Applied Superconductivity for Accelerator Magnets

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CERN

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Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Wires, tapes and cables
  - Operating margins
  - Cooling of superconducting magnets
  - Stability, quench and protection
- The making of a superconducting magnet
- Examples of superconducting magnet systems

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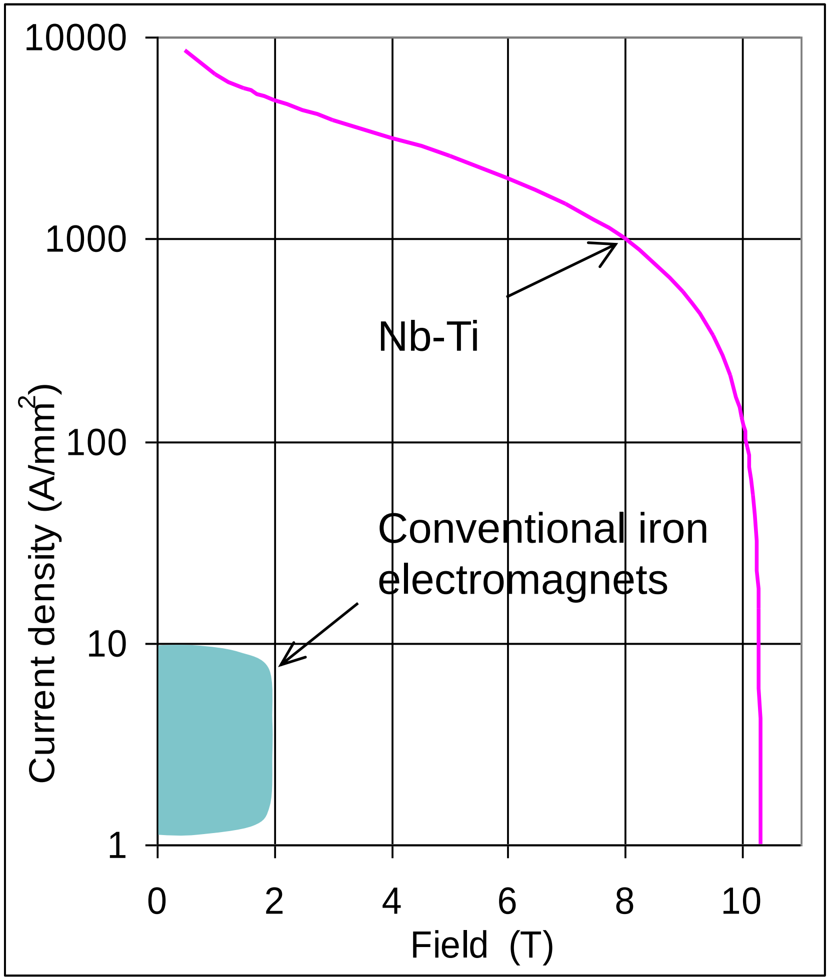
Graphics by courtesy of M.N. Wilson

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

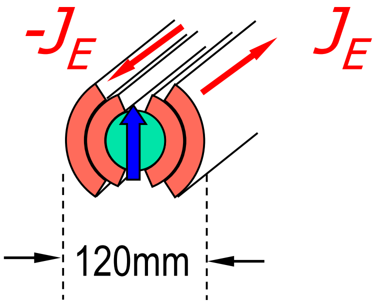
High current density - dipoles

- The field produced by an ideal dipole is:

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

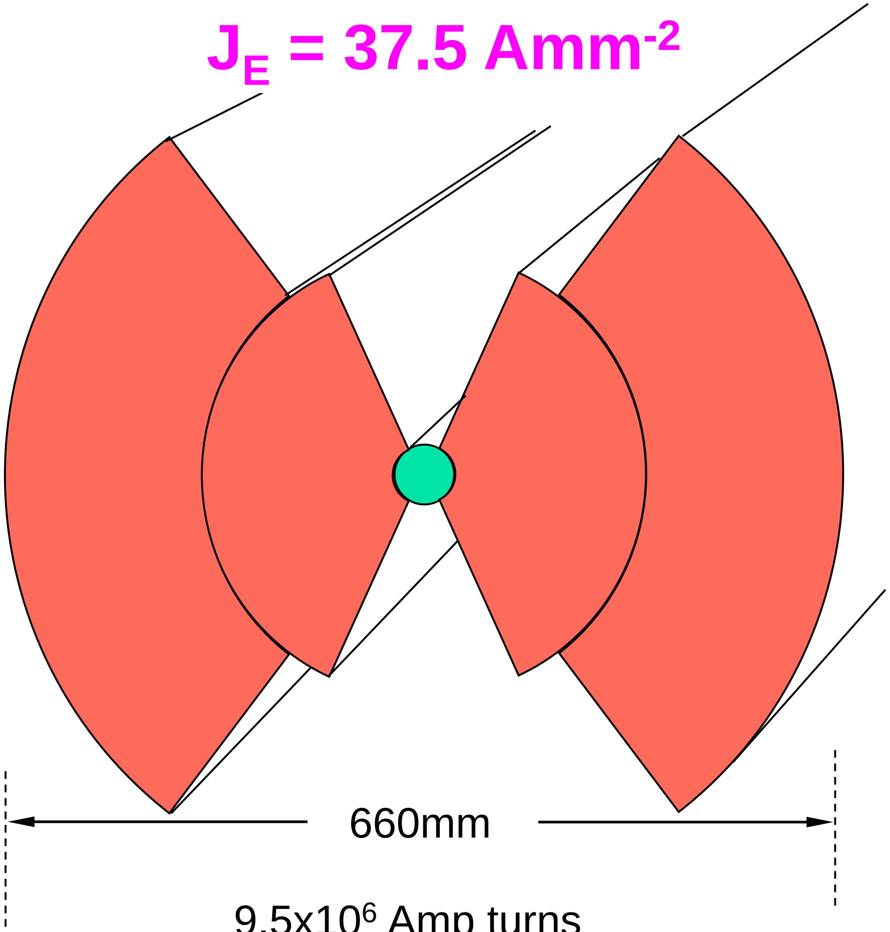
J_E = 375 Amm^{-2}

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

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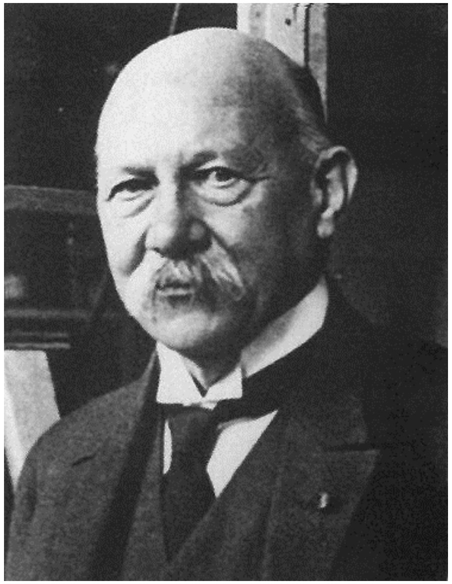
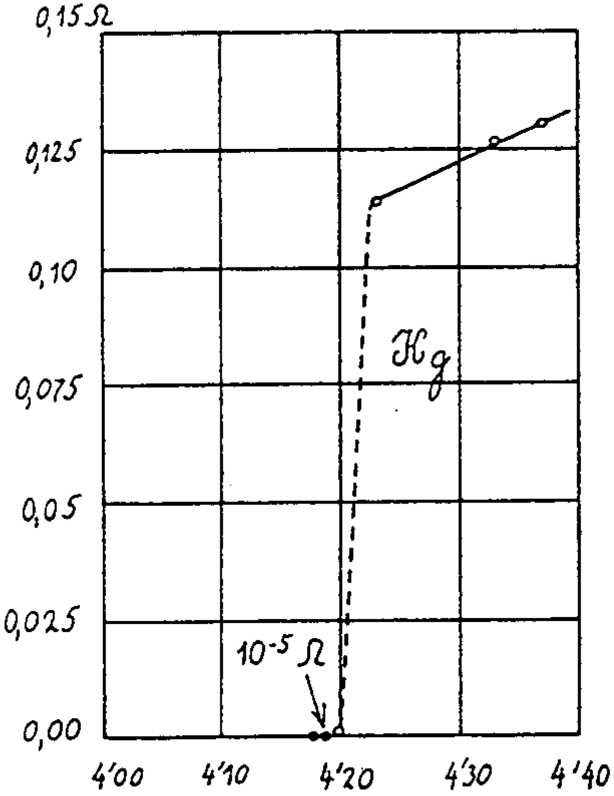
Superconductors Pre-history





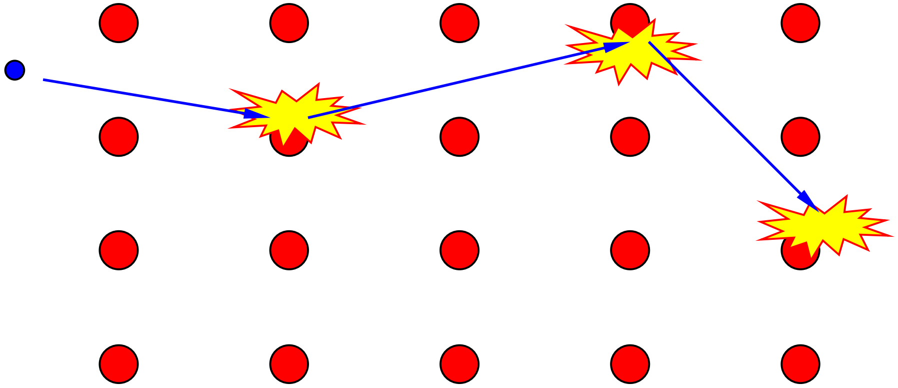
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)

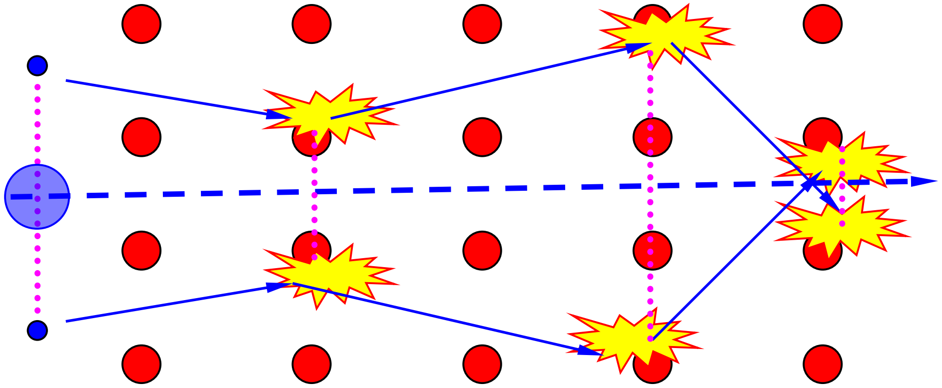
Cooper Pairs

Bardeen, Cooper and Schrieffer

- Normal conductor
  - scattering of e^-
  - finite resistance



- Superconductor
  - paired electrons are bosons, a quasi particle in condensed state
  - zero resistance



Pairing mechanism

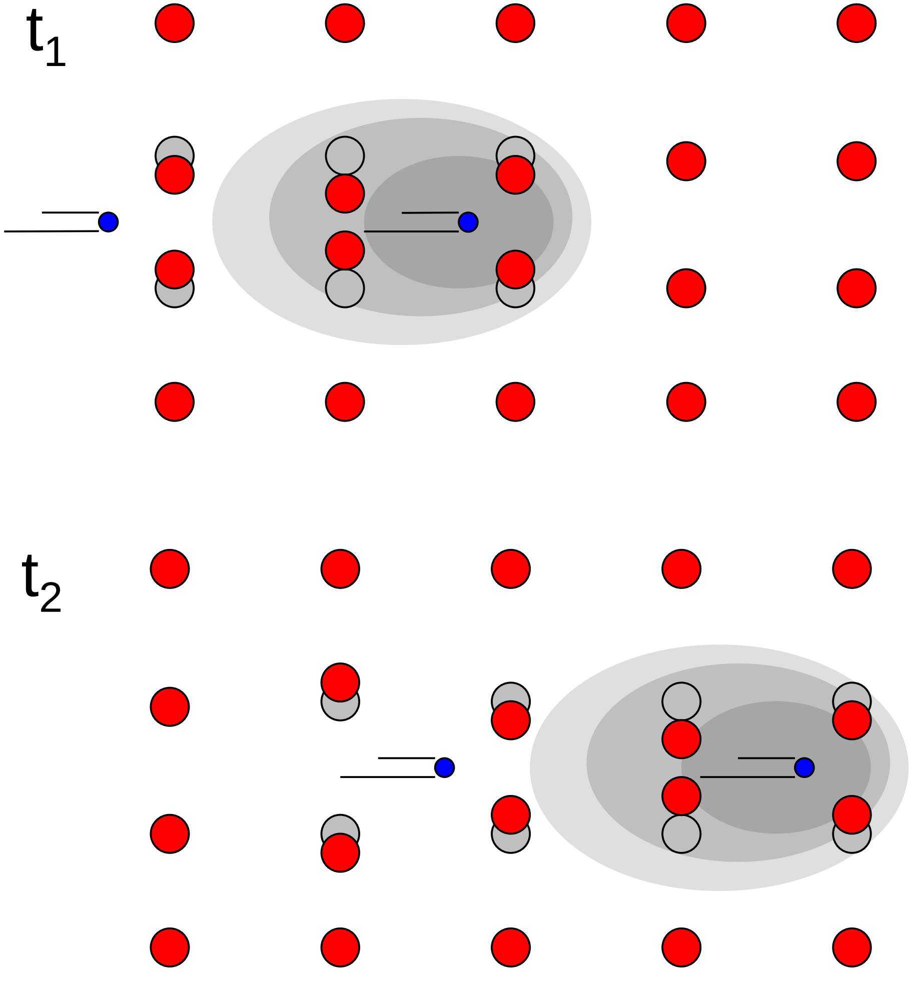
Lattice displacement

⇓

phonons (sound)

⇓

coupling of charge carriers



Bardeen, Cooper, Schrieffer (BCS) - 1957

First (not last) superconducting magnet project cancelled

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

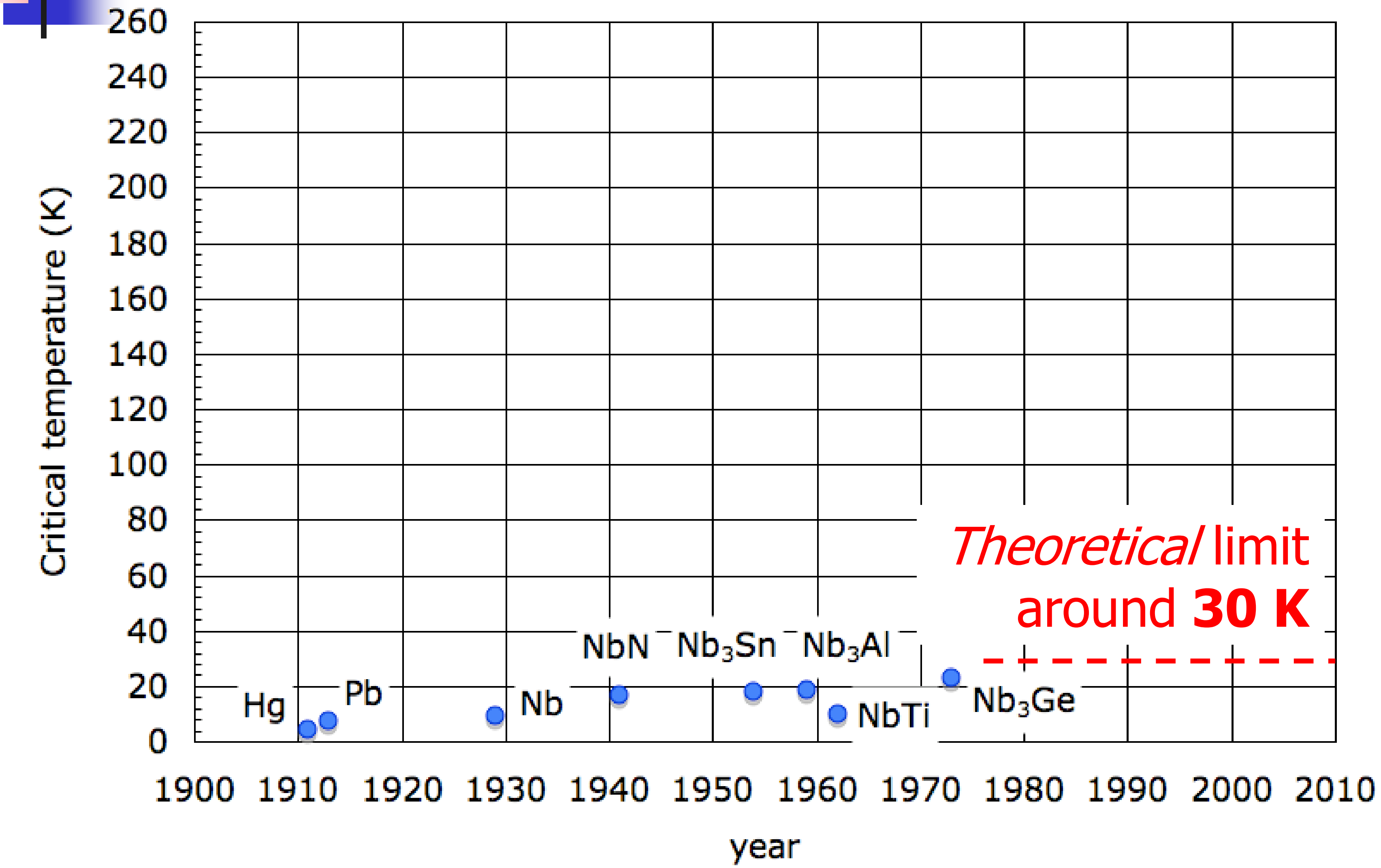
Third International Congress of Refrigeration, Chicago (1913)

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…

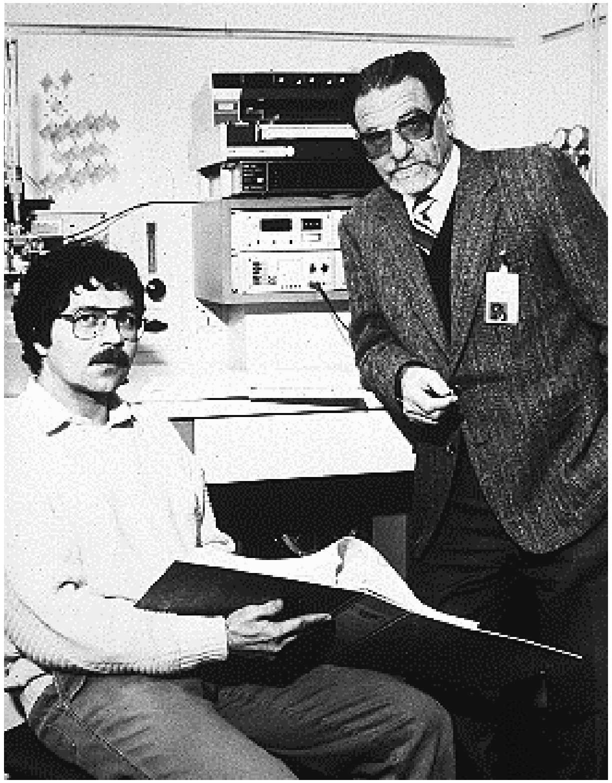
Low-Tc timeline - depressing…



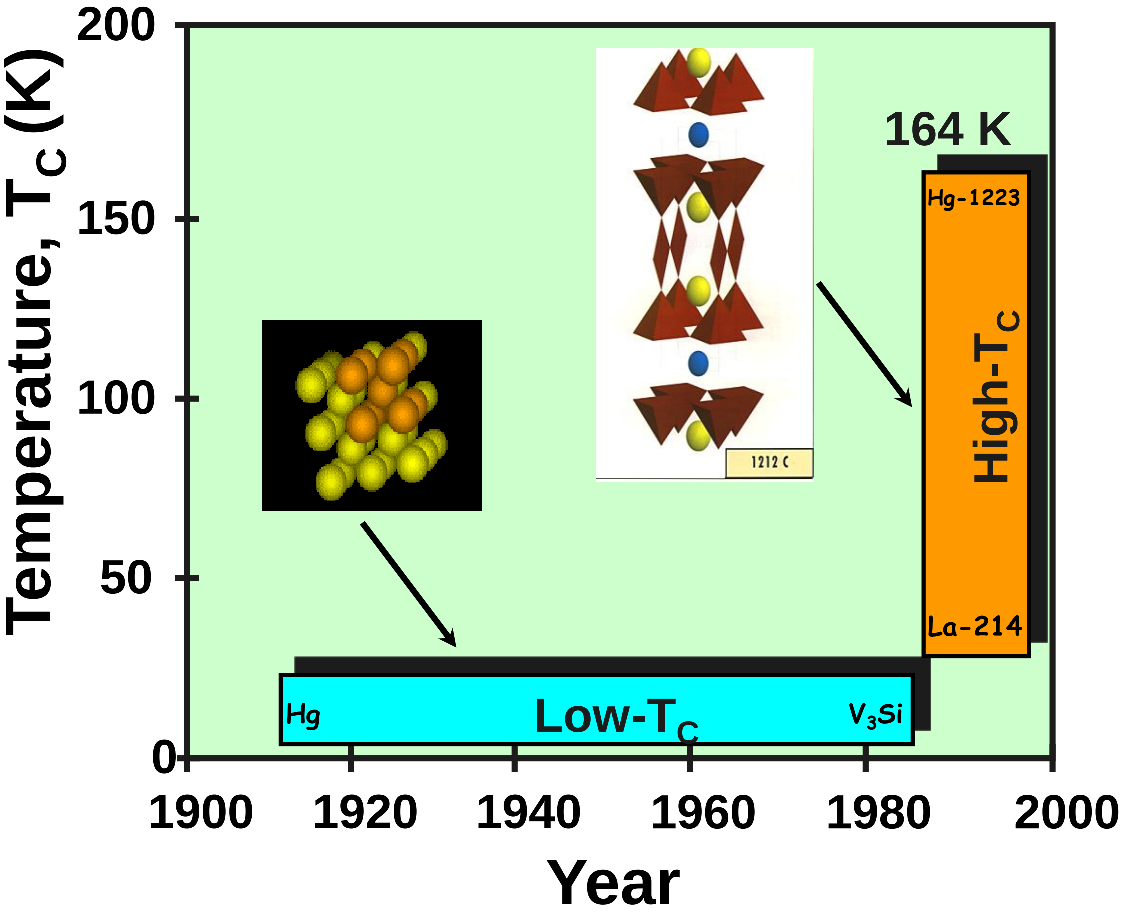
Theoretical limit
around **30 K**

Graphics by courtesy of P. Grant

1986 - A Big Surprise



Bednorz and Mueller
IBM Zuerich, 1986



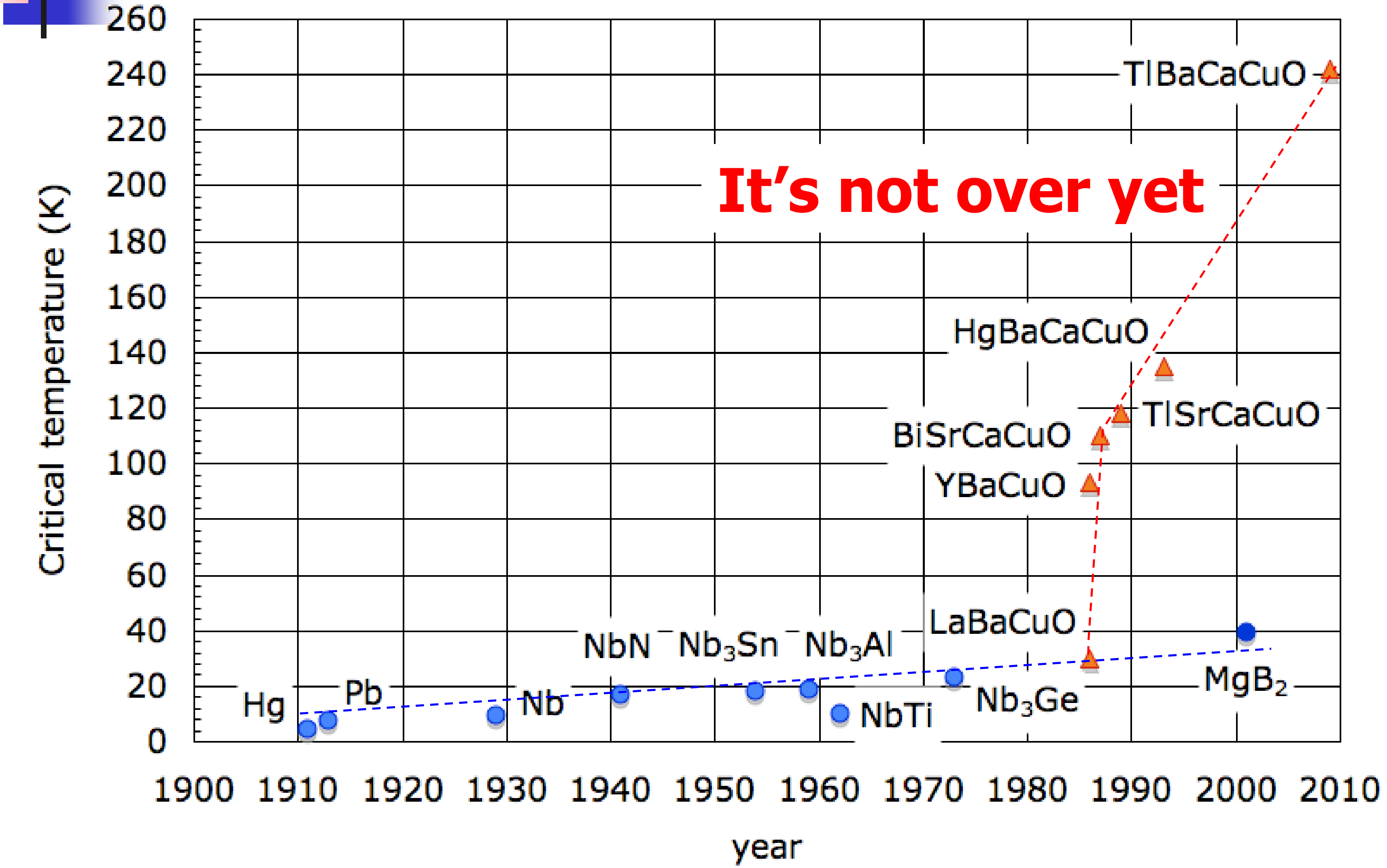
1987 - The prize !

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

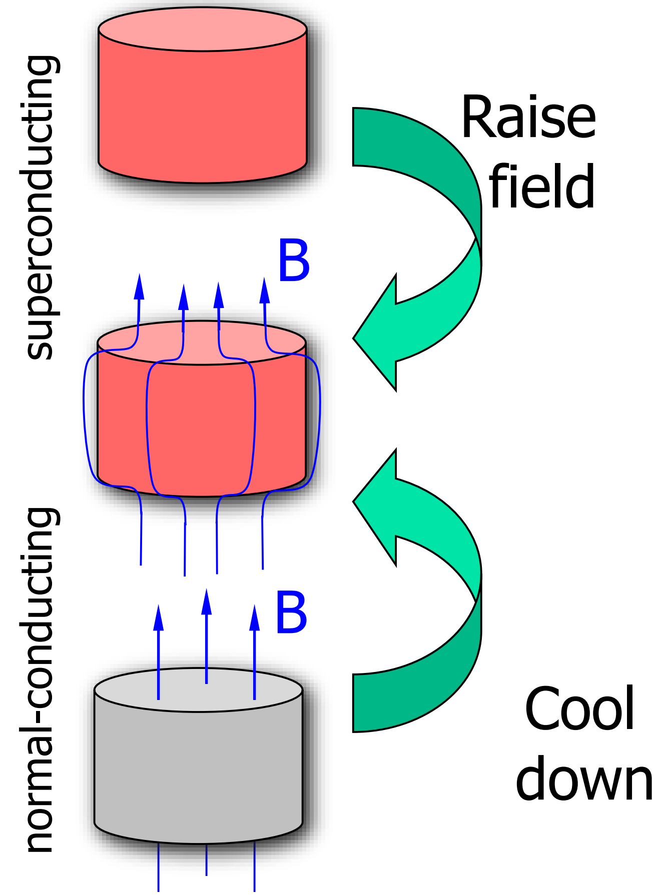
High-Tc timeline - impressive !!!



It's not over yet

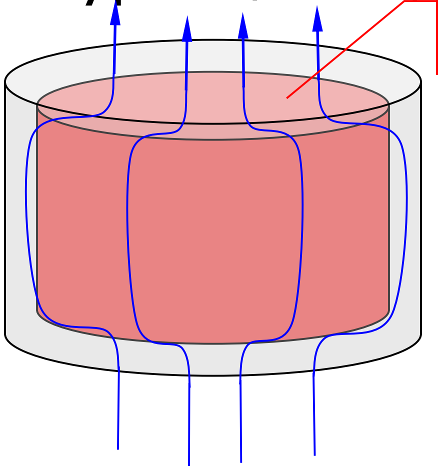
Hey, what about field ?

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

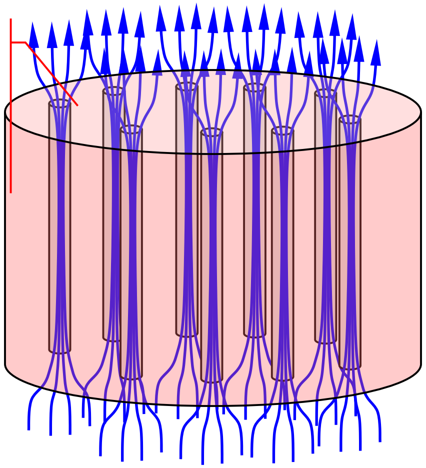
Type II ($\kappa > 1/\sqrt{2}$)

Partial field exclusion

Lattice of fluxons

Dirty materials: alloys intermetallic, ceramic

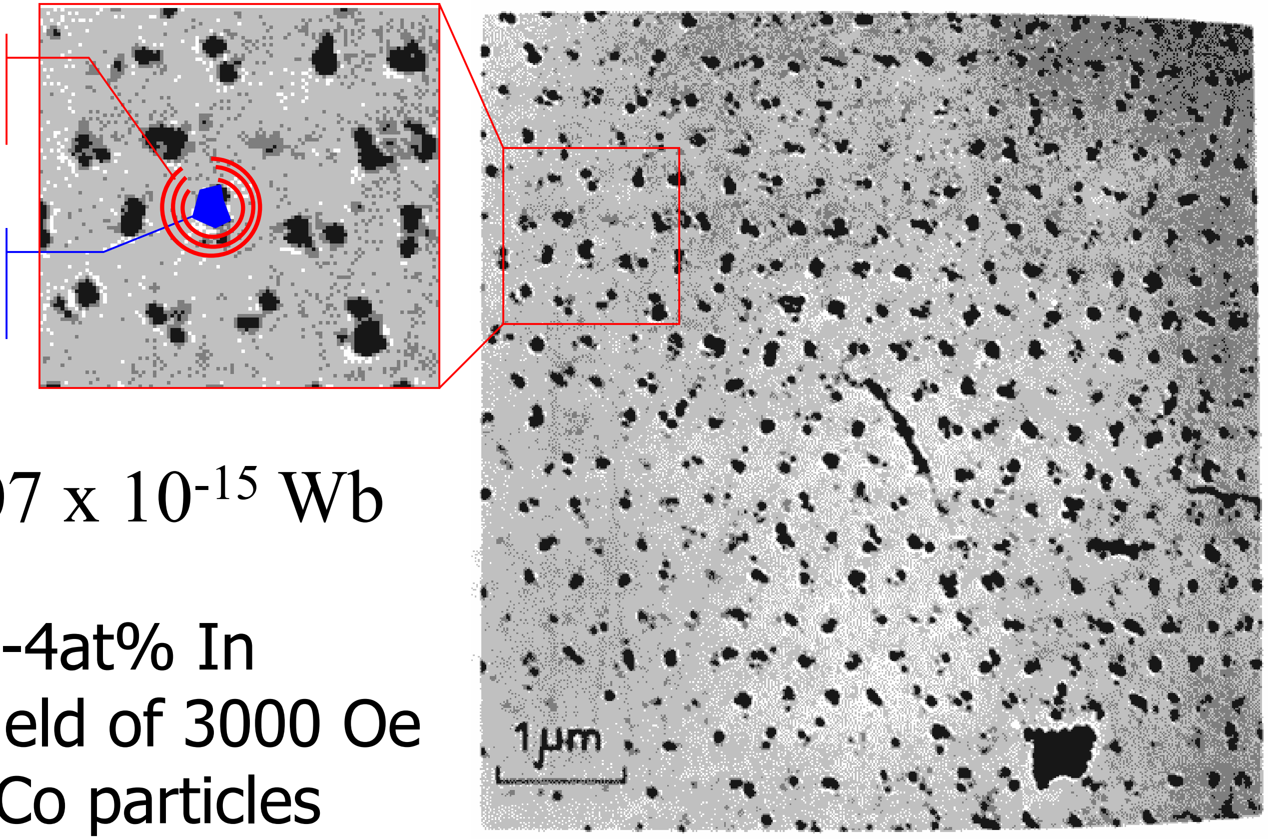
$B_C \approx 10 \ldots 10^2$ T



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

Graphics by courtesy of Superconductor Lab, Oslo

Lattice of quantum flux lines



Supercurrent

Flux quantum

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

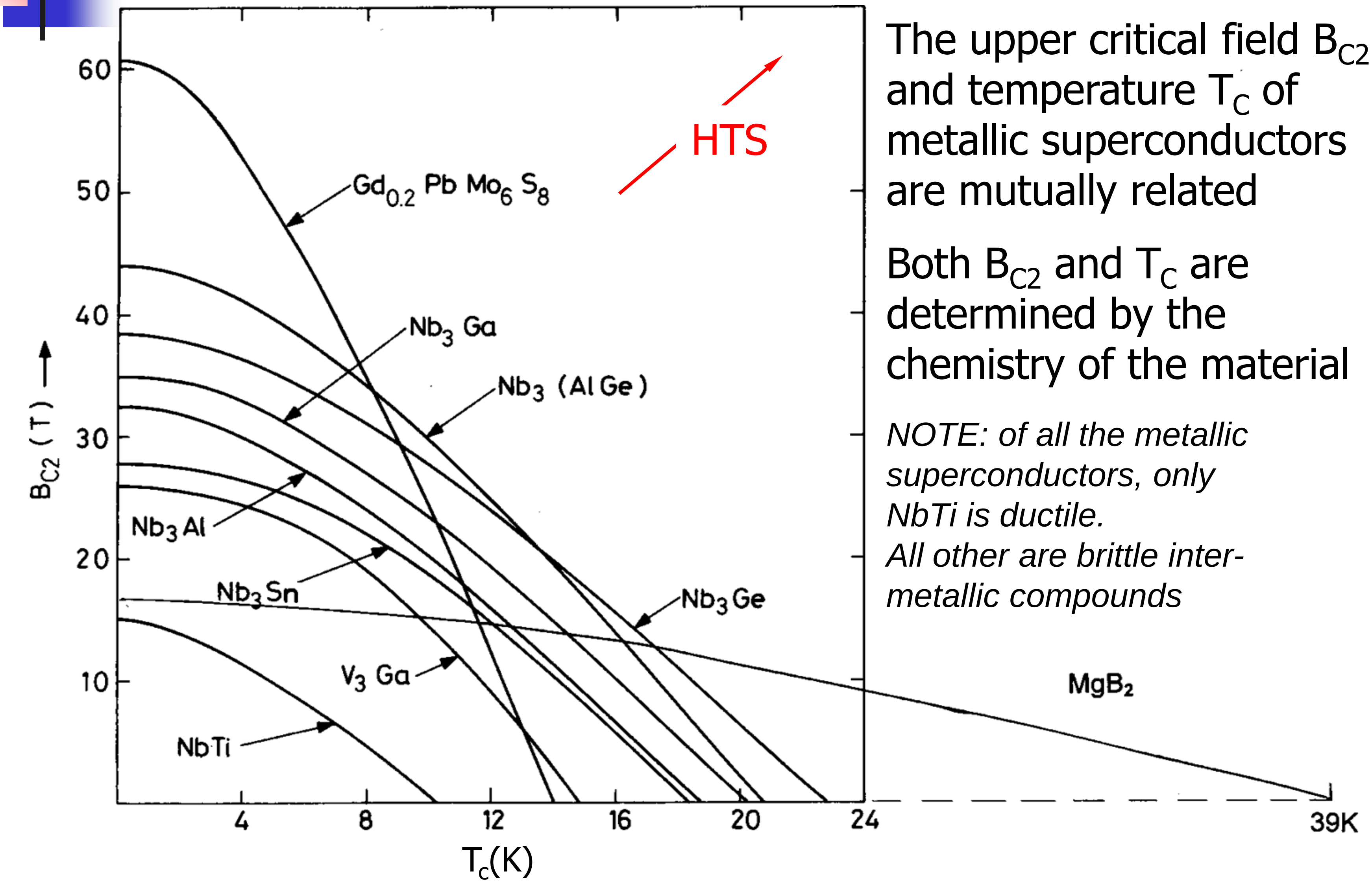
Observation on Pb-4at% In magnetised by a field of 3000 Oe and decorated by Co particles

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.

Essmann & Träuble, 1967

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

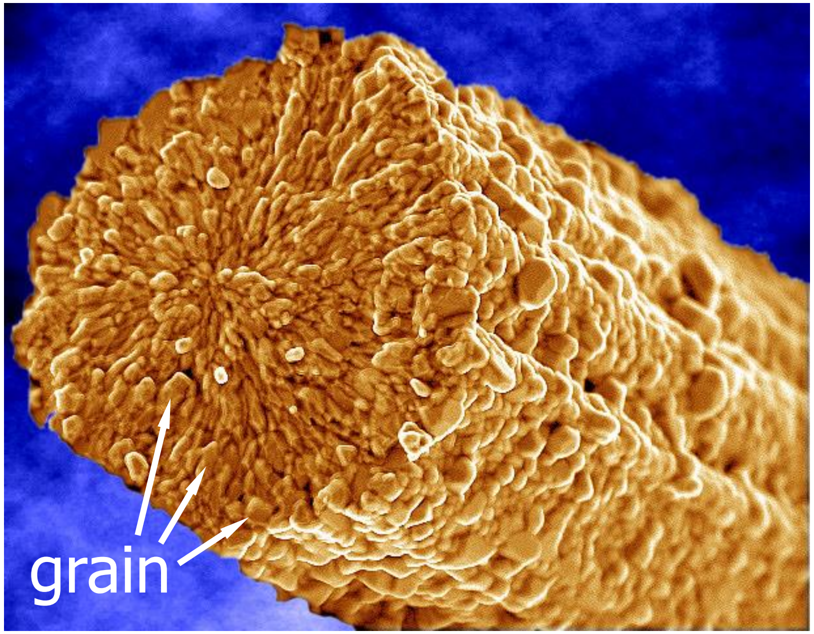
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning mechanisms

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds



Microstructure of Nb_3Sn

Jc(B,T,…)

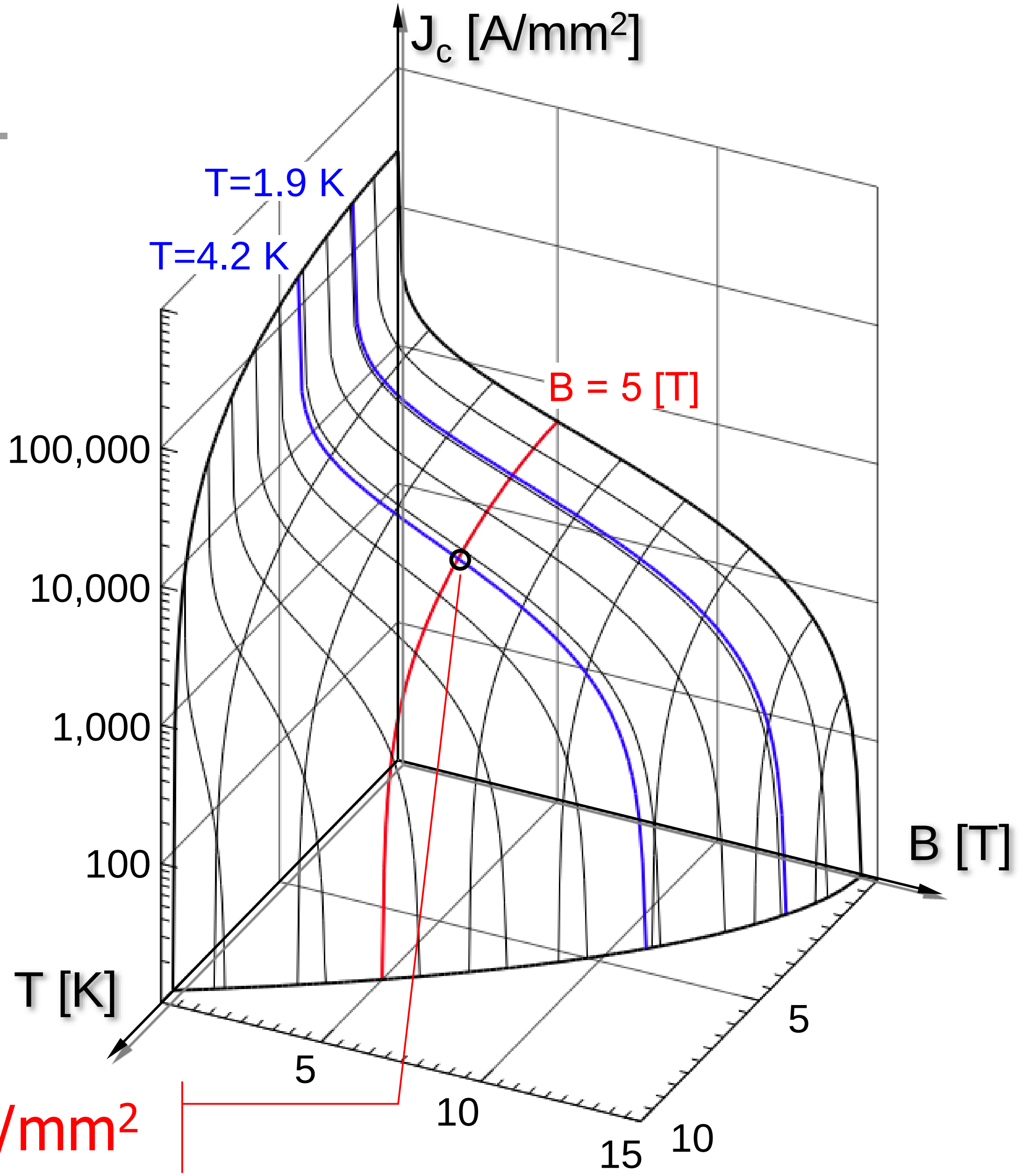
- The maximum current that can be carried by the superconductor is the current at which:

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

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

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

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 $I_C = A_{SC} \times J_C$

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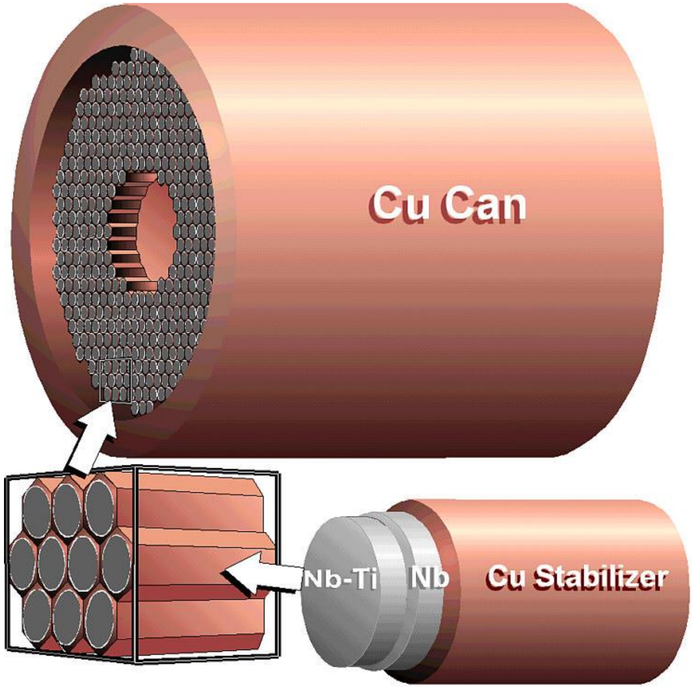
From materials to magnets

- 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



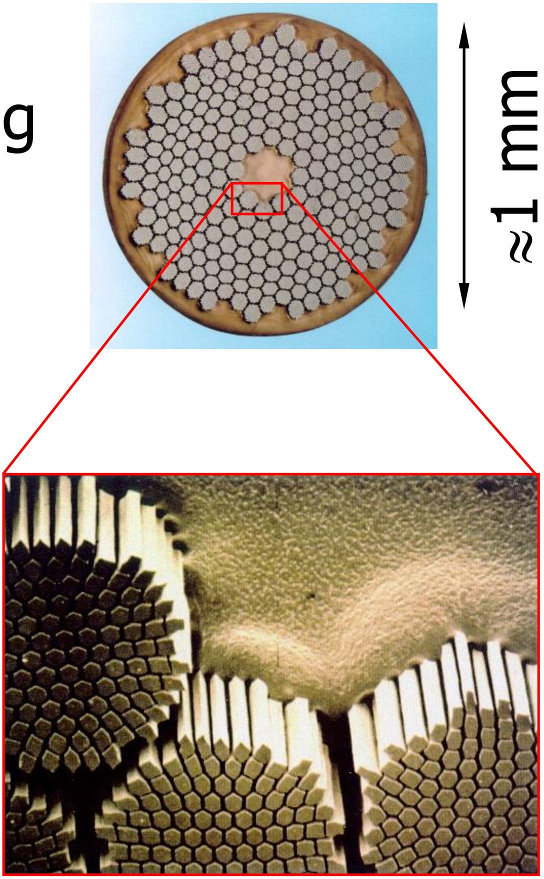
NbTi is a ductile alloy that can sustain large deformations

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

extrusion
cold drawing

⇒

heat
treatments

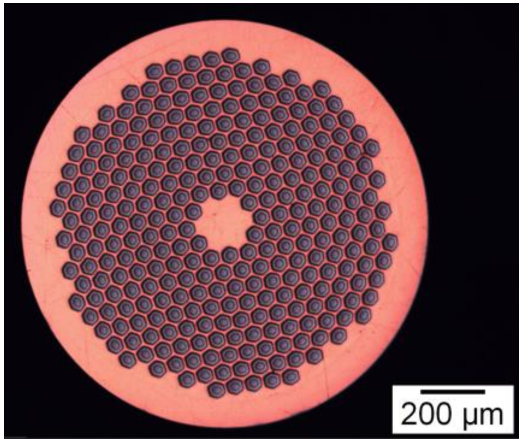


LHC wire

Graphics by courtesy of Applied Superconductivity Center at NHMFL

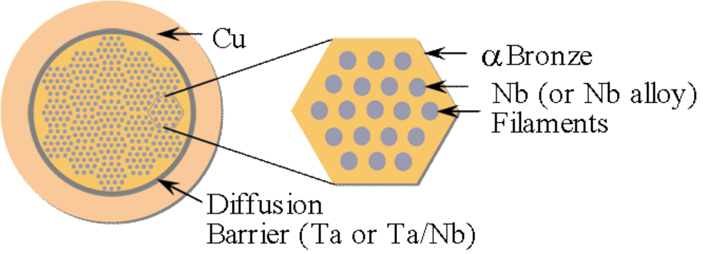
Nb_3Sn manufacturing routes

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

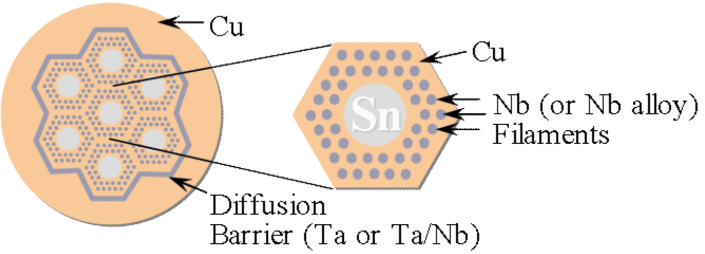


$I_C(12\ T, 4.2\ K) \approx 1.5\ kA$

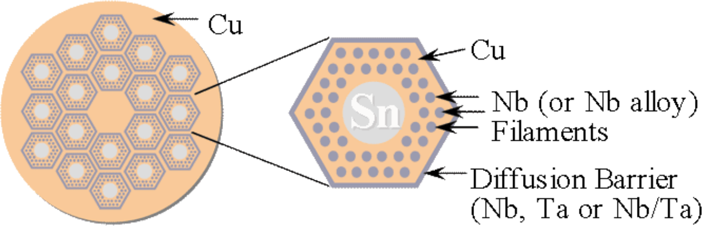
Bronze Process



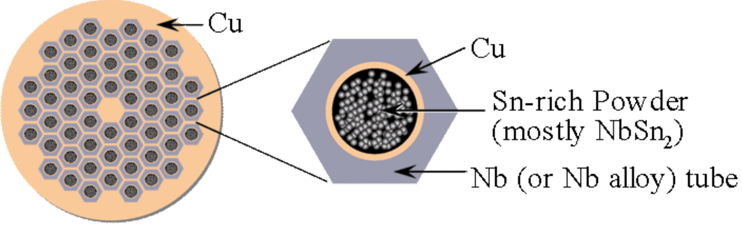
Internal Sn (Single Barrier)



Internal Sn (Distributed Barrier)



Powder in Tube (PIT)

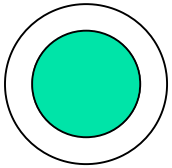


Graphics by courtesy of M.N. Wilson and Applied Superconductivity Center at NHMFL

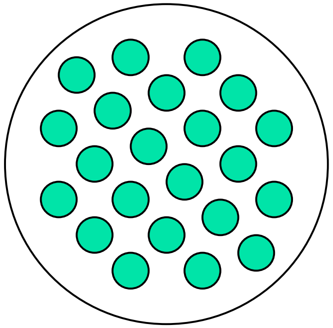
BSCCO manufacturing routes

Oxide powder in tube OPIT

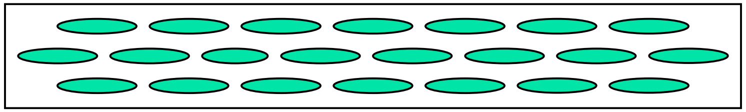
1) draw down BSCCO powder in a silver tube



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

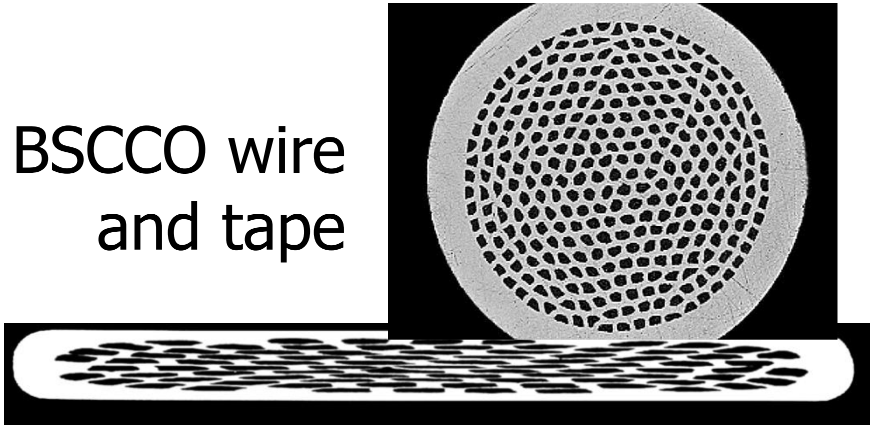


3) roll the final wire to tape and heat treat at 800 - 900C in oxygen to melt the B2212



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

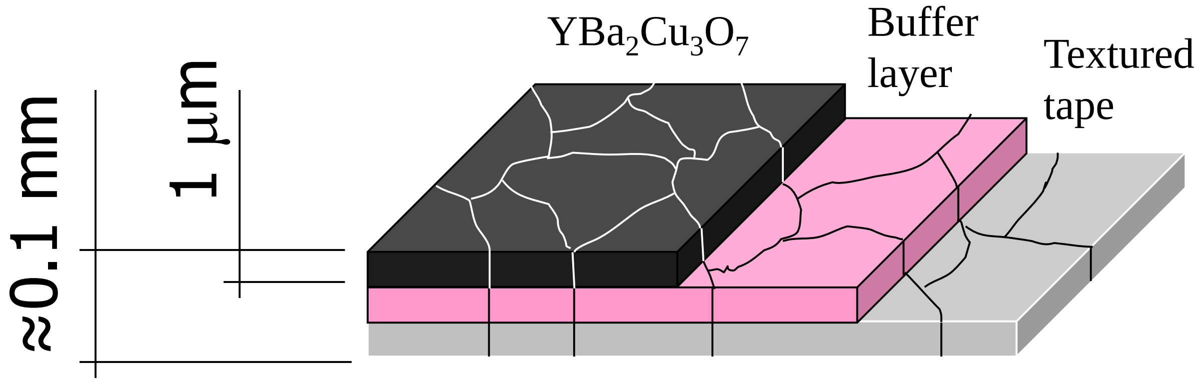
BSCCO wire and tape



YBCO tape (developmental)

YBCO 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 $YBa_2Cu_3O_7$ such that the texture of the YBCO follows that of the buffer and substrate



Engineering current density

- All wires, tapes and cables contain additional components:
  - Left-overs from the precursors of the SC formation
  - Barriers, texturing and buffering layers
  - Low resistance matrices **(?)**
- The SC *material fraction* is hence always < 1:

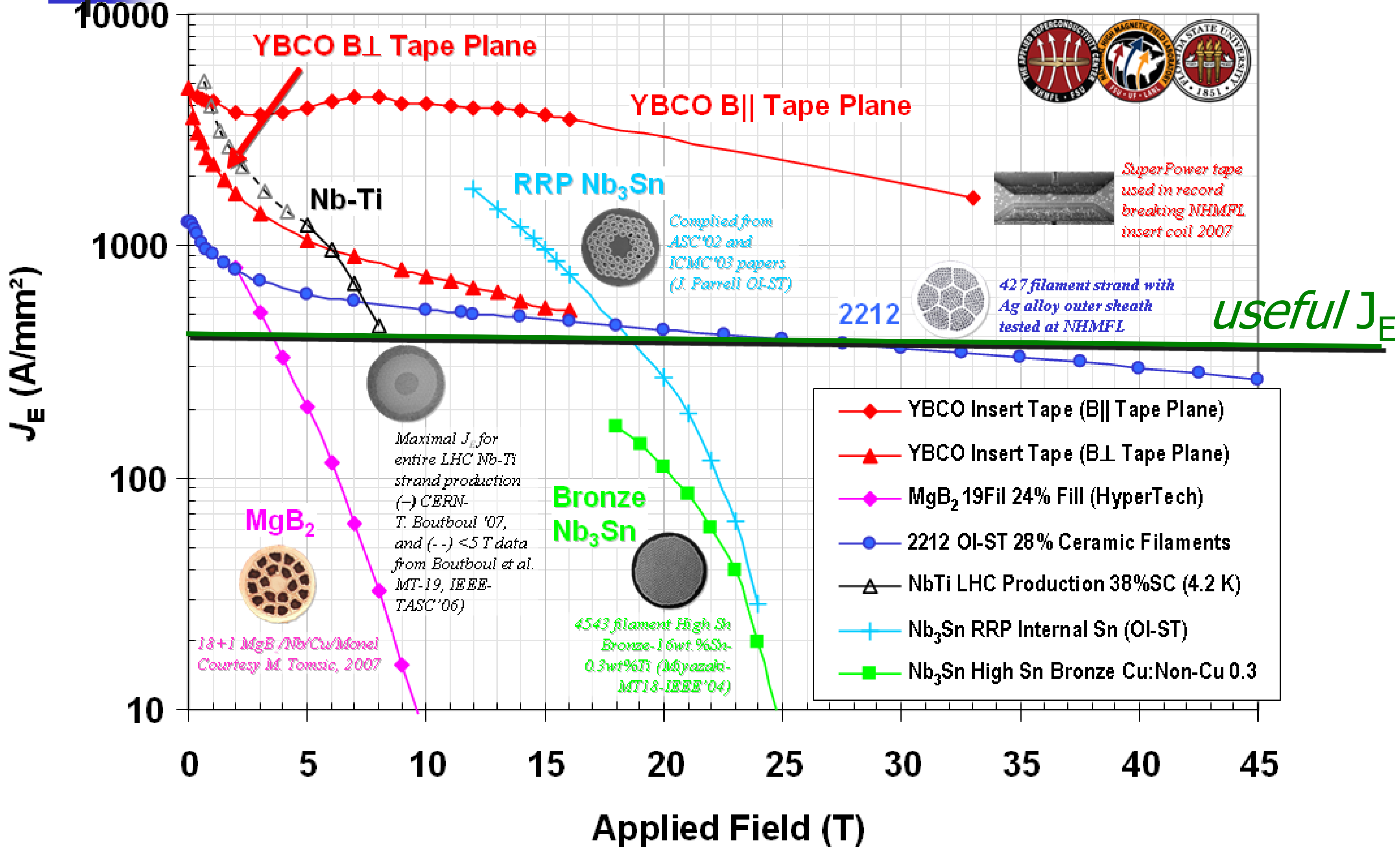
$$\lambda = A_{SC} / A_{total}$$

- To compare materials on the same basis, we use an *engineering current density*:

$$J_E = J_C \times \lambda$$

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_2/Nb/Cu/Monel Courtesy M. Tomsic, 2007

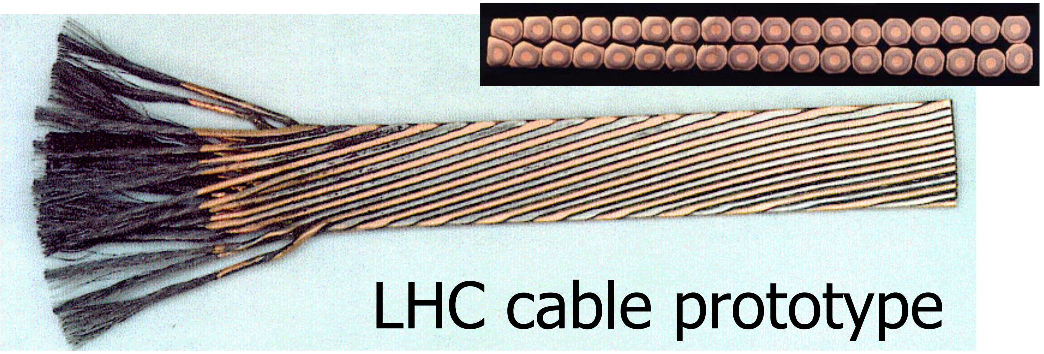
4543 filament High Sn Bronze-16wt.%Sn-0.3wt%Ti (Miyazaki-MT18-IEEE'04)

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

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

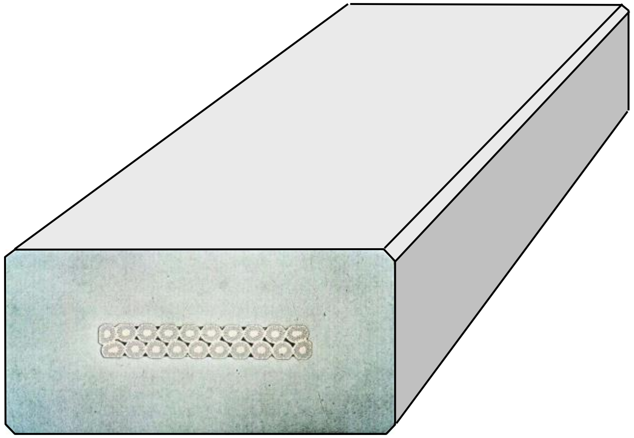


LHC cable prototype

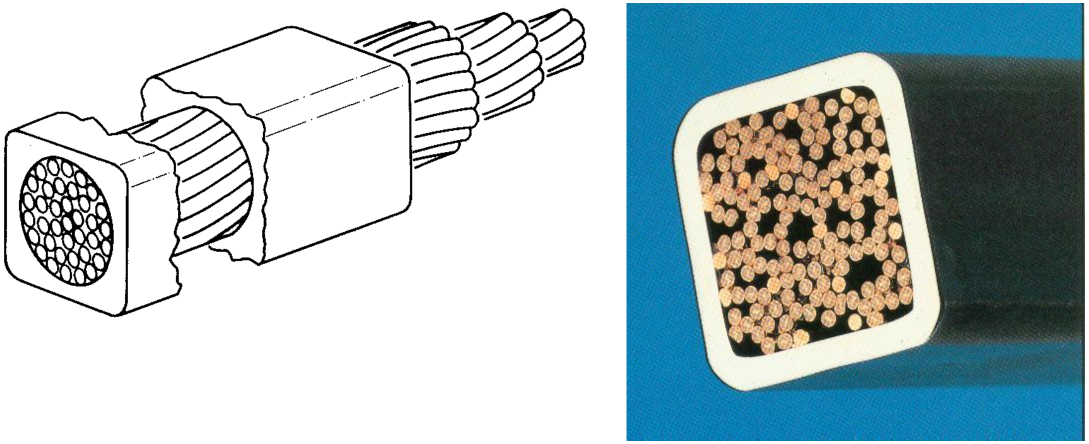
$J_E \approx 50$ A/mm^2

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



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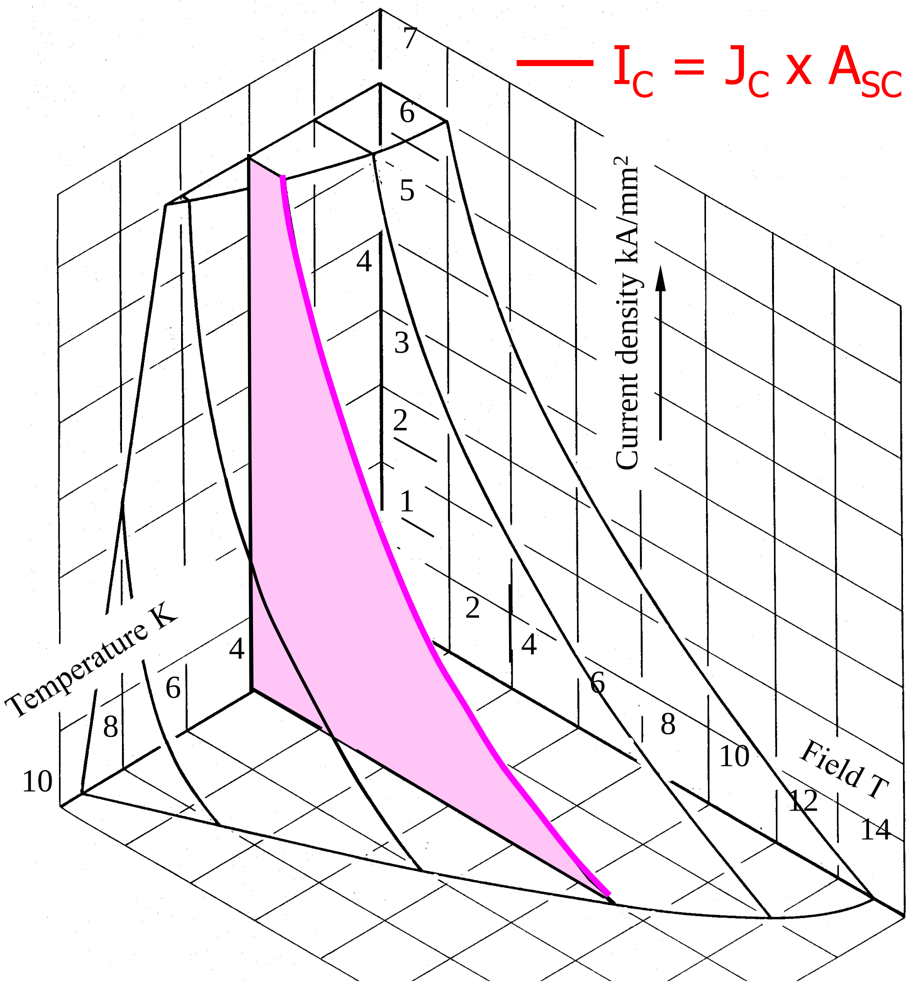
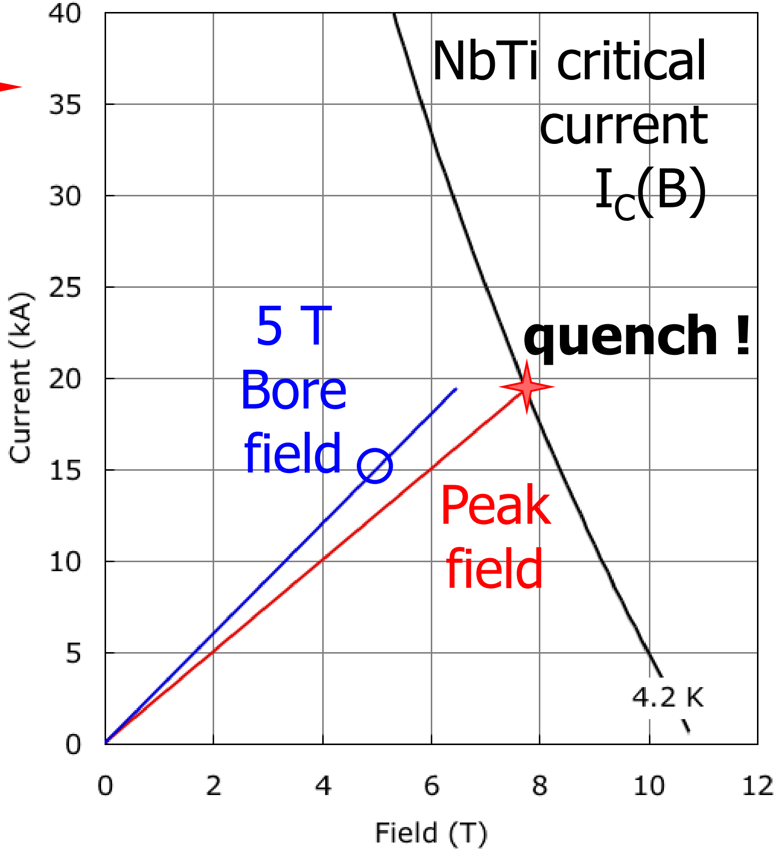
Critical line and magnet load lines

NbTi critical surface



$I_C = J_C \times A_{SC}$

e.g. a 5 T magnet design

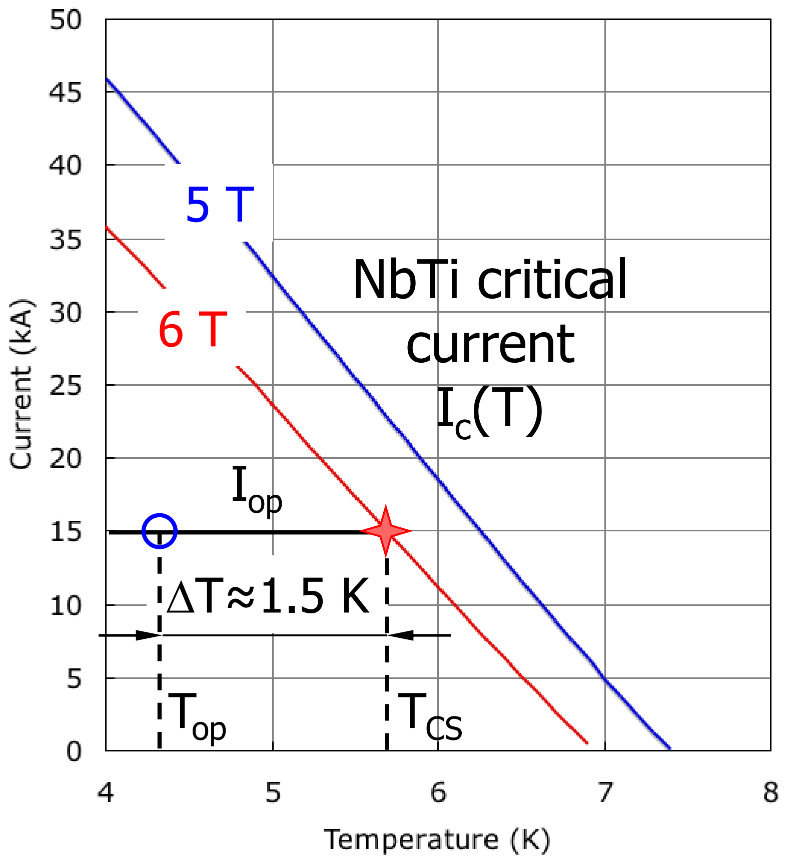


we expect the magnet to go resistive i.e. to **'quench',** where the peak field load line crosses the critical current line

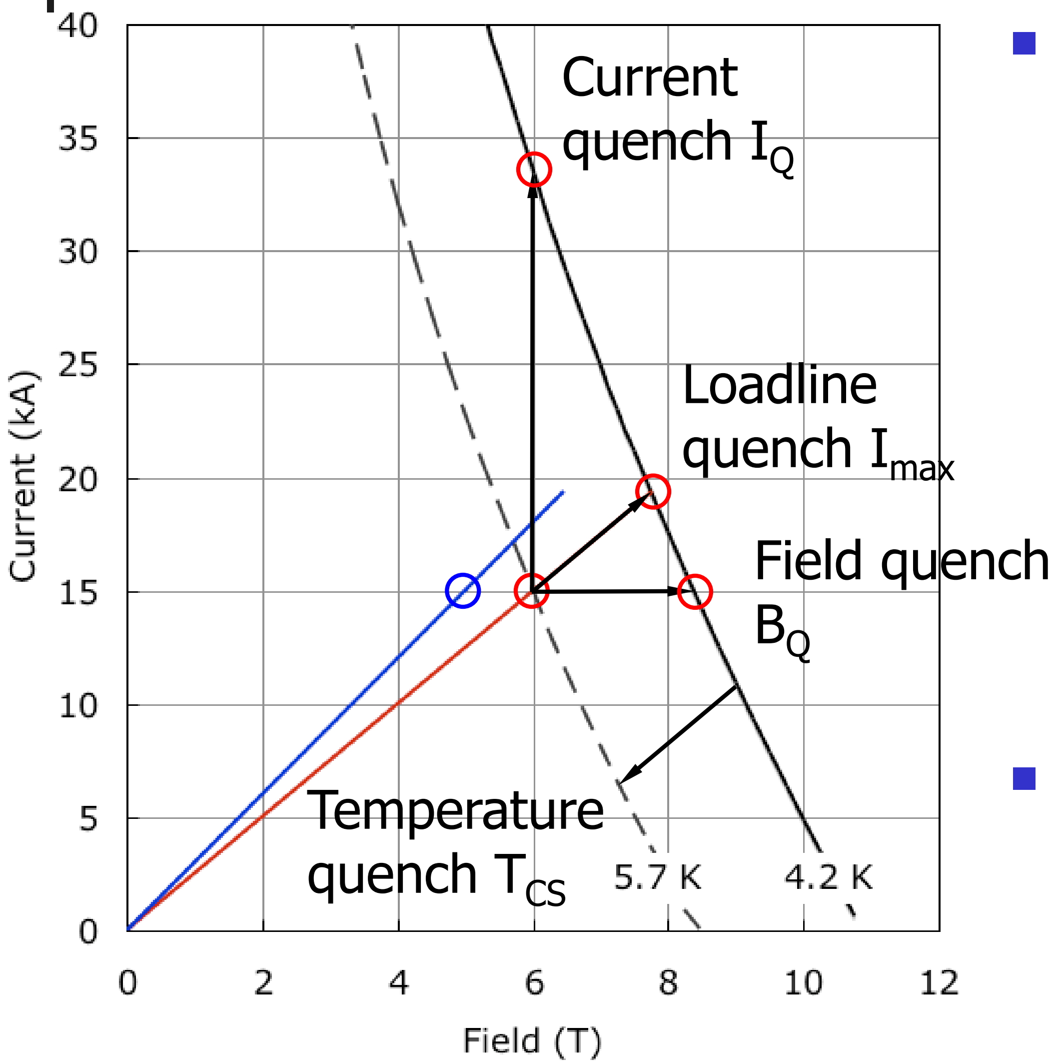
Temperature margin

- Temperature rise may be caused by
  - sudden mechanical energy release
  - AC losses
  - Resistive heat at joints
  - Beams, neutrons, etc.
- We should allow *temperature headroom* for all foreseeable and unforeseeable events, i.e. a temperature margin:

$$\Delta T = T_{CS}-T_{op}$$



Operating margins



- Practical operation always requires margins:
  - Critical current margin: $I_{op}/I_Q \approx 50$ %
  - Critical field margin: $B_{op/}B_Q \approx 75$ %
  - Margin along the loadline: $I_{op}/I_{max} \approx 85$ %
  - Temperature margin: $T_{CS} - T_{op} \approx 1 \ldots 2$ K
- The margin needed depends on the design and operating conditions

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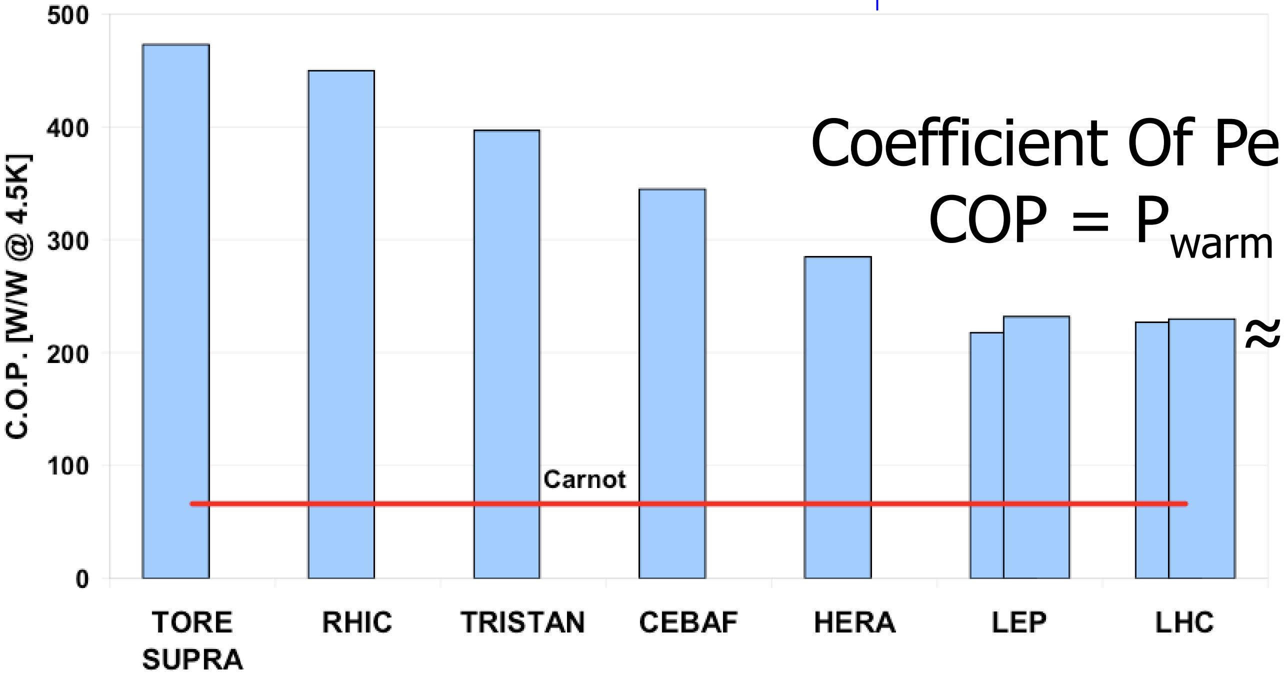
Basic thermodynamics

- The maximum efficiency that can be achieved by a heat machine is that of the Carnot cycle:

Work at the warm end

$$W/Q = (T_{hot} - T_{cold}) / T_{cold}$$

Heat at the cold end



Coefficient Of Performance

$COP = P_{warm} / P_{cold}$

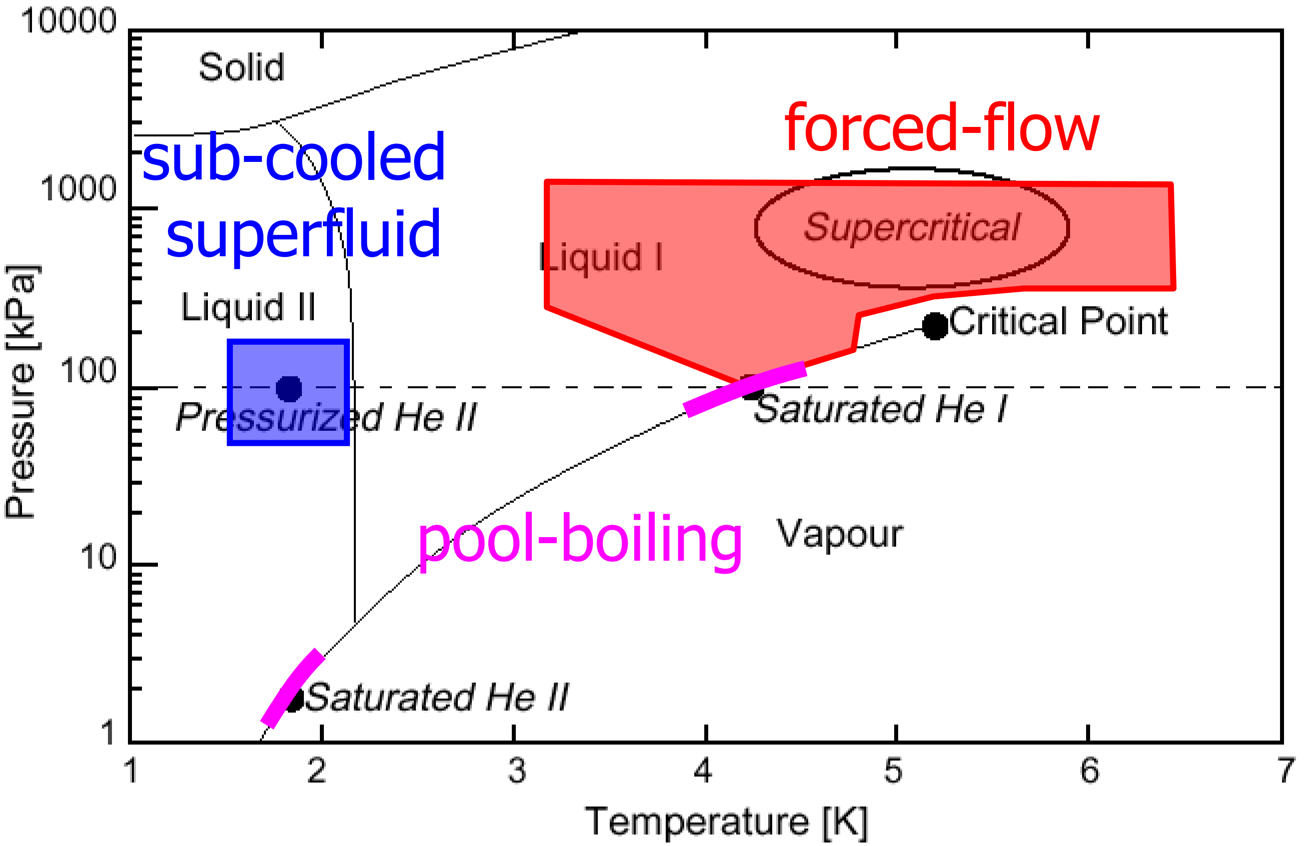
≈ 250

Fridge’s

Cryocoolers: ≈1.5 W @ 4.2 K

LHC refrigerators: ≈140 kW @ 4.2 K

Helium as a low-temperature coolant



Waiting for the room-temperature superconductor,
the best is to take a course on cryogenics !

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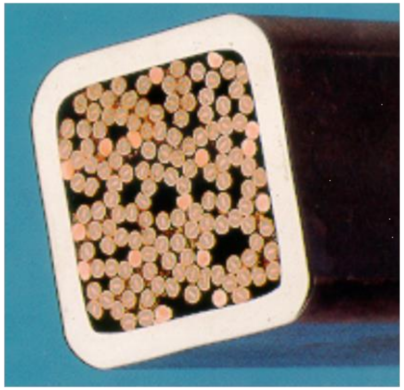
Stability as a heat balance

perturbation

Joule heating



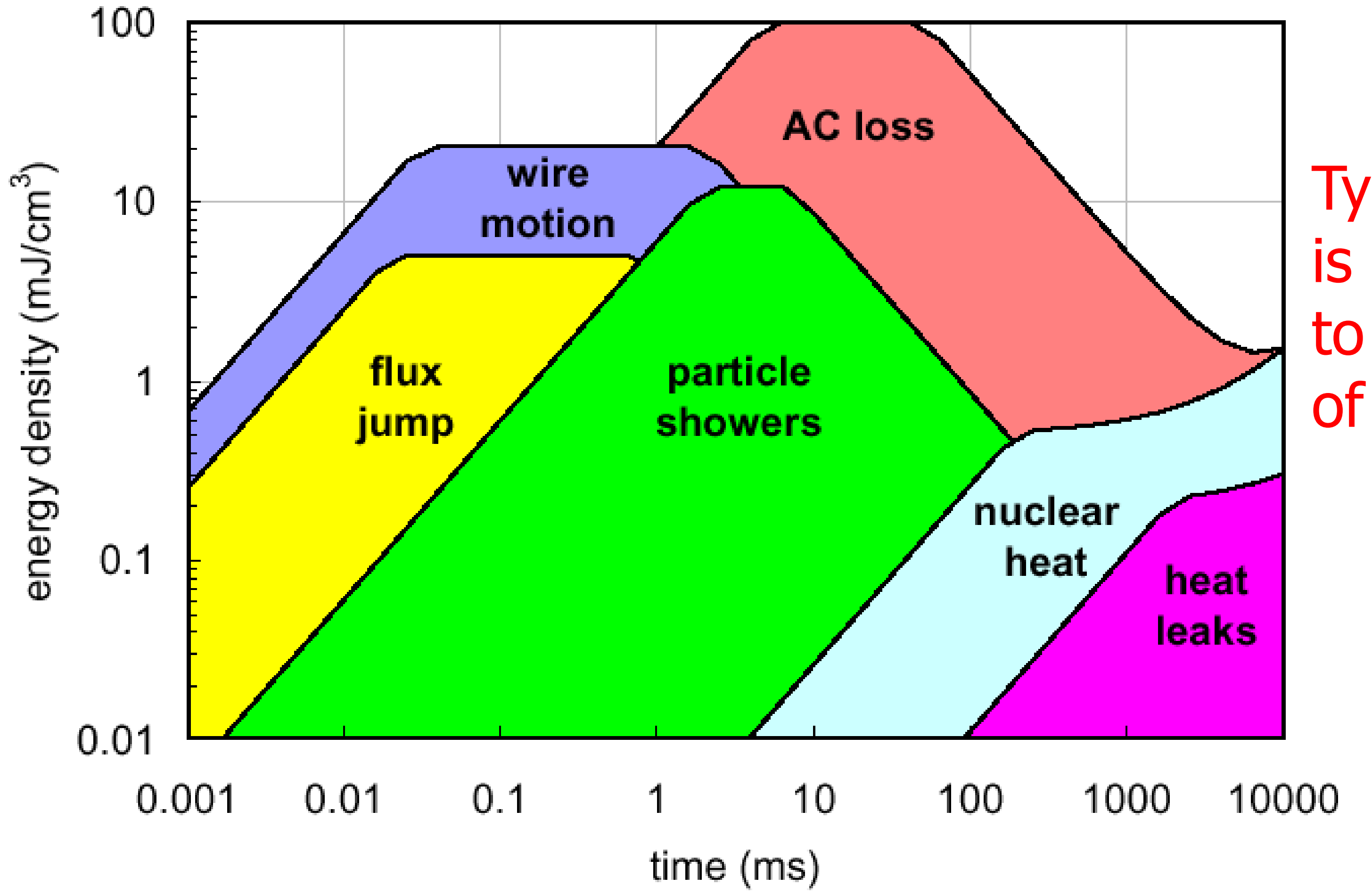
superconducting cable

heat capacity

conduction

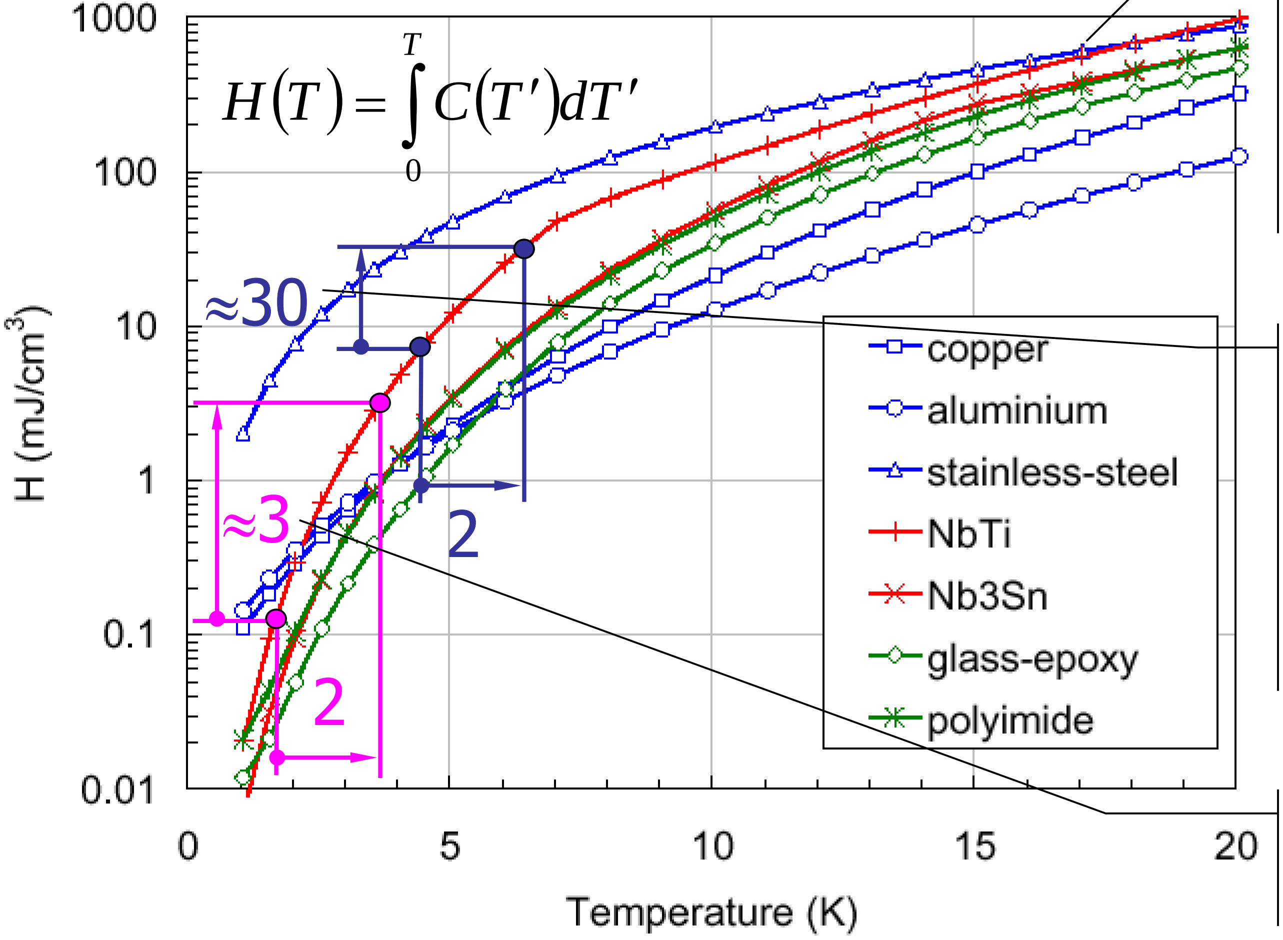
cooling

Perturbation overview



Typical range is from a few to a few tens of mJ/cm^3

Enthalpy reserve



Enthalpy reserve increases massively at increasing T: stability is not an issue for HTS materials

Enthalpy reserve is of the order of the expected perturbation spectrum: stability is an issue for LTS magnets

do not sub-cool if you can only avoid it !

Why is quench a problem ?

- the magnetic energy stored in the field:

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$

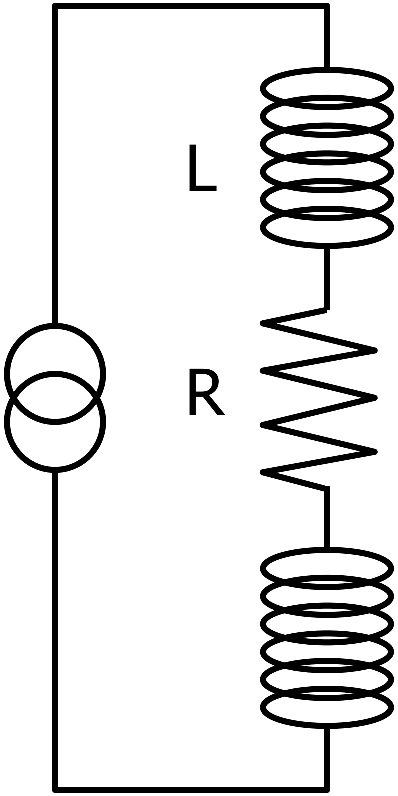
is converted to heat through Joule heating RI^2. *If this process happened uniformly* in the winding pack:

  - Cu melting temperature 1356 K
  - corresponding E_m=5.2 10^9 J/m^3

limit would be $B_{max} \leq$ 115 T: NO PROBLEM !

BUT

the process does not happen uniformly (as little as 1 % of mass can absorb total energy)

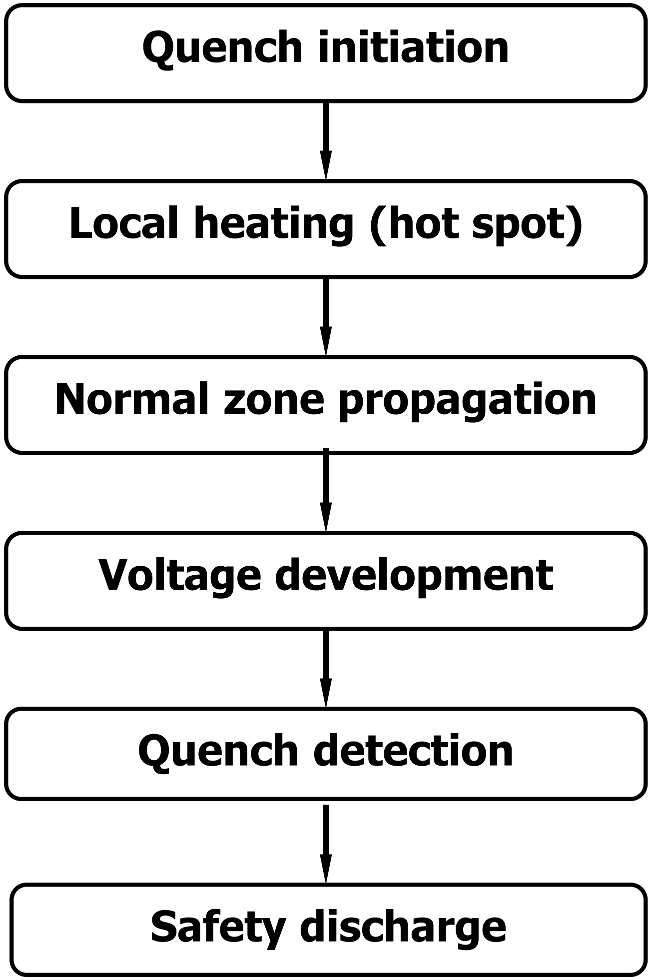


Courtesy of A. Siemko, CERN

This is why it is important !

Typical quench sequence

A quench is a part of the normal life of a superconducting magnet. Appropriate detection and protection strategies should be built in the design from the start



Quench initiation

Local heating (hot spot)

Normal zone propagation

Voltage development

Quench detection

Safety discharge

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

Overview

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- A superconductor physics primer
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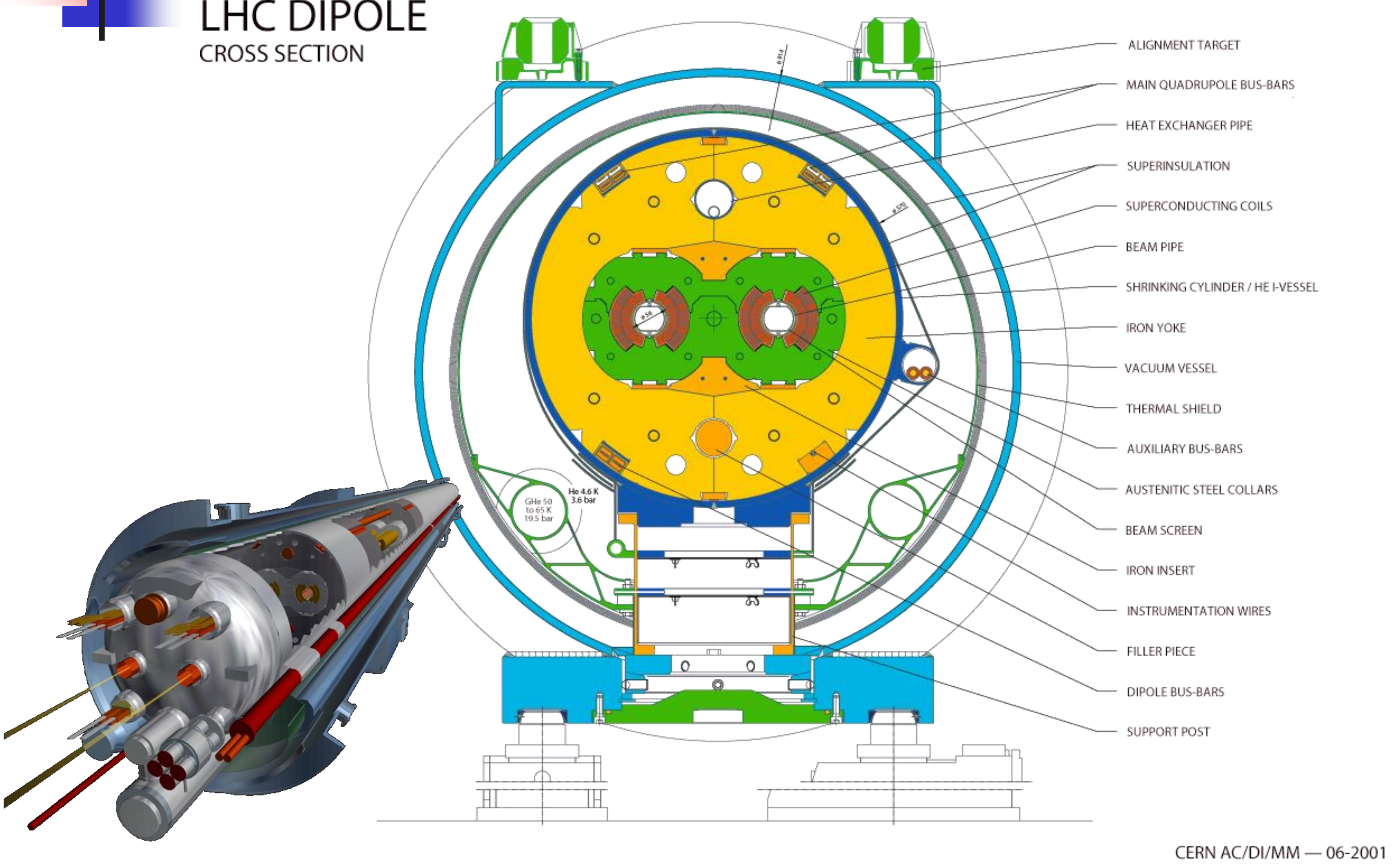
LHC dipole

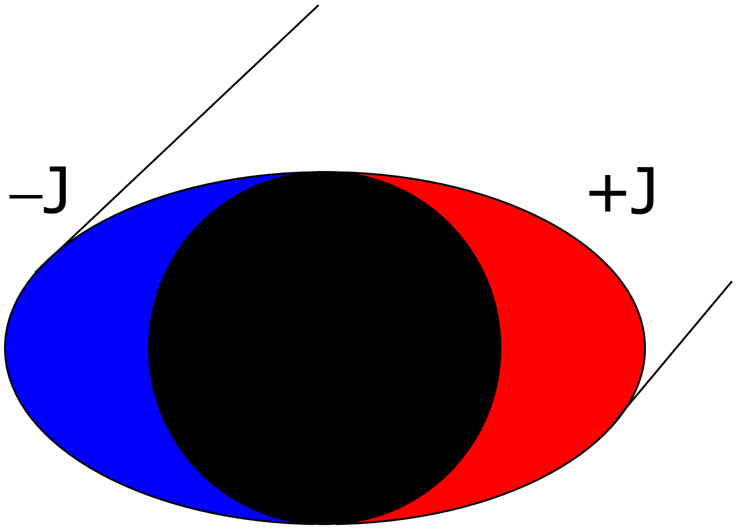
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)



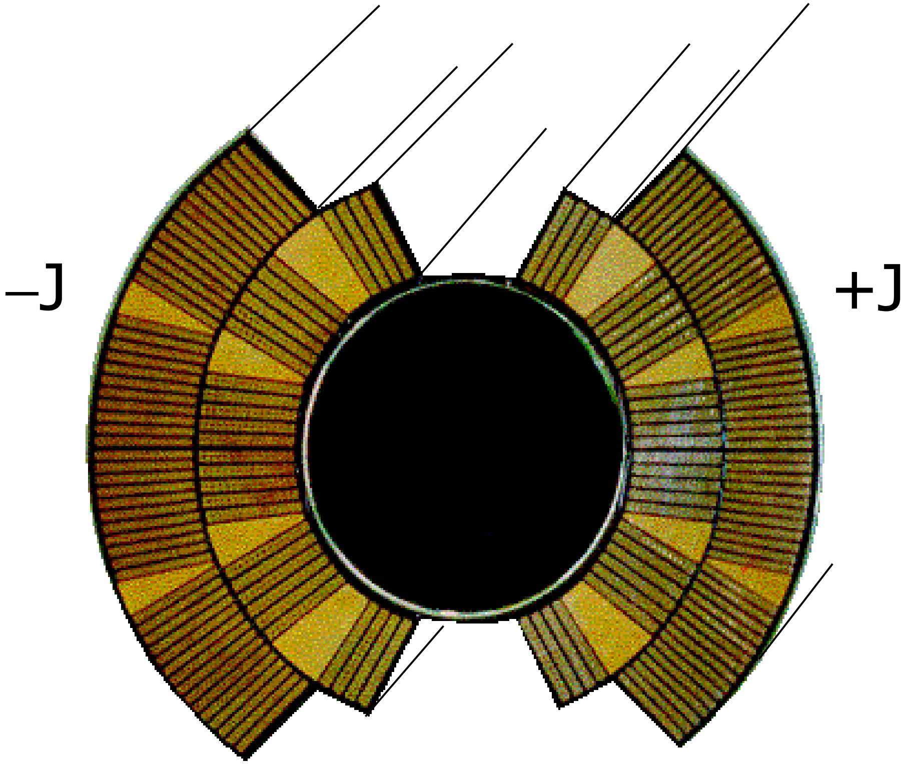
LHC DIPOLE
CROSS SECTION

CERN AC/DI/MM — 06-2001

Superconducting dipole magnet coil

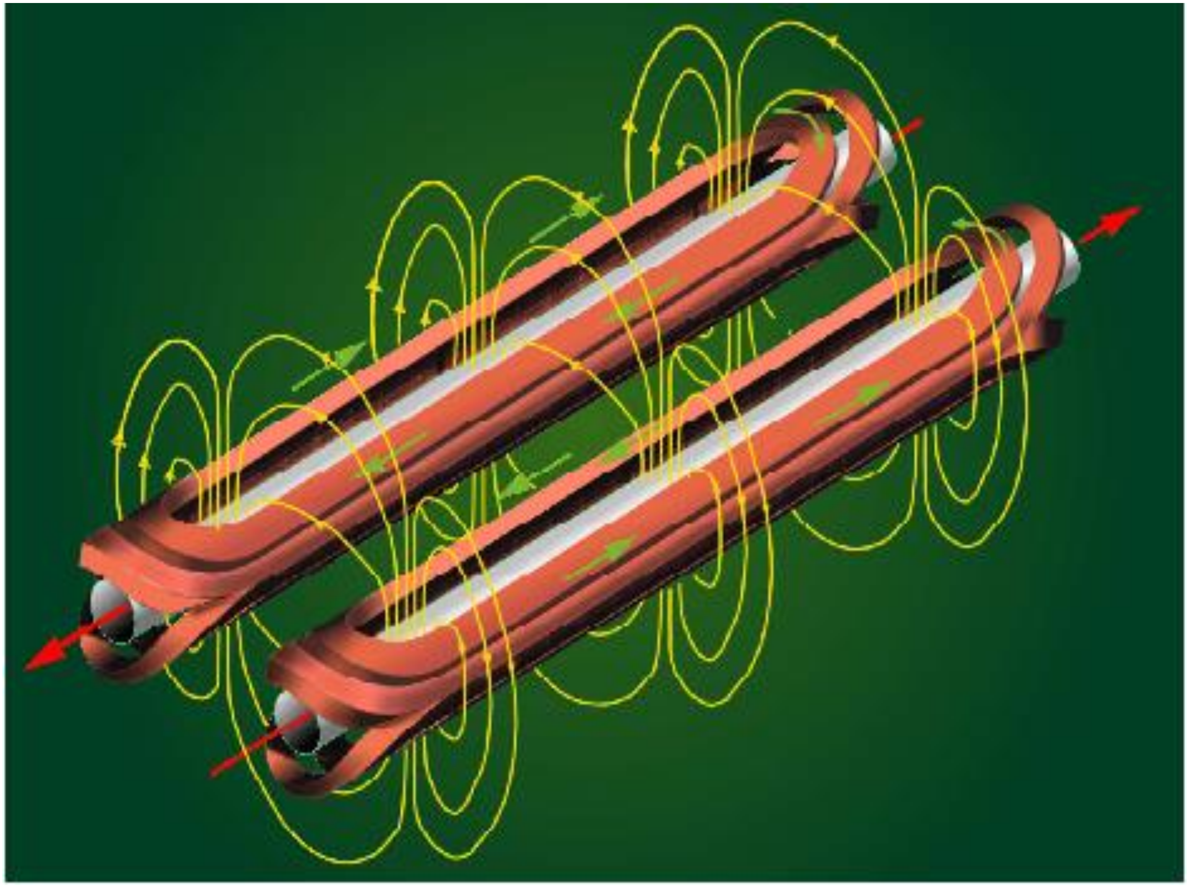


Ideal current distribution that generates a perfect dipole



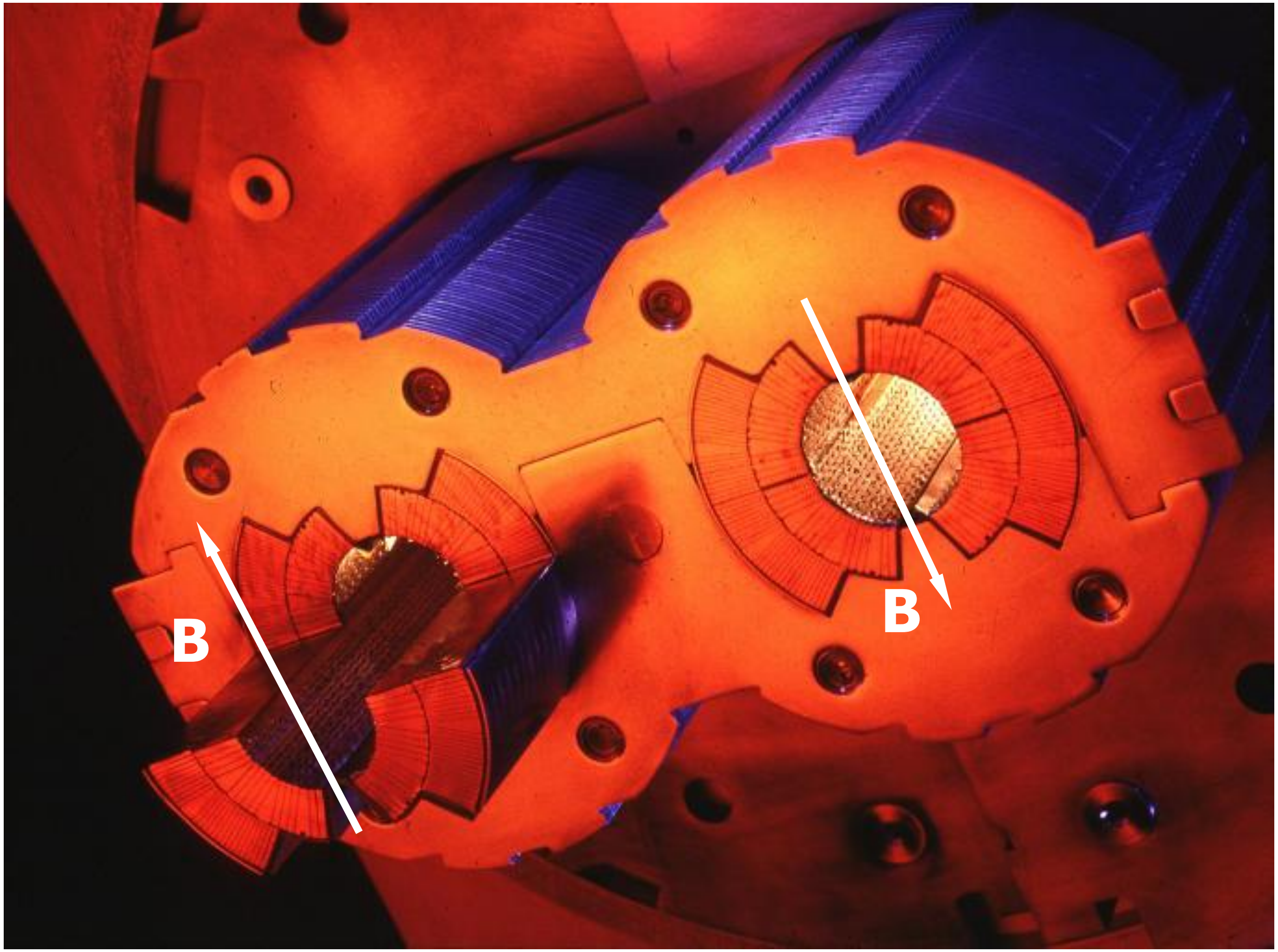
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle

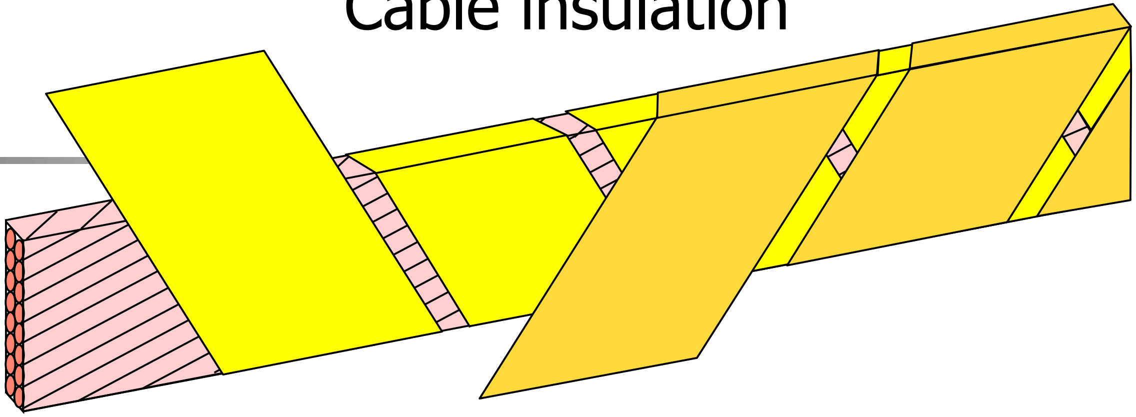


Combine two magnets in one
Save volume, material, cost

LHC dipole coils

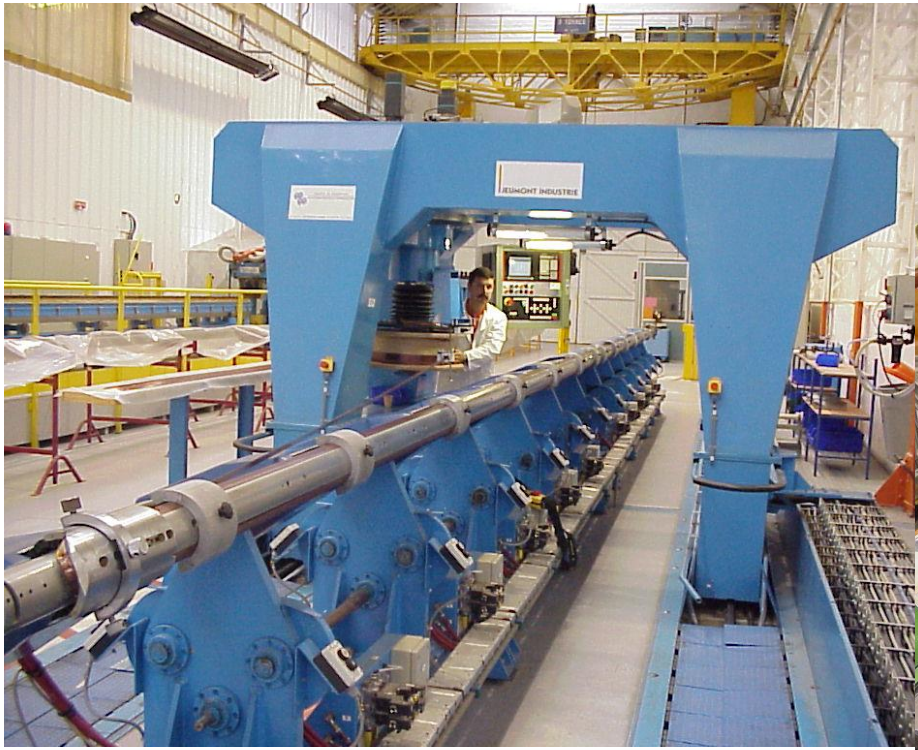


Coil winding



Cable insulation

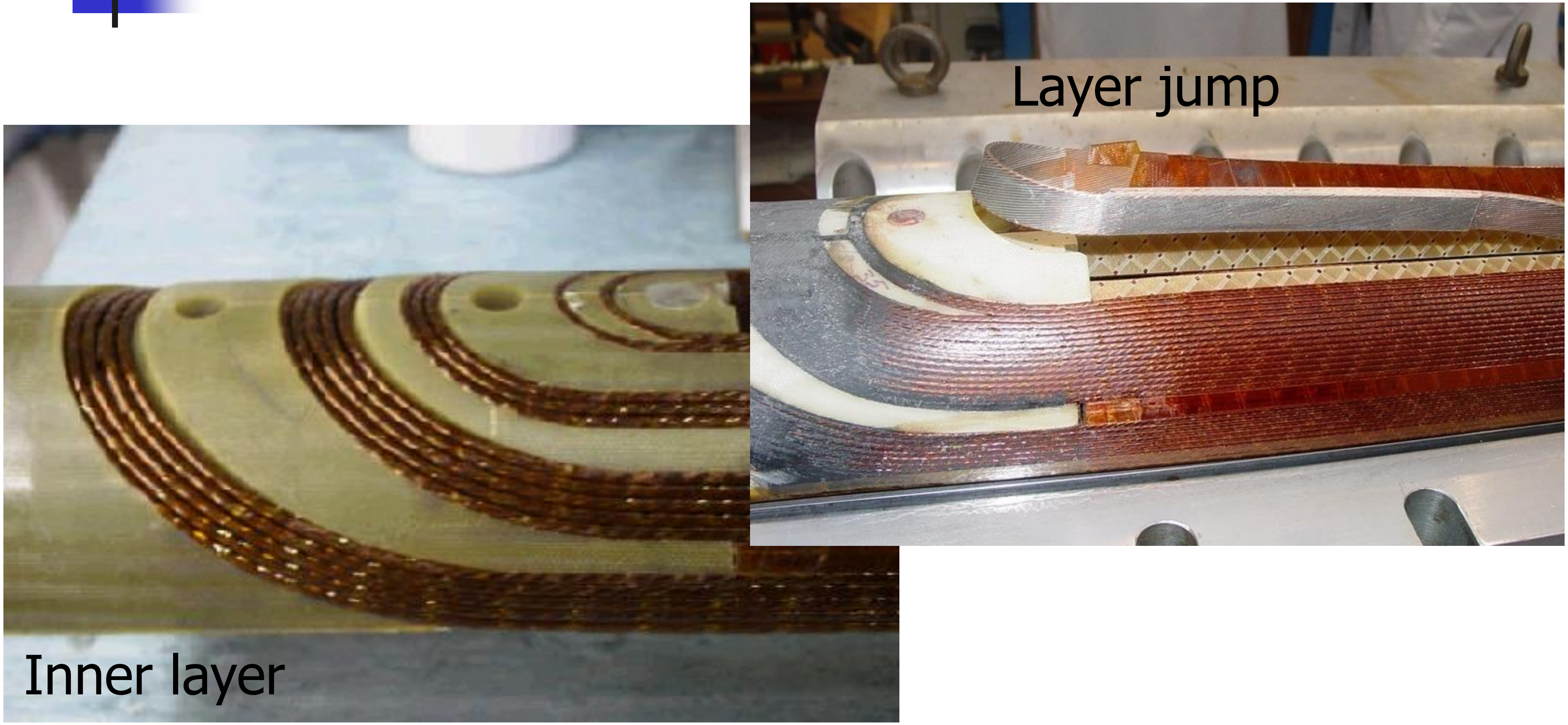
10 μm precision !



Coil winding machine

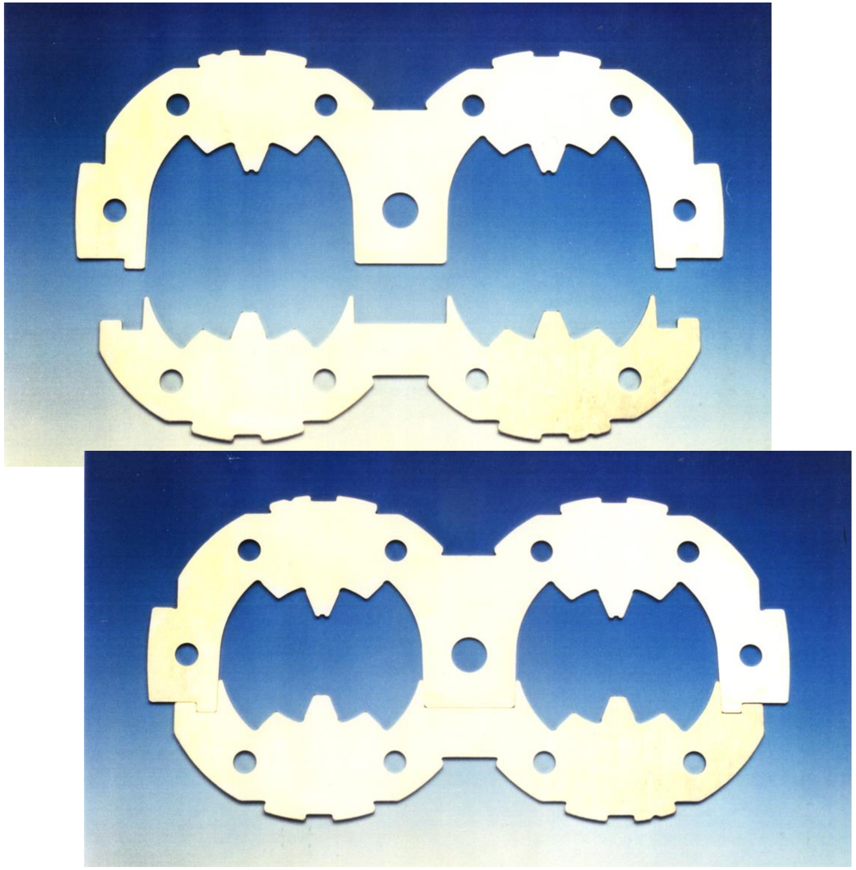
Stored coils

Ends

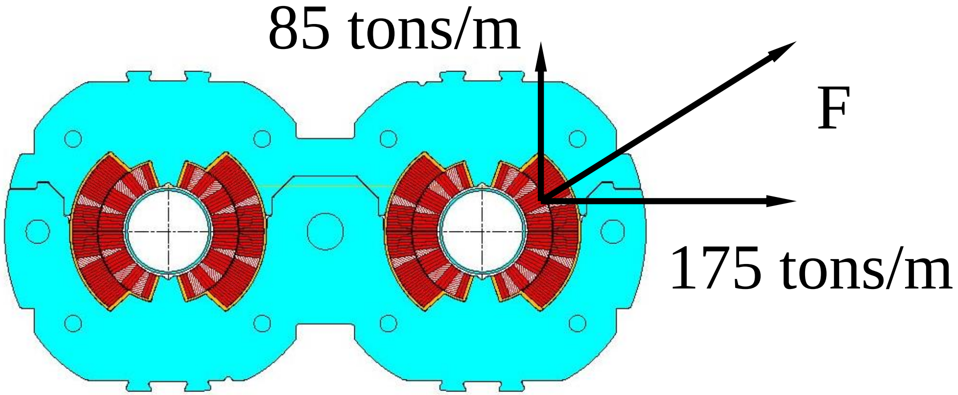


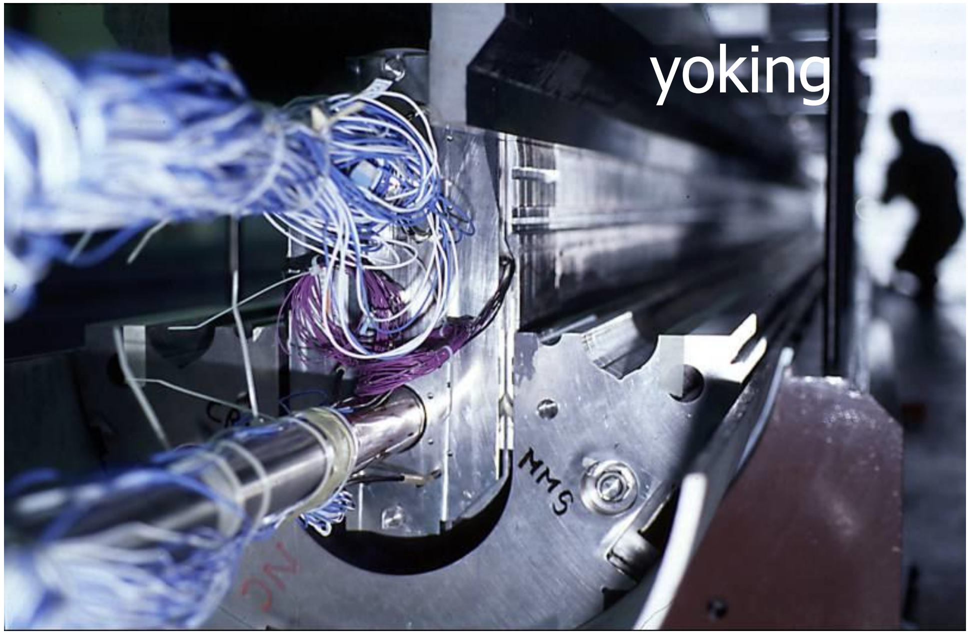
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking



collaring

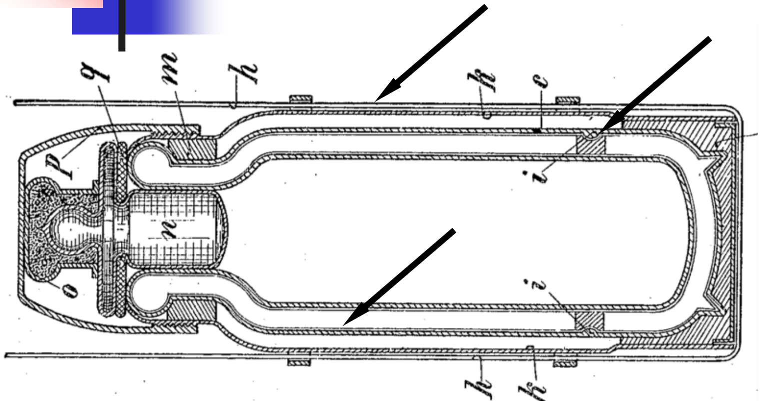




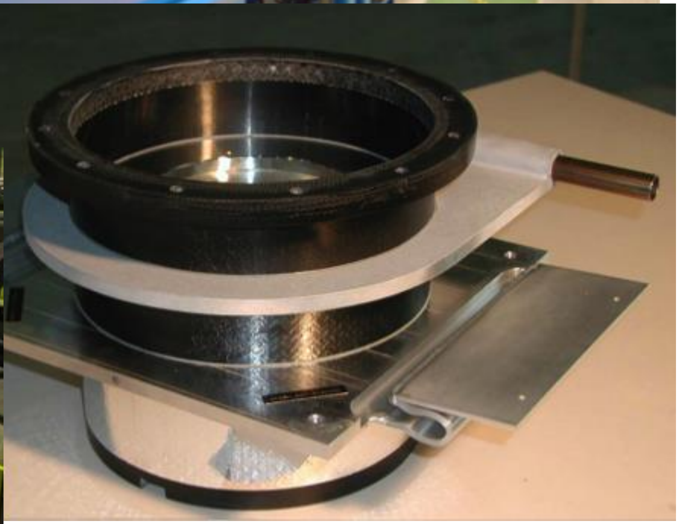
yoking

Cold mass

Cryostat



Thermal screens



Low conduction foot

Current leads

Warm end (300K)

Intermediate
temperature (50K)

HTS

Cold end (4K)

Finally, in the tunnel !

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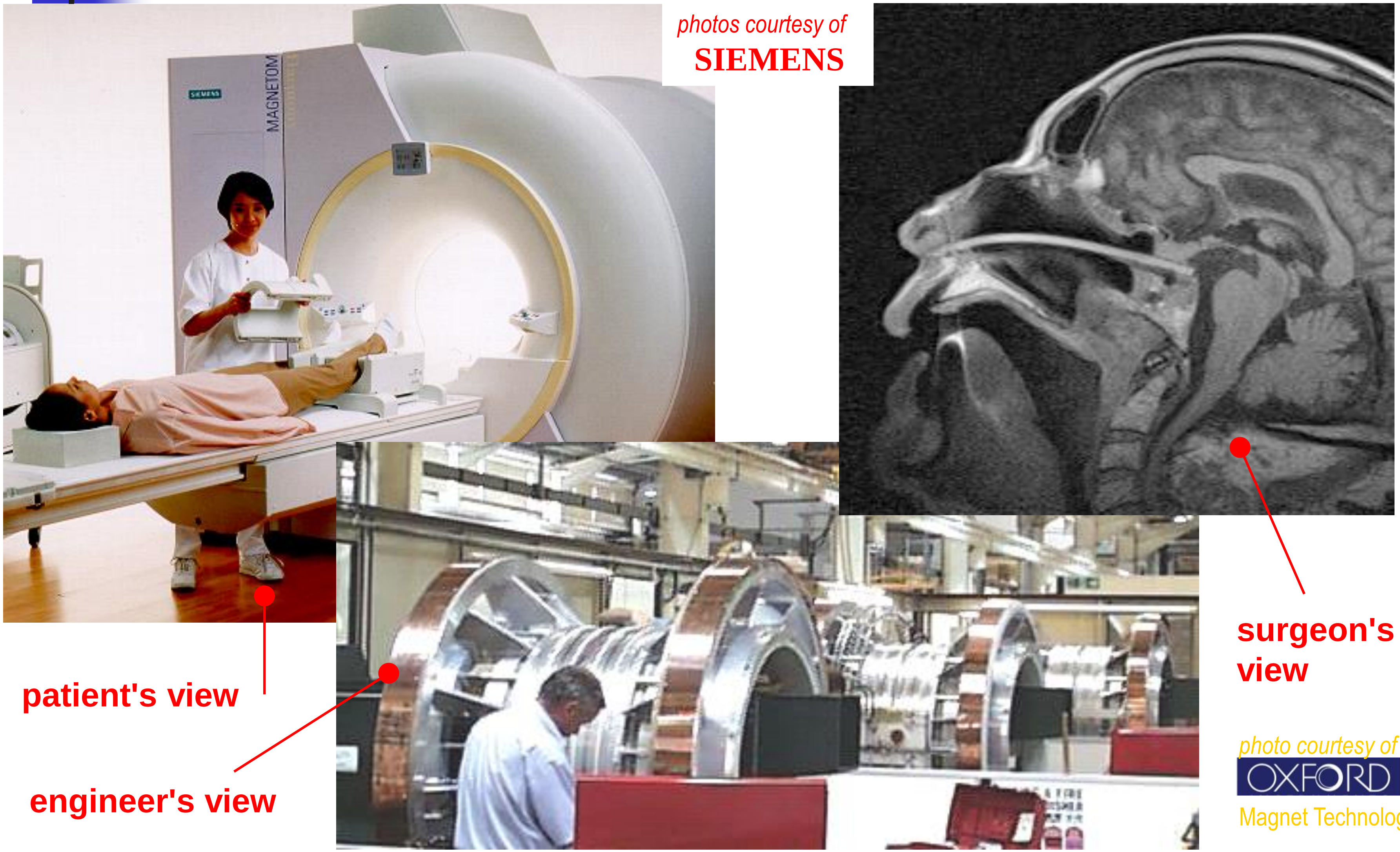
Magnetic Resonance Imaging (MRI)



photos courtesy of
SIEMENS

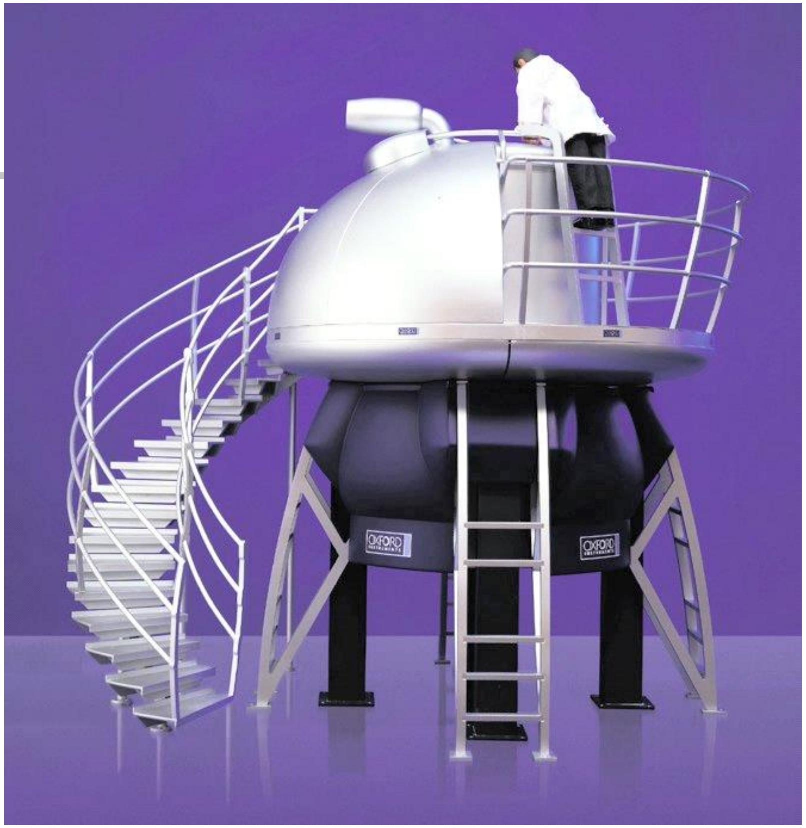
patient's view

engineer's view

surgeon's view

photo courtesy of
OXFORD
Magnet Technology

NMR spectroscopy



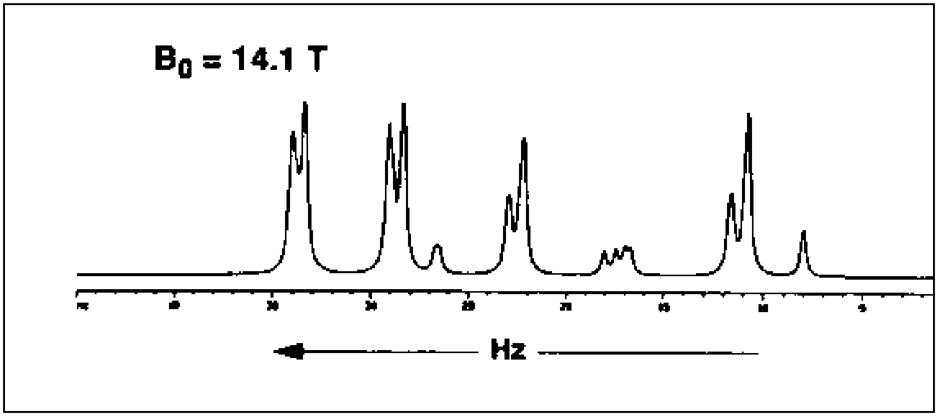
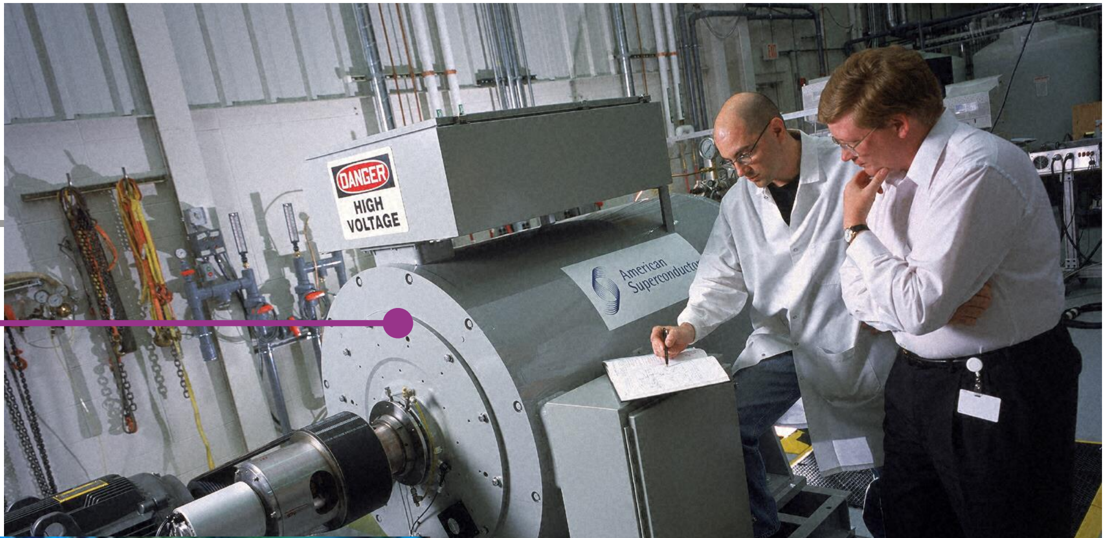


photo courtesy of
OXFORD
Magnet Technology

Motors & generators



Motor with HTS rotor
American Superconductor and Reliance

700 MW generator

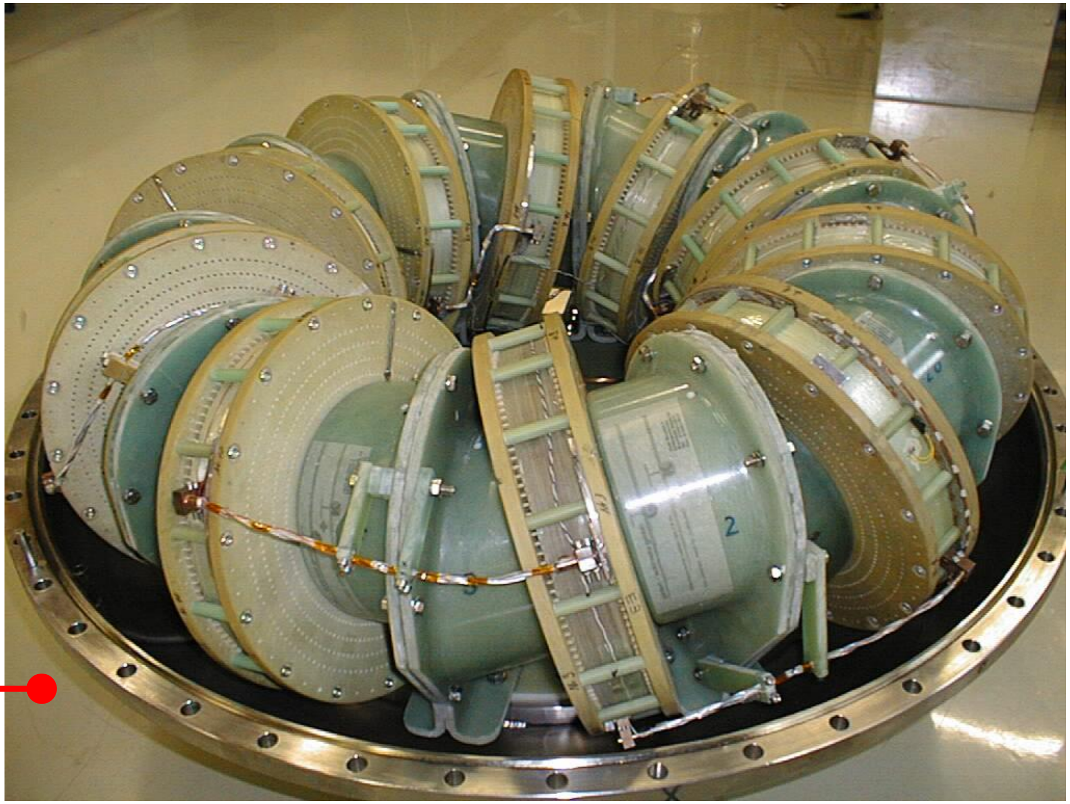
NbTi rotor

Hitachi, Toshiba, Mitsubishi

Transformers & energy storage

HTS Transformer
630 kVA,   18.7kV to 0.42 kV

ABB



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

KfZ Karlsruhe

Magnetic separation

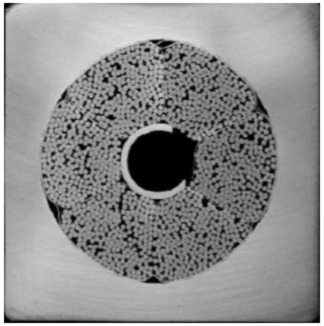
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

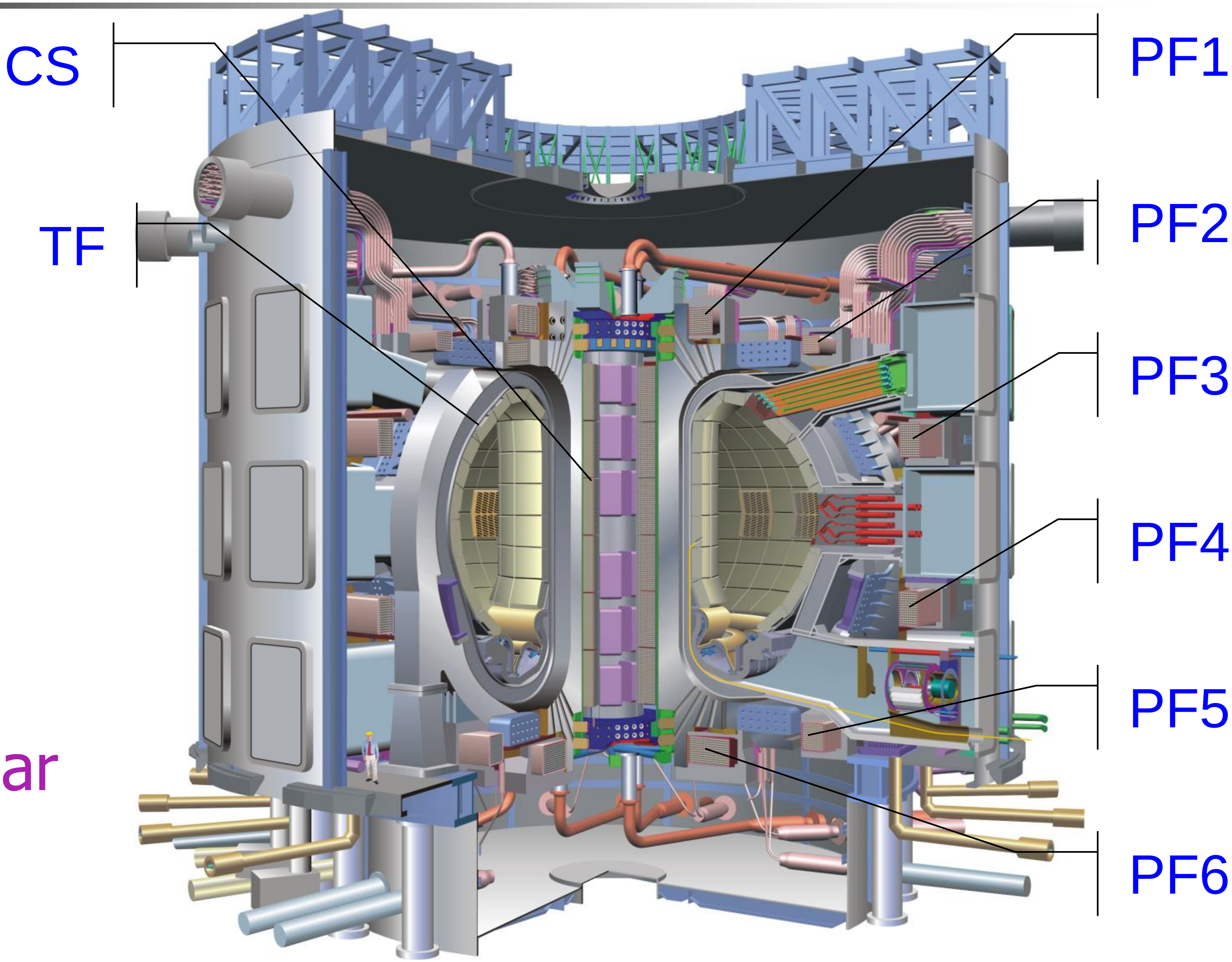
photo courtesy of
Carpco

Thermonuclear fusion

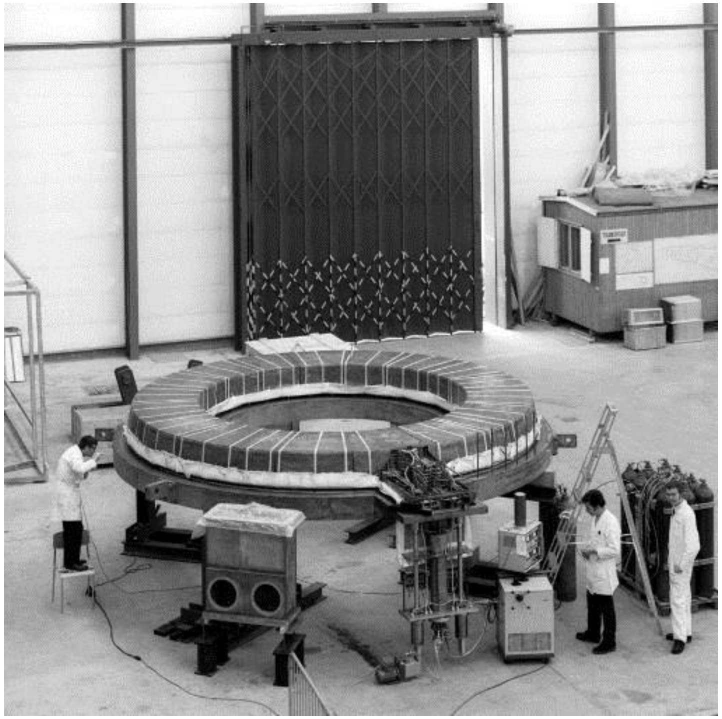


ITER

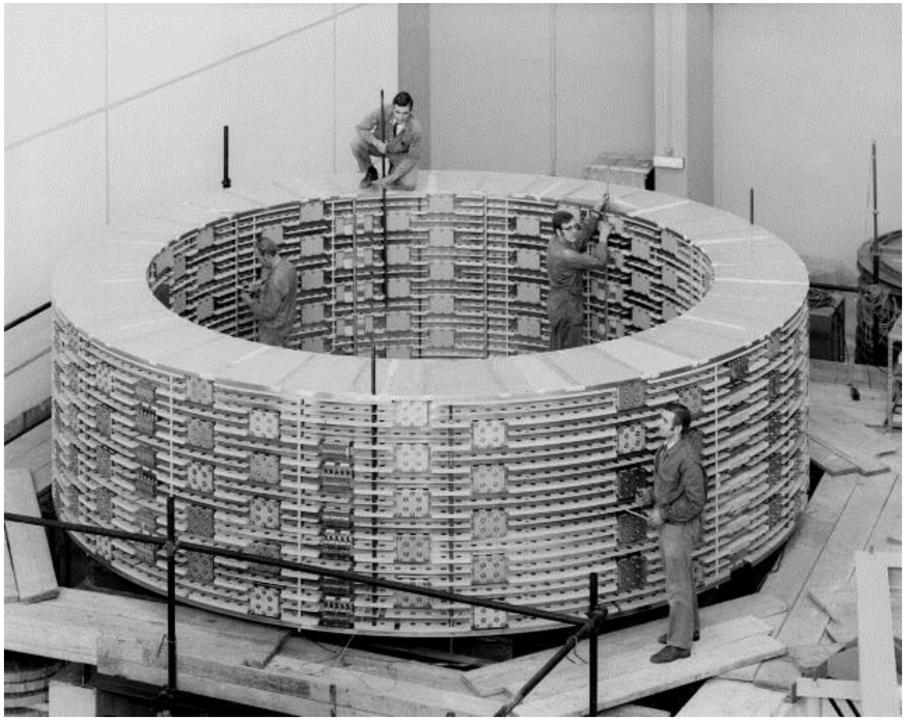
International
Thermonuclear
Experimental
Reactor



HEP detectors of the past...

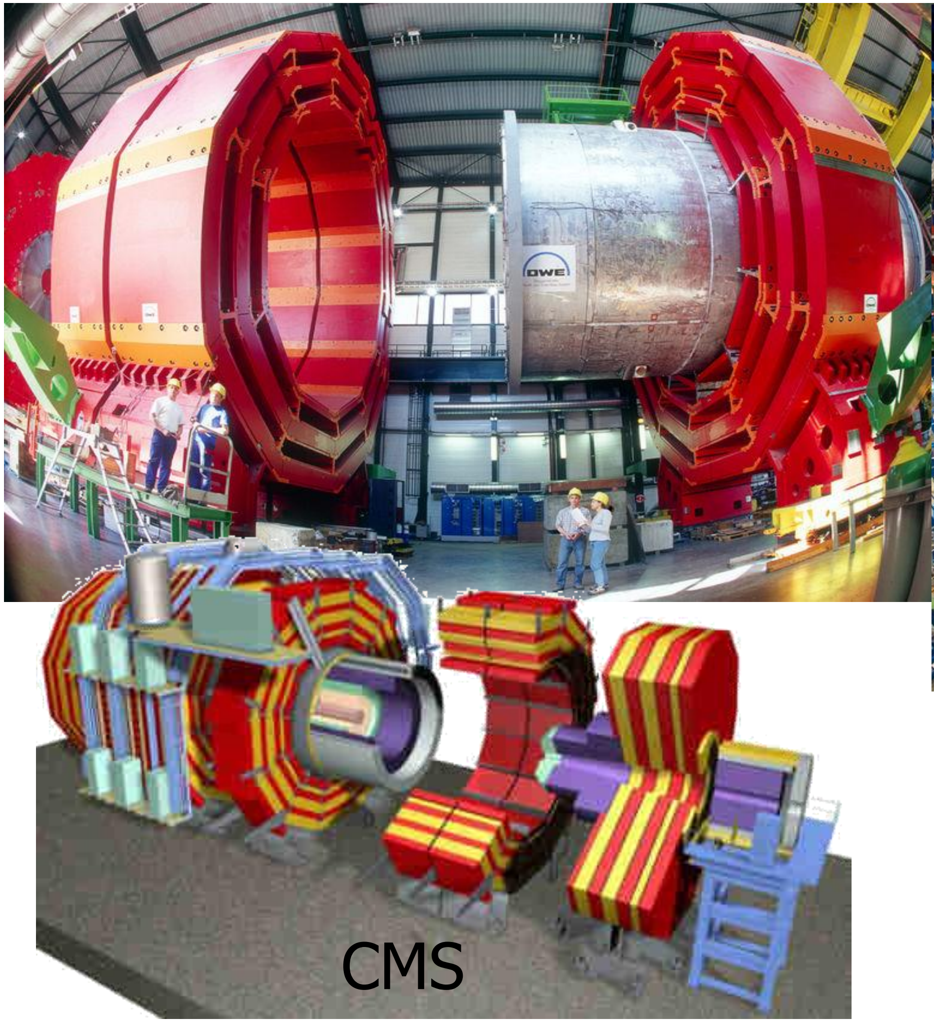


Omega

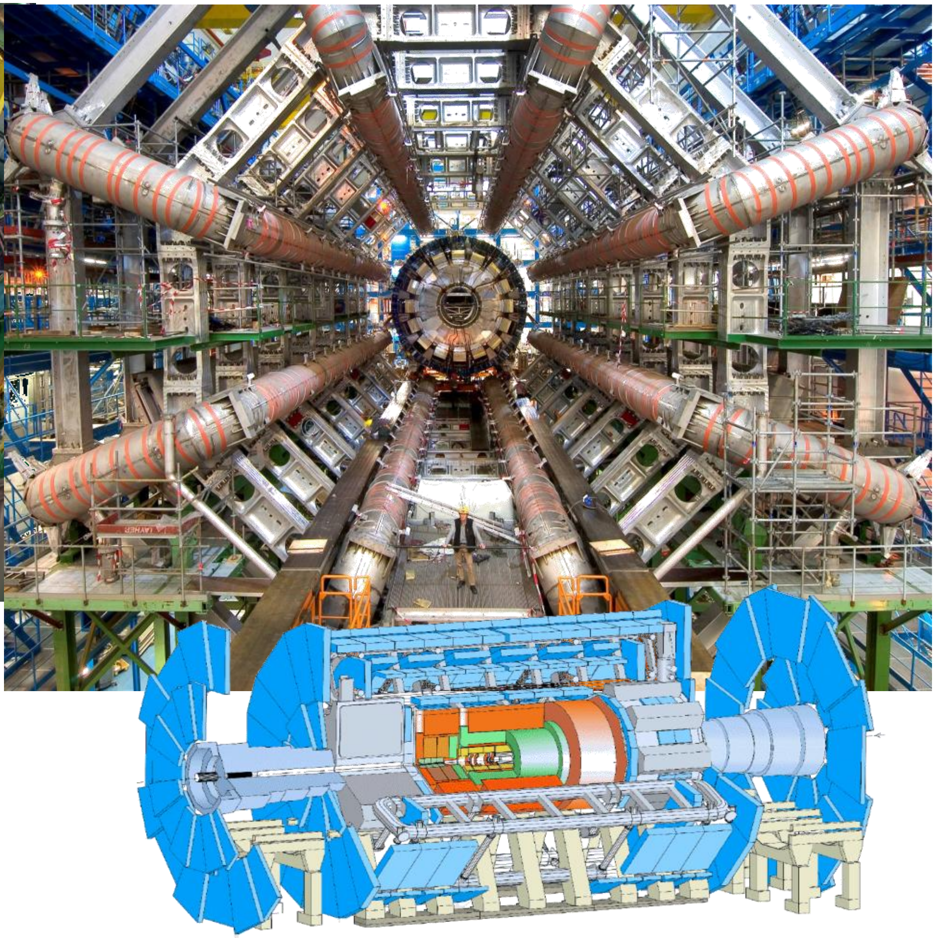


BEBC

… and HEP of the present (CMS and ATLAS)

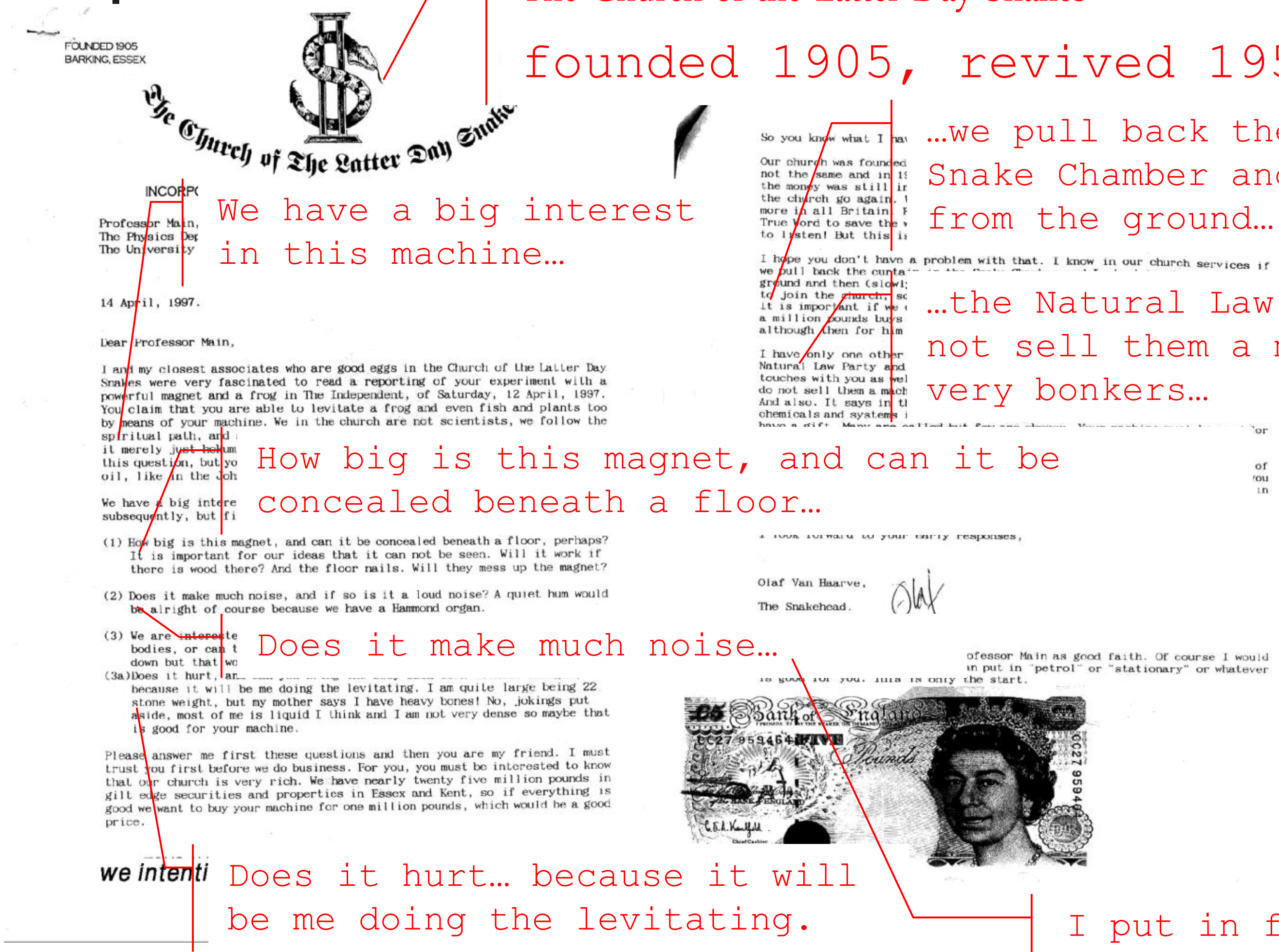


CMS



ATLAS

Other uses of superconductivity



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 helium
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 (slowly
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.

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

The Church of the Latter Day Snakes

founded 1905, revived 1950

We have a big interest in this machine…

…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…

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.

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