Superconductors and Superconducting Magnets

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Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting materials and cables
- The making of a superconducting magnet
- Examples of superconducting magnet systems

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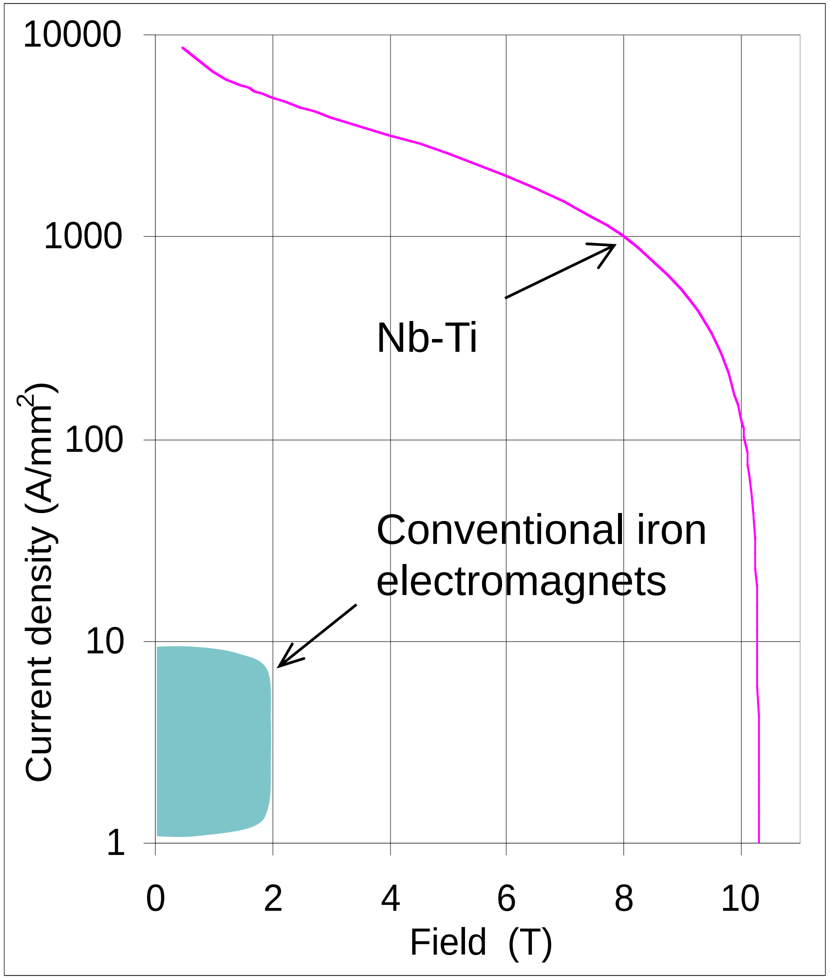
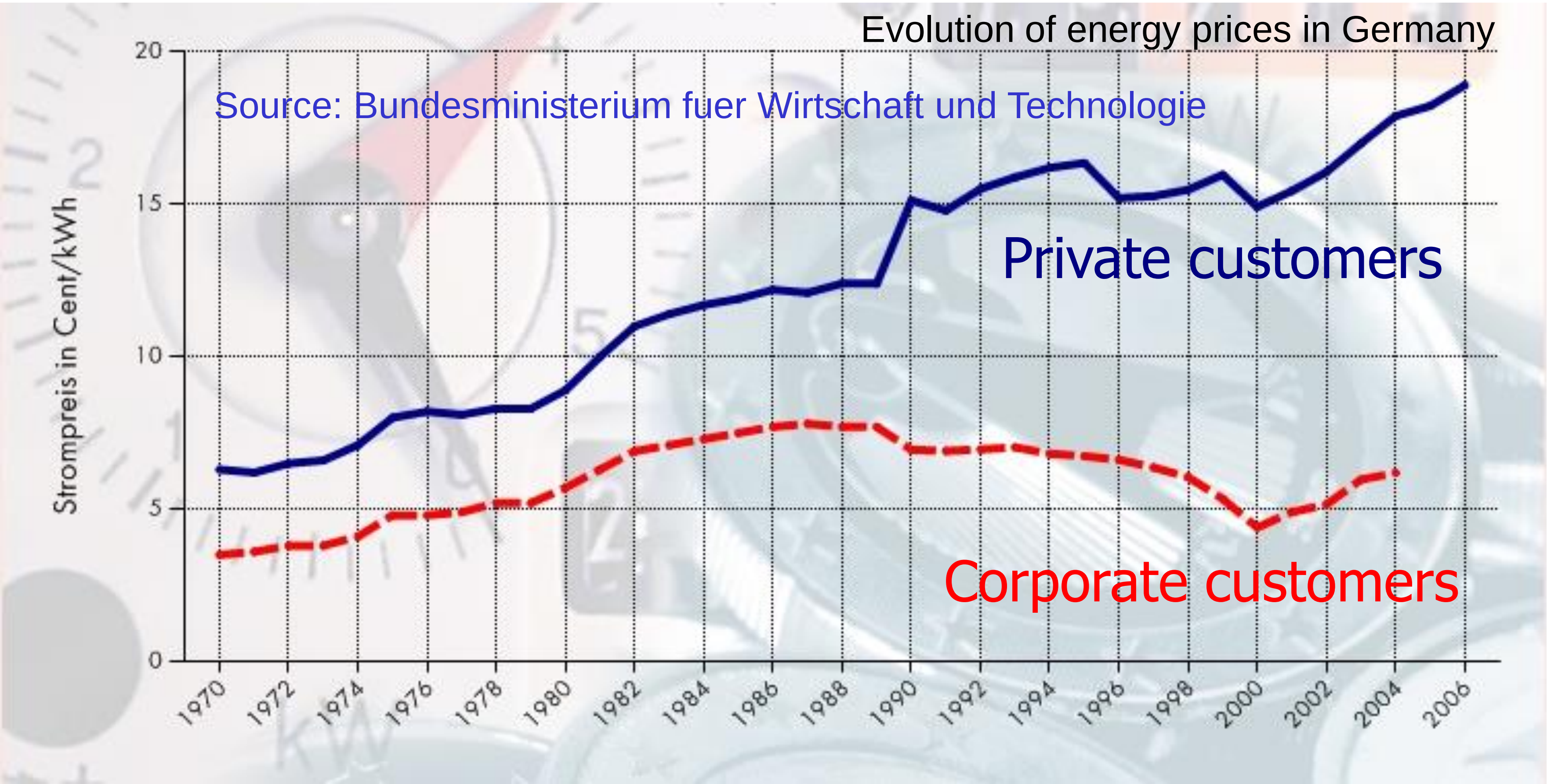
Why superconductivity anyhow ?

- **Abolish Ohm's law !**
  - no power consumption (although need refrigeration power)
  - high current density
  - ampere turns are cheap, so don't need iron (although often use it for shielding)
- Consequences
  - lower running cost ⇒ new commercial possibilities
  - energy savings
  - high current density ⇒ smaller, lighter, cheaper magnets ⇒ reduced capital cost
  - higher magnetic fields economically feasible ⇒ new research possibilities



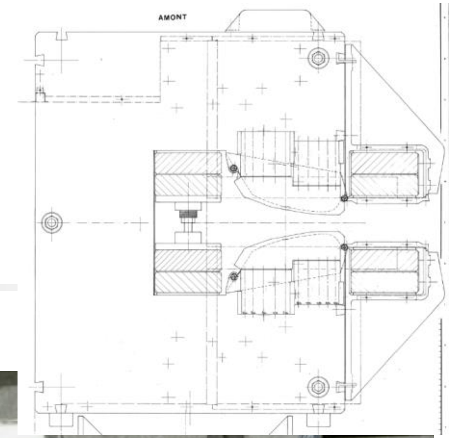
Cost of energy (electricity)

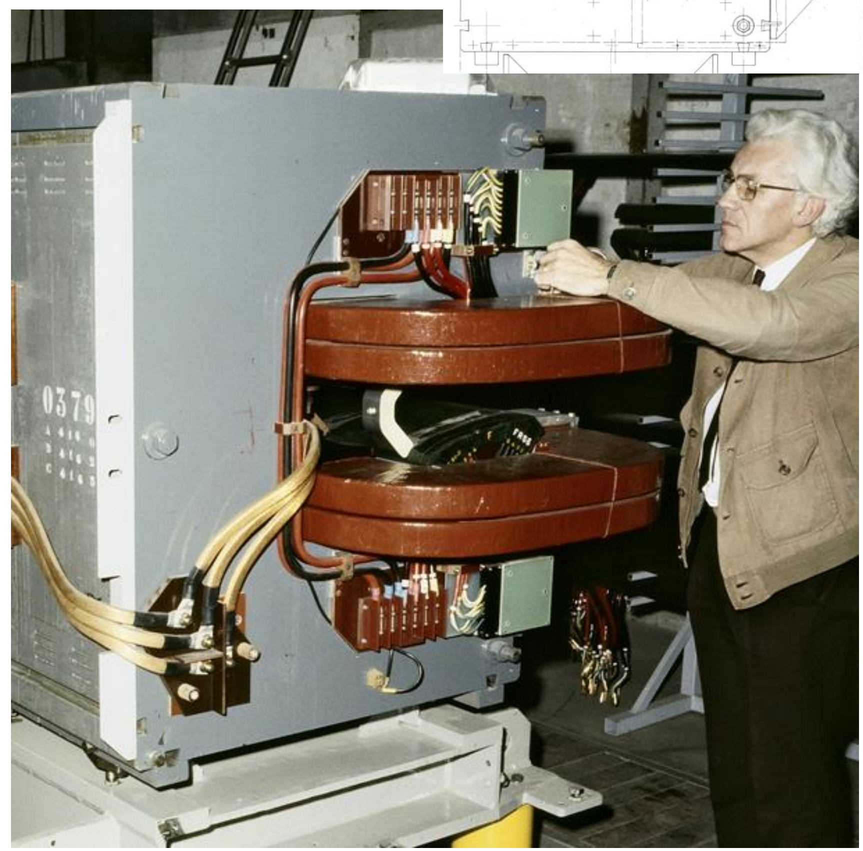


Energy efficiency is an inevitable design constraint !

NC vs. SC Magnets - 1/2

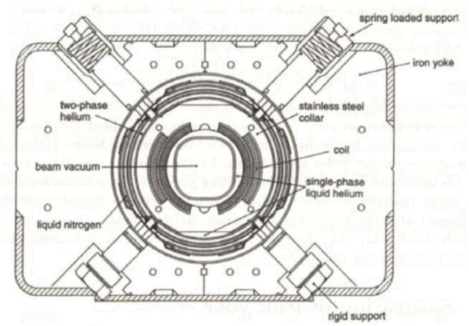
- *Normal conducting* accelerator magnets
  - Magnetization *ampere-turns* are *cheap*
  - Field is generated by the iron yoke (but limited by saturation, e.g. ≈ 2 T for iron)
  - Low current density in the coils to limit electric power and cooling needs
  - Bulky and heavy, large mass of iron (cost driver)



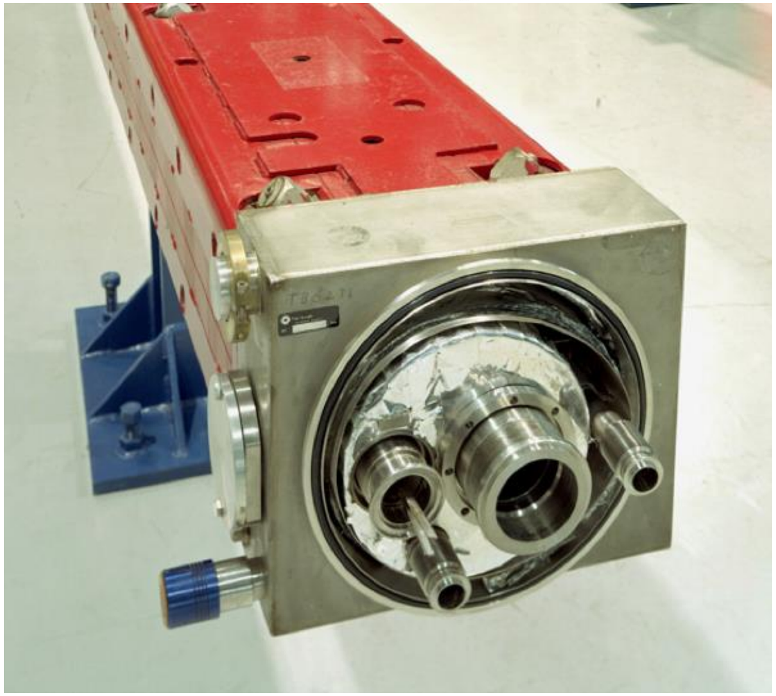


One of the dipole magnets of the PS, in operation at CERN since 1959

NC vs. SC Magnets - 2/2



- Superconducting accelerator magnets
  - Superconducting *ampere-turns* are *cheap*
  - Field generated by the coil current (but limited by critical current, e.g. ≈ 10 T for NbTi)
  - High current density, compact, low mass of high-tech SC material (cost driver)
  - Requires efficient and reliable cryogenics cooling for operation (availability driver)

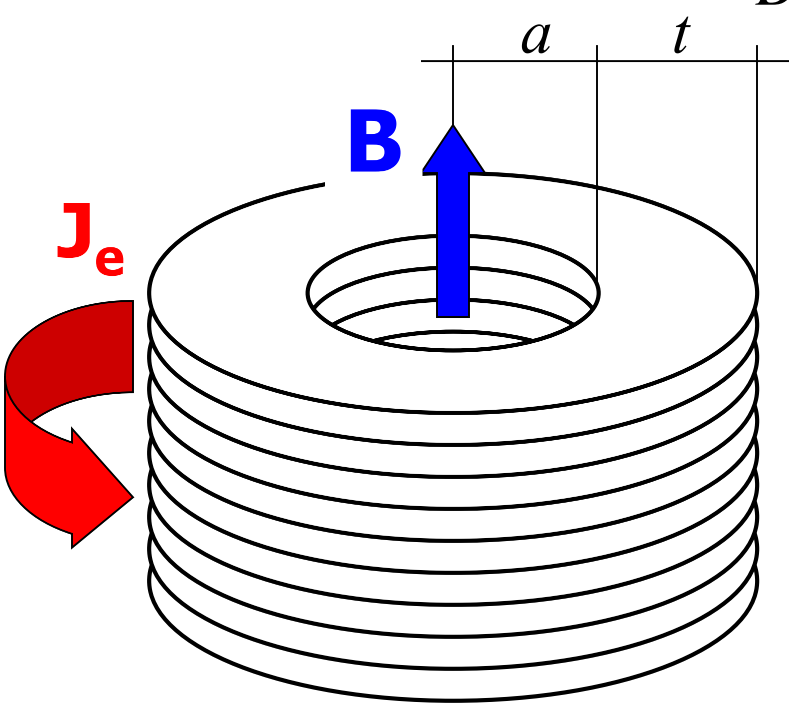


A superconducting dipole magnet of the Tevatron at FNAL, the first superconducting synchrotron, 1983

High current density: solenoids

- The field produced by an infinitely long solenoid is:

$$B = \mu_o J_e \, t$$



all-SC solenoid record field: 24 T (NIMS, 2011)

- In solenoids of finite length the central field is:

$$B = \mu_o f J_e \, t$$

where f < 1, typically ~ 0.8

- The thickness (volume and cost) for a given field is inversely proportional to the engineering current density J_e

Graphics by courtesy of M.N. Wilson

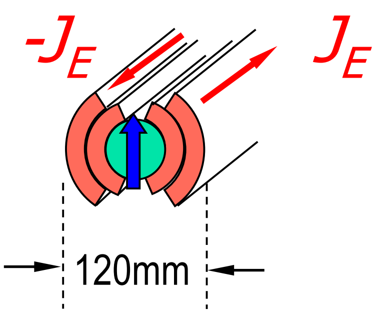
High current density - dipoles

- The field produced by an ideal dipole (see later) is:

$$B = \mu_o J_e \frac{t}{2}$$

J_E = 375 Amm^{-2}

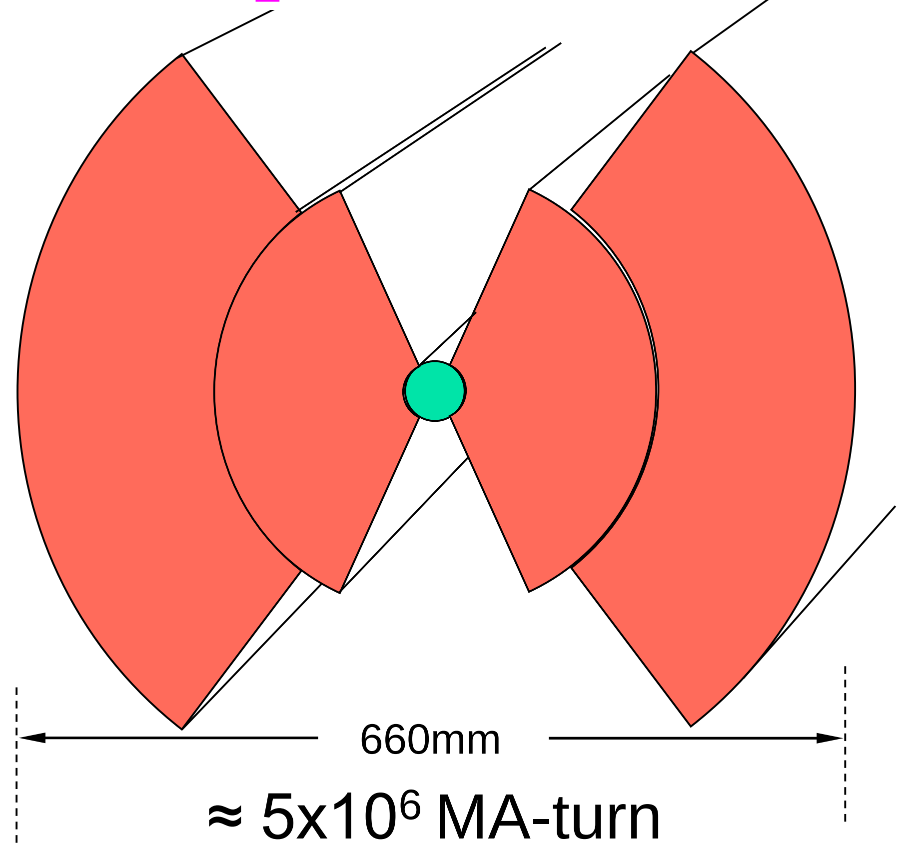
LHC dipole



≈ $1x10^6$ MA-turn

all-SC dipole record field:
16 T (LBNL, 2003)

J_E = 37.5 Amm^{-2}



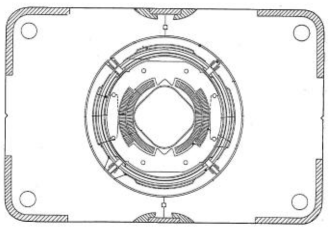
≈ $5x10^6$ MA-turn
≈ 6 MW/m

The *Hall of Fame* of SC colliders

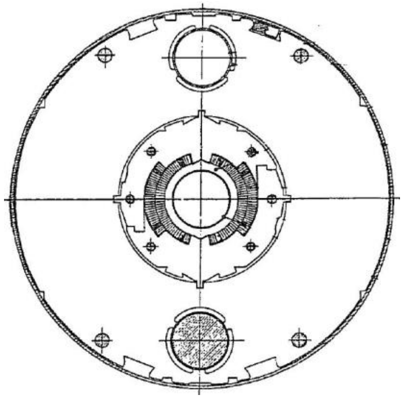
		Tevatron	HERA	RHIC	LHC
Maximum energy	(GeV)	980	920[1]	250[2] 100/n[3]	7000
Injection energy	(GeV)	151	45	12	450
Ring length	(km)	6.3	6.3	3.8	26.7
Dipole field	(T)	4.3	5.0	3.5	8.3
Aperture	(mm)	76	75	80	56
Configuration		Single bore	Single bore	Single bore	Twin bore
Operating temperature	(K)	4.2	4.5	4.3-4.6	1.9
First beam		7-1983	4-1991	6-2000	9-2008

(1) energy of the proton beam, colliding with the 27.5 GeV electron beam
(2) energy for proton beams
(3) energy per nucleon, for ion beams (Au)

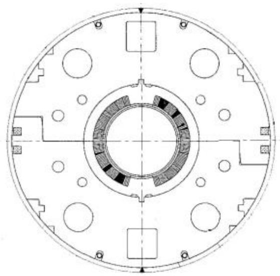
Champion dipoles cross sections



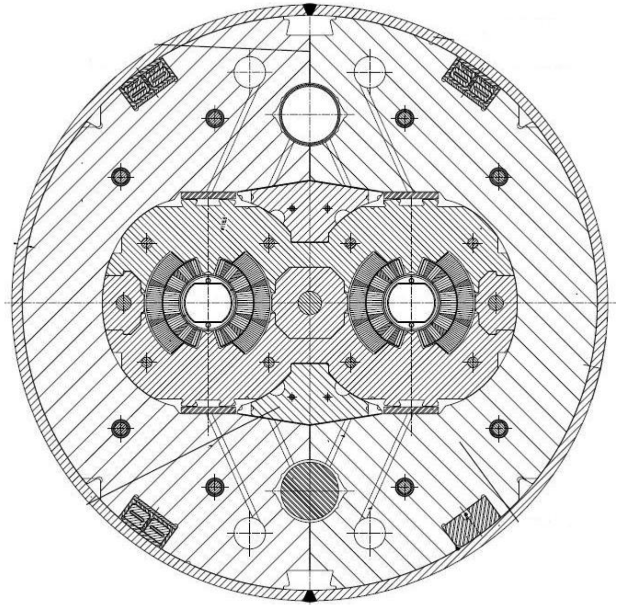
Tevatron
Bore: 76 mm
Field: 4.3 T



HERA
Bore: 75 mm
Field: 5.0 T

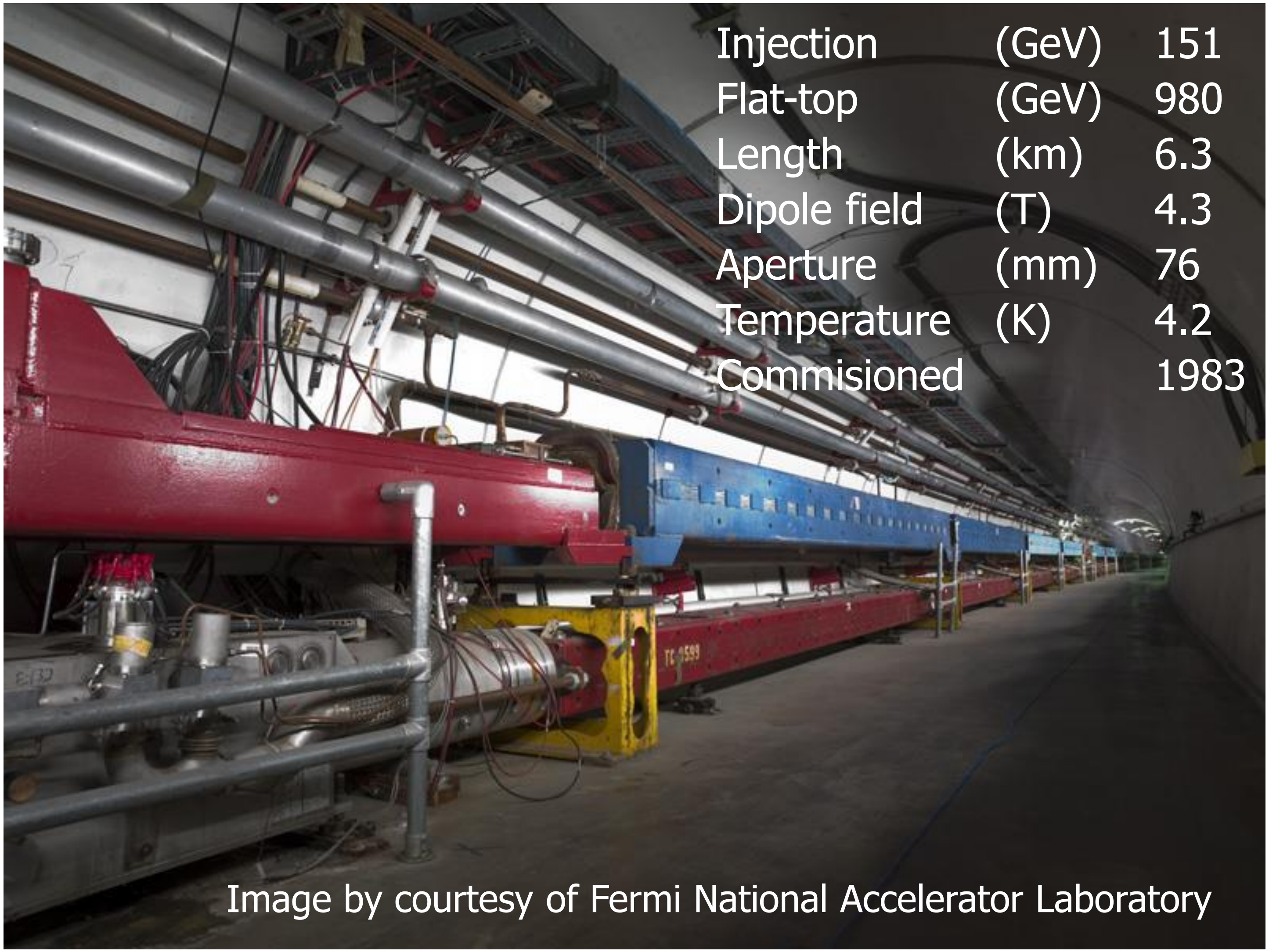


RHIC
Bore: 80 mm
Field: 3.5 T



LHC
Bore: 56 mm
Field: 8.3 T

Tevatron at FNAL (Chicago, IL, USA)



HERA at DESY (Hamburg, D)

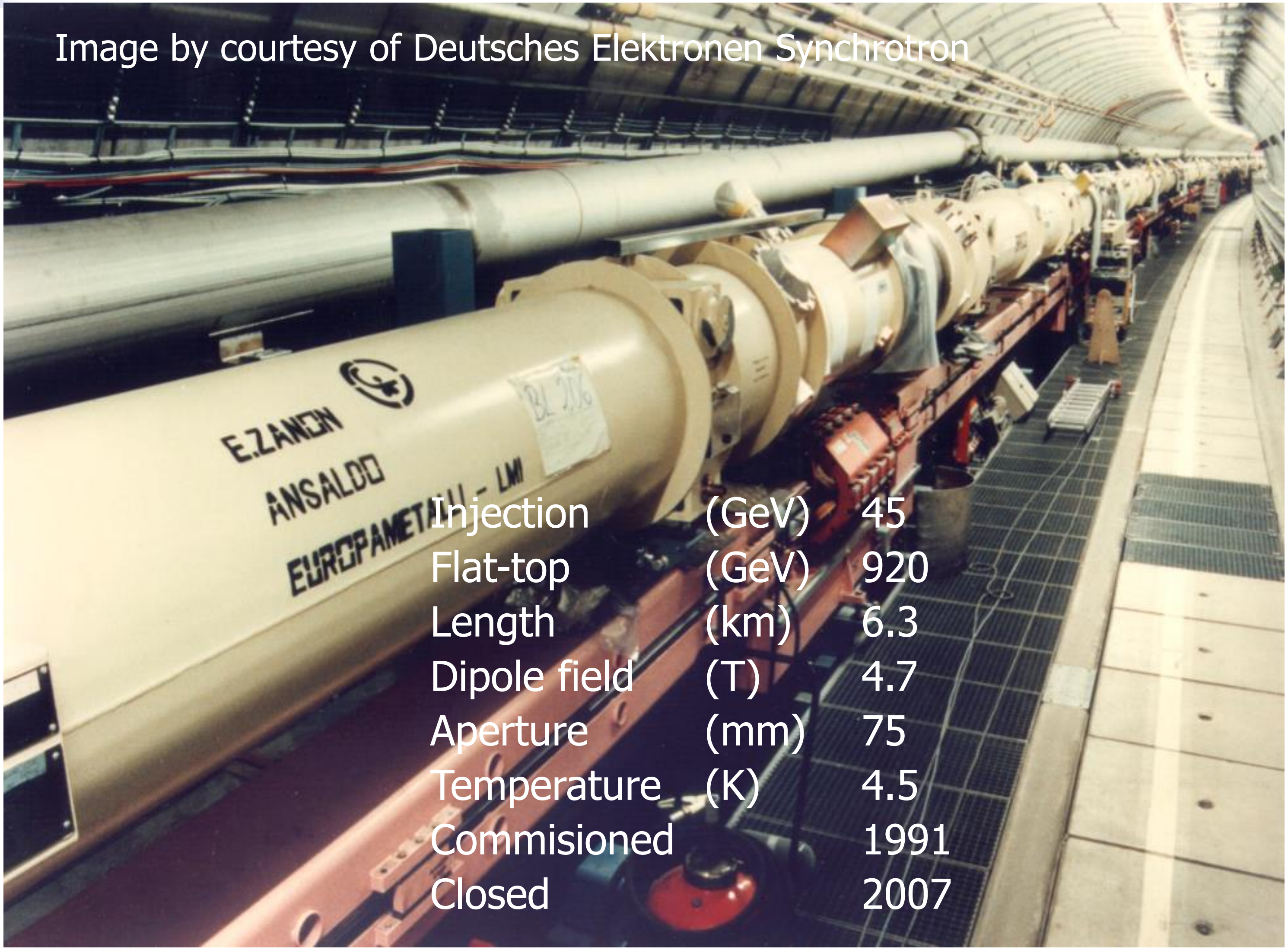


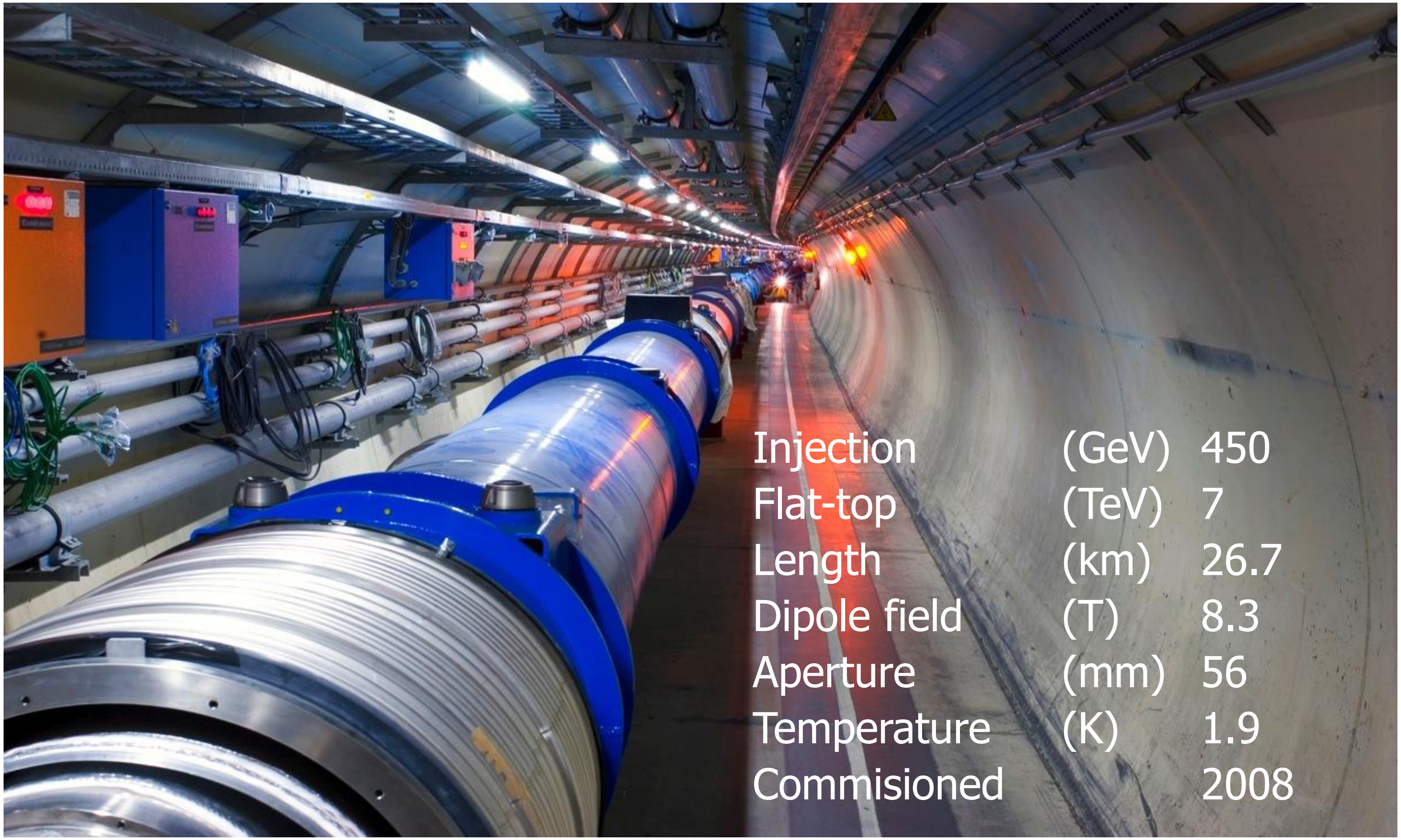
Image by courtesy of Deutsches Elektronen Synchrotron

Injection	(GeV)	45
Flat-top	(GeV)	920
Length	(km)	6.3
Dipole field	(T)	4.7
Aperture	(mm)	75
Temperature	(K)	4.5
Commisioned		1991
Closed		2007

RHIC at BNL (Upton, NY, USA)

Injection	(GeV)	12/n
Flat-top	(GeV)	100/n
Length	(km)	3.8
Dipole field	(T)	3.5
Aperture	(mm)	80
Temperature	(K)	4.3-4.6
Commisioned		2000

LHC at CERN (Geneva, CH)



Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

Motivation - Re-cap

- Superconductors are used to abolish Ohm's law, either to:
  - Decrease power consumption, and thus improve the performance and operation balance (cost + efficiency) replacing existing technology $\Rightarrow$ *technology displacer*
  - Allow to reach higher magnetic field, over larger bore and for longer time, allowing new physics or technological opportunities $\Rightarrow$ *technology enabler*

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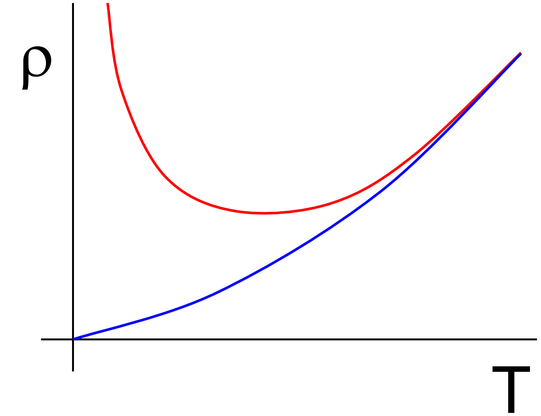
A great physics problem in 1900

- What is the limit of electrical resistivity at the absolute zero ?



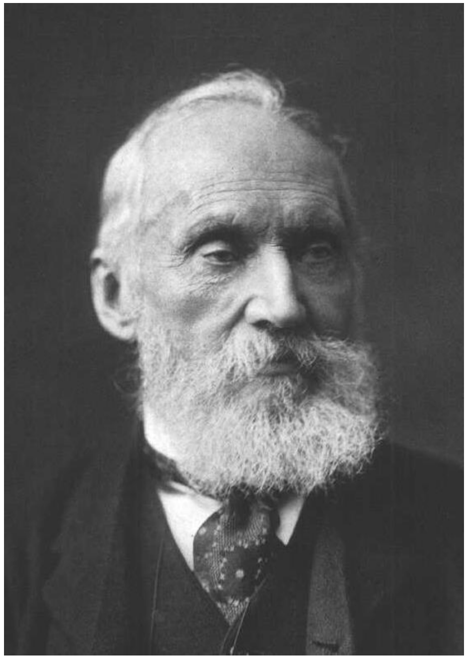
… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

"*X-rays are an hoax*"

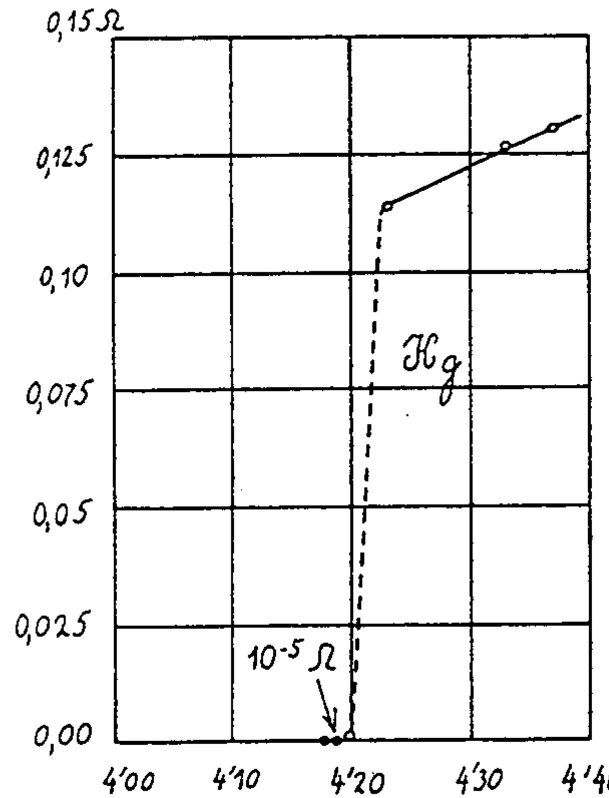
"*I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of*"

"*There is nothing new to be discovered in physics now. All that remains is more and more precise measurement*"

W. Thomson (Lord Kelvin)



Superconductors Pre-history



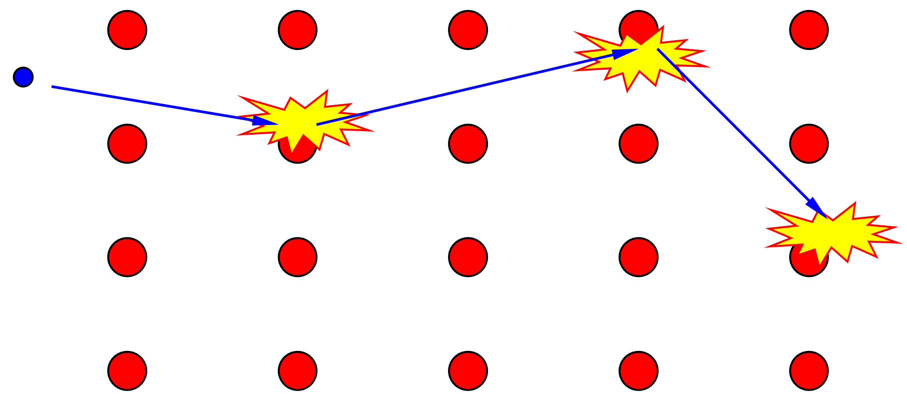
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)

Cooper Pairs

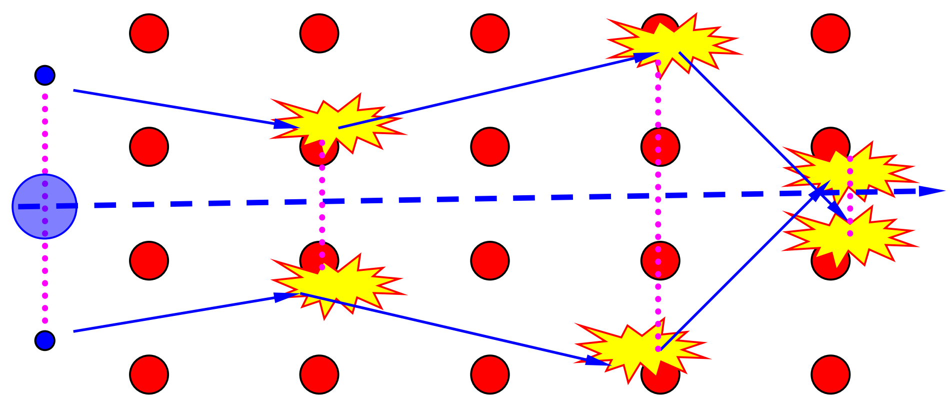
Bardeen, Cooper and Schrieffer

- Normal conductor
  - scattering of e^-
  - finite resistance due to energy dissipation



Proper physics: a gas of Fermions. The conduction electrons at the Fermi surface have large energy (few eV) and interact with lattice defects, displacements or thermal excitations (hence $\rho(T)$)

- Superconductor
  - paired electrons forming a quasi particle in *condensed* state
  - zero resistance because the scattering does not excite the quasi-particle



Proper physics: paired electrons in the vicinity of the Fermi surface, with opposite momentum and spin (bosons with zero spin). The binding energy introduces a small energy gap between paired and unpaired state. An external electric field makes the pair drift.

Pairing mechanism

Lattice displacement

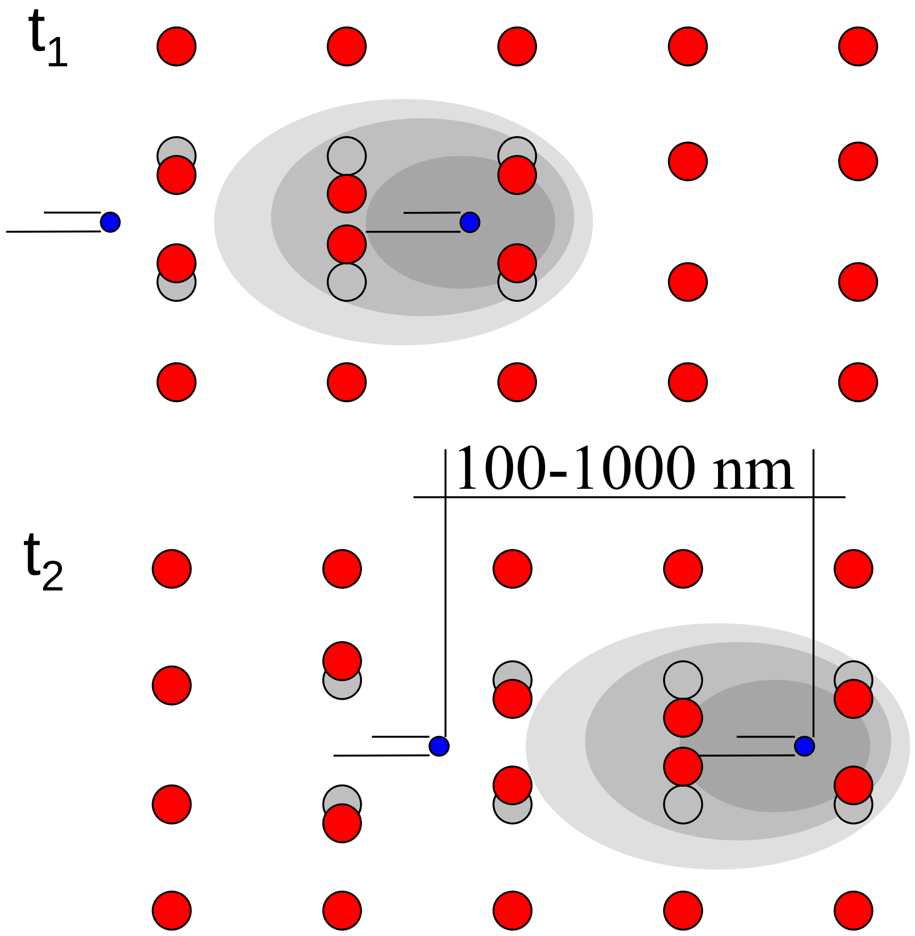
⇓

phonons (sound)

⇓

coupling of charge carriers

Only works at low temperature



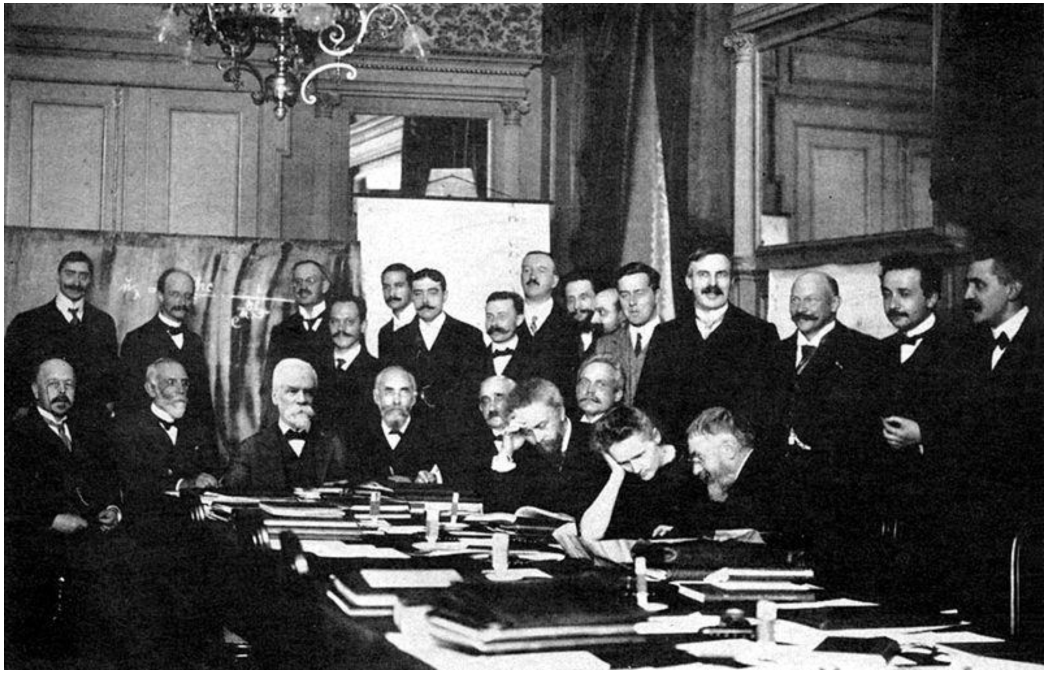
Bardeen, Cooper, Schrieffer (BCS) - 1957

Proper physics: the binding energy is small, of the order of 10^{-3} eV. Pairs can be broken easily by thermal energy. The interaction is long range, and Cooper pairs overlap and can exchange electrons

First (not last) superconducting magnet project cancelled

A 100 kGauss magnet ! (H. K. Onnes)

Third International Congress of Refrigeration, Chicago (1913)



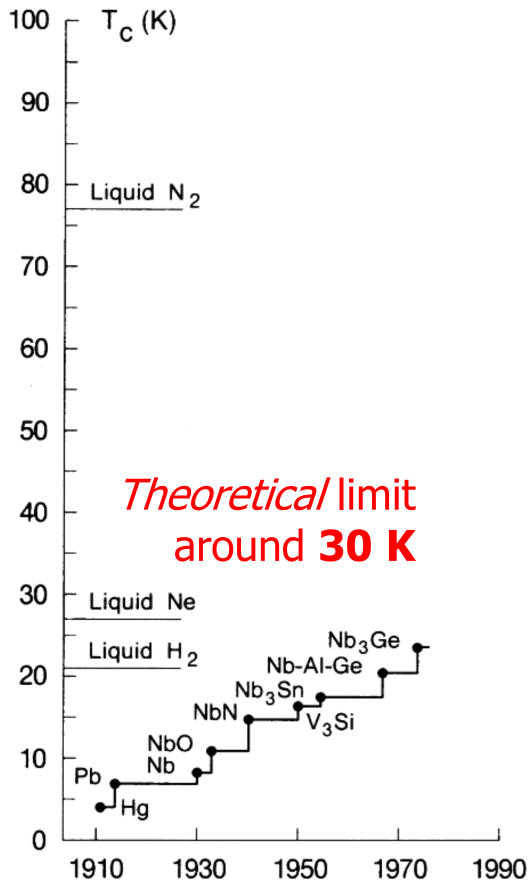
The 10 T magnet project was stopped when it was observed that superconductivity in Hg and Pb was destroyed by the presence of an external magnetic field as small as 500 Gauss (0.05 T)

Solvay conference (1914)

Superconductivity languished for 40 years…

1986 - A Big Surprise

One Thousand and One Superconductors
B. Matthias (1918-1980)

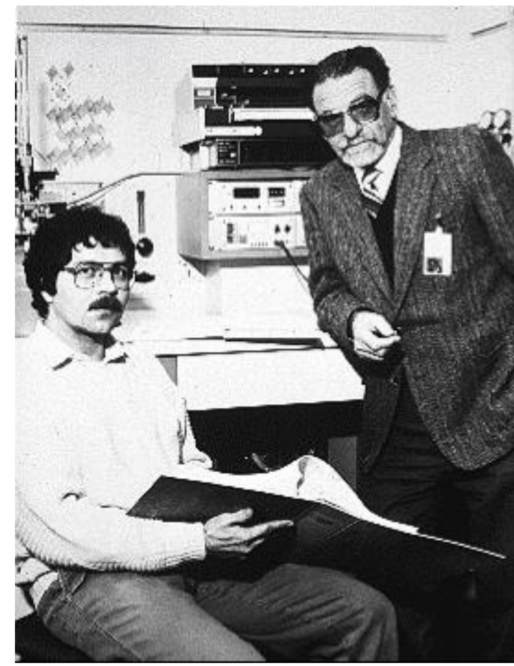


Theoretical limit around **30 K**

Fig. 1. Evolution of the superconductive transition temperature subsequent to the discovery of the phenomenon.

The Discovery of a Class of High-Temperature Superconductors

K. ALEX MÜLLER AND J. GEORG BEDNORZ



Bednorz and Mueller
IBM Zuerich, 1986

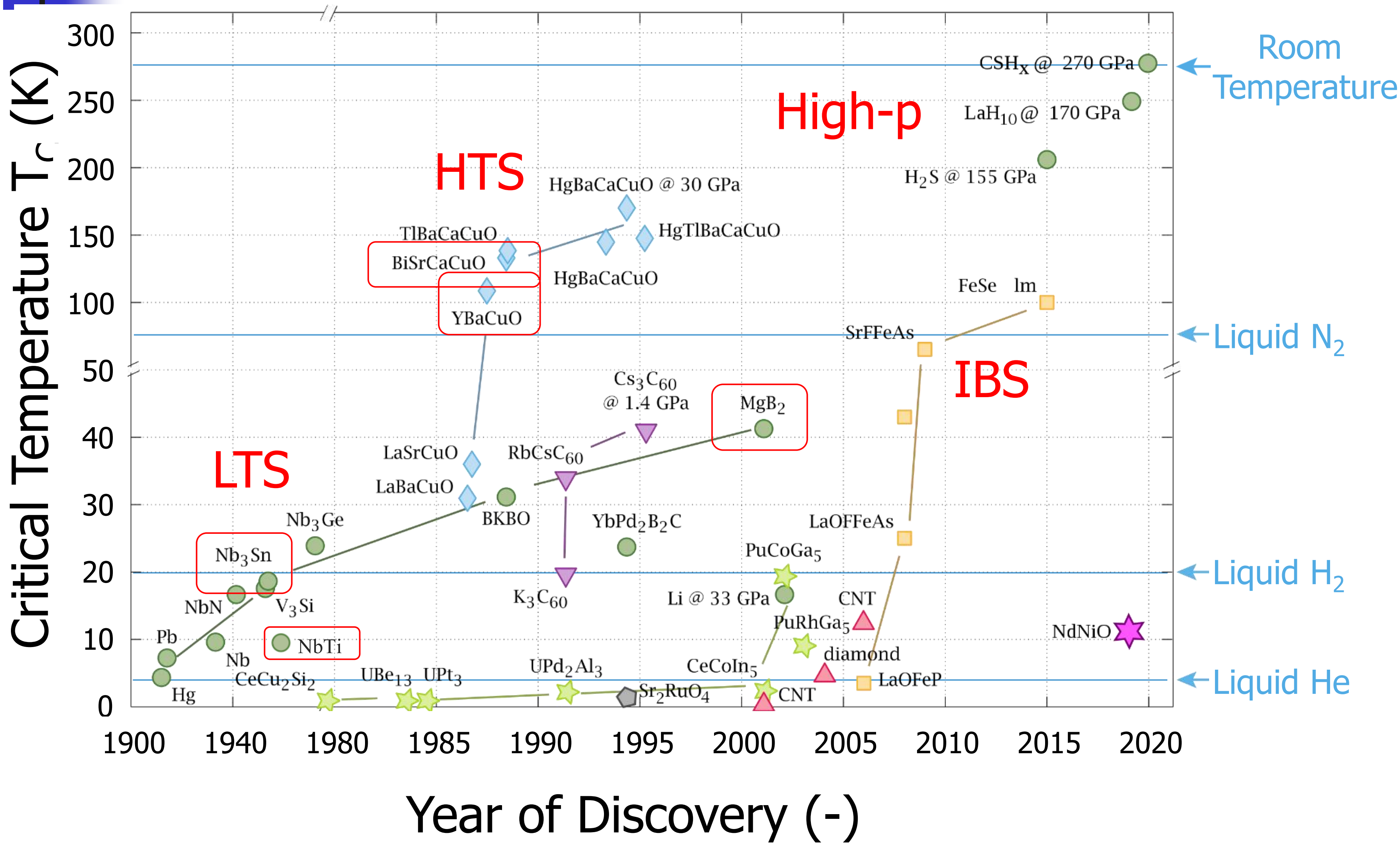
1987 - The prize !

Associated Press

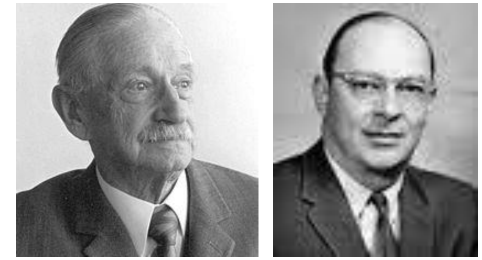
J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

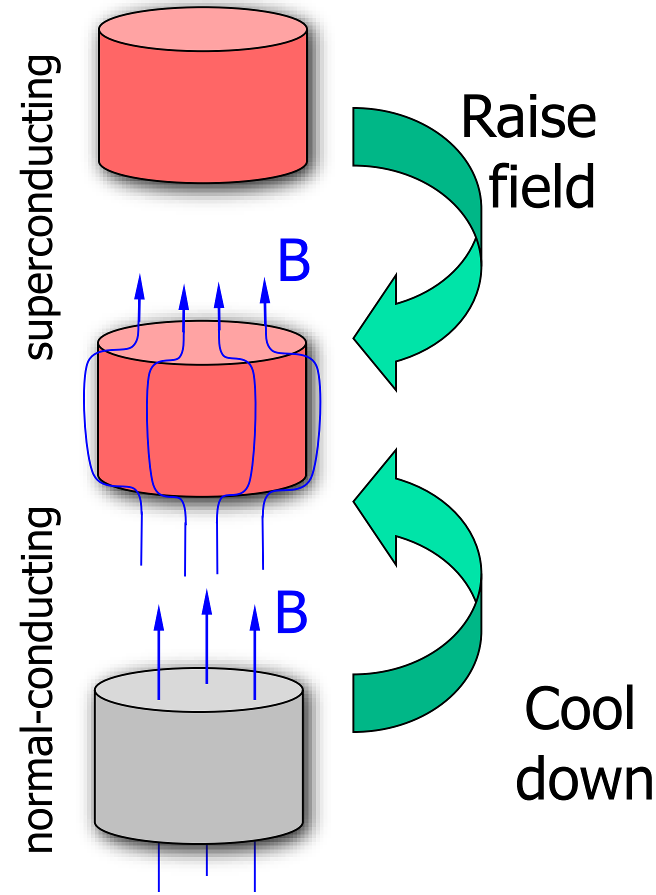
High-Tc timeline



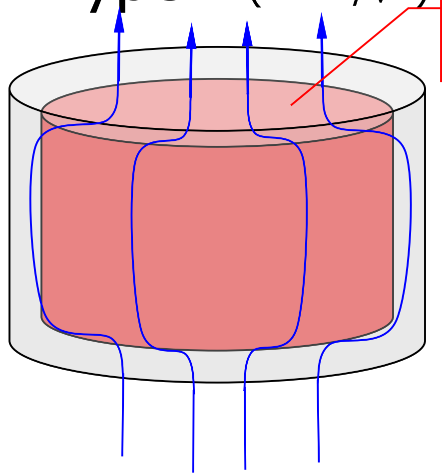
Hey, what about field ?



W. Meissner, R. Ochsenfeld



Type I ($\kappa < 1/\sqrt{2}$)



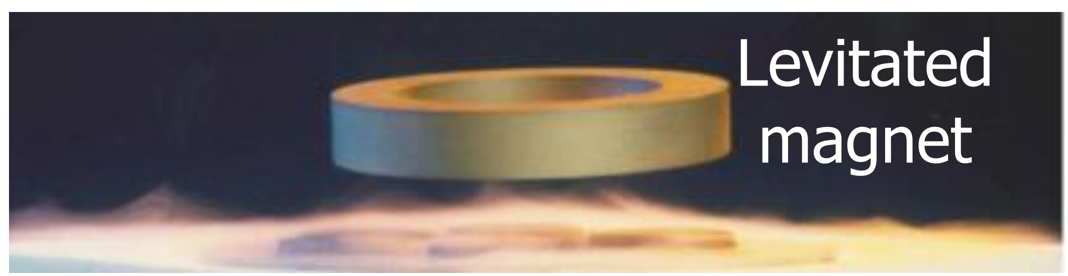
Complete field exclusion

Pure metals

$B_C \approx 10^{-3} \ldots 10^{-2}$ T

Meissner & Ochsenfeld, 1933

Example of magnetic levitation



Superconducting disk

Free energy and critical field

- Let us define the Gibbs free energy of a material in a magnetic field:

$$G = \underbrace{U - TS}_{\text{Thermal energy}} - \underbrace{\mu_0\, \mathbf{M} \cdot \mathbf{H}}_{\text{Magnetic energy}}$$

- A system in equilibrium will tend to a minimum of G
- In zero applied field, the SC phase (being in a condensed state) has lower free energy than the normal phase:

$$G_{sup}(H=0) < G_{normal}(H=0)$$

- The field expulsion ($\mathbf{M}=-\mathbf{H}$) corresponds to a magnetic energy density:

$$-\mu_0\, \mathbf{M} \cdot \mathbf{H} = \mu_0/2\, H^2$$

- The material *prefers* to expel the magnetic field (Meissner effect) until the free energy of the SC phase in field equals the free energy of the normal state:

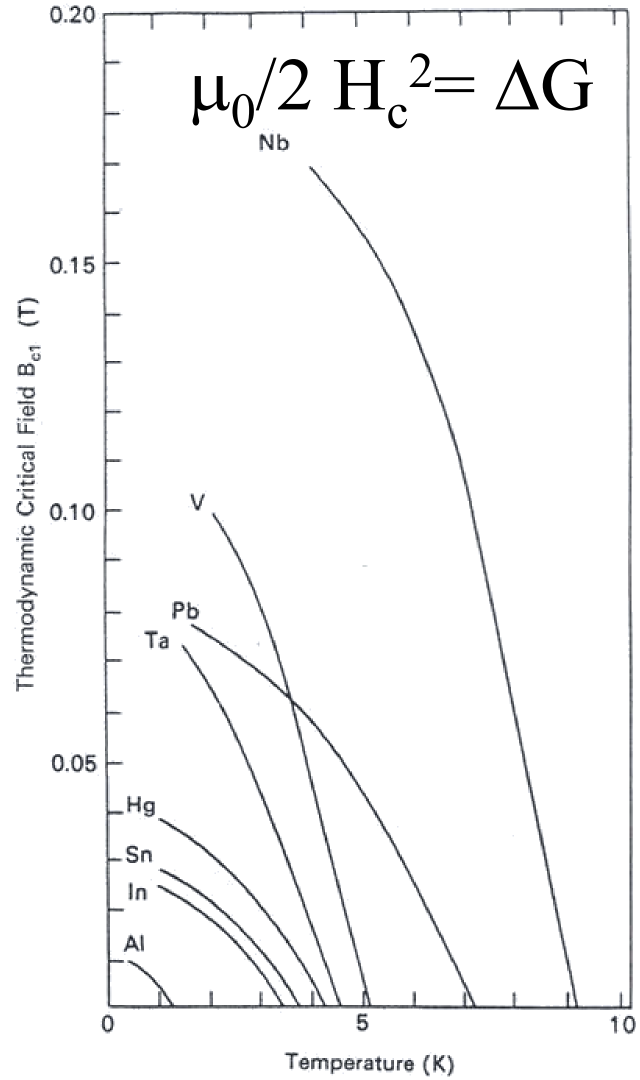
$$\mu_0/2\, H_c^2 = G_{normal} - G_{sup}(H=0)$$

Thermodynamic critical field

Type I – critical field

- The difference in free energy ΔG among the SC and normal state is small
- The corresponding values of the thermodynamic critical field are also small, i.e. in the range of few mT to barely above 100 mT

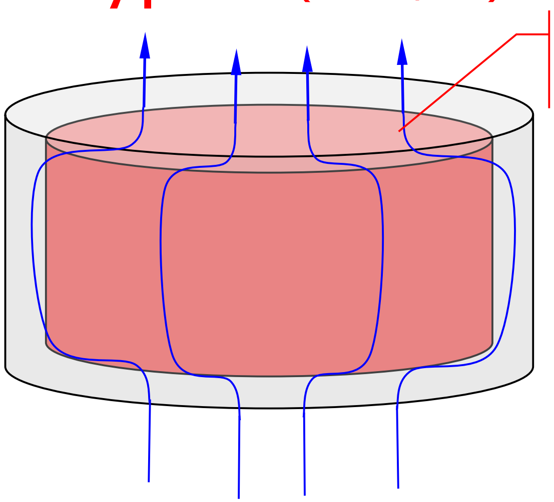
Not very useful for magnet engineers !



Energy efficient fluxons

Landau, Ginzburg and Abrikosov

Type I ($\kappa < 1/\sqrt{2}$)



Complete field exclusion

Pure metals

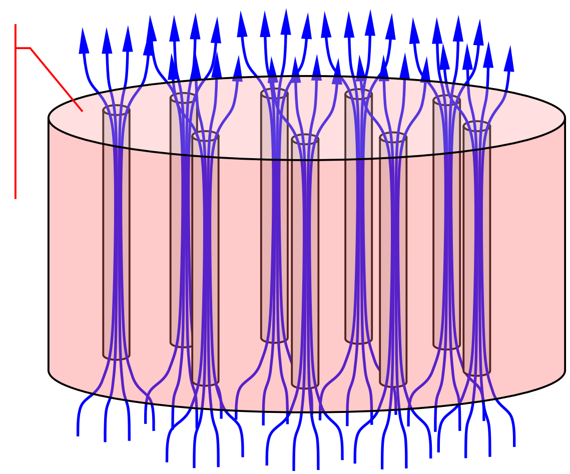
$B_C \approx 10^{-3} \ldots 10^{-2}$ T

Meissner & Ochsenfeld, 1933

Type II ($\kappa > 1/\sqrt{2}$)

Partial field exclusion

Lattice of fluxons



Dirty materials: alloys intermetallic, ceramic

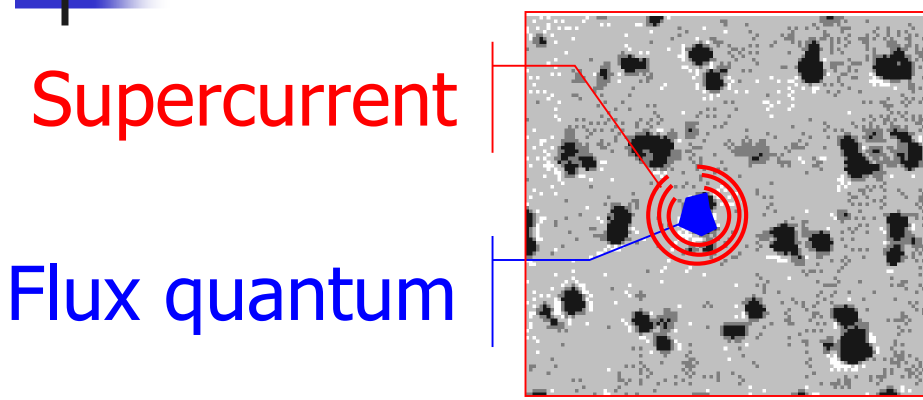
$B_C \approx 10 \ldots 10^2$ T

Ginsburg, Landau, Abrikosov, Gor' kov, 1950…1957

Values of λ_L , ξ and κ

Material	λ_L (nm)	$\xi(B=0)$ (nm)	κ (-)	
Al	16	1600	0.01	Type I
Pb	32	510	0.06	Type I
In	24	360	0.07	Type I
Cd	110	760	0.15	Type I
Sn	30	170	0.18	Type I
Nb	40	39	1	Type II
Nb_3Sn	200	12	≈ 20	Type II
MgB_2	185	5	≈ 40	Type II
YBCO	200	1.5	≈ 75	Type II

Lattice of quantum flux lines



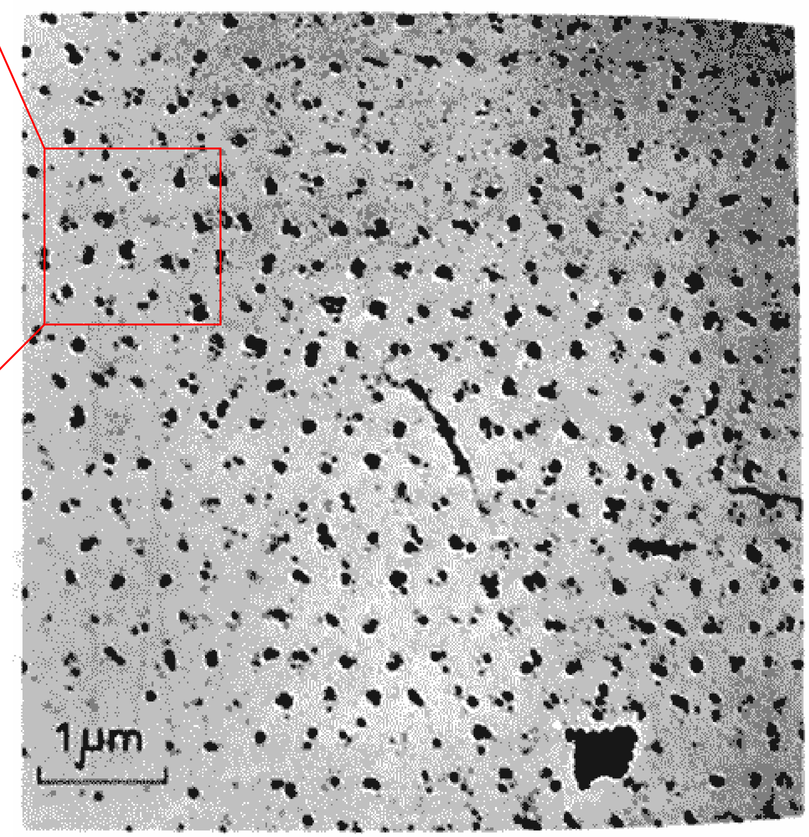


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

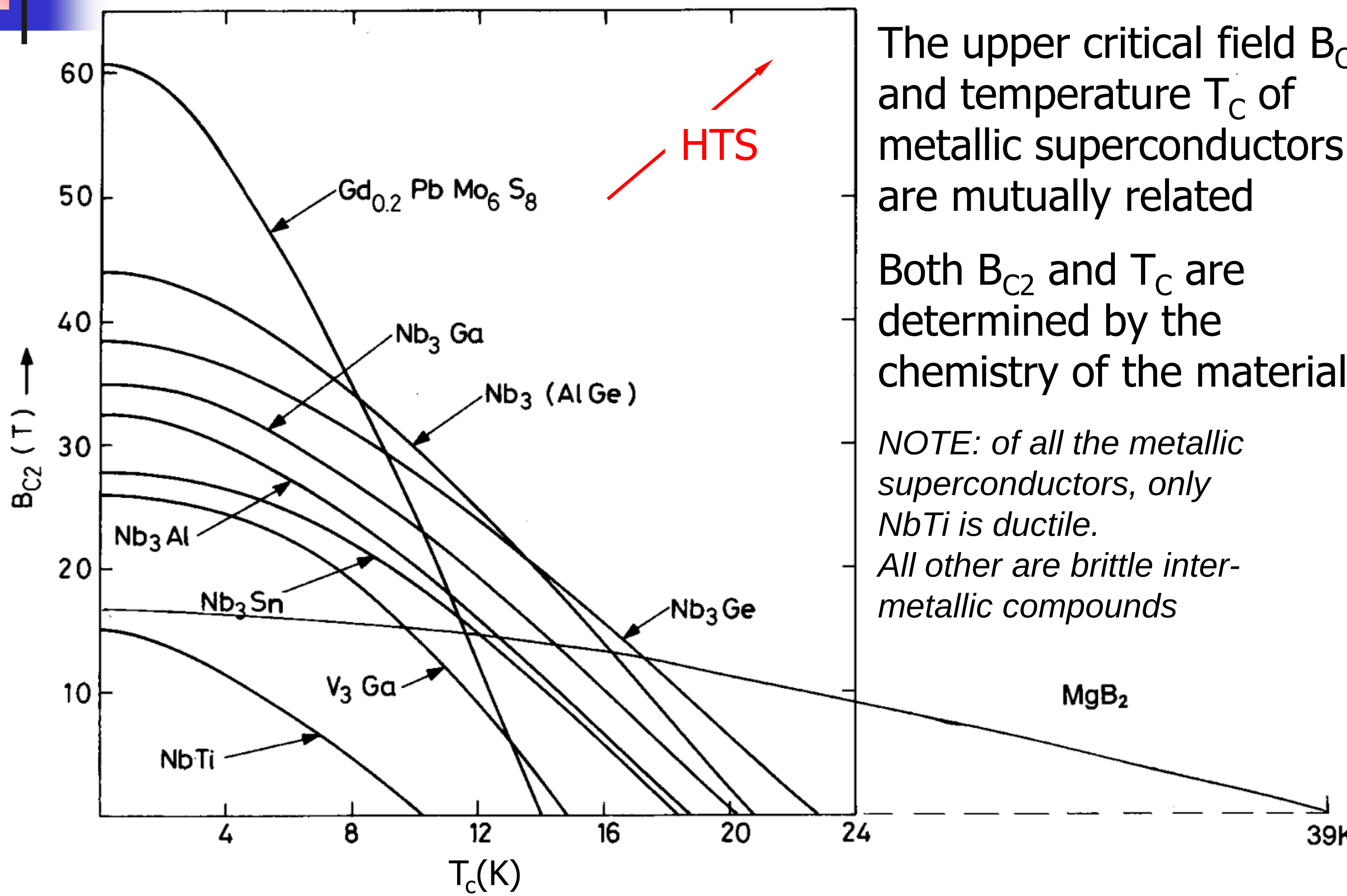
$$\Phi_0 = h/2e = 2.07 \times 10^{-15}\ \mathrm{Wb}$$

Observation on Pb-4at% In magnetised by a field of 3000 Oe and decorated by Co particles

Essmann & Träuble, 1967

Graphics by courtesy of M.N. Wilson

Type II – critical field



The upper critical field B_{C2} and temperature T_C of metallic superconductors are mutually related

Both B_{C2} and T_C are determined by the chemistry of the material

NOTE: of all the metallic superconductors, only NbTi is ductile.
All other are brittle inter-metallic compounds

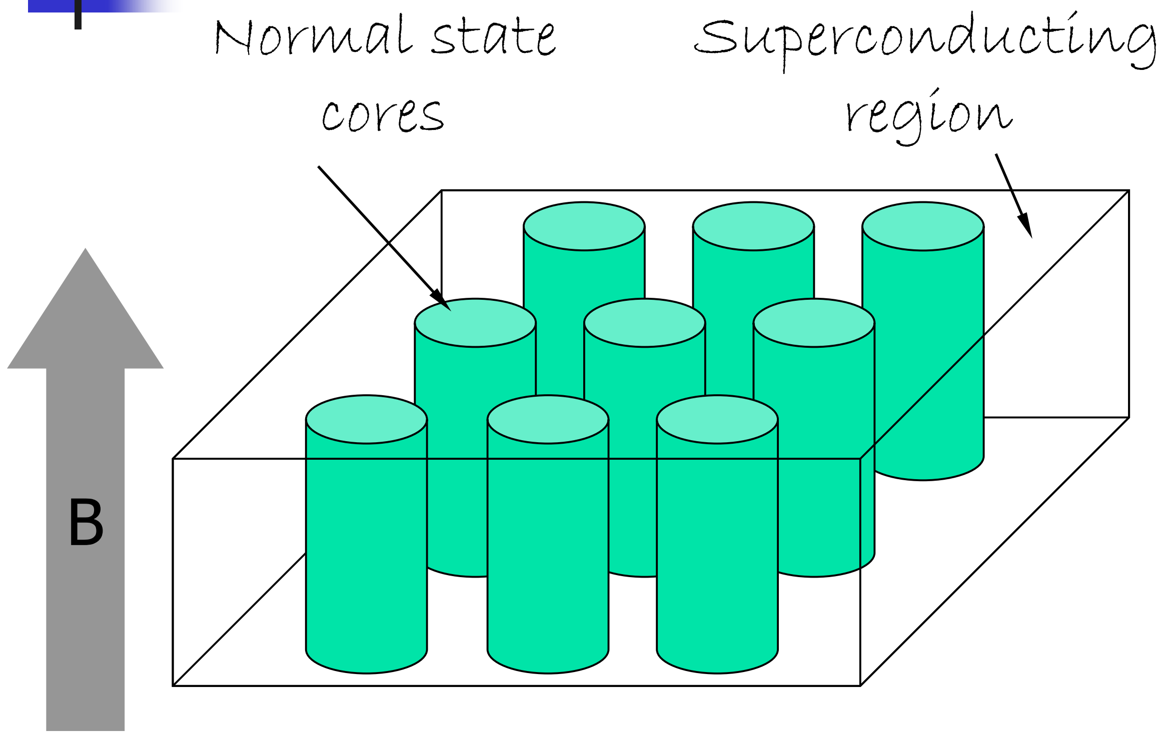
Hey, what about current ?

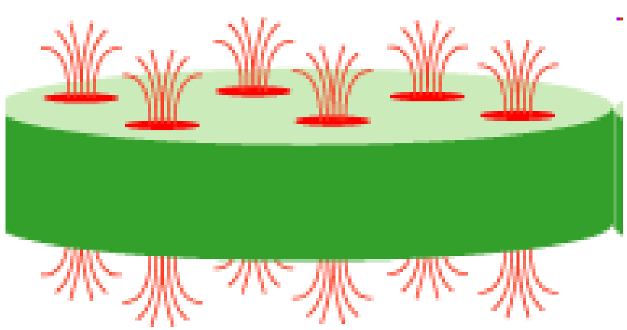
- A current flowing in a magnetic field is subject to the Lorentz force that deviates the charge carriers:

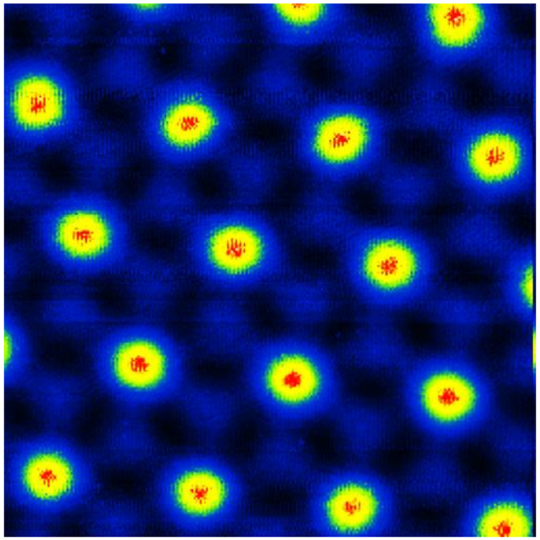
$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

- This translates into a *motion of the fluxoids* across the superconductor ⇒ energy dissipation ⇒ loss of superconductivity
- To carry a significant current we need to *lock the fluxoids* so to resist the Lorentz force. For this we mess-up the material and create **pinning centers** that exert a pinning force F_P

Type II Superconductors ($\xi < \lambda$)





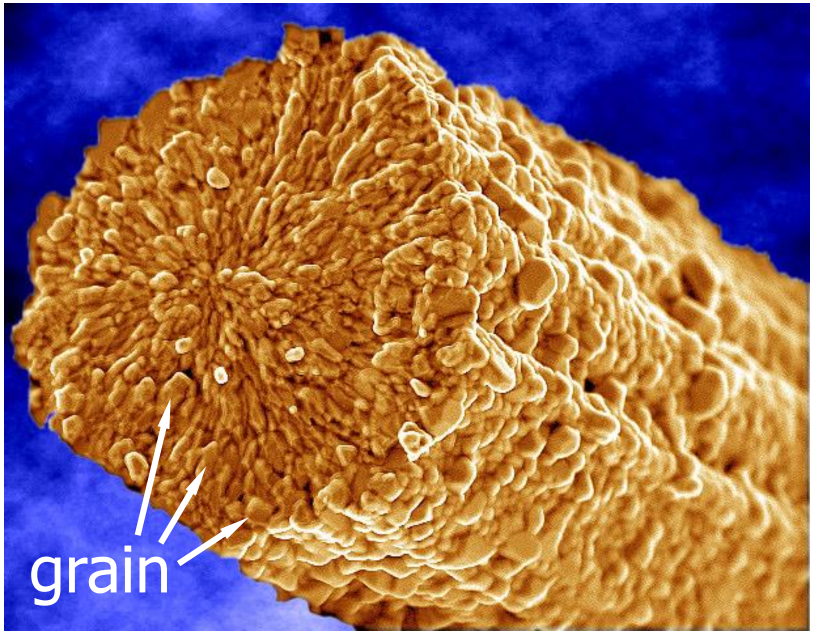


Pinning centers

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds



Microstructure of Nb_3Sn

Jc(B,T,…)

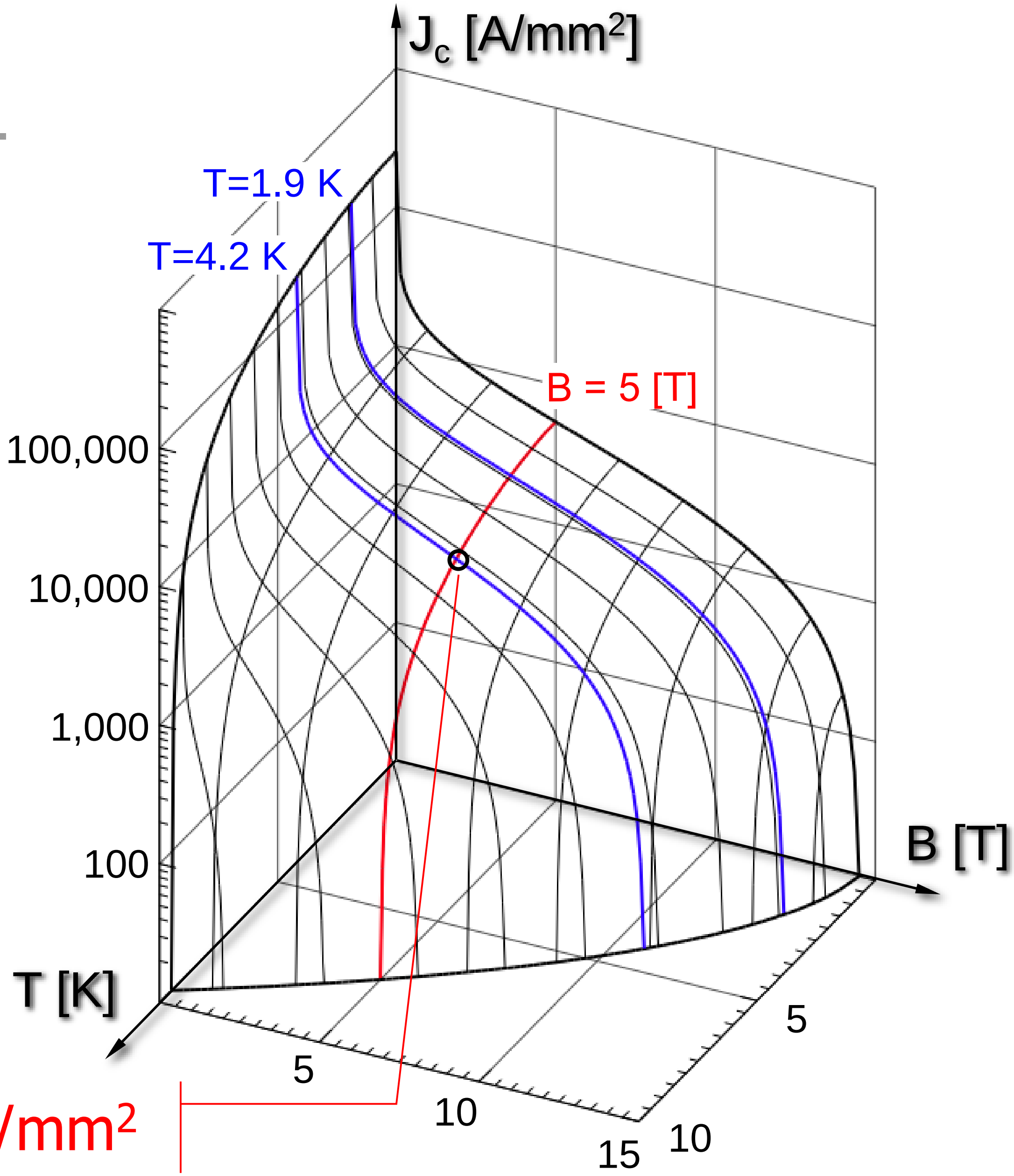
- The maximum current that can be carried by the superconductor is the current at which:

$$|\mathbf{J} \times \mathbf{B}| = F_P$$

- The above expression defines a **critical surface**:

$$J_C(B,T,\ldots) = F_P / B$$

Critical surface of a LHC NbTi wire



Jc (5 T, 4.2 K) ≈ 3000 A/mm²

Superconductors physics - Re-cap

- Superconducting materials are only useful if they are ***dirty*** (type II - high critical field) and ***messy*** (strong pinning centers)
- A superconductor is such only in conditions of temperature, field and current density within the critical surface, and it is a normal-conductor above these conditions. The transition is defined by a critical current density $J_C(B,T,\ldots)$
- The maximum current that can be carried is the $I_C = A_{SC} \times J_C$

Superconductor types – 1/2

- Magnetic field exclusion:
  - **Type I** – full exclusion of field lines from the material bulk up to *lower critical field* B_{C1}
  - **Type II** – full exclusion of field lines from the material bulk up to B_{C1} followed by partial flux penetration (vortices) up to *upper critical field* B_{C2}
- Underlying theory:
  - **Conventional** – explained by BCS theory (usually applying to LTS)
  - **Unconventional** – needs theory different from BCS (usually applying to HTS)

Superconductor types – 2/2

- Critical temperature:
  - **LTS** – low-temperature superconductors, critical temperature T_C up to (about) 30 K
  - **HTS** – high-temperature superconductors, critical temperature T_C above 30 K, in the range of liquid nitrogen (77K) and higher

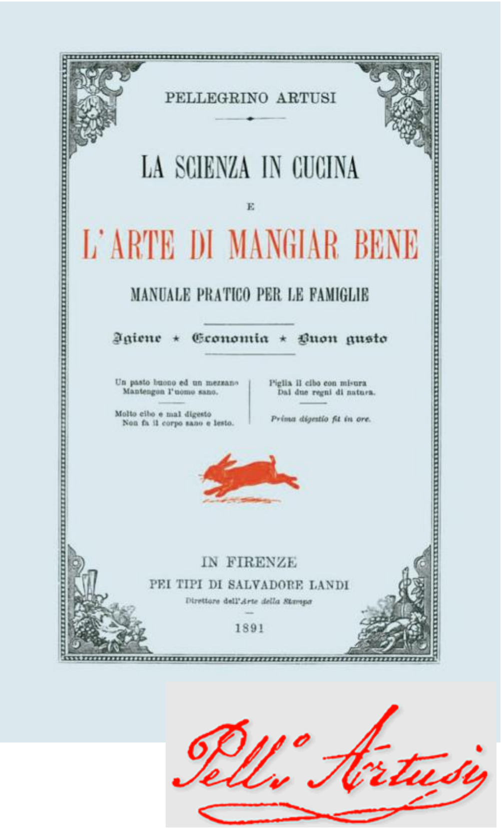
  NOTE: MgB_2 is a special case: TC ≈ 40 K but explained by LTS theory
- Material class:
  - **Elements** (e.g. Pb, Hg)
  - **Alloys** (e.g. Nb-Ti, Nb-Zr)
  - **Compounds** (e.g. Nb_3Sn)
  - **Ceramics** (e.g. REBCO)
  - **Pnictides** (e.g. IBS)
  - **Organic**, **Sulfides**, …

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting materials and cables
- The making of a superconducting magnet
- Examples of superconducting magnet systems

Superconducting magnet *cook-book*

- Devise the desired magnetic configuration for the specified field, bore homogeneity and duty cycle
- Analyze mechanically and thermally
- Design a cable to fit the winding, by choosing cross sections and cable configuration with:
  - Superconductor A_{SC} to carry the current with sufficient margin
  - Stabilizer A_{ST} sufficient for stability and protection
  - Sufficiently low AC loss
- Insulate cable, wind coils, mount in a supporting and magnetic structure, insert in a cryostat
- Top-off with current leads and instrumentation as desired
- Cool properly to cryogenic temperatures
- Power up, shake with quenches
- Enjoy the field according to your taste



Science in the Kitchen,
P. Artusi, 1891

From materials to magnets

- Materials must be made in high-current wires, tapes and cables for use in magnets
- The manufacturing route depends, among others on:
  - The material (e.g. alloy or chemical compound),
  - The material synthesis (e.g. reaction conditions or a crystal growth method)
  - The material mechanical properties (e.g. ductile or fragile)
  - The compatibility with other materials involved (e.g. precursors or mechanical supports)

A summary of *technical materials*

	LTS				HTS		
	Nb-Ti	Nb_3Sn	Nb_3Al	MgB_2	YBCO	BSCCO	IBS
	1961	1954	1958	2001	1987	1988	2006
Tc (K)	9.2	18.2	19.1	39	≈93	95[5] 108[6]	16[7] 38[8] 55[9]
Bc (T)	14.5	≈30	33	18[1] 36…74[2]	≈120[3] ≈250[4]	≈200	40[7] 80[8] 100[9]

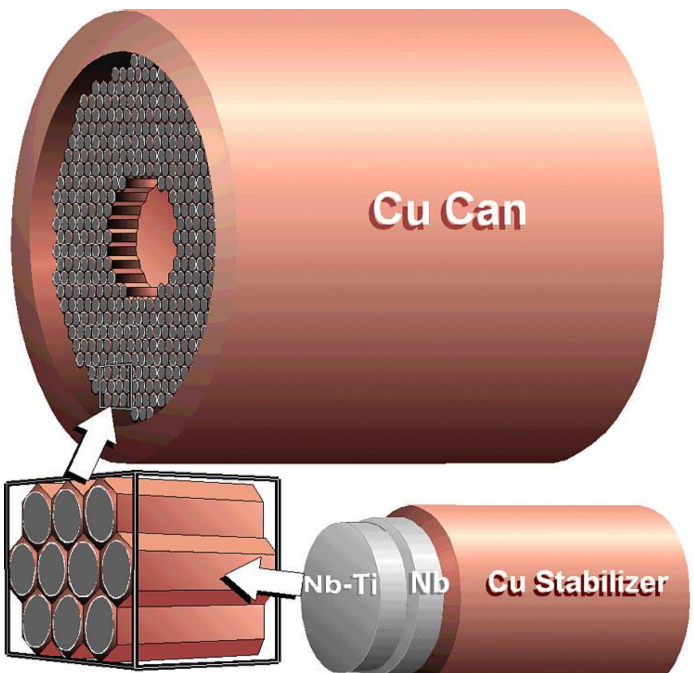
Notes:
(1) wires and tapes
(2) thin layers
(3) B parallel to c-axis
(4) B in the ab-plane
(5) BSCCO-2212
(6) BSCCO-2223
(7) IBS-11
(8) IBS-122
(9) IBS-1111

HTS are not only superconducting at high temperature, they also have an exceptional critical field ! (important for high magnetic field applications)

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb-Ti manufacturing route

NbTi billet

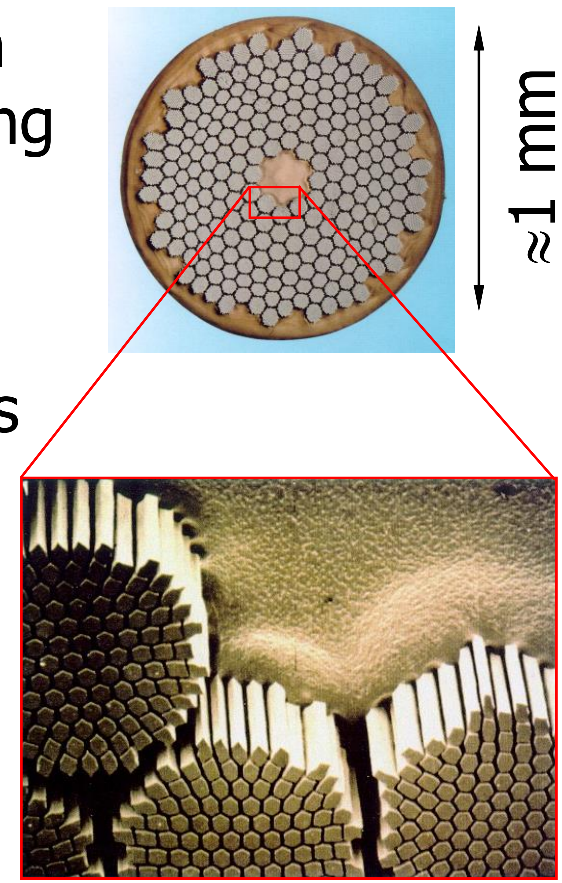


NbTi is a ductile alloy that can sustain large deformations

$I_C(5\ T, 4.2\ K) \approx 1\ kA$

extrusion
cold drawing

heat
treatments



LHC wire

NbTi: an industrial process

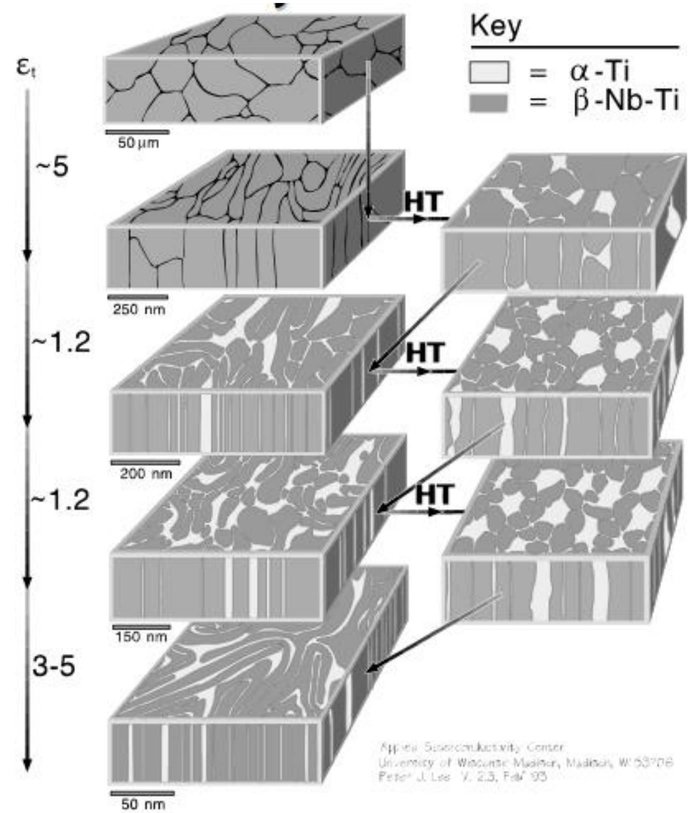
Nb-Ti/Cu billet extrusion

A large size draw of Nb-Ti superconducting strand on a bull-block.

Images courtesy of Seung Hong - OI-ST

OXFORD

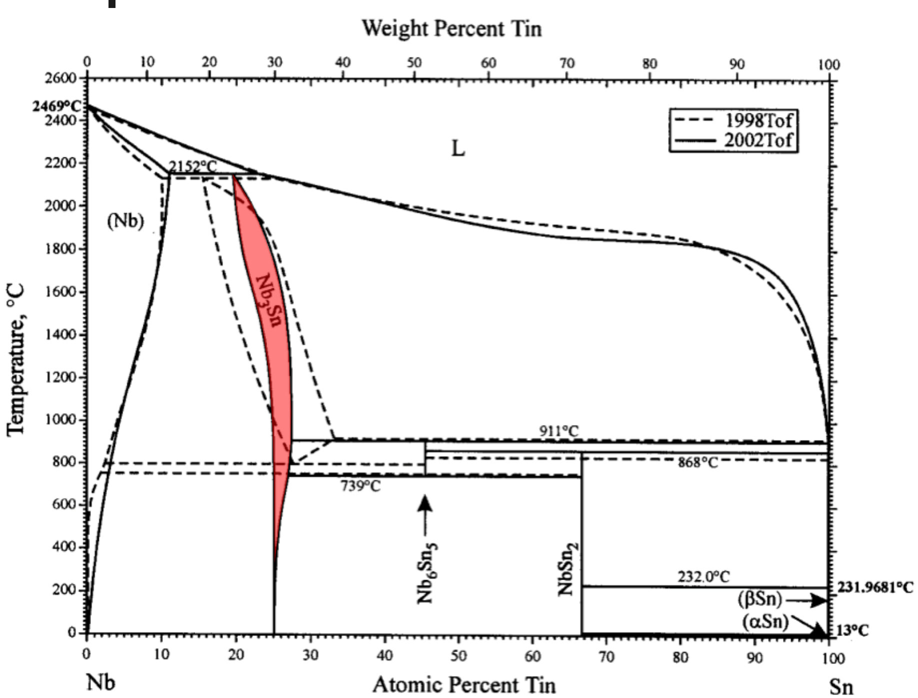
The *trick* to high Jc in NbTi



Intermediate heat treatment is necessary to form precipitates (pinning centers) and improve draw-ability. Subsequent drawing elongates the precipitates to the desired spacing

1998Tof: C. Toffolon, C. Servant, and B. Sundman: *J. Phase Equilibria*, 1998, *19*(5), pp. 479-85.
2002Tof: C. Toffolon, C. Servant, J.C. Gachon, and B. Sundman: *J. Phase Equilibria*, 2002, *23*(2), pp. 134-39.

Nb_3Sn synthesis



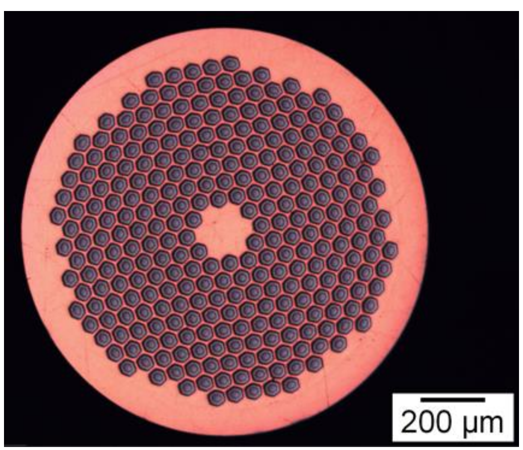
- Initial Nb_3Sn synthesis routes (Kunzler) required **high-temperature heat treatment** (> 950 ° C)

- Breakthrough achieved by three groups in 1969-1970:
  - K. Tachikawa at the National Research Institute for Metals in Japan
  - A. R. Kaufman at the Whittaker Corporation in the USA
  - E . W. Howlett at the Atomic Energy Research Establishment at Harwell in Great Britain.
- A15 compound layers (V_3Ga and Nb_3Sn) could be formed by **solid diffusion** at the interface of Nb/V and Cu-Sn/Ga at modest temperatures, of the order of ***700 ° C***
- In addition, Cu **de-stabilizes** Sn-rich compounds

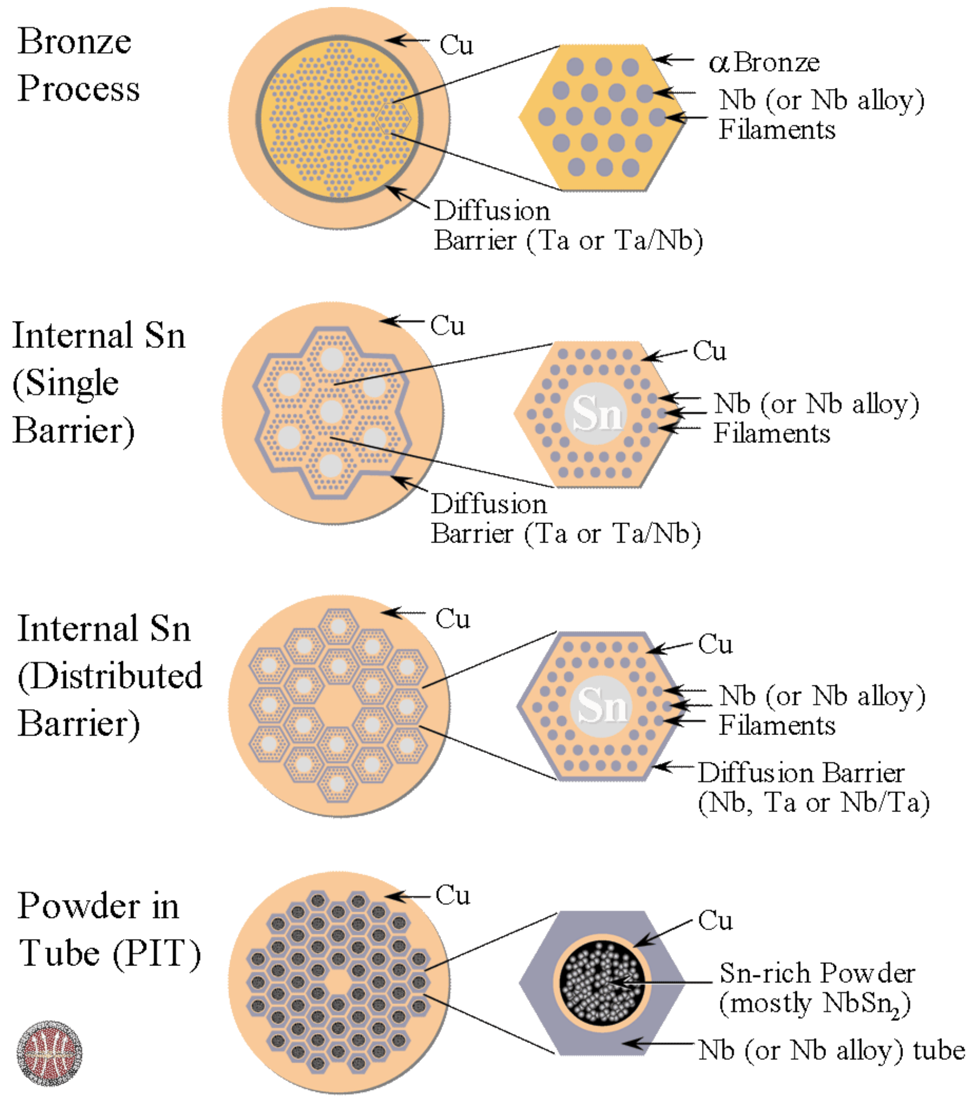
Graphics by courtesy of Applied Superconductivity Center at NHMFL

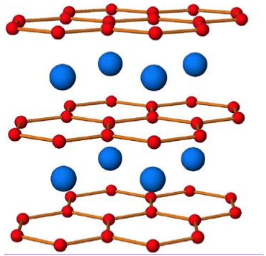
Nb_3Sn manufacturing routes

Nb_3Sn is brittle and cannot be drawn in final form. The precursors are drawn and only later the wire is heat-treated to ≈650 C for several hrs, to form the Nb_3Sn phase



I_C(12 T, 4.2 K) ≈ 1.5 kA





MgB_2 manufacturing routes

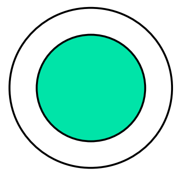
- Technical MgB_2 is manufactured wires and tapes
  - Powder-in-Tube
    - In-situ
    - Ex-situ
  - Mg diffusion

- The precursor (Mg/B or MgB_2 powders) requires a high-temperature heat treatment to form the brittle superconducting phase
- The MgB_2 must be clad in Fe/Nb/Ni to protect Cu
- Critical manufacturing issues:
  - Powder quality, granulometry, mixing, final porosity
- Doping with impurities the Mg/B powder is beneficial to J_C:
  - SiC, C, B_4C, C nanotubes, Hydrocarbons
  - C substitutes B $MgB_{2-x}C_x$

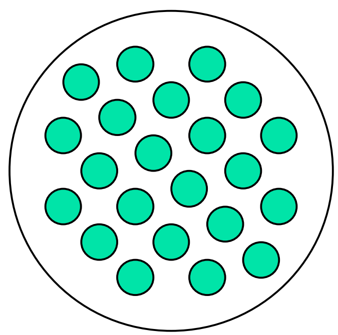
BSCCO manufacturing routes

Oxide powder in tube OPIT

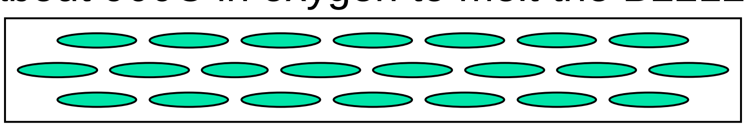
1) draw down BSCCO powder in a silver tube



2) stack many drawn wires in another silver tube and draw down again



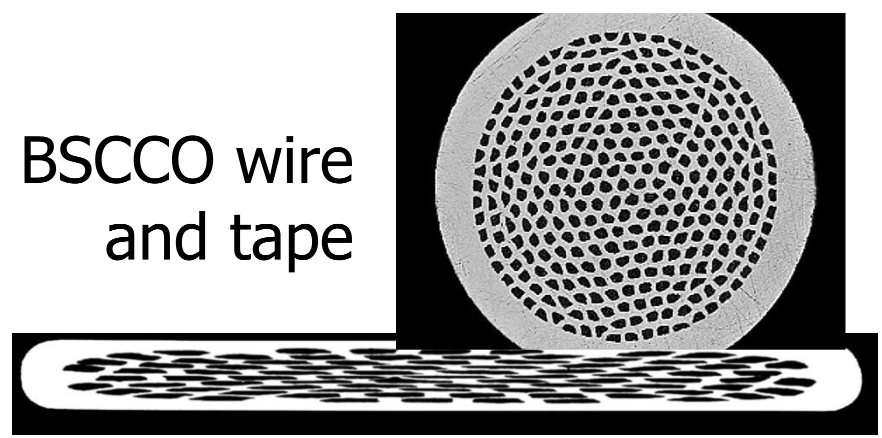
3) roll the final wire to tape and heat treat at about 900C in oxygen to melt the B2212



Graphics by courtesy of M.N. Wilson and Applied Superconductivity Center at NHMFL

BSCCO is also brittle: a special sequence of rolling and sintering heat treatments must used. Silver has the important feature that it is transparent to Oxygen at high temperature, but does not react with it

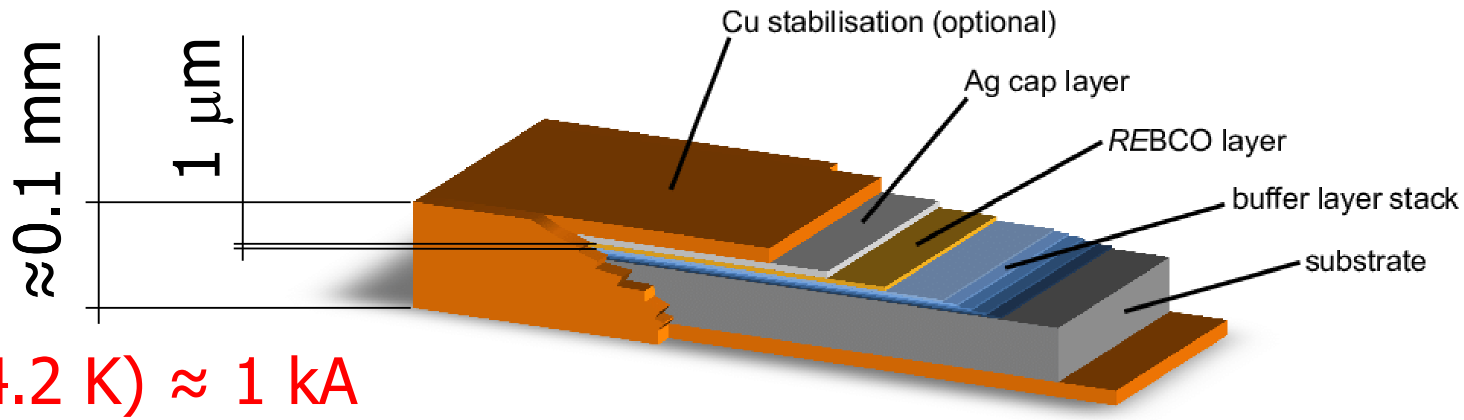
BSCCO wire and tape



REBCO manufacturing routes

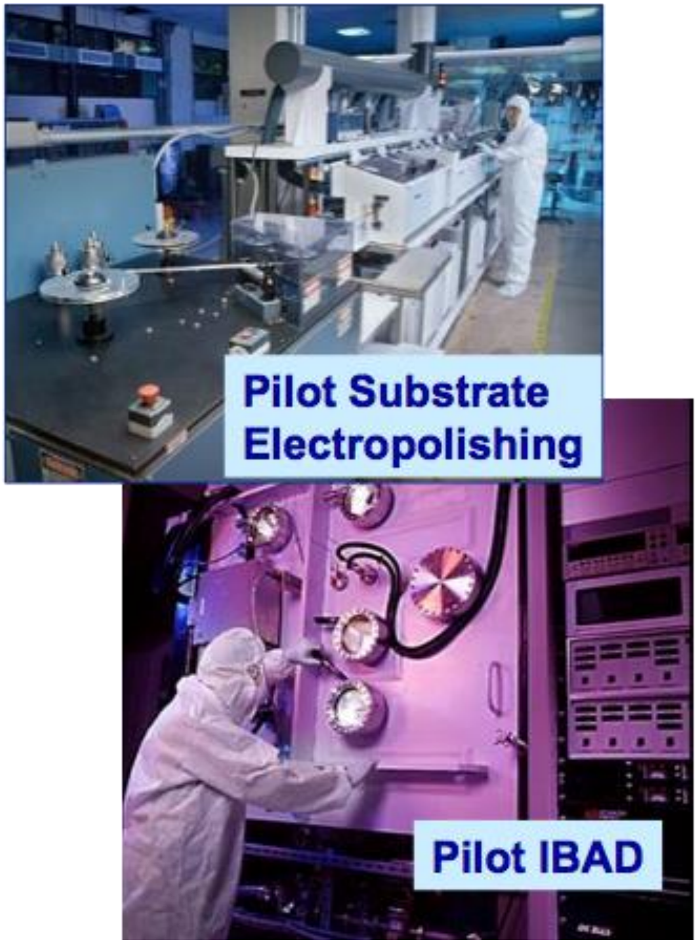
REBCO has better critical properties than BSCCO but, unlike BSCCO, grains do not align during processing. If grains are not aligned the supercurrent cannot jump between the grains. The manufacturing processes are all forcing a certain degree of alignment in the microstructure

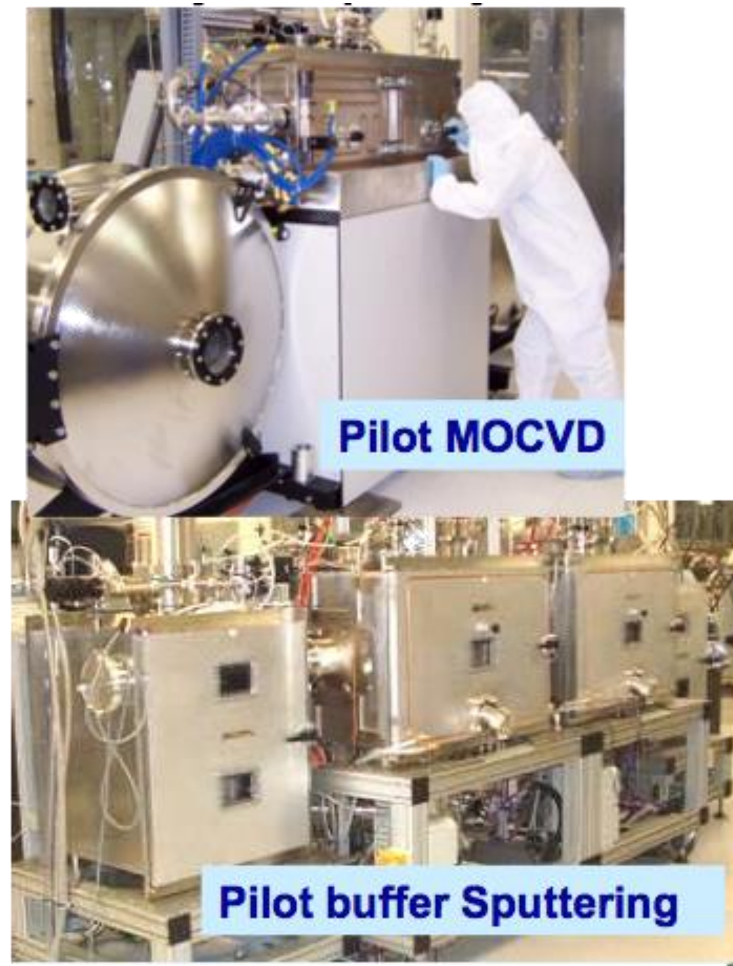
1) produce a tape with an aligned texture
2) coat the tape with a buffer layer
3) coat the buffer with a layer RE-$Ba_2Cu_3O_7$ such that the texture of the RE-BCO follows that of the buffer and substrate



I_C(20 T, 4.2 K) ≈ 1 kA

YBCO production: high-tech



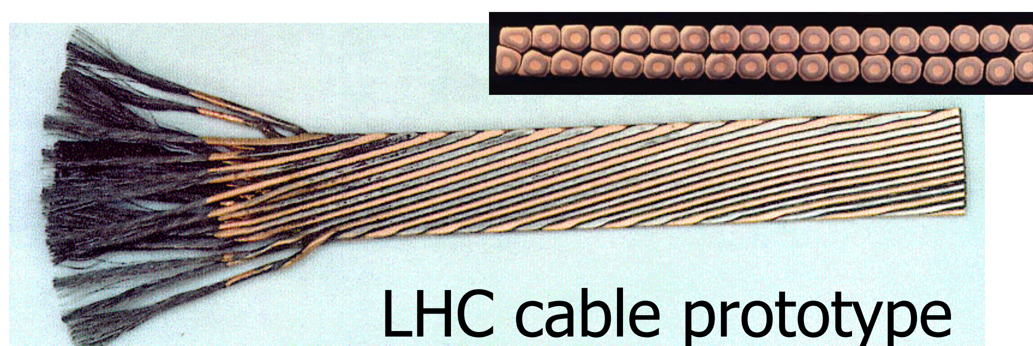


Work in clean-room conditions, costly processing of long lengths

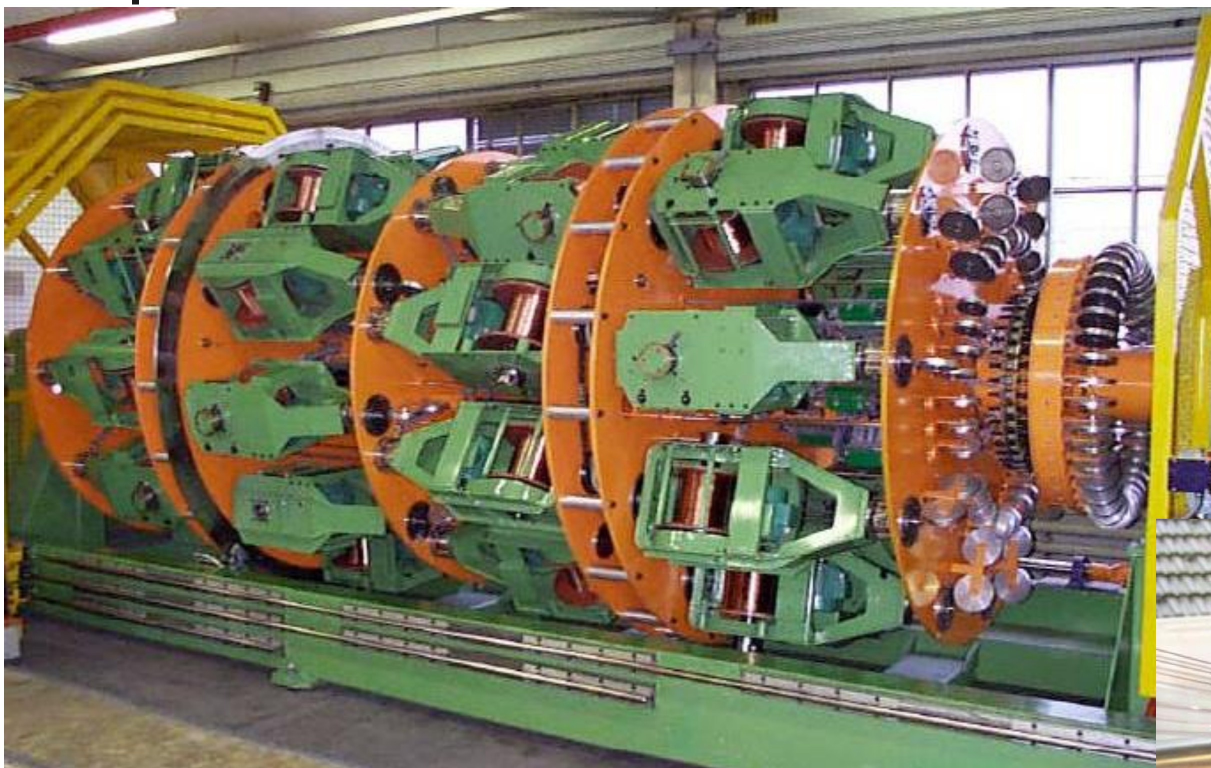
$J_E \approx 500\ A/mm^2$

Practical conductors: high J_E

- Multifilamentary wires have current carrying capability of 100… 1000 A
- Insulated with varnish or glass-braids they can be used to make all kind of small size magnets
- Large size magnets (e.g. LHC dipoles) require invariably large operating currents (10 to 100 kA) to:
  - Decrease inductance,
  - Lower the operating voltage,
  - Ease magnet protection **(?)**
- Rutherford cables are ideally suited for this task

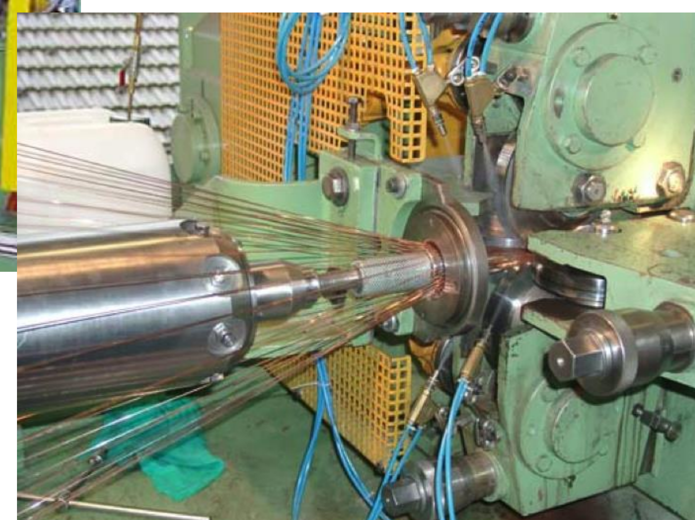


Rutherford cable machine @ CERN



Strand spools on rotating tables

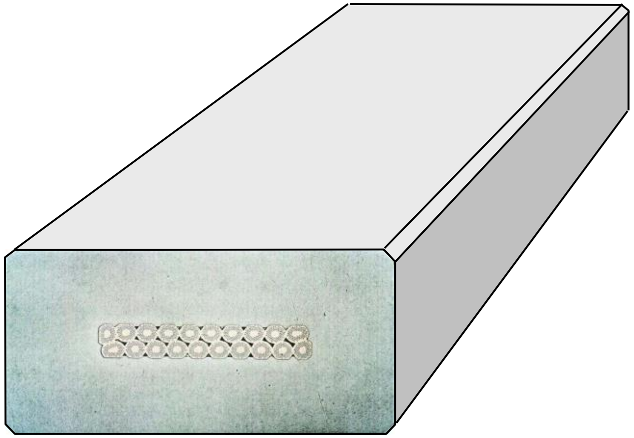
Strands fed through a cabling tongue to shaping rollers

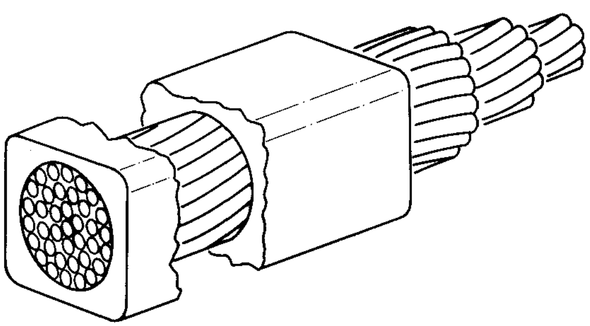


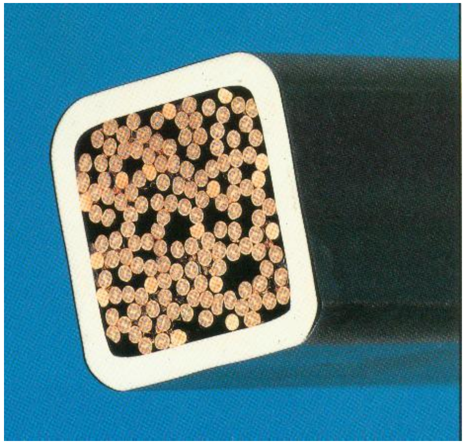
$J_E \approx 50\ A/mm^2$

Practical conductors: low J_E

- Super-stabilized conductor, a superconducting cable (e.g. Rutherford) backed by a large amount of good normal conductor (e.g. Al)
- Internally-cooled conductor, e.g. Cable-In-Conduit Conductor (CICC), a rope of wires inserted in a robust conduit that provides a channel for cooling

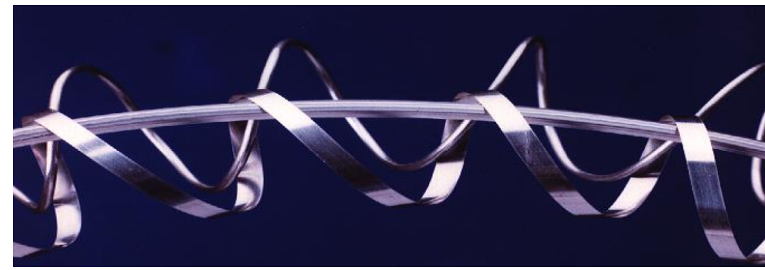




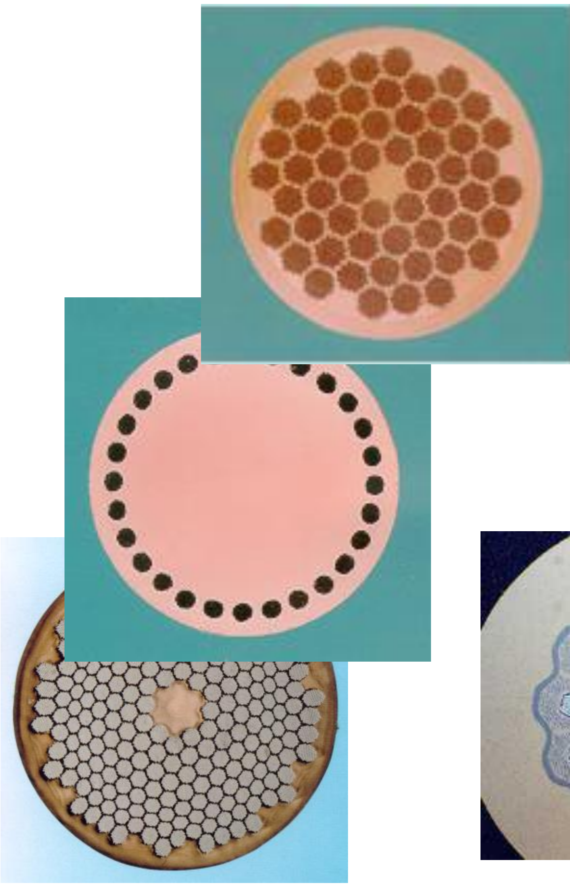


Superconducting wires and tapes for all taste…

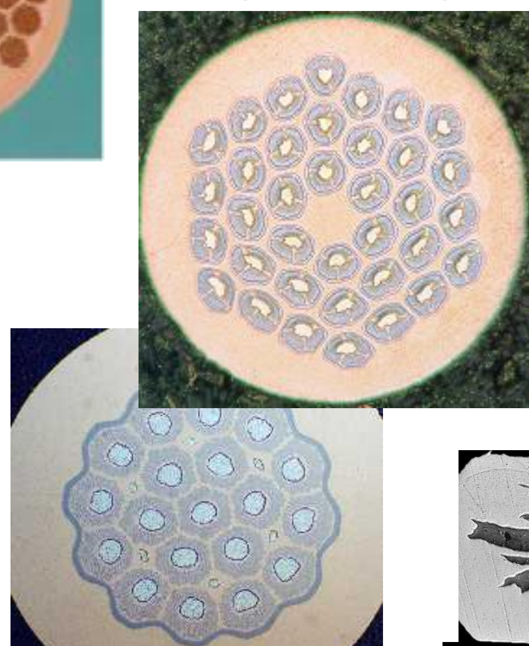
YBCO



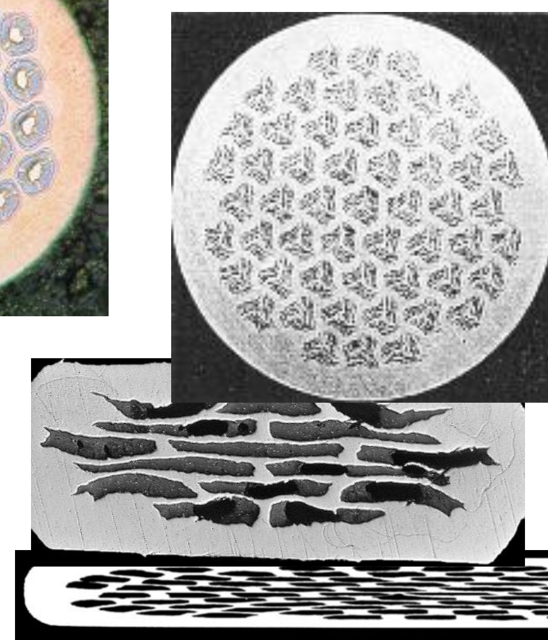
NbTi



Nb_3Sn, Nb_3Al



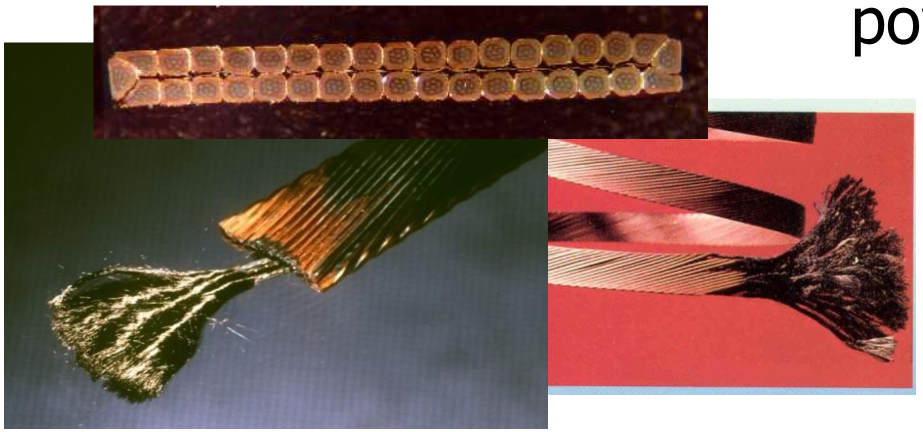
BSCCO



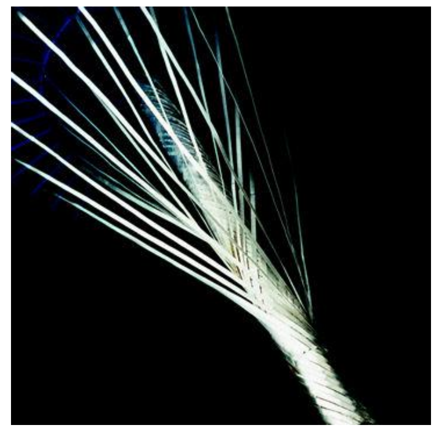
MgB_2

… and superconducting cables

Rutherford

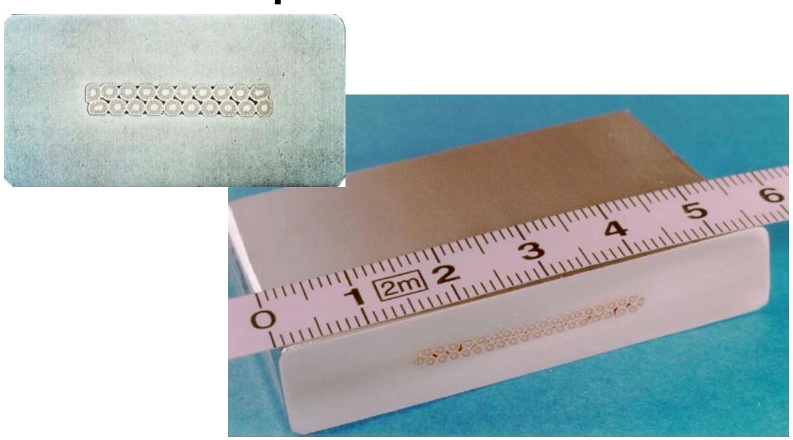


Braids for
power transmission



CICC

Super-stabilized



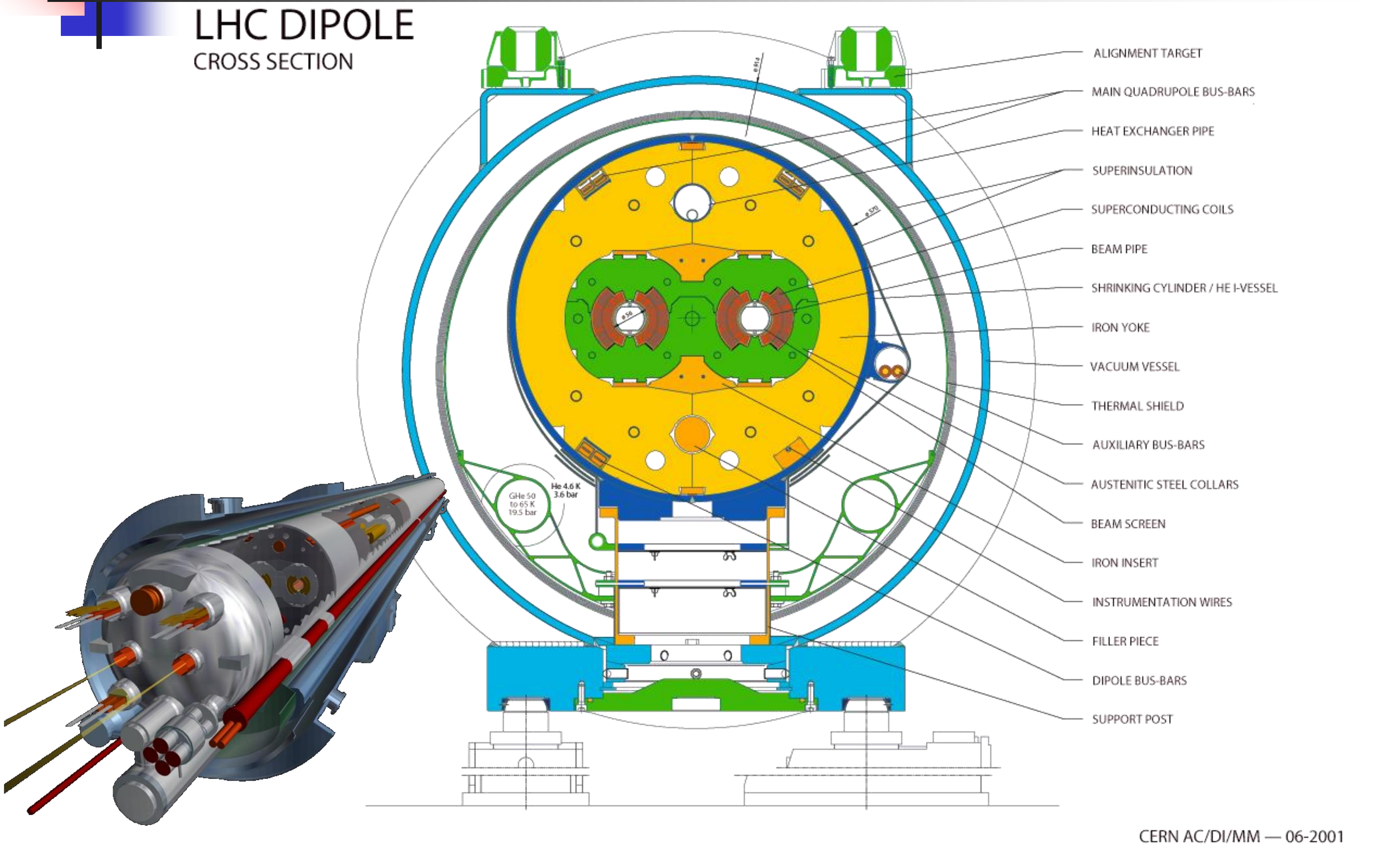
Internally cooled

Overview

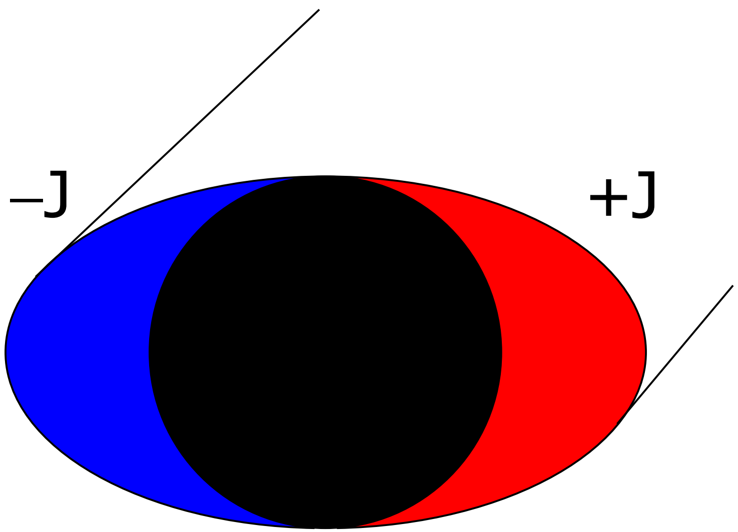
- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting materials and cables
- The making of a superconducting magnet
- Examples of superconducting magnet systems

LHC dipole

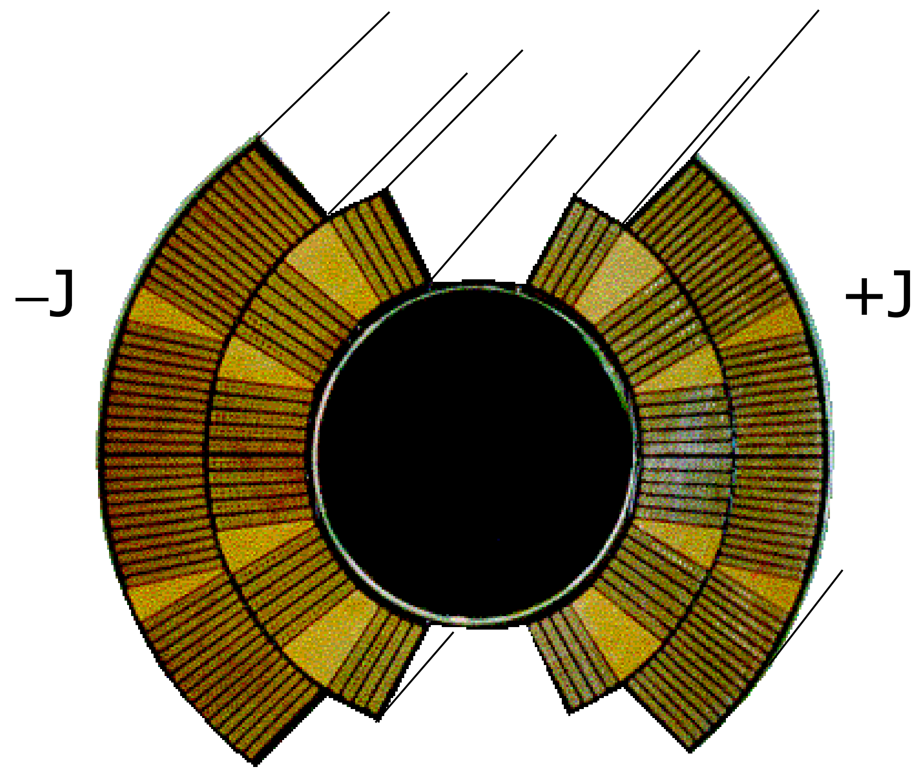
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)



Superconducting dipole magnet coil

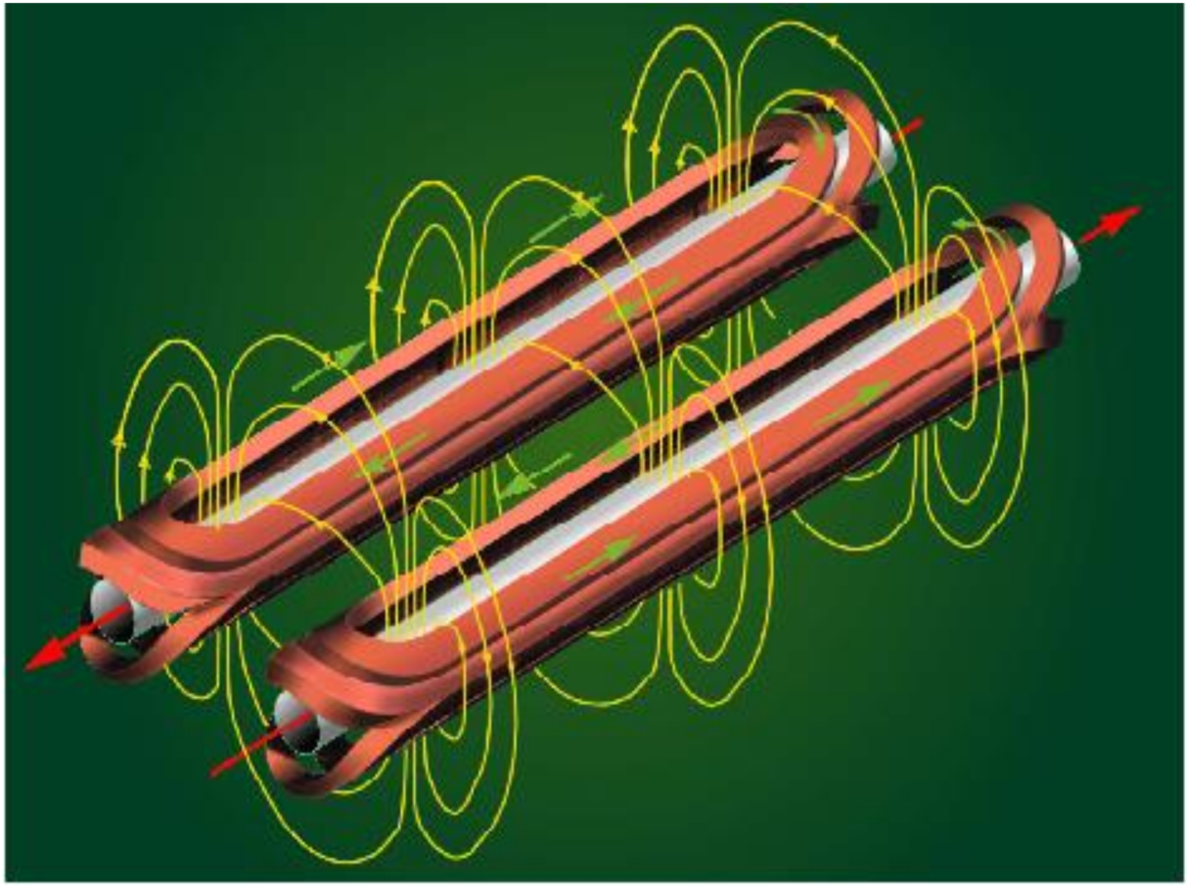


Ideal current distribution that generates a perfect dipole



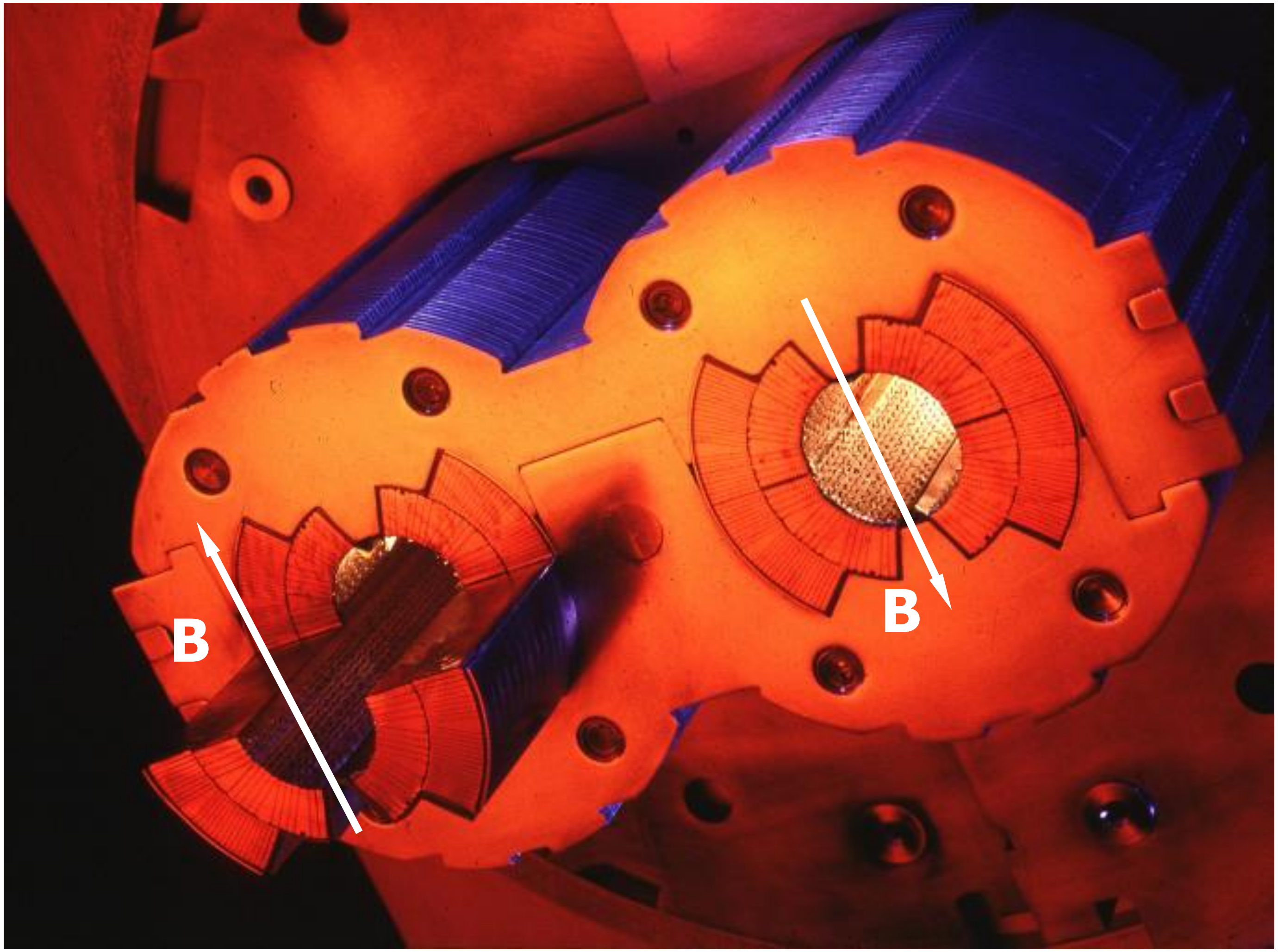
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle

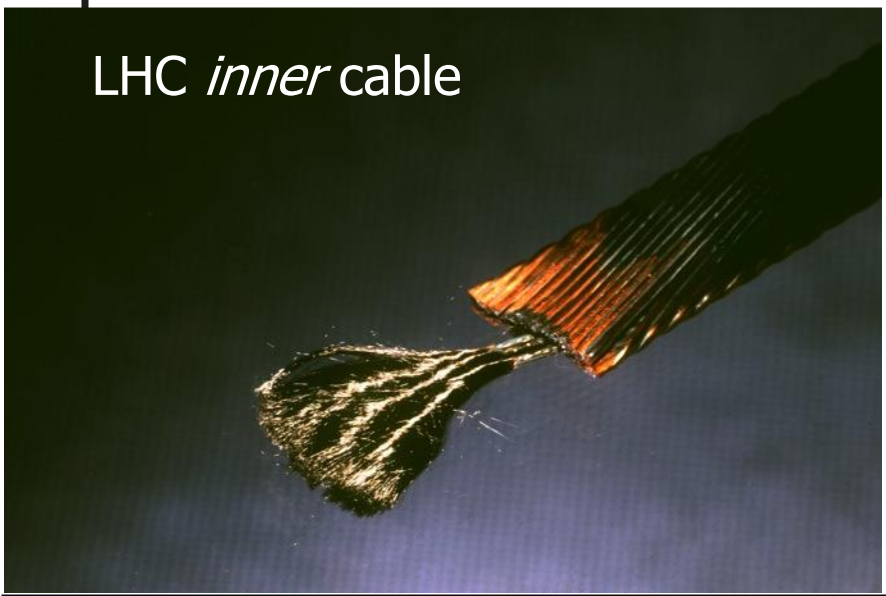


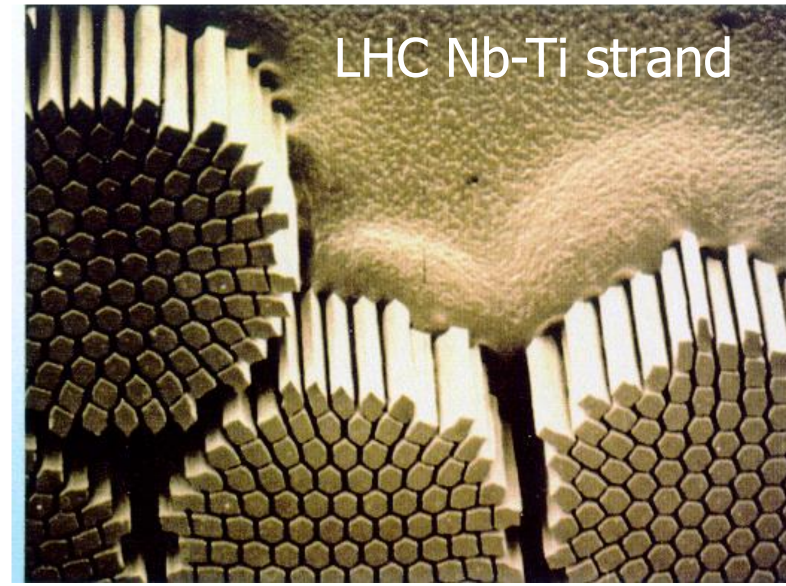
Combine two magnets in one
Save volume, material, cost

LHC dipole coils



Fine cables

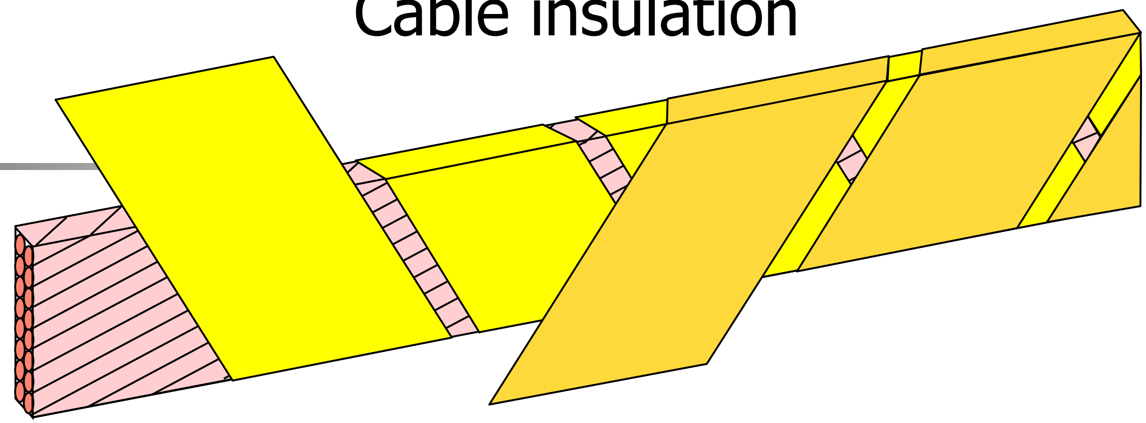




7500 km of superconducting cables with tightly controlled properties (state-of-the-art production)

Coil winding

Cable insulation

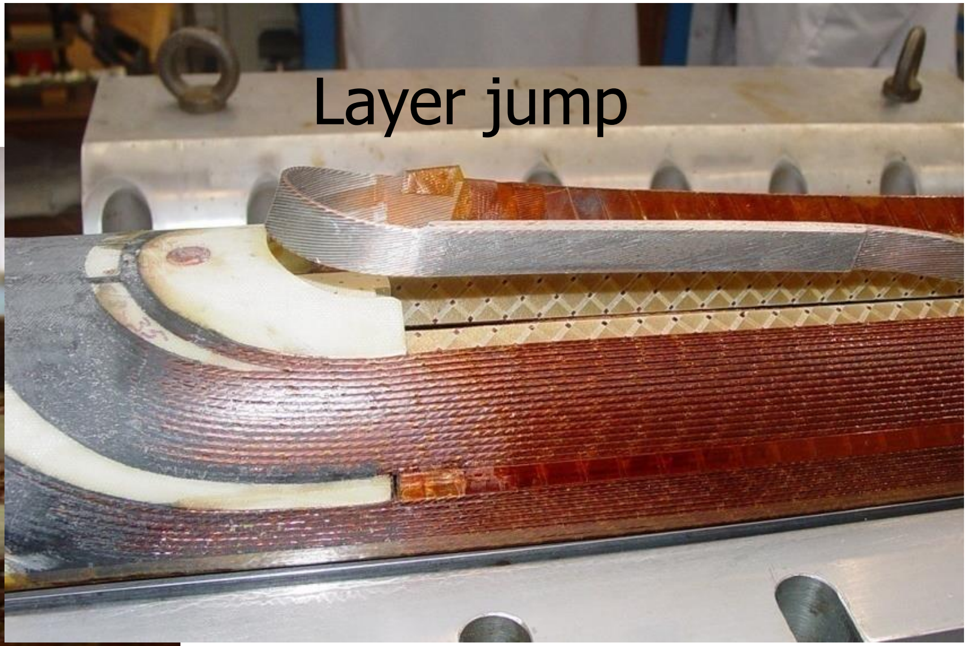


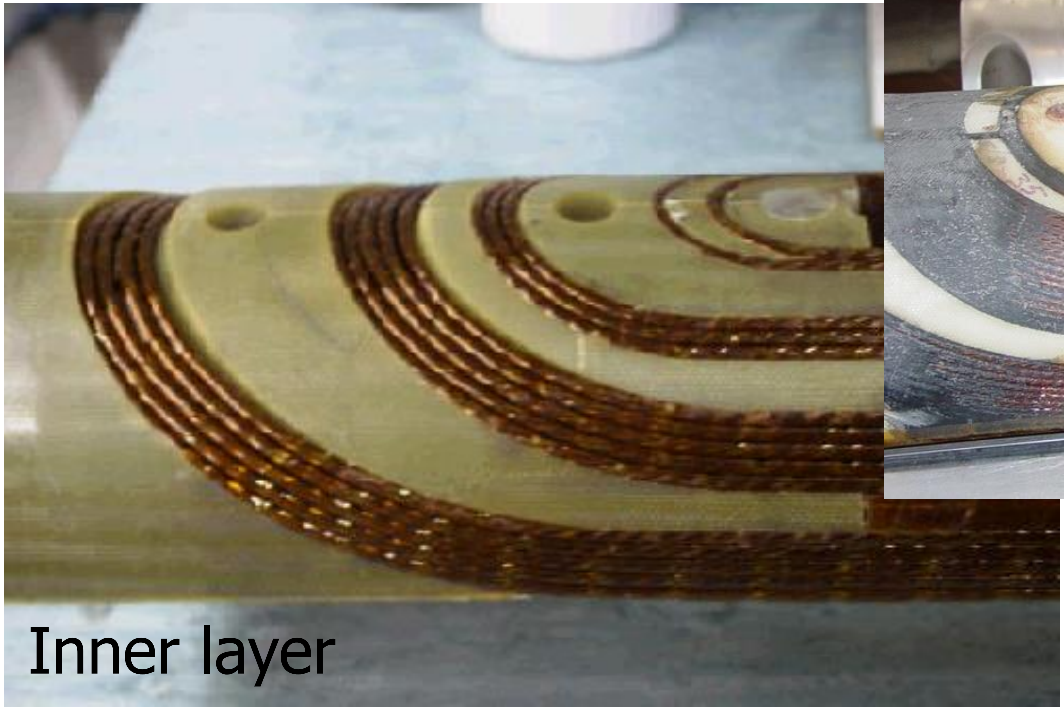
10 μm precision !

Coil winding machine

Stored coils

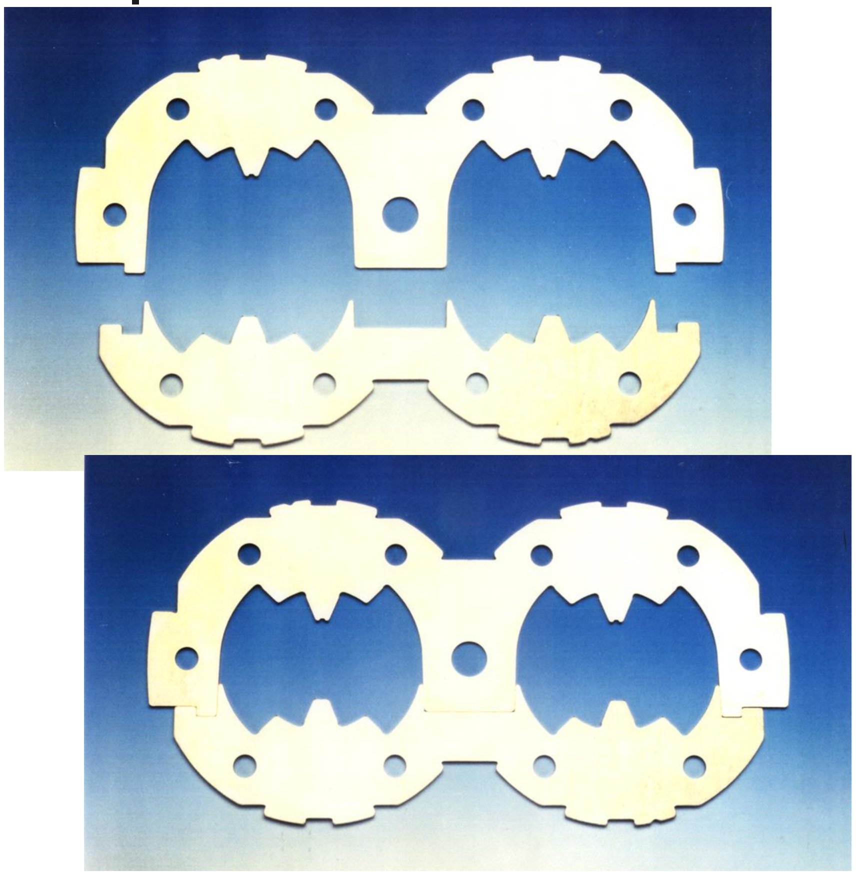
Ends

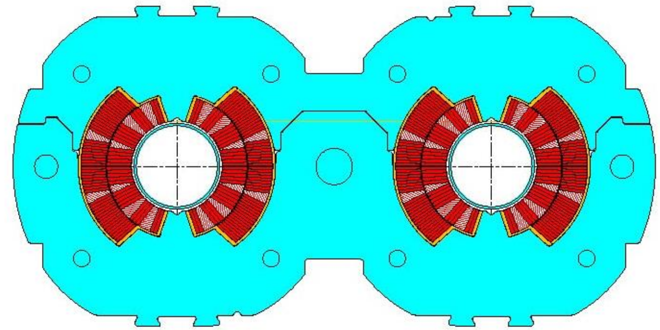




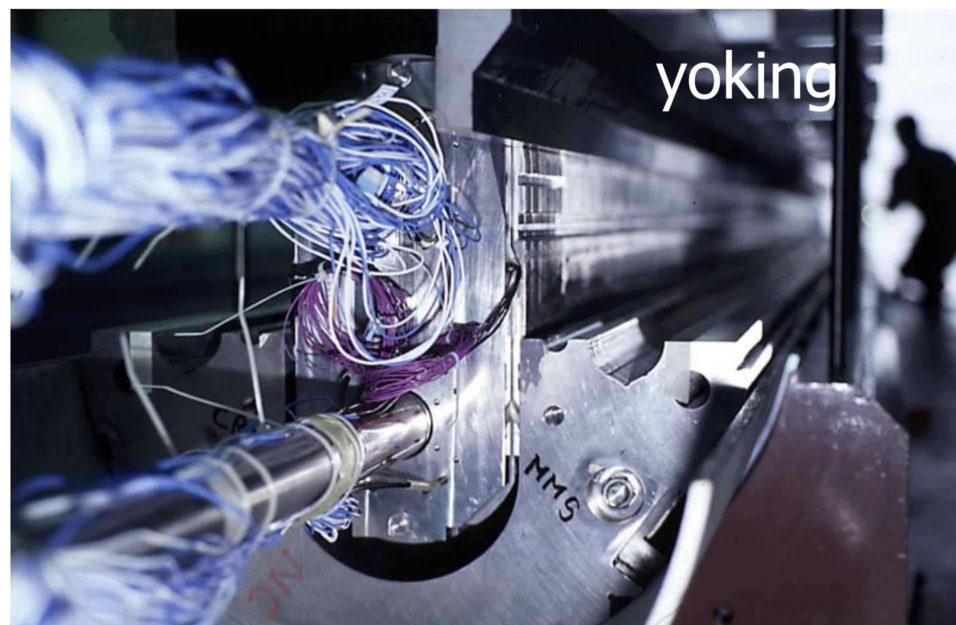
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking





collaring

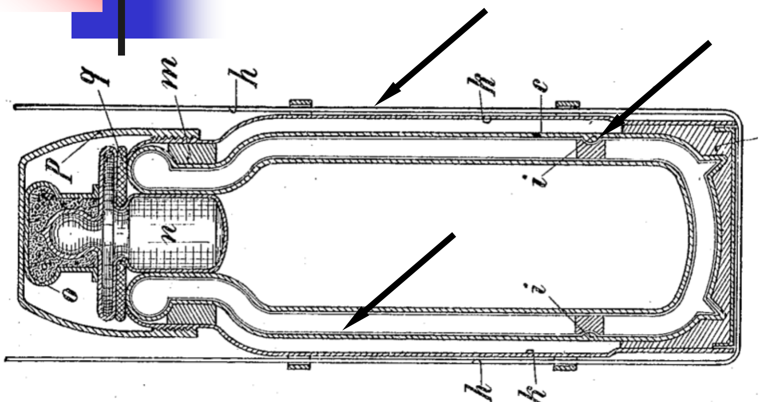


Magnet assembly

Alstom
Noell
Ansaldo

Cold mass

Cryostat



Vacuum enclosure

Thermal screens

Low conduction foot

Cryo-magnets and tests

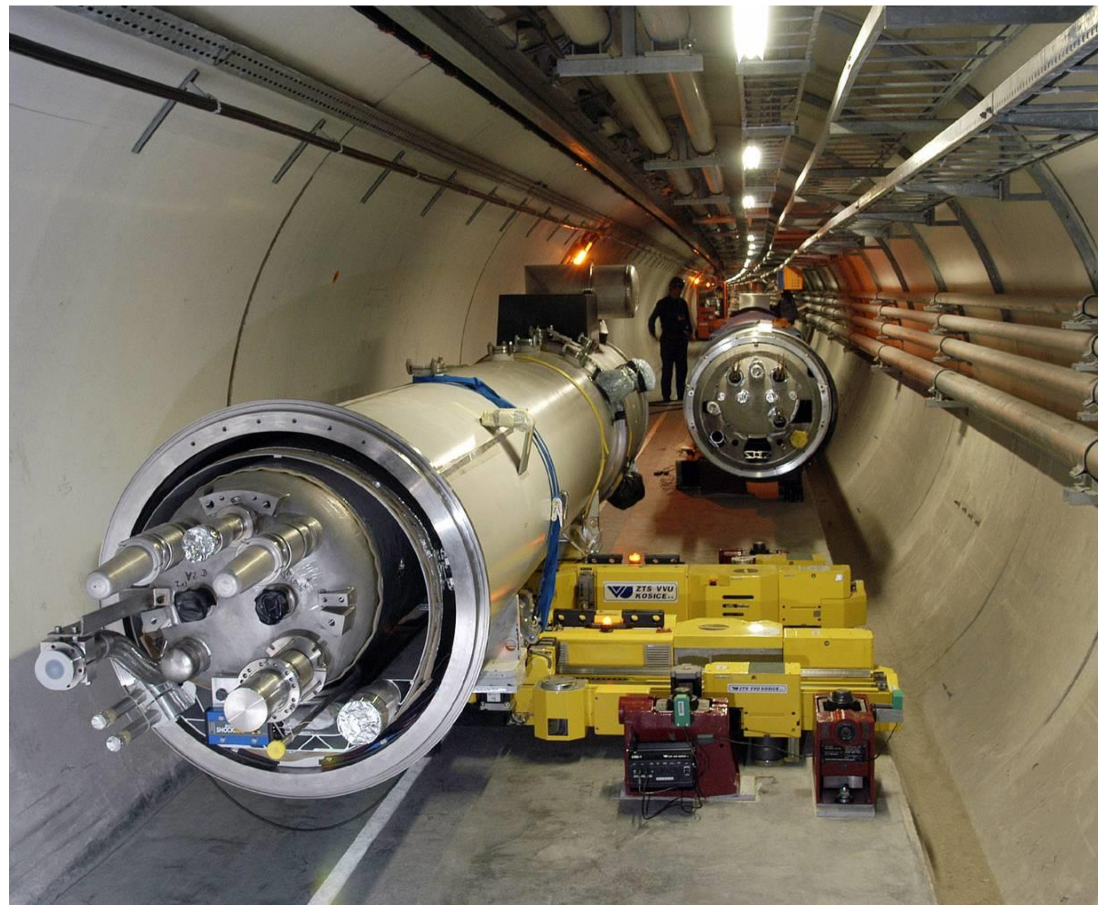
Magnet reception, cryostating, preparation for cold test and "stripping" for installation

Magnet powering tests and magnetic measurements

Magnet installation

Descent in the tunnel

Magnet transport and installation



Interconnection

65'000 electrical joints

Induction-heated soldering

Ultrasonic welding

Very low resistance

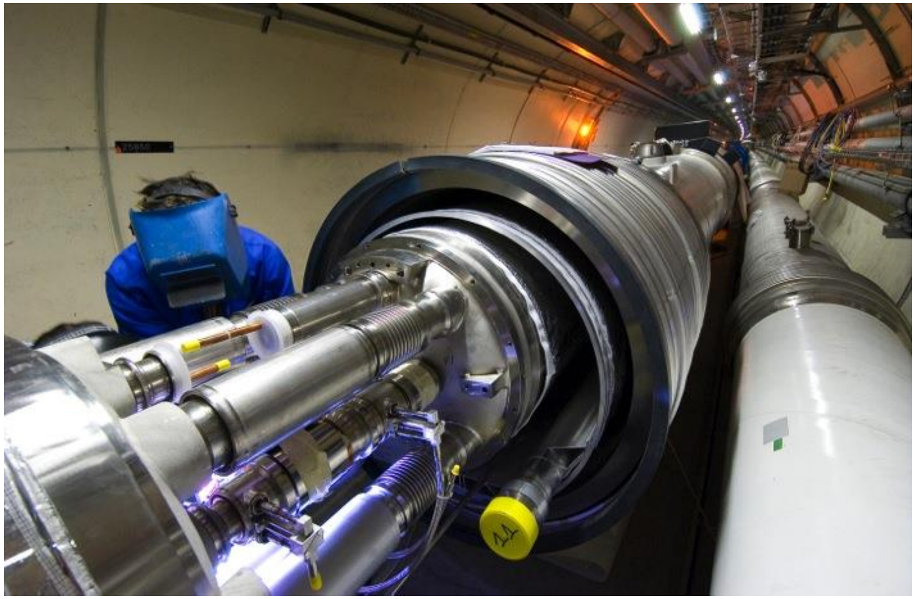
HV electrical insulation

40'000 cryogenic junctions

Orbital TIG welding

Weld quality

Helium leaktightness



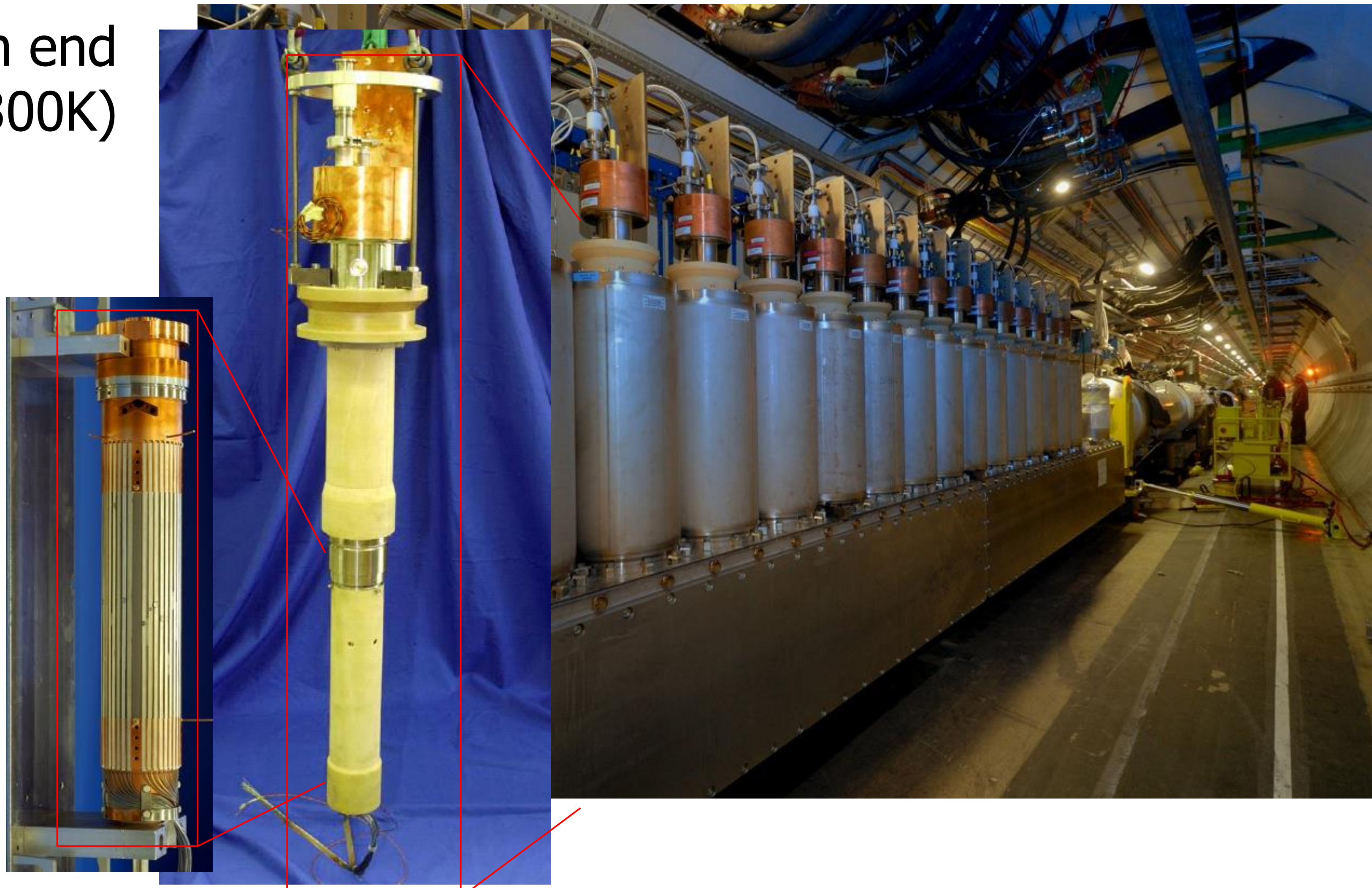
Large scale use of HTS

Warm end
(300K)

50 K

BSCCO
2223

4.2 K



Finally, in the tunnel !

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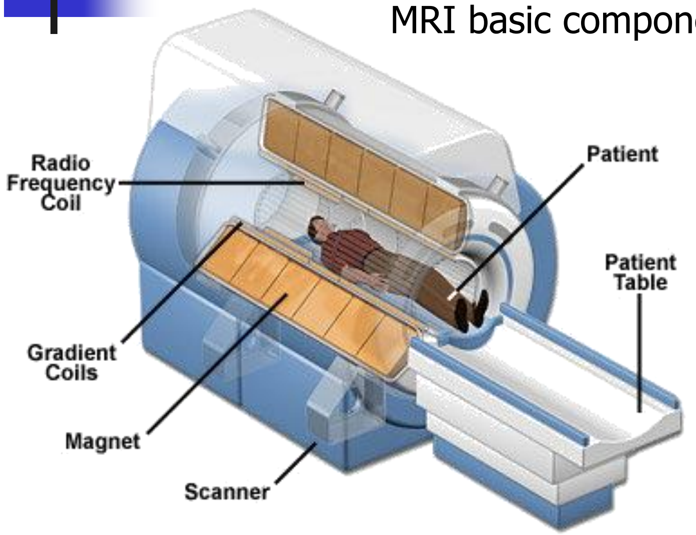
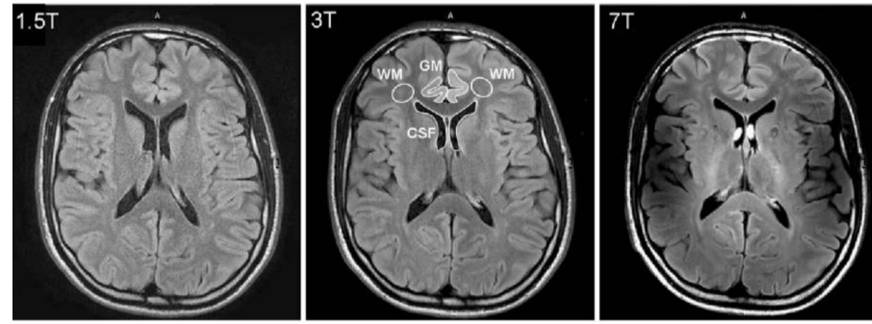
Magnetic Resonance Imaging (MRI)

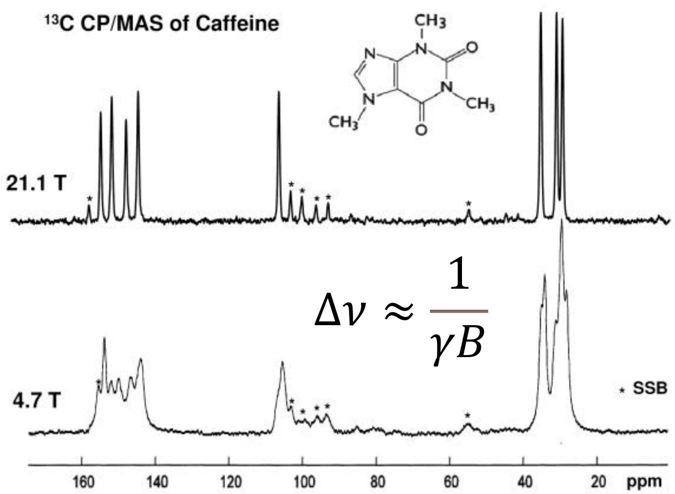
MRI basic components



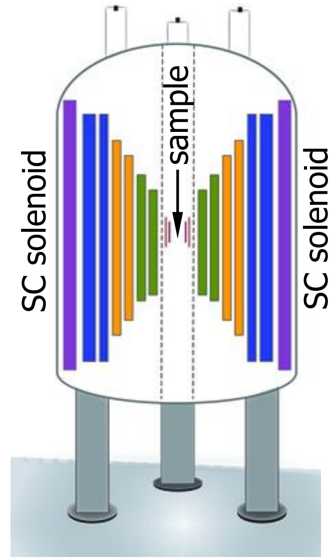


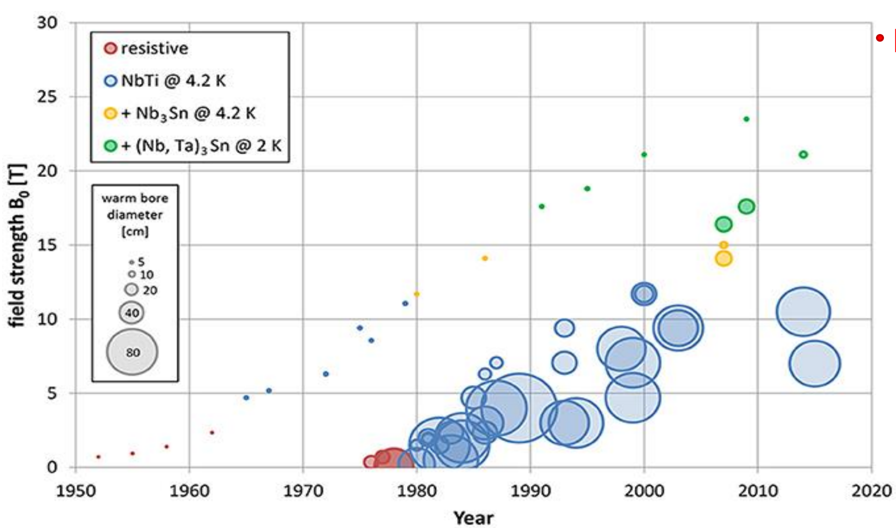
Superconducting magnet manufacturing at Siemens Magnet Technology

Nuclear Magnetic Resonance (NMR)

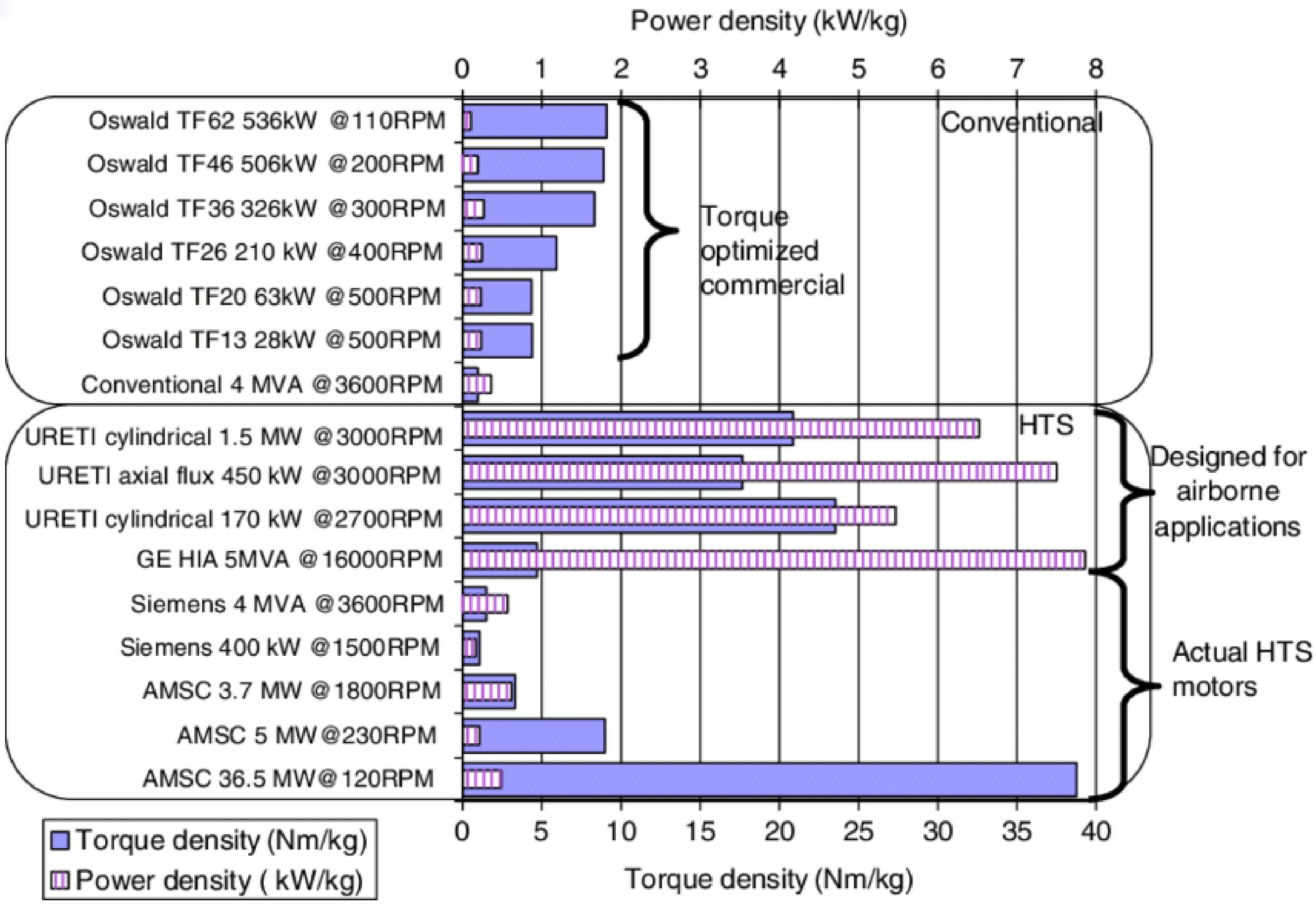


$$\Delta\nu \approx \frac{1}{\gamma B}$$





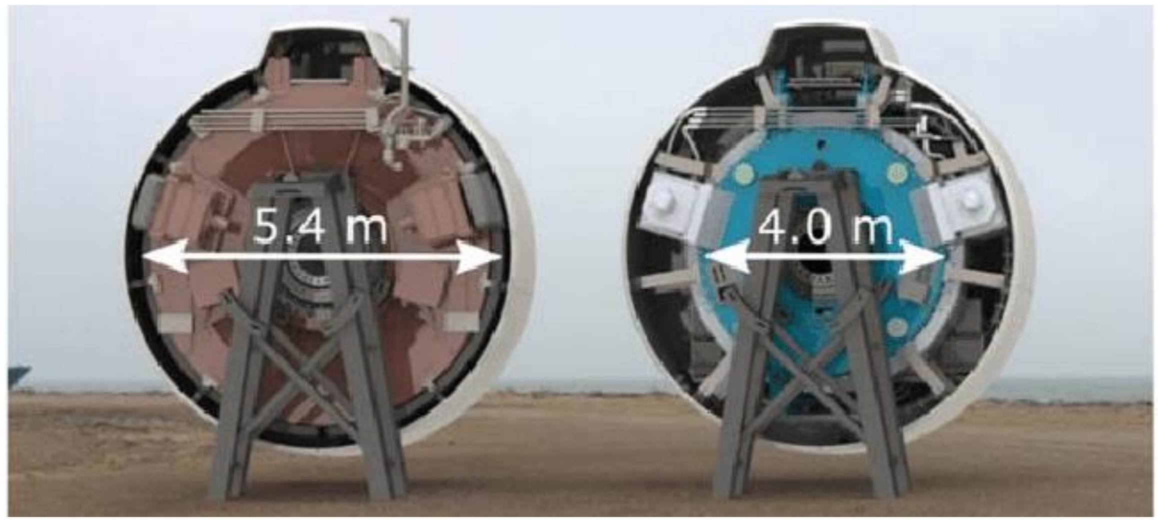
Motors and generators



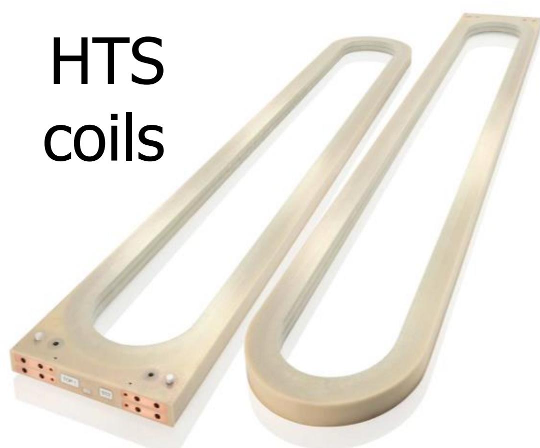
Superconductors offer higher power and torque density

Motors & generators

3.6 MW generator



HTS
coils

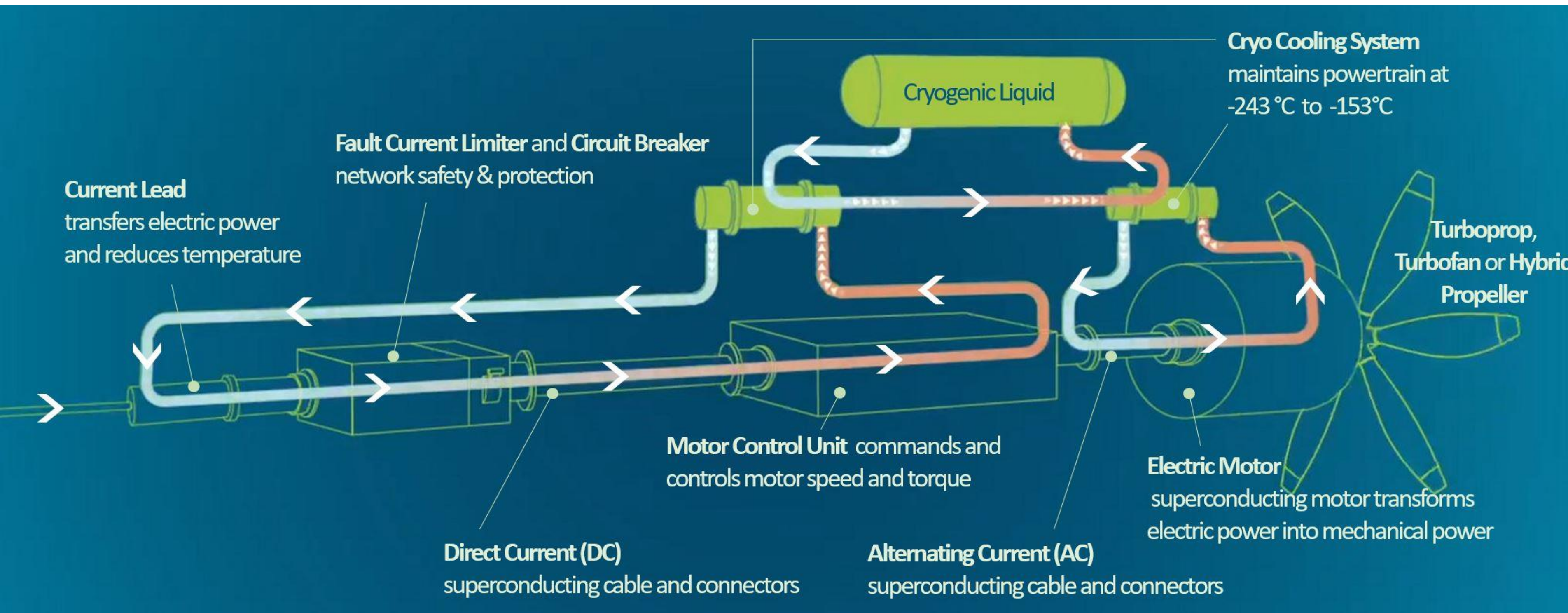


ecoswing

ASCEND

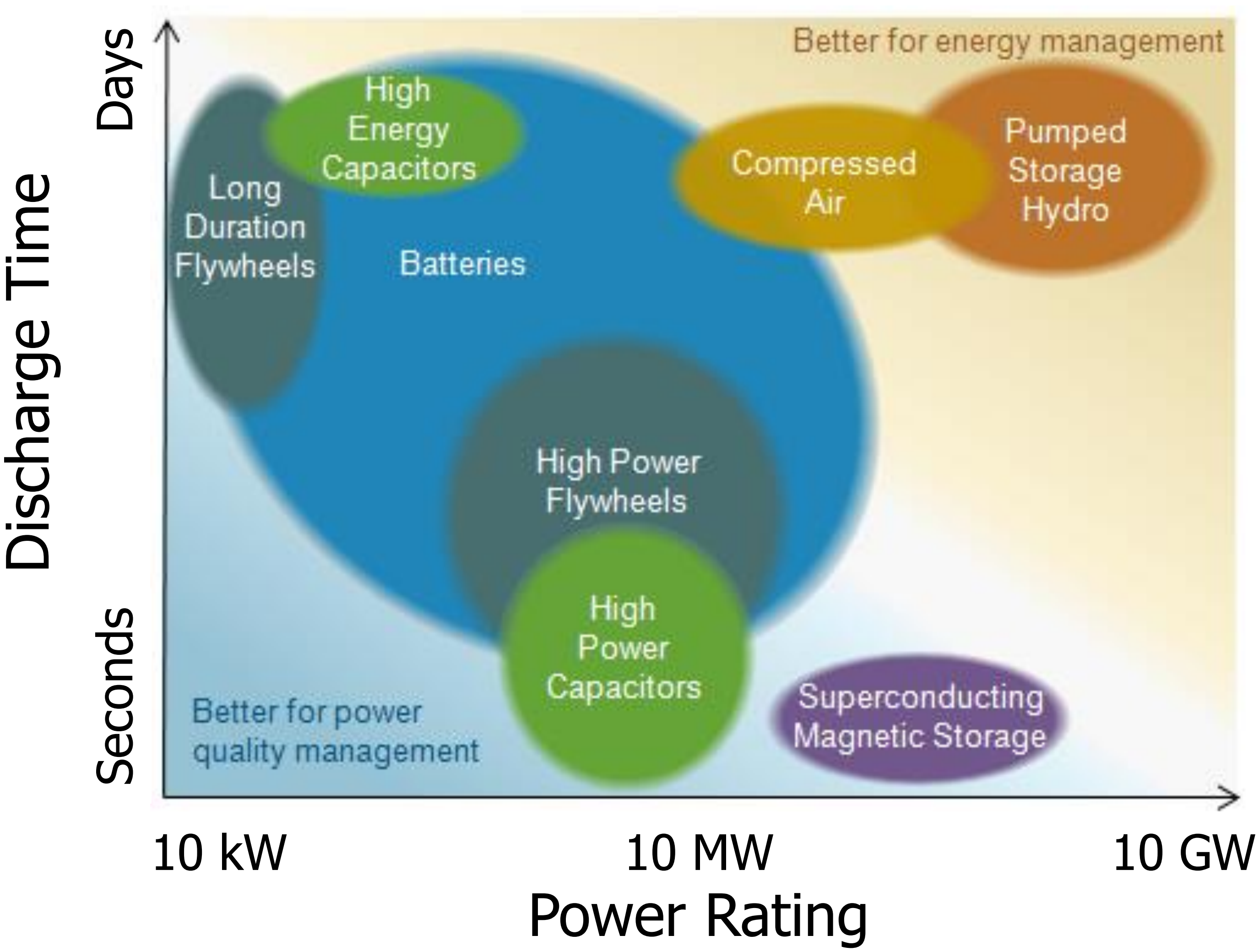
AIRBUS

High power density (motor) and lossless power transmission (cables and leads) to aviation increase efficiency and reduce emissions

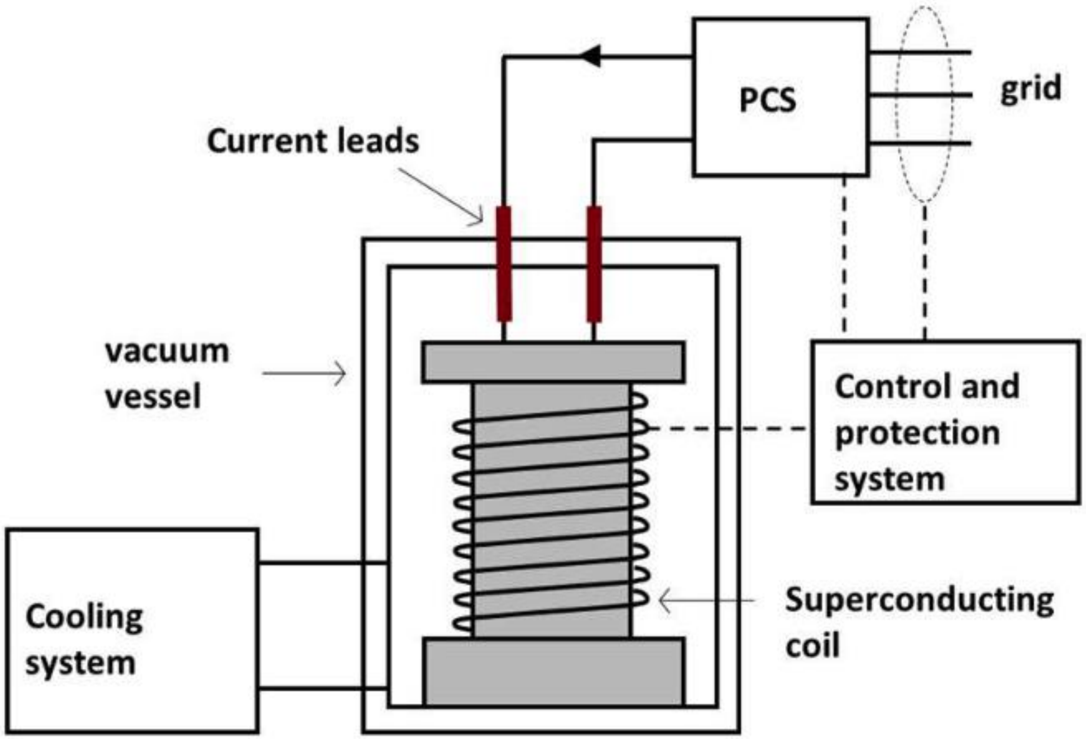


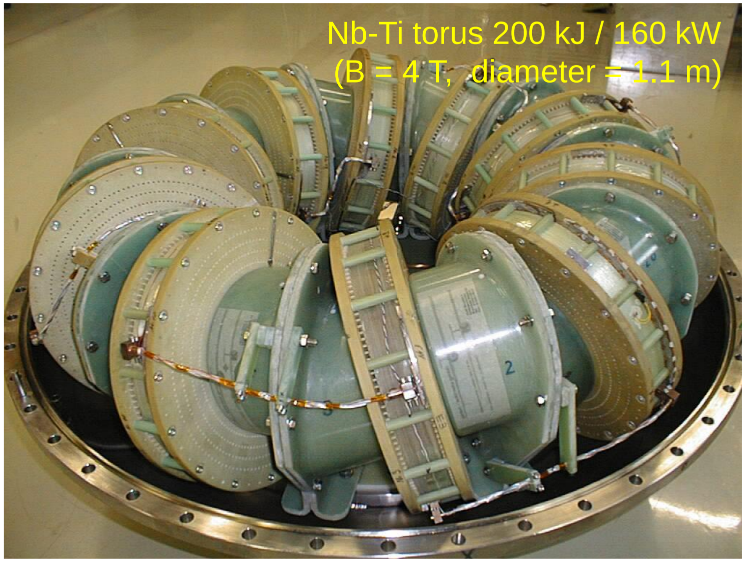
Advanced Superconducting and Cryogenic Experimental powertraiN Demonstrator

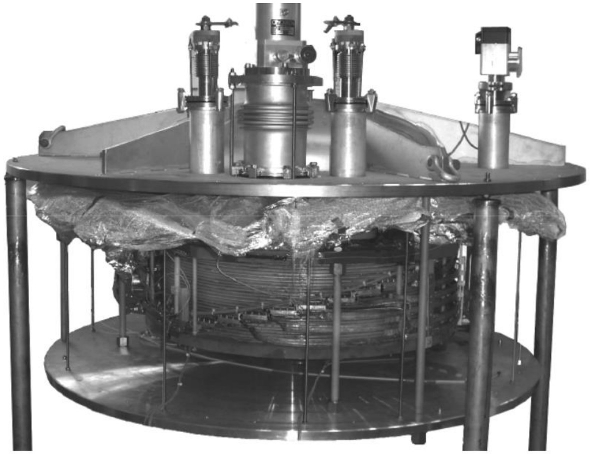
Energy storage by technology



SC Magnetic Energy Storage





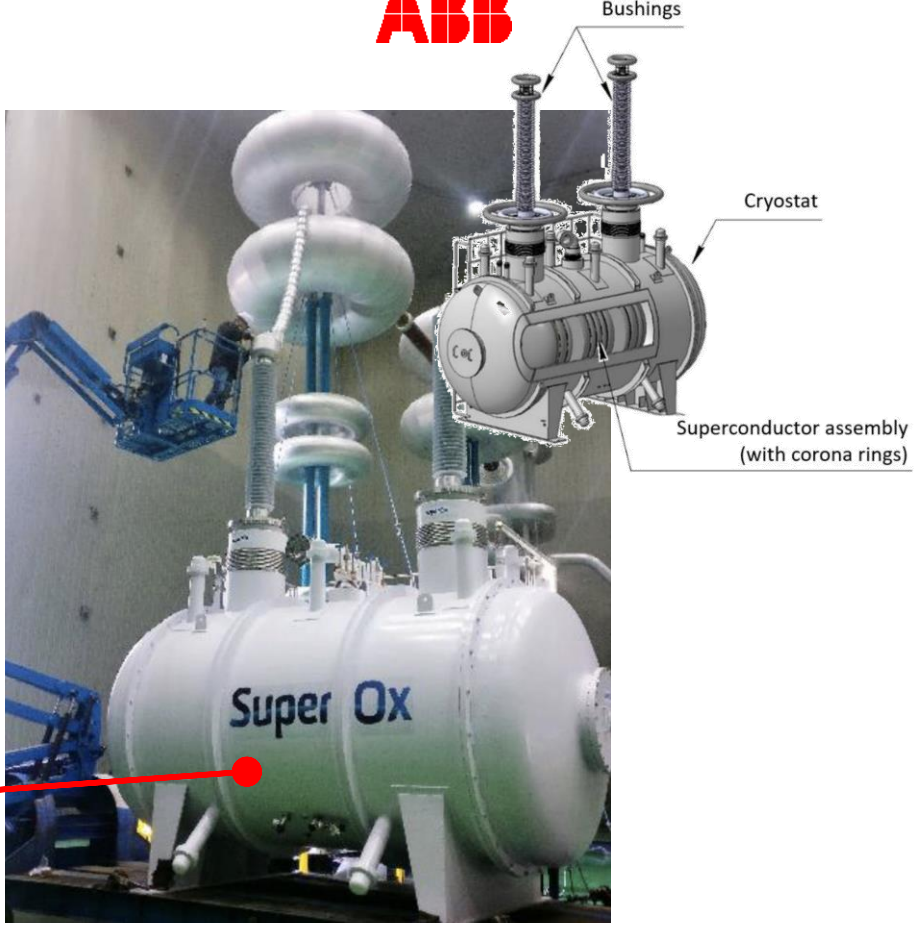


HTS solenoid 814 kJ
(B = 5 T, diameter = 814 mm

Transformers & FCL

HTS Transformer
630 kVA,   18.7kV to 0.42 kV

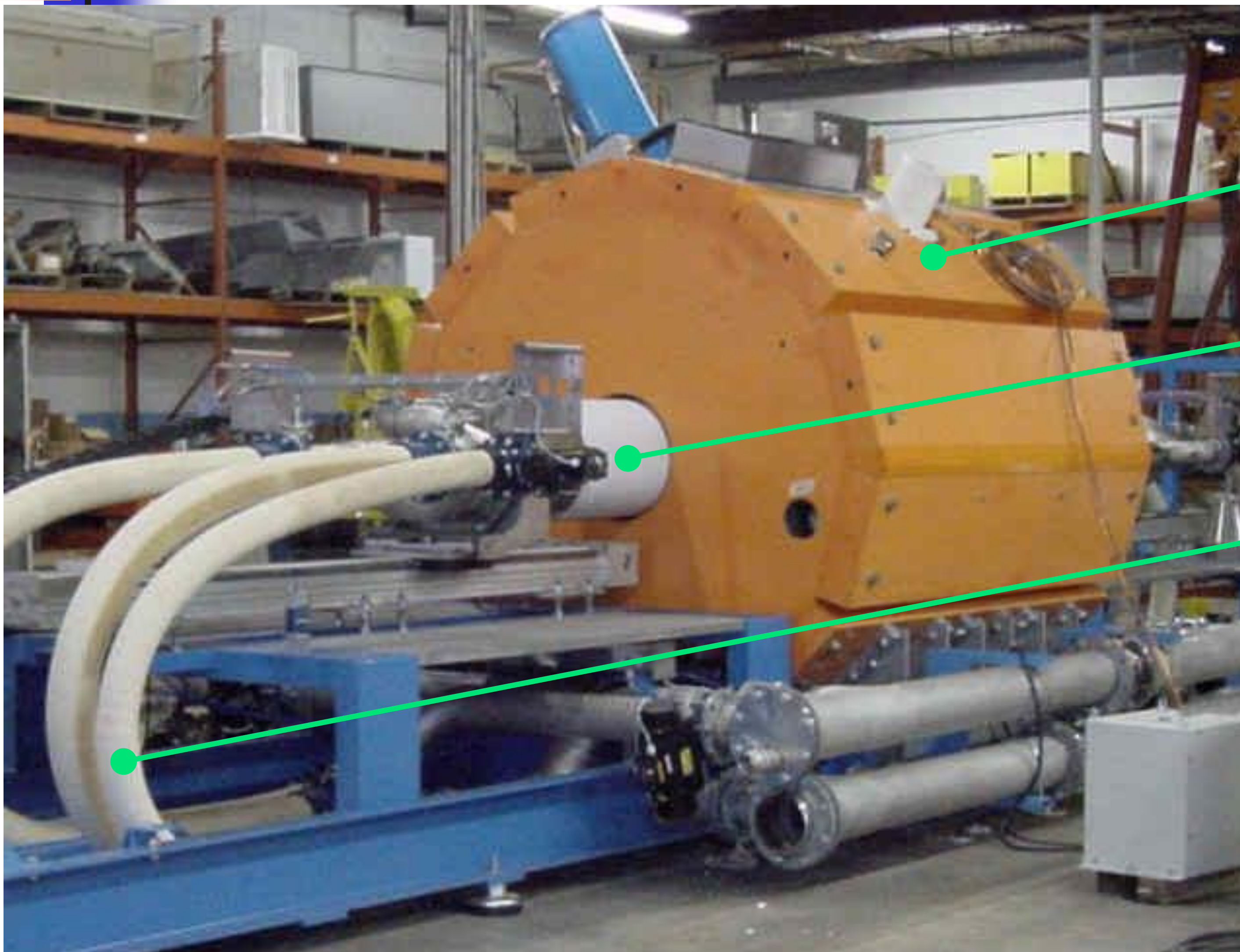
ABB



SC Fault Current Limiter
3.4 kA / 220 kV

SuperOx

Magnetic separation

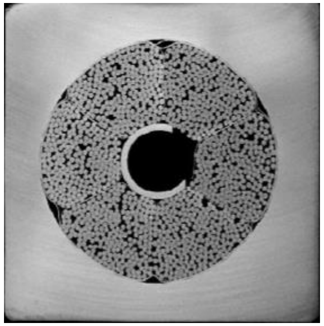


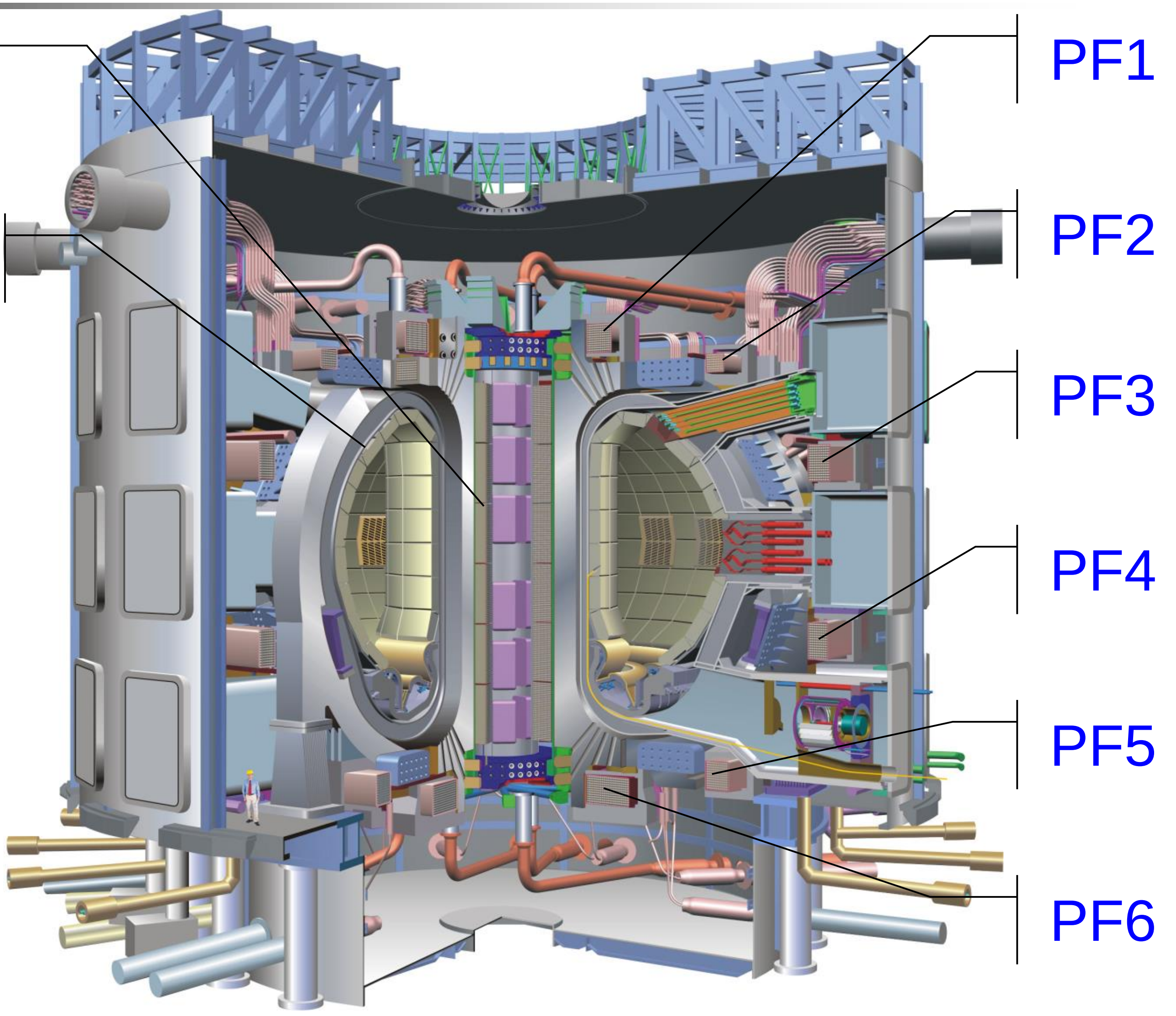
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

Thermonuclear fusion

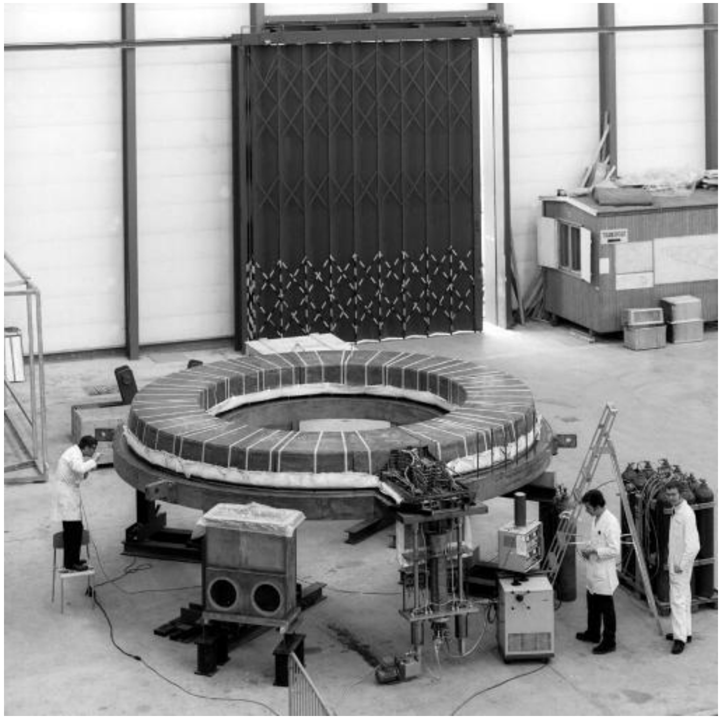




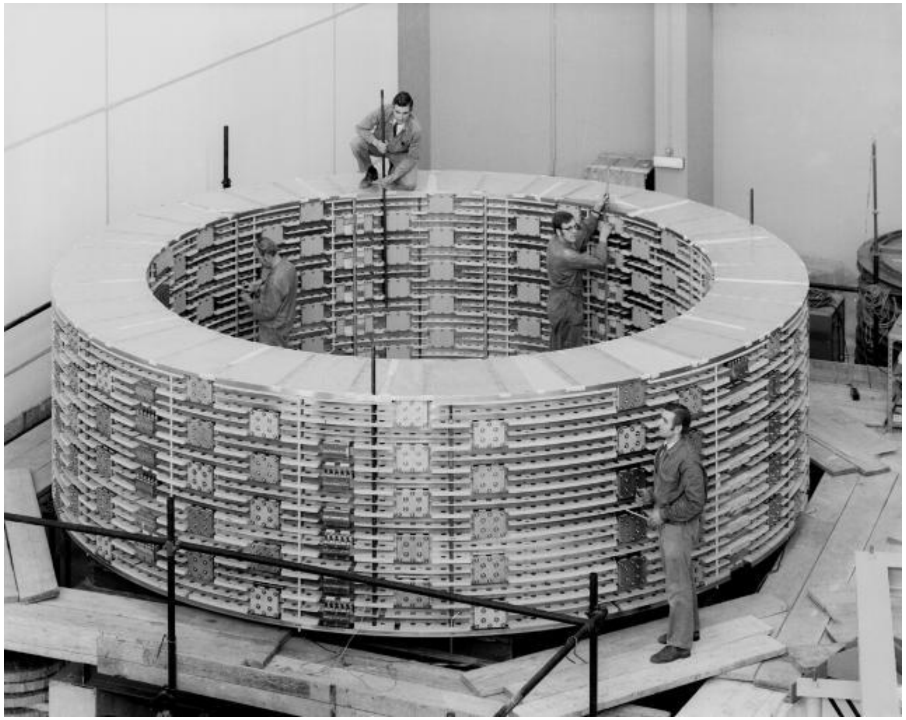
ITER

International
Thermonuclear
Experimental
Reactor

HEP detectors of the past…

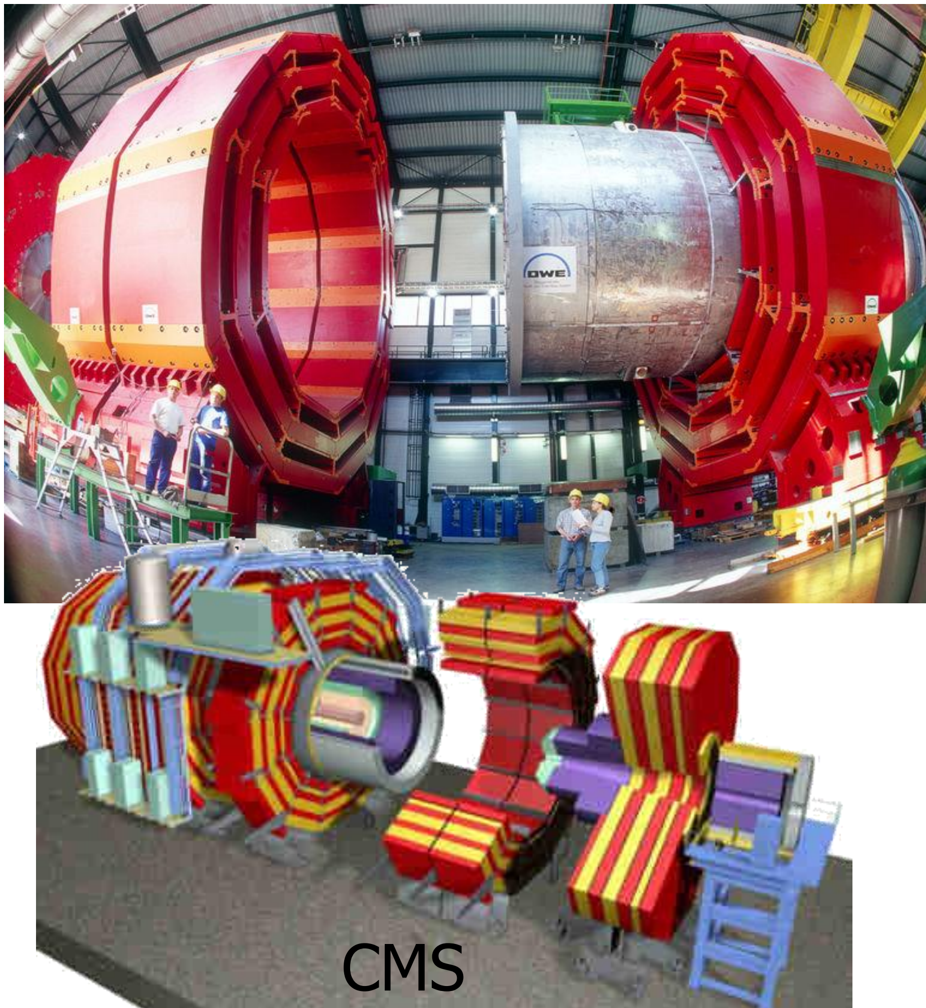


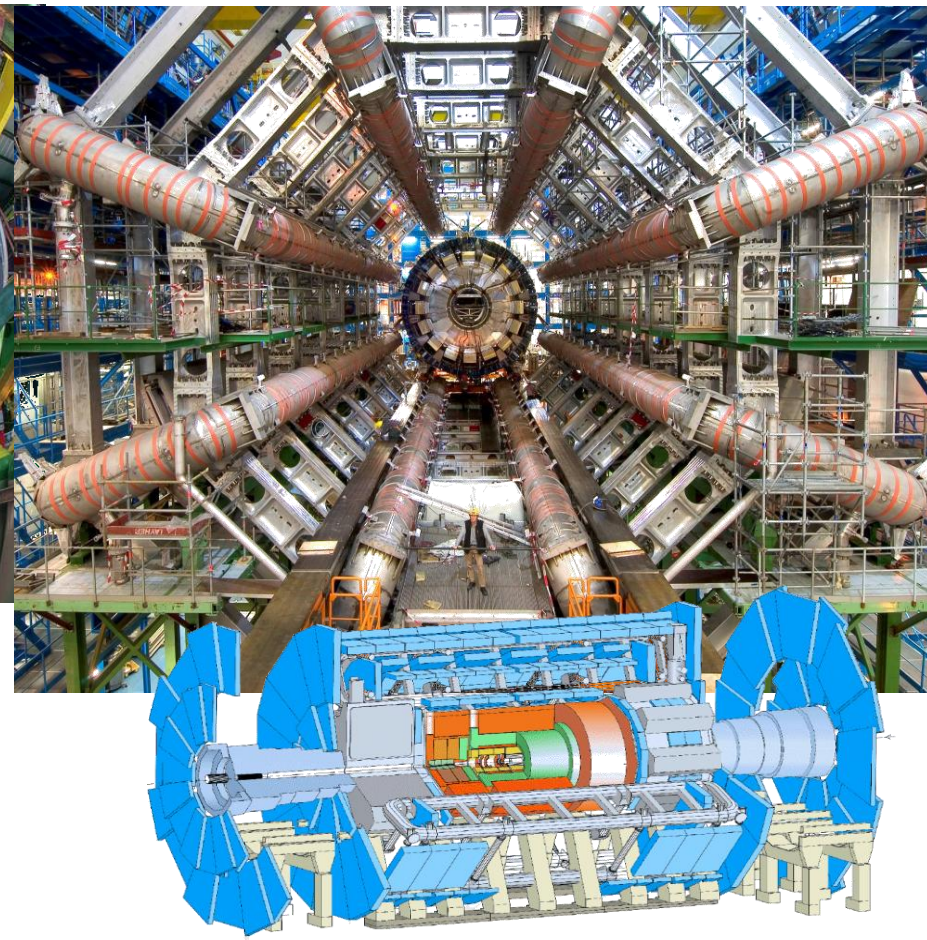
Omega



BEBC

… and HEP of the present (CMS and ATLAS)





ATLAS

Other uses of superconductivity

FOUNDED 1905
BARKING, ESSEX

The Church of the Latter Day Snakes
founded 1905, revived 1950

…we pull back the curtain in the Snake Chamber and I start to rise up from the ground…

We have a big interest in this machine…

…the Natural Law Party… please do not sell them a machine… **they** are very bonkers…

14 April, 1997.

Dear Professor Main,

How big is this magnet, and can it be concealed beneath a floor…

(1) How big is this magnet, and can it be concealed beneath a floor, perhaps? It is important for our ideas that it can not be seen. Will it work if there is wood there? And the floor nails. Will they mess up the magnet?

(2) Does it make much noise, and if so is it a loud noise? A quiet hum would be alright of course because we have a Hammond organ.

Does it make much noise…

Olaf Van Haarve,
The Snakehead.

Does it hurt… because it will be me doing the levitating.

I put in five pounds for you… This is only the start.

Letter to Prof. Main, University of Nottingham, 14 April 1997

A word of closing

- Superconducting magnet design is a lot about superconductors (materials, wires, cables, and their electric and thermal properties)…
- … but not only !
  - High field & forces bear mechanical problems that are tough to solve ($B=10$ T $\Rightarrow$ $p_{mag}=400$ bar !)
  - Materials at low temperature are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - Cooling is an applied science by itself

Where to find out more - 1/3

- Superconducting magnets:
  - Case Studies in Superconducting Magnets: Y. Iwasa, Plenum Press, New York (1994), ISBN 0-306-44881-5.
  - Superconducting Magnets: M.N. Wilson, Oxford University Press (1983) ISBN 0-019-854805-2
  - High Field Superconducting Magnets: F.M. Asner, Oxford University Press (1999) ISBN 0 19 851764 5
  - Superconducting Accelerator Magnets: K.H. Mess, P. Schmuser, S. Wolf, World Scientific, (1996) ISBN 981-02-2790-6
  - Stability of Superconductors: L. Dresner, Plenum Press, New York (1994), ISBN 0-306-45030-5
  - Handbook of Applied Superconductivity ed. B. Seeber, UK Institute Physics 1998
  - Proc Applied Superconductivity Conference: IEEE Trans Magnetics, 1975 to 1991, and IEEE Trans Applied Superconductivity, 1993 to 2012,
  - Proc European Conference on Applied Superconductivity EUCAS, UK Institute Physics
  - Proc International Conference on Magnet Technology; MT-1 to MT-20 (2007) mainly as IEEE Trans Applied Superconductivity and IEEE Trans Magnetics

Where to find out more - 2/3

- Cryogenics
  - Helium Cryogenics S.W. Van Sciver, Plenum Press, 86 ISBN 0-0306-42335-9
  - Cryogenic Engineering, B.A. Hands, Academic Press 86 ISBN 0-012-322991-X
  - Cryogenics: published monthly by Elsevier
- Materials - Superconducting properties
  - Superconductor Science and Technology, published monthly by Institute of Physics (UK).
  - IEEE Trans Applied Superconductivity, published quarterly
  - Superconductivity of metals and Cuprates, J.R. Waldram, Institute of Physics Publishing (1996) ISBN 0 85274 337 8
  - High Temperature Superconductors: Processing and Science, A. Bourdillon and N.X. Tan Bourdillon, Academic Press, ISBN 0 12 117680 0

Where to find out more - 3/3

- Materials - Mechanical properties
  - Materials at Low Temperature, Ed. R.P. Reed and A.F. Clark, Am. Soc. Metals 1983. ISBN 0-87170-146-4
  - Handbook on Materials for Superconducting Machinery, Batelle Columbus Laboratories, 1977.
  - Nonmetallic materials and composites at low temperatures, Ed. A.F. Clark, R.P. Reed, G. Hartwig, Plenum Press
  - Nonmetallic materials and composites at low temperatures 2, Ed. G. Hartwig, D. Evans, Plenum Press, 1982