Applied Superconductivity for Accelerator Magnets

Luca.Bottura@cern.ch

Summer Student Lecture 2011

Overview

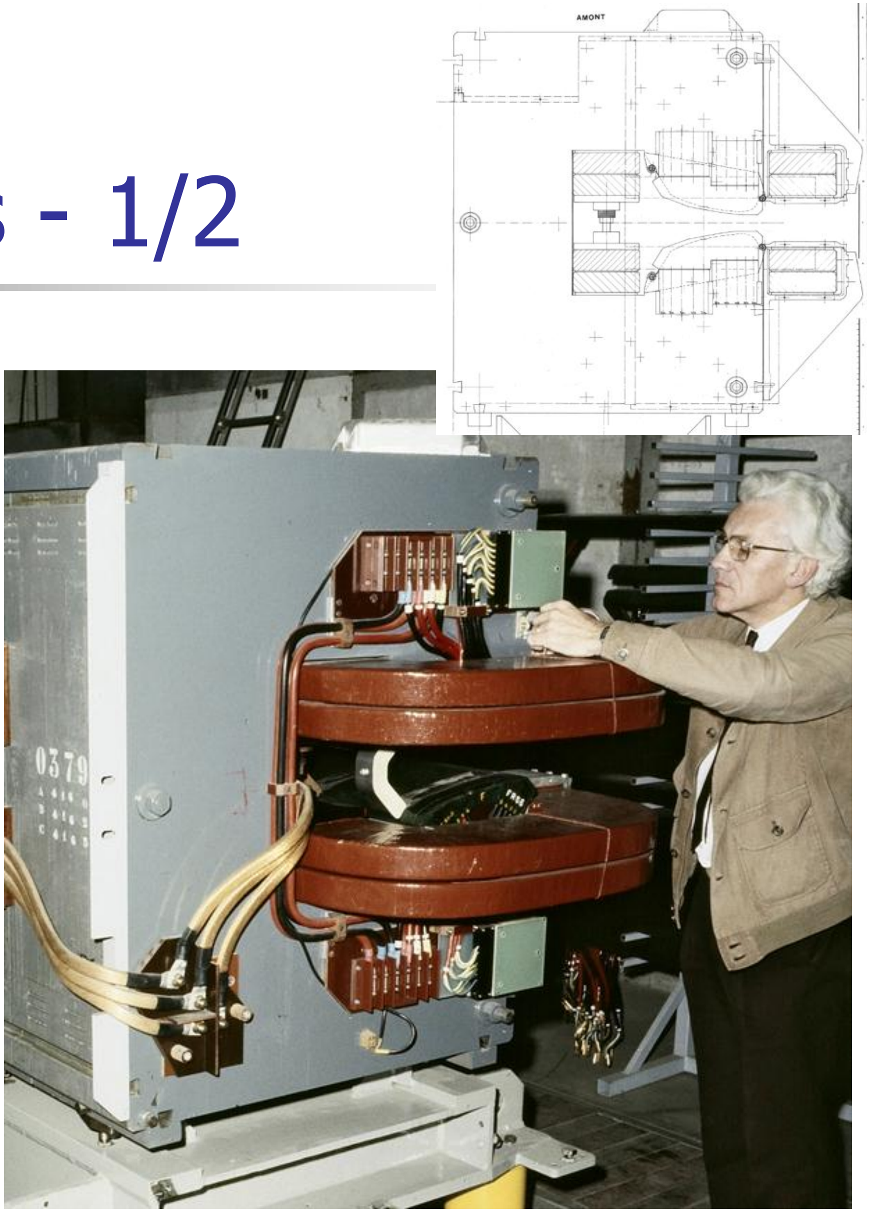
- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
- The making of a superconducting magnet
- Examples of superconducting magnet systems

Overview

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

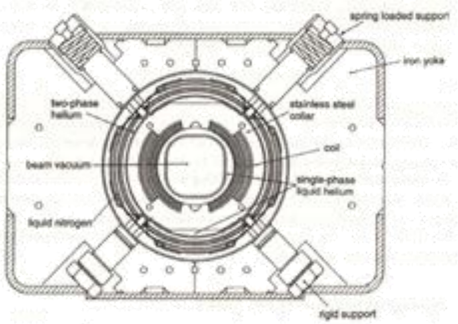
NC vs. SC Magnets - 1/2

- *Normal conducting* accelerator magnets
  - *Magnetization* ampere-turns are *cheap*
  - Field is generated by the iron yoke (but limited by saturation to ≈ 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)

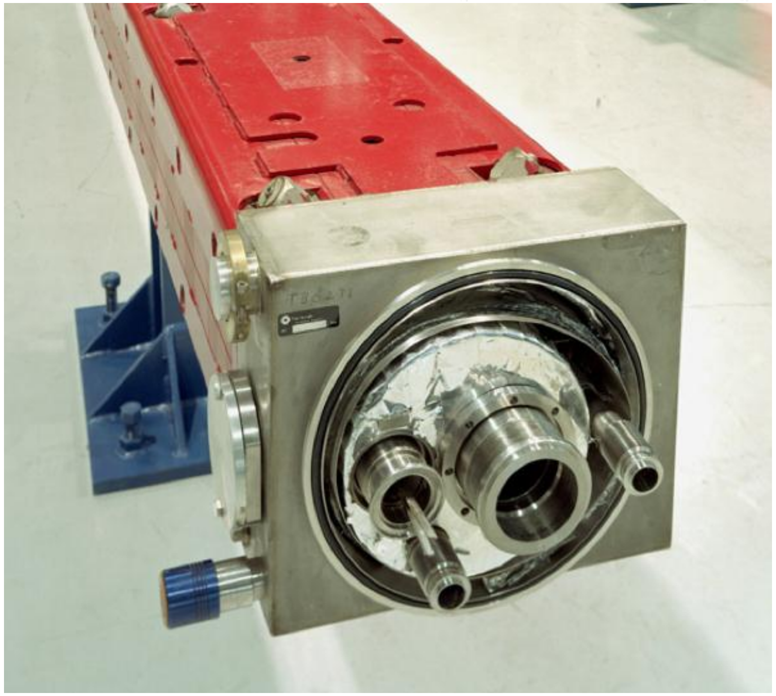


One of the dipole magnets of the PS, in operation at CERN since 51 years

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 to ≈ 10 T for Nb-Ti)
  - High current density, compact, low mass of high-tech SC material (cost driver)
  - Requires efficient and reliable cryogenics cooling for operation (availability driver)

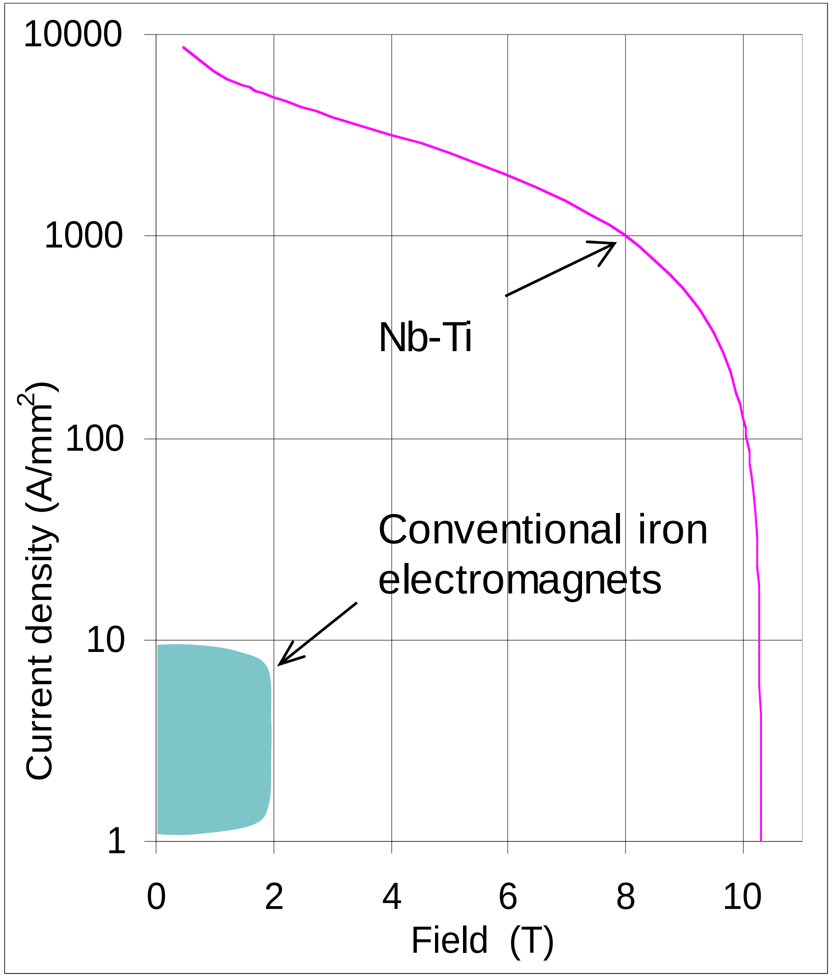


A superconducting dipole magnet of the Tevatron at FNAL, the first superconducting synchrotron, 1983

Graphics by courtesy of M.N. Wilson

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



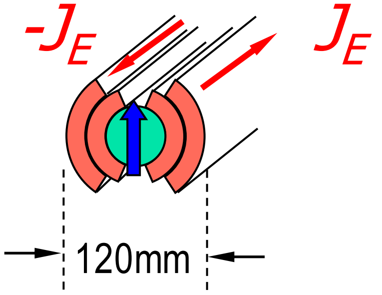
Graphics by courtesy of M.N. Wilson

High current density - dipoles

- The field produced by an ideal dipole is:

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

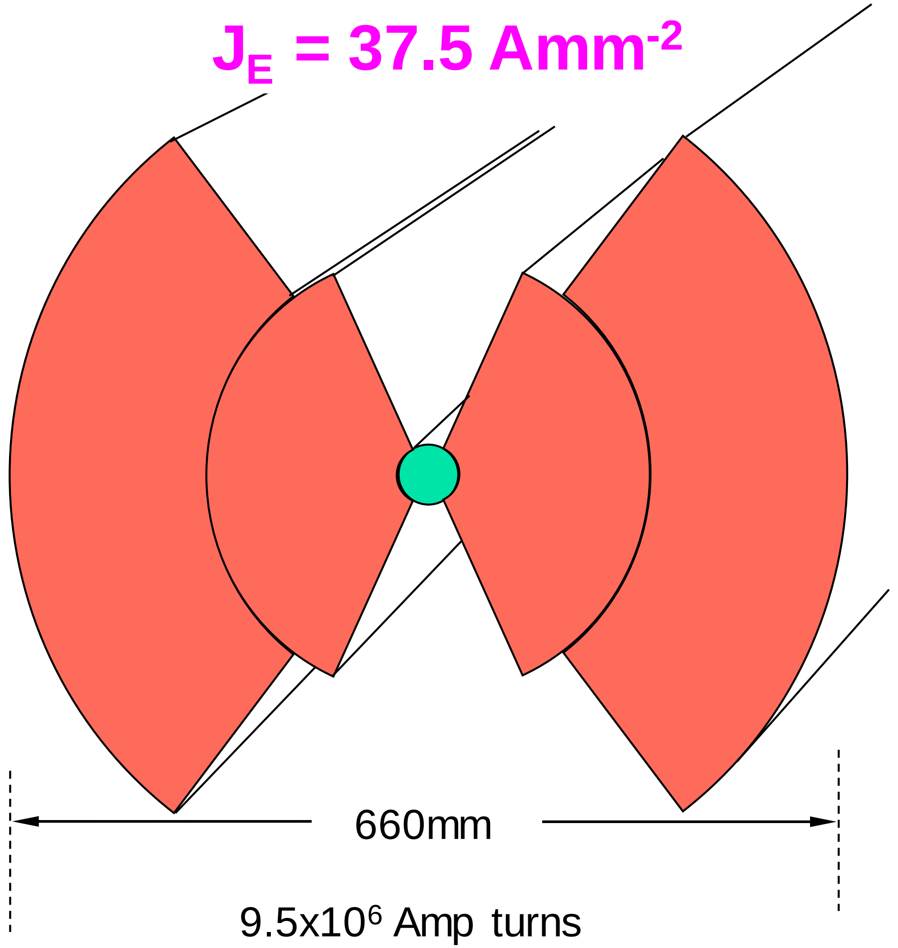
J_E = 375 Amm^{-2}



LHC dipole

9.5x10^5 Amp turns
=1.9x10^6 A.m per m

J_E = 37.5 Amm^{-2}



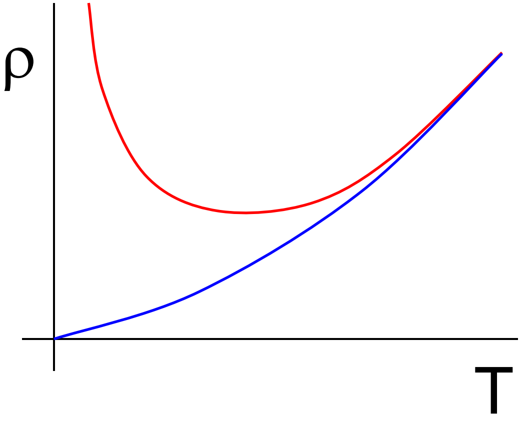
9.5x10^6 Amp turns
=1.9x10^7 A.m per m

Overview

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

A great physics problem in 1900

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



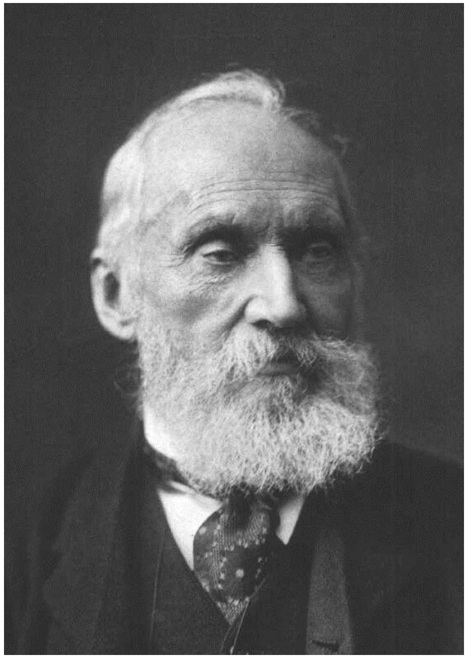
… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

“*X-rays are an hoax*”

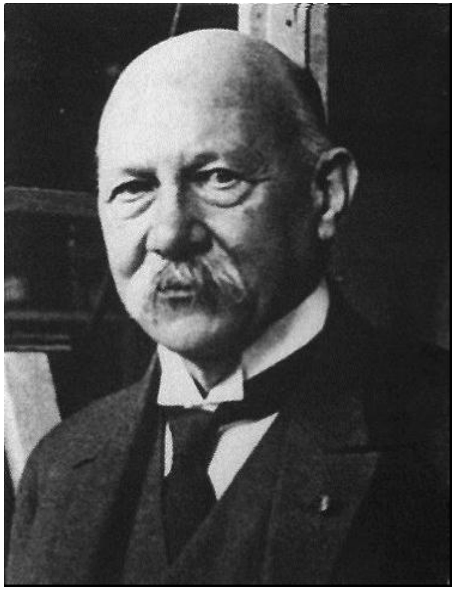
“*I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of*”

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

W. Thomson (Lord Kelvin)

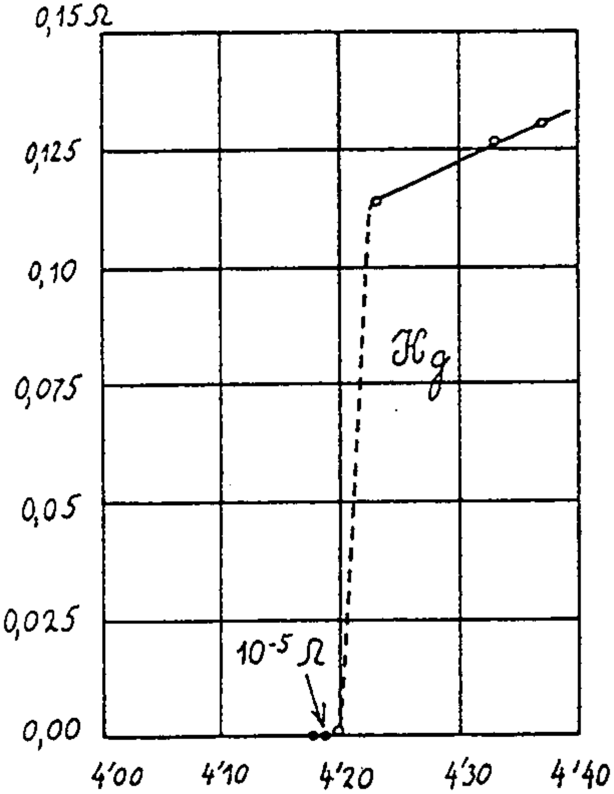


Superconductors Pre-history



… 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*…

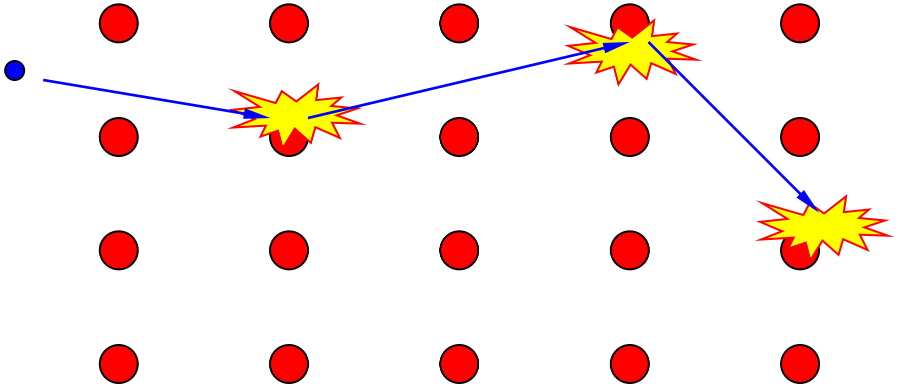
H. Kamerlingh-Onnes (1911)



Cooper Pairs

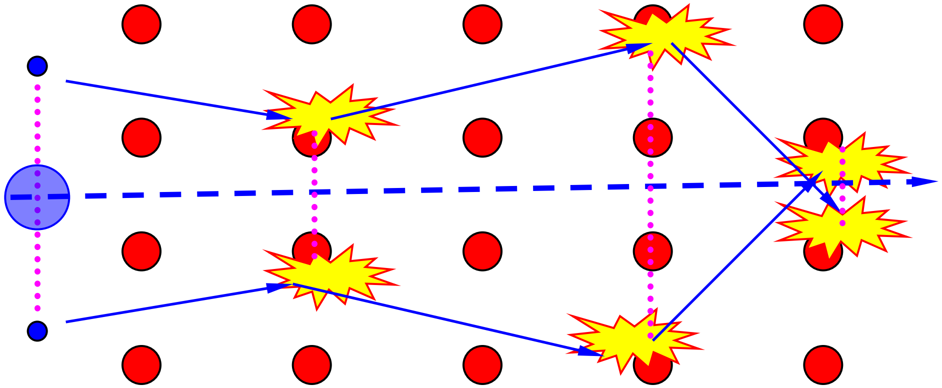
Bardeen, Cooper and Schrieffer

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



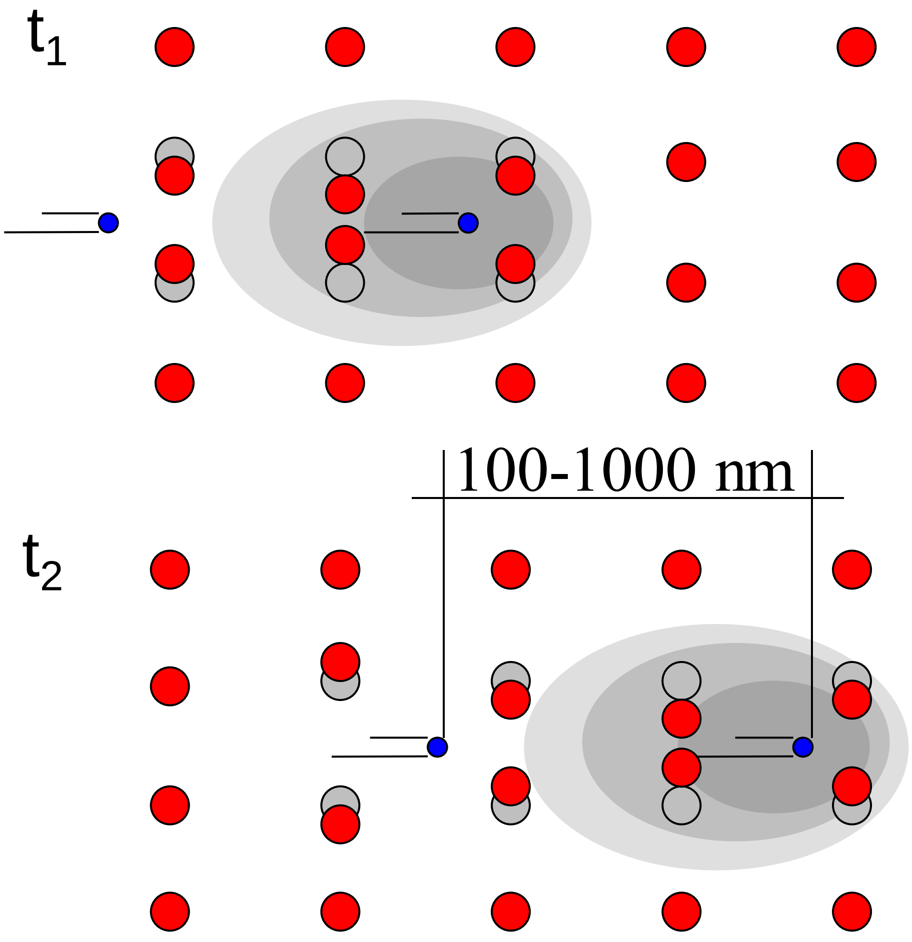
Proper physics: a gas of Fermions. The conduction electrons at the Fermi surface have large energy (few eV) and interact with lattice defects, displacements or thermal excitations (hence $\rho(T)$)

- 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)

Solvay conference (1914)

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)

Superconductivity languished for 40 years…

Flourishing of materials, but depressing Tc…

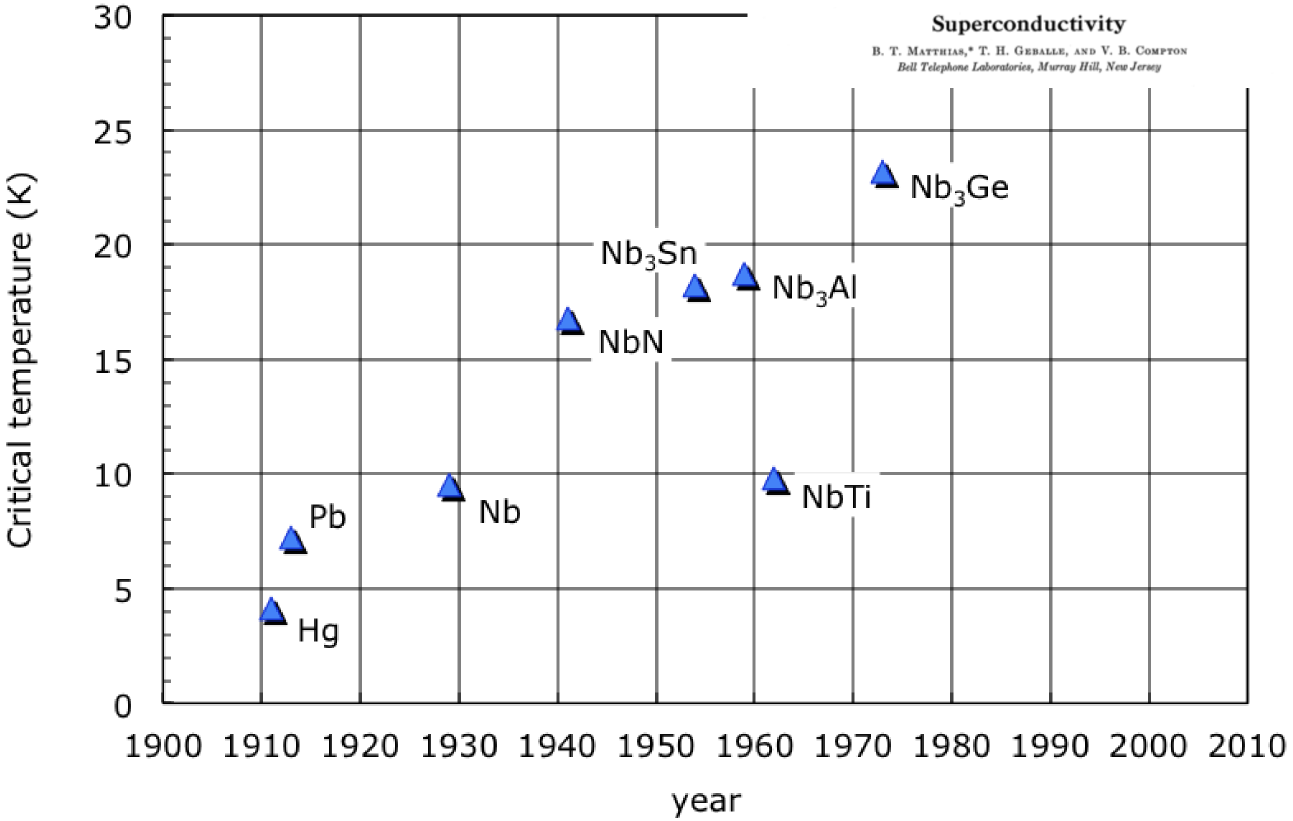
Theoretical limit
around **30 K**

REVIEWS OF
MODERN PHYSICS

VOLUME 35, NUMBER 1 JANUARY 1963

Superconductivity

B. T. MATTHIAS,* T. H. GEBALLE, AND V. B. COMPTON
Bell Telephone Laboratories, Murray Hill, New Jersey

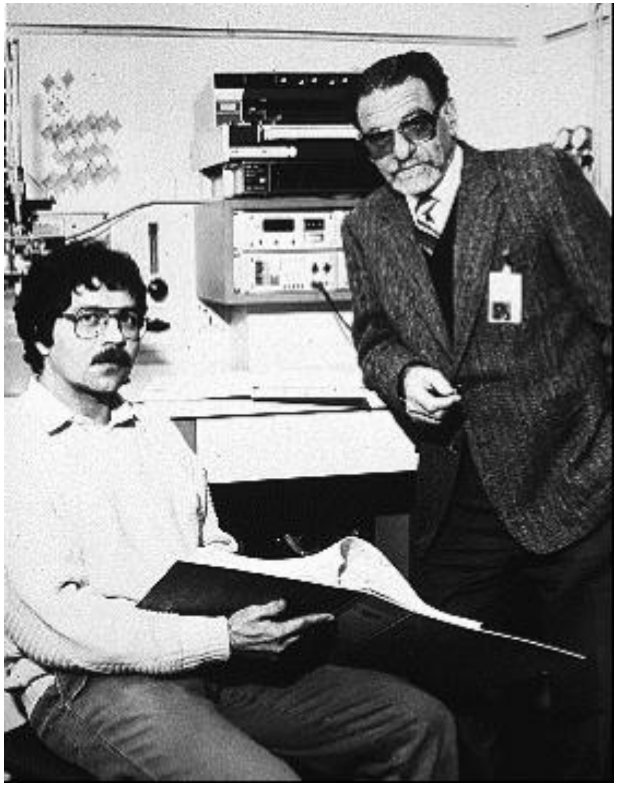


One Thousand and
One Superconductors
B. Matthias (1918-1980)

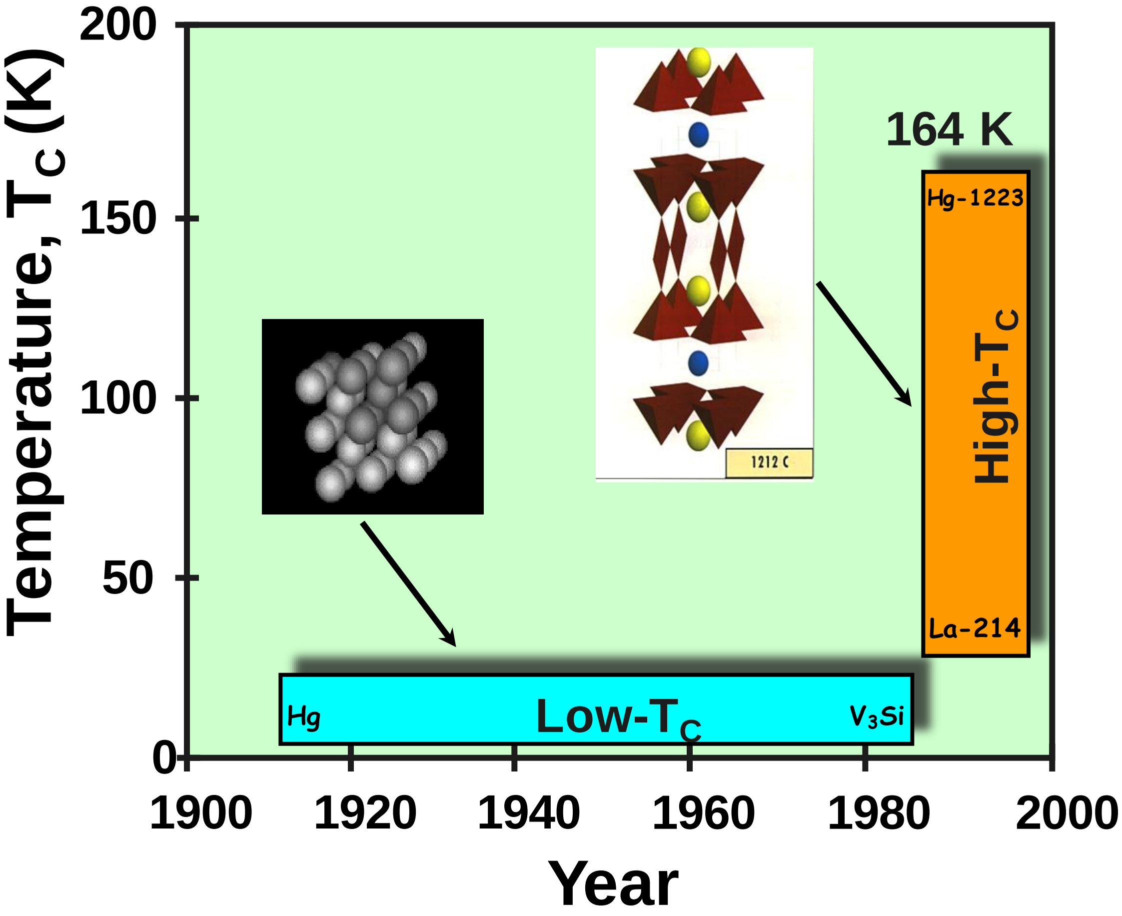
Superconductivity was a *physicist playground* till the late 1950's

Graphics by courtesy of P. Grant

1986 - A Big Surprise



Bednorz and Mueller
IBM Zuerich, 1986



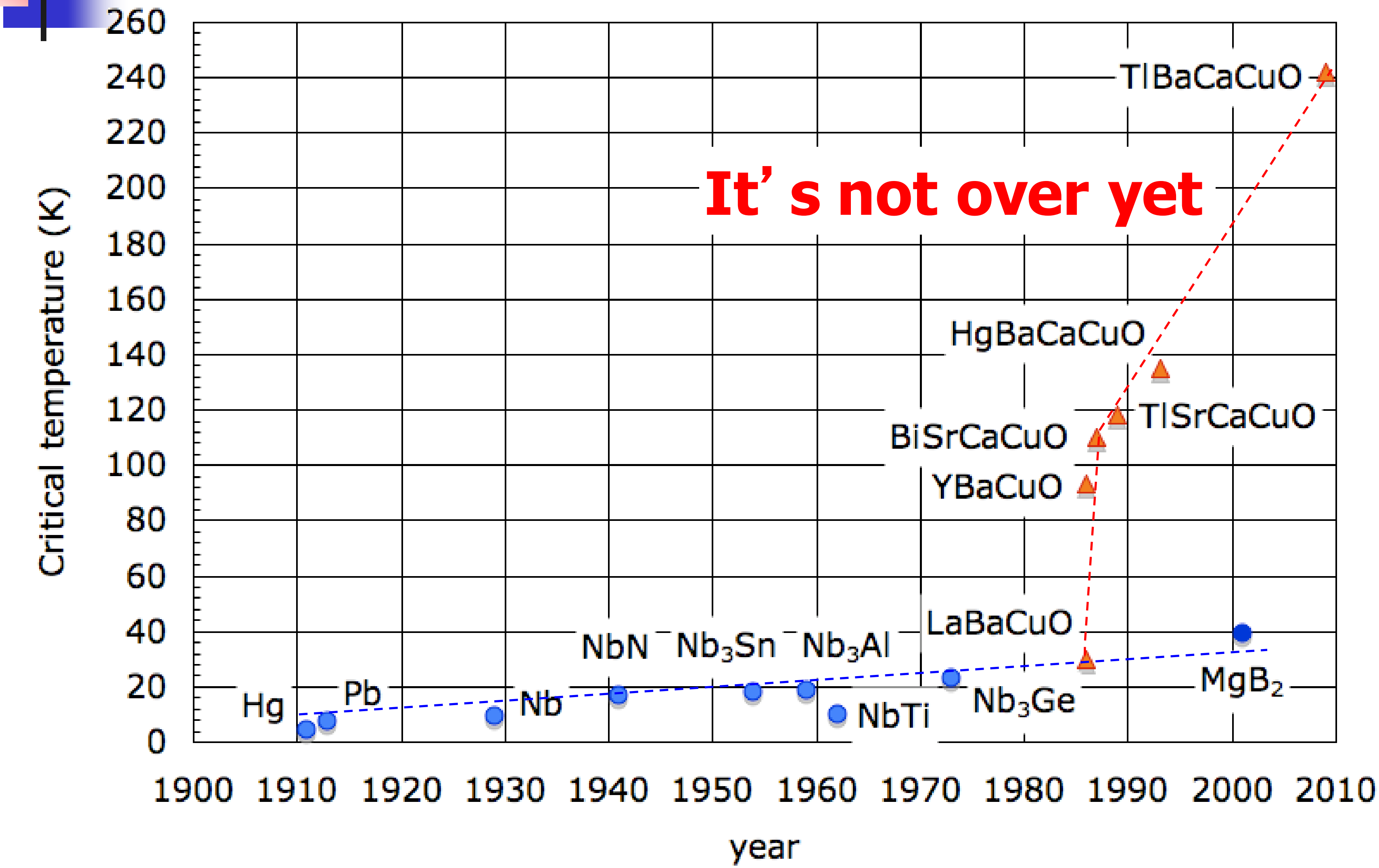
1987 - The prize !

Associated Press

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

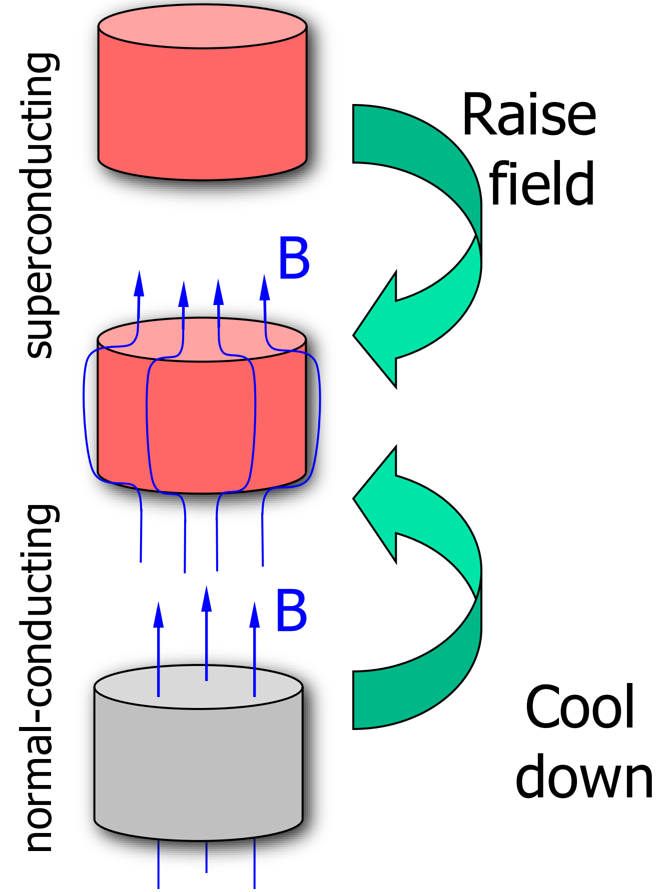
2 Get Nobel for Unlocking Superconductor Secret

High-Tc timeline - impressive !!!



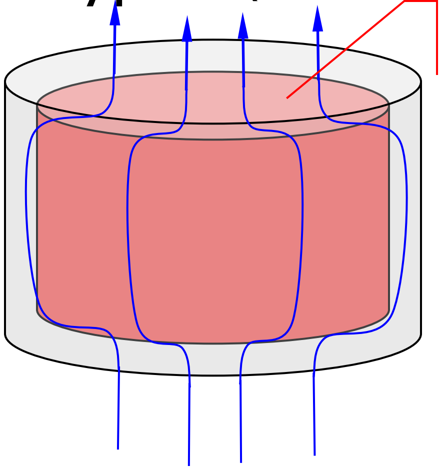
Hey, what about field ?

Landau, Ginsburg and Abrikosov



Meissner & Ochsenfeld, 1933

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



Complete field exclusion

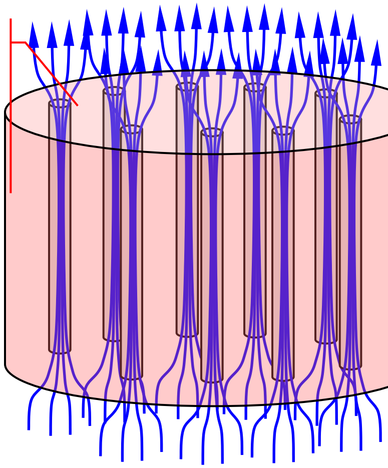
Pure metals

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

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

Partial field exclusion

Lattice of fluxons



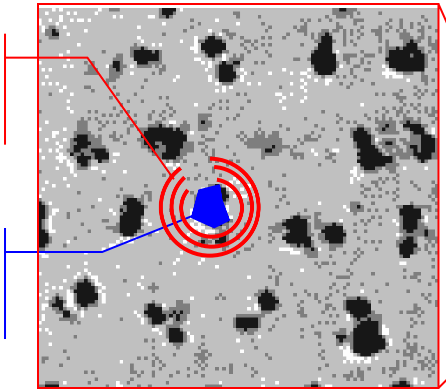
Dirty materials: alloys intermetallic, ceramic

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

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

Graphics by courtesy of Superconductor Lab, Oslo

Lattice of quantum flux lines



Supercurrent

Flux quantum

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

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

Essmann & Träuble, 1967

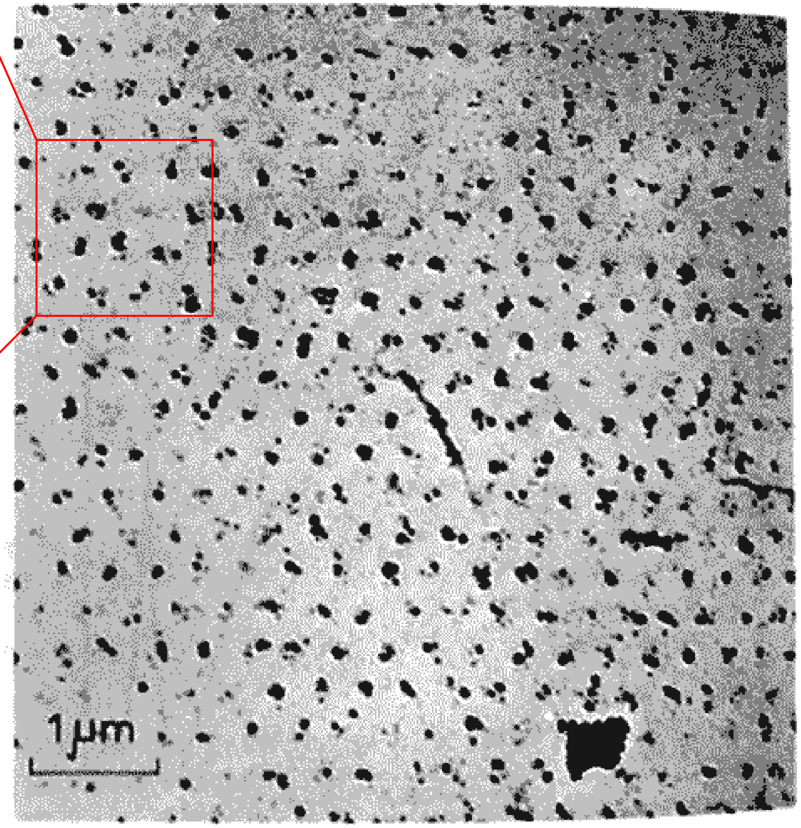
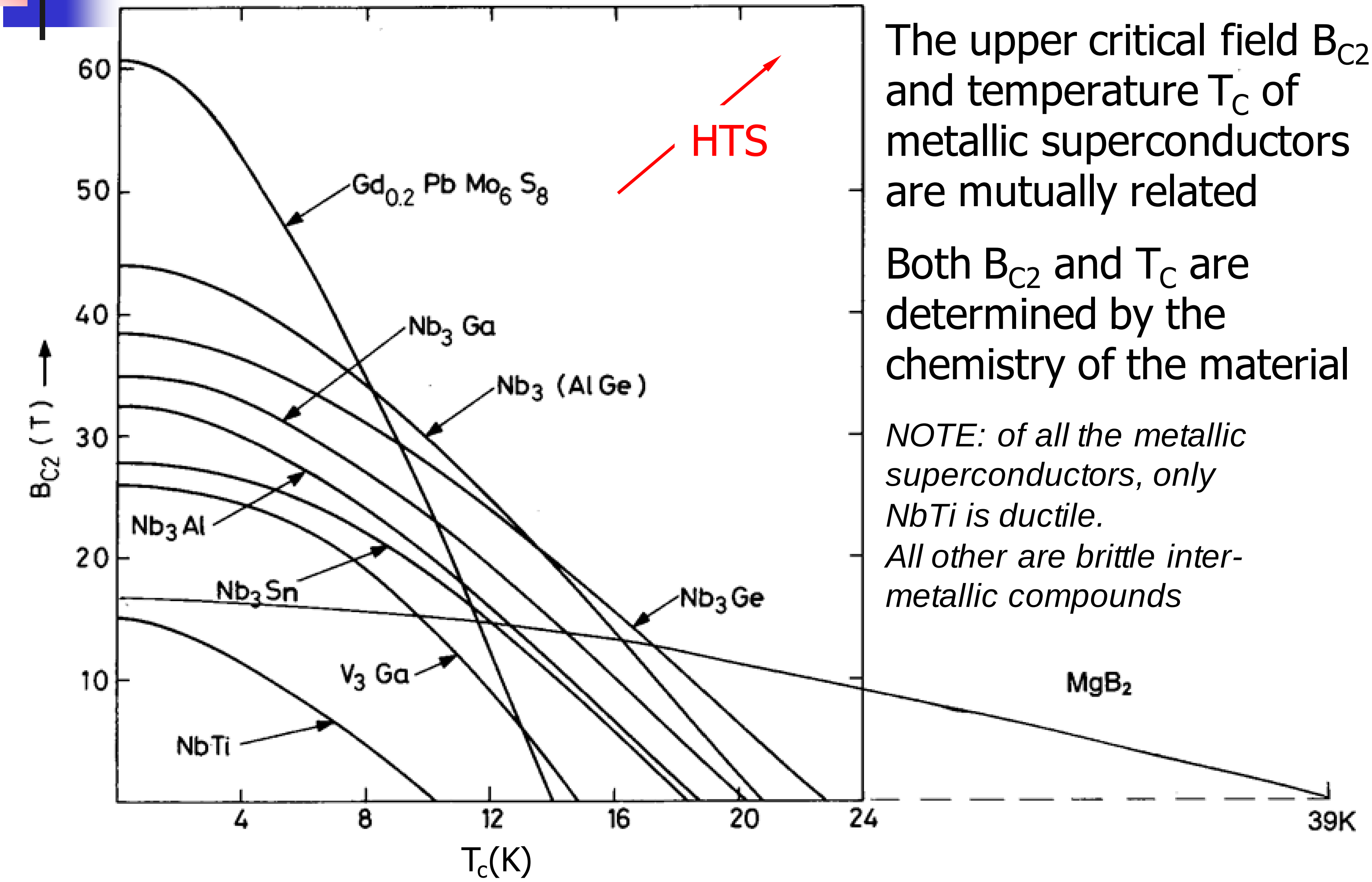


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Graphics by courtesy of M.N. Wilson

Critical temperature and 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

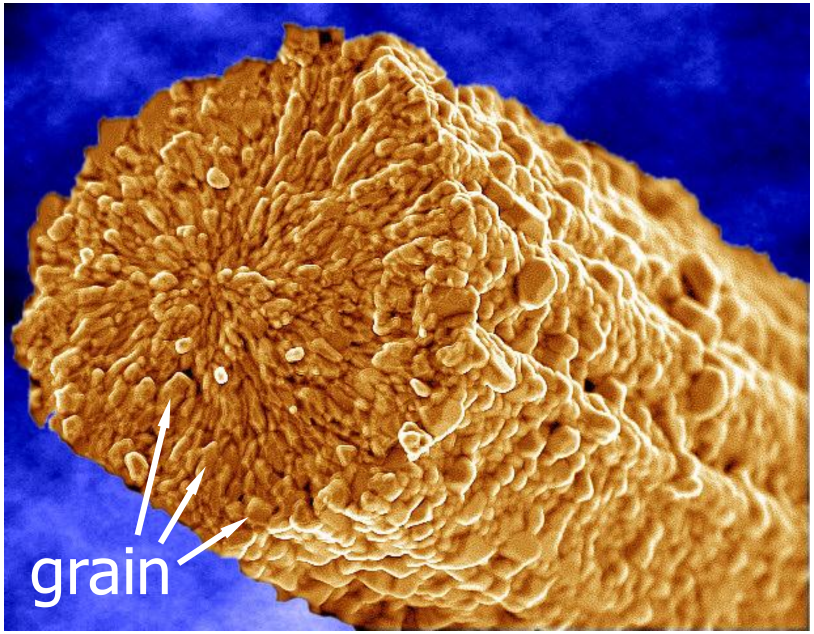
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning mechanisms

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds



Microstructure of Nb_3Sn

Jc(B,T,…)

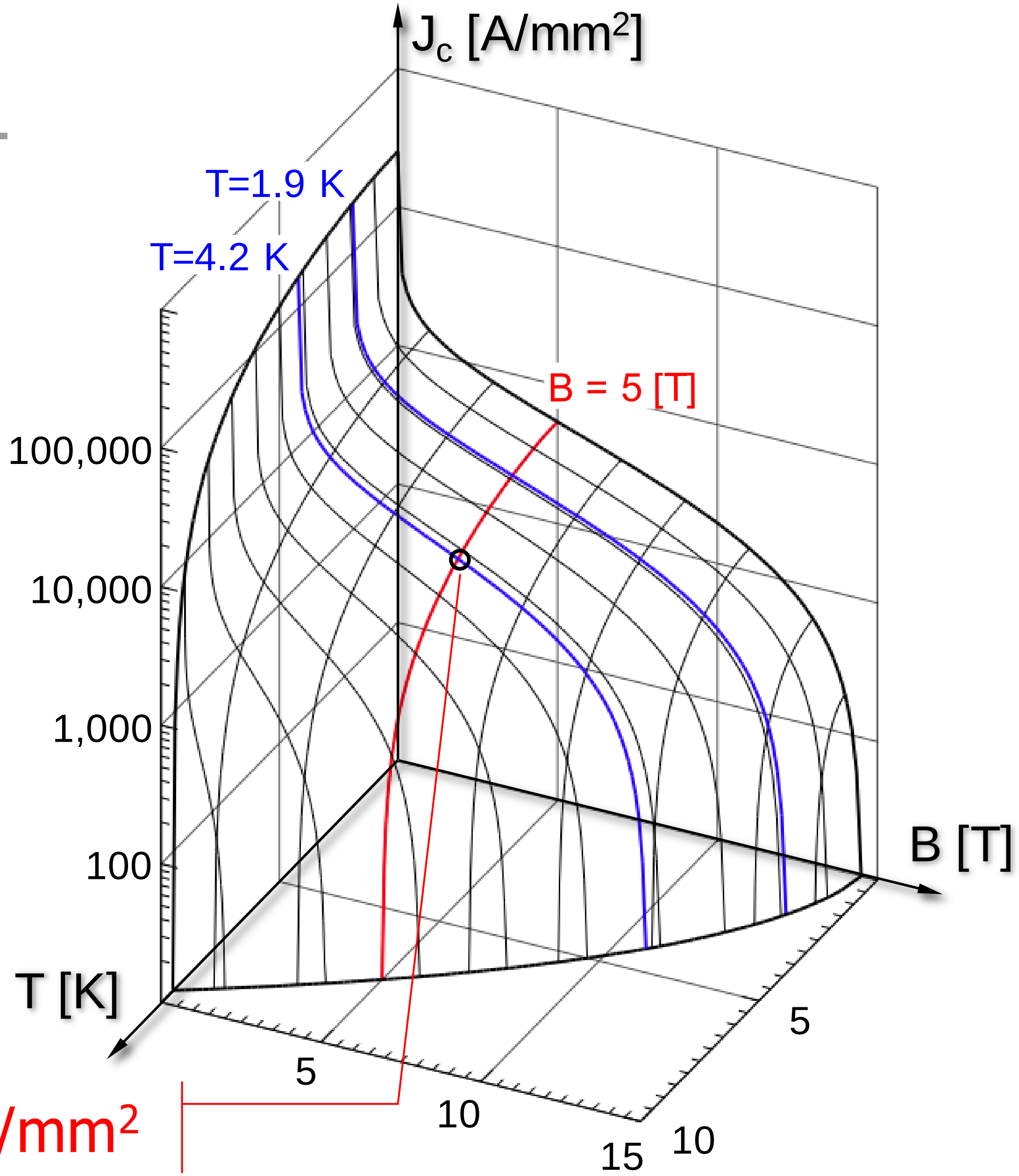
- The maximum current that can be carried by the superconductor is the current at which:

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

- 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/mm^2

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 $I_C = A_{SC} \times J_C$

Overview

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

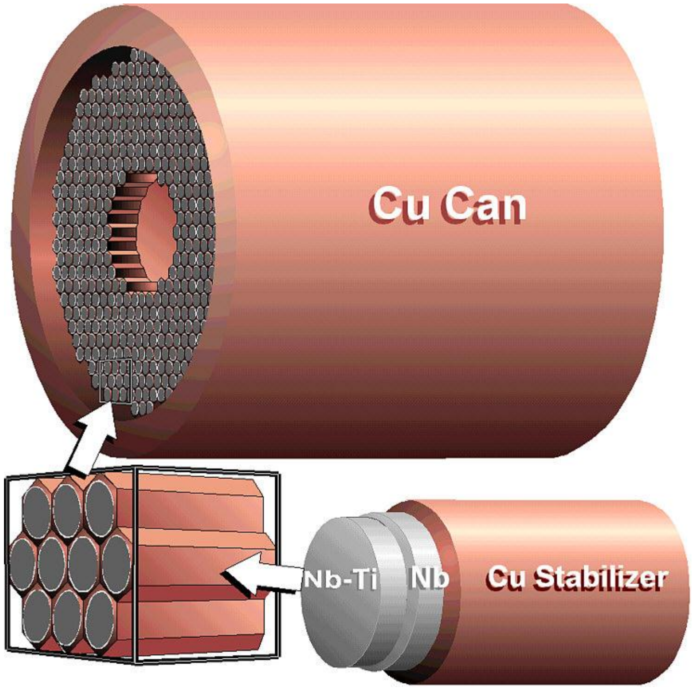
From materials to magnets

- 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)

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb-Ti manufacturing route

NbTi billet

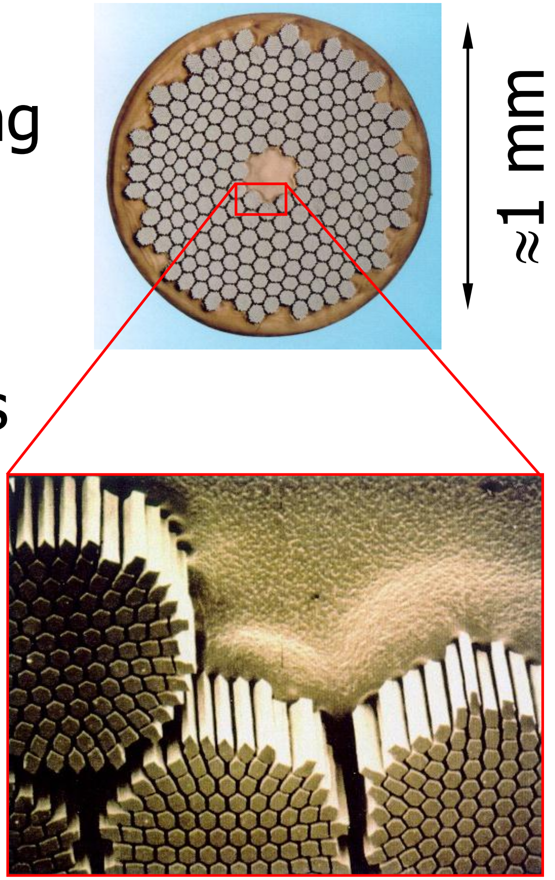


NbTi is a ductile alloy that can sustain large deformations

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

extrusion
cold drawing

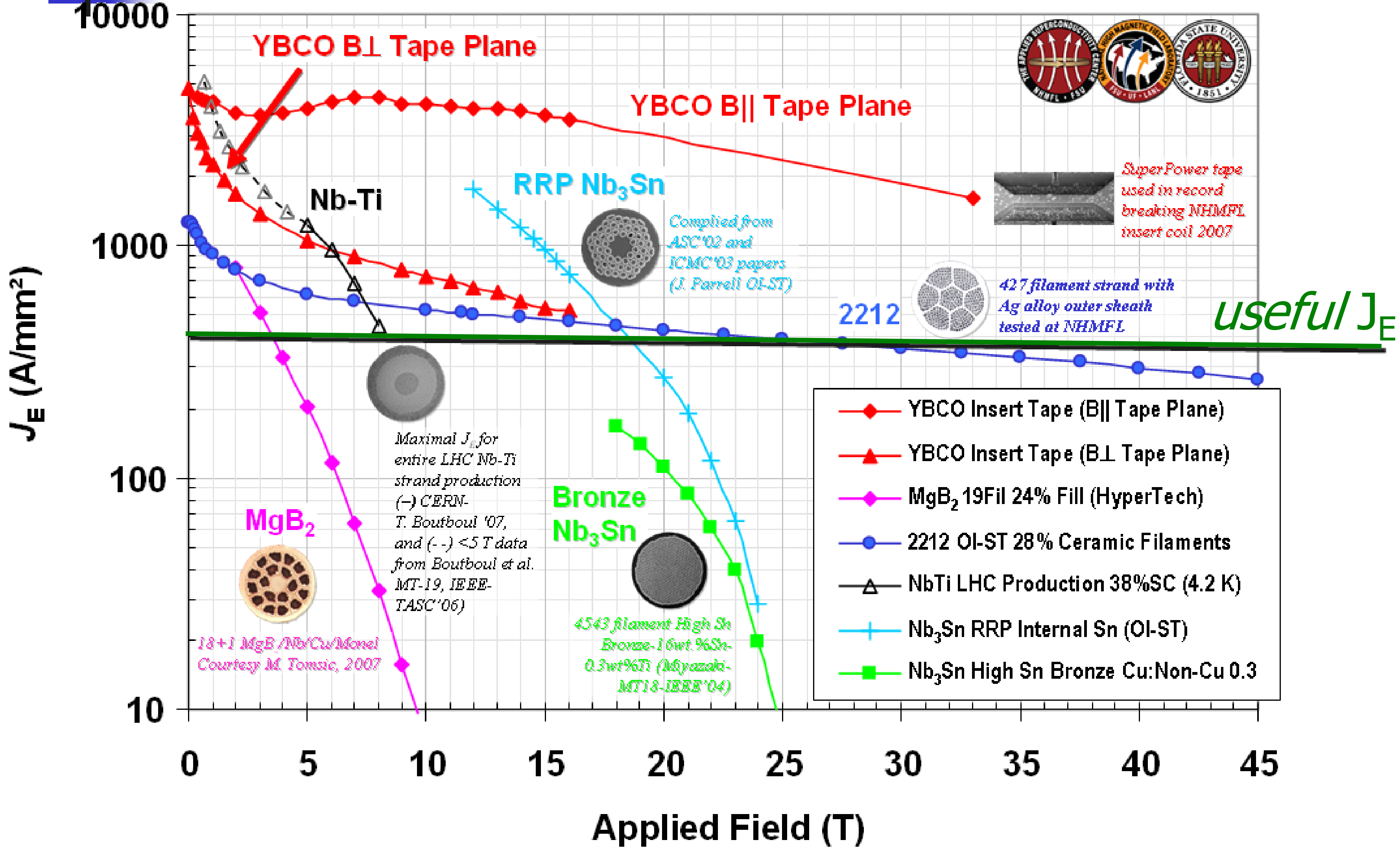
heat
treatments



LHC wire

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Best of Superconductors J_E



SuperPower tape used in record breaking NHMFL insert coil 2007

Complied from ASC'02 and ICMC'03 papers (J. Parrell OI-ST)

427 filament strand with Ag alloy outer sheath tested at NHMFL

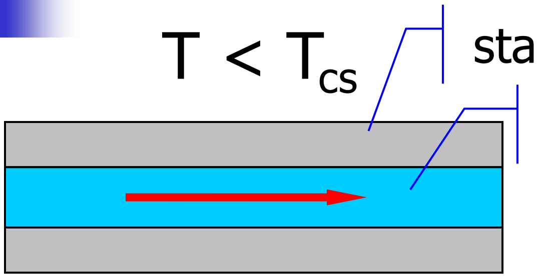
Maximal J_E for entire LHC Nb-Ti strand production (–) CERN-T. Boutboul '07, and (- -) <5 T data from Boutboul et al. MT-19, IEEE-TASC'06)

18+1 MgB /Nb/Cu/Monel Courtesy M. Tomsic, 2007

4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

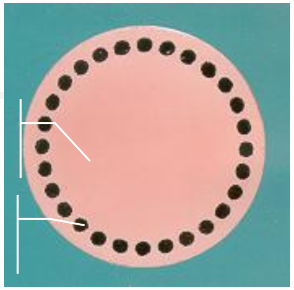
Current sharing

$T < T_{cs}$



stabilizer

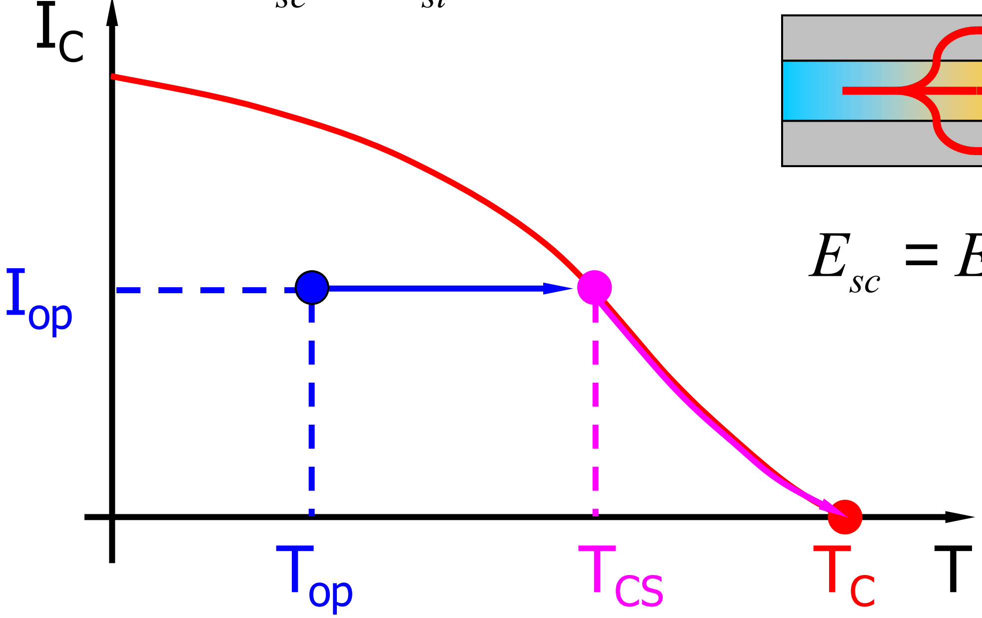
superconductor



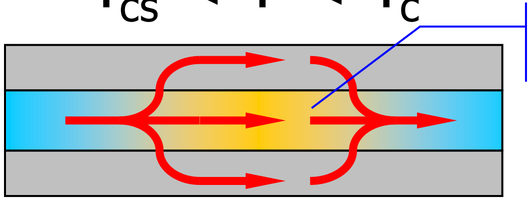
stabilizer

superconductor

$$E_{sc} = E_{st} = 0$$



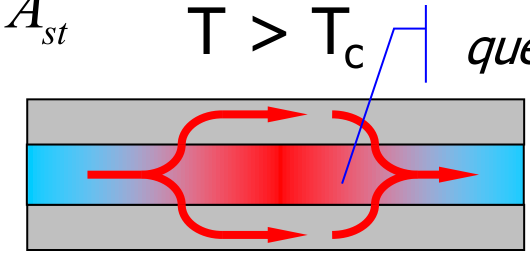
$T_{cs} < T < T_c$



curent sharing

$$E_{sc} = E_{st} = I_{st}\frac{h_{st}}{A_{st}}$$

$T > T_c$



quenched

$$E_{sc} = E_{st} = I_{op}\frac{h_{st}}{A_{st}}$$

Quench and protection recipes

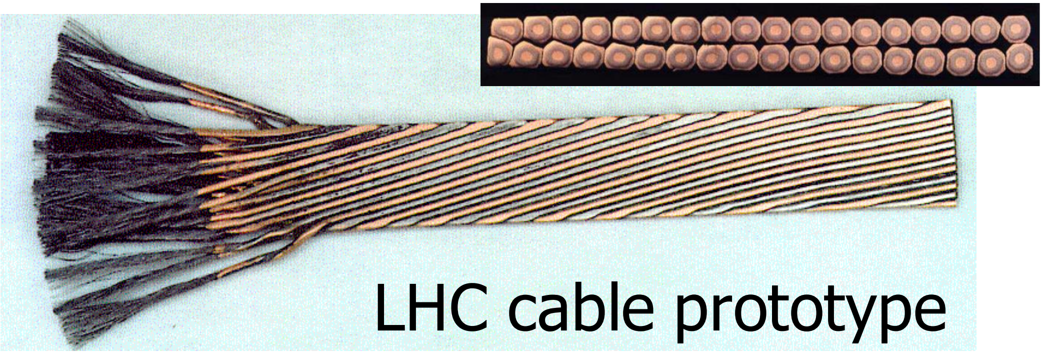
- A good conducting material (Ag, Al, Cu) must be added in parallel to the superconductor to limit the maximum temperature during a *quench*
- The effect of a quench can be mitigated by
  - Adding stabilizer (⇔ operating margin, stability)
  - Reducing operating current density (⇔ economics of the system)
  - Reducing the magnet inductance (large cable current) and increasing the discharge voltage to discharge the magnet as quickly as practical

$J_E \approx 500\ \mathrm{A/mm^2}$

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

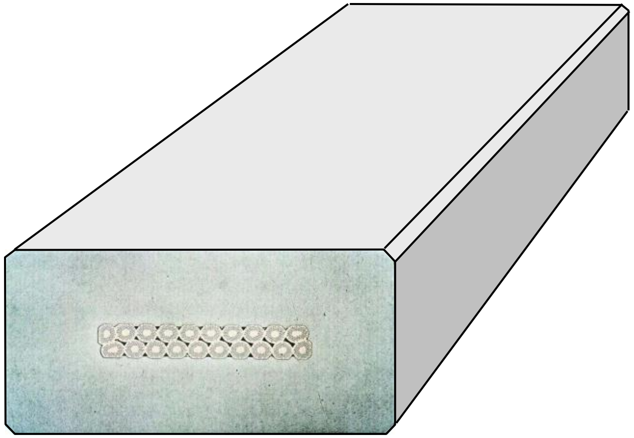


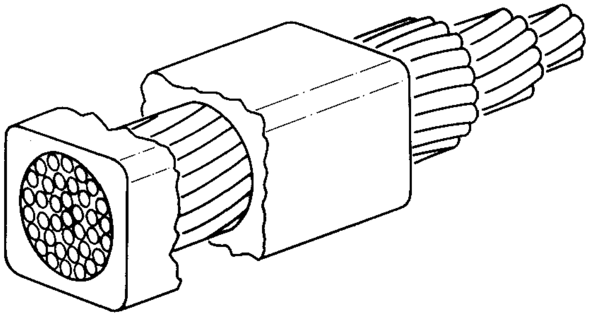
LHC cable prototype

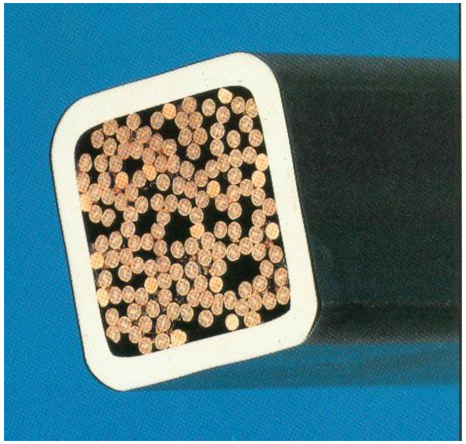
$J_E \approx 50\ \mathrm{A/mm^2}$

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

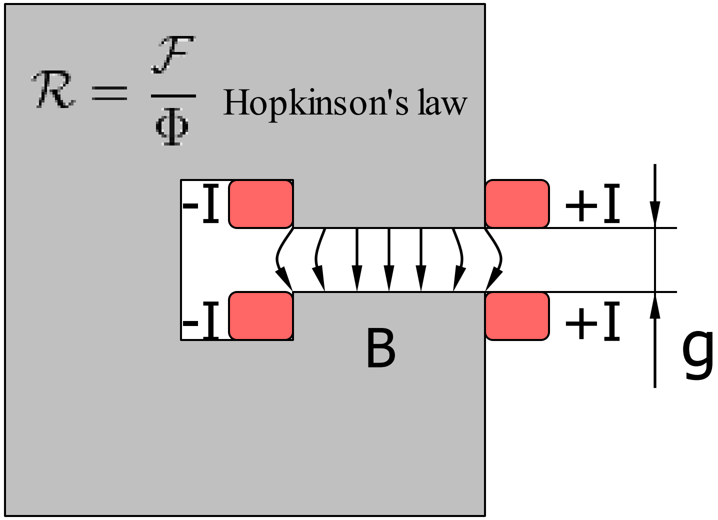






Magnetic design

- NC: magneto motive force, reluctance and pole shapes



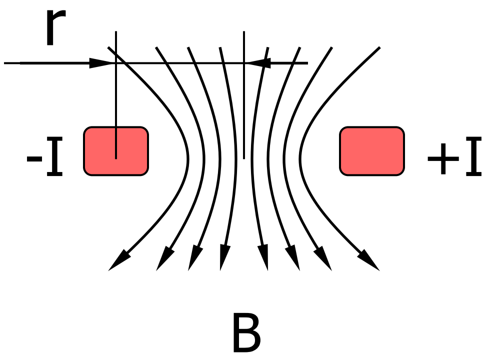
$$\mathcal{R} = \frac{\mathcal{F}}{\Phi}$$ Hopkinson's law

$$B \approx \mu_0 NI / g$$

g =100 mm
NI =100 kAturn
B =1.25 T

- SC: Biot-Savart law and coil shapes

$$\mathbf{B} = \int \frac{\mu_0}{4\pi} \frac{I d\mathbf{l} \times \mathbf{r}}{|r|^3}$$ Biot-Savart law

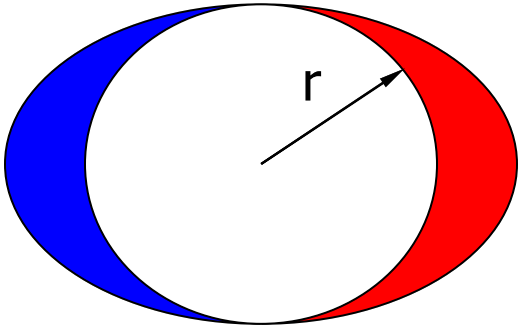


$$B \approx \mu_0 NI / \pi r$$

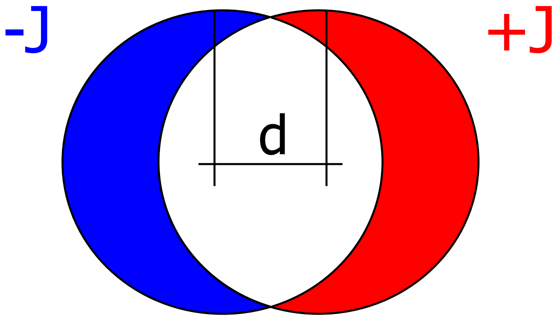
r =45 mm
NI =1 MAturn
B =8.84 T

Design of an ideal dipole magnet

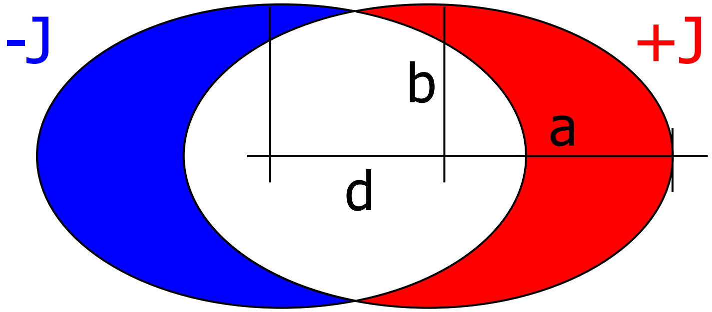
$I=I_0 \cos(\theta)$ ➡ $B_1=-\mu_0 I_0/2\ r$



Intersecting circles ➡ $B_1=-\mu_0 J\ d/2$



Intersecting ellipses ➡ $B_1=-\mu_0 J\ d\ b/(a+b)$

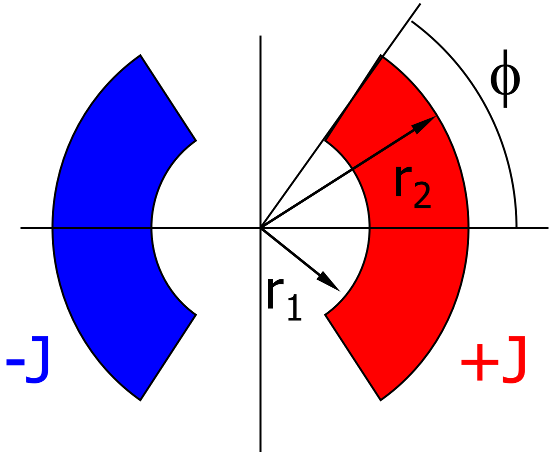


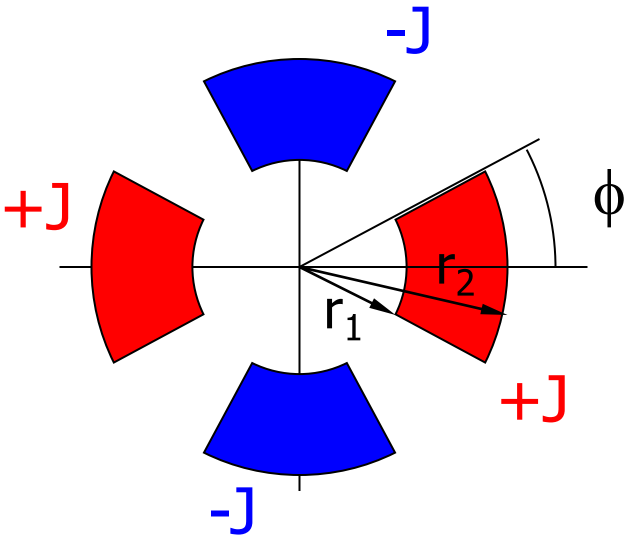
Several solutions are possible and can be extended to higher order multi-pole magnets

None of them is practical !

Magnetic design - sector coils

- Dipole coil
- Quadrupole coil



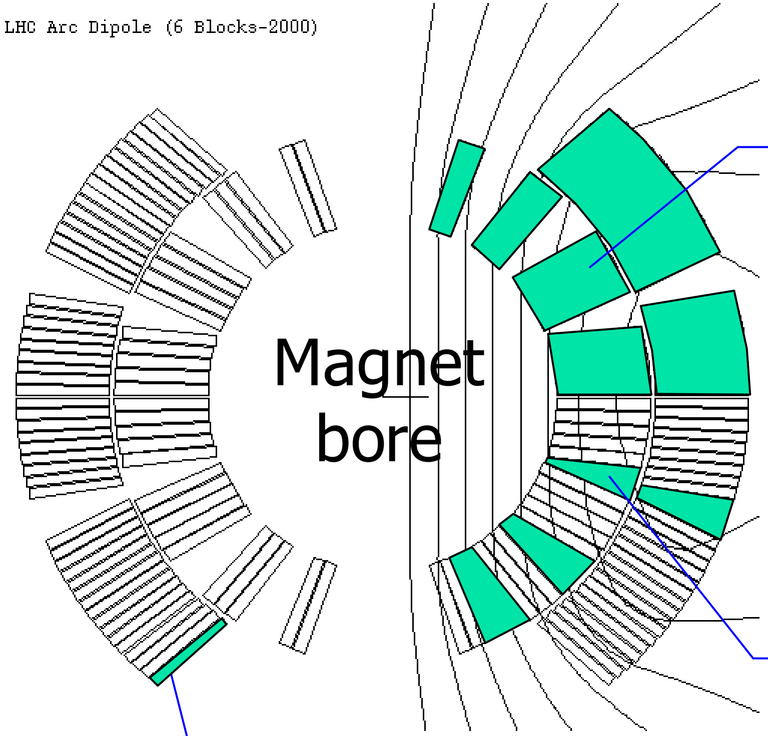


$B_1=-2\mu_0/\pi\ J\ (r_2 - r_1)\ \sin(\phi)$

$B_2=-2\mu_0/\pi\ J\ \ln(r_2/r_1)\ \sin(2\phi)$

This is getting much more practical for the construction of superconducting coils !

Technical coil windings

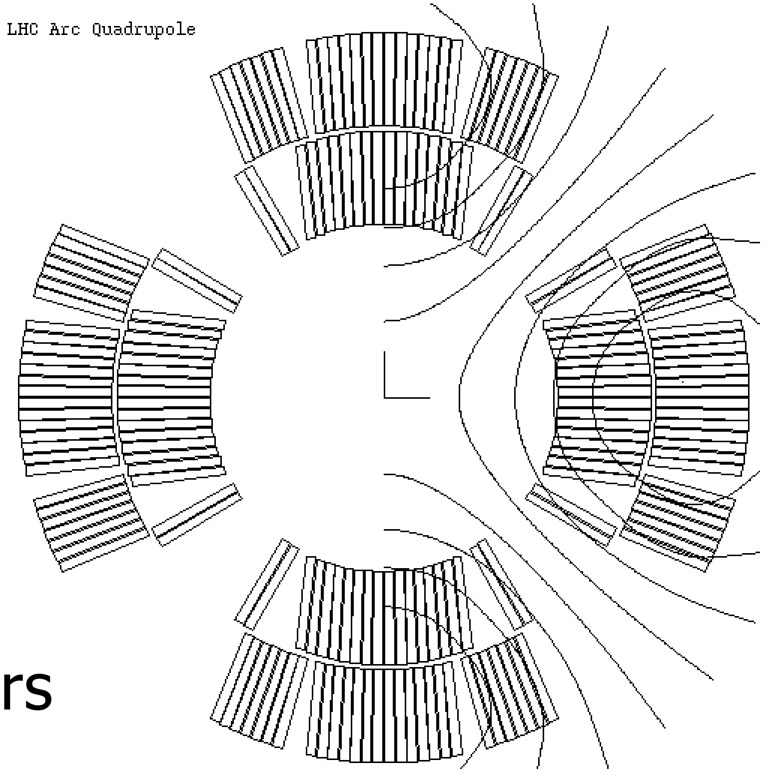


Magnet bore

Coil blocks

Spacers

Superconducting cable

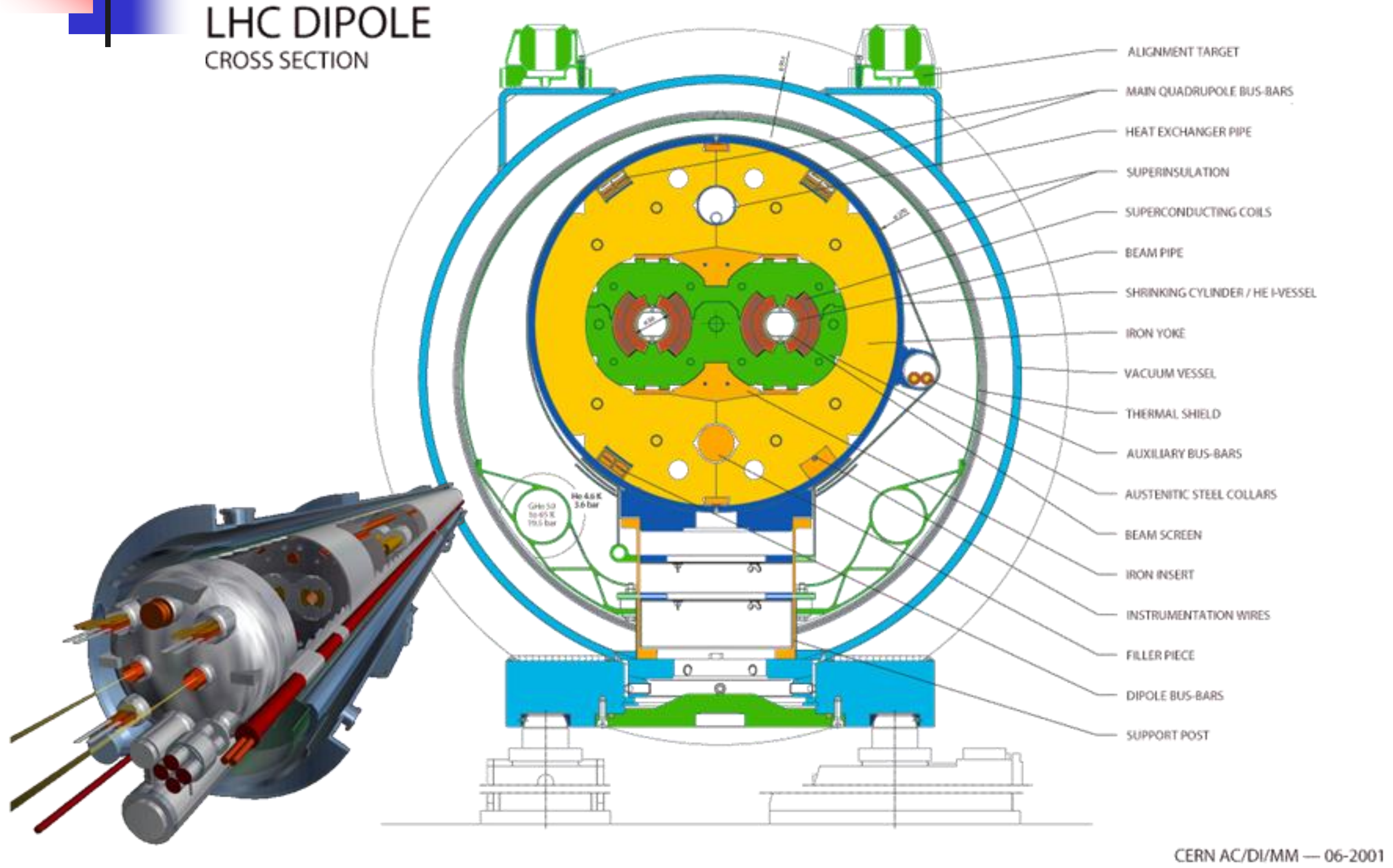


Overview

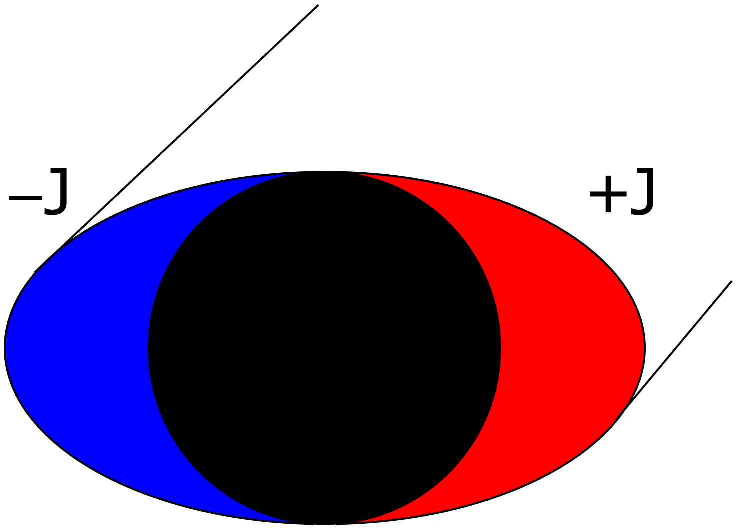
- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
- The making of a superconducting magnet
- Examples of superconducting magnet systems

LHC dipole

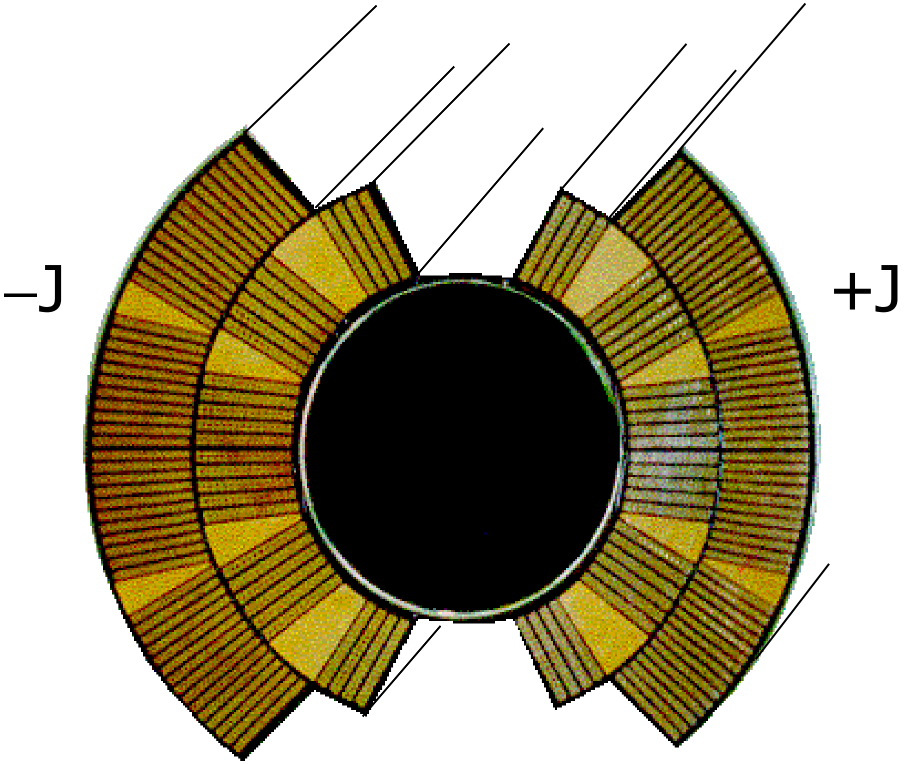
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)



Superconducting dipole magnet coil

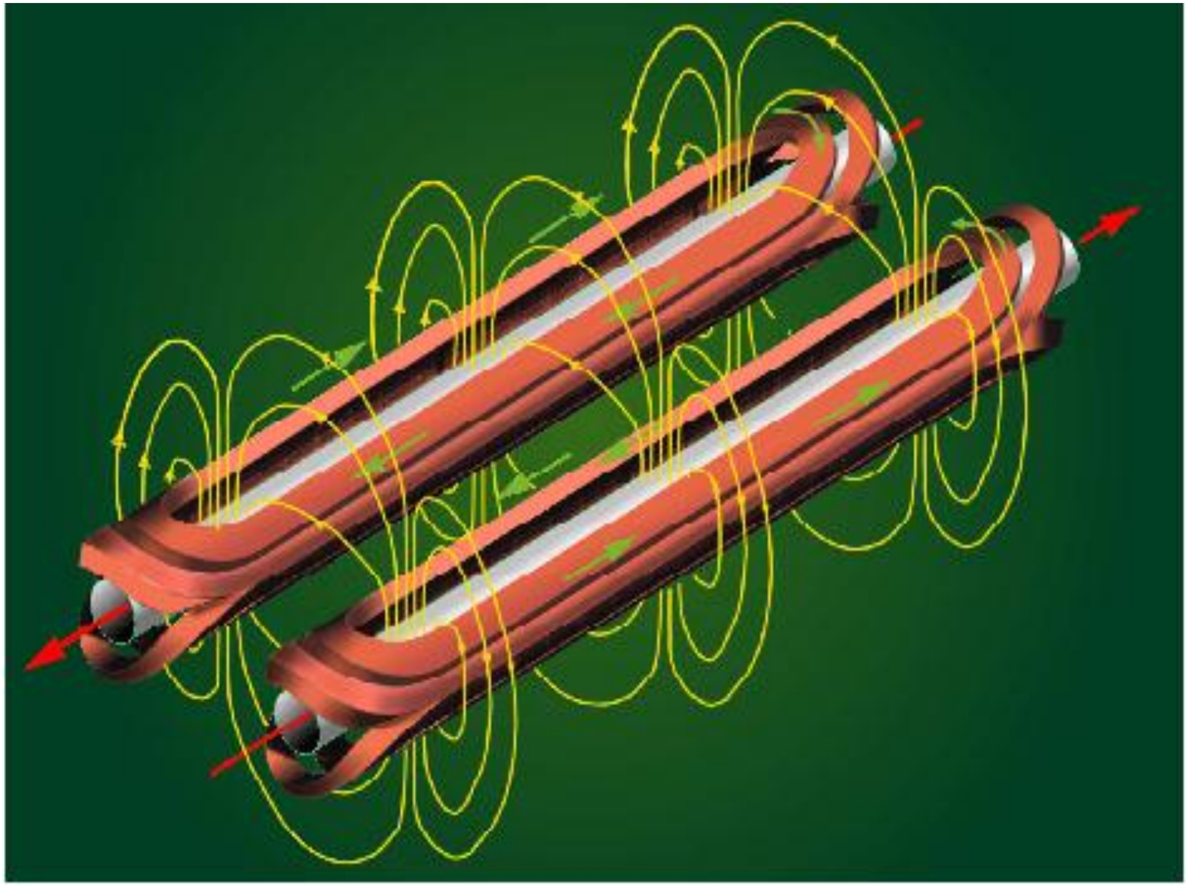


Ideal current distribution that generates a perfect dipole



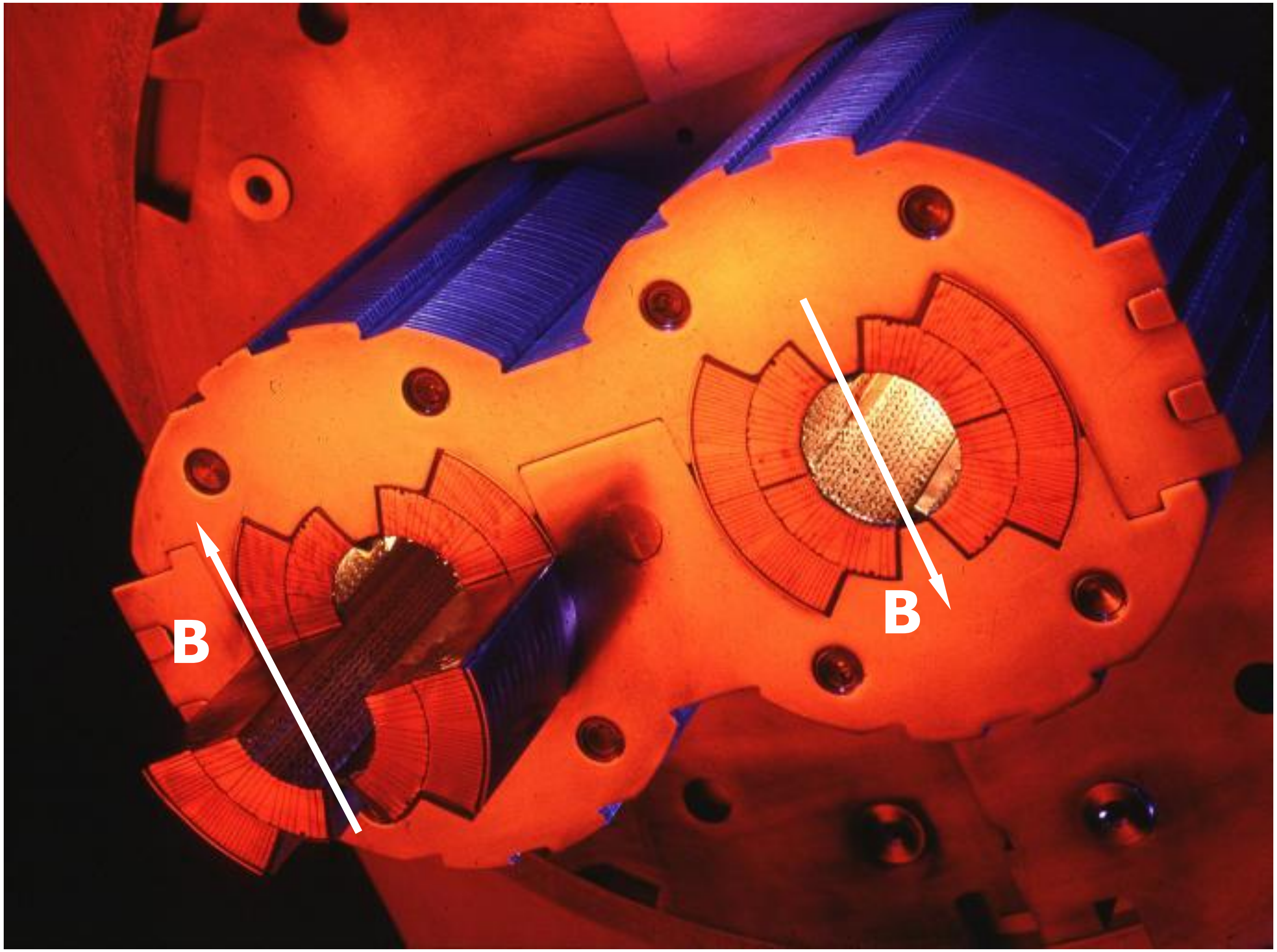
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle

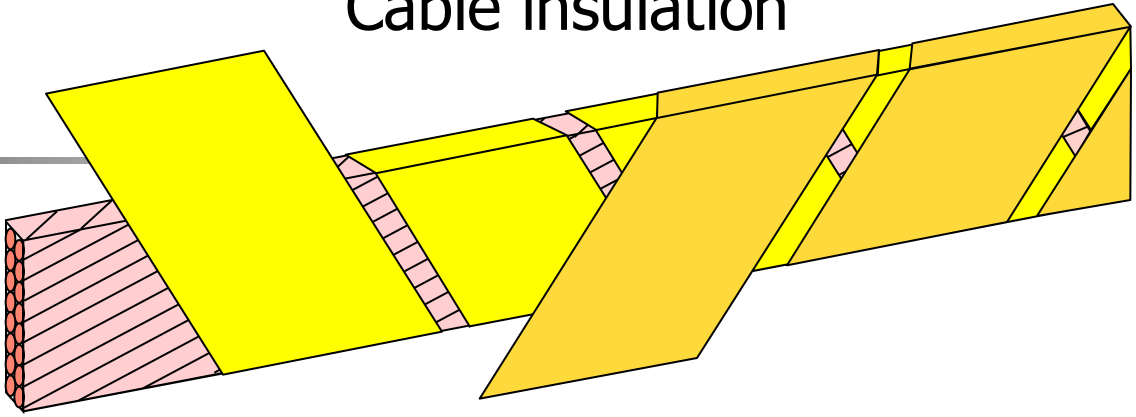


Combine two magnets in one
Save volume, material, cost

LHC dipole coils

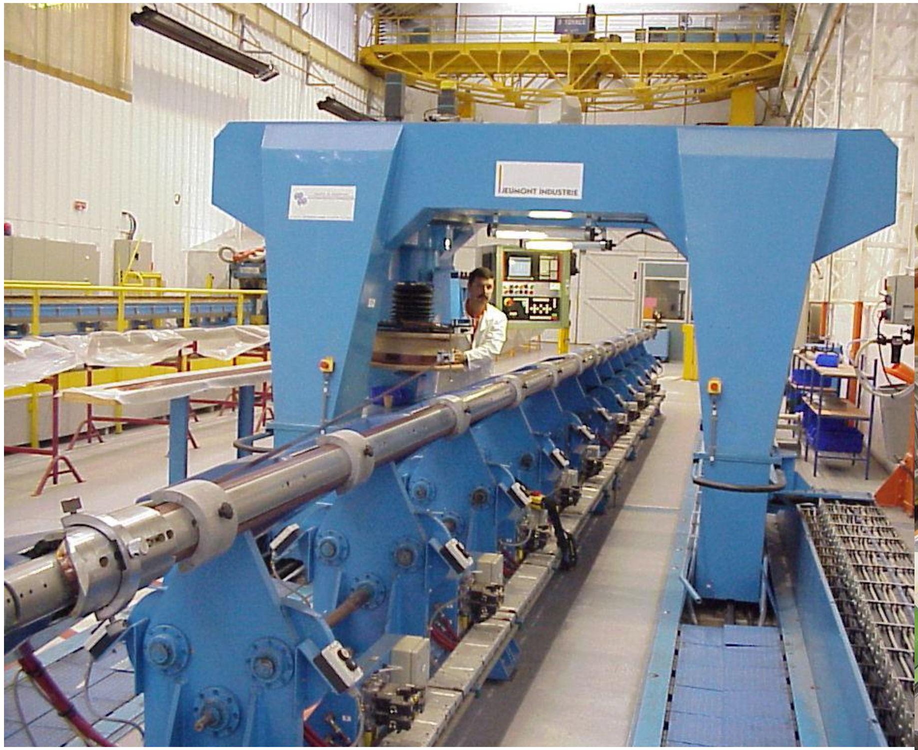


Coil winding



Cable insulation

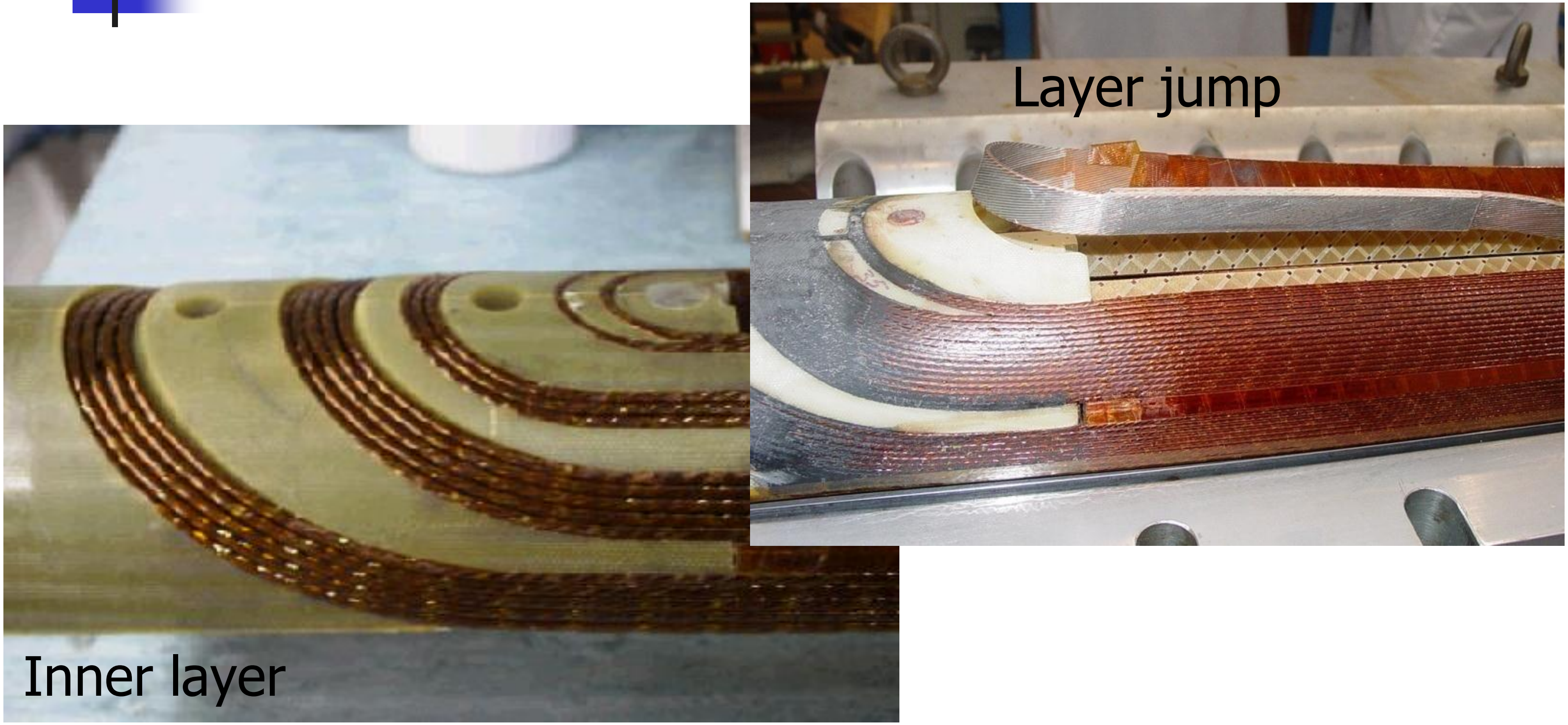
10 μm precision !



Coil winding machine

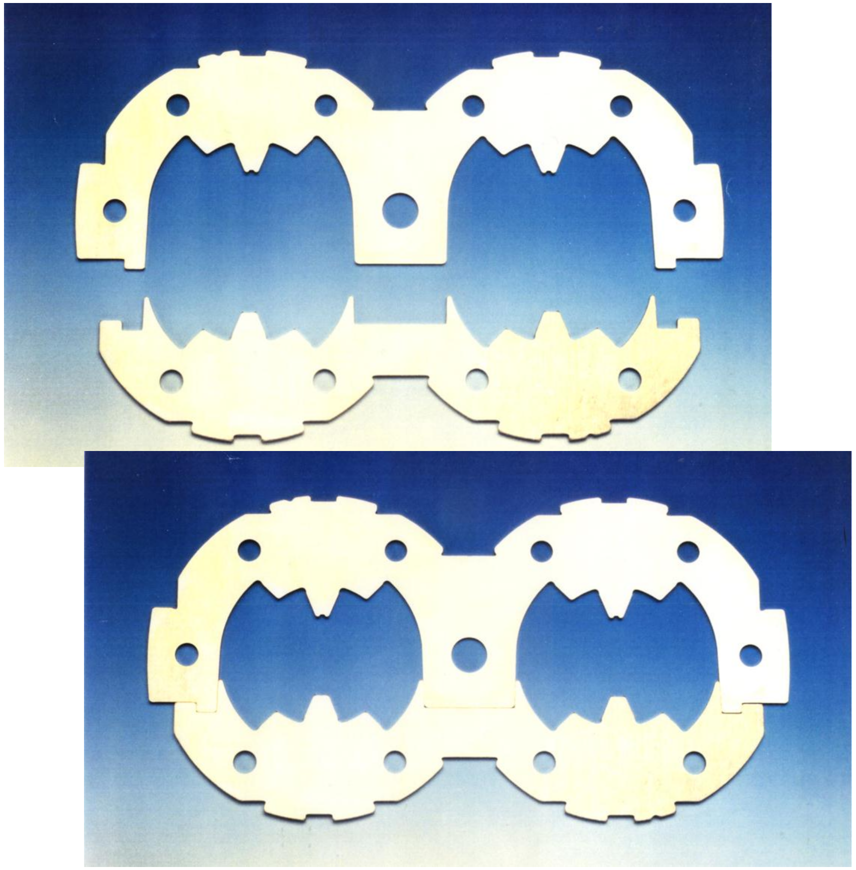
Stored coils

Ends

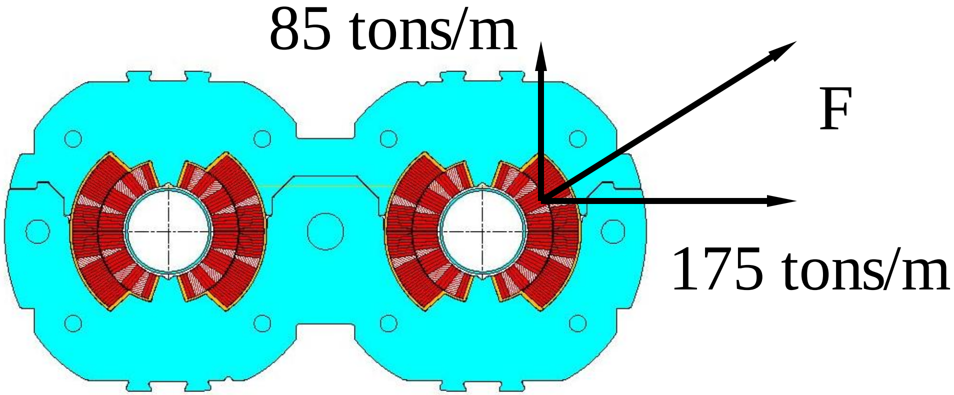


Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking

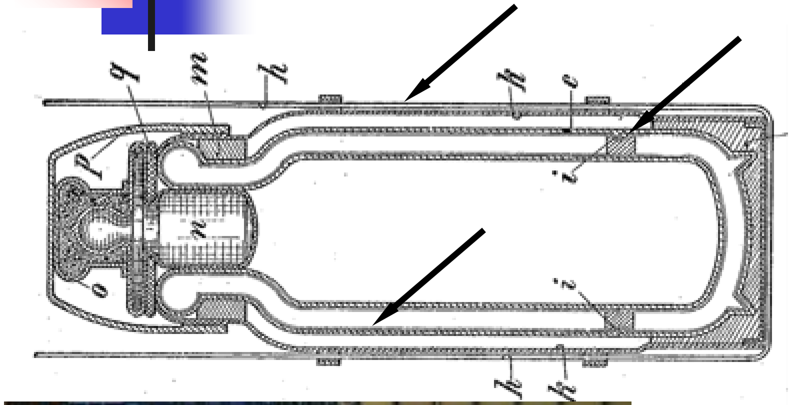


collaring



Cold mass

Cryostat




Vacuum enclosure

Thermal screens

Low conduction foot

Current leads

Warm end (300K)

Intermediate temperature (50K)

HTS

Cold end (4K)

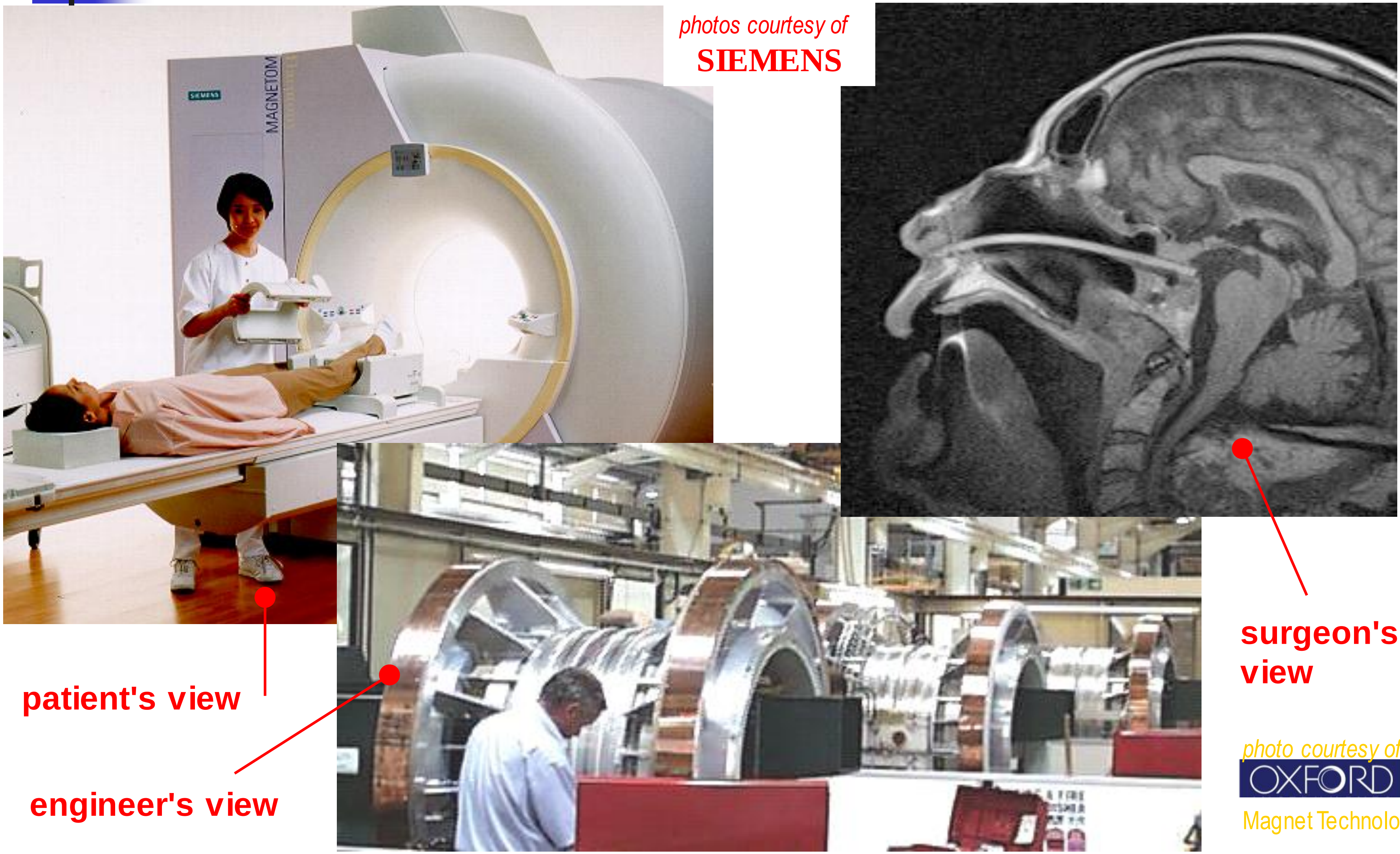
Finally, in the tunnel !

Overview

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

Magnetic Resonance Imaging (MRI)

photos courtesy of **SIEMENS**



patient's view

engineer's view

surgeon's view

photo courtesy of OXFORD Magnet Technology

NMR spectroscopy

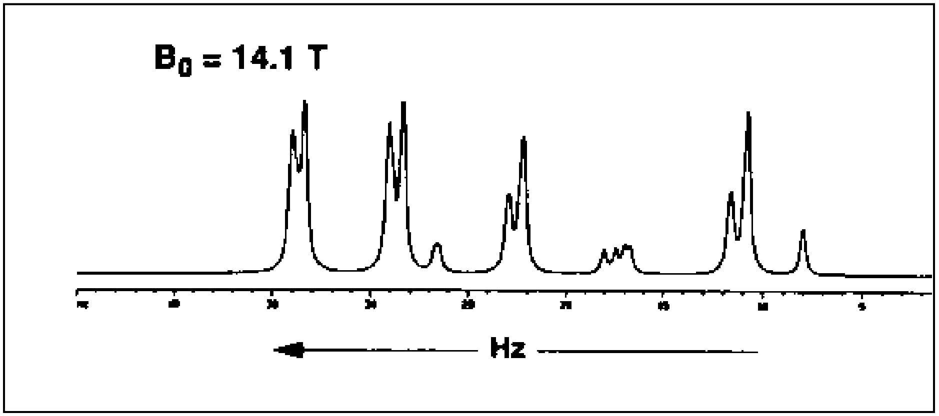
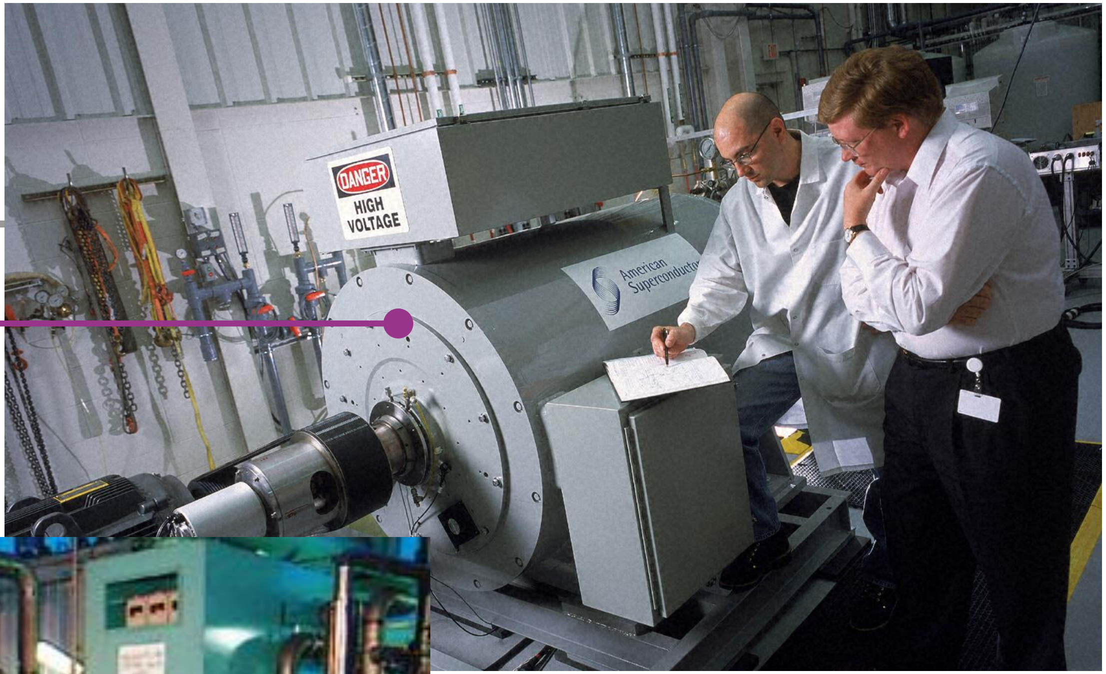


photo courtesy of
OXFORD
Magnet Technology

Motors & generators



Motor with HTS rotor

American Superconductor and Reliance

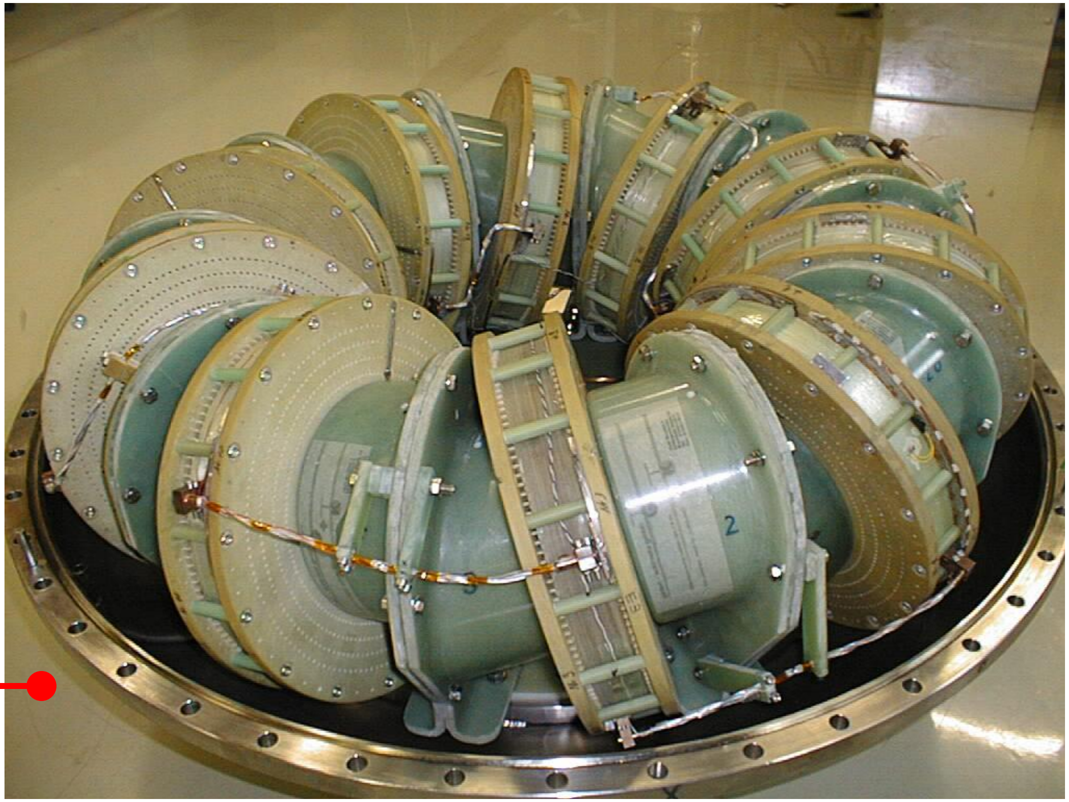
700 MW generator

NbTi rotor

Hitachi, Toshiba, Mitsubishi

Transformers & energy storage

HTS Transformer
630 kVA, 18.7kV to 0.42 kV



Toroidal magnet of 200 kJ / 160 kW
energy store
(B = 4 T, dia. = 1.1 m)

KfZ Karlsruhe

Magnetic separation

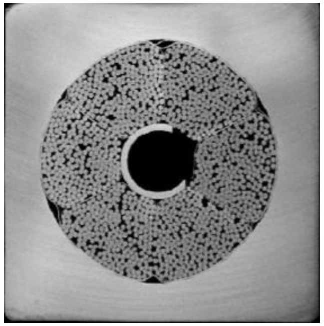
photo courtesy of
Carpco

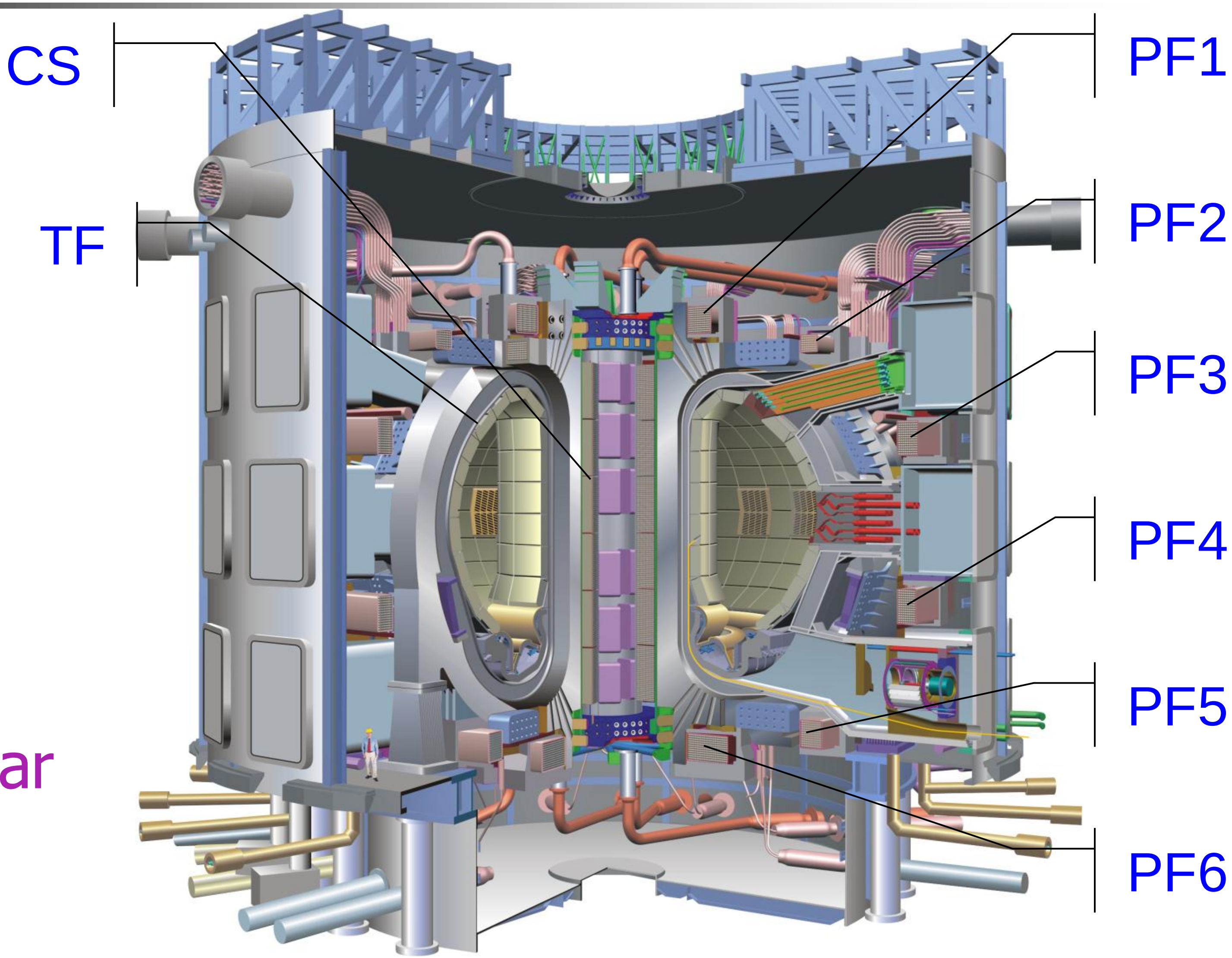
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

Thermonuclear fusion

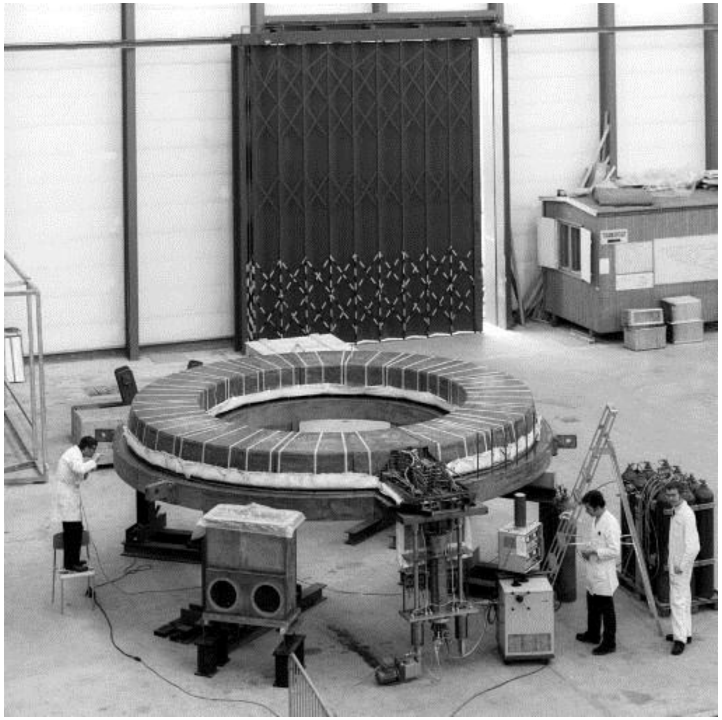




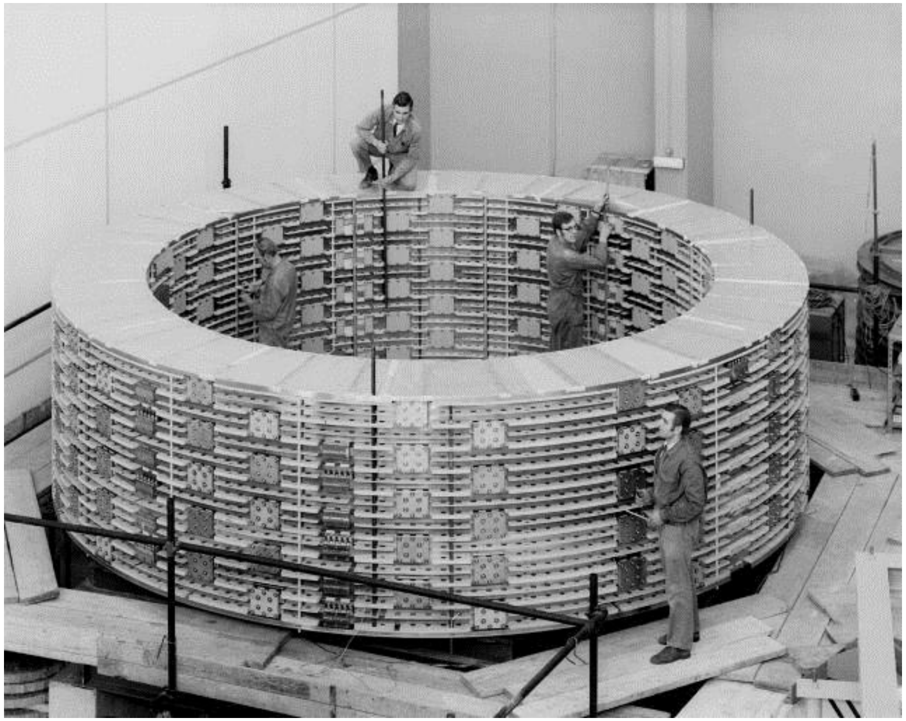
ITER

International
Thermonuclear
Experimental
Reactor

HEP detectors of the past...

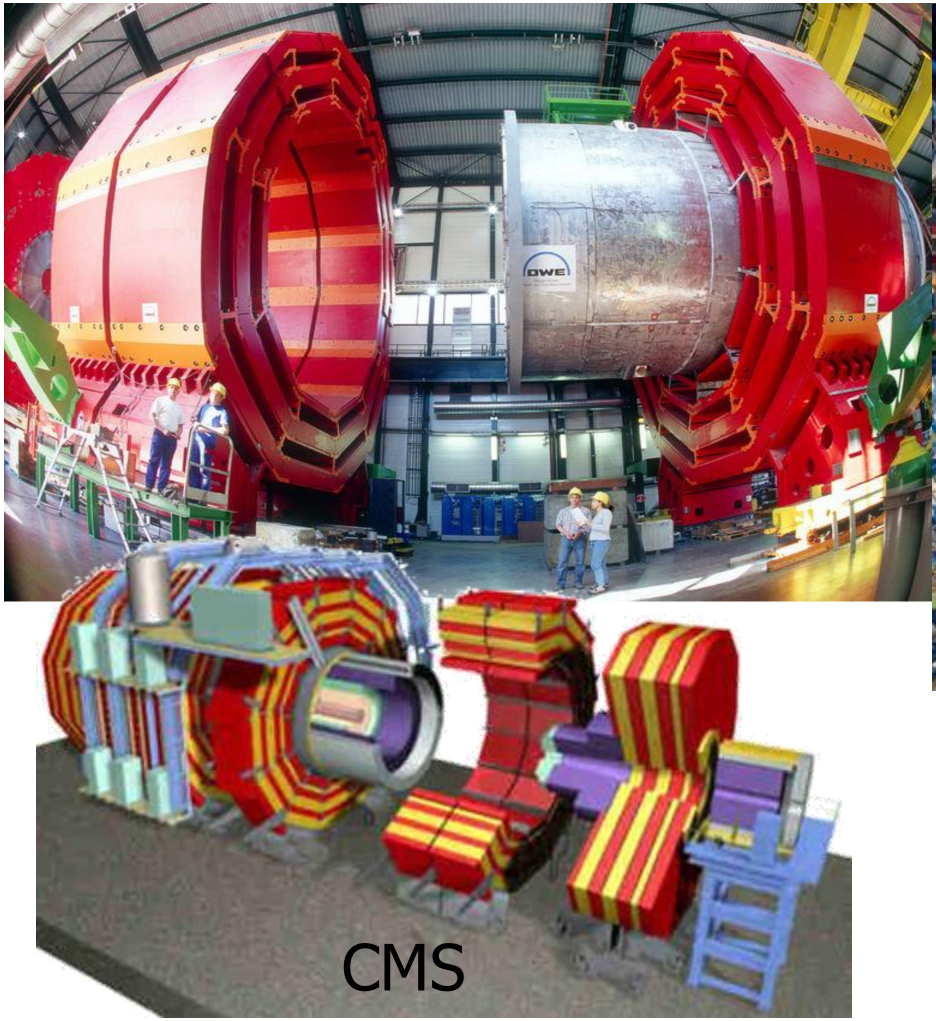


Omega

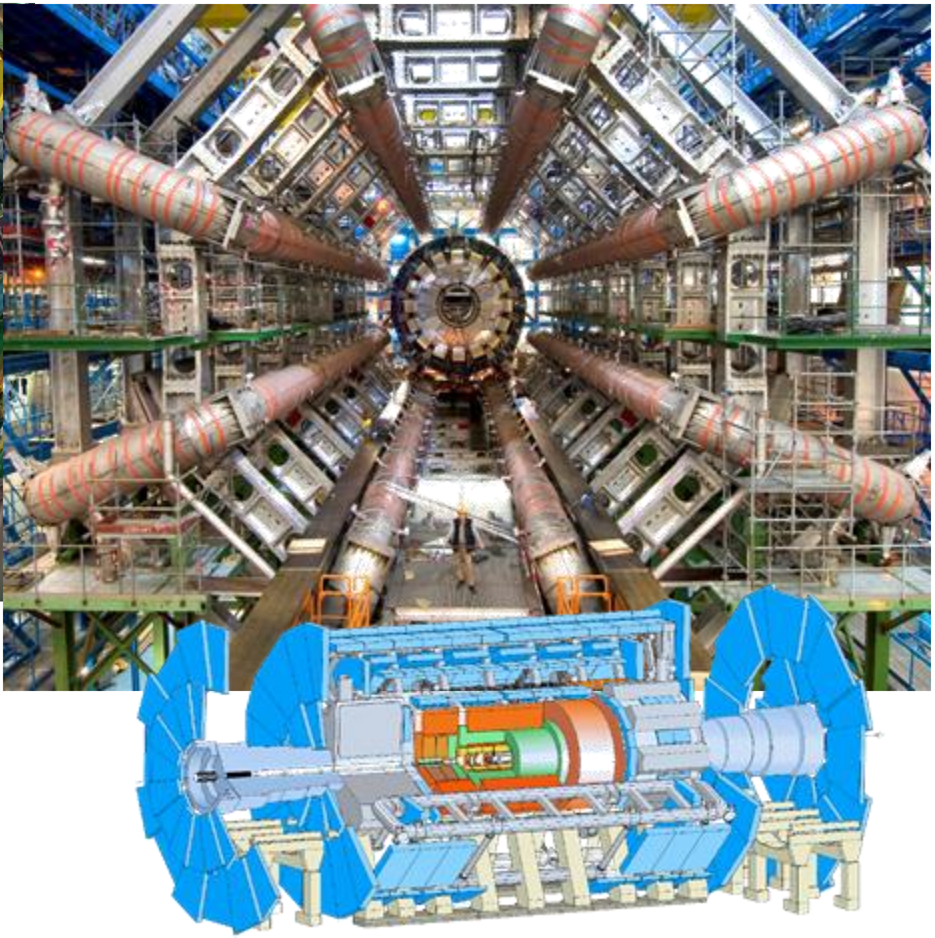


BEBC

… and HEP of the present (CMS and ATLAS)



CMS

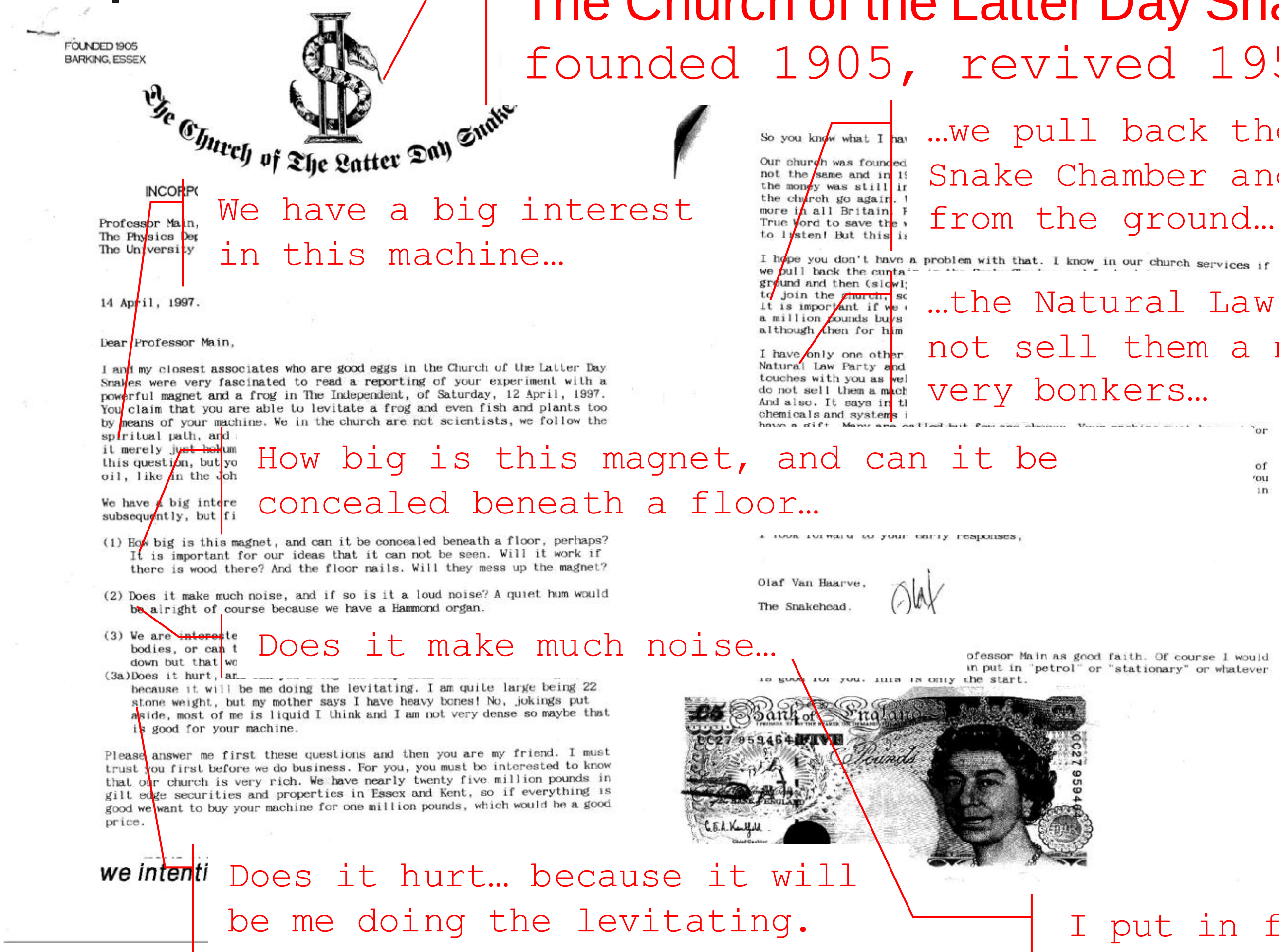


ATLAS

Other uses of superconductivity

The Church of the Latter Day Snakes

founded 1905, revived 1950



FOUNDED 1905
BARKING, ESSEX

The Church of The Latter Day Snake

INCORP

Professor Main,
The Physics Dep
The University

14 April, 1997.

Dear Professor Main,

I and my closest associates who are good eggs in the Church of the Latter Day Snakes were very fascinated to read a reporting of your experiment with a powerful magnet and a frog in The Independent, of Saturday, 12 April, 1997. You claim that you are able to levitate a frog and even fish and plants too by means of your machine. We in the church are not scientists, we follow the spiritual path, and
it merely just hokum
this question, but yo
oil, like in the Joh

We have a big intere
subsequently, but fi

(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.

(3) We are intereste
bodies, or can t
down but that wo

(3a) Does it hurt, an
because it will be me doing the levitating. I am quite large being 22 stone weight, but my mother says I have heavy bones! No, jokings put aside, most of me is liquid I think and I am not very dense so maybe that is good for your machine.

Please answer me first these questions and then you are my friend. I must trust you first before we do business. For you, you must be interested to know that our church is very rich. We have nearly twenty five million pounds in gilt edge securities and properties in Essex and Kent, so if everything is good we want to buy your machine for one million pounds, which would be a good price.

we intenti

So you know what I hav

Our church was founded
not the same and in 19
the money was still in
the church go again.
more in all Britain.
True Word to save the
to listen! But this is

I hope you don't have a problem with that. I know in our church services if we pull back the curta
ground and then (slowl
to join the church, so
it is important if we
a million pounds buys
although then for him

I have only one other
Natural Law Party and
touches with you as wel
do not sell them a mach
And also. It says in th
chemicals and systems i

or

of
you
in

I look forward to your early responses,

Olaf Van Haarve,

The Snakehead.

Olaf

ofessor Main as good faith. Of course I would
in put in "petrol" or "stationary" or whatever
is good for you. This is only the start.

We have a big interest in this machine…

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

Does it make much noise…

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

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

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

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 $\Rightarrow$ $p_{mag}=1600$ 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, pub Plenum Press, New York (1994), ISBN 0-306-44881-5.
  - Superconducting Magnets: MN Wilson, pub Oxford University Press (1983) ISBN 0-019-854805-2
  - High Field Superconducting Magnets: FM Asner, pub Oxford University Press (1999) ISBN 0 19 851764 5
  - Superconducting Accelerator Magnets: KH Mess, P Schmuser, S Wolf., pub World Scientific, (1996) ISBN 981-02-2790-6
  - Stability of Superconductors: L. Dresner, pub Plenum Press, New York (1994), ISBN 0-306-45030-5
  - Handbook of Applied Superconductivity ed B Seeber, pub UK Institute Physics 1998
  - Proc Applied Superconductivity Conference: pub as IEEE Trans Applied Superconductivity, Mar 93 to 99, and as IEEE Trans Magnetics Mar 75 to 91
  - Proc European Conference on Applied Superconductivity EUCAS, pub UK Institute Physics
  - Proc International Conference on Magnet Technology; MT-1 to MT-20 (2007) pub mainly as IEEE Trans Applied Superconductivity and IEEE Trans Magnetics

Where to find out more - 2/3

- Cryogenics
  - Helium Cryogenics Van Sciver SW, pub Plenum 86 ISBN 0-0306-42335-9
  - Cryogenic Engineering, Hands BA, pub 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, pub quarterly
  - Superconductivity of metals and Cuprates, JR Waldram, Institute of Physics Publishing (1996) ISBN 0 85274 337 8
  - High Temperature Superconductors: Processing and Science, A Bourdillon and NX Tan Bourdillon, Academic Press, ISBN 0 12 117680 0

Where to find out more - 3/3

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

Free energy and critical field

- The Gibbs free energy of a material in a magnetic field is given by:

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

- The superconducting phase, by excluding the magnetic field ($\mathbf{M}=-\mathbf{H}$), has lower free energy: $G_{\text{sup}}(H=0) < G_{\text{normal}}$
- The material will reach critical conditions when the energy of the field will equal the jump in free energy:

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

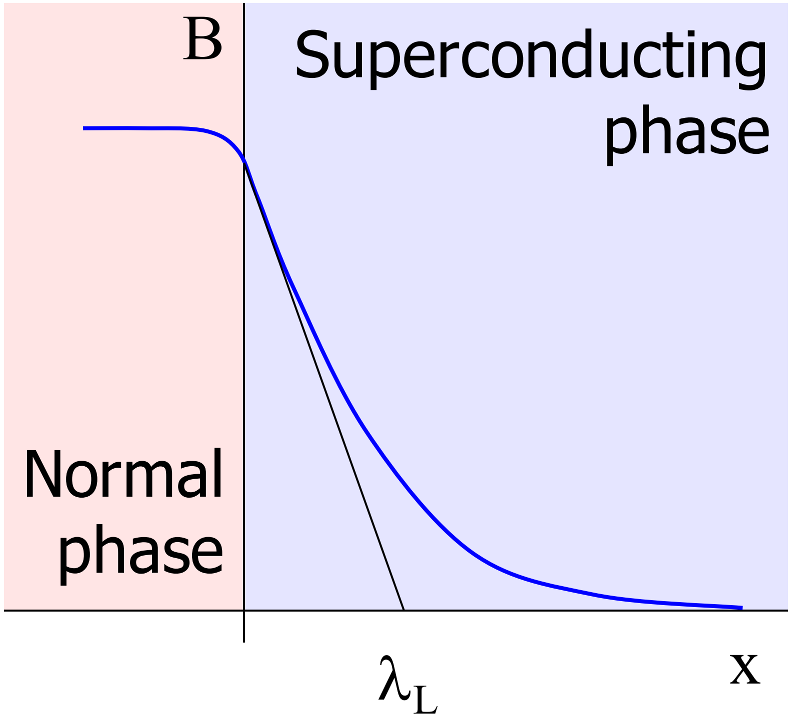
London penetration length λ_L

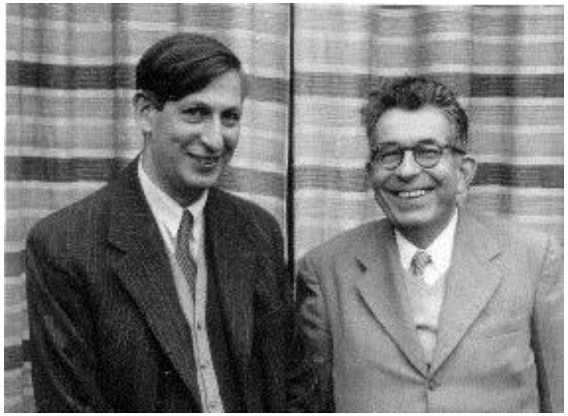
- Field profile

$$B(x) = B_0 \exp\left(-\frac{x}{\lambda_L}\right),$$

- *London* penetration length

$$\lambda_L = \left(\frac{m}{\mu_0 n q^2}\right)^{\frac{1}{2}}$$





H. and F. London, 1935

λ_L is of the order of 20 to 100 nm in typical superconducting materials

Coherence length ξ

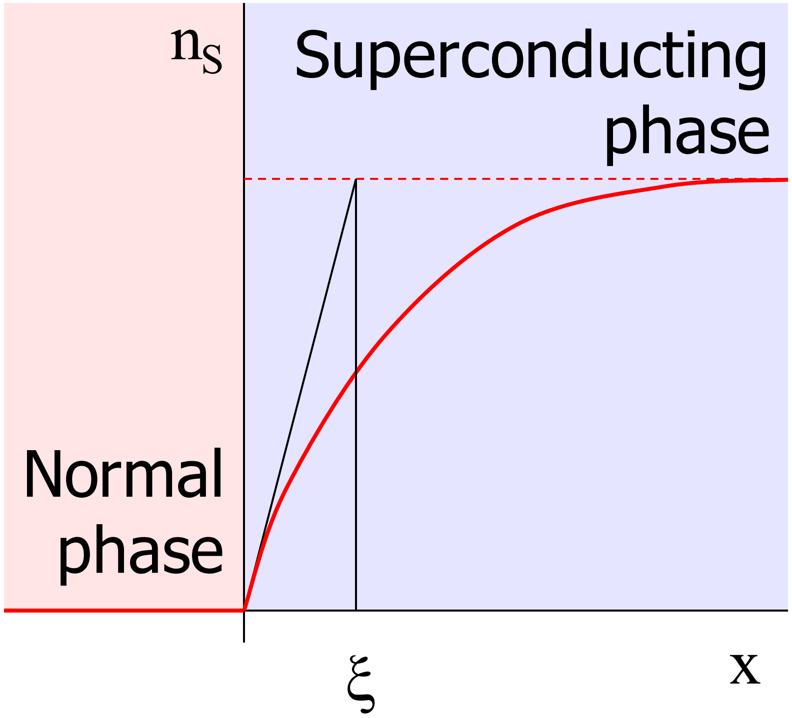
- The density of paired electron n_S cannot change quickly at an interface, but rises smoothly from zero (at the surface) to the asymptotic value
- The characteristic length of this transition is the coherence length

Fermi velocity

$$\xi = \sqrt{\frac{\hbar^2}{2m|\alpha|}} = \frac{2\hbar v_f}{\pi E_g}$$

SC energy gap

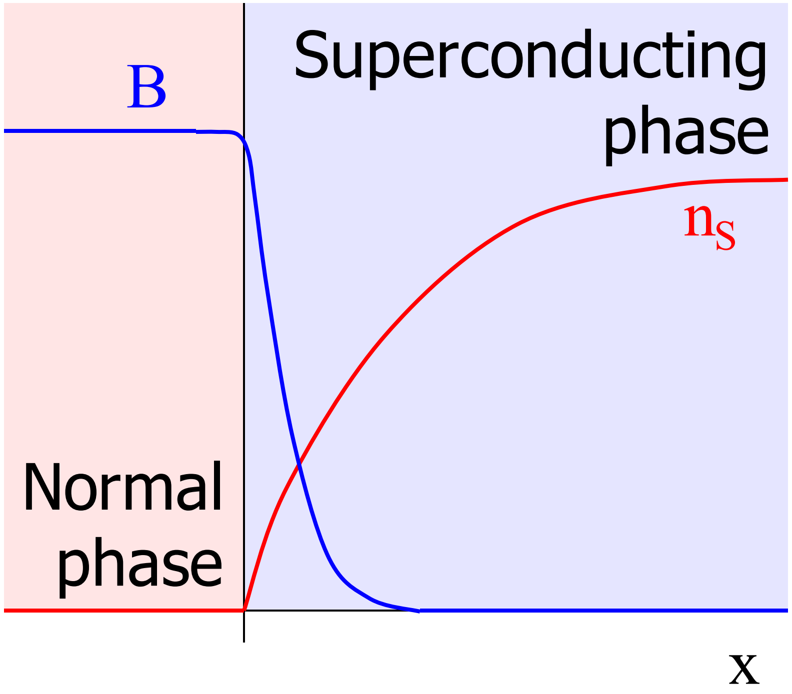
Ginzburg–Landau, 1950



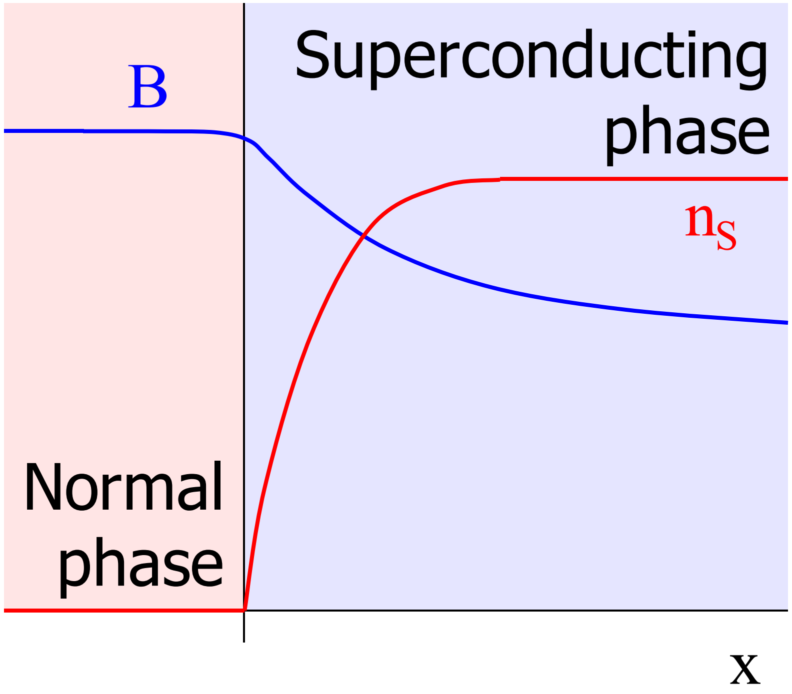
ξ is of the order of 1 to 1000 nm in typical superconducting elements and alloys

Ginzburg-Landau parameter κ

- Different behaviors are found as a function of the Ginzburg-Landau parameter $\kappa = \lambda_L / \xi$



$\lambda_L \ll \xi \Rightarrow \kappa \ll 1$



$\lambda_L \gg \xi \Rightarrow \kappa \gg 1$

Ginzburg–Landau, 1950

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	
In	24	360	0.07	
Cd	110	760	0.15	
Sn	30	170	0.18	
Nb	32	39	0.82	Type II
Nb_3Sn			≈ 30	