The world of vortices

vortex lattice, pinning

small-angle neutron scattering

superconducting cables and
superconducting magnets

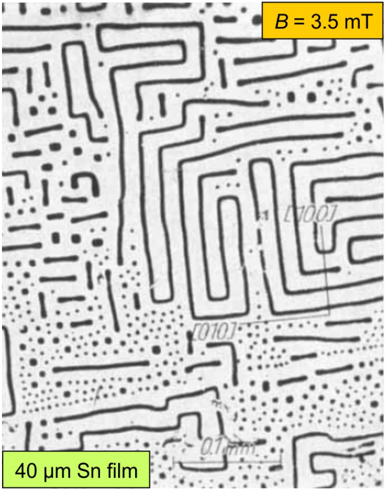
by Alexander Tsirlin, Leipzig University

Lecture 7: May 23, 2024

Intermediate state vs. vortex state

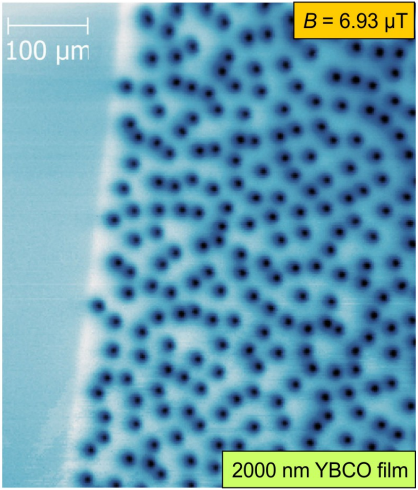
Intermediate state

(type-I superconductor)



Vortex state

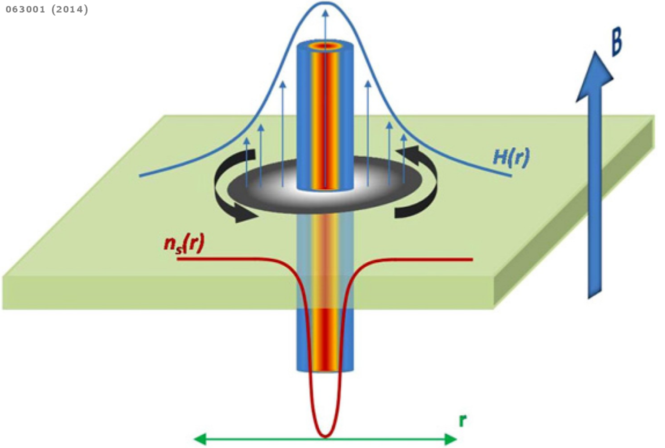
(type-II superconductor)



phys. stat. sol. 13, 471 (1972); Sci. Reports 5, 8677 (2015)

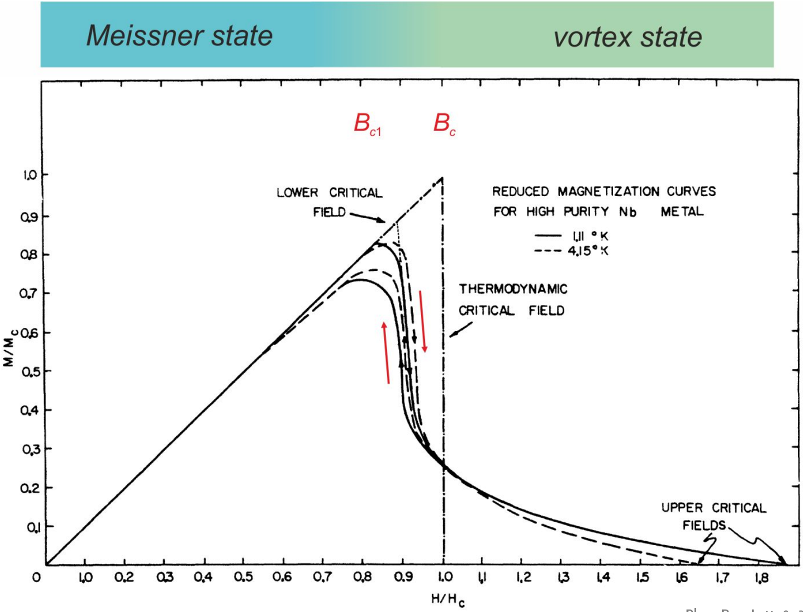
Isolated vortex

Supercond. Sci. Tech. 27, 063001 (2014)



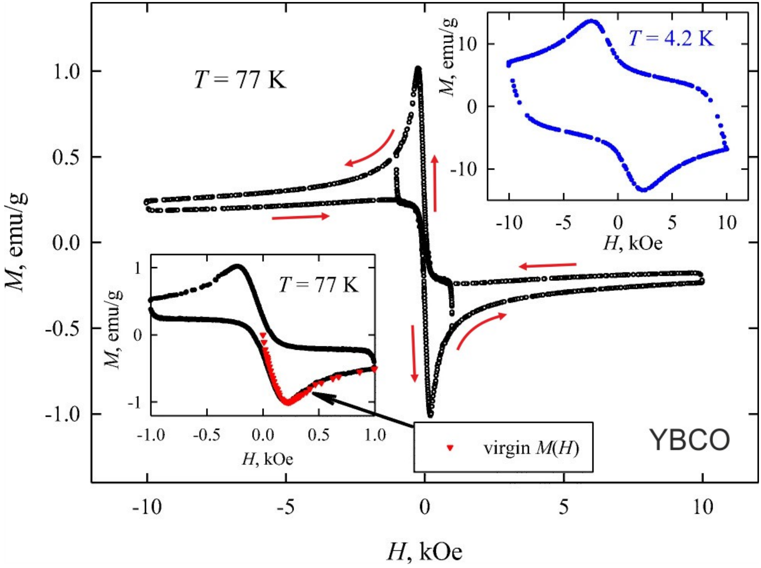
- Magnetic flux enclosed in a cylinder
- Supercurrent embraces the vortex
- $\xi \ll \lambda$, i.e., $\Psi \neq 0$ except in the vortex core (of the size of ξ)

Hysteresis of magnetization: surface barrier



Phys. Rev. Lett. 9, 370 (1962)

Hysteresis of magnetization: pinning



J. Supercond. Nov. Magn. 34, 1067 (2021)

Vortex lattice

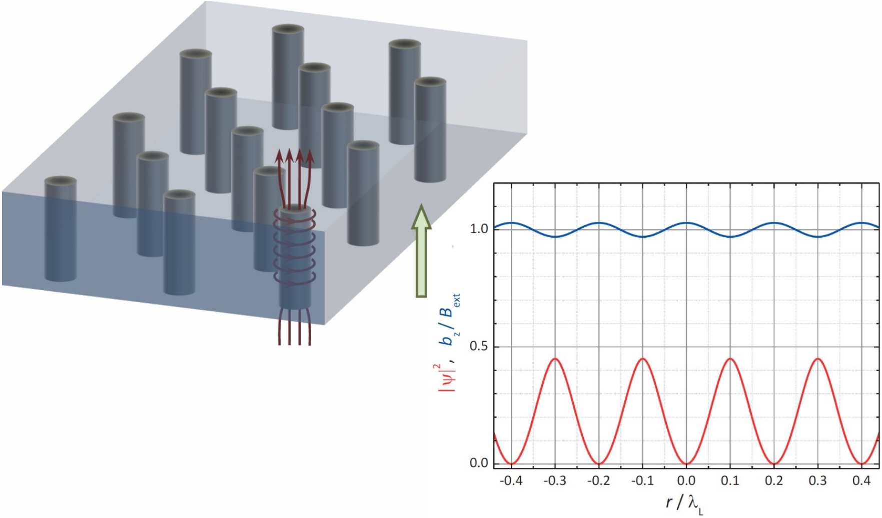
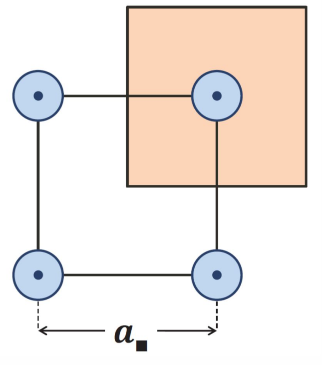
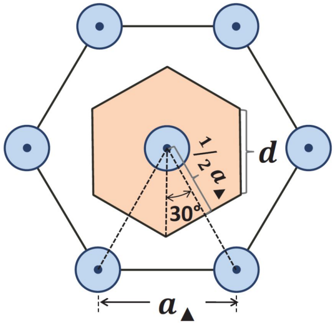


Image credit: Gross and Marx, Festkörperphysik

Types of the vortex lattice



square lattice

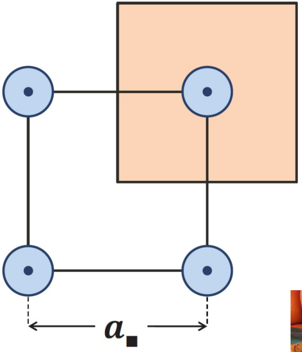


triangular lattice

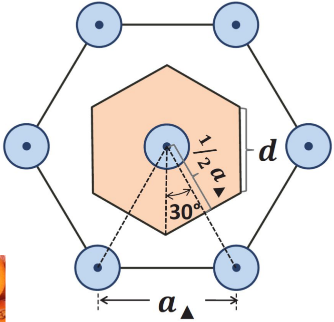
Image credits:

Gross and Marx, Festkörperphysik

Types of the vortex lattice



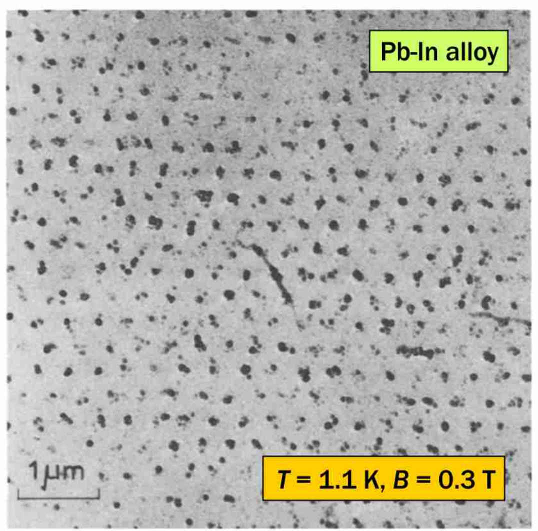
square lattice



triangular lattice

Image credits:
Rabe! (CC-BY-SA)
Gross and Marx, Festkörperphysik

Vortex lattice, triangular



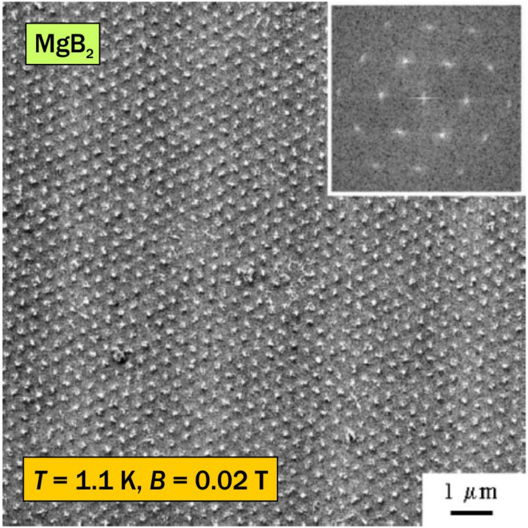
$\kappa = 1.35$ at 1.1 K

Triangular vortex lattice observed by electron microscopy

on a sample decorated with ferromagnetic particles

Phys. Lett. 24A, 526 (1967)

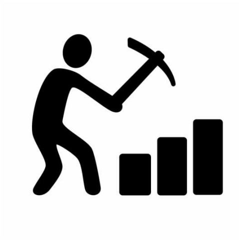
Vortex lattice, triangular



Fourier transform

Triangular vortex lattice observed by scanning tunneling microscopy on a decorated sample

Phys. Rev. B 67, 092512 (2003)



Experiment

small-angle neutron scattering

Scattering experiment

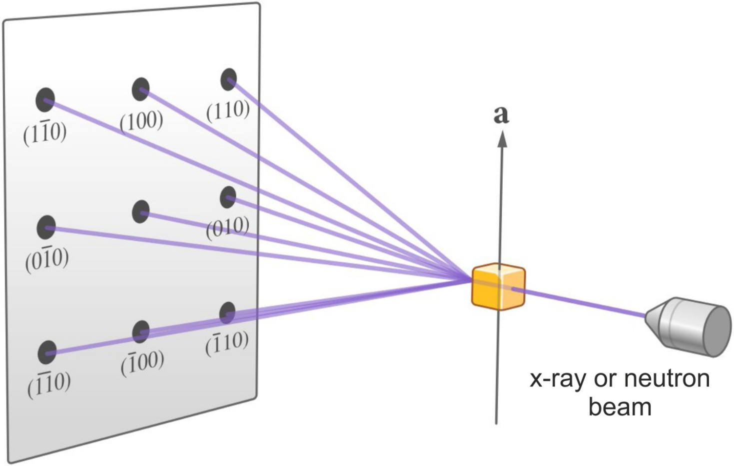


Image credit: LibreTexts Chemistry (CC-BY-SA)

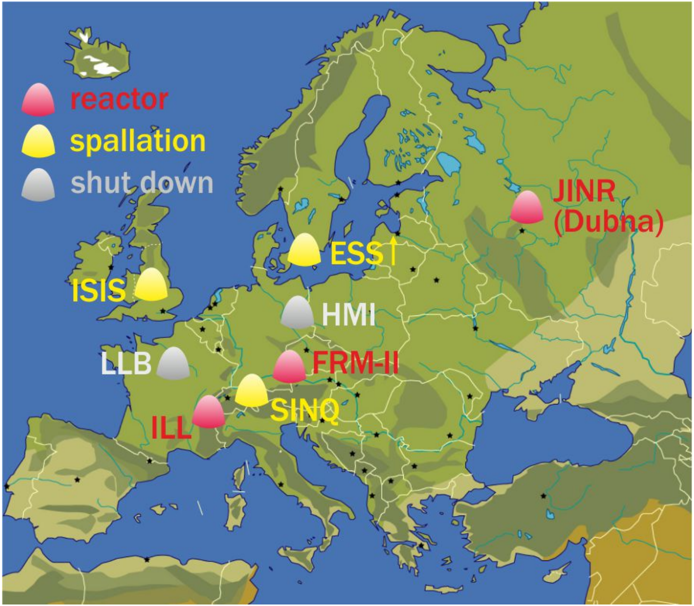
Neutron sources

- **Nuclear reactor:**
  stable and robust neutron source,
  but requires huge infrastructure
  + environmental concerns

- **Spallation source:**
  neutrons may arrive in pulses
  less stable in general,
  but more environment-friendly,
  and higher flux can be achieved

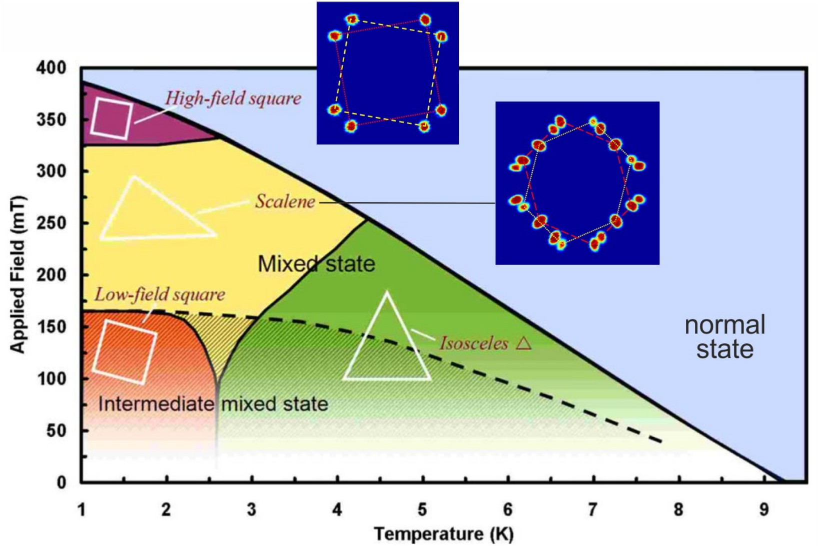
Image credits: Andreas Battenberg / TUM (fair use) and U.S. Department of Energy (public domain)

Neutron sources in Europe



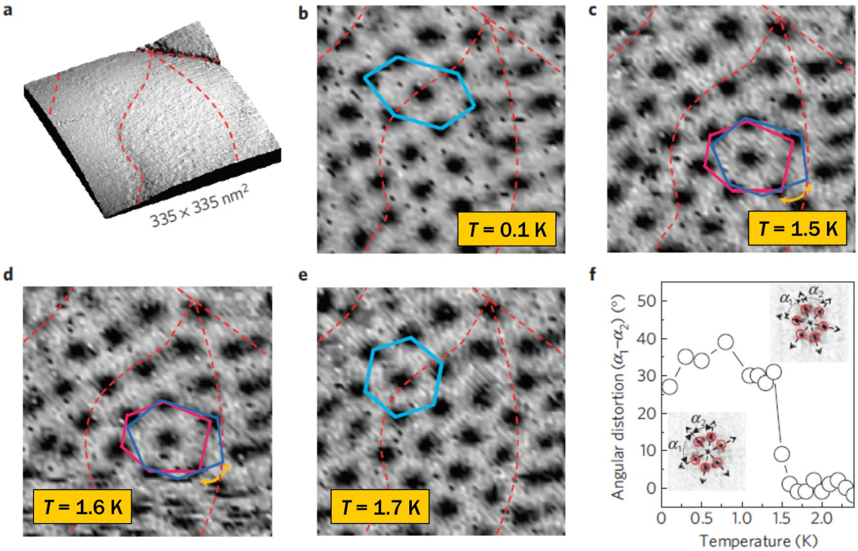
Map source: Johomaps

Vortex lattice of niobium metal



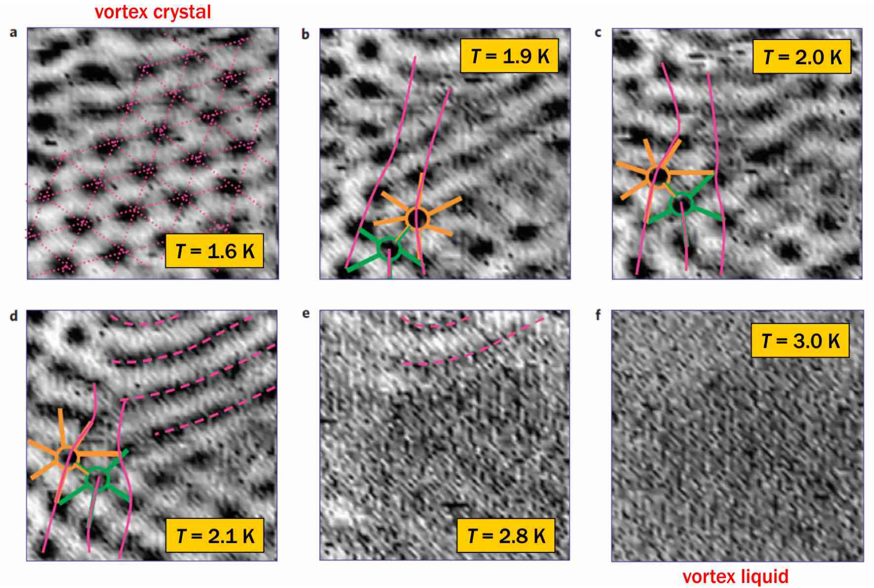
Phys. Rev. B 79, 014518 (2009)

Zoo of vortex states



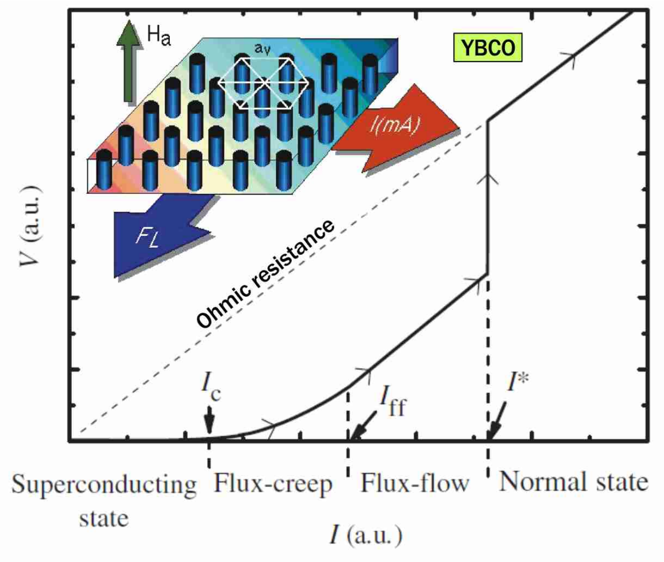
STS measurements on an amorphous W film, $B = 1\,\mathrm{T}$: I. Guillamón *et al.* Nature Phys. 5, 651 (2009)

Zoo of vortex states



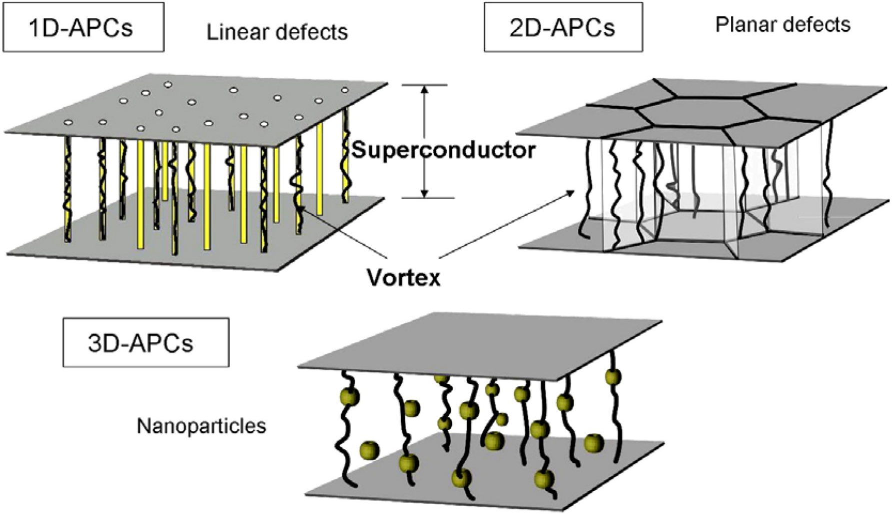
STS measurements on an amorphous W film, $B = 2\,\mathrm{T}$: I. Guillamón *et al.* Nature Phys. 5, 651 (2009)

Resistive behavior of a superconductor



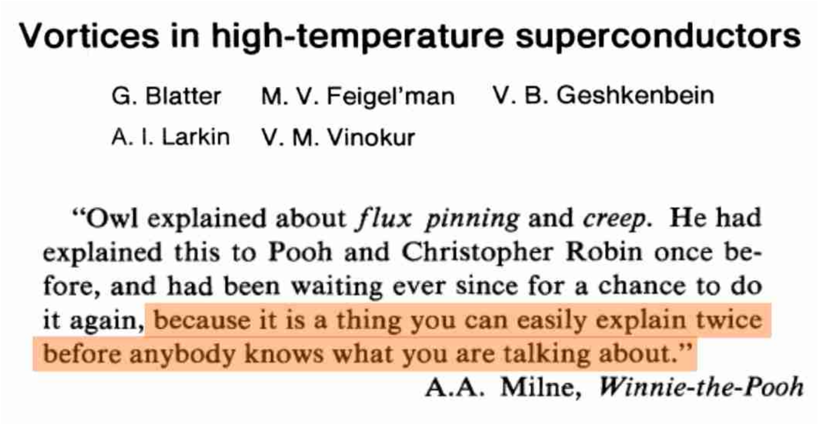
Eur. Phys. J. B 33, 757 (2012)

Flux line pinning



Supercond. Sci. Technol. 23 014001 (2010)

Zoology of vortex states



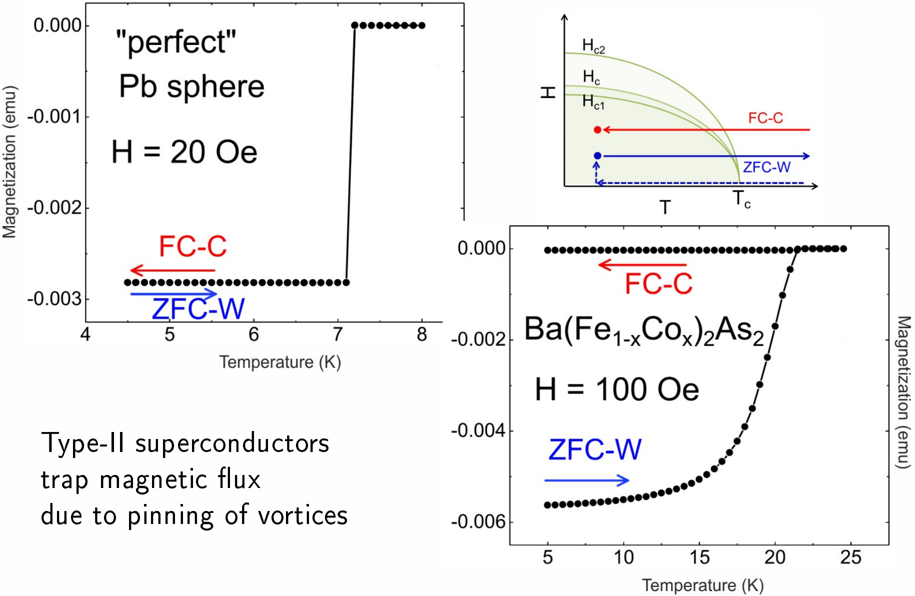
Vortices in high-temperature superconductors

G. Blatter M. V. Feigel'man V. B. Geshkenbein
A. I. Larkin V. M. Vinokur

> "Owl explained about *flux pinning* and *creep*. He had explained this to Pooh and Christopher Robin once before, and had been waiting ever since for a chance to do it again, because it is a thing you can easily explain twice before anybody knows what you are talking about."
>
> A.A. Milne, *Winnie-the-Pooh*

Rev. Mod. Phys. 66, 1125 (1994)

Flux trapping



Type-II superconductors
trap magnetic flux
due to pinning of vortices

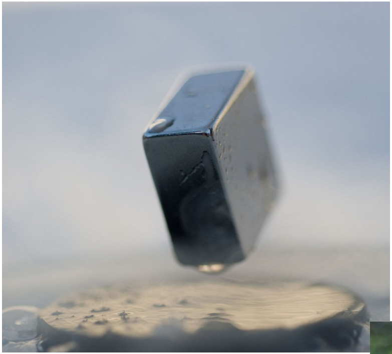
New J. Phys. 20, 043010 (2018)

Quantum locking

magnet **levitates** above the fixed superconductor

Image credit: J. Bobroff (CC-BY-SA)

Quantum locking



magnet **levitates**
above the fixed
superconductor

superconductor remains **locked**
under the fixed magnet

Image credit: J. Bobroff (CC-BY-SA)
Colorado State University (fair use)

Material / Technology

superconducting cables and magnets

Superconducting cables

Image credit: Rama (CC-BY-SA)

Superconducting cables

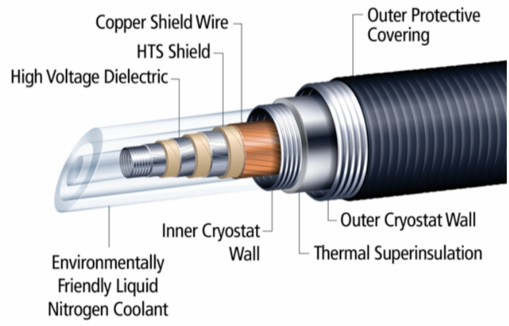
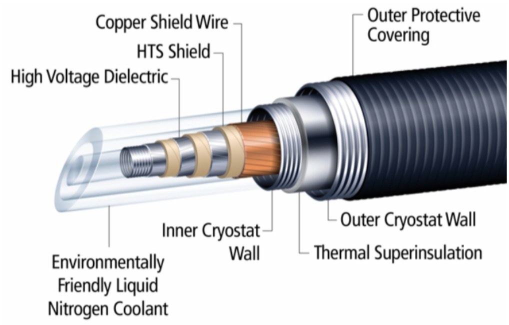


Image credit: Nexans (fair use) and SEI Technical Review 76, 45 (2013)

Superconducting cables



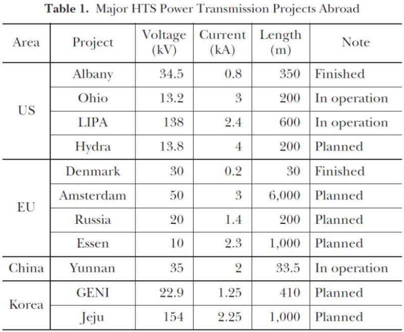


Table 1. Major HTS Power Transmission Projects Abroad

Area	Project	Voltage (kV)	Current (kA)	Length (m)	Note
US	Albany	34.5	0.8	350	Finished
	Ohio	13.2	3	200	In operation
	LIPA	138	2.4	600	In operation
	Hydra	13.8	4	200	Planned
EU	Denmark	30	0.2	30	Finished
	Amsterdam	50	3	6,000	Planned
	Russia	20	1.4	200	Planned
	Essen	10	2.3	1,000	Planned
China	Yunnan	35	2	33.5	In operation
Korea	GENI	22.9	1.25	410	Planned
	Jeju	154	2.25	1,000	Planned

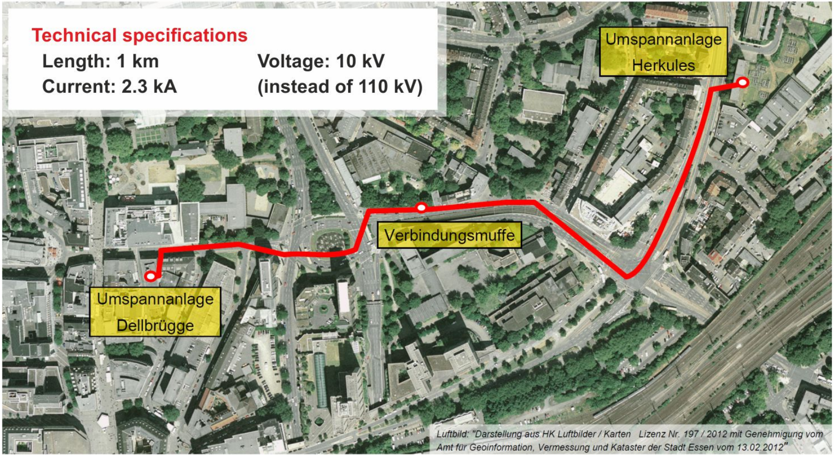
- **1975-85, Brookhaven cable:** 115 m, Nb_3Sn, He cooling
- **2004, Super-ACE cable (Japan):** 500 m, BSCCO (cuprate), nitrogen cooling
- **2008, LIPA I (US, Long Island):** 600 m, BSCCO (cuprate), nitrogen cooling

Image credit: Nexans (fair use) and SEI Technical Review 76, 45 (2013)

Test installation

City of Essen
commissioned in 2014

AMPACITY
Intelligente Netze für die Stadt



Technical specifications

Length: 1 km
Current: 2.3 kA
Voltage: 10 kV
(instead of 110 kV)

Luftbild: "Darstellung aus HK Luftbilder / Karten Lizenz Nr. 197 / 2012 mit Genehmigung vom Amt für Geoinformation, Vermessung und Kataster der Stadt Essen vom 13.02.2012"

Image credit: RWE Deutschland; IEEE Xplore 16, 13733637 (2013)

First commercial cable

amsc

American Superconductors

We don't generate energy
We keep it moving

Nexans

Electrify the future

Images from ACMS and Nexans (fair use)

First commercial cable

American Superconductors

We don't generate energy
We keep it moving

Electrify the future

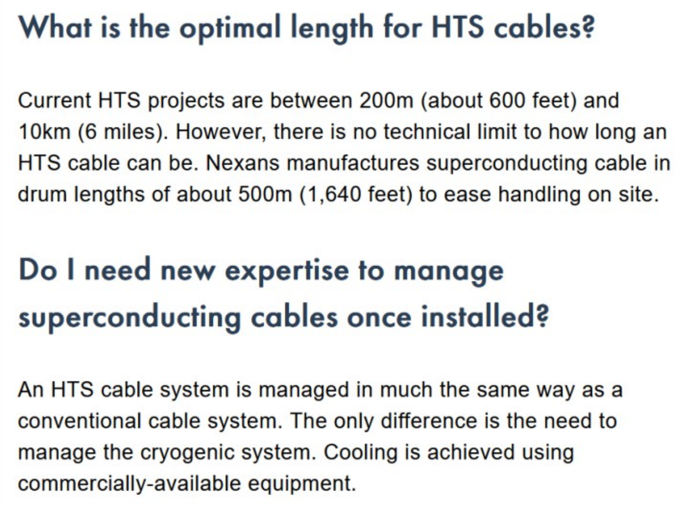
Average thickness:	0.17 mm - 0.21 mm
Minimum width:	4.70 mm
Maximum width:	4.95 mm

Amperium® wire

at least 109 A/mm^2

Images from ACMS and Nexans (fair use)

First commercial cable



What is the optimal length for HTS cables?

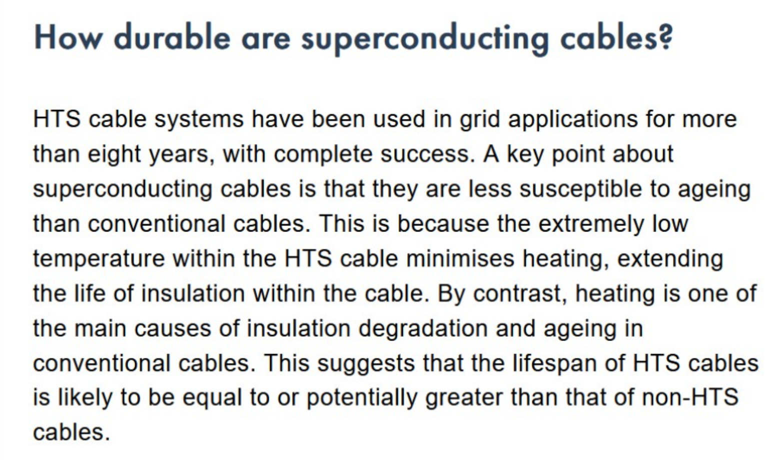
Current HTS projects are between 200m (about 600 feet) and 10km (6 miles). However, there is no technical limit to how long an HTS cable can be. Nexans manufactures superconducting cable in drum lengths of about 500m (1,640 feet) to ease handling on site.

Do I need new expertise to manage superconducting cables once installed?

An HTS cable system is managed in much the same way as a conventional cable system. The only difference is the need to manage the cryogenic system. Cooling is achieved using commercially-available equipment.

Source: ACMS

First commercial cable



How durable are superconducting cables?

HTS cable systems have been used in grid applications for more than eight years, with complete success. A key point about superconducting cables is that they are less susceptible to ageing than conventional cables. This is because the extremely low temperature within the HTS cable minimises heating, extending the life of insulation within the cable. By contrast, heating is one of the main causes of insulation degradation and ageing in conventional cables. This suggests that the lifespan of HTS cables is likely to be equal to or potentially greater than that of non-HTS cables.

Source: ACMS

Recent projects

2021: Resilient Electric Grid (REG) system in Chicago

200 m, 12 kV, 3 kA

Image credits: a4gpa (CC-BY-SA)

Recent projects

2021: Resilient Electric Grid
(REG) system in Chicago

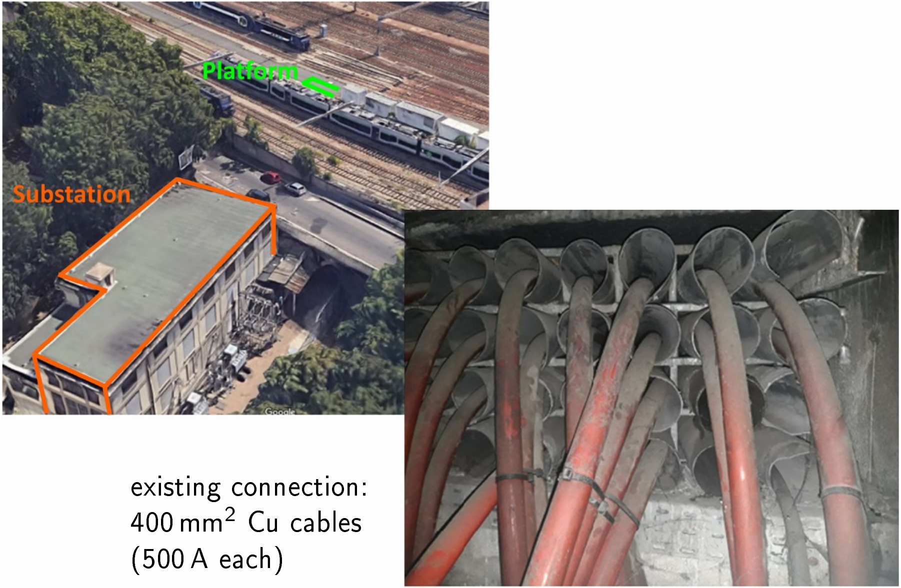
200 m, 12 kV, 3 kA

ongoing: SuperRail
power supply
at Paris-Montparnasse train station

$2 \times 80\,m$, *1.5 kV, up to 3.5 kA*

Image credits: a4gpa Cheng-en Cheng (CC-BY-SA)

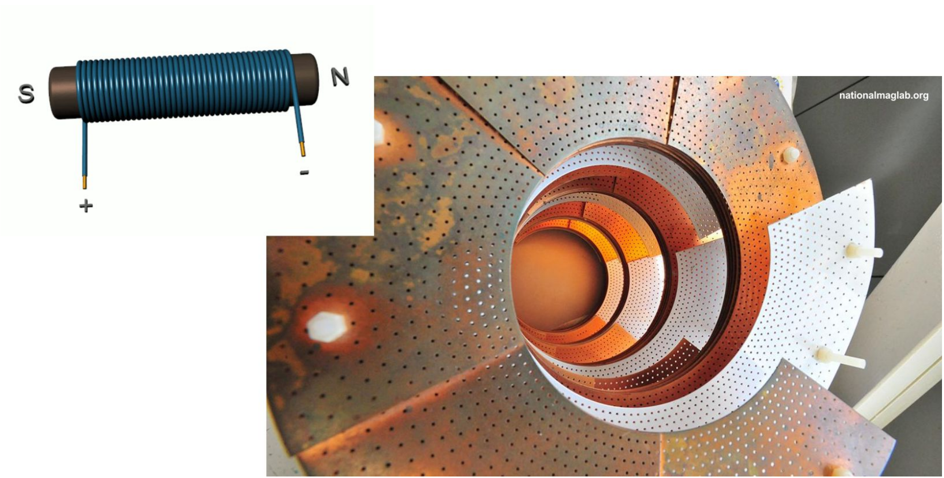
Recent projects: SuperRail



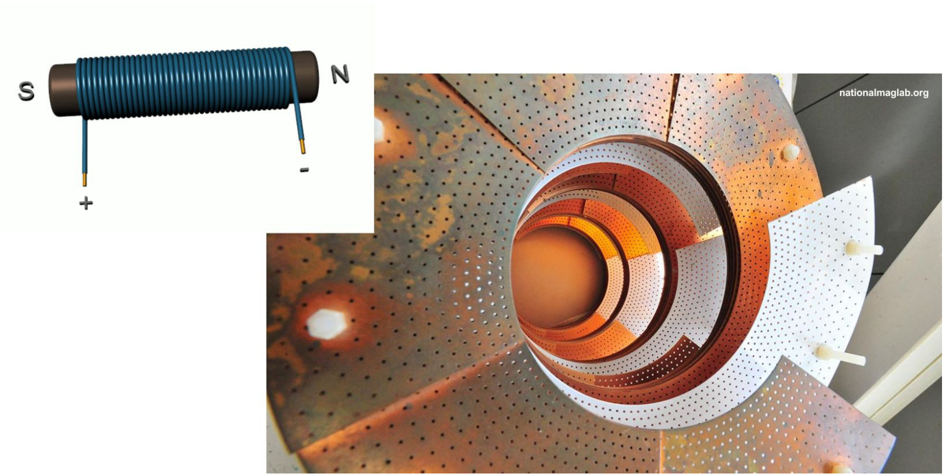
existing connection:
400 mm^2 Cu cables
(500 A each)

IEEE Trans. Appl. Supercond. 34, 4802207 (2024)

Electromagnets (resistive magnets)



Electromagnets (resistive magnets)



Cooling is the main problem; present-day limit – about 35 T
with the power consumption of about 30 MW

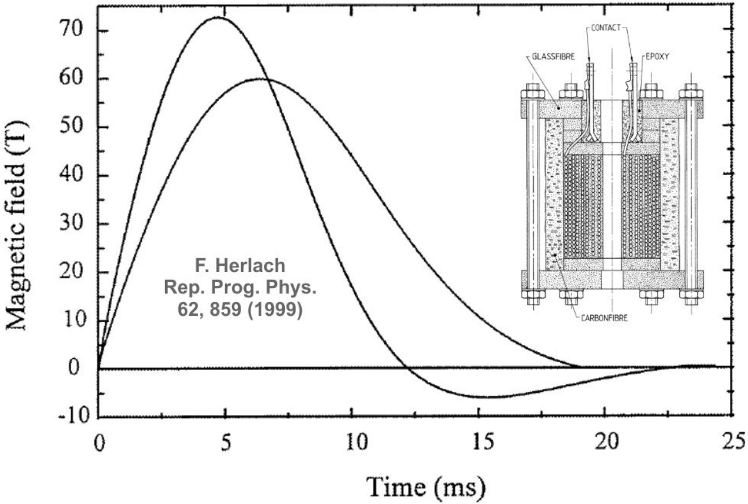
Superconducting magnets

Zero resistivity, hence no need for cooling.

Field range is limited by the critical field of the superconductor, and by the **critical current** determined by pinning

Commercial magnets: up to 22 T, prototypes: up to 32 T

Pulsed magnets



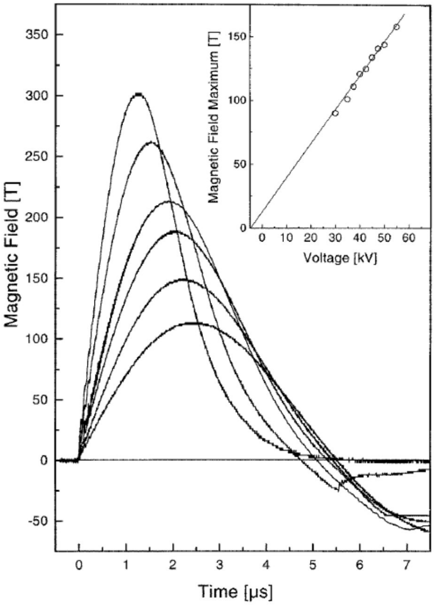
F. Herlach
Rep. Prog. Phys.
62, 859 (1999)

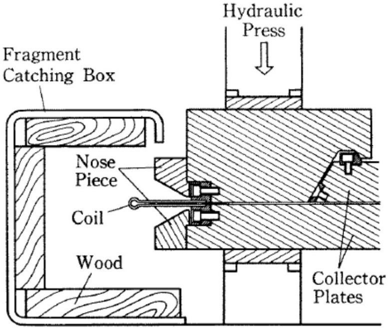
Fields up to 90 – 100 T routinely available, longer pulses possible too

European high-field network (EMFL)

Image source: mgml.eu

Single-coil magnets

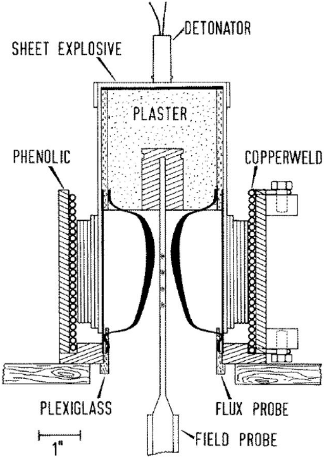


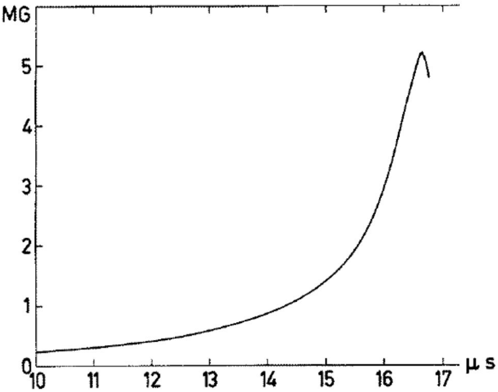


Fields up to **300 T** available

Rep. Prog. Phys. 62, 859 (1999)

Explosion magnets

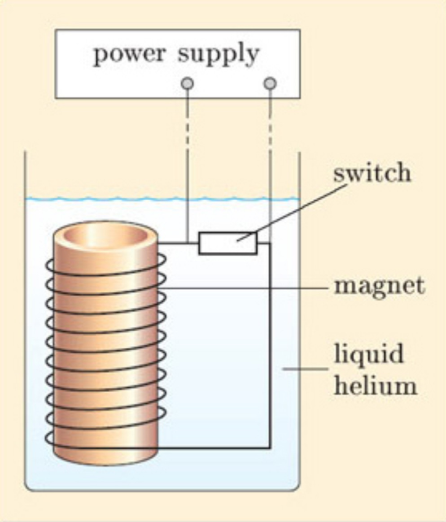




Fields above 1000 T recorded
No real use for condensed-matter experiments (yet?)

Supercond. Sci. Technol. 19, R41 (2006)

Superconducting magnet

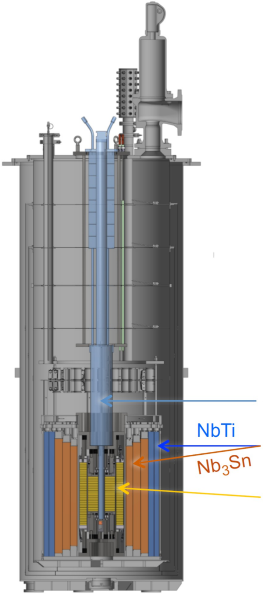


Switch in the normal state:
magnet charging

Switch in the SC state:
persistent mode
(current circulates in the loop)

Image credit: The Open University

32 T superconducting magnet



sample environment

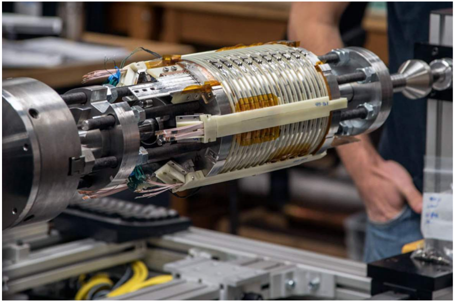
NbTi

15 T field in total

Nb_3Sn

high-T_c (REBCO) superconductor

another 17 T



Mass: 2.3 ton

Current: 170 A/mm^2 (high-T_c coil)

Stored energy: 8.6 MJ

Image credit: MagLab

Quench

Exceeding B_{c2} or j_c leads to a violent release of heat

Magnet can be damaged

Image credit: MagLab

Quench

Exceeding B_{c2} or j_c leads to a violent release of heat

Magnet can be damaged

DO NOT QUENCH SUPERCONDUCTING MAGNETS!

Image credit: MagLab