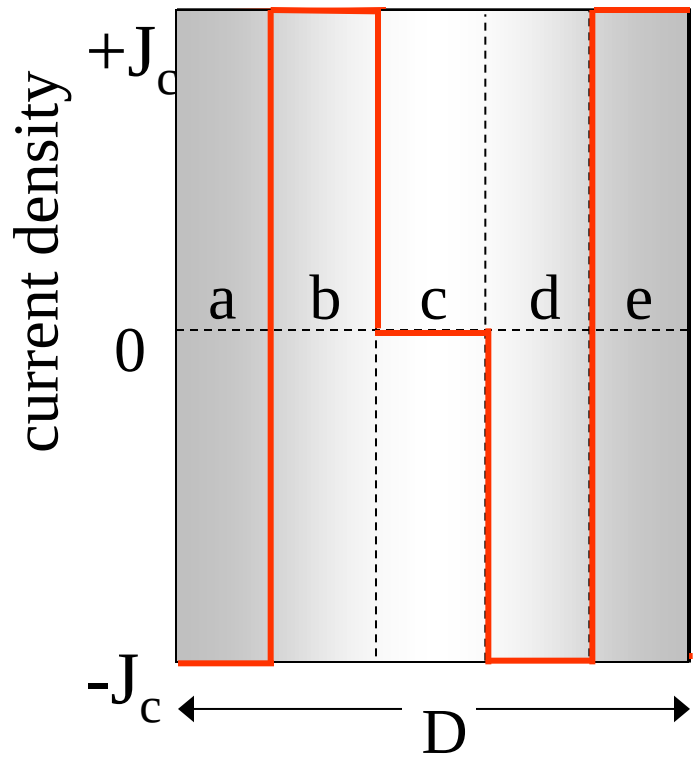
B

fully penetrated

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





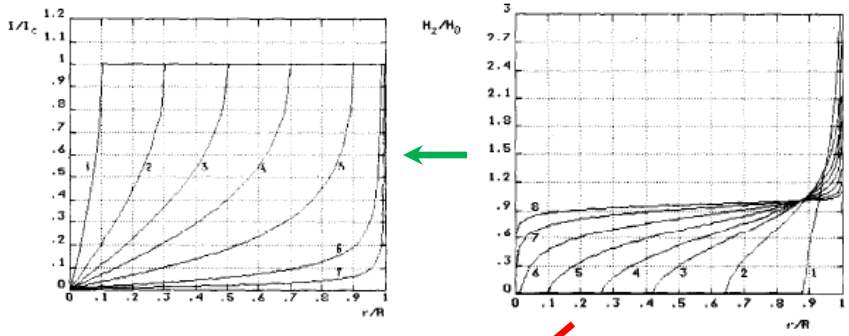
Bean critical state: thin films

UiO : University of Oslo

UNIVERSITY OF BIRMINGHAM

Inductance measurements of HTSC films with high critical currents

P.N. Mikheenko and Yu.E. Kuzovlev Physica C 204 (1993) 229–236
North-Holland

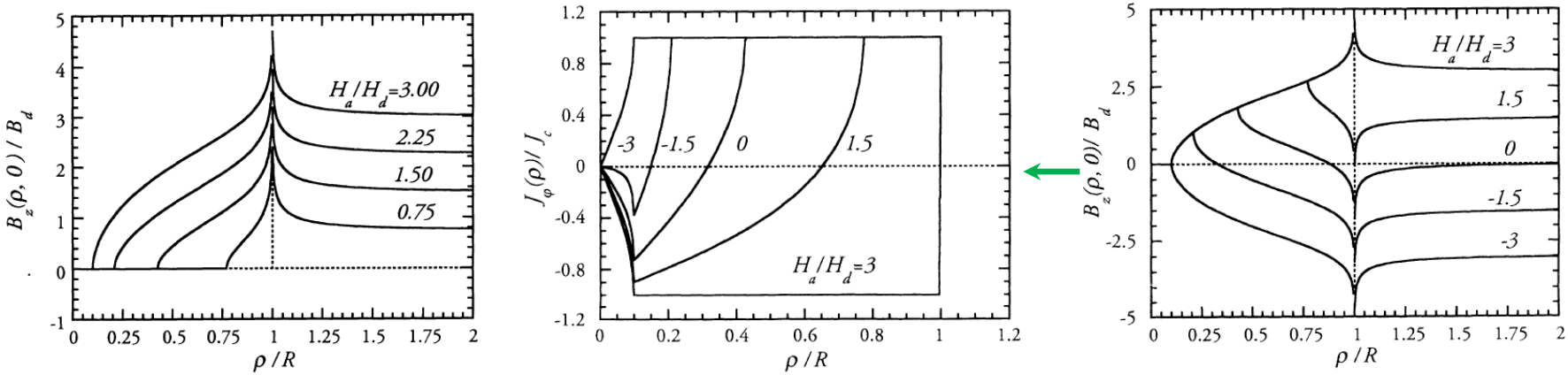


PHYSICAL REVIEW B VOLUME 50, NUMBER 13 1 OCTOBER 1994-I

Hysteretic ac losses and susceptibility of thin superconducting disks

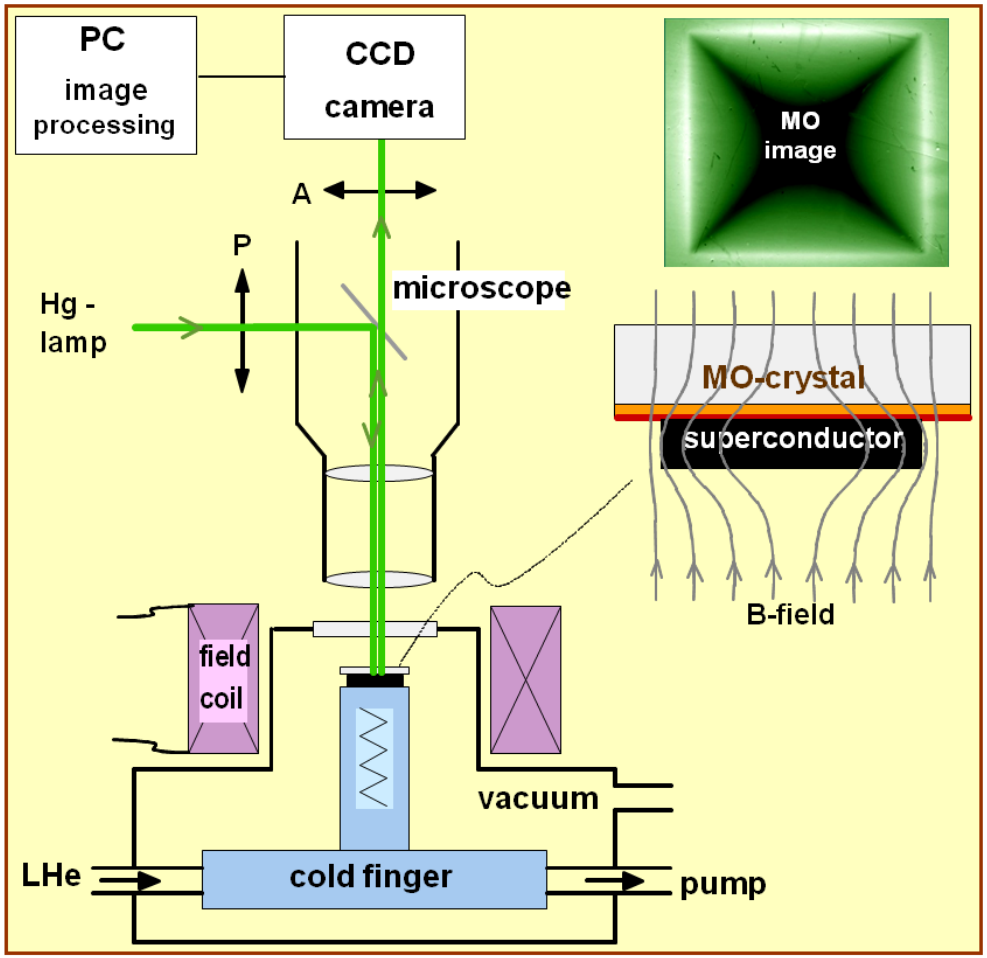
John R. Clem and Alvaro Sanchez

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.

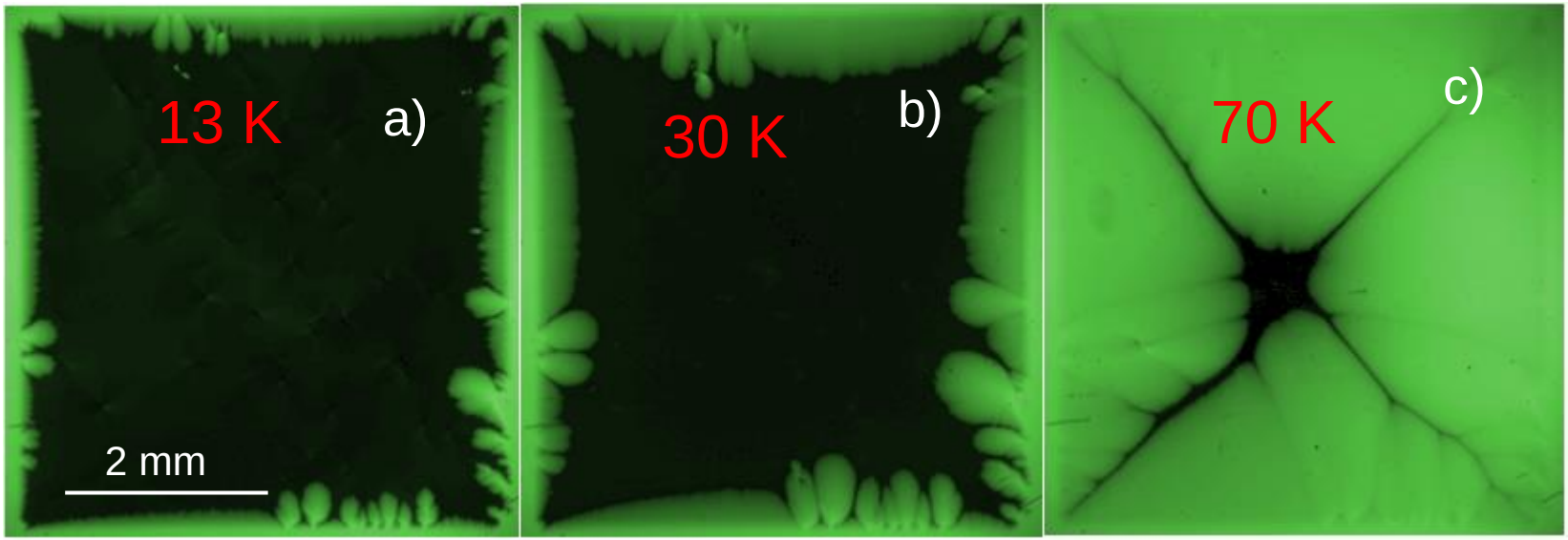
Faraday effect and magneto-optical imaging



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.

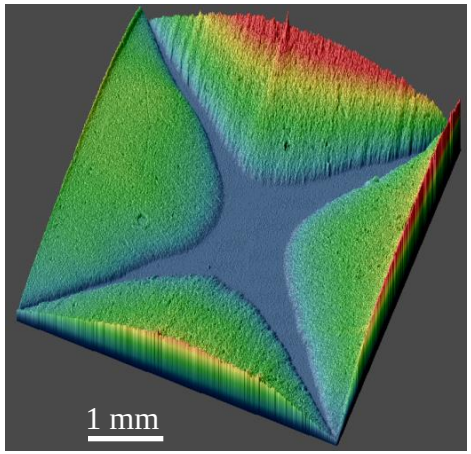
Magneto-optical imaging of $YBa_2Cu_3O_x$ thin films



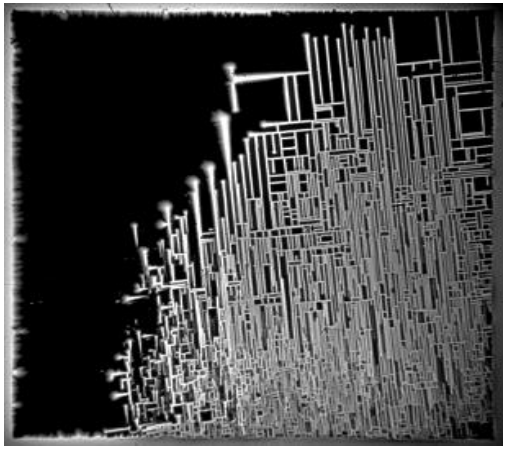
Magneto-optical image of an YBCO film at magnetic field of 85 mT and temperature of 13 K (a), 30 K (b) and 70 K (c).

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).

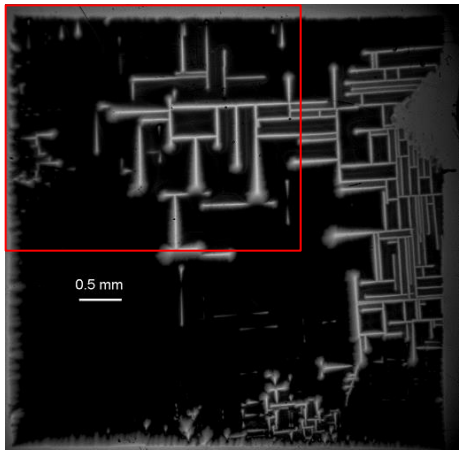
Magnetic flux penetration in superconducting films



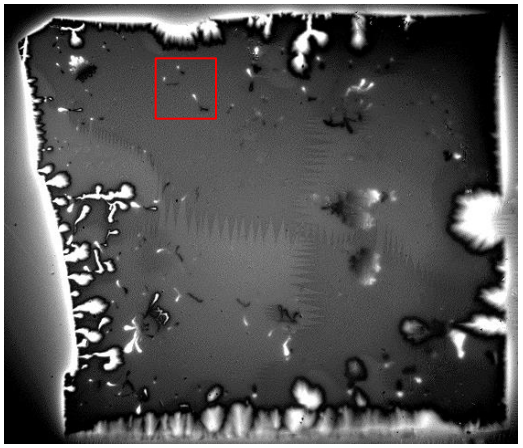
T = 70 K, ideal YBCO



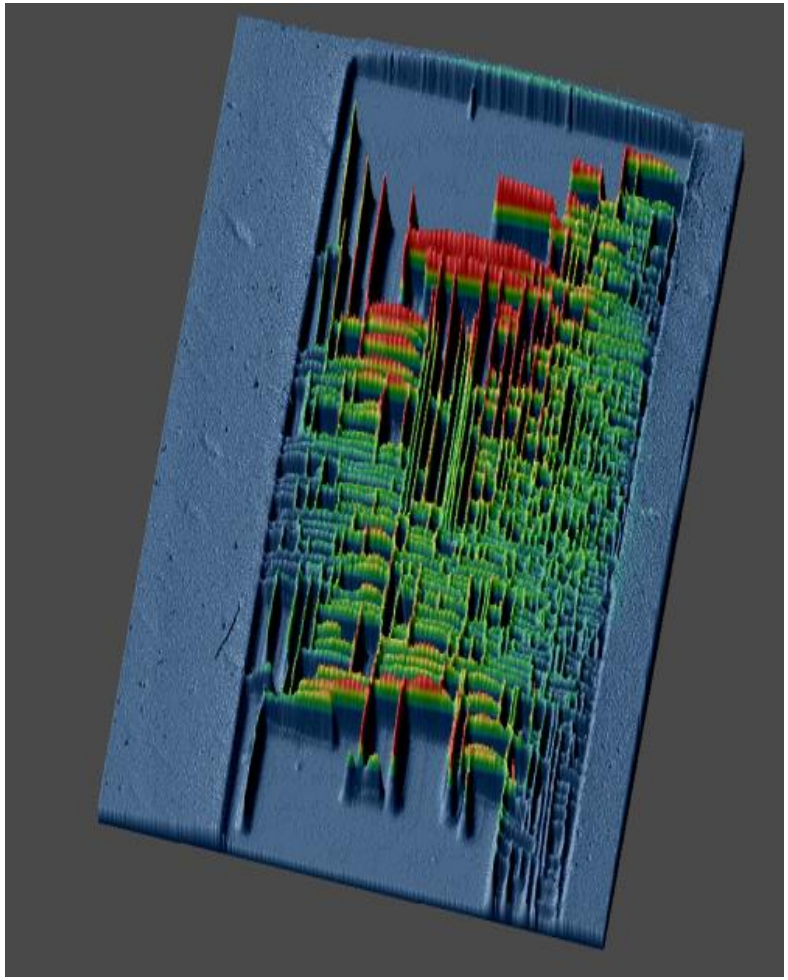
T = 4 K, YBCO



T = 4 K , YBCO

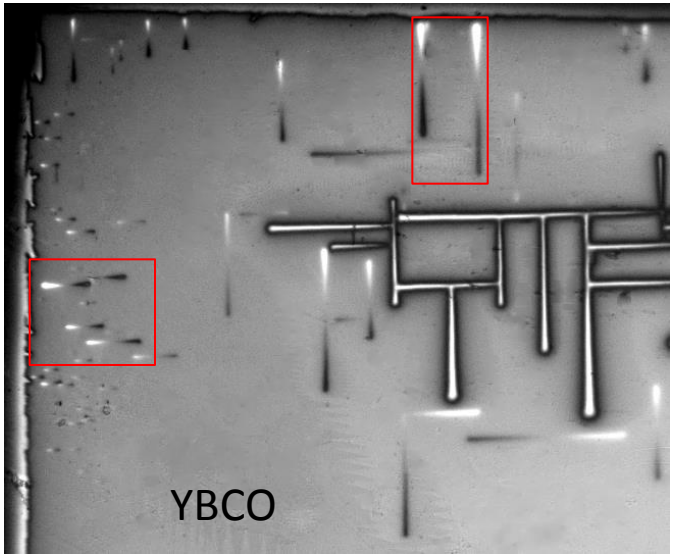


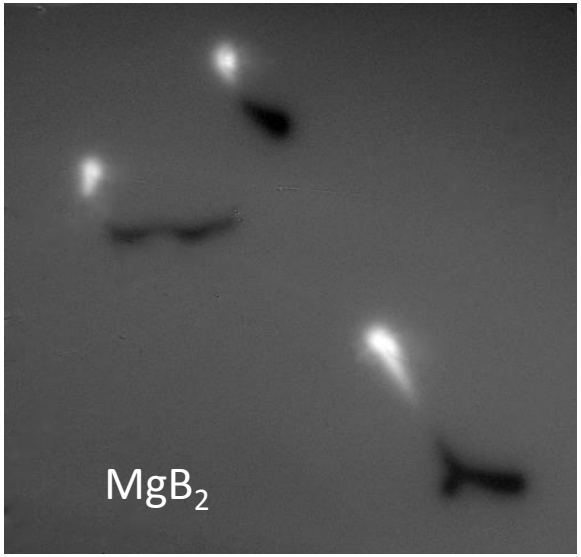
T = 4 K , MgB_2

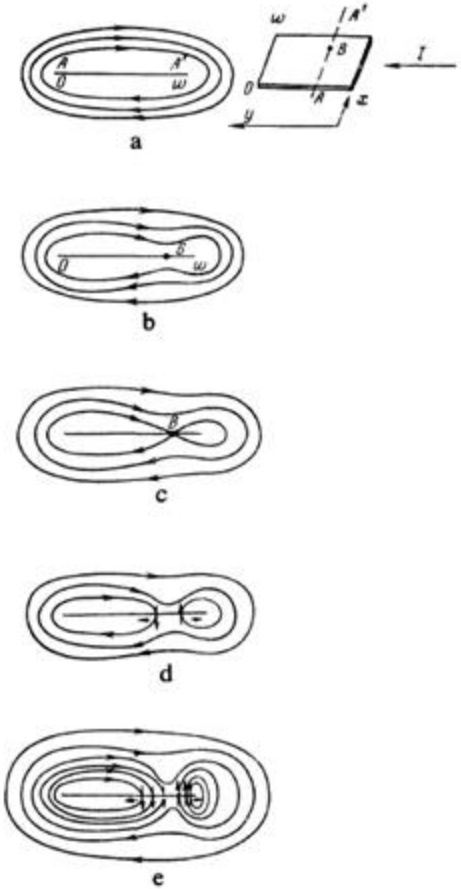


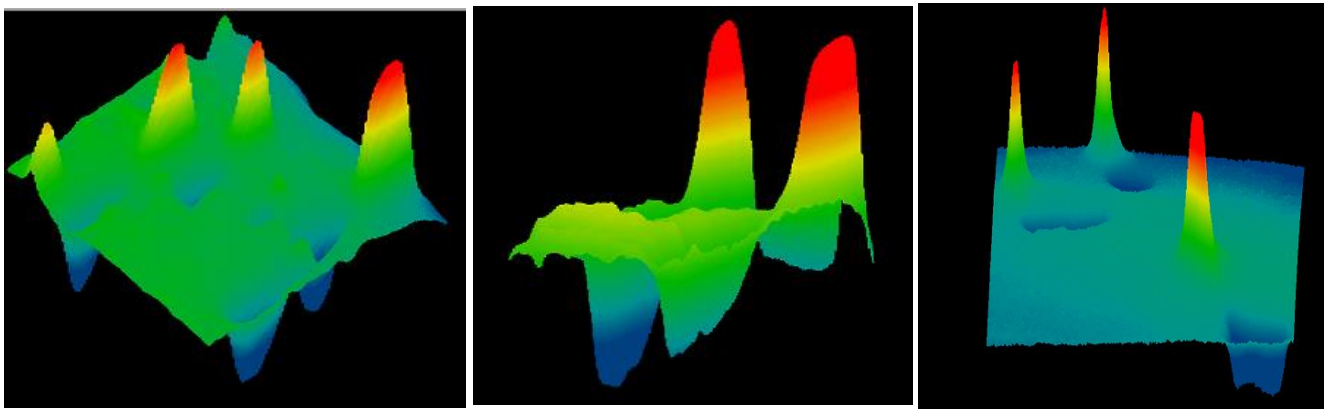
T = 20 K , YBCO

Magnetic flux penetration on intrinsic defects



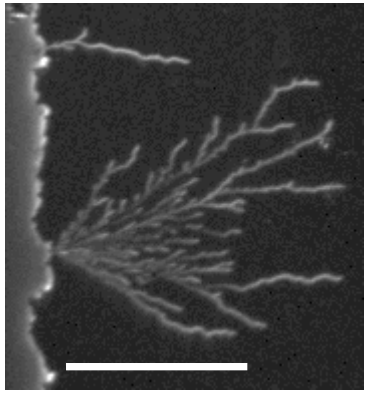


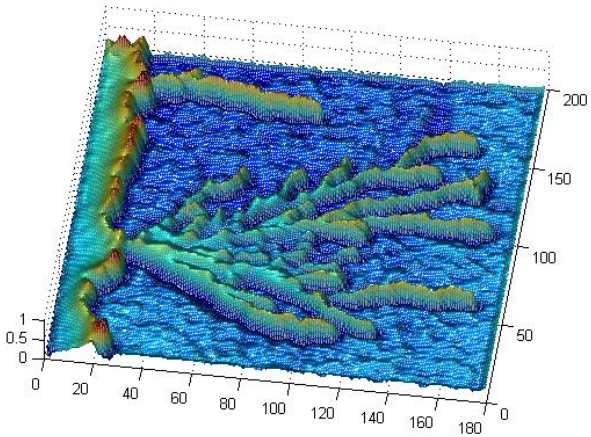


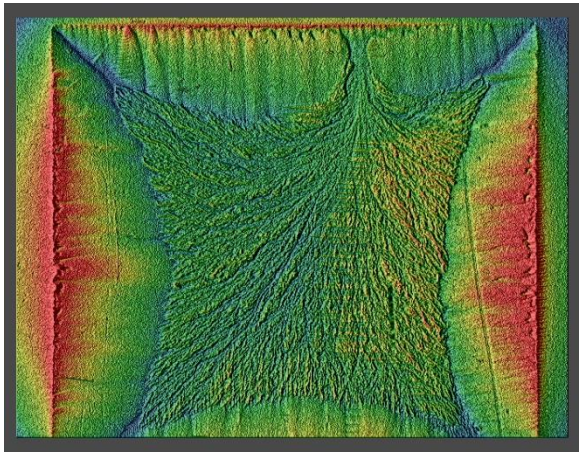


Yu. M. Ivanchenko and P. N. Mikheenko, New mechanism of penetration of vortices into current-saturated superconducting films, Zh. Eksp. Teor. Fiz. 85,2116-2127 (1983)

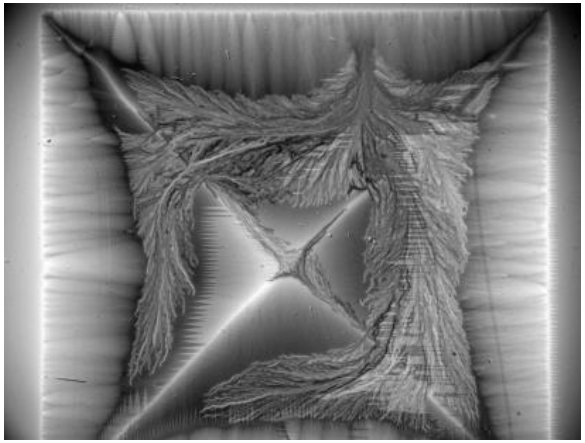
Dendritic flux avalanches in superconducting NbN films



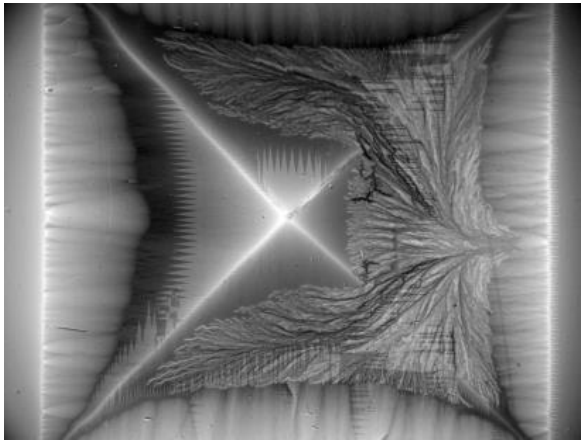




1 mm



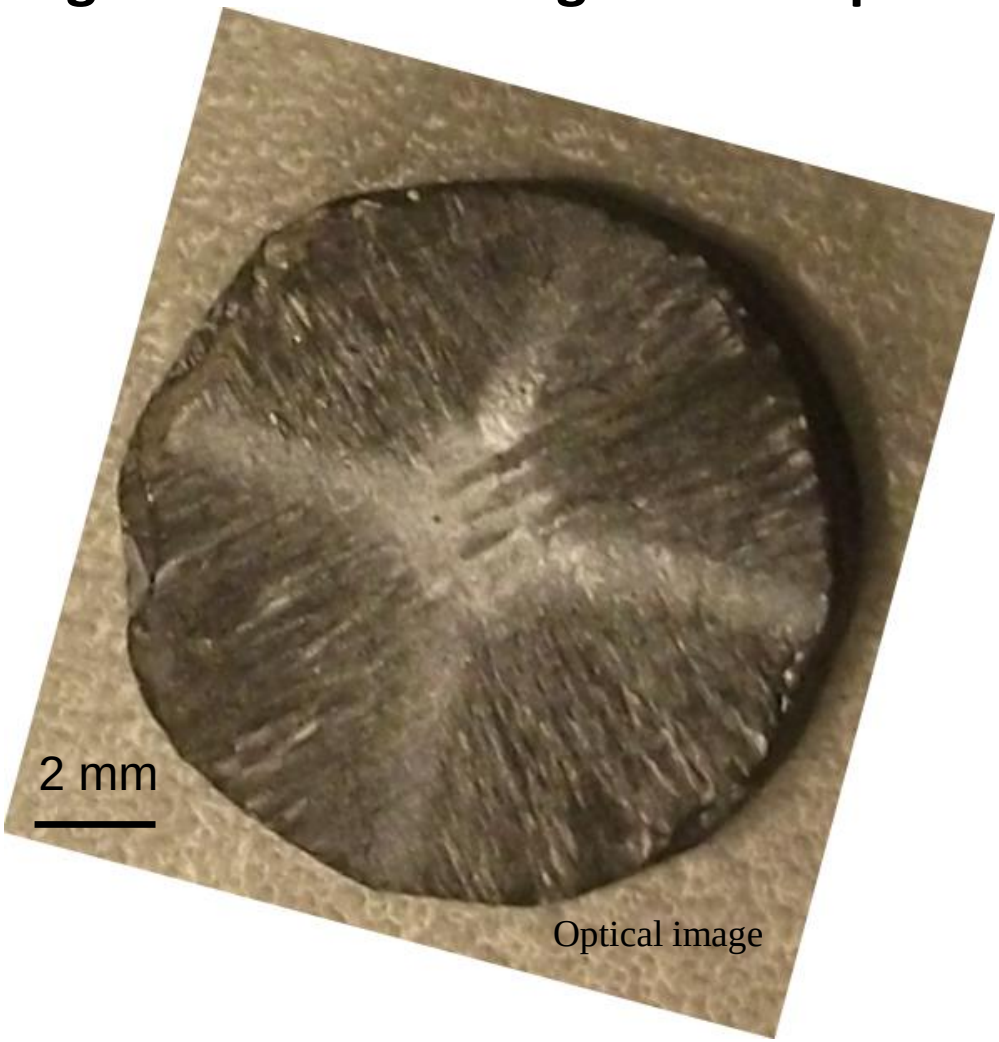
1 mm



1 mm

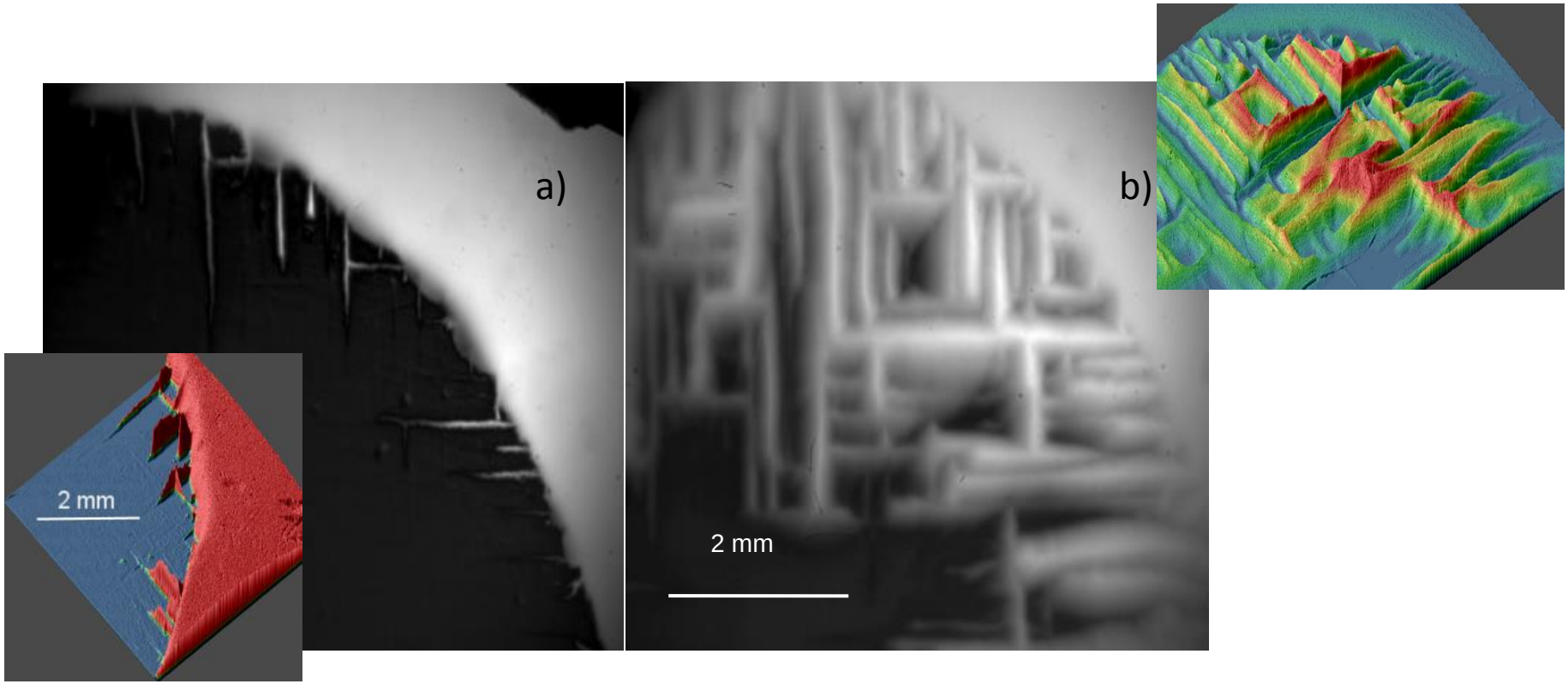
The avalanches propagate with very high speed up to 100km/s.

Trapped magnetic flux in melt grown sample at 79 K



The sample was zero field cooled to 79 K. At this temperature magnetic field of 85 mT was applied and than removed. A set of magneto-optical images was recorded at different positions in the sample.

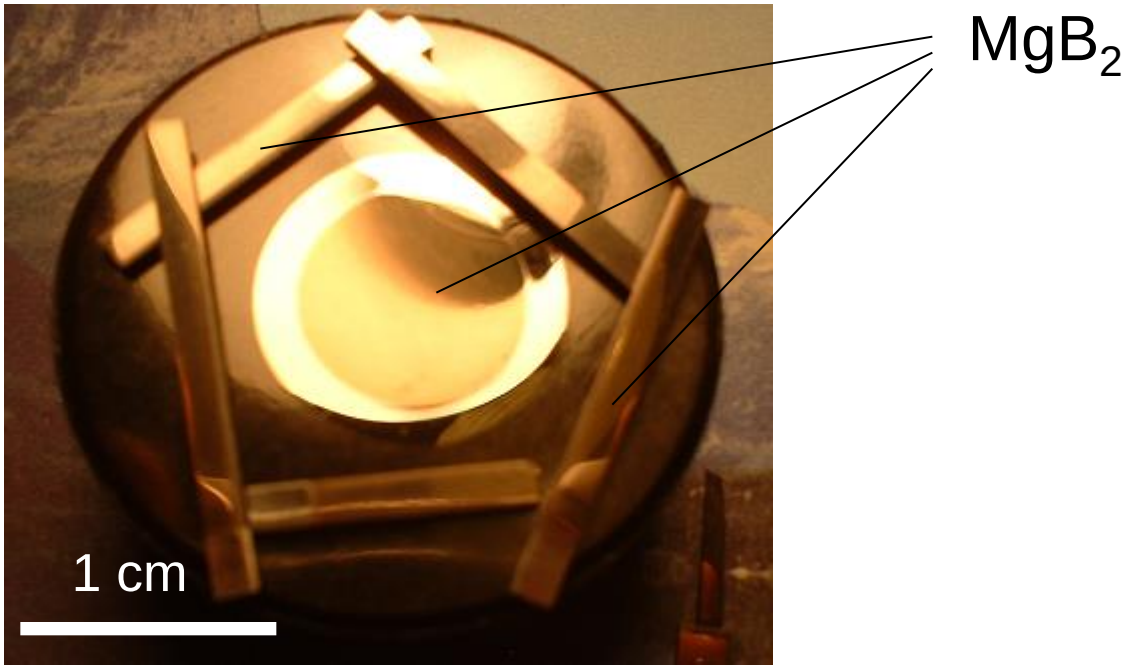
Magneto-optical imaging of bulk $YBa_2Cu_3O_x$



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.

Properties of MgB_2

- High critical temperature (~40 K, twice above boiling temperature of liquid hydrogen, 20.3 K)
- High critical current in bulk (~ 10^6 A/cm^2 at 20 K)
- Low mass density (2.62 g/cm^3)

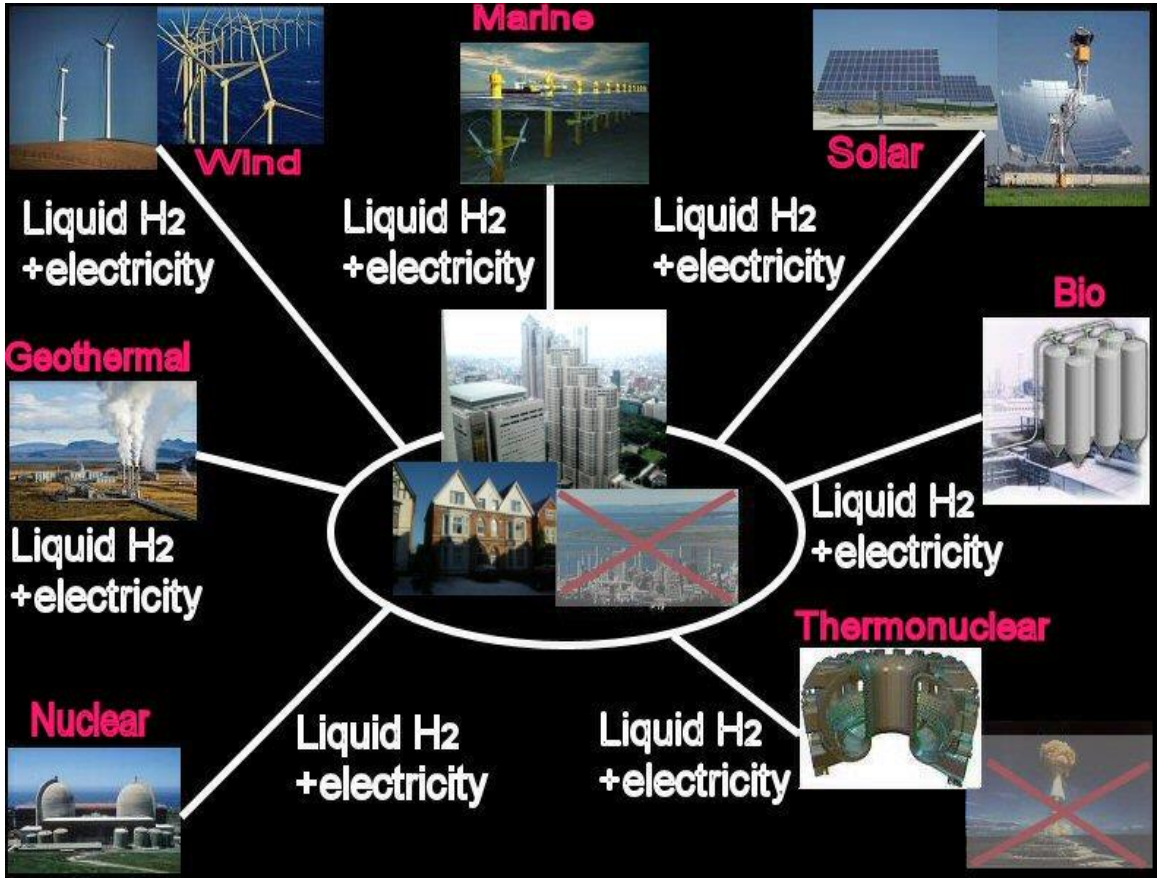


MgB_2 is an excellent material for liquid-hydrogen superconducting applications

Synergy of superconductivity and hydrogen economy

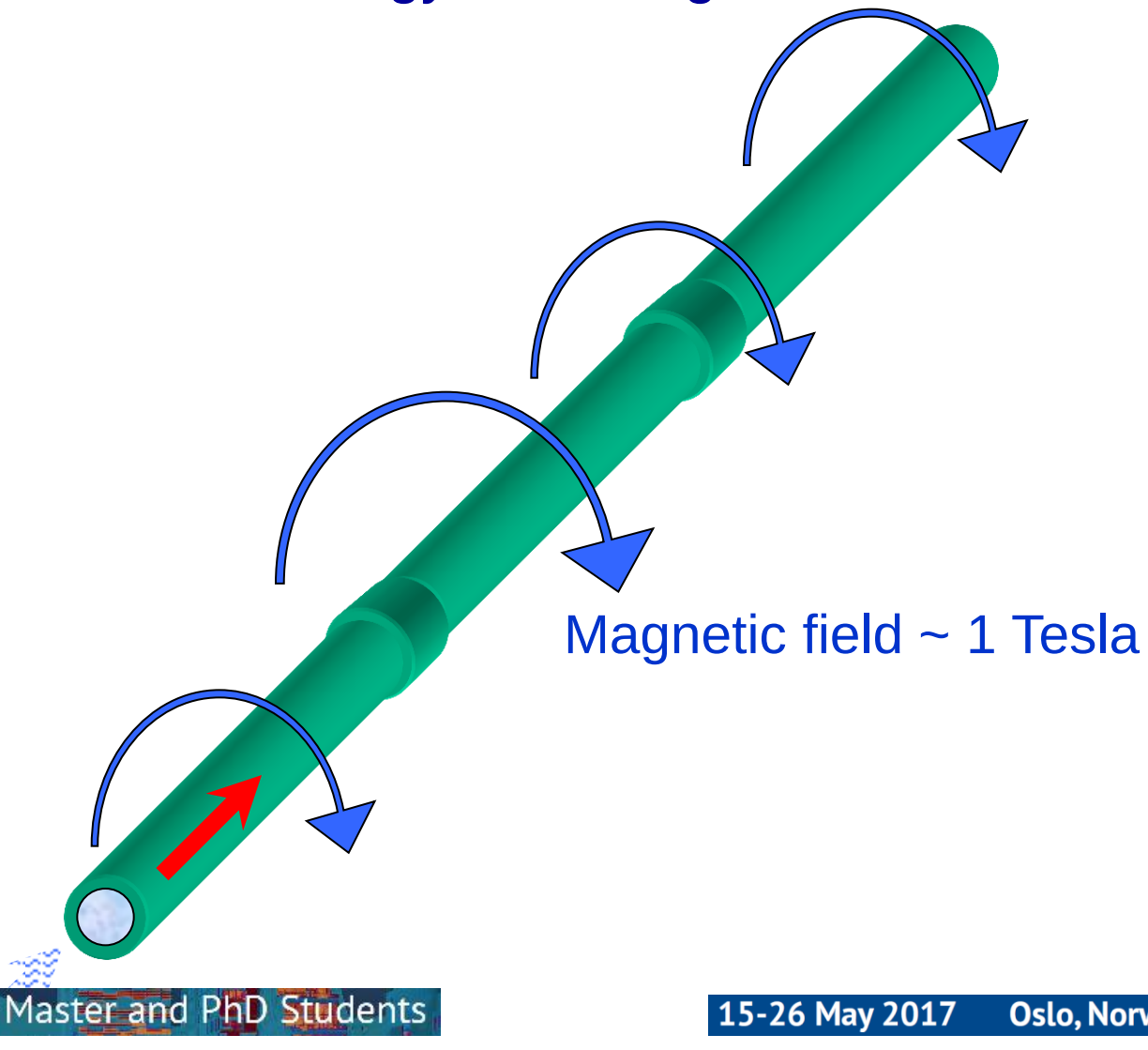
- *Superconductivity* offers compactness, high efficiency, savings in energy and a range of new applications in liquid hydrogen
- *Superconducting* pipelines can provide infrastructure for hydrogen economy
- Fully superconducting vehicles (cars, planes, ships, submarines) could be developed featuring *superconducting* motors, generators, energy storage units; loss-free wiring, current limiters, electronics, computers *etc*.
- *Superconducting* Home Energy Units can be designed
- *Superconductivity* could help addressing global problems on the planetary scale

Rise of renewable energy sources



- Hydrogen and electricity can easily be produced by renewable energy sources solving simultaneously problem of energy storage.
- Hydrogen can release full potential of superconductivity starting with building infrastructure for hydrogen economy.

Superconducting pipelines: transport of liquid hydrogen and electrical energy, levitating train



UiO : University of Oslo

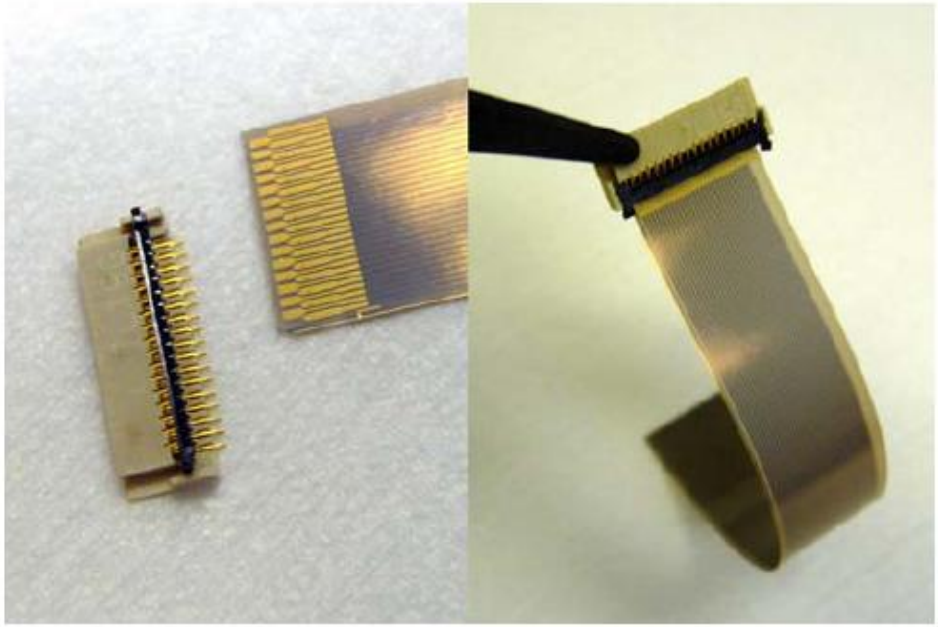
UNIVERSITY OF BIRMINGHAM

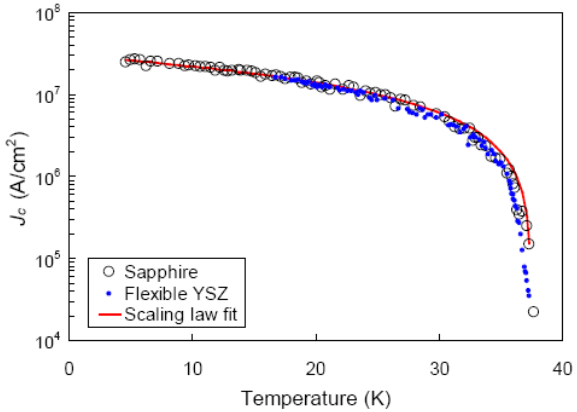
Flexible Flat Cables by reactive evaporation

IEEE/CSC & ESAS European Superconductivity News Forum (ESNF), No. 14, October 2010
(ASC 2010 preprint 1EY-02 submitted to IEEE Transactions on Applied Superconductivity and pre-published by ESNF conforming to IEEE Policy on Electronic Dissemination, Section 8.1.9)

Magnesium Diboride Flexible Flat Cables for Cryogenic Electronics

Chris S. Yung and Brian H. Moeckly





Advanced MgB_2 techniques: thin films deposition

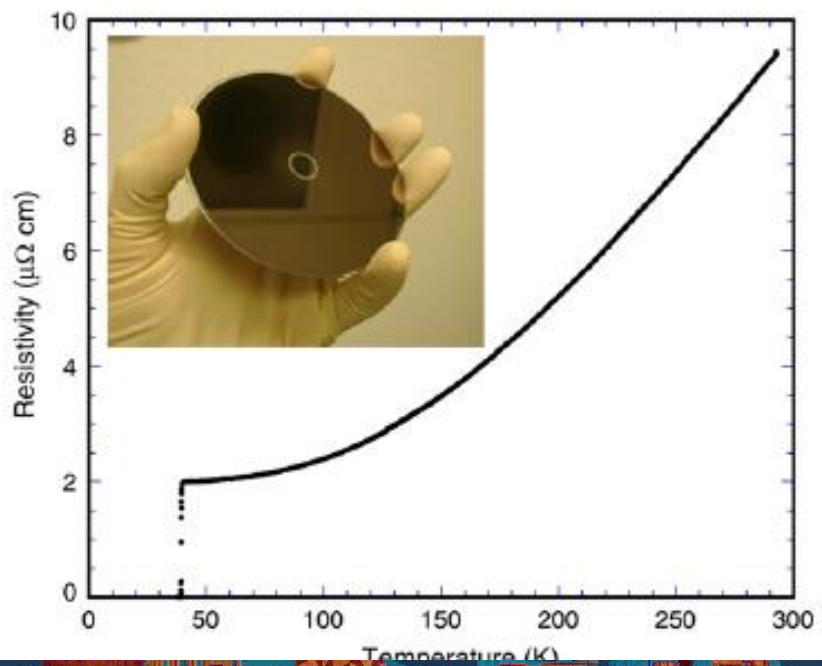
INSTITUTE OF PHYSICS PUBLISHING SUPERCONDUCTOR SCIENCE AND TECHNOLOGY
Supercond. Sci. Technol. 19 (2006) L21–L24 doi:10.1088/0953-2048/19/6/L02

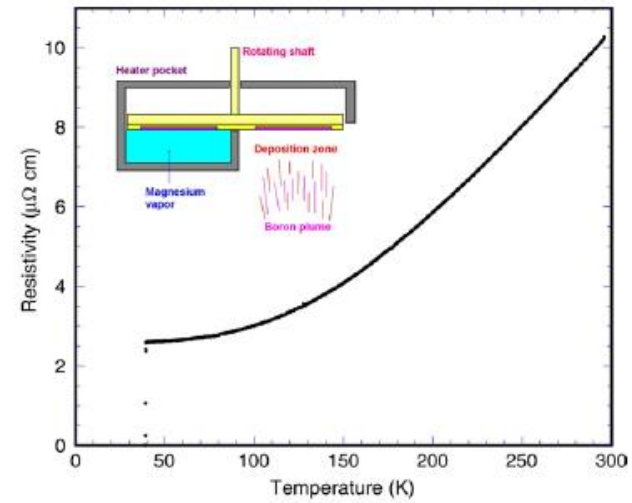
RAPID COMMUNICATION

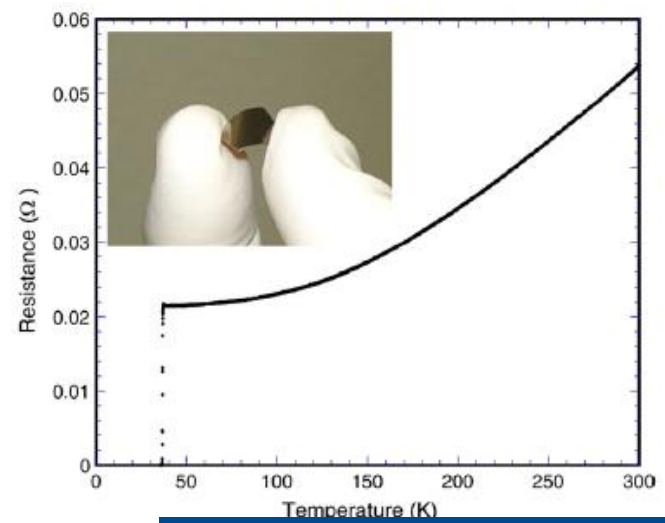
Growth of high-quality large-area MgB_2 thin films by reactive evaporation

B H Moeckly and W S Ruby

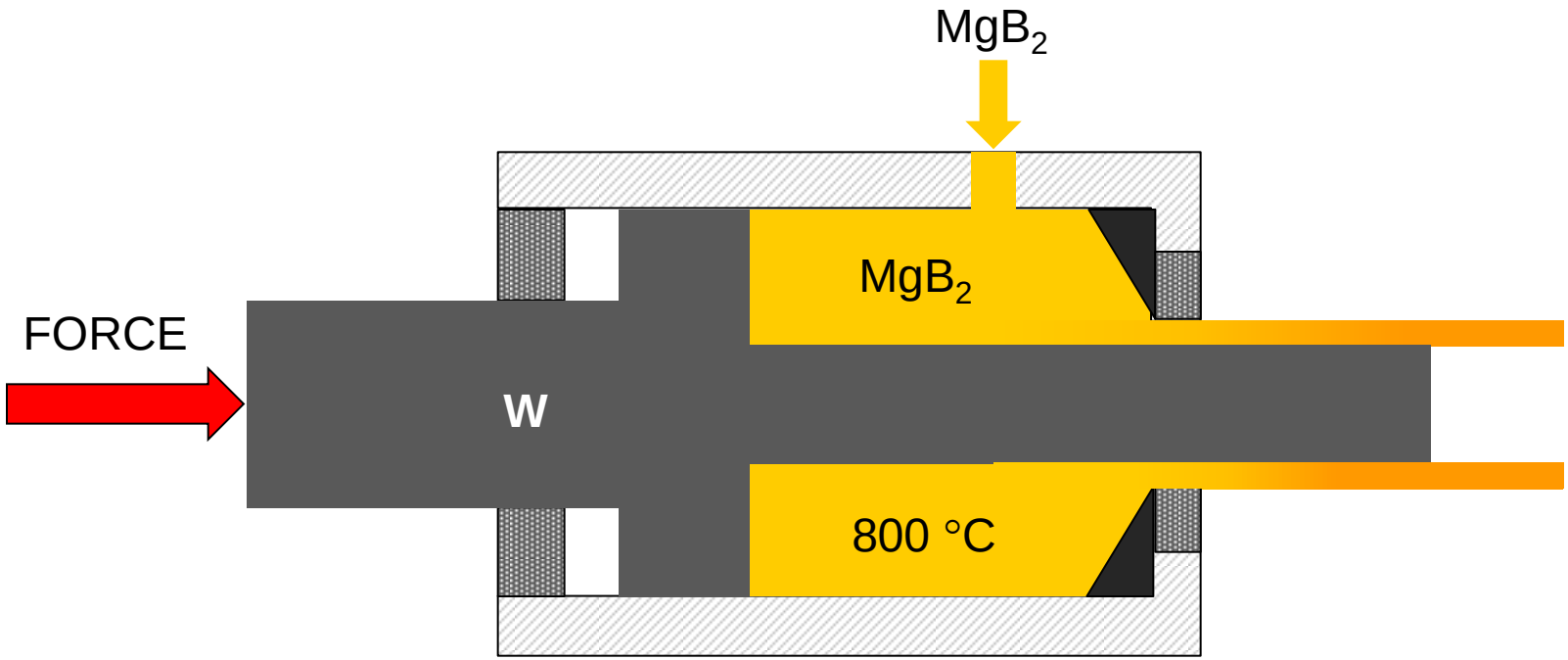
Superconductor Technologies, Inc., 460 Ward Drive, Santa Barbara, CA 93111, USA







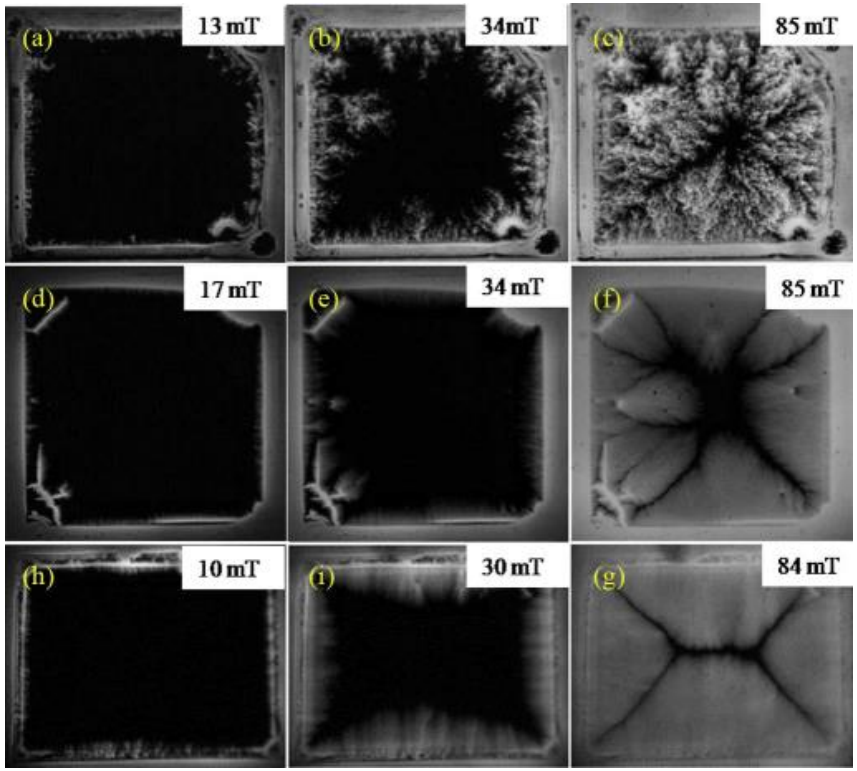
Hydrostatic extrusion of MgB_2 pipes of small diameter



P. Mikheenko, Superconductivity for hydrogen economy, Journal of Physics: Conference Series **286** 012014 (2011). **MgB_2 pipes, liquid H_2**

Return of $YBa_2Cu_3O_{7-\delta}$ (YBCO)

Aerogel: progress in non-vacuum thermal insulation.



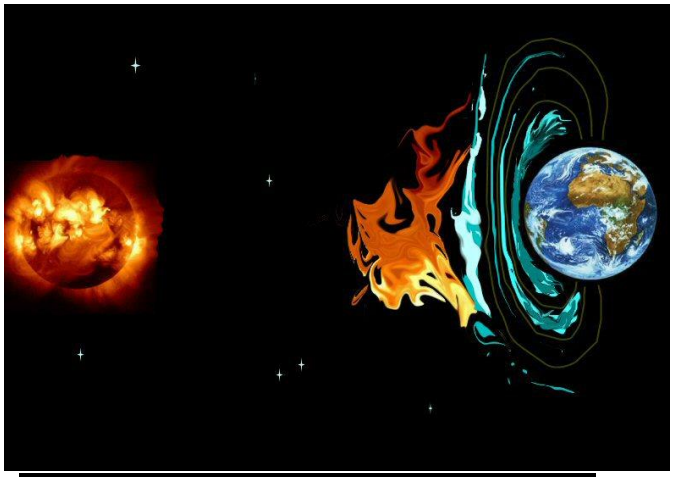
MOI images of metalorganic YBCO films at 20 K.

YBCO can significantly relax cooling requirements for liquid hydrogen economy.

Y. Zhao, Qureishy, T. Qureishy, P. Mikheenko, J. -C. Grivel, Characterization of $YBa_2Cu_3O_{7-\delta}$ films with various porous structures grown by metalorganic decomposition route, IEEE Trans. Appl. Superconductivity 26 7200204 (2016).

Global applications of superconductivity

Magnetic field protection of Earth during poles reversal

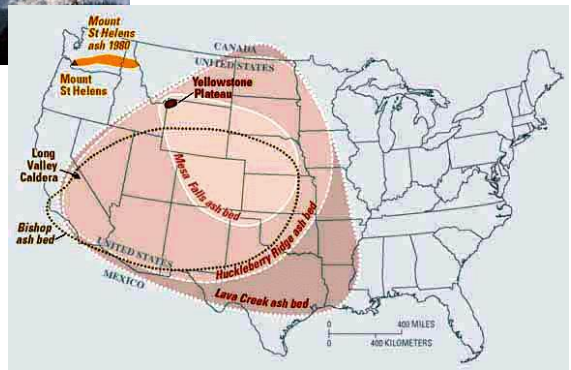


The liquid hydrogen-cooled superconducting pipeline encircling planet could be built

The superconducting pipeline would need to withstand a current of 10^9 A

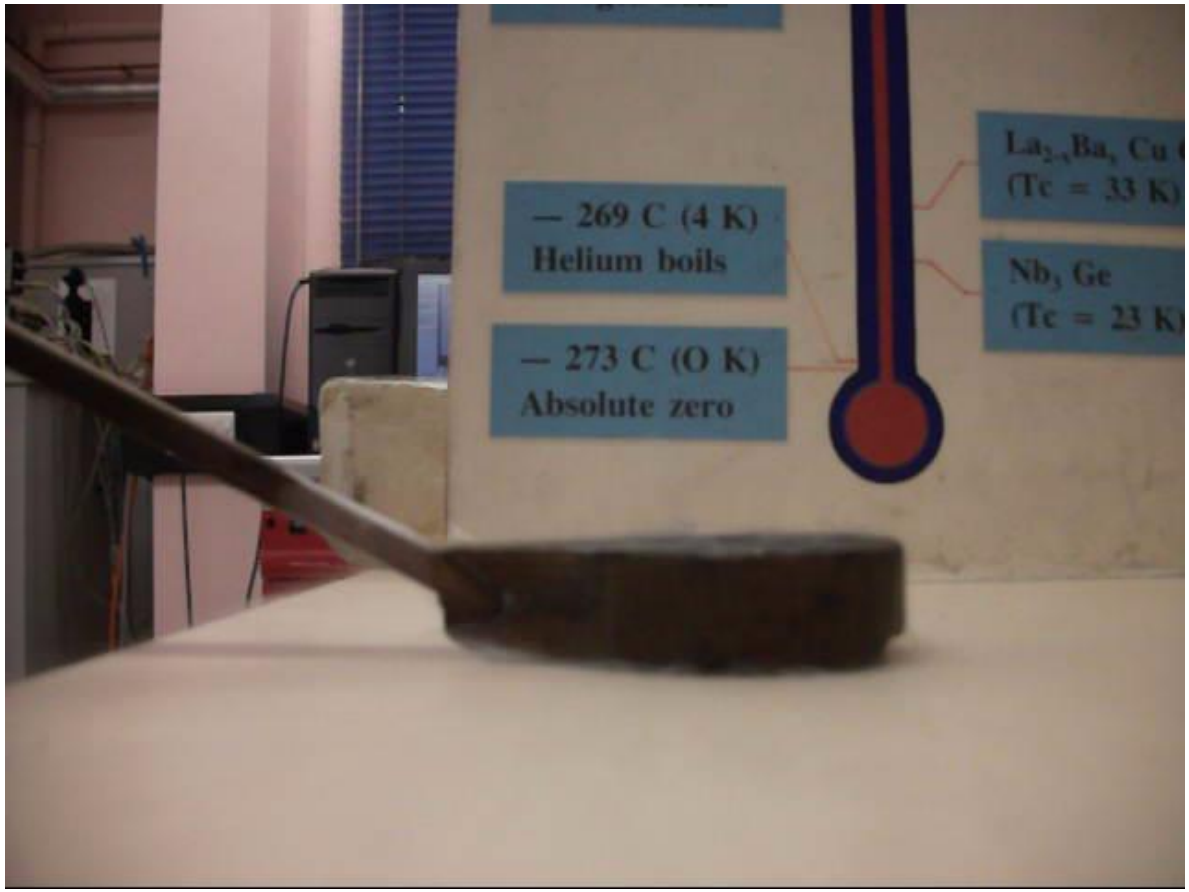
Prevention of super-volcano eruption

The superconducting pipeline encircling super-volcano could be used to extract energy and prevent its eruption

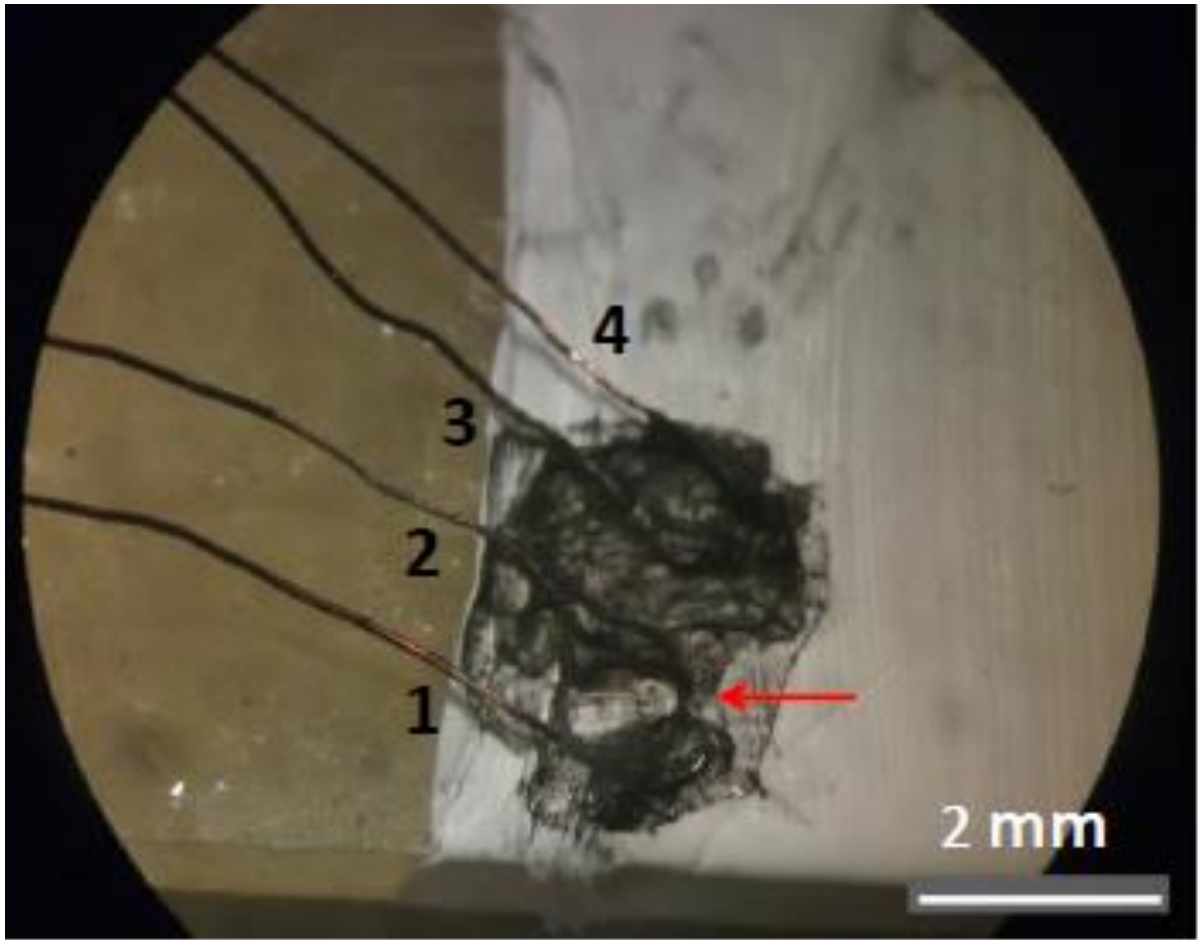


Space applications of superconductivity

Superconductors can be used for the protection of space stations and space ships from cosmic radiation and in the asteroid defence

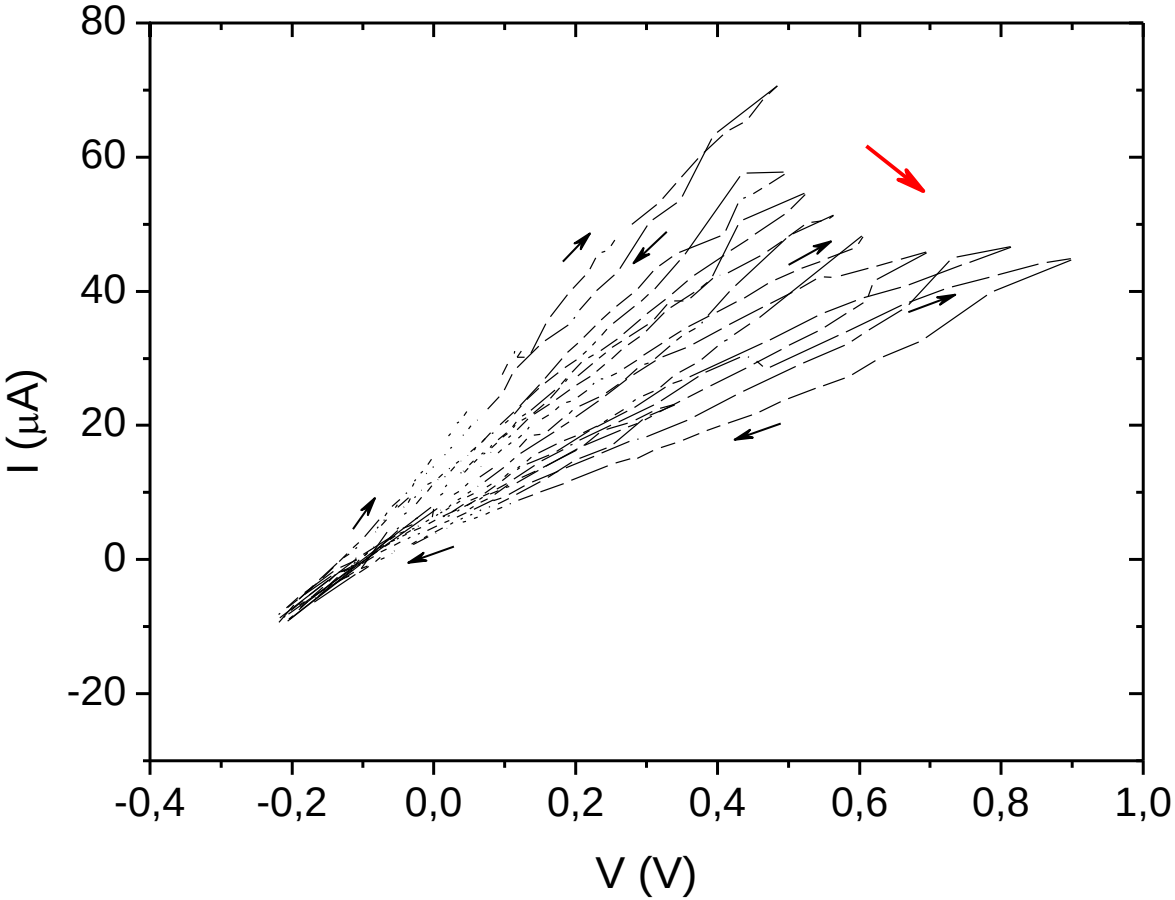


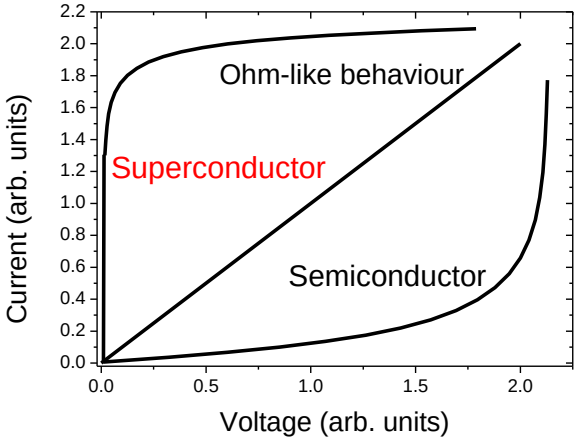
Four-electrodes transport measurements



Optical image of a slice of brain exposed to water solution of graphene flakes and connected to the wires. The electrical current was passed between leads 1 and 4 and potential was measured between 2 and 3. The red arrow marks narrow constriction between the leads 1 and 2. A dark spot close to the sample contains remnants of graphene leaked from the slice. White area is an insulating polytetrafluoroethylene (PTFE) tape

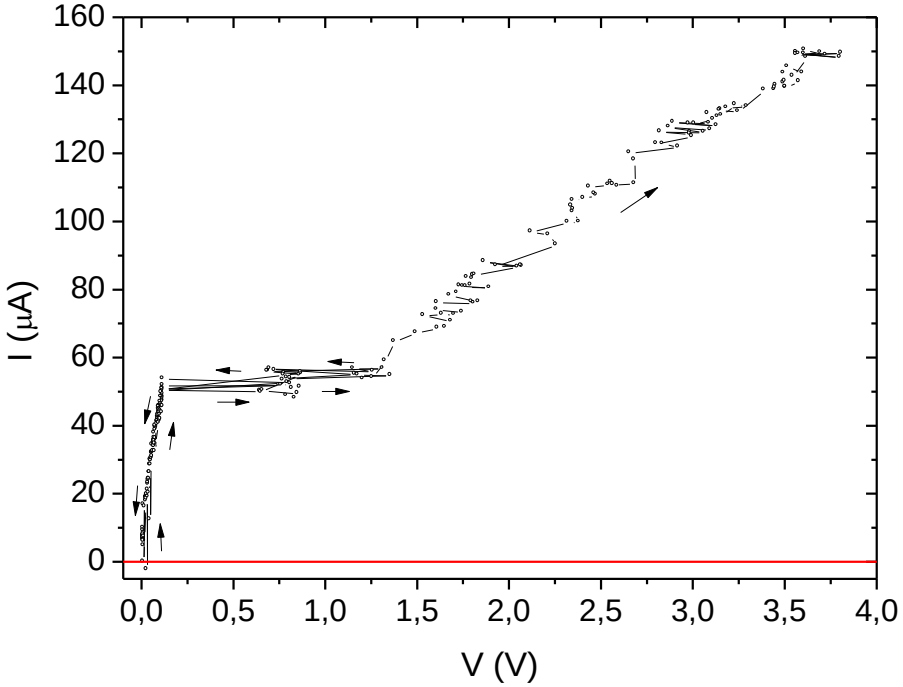
Transport measurements of muscles tissue



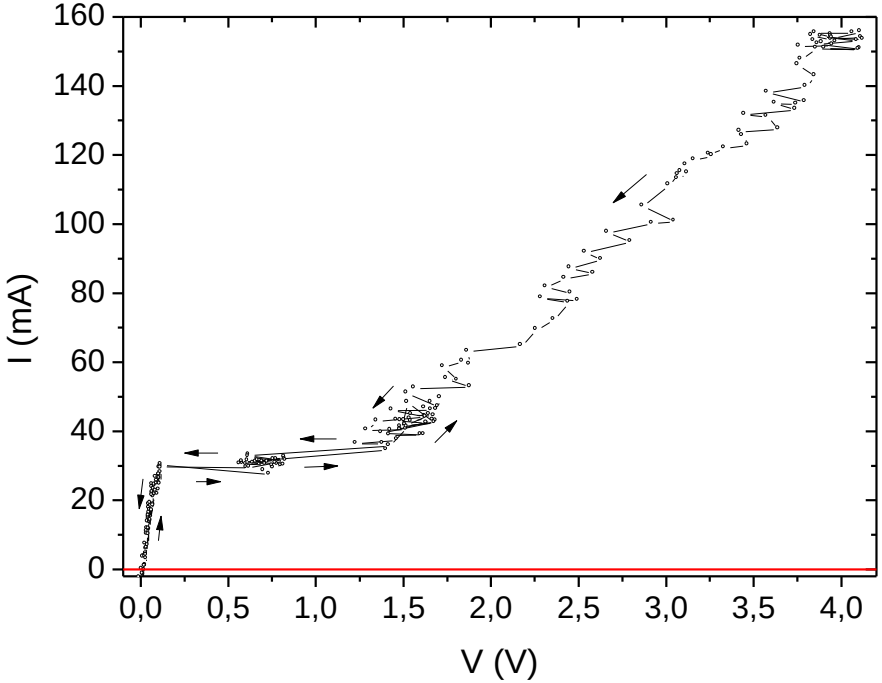


IV curves of the muscles tissue recorded in the process of the drying of the sample. Small black arrows show direction of the record. Large red arrow indicates increase of resistance in the process of measurement.

Transport measurements of brain tissue



Current-voltage characteristic of the brain tissue measured in the four-probe configuration. Small black arrows show direction of the record.



Current-voltage characteristic of the brain slice shown in three-probe configuration with current leads 2 and 4, and potential leads 2 and 3.

Superconductivity in brain?

Advances in Cryogenic Engineering

VOLUME 17

A Collection of Invited Papers
and Contributed Papers Presented
at National Technical Meetings
During 1970 and 1971

K. D. TIMMERHAUS, *Editor*
Engineering Research Center
University of Colorado
Boulder, Colorado

SPRINGER SCIENCE+
BUSINESS MEDIA, LLC 1972

SPECULATIONS OF SUPERCONDUCTIVITY IN BIOLOGICAL AND ORGANIC SYSTEMS*†

E. H. Halpern and A. A. Wolf

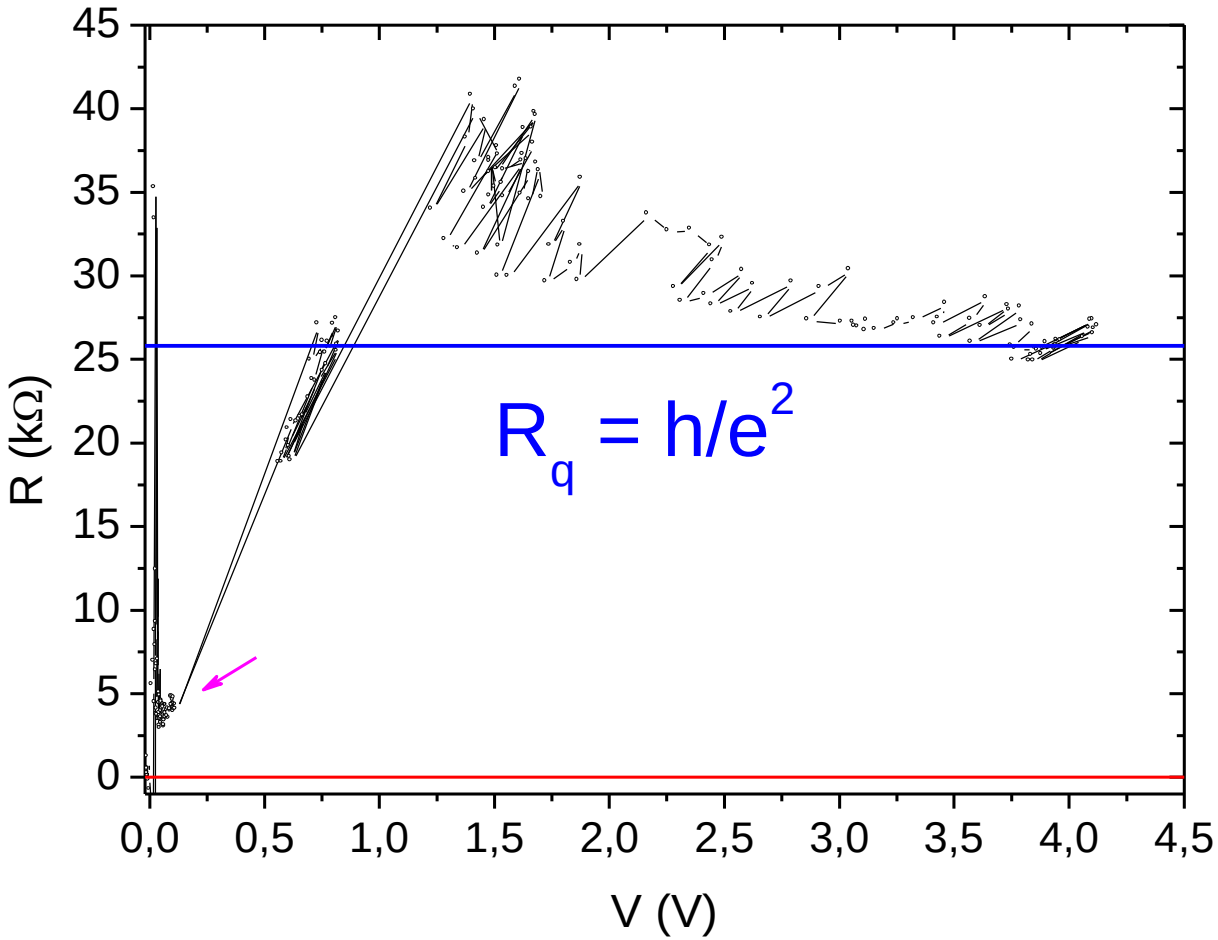
Naval Ship Research and Development Center
Annapolis, Maryland

SPECULATIONS AS TO WHERE SUPERCONDUCTIVITY CAN BE FOUND IN BIOLOGICAL SYSTEMS

It may be reasonable to expect superconductivity in regions of highest organization in biological systems. This would be found in the central nervous system and brain, where information is stored and processed, and where complex functions such as long-term memory and consciousness are centered. Consciousness is controlled by an energy flow through the brain, which is, in turn, controlled by blood flow bringing oxygen to the brain. This flow creates order in the molecular structure of various centers of the brain. John [12] described the mechanism of memory in terms of decreasing entropy with time in the higher-order centers of the brain.

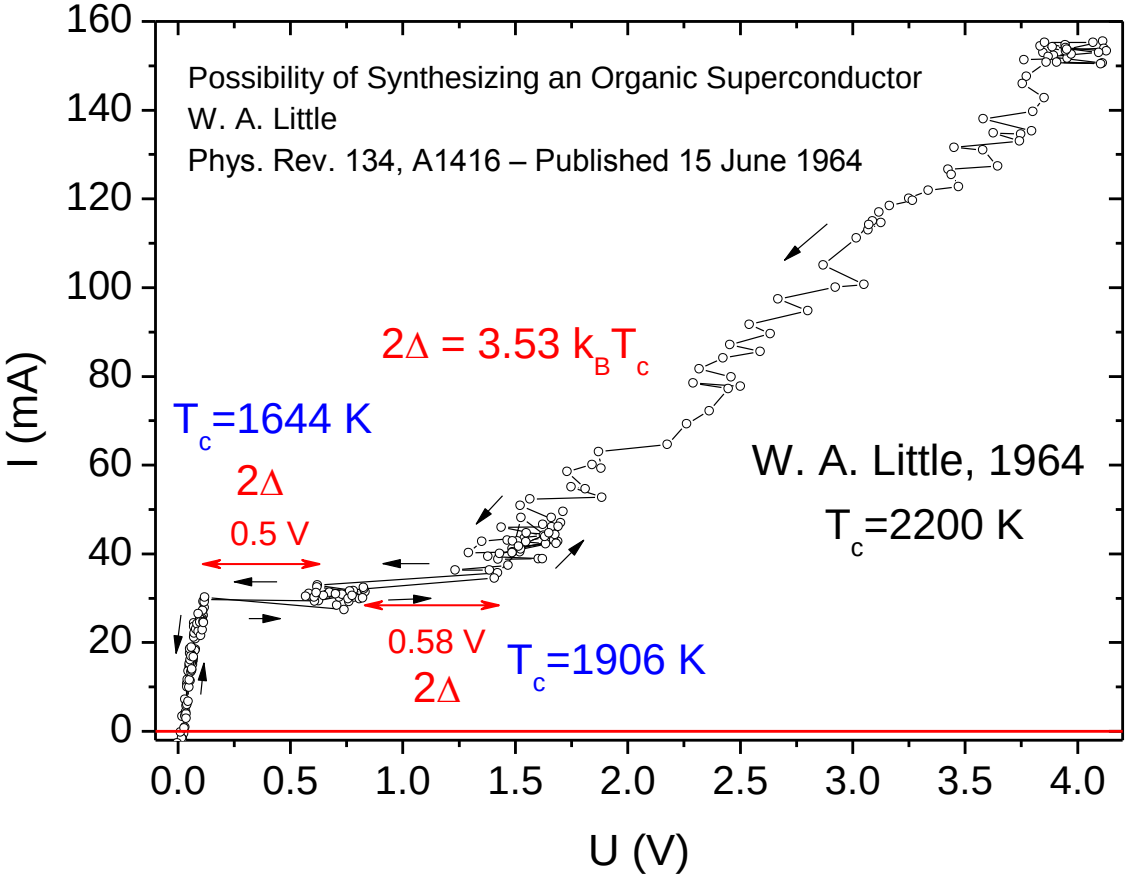
It is certainly conceivable to explain long-term memory (70 to 100 years lifetime of a person) in terms of persistent currents. That persistent currents exist seems to have been established by the response of living systems to strong magnetic fields. No theories of memory today seek to explain this phenomenon in terms of superconductivity. Certainly the work of Ladik *et al.* [5] on DNA as a room-temperature superconductor has bearing on the problem. DNA is critical to information storage and transfer of cell functions and reproduction of molecules.

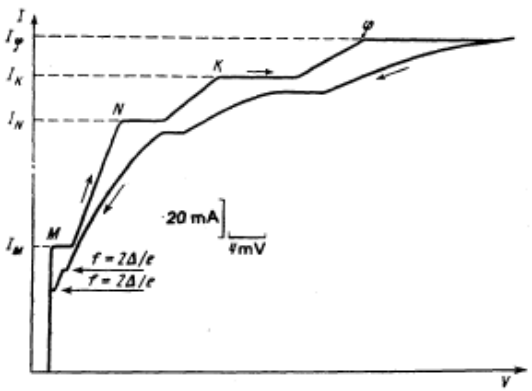
Quantum behaviour in brain



Current-voltage characteristic of the brain slice re-plotted as voltage dependence of the resistance.

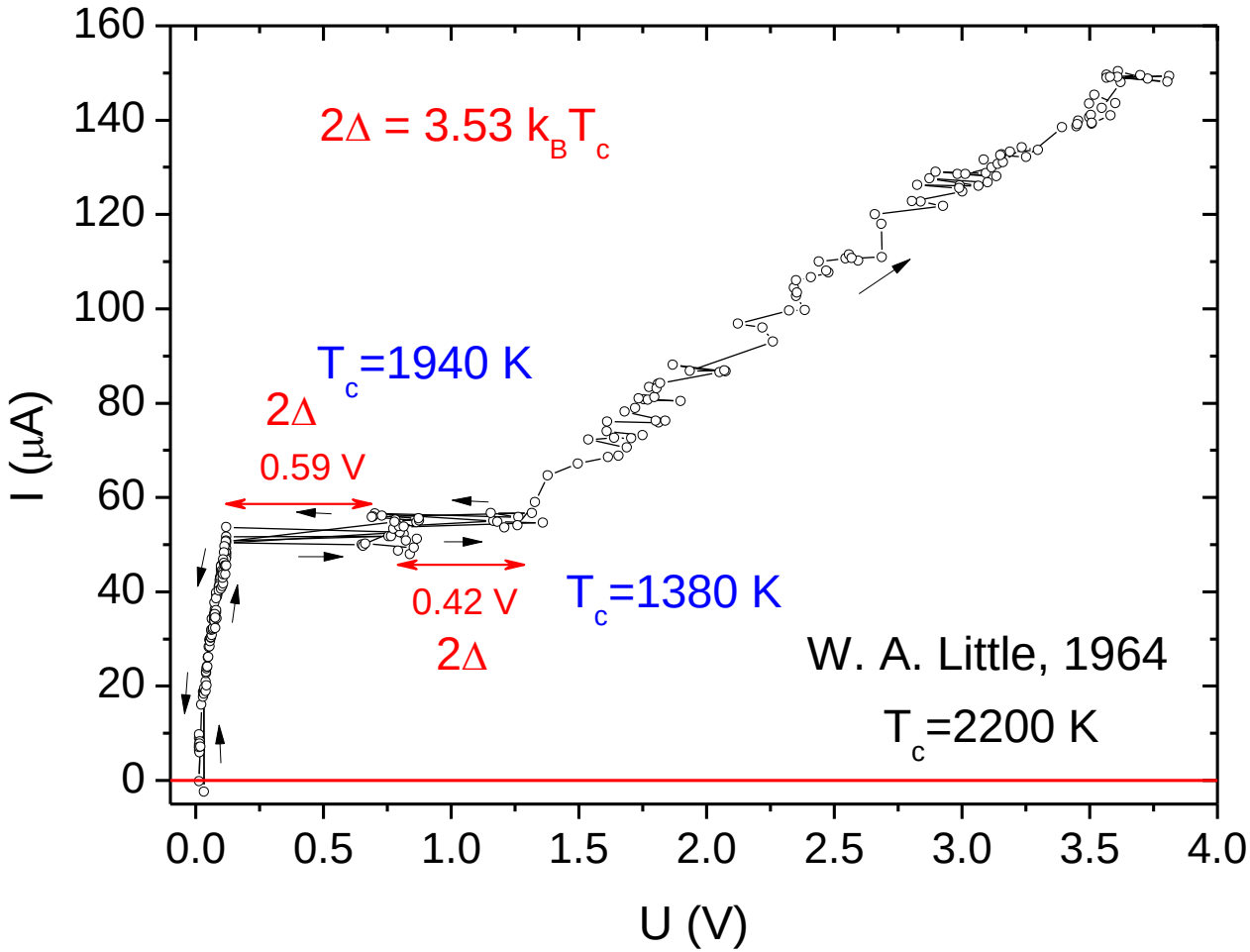
Link between energy gap and critical temperature





Yu.M.Ivanchenko, P.N.Mikheenko, V.F.Khirnyi, Kinetics of the destruction of superconductivity by the current in the thin films. Zhurnal eksperimentalnoi i teoreticheskoi fiziki, v.**80**, N 1, p.161-182 (1981).

Link between energy gap and critical temperature



Conclusions

- Superconductivity is important phenomenon in condensed matter physics that enables rapid progress in different areas of science and technology including cosmology, cancer therapy, relativistic heavy ion collisions and dark matter research.

- Superconductivity plays special role in building fossil fuel-free renewable energy economy. A concept of Smart Superconducting Grid is suggested for delivering simultaneously losses-free electricity and liquid fuel (hydrogen).

- Development of superconducting materials and techniques for renewal economy is well under the way

- There is impressive progress in the synthesis of new superconducting materials and the search for superconductors with a higher critical temperature.