

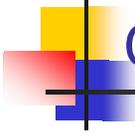
Applied Superconductivity for Accelerator Magnets

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Italian Teachers Programme - 2011

CERN

15/16 February, 2011



Overview

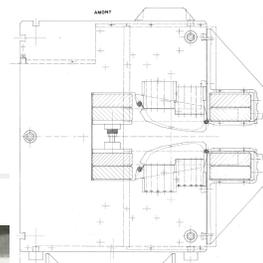
- Magnets NC vs. SC - a motivation
- A superconductor physics primer
- From material physics to magnet engineering
- Superconducting magnet design
 - Magnetic design
 - Operating margins
 - Stability, quench and protection
 - Magnetization and AC loss
 - Cooling of superconducting magnets
 - Low-temperature mechanics
- The making of a superconducting magnet
- Other examples of superconducting magnet systems

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NC vs. SC Magnets - 1/2

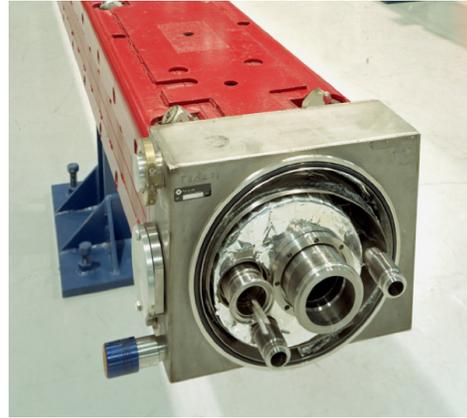
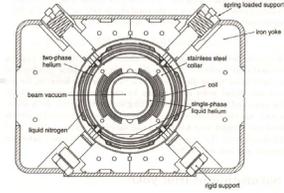
- *Normal conducting* accelerator magnets
 - *Magnetization* ampere-turns are *cheap*
 - Field is generated by the iron yoke (but limited by saturation to ≈ 2 T for iron)
 - Low current density in the coils to limit electric power and cooling needs
 - Bulky and heavy, large mass of iron (cost driver)



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)

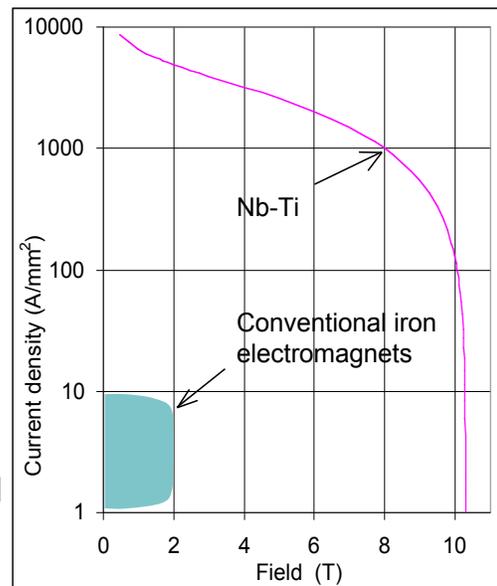


A superconducting dipole magnet of the Tevatron at FNAL, the first superconducting synchrotron, 1983

Graphics by courtesy of M.N. Wilson

Why superconductivity ?

- **Abolish Ohm's law !**
 - No power consumption (but needs refrigeration power)
 - High current density
 - Large ampere turns in small volume, so don't need iron (although often used for shielding)
- Consequences
 - lower running cost \Rightarrow new commercial possibilities
 - energy savings
 - high current density \Rightarrow smaller, lighter, cheaper magnets \Rightarrow reduced capital cost
 - higher magnetic fields economically feasible \Rightarrow new research possibilities

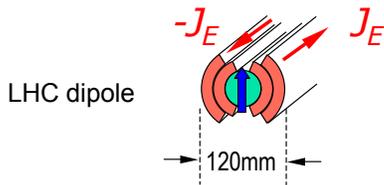


The advantage of high current density

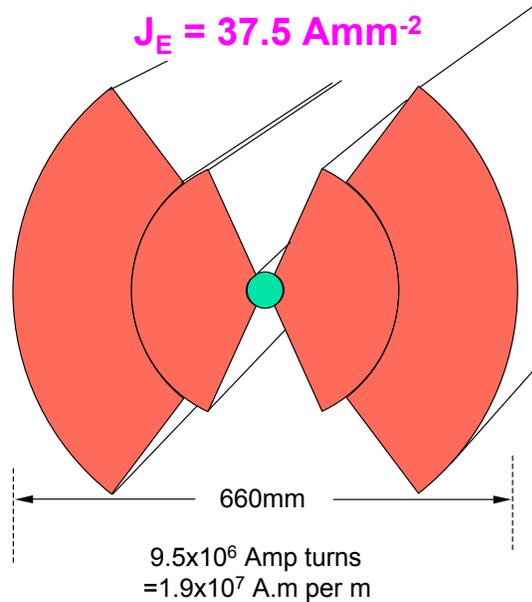
- The field produced by an ideal dipole is:

$$B \approx 1/\pi \mu_0 J_E t$$

$$J_E = 375 \text{ Amm}^{-2}$$



$$9.5 \times 10^5 \text{ Amp turns} \\ = 1.9 \times 10^6 \text{ A.m per m}$$

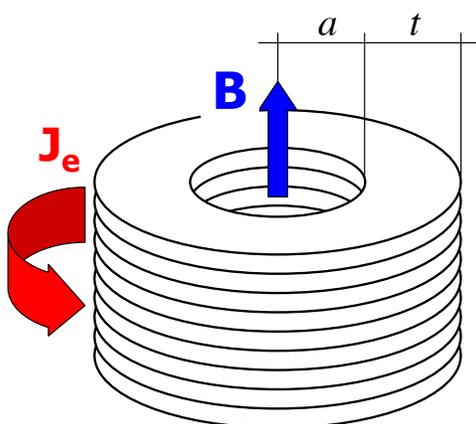


$$9.5 \times 10^6 \text{ Amp turns} \\ = 1.9 \times 10^7 \text{ A.m per m}$$

High current density: solenoids

- The field produced by an infinitely long solenoid is:

$$B = \mu_0 J_e t$$



- In solenoids of finite length the central field is:

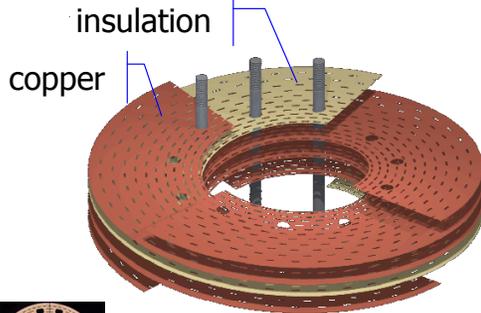
$$B = \mu_0 f J_e t$$

where f is a factor less than 1, typically ~ 0.8

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

As usual, there are exceptions to the established rules

- Normal conducting magnets for *very high field* applications



Florida-Bitter plate producing 30 T in a 15 T insert at *NHMFL*

- Superconducting magnets for *low field* applications



MgB₂ tape

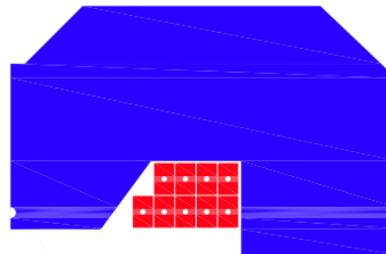
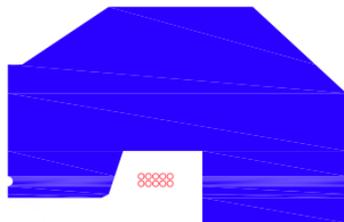
We forget exceptions for the rest of the talk !

Abolish Ohm's law - The (f)lower-power dipole



Super-conducting dipole

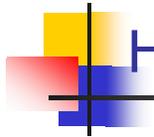
Normal-conducting dipole



Iron weight [tons]	10
Peak voltage [V]	34
Average AC loss power [W]	1.3

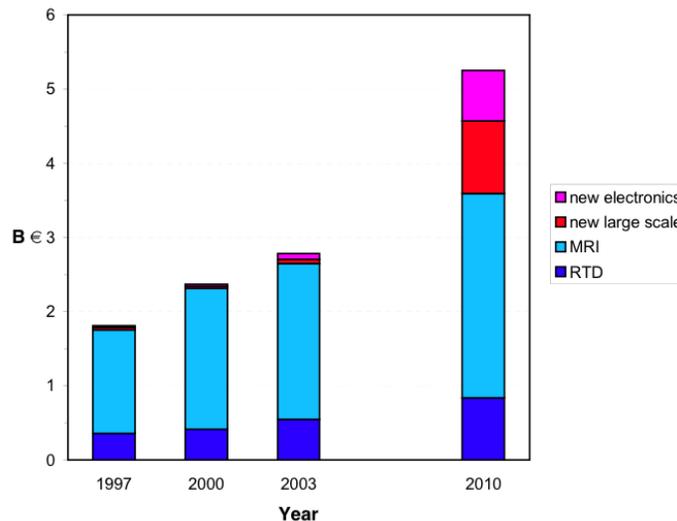
Iron weight [tons]	15
Peak voltage [V]	41
Resistive power [W]	27000

Potential for saving 7 MW of the 15 MW estimated total power consumption of an accelerator complex



How large is the market volume ?

Worldwide Markets for Superconductivity
Conectus, December 2001



* CONSortium of European Companies (determined) To Use Superconductivity



Motivation - Re-cap

- The main motivation to design magnets using superconductors is to **abolish Ohm's law**
- This is used either to:
 - Decrease power consumption, and thus improve the performance and operation balance (cost + efficiency) replacing existing technology ⇒ *technology displacer*
 - Allow to reach higher magnetic field, over larger bore and for longer time, allowing new physics or technological opportunities ⇒ *technology enabler*

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A great physics problem in 1900

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

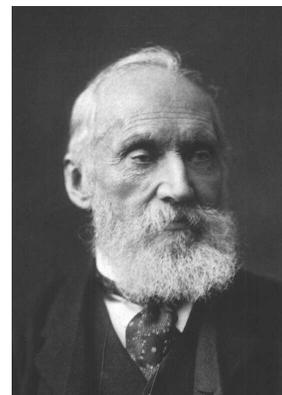
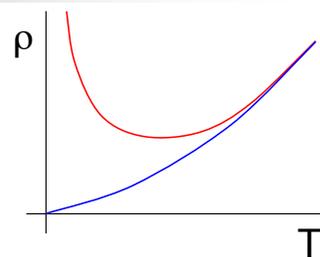
... electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

"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)

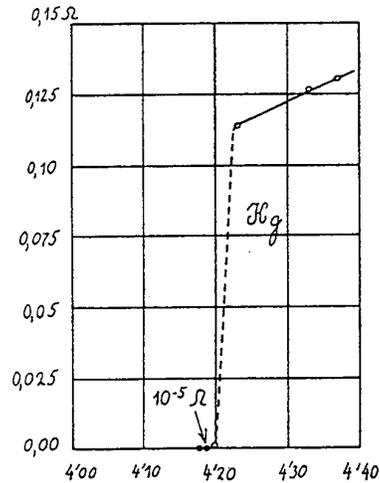


Superconductors Pre-history



... 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)



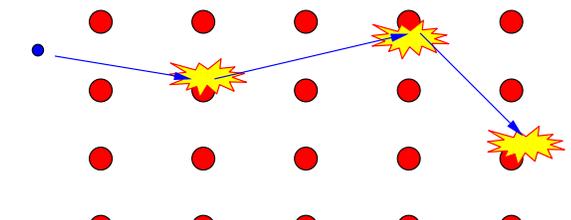
Cooper Pairs



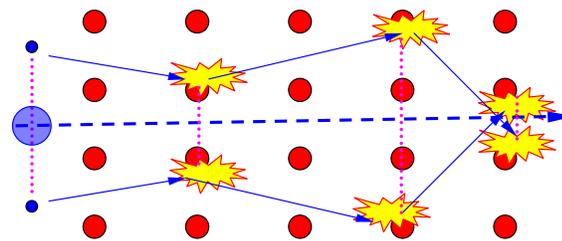
Bardeen, Cooper and Schrieffer

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

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



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 $\rho(T)$)

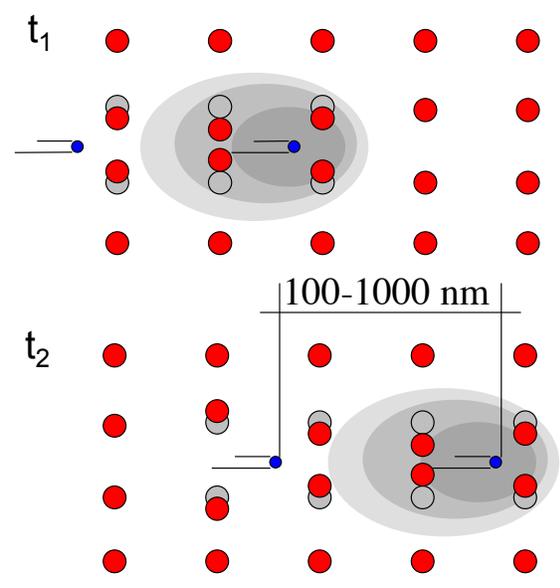


Proper physics: paired electrons in the vicinity of the Fermi surface, with opposite momentum and spin (bosons with zero spin). The binding energy introduces a small energy gap between paired and unpaired state. An external electric field makes the pair drift.

Pairing mechanism

Lattice displacement
 ↓
 phonons (sound)
 ↓
 coupling of charge carriers

Only works at low temperature

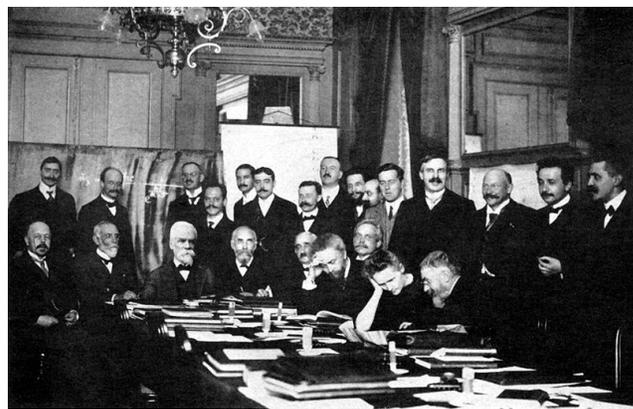


Bardeen, Cooper, Schrieffer (BCS) - 1957

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)

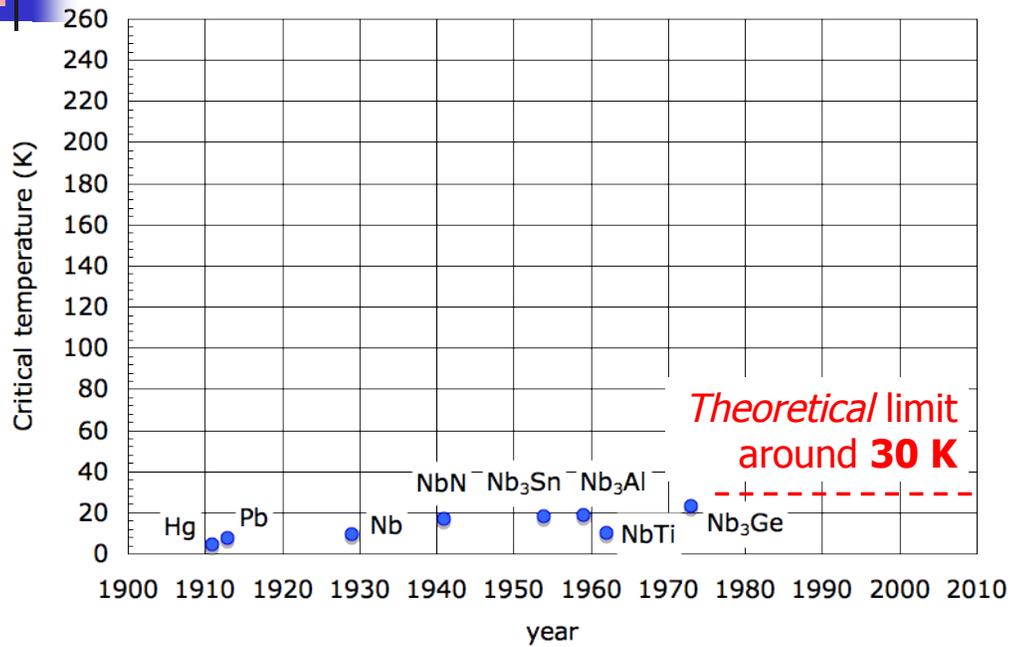


Solvay conference (1914)

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)

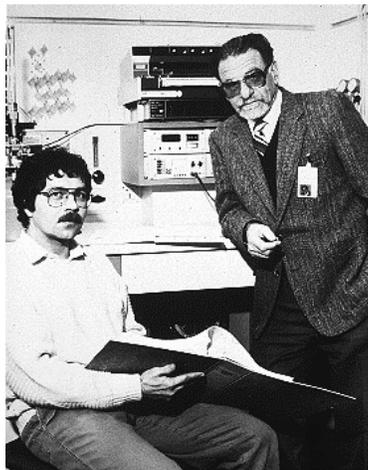
Superconductivity languished for 40 years...

Low-Tc timeline - depressing...

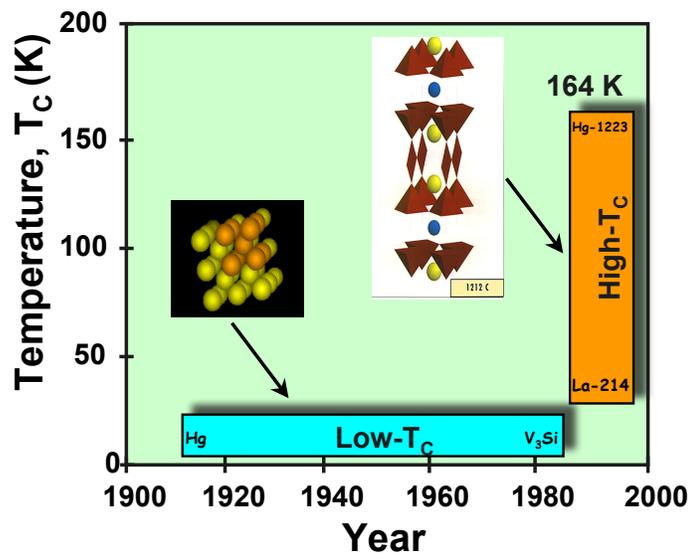


Graphics by courtesy of P. Grant

1986 - A Big Surprise



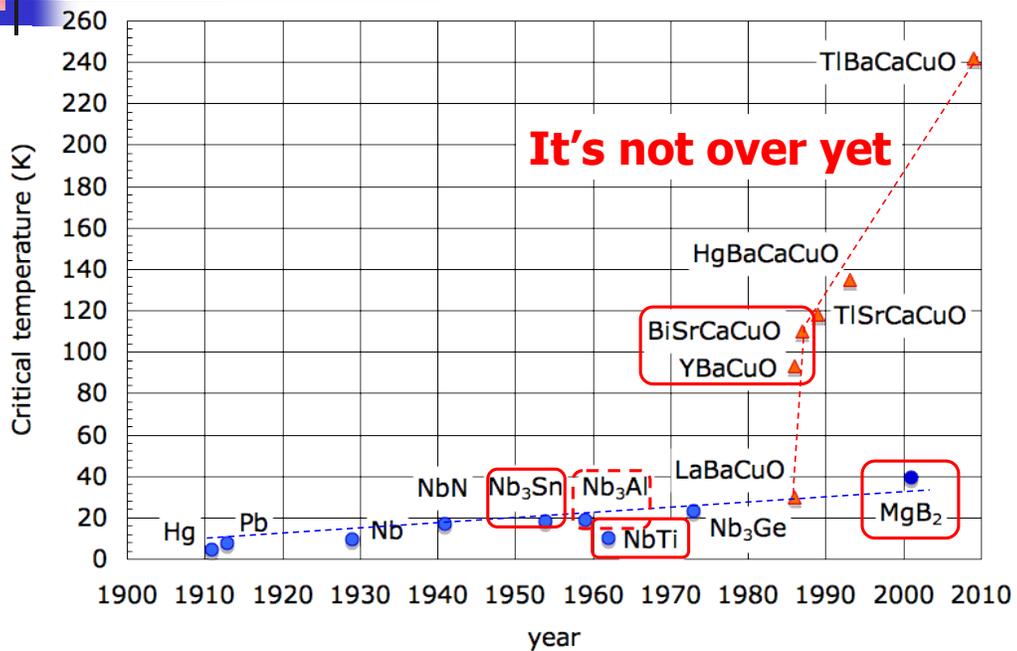
Bednorz and Mueller
IBM Zuerich, 1986



1987 - The prize !



High-Tc timeline - impressive !!!

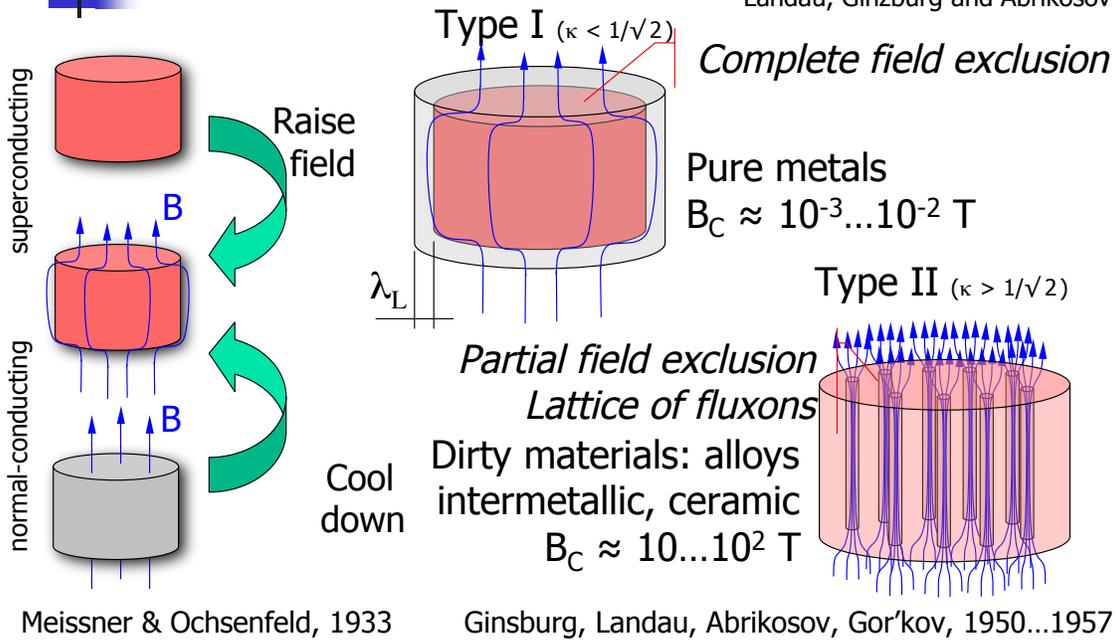


$$\kappa = \lambda_L / \xi$$



Landau, Ginzburg and Abrikosov

Hey, what about field ?



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

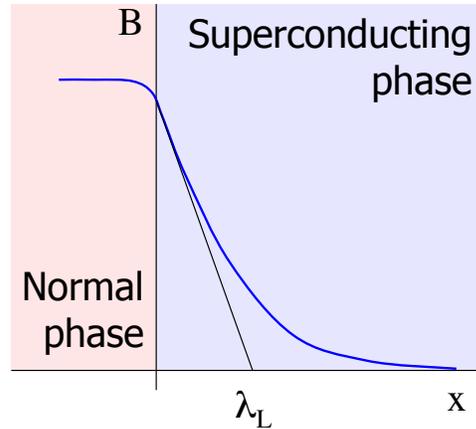
$$B(x) = B_0 \exp\left(-\frac{x}{\lambda_L}\right),$$

- London penetration length

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



H. and F. London, 1935



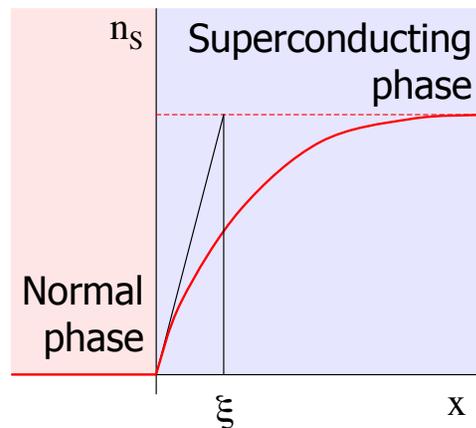
λ_L is of the order of 20 to 100 nm in typical superconducting materials

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

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

Fermi velocity
SC energy gap

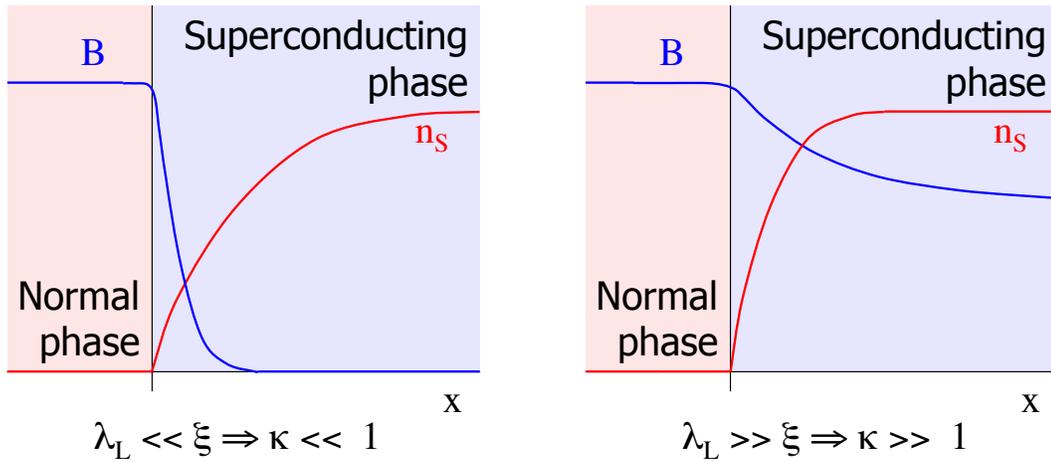


ξ is of the order of 1 to 1000 nm in typical superconducting elements and alloys

Ginzburg–Landau, 1950

Ginzburg-Landau parameter κ

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



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 ₃ Sn			≈ 30	

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

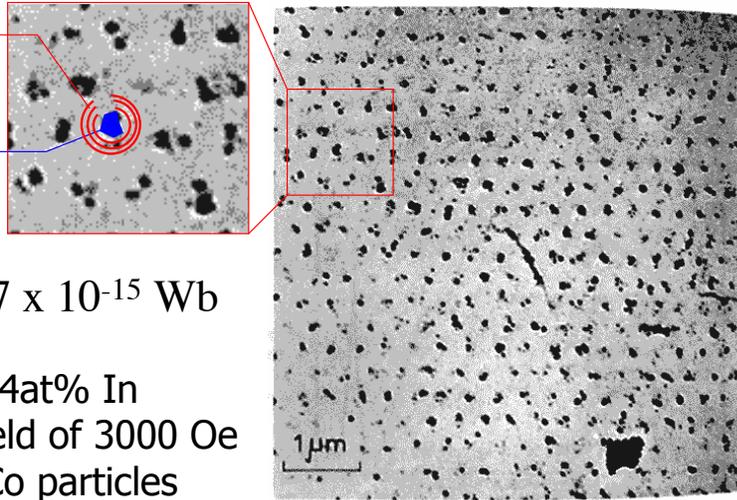
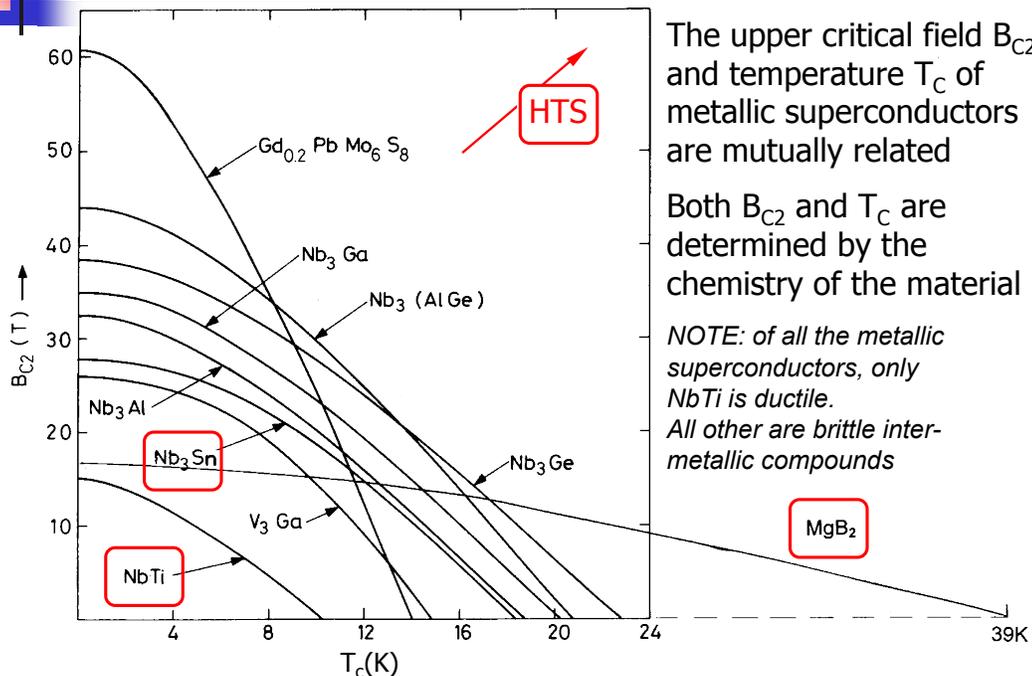


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.10K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Graphics by courtesy of M.N. Wilson

Critical temperature and field



Hey, what about current ?

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

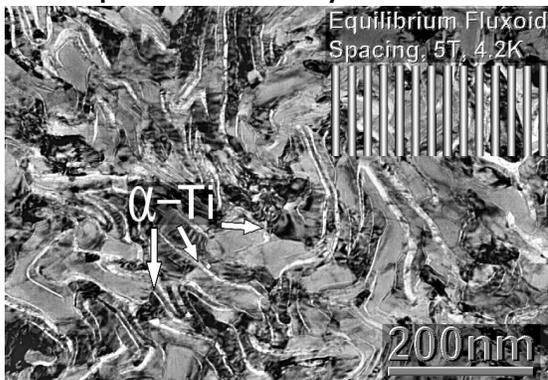
$$\mathbf{F} = \mathbf{J} \times \mathbf{B}$$

- This translates into a *motion of the fluxoids* across the superconductor \Rightarrow energy dissipation \Rightarrow 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

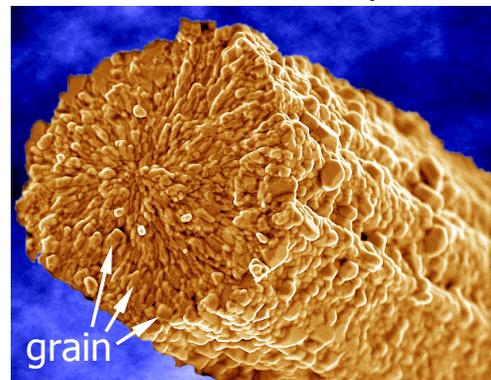
Pinning mechanisms

Precipitates in alloys



Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds



Microstructure of Nb₃Sn

Critical surface of a LHC NbTi wire

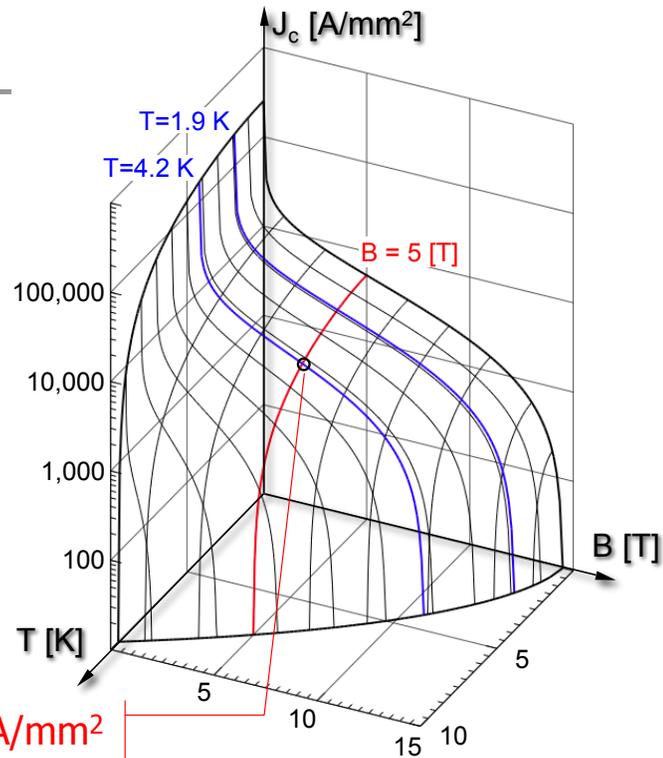
$$J_c(B, T, \dots)$$

- 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**:

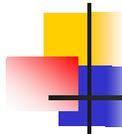
$$J_c(B, T, \dots) = F_p / B$$



$$J_c(5 \text{ T}, 4.2 \text{ K}) \approx 3000 \text{ A/mm}^2$$

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** $J_c(B, T, \dots)$
- The maximum current that can be carried is the $I_c = A_{sc} \times J_c$



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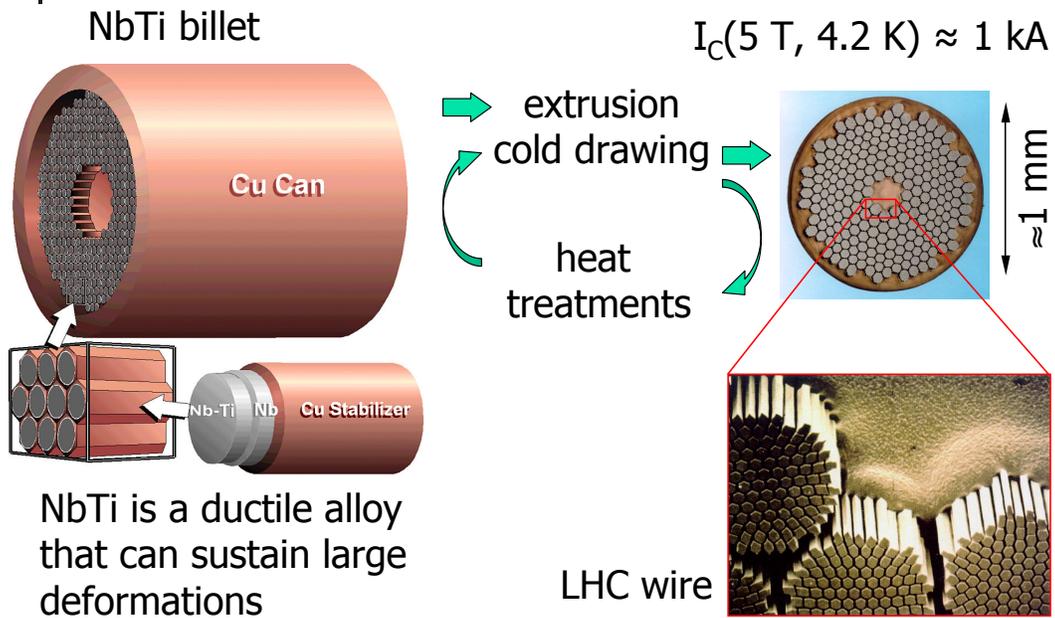


From materials to magnets

- Materials must be made in **high-current wires, tapes and cables⁽¹⁾** 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)

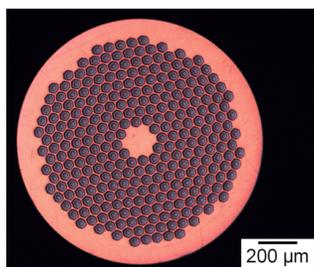
⁽¹⁾ See: **Stability, quench and protection**

Nb-Ti manufacturing route

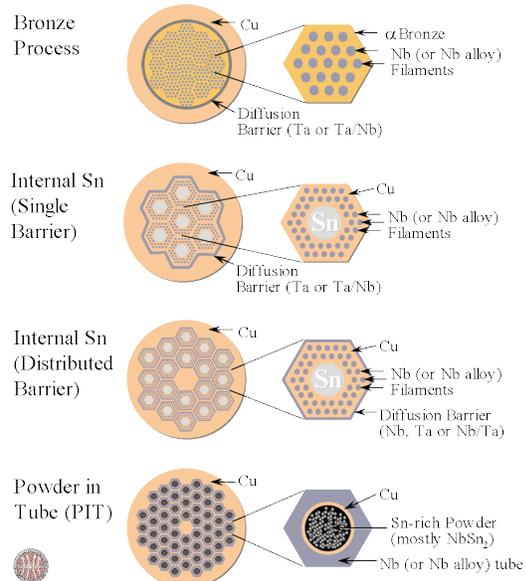


Nb₃Sn manufacturing routes

Nb₃Sn is brittle and cannot be drawn in final form. The precursors are drawn and **the wire is heat-treated at about 650 C for several hours, to form the Nb₃Sn phase**



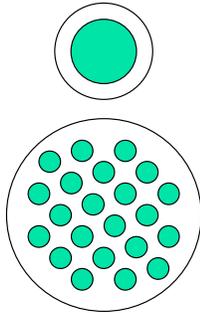
$I_c(12\text{ T}, 4.2\text{ K}) \approx 1.5\text{ kA}$



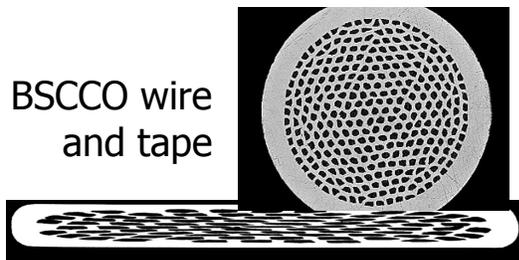
BSCCO manufacturing routes

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



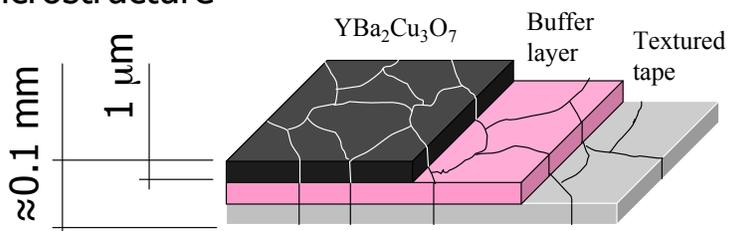
BSCCO is also brittle: a special sequence of rolling and sintering heat treatments must be used. Silver has the important feature that it is transparent to Oxygen at high temperature, but does not react with it



YBCO tape

YBCO has better critical properties than BSCCO but, unlike BSCCO, grains do not align during processing. If grains are not aligned the super-current 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 $\text{YBa}_2\text{Cu}_3\text{O}_7$ such that the texture of the YBCO follows that of the buffer and substrate



Engineering current density

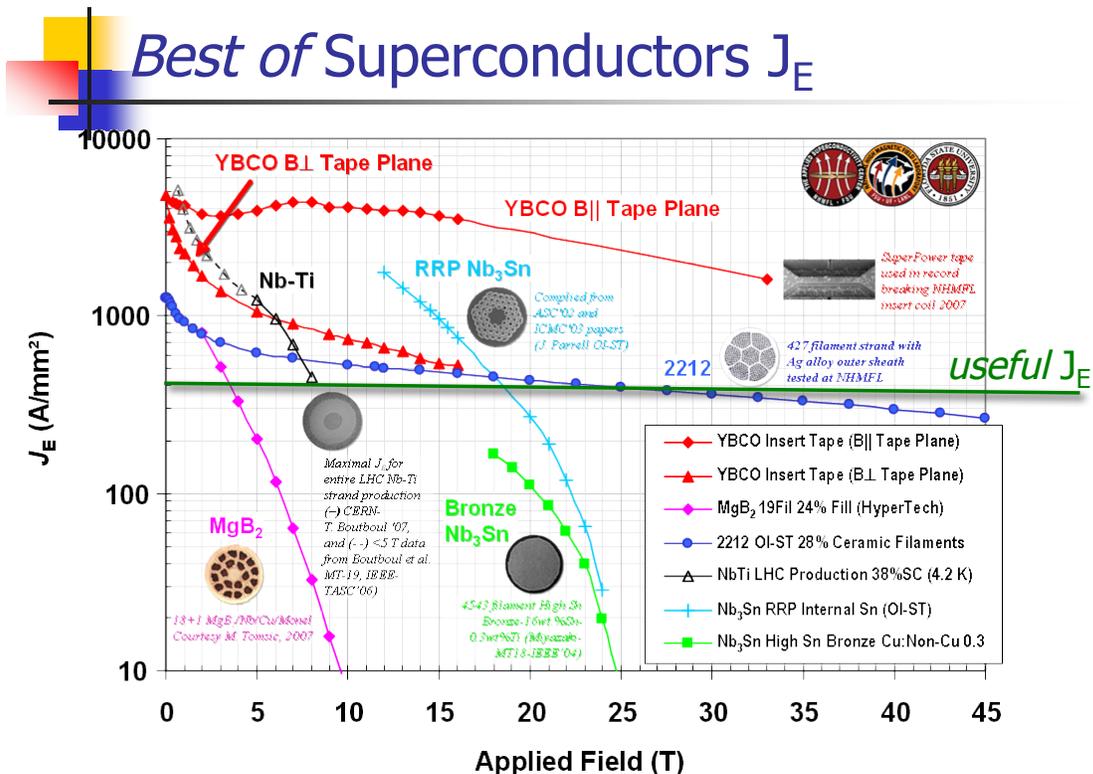
- All wires, tapes and cables consist of an array of **fine filaments**⁽¹⁾, and contain additional components:
 - Left-overs from the precursors of the SC formation
 - Barriers, texturing and buffering layers
 - Low resistance matrices**⁽²⁾
- The SC *material fraction* $\lambda = A_{SC} / A_{total}$ is hence always < 1 . To compare materials on the same basis, we use an *engineering current density*:

$$J_E = J_C \times \lambda$$

(1) See: Magnetization and AC loss

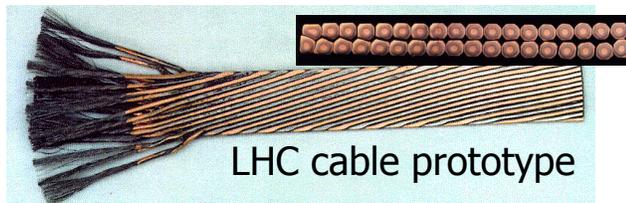
(2) See: Stability, quench and protection

Graphics by courtesy of Applied Superconductivity Center at NHMFL



Practical conductors: high J_E

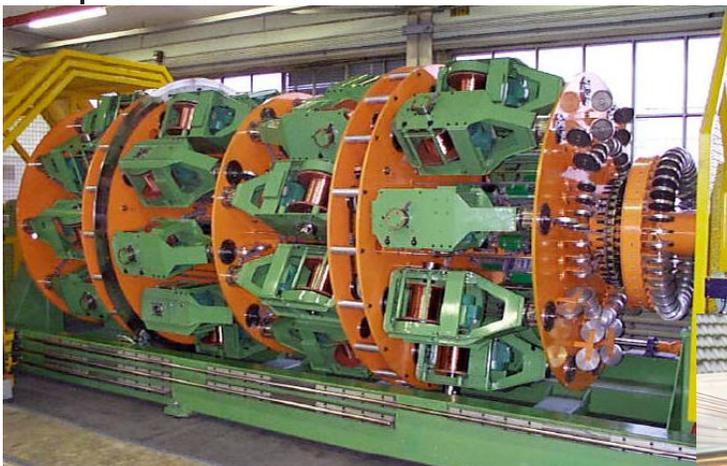
- Multifilamentary wires have current carrying capability of 100... 1000 A and can be used to make all kind of small size magnets
- Large size magnets (e.g. LHC dipoles) need large operating currents (10 to 100 kA) to:
 - Decrease inductance,
 - Lower the operating voltage,
 - Ease magnet protection⁽¹⁾
- Rutherford cables are ideally suited for this task



LHC cable prototype

⁽¹⁾ See: Stability, quench and protection

Rutherford cable machine @ CERN



Strand spools on rotating tables

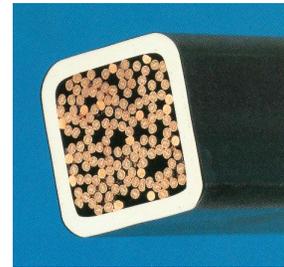
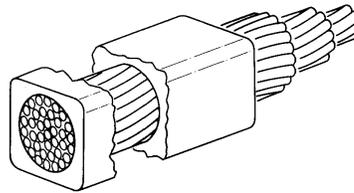
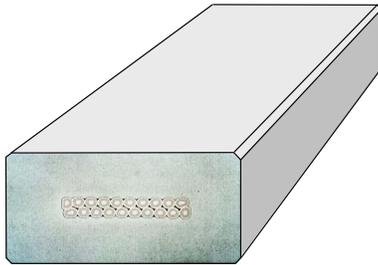
Strands fed through a cabling tongue to shaping rollers



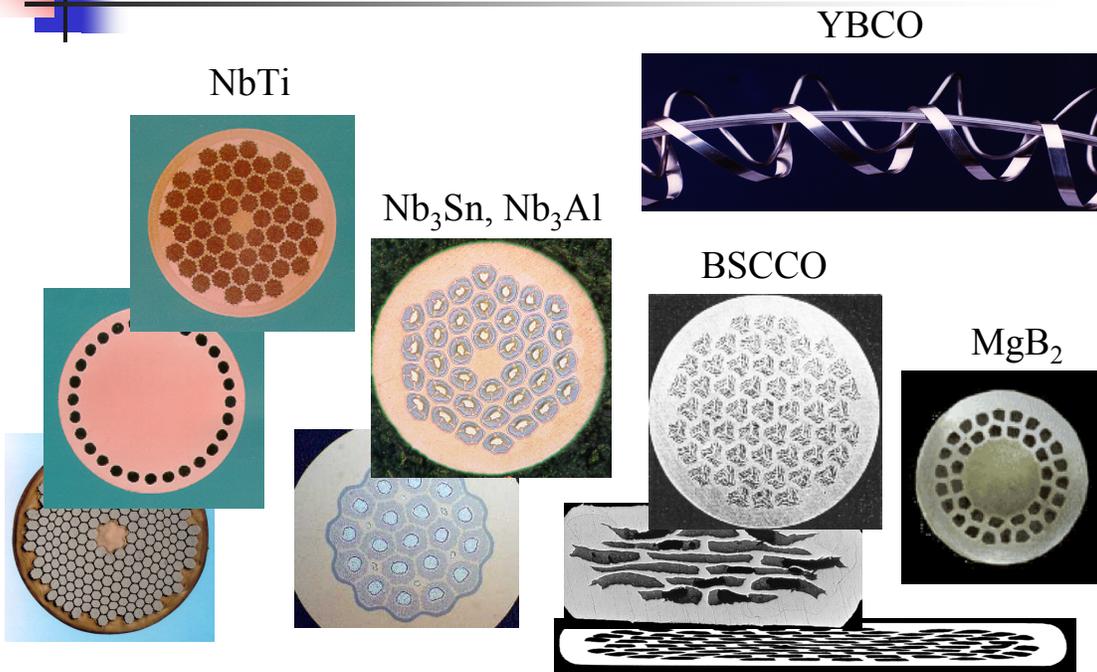
$$J_E \approx 50 \text{ A/mm}^2$$

Practical conductors: low J_E

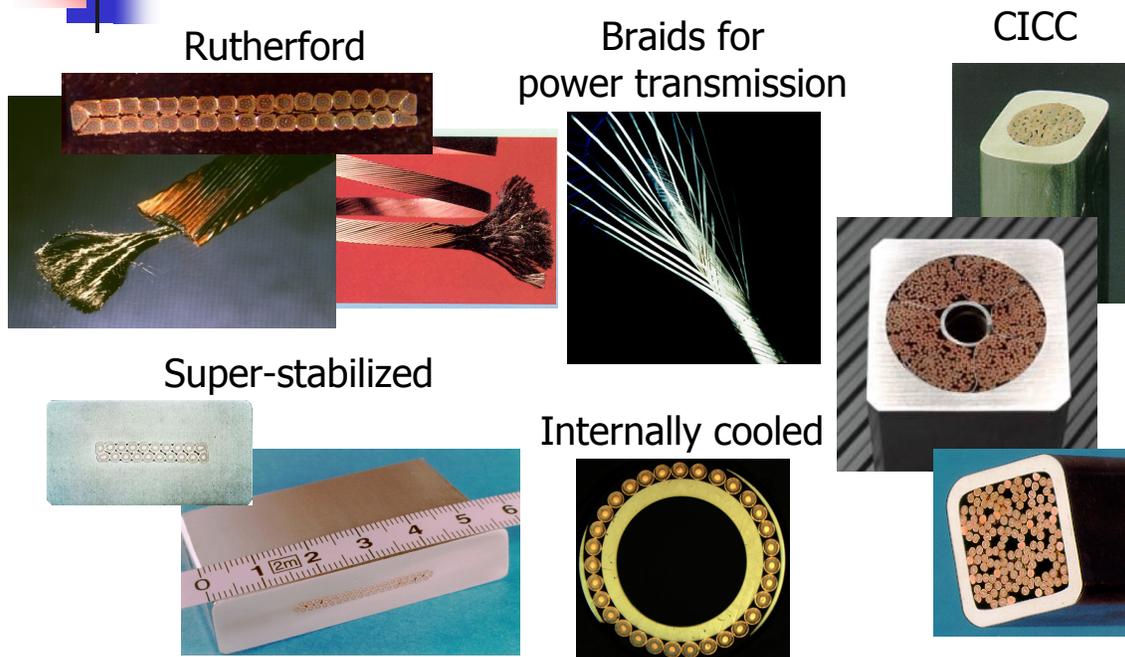
- Super-stabilized conductor, a superconducting cable (e.g. Rutherford) backed by a large amount of good normal conductor (e.g. Al)
- Internally-cooled conductor, e.g. Cable-In-Conduit Conductor (CICC), a rope of wires inserted in a robust conduit that provides a channel for cooling



Superconducting wires and tapes for all taste...



... and superconducting cables

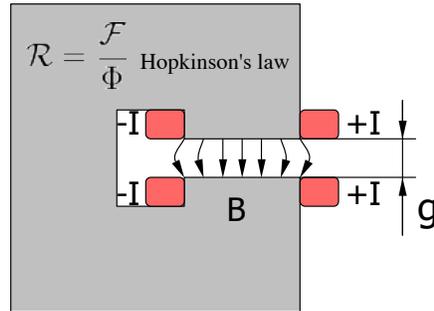


Overview

- Magnets NC vs. SC - a motivation
- A superconductor physics primer
- From material physics to magnet engineering
- **Superconducting magnet design**
 - **Magnetic design**
 - Operating margins
 - Stability, quench and protection
 - Magnetization and AC loss
 - Cooling of superconducting magnets
 - Low-temperature mechanics
- The making of a superconducting magnet
- Other examples of superconducting magnet systems

Magnetic design

- NC: magneto motive force, reluctance and pole shapes

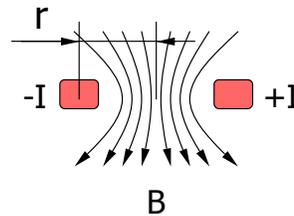


$$B \approx \mu_0 NI / g$$

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

- SC: Biot-Savart law and coil shapes

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

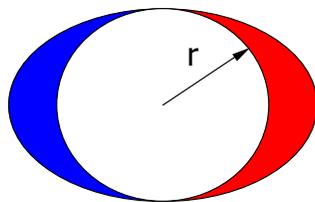


$$B \approx \mu_0 NI / \pi r$$

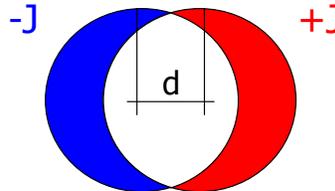
r	= 45 mm
NI	= 1 MAturn
B	= 8.84 T

Design of an ideal dipole magnet

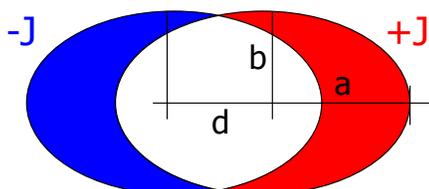
$$I = I_0 \cos(\theta) \Rightarrow B_1 = -\mu_0 I_0 / 2 r$$



$$\text{Intersecting circles} \Rightarrow B_1 = -\mu_0 J d / 2$$



$$\text{Intersecting ellipses} \Rightarrow B_1 = -\mu_0 J d b / (a+b)$$

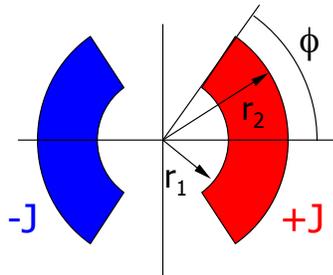


Several solutions are possible and can be extended to higher order multi-pole magnets

None of them is practical !

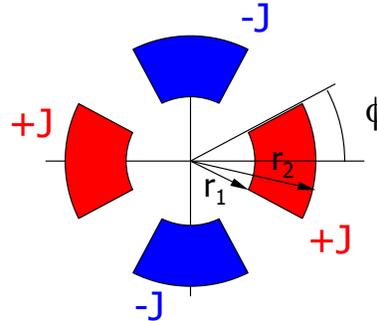
Magnetic design - sector coils

- Dipole coil



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

- Quadrupole coil



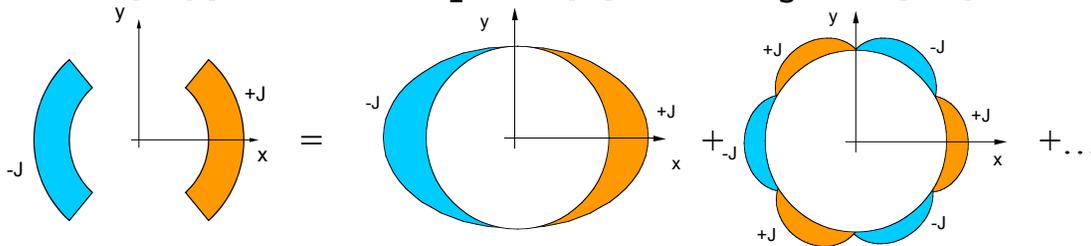
$$B_2 = -2\mu_0/\pi J \ln(r_2/r_1) \sin(2\phi)$$

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

Harmonics of the field

- A technical current distribution can be considered as a series approximation:

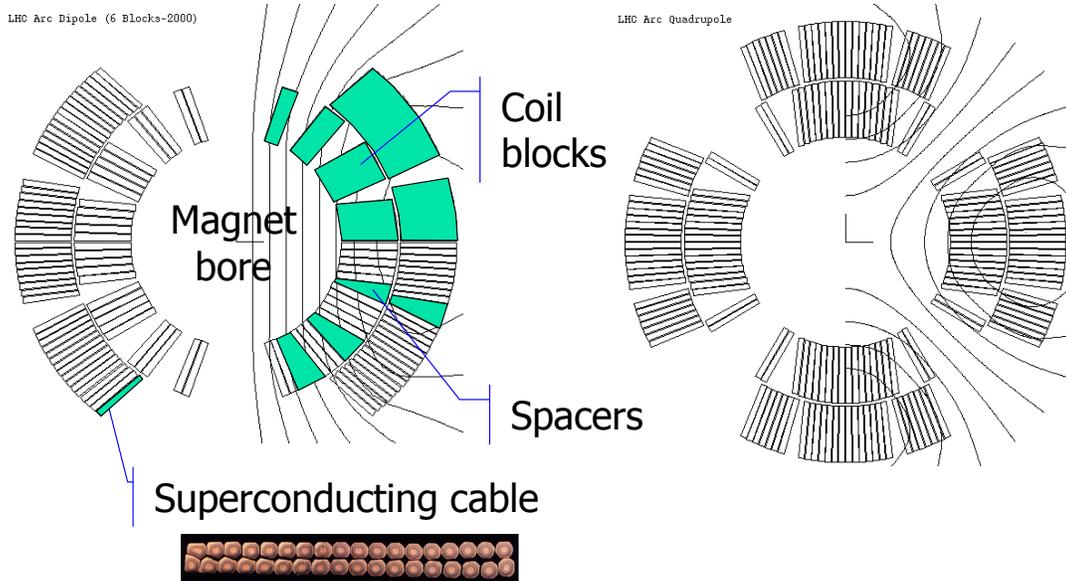
$$J(x,y) = J_1 \cos(\theta) + J_3 \cos(3\theta) + \dots$$



$$B = B_1 + B_3 + \dots$$

Technical windings contain field errors that can be minimized by proper placing of the conductors

Technical coil windings

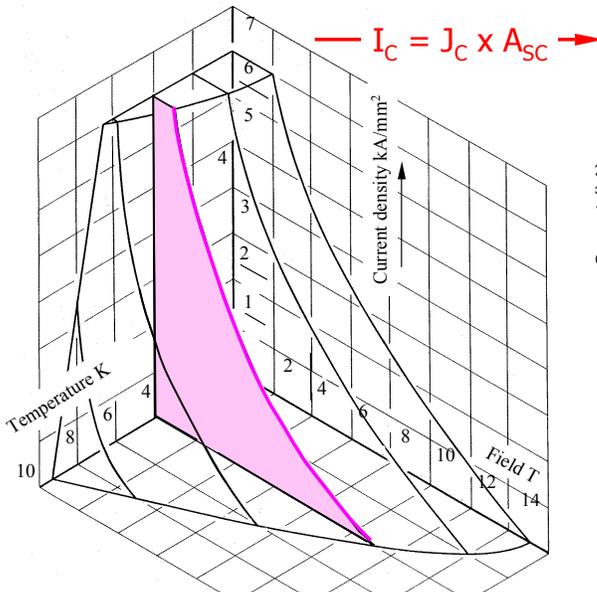


Overview

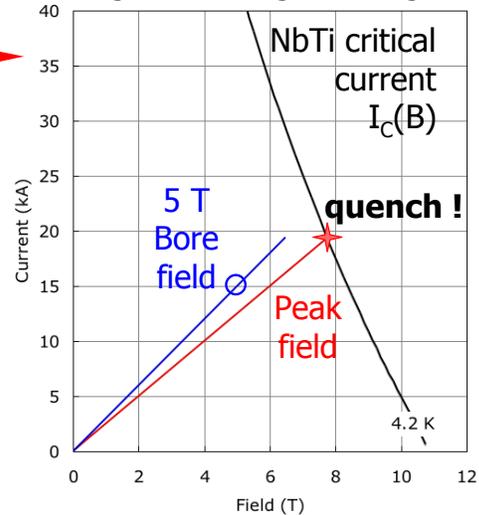
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Critical line and magnet load lines

NbTi critical surface



e.g. a 5 T magnet design

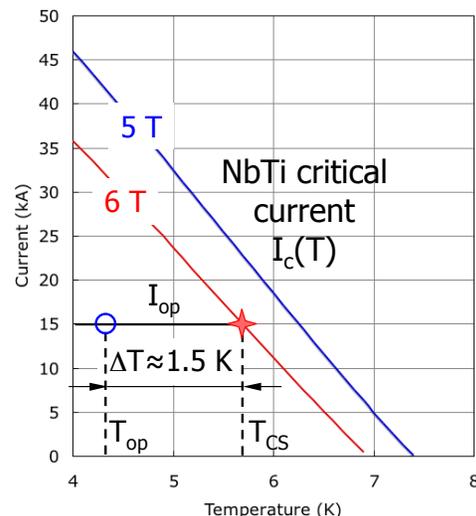


we expect the magnet to go resistive i.e. to 'quench', where the peak field load line crosses the critical current line

Temperature margin

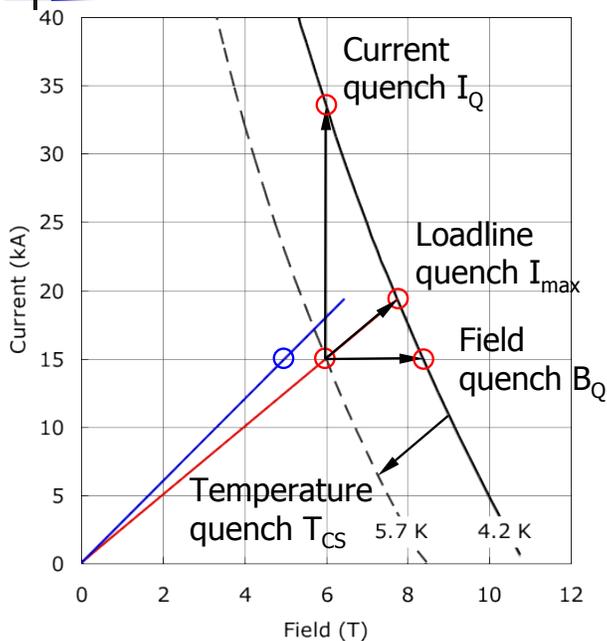
- Temperature rise may be caused by
 - sudden mechanical energy release
 - AC losses
 - Resistive heat at joints
 - Beams, neutrons, etc.
- We should allow *temperature headroom* for all foreseeable and unforeseeable events⁽¹⁾, i.e. a **temperature margin**:

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



⁽¹⁾ See: Stability, quench and protection

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: $T_{CS} - T_{op} \approx 1...2\text{ K}$
- The margin needed depends on the design and operating conditions

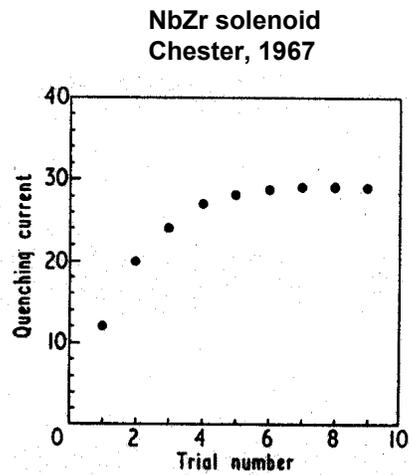
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Training...

- Superconducting solenoids built from NbZr and Nb₃Sn in the early 60's quenched much below the rated current ...
- ... the quench current increased gradually quench after quench: **training**

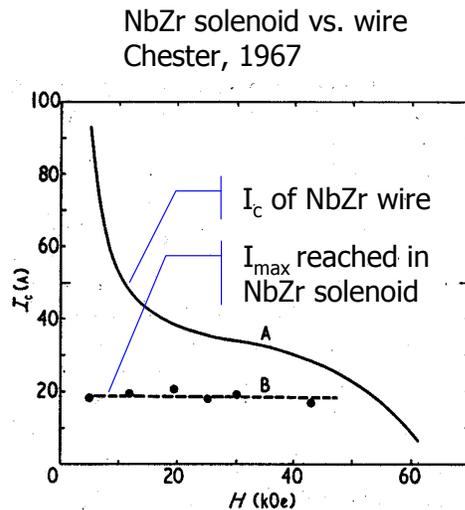
M.A.R. LeBlanc, Phys. Rev., **124**, 1423, 1961.



P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

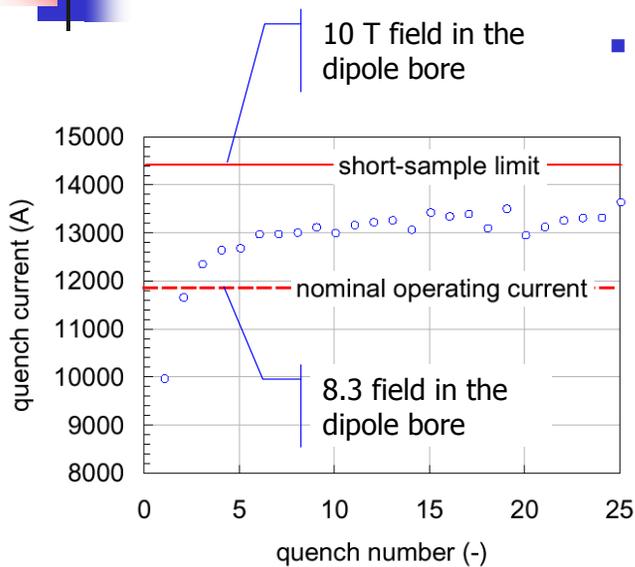
... and degradation

- ... but did not quite reach the expected maximum current for the superconducting wire !
- This was initially explained as a local damage of the wire: **degradation**, a very misleading name.
- All this had to do with **stability** !



P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

Training today



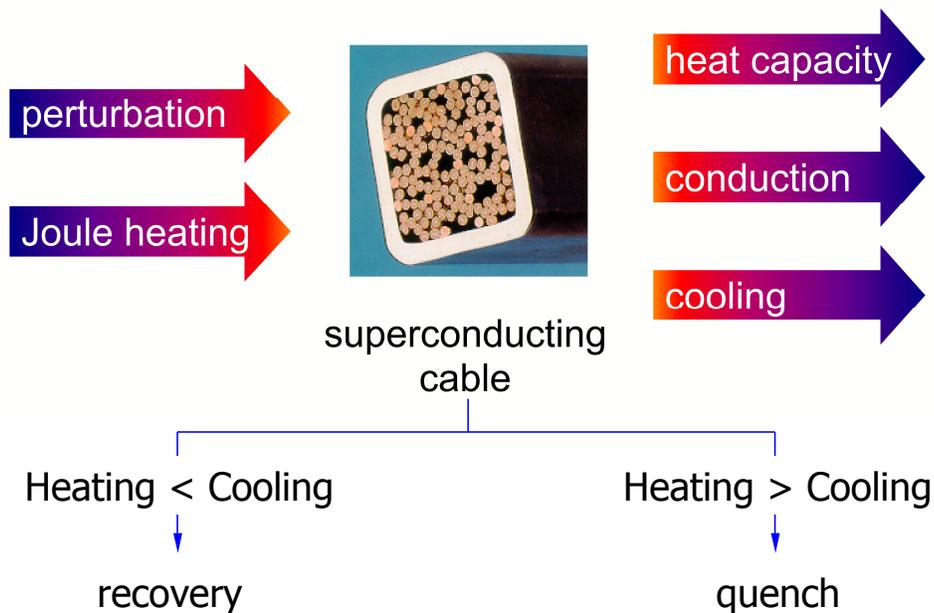
Courtesy of A. Siemko, CERN, 2002

■ training of an LHC short dipole model at superfluid helium

- still (limited) training may be necessary to reach nominal operating current
- short sample limit is not reached, even after a long training sequence

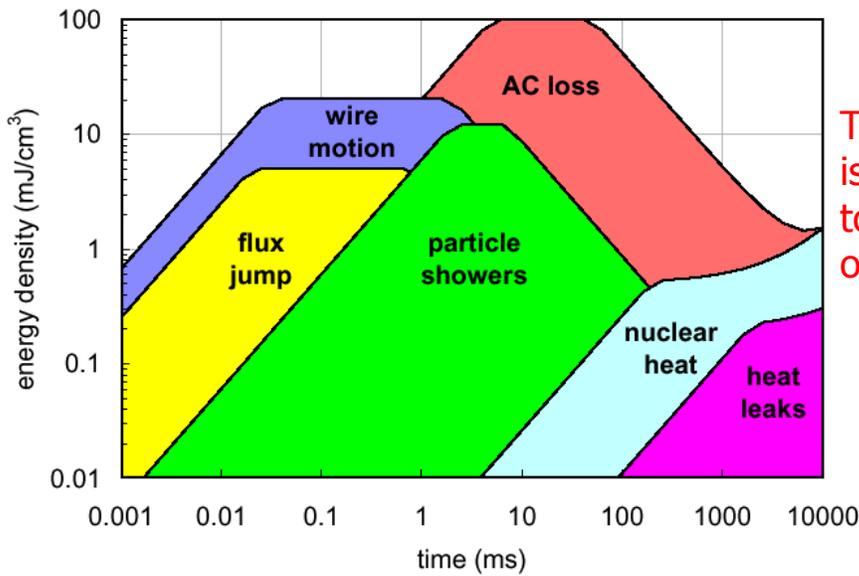
stability is (still) important !

Stability and quench: a heat balance



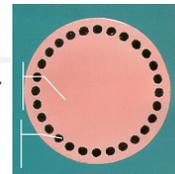
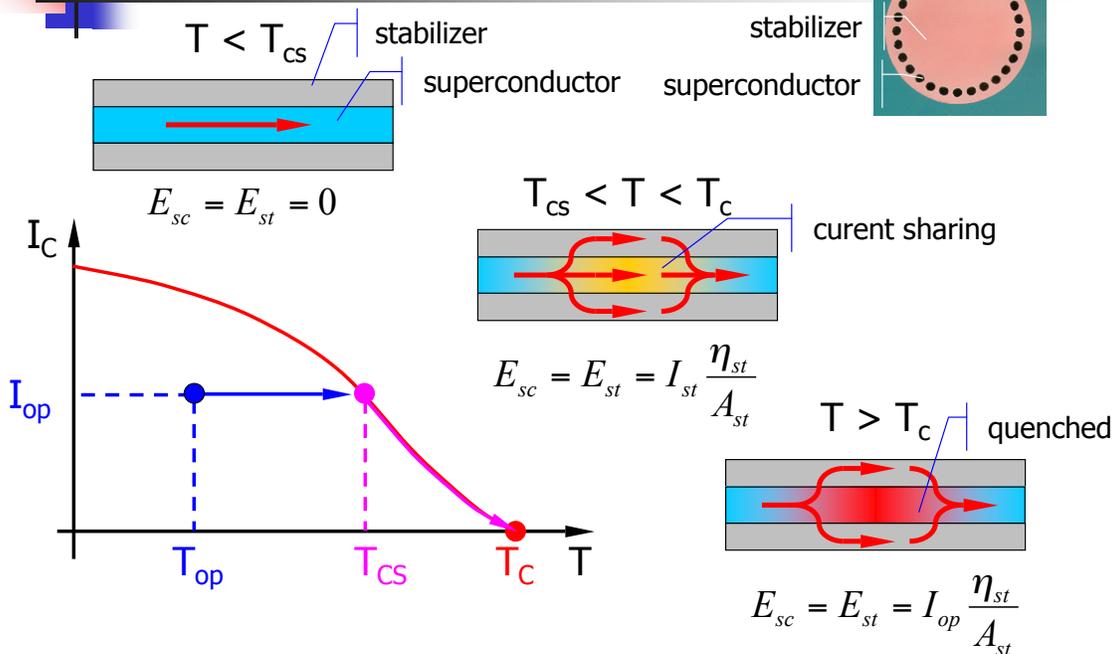
jump

Perturbation overview

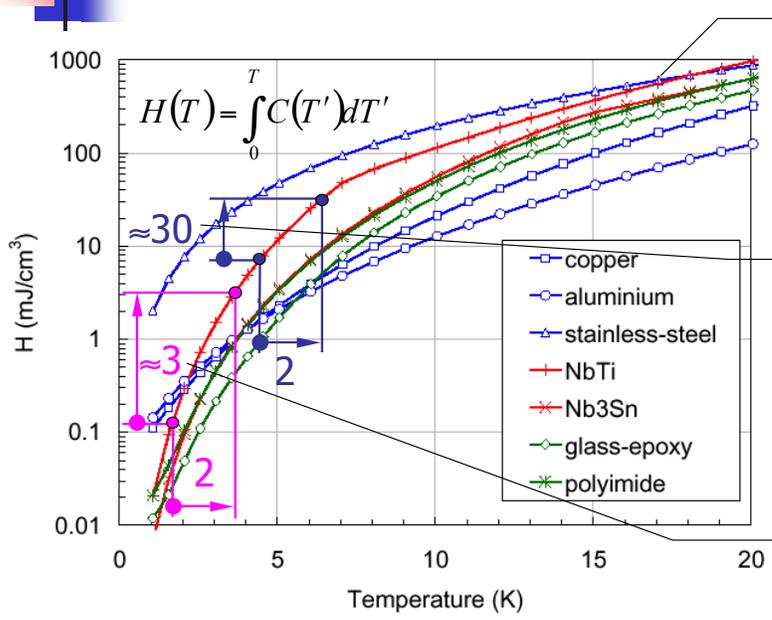


Typical range is from a few to a few tens of mJ/cm^3

Current sharing



Enthalpy reserve

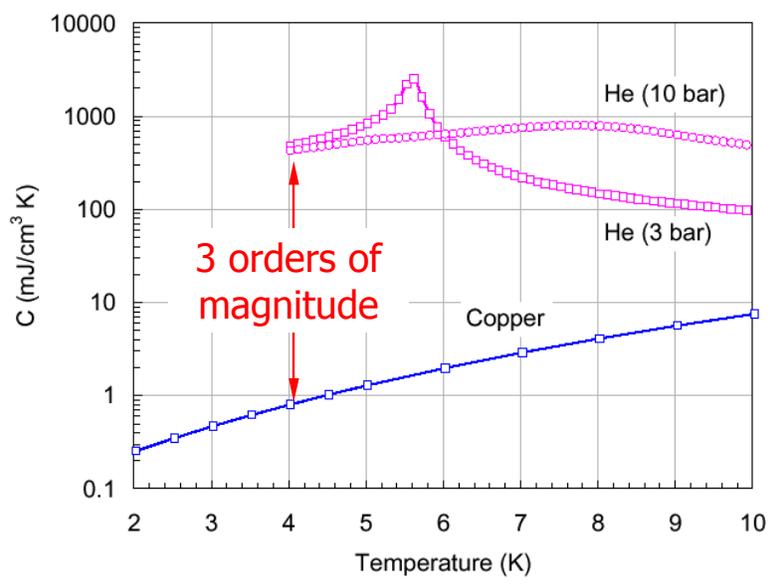


Enthalpy reserve increases massively at increasing T: **stability is not an issue for HTS materials**

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 !

Helium is a great heat sink !



Stability recipes

- A sound design is such that **the expected energy spectrum is smaller than the expected stability margin**
- To increase stability:
 - Increase **temperature margin**
 - Increase **heat removal** (e.g. conduction or heat transfer)
 - Decrease Joule heating by using a stabilizer with **low electrical conductance**
 - Make best use of **heat capacity**
 - Avoid sub-cooling (heat capacity increases with T, this is why stability is not an issue for HTS materials)
 - Access to helium for low operating temperatures

What if it *quenches* ?

- the magnetic energy stored in the field:

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

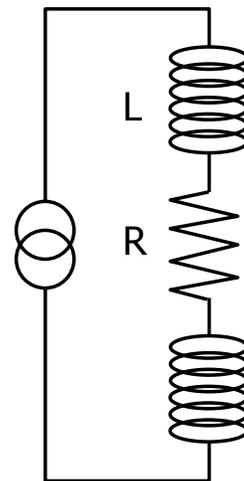
is converted to heat through Joule heating RI^2 .
If this process happened uniformly in the winding pack:

- Cu melting temperature 1356 K
- corresponding $E_m = 5.2 \cdot 10^9 \text{ J/m}^3$

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

BUT

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



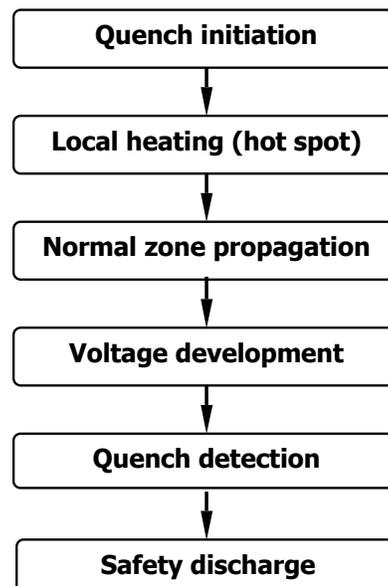
Lots of energy !



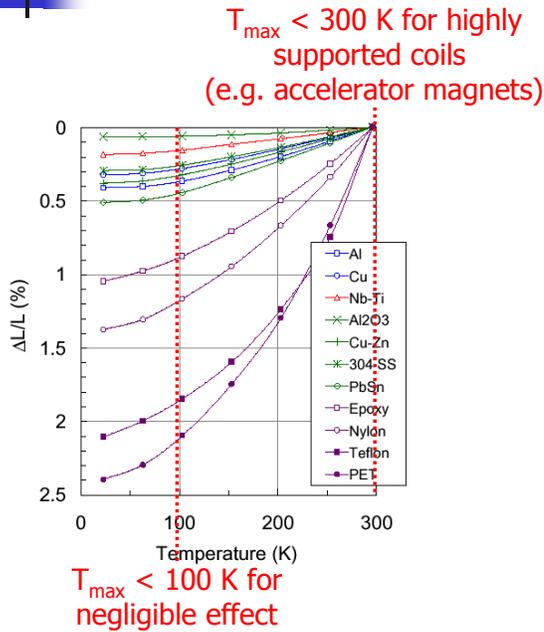
jump

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



Hot-spot limits



- the quench starts in a point and propagates with a *quench propagation velocity*
- the initial point will be the *hot spot* at temperature T_{max}
- T_{max} must be limited to:
 - limit thermal stresses (see graph)
 - avoid material damage (e.g. resins have typical T_{cure} 100...200 °C)

B.J. Maddock, G.B. James, Proc. IEE, **115** (4), 543, 1968

Adiabatic hot spot temperature

- adiabatic conditions at the hot spot :

$$C \frac{\partial T}{\partial t} = q_J \quad \text{where:} \quad q_J = \frac{\eta_{st}}{A_{st}} \frac{I^2}{A}$$

- can be integrated:

total volumetric heat capacity
stabilizer resistivity

$$\int_{T_{op}}^{T_{max}} \frac{C}{\eta_{st}} dT = \frac{1}{f_{st}} \int_0^{\infty} J^2 dt$$

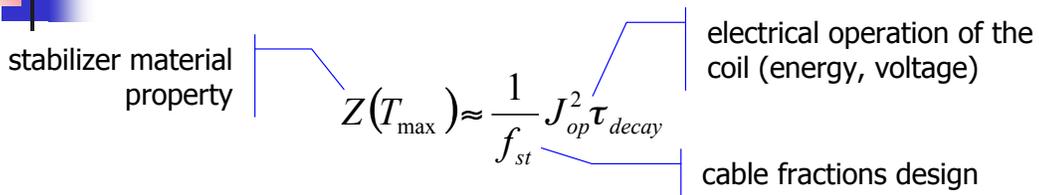
stabilizer fraction
cable operating current density

$$Z(T_{max}) = \int_{T_{op}}^{T_{max}} \frac{C}{\eta_{st}} dT$$

$$\int_0^{\infty} J^2 dt \approx J_{op}^2 \tau_{decay}$$

The function $Z(T_{max})$ is a *cable property*

How to limit T_{max}

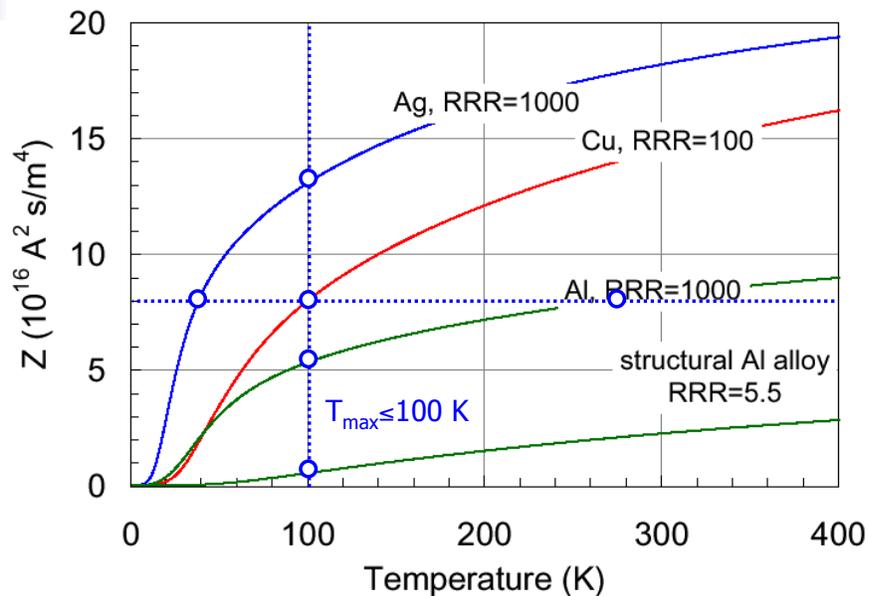


implicit relation between T_{max} , f_{st} , J_{op} , τ_{decay}

- to decrease T_{max}
 - reduce operating current density ($J_{op} \downarrow$)
 - discharge quickly ($\tau_{decay} \downarrow$)
 - add stabilizer ($f_{st} \uparrow$)
 - choose a material with large $Z(T_{max}) \uparrow$

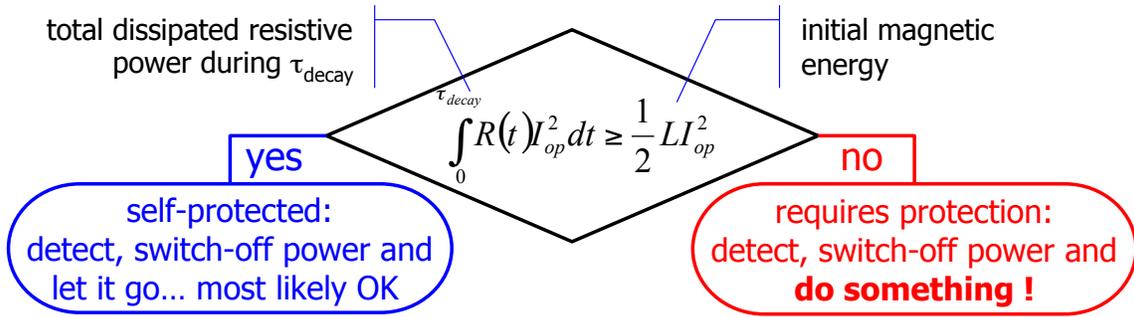
$$Z(T_{max}) \approx \frac{1}{f_{st}} J_{op}^2 \tau_{decay}$$

$Z(T_{max})$ for typical stabilizers



Quench protection

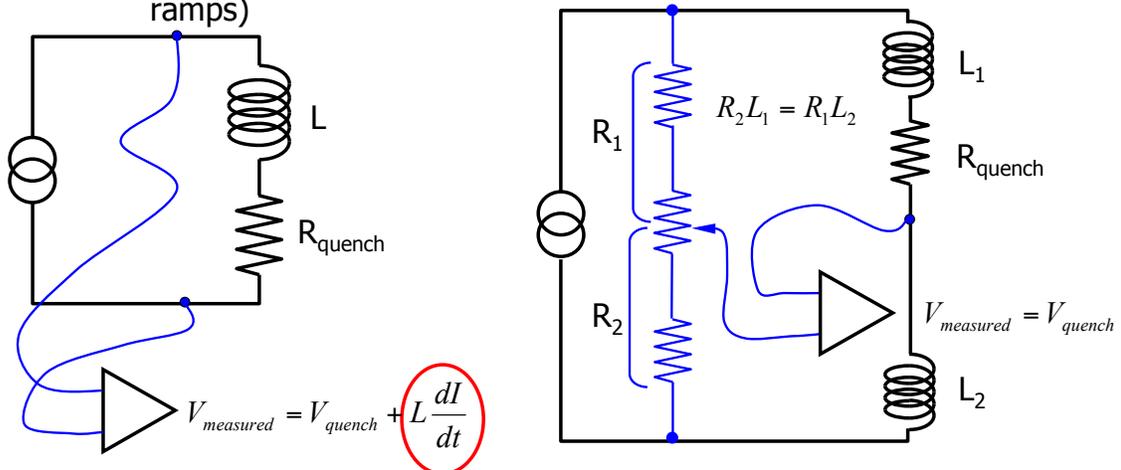
- The magnet stores a magnetic energy $\frac{1}{2} L I^2$
- During a quench it dissipates a power $R I^2$ for a duration τ_{decay} characteristic of the powering circuit



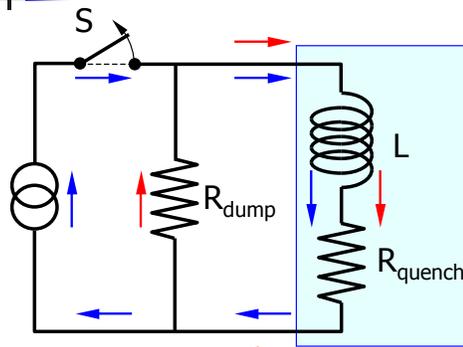
WARNING: the reasoning here is qualitative, conclusions require in any case detailed checking

Quench detection: voltage

- a direct quench voltage measurement is subject to inductive pick-up (ripple, ramps)
- immunity to inductive voltages (and noise rejection) is achieved by *compensation*



Strategy 1: energy dump



$$R_{dump} \gg R_{quench}$$

← normal operation

← quench

- the magnetic energy is extracted from the magnet and dissipated in an external resistor:

$$I = I_{op} e^{-\frac{(t-\tau_{detection})}{\tau_{dump}}} \quad \tau_{dump} = \frac{L}{R_{dump}}$$

- the integral of the current:

$$\int_0^{\infty} J^2 dt \approx J_{op}^2 \left(\tau_{detection} + \frac{\tau_{dump}}{2} \right)$$

- can be made small by:
 - fast detection
 - fast dump (large R_{dump})

Dump time constant

- magnetic energy:

$$E_m = \frac{1}{2} L I_{op}^2$$

- maximum terminal voltage:

$$V_{max} = R_{dump} I_{op}$$

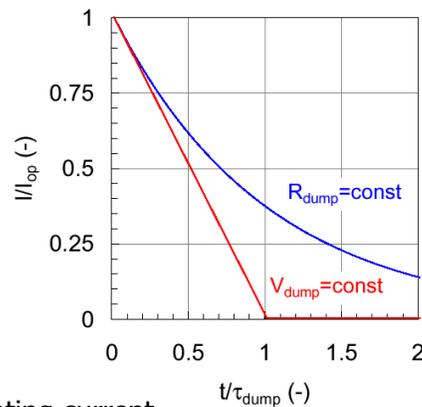
- dump time constant:

$$\tau_{dump} = \frac{L}{R_{dump}} = \frac{2E_m}{V_{max} I_{op}}$$

maximum terminal voltage

operating current

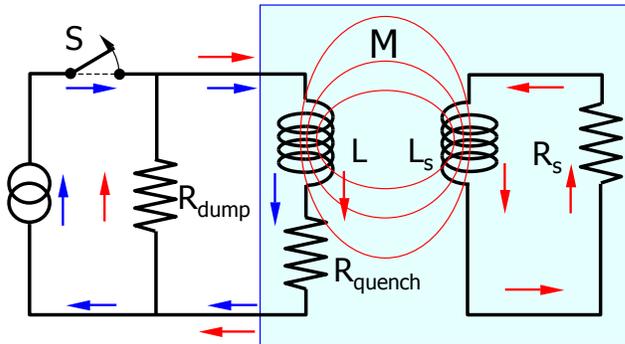
interesting alternative:
non-linear R_{dump} or voltage source



increase V_{max} and I_{op} to achieve fast dump time

Strategy 2: coupled secondary

- the magnet is coupled inductively to a secondary that absorbs and dissipates a part of the magnetic energy



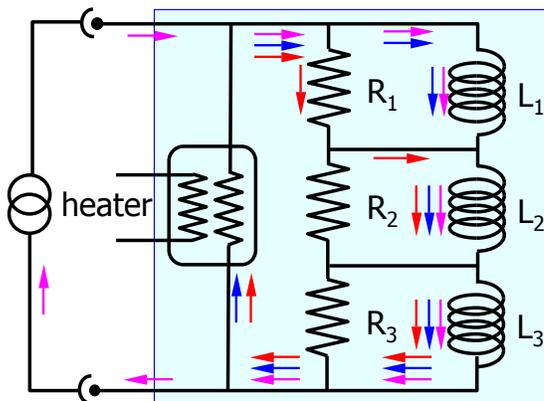
- advantages:
 - magnetic energy partially dissipated in R_s (lower T_{max})
 - lower effective magnet inductance (lower voltage)
 - heating of R_s can be used to speed-up quench propagation (quench-back)
- disadvantages:
 - induced currents (and dissipation) during ramps

← normal operation
 ← quench

P.F. Smith, Rev. Sci. Instrum., **34** (4), 368, 1963.

Strategy 3: subdivision

- the magnet is divided in sections, with each section shunted by an alternative path (resistance) for the current in case of quench

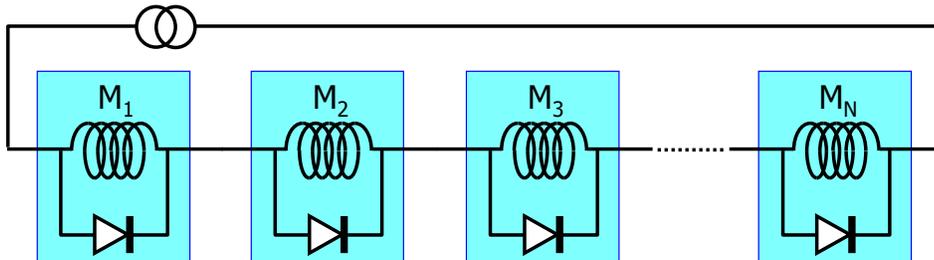


- advantages:
 - passive
 - only a fraction of the magnetic energy is dissipated in a module (lower T_{max})
 - transient current and dissipation can be used to speed-up quench propagation (quench-back)
- disadvantages:
 - induced currents (and dissipation) during ramps

← charge
 ← normal operation
 ← quench

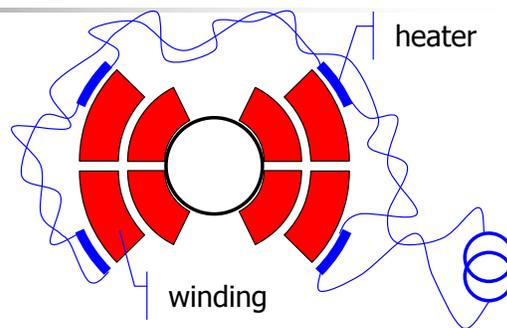
Magnet strings

- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
 - energy dump takes very long time (10...100 s)
 - the magnet string is *subdivided* and each magnet is bypassed by a diode (or thyristor)
 - the diode acts as a shunt during the discharge



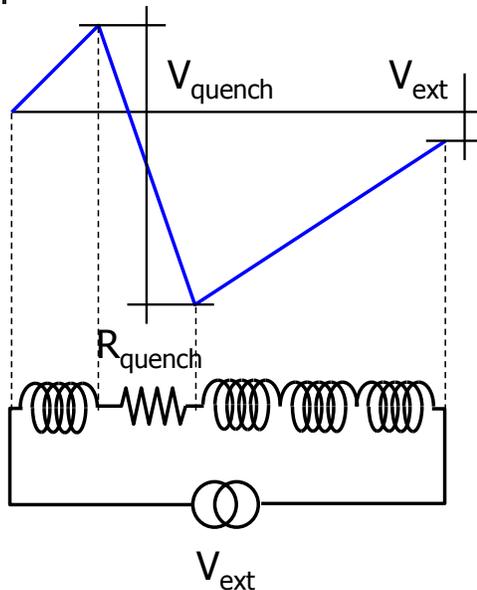
Strategy 4: heaters

- the quench is spread actively by firing heaters embedded in the winding pack, in close vicinity to the conductor
- heaters are mandatory in:
 - high performance, aggressive, cost-effective and highly optimized magnet designs...
 - ...when you are really desperate



- **advantages:**
 - homogeneous spread of the magnetic energy within the winding pack
- **disadvantages:**
 - active
 - high voltages at the heater

Quench voltage



- electrical stress can cause serious damage (arcing) to be avoided by proper design:
 - insulation material
 - insulation thickness
 - electric field concentration
- **REMEMBER: in a quenching coil the maximum voltage is not necessarily at the terminals**
- the situation in subdivided and inductively coupled systems is complex, may require extensive simulation

jump

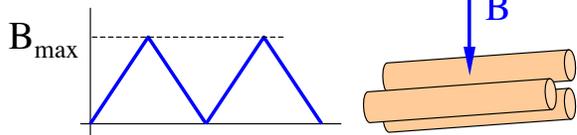
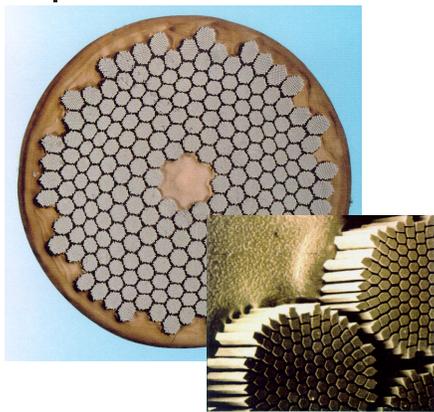
Quench and protection recipes

- 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 (\Leftrightarrow operating margin, stability)
 - Reducing operating current density (\Leftrightarrow 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

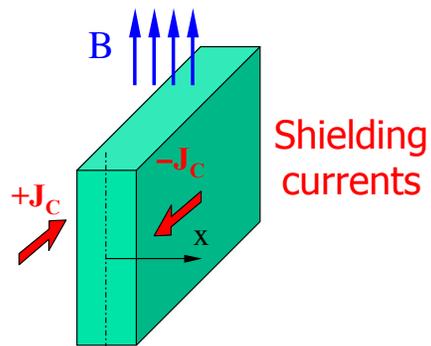
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A superconductor in varying field



A filament in a time-variable field

A simpler case: an infinite slab in a uniform, time-variable field

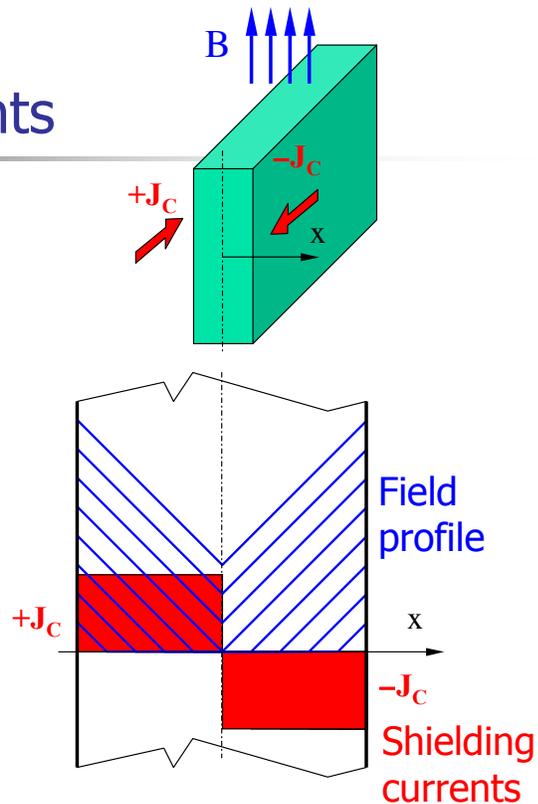


Quiz: how much is J ?

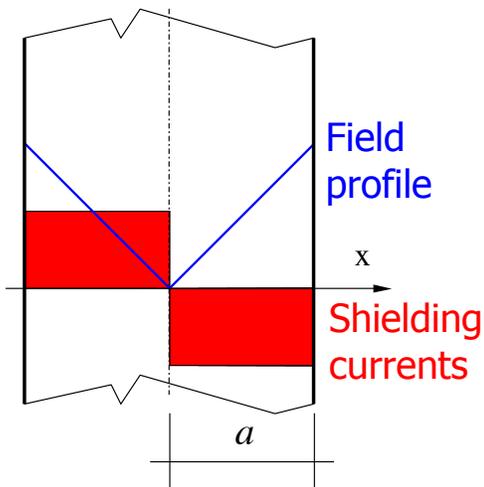
Persistent currents

- dB/dt produces an electric field E in the superconductor which drives it into the resistive state
- When the field sweep stops the electric field vanishes $E \Rightarrow 0$
- The superconductor goes back to J_c and then stays there
- This is the critical state (Bean) model: *within a superconductor, the current density is either $+J_c$, $-J_c$ or zero, there's nothing in between!*

$$J = \pm J_c$$



Magnetization



- Seen from outside the sample, the persistent currents produce a magnetic moment. We can define a *magnetization*:

$$M = \frac{1}{a} \int_0^a J_c x dx = \frac{J_c a}{2}$$

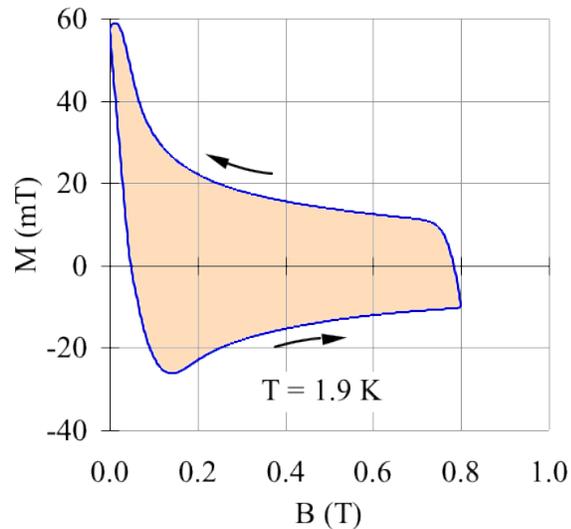
- The magnetization is proportional to the critical current density and to the size of the superconducting slab (**filament diameter !**)

Hysteresis loss

- The response of a superconducting wire in a changing field is a field-dependent magnetization (remember $M \propto J_c(B)$)
- The work done by the external field is:

$$Q = \oint \mu_0 M dH = \oint \mu_0 H dM$$

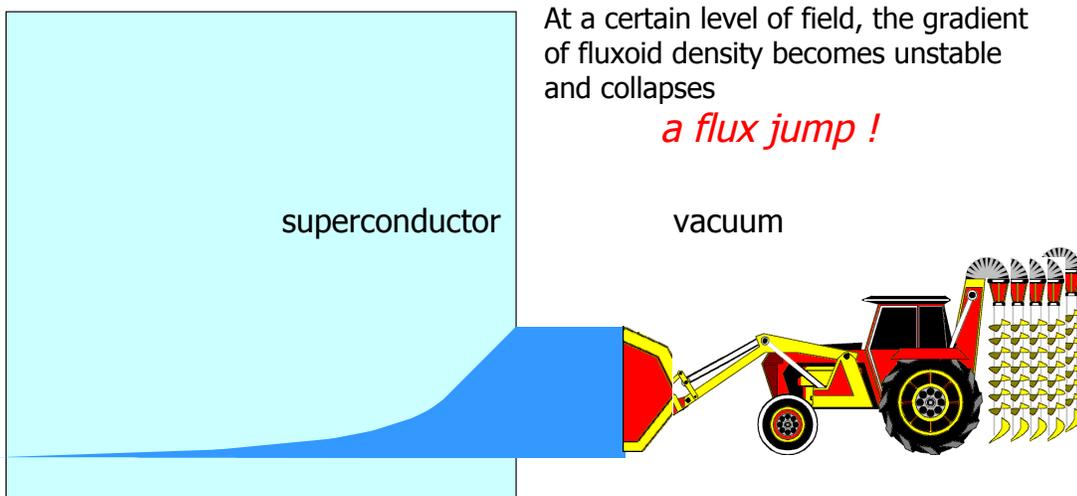
i.e. the **area of the magnetization loop**



Graphics by courtesy of M.N. Wilson

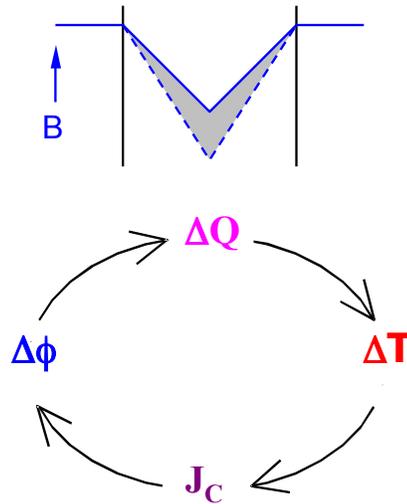
A different view of flux penetration

The screening currents are a gradient in fluxoid density. The increasing external field exerts pressure on the fluxoids against the pinning force, and causes them to penetrate, with a characteristic gradient in fluxoid density (J_c)



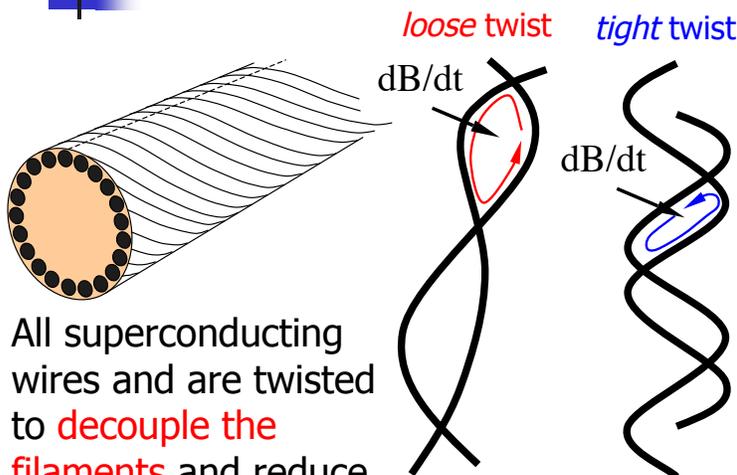
Flux jumps

- Unstable behaviour is shown by all superconductors when subjected to a magnetic field:
 - B induces screening currents, flowing at critical density J_C
 - A change in screening currents allows flux to move into the superconductor
 - The flux motion dissipates energy
 - The energy dissipation causes local temperature rise
 - J_C density falls with increasing temperature



Flux jumping is cured by making superconductor in the form of fine filaments. This weakens the effect of $\Delta\phi$ on ΔQ

Filaments coupling



All superconducting wires and are twisted to **decouple the filaments** and reduce the magnitude of eddy currents and associated loss

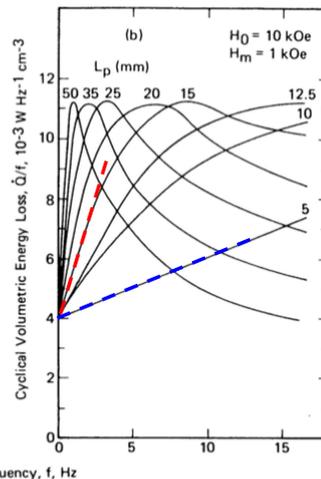
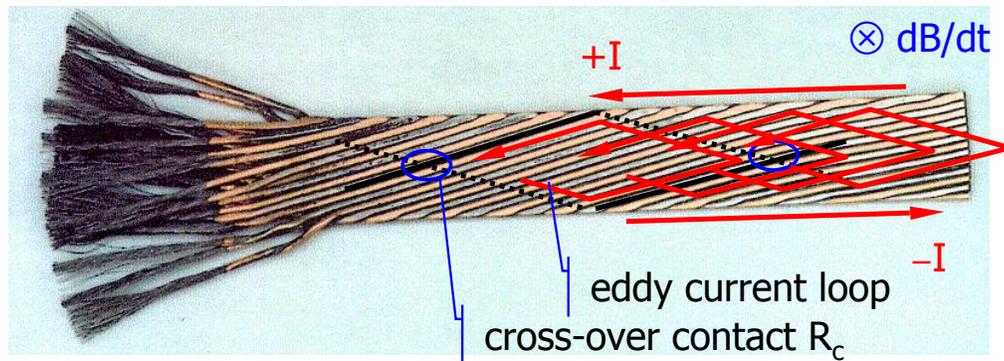


Figure 26-8. Energy loss per cycle ($= \dot{Q}/f$) plotted versus frequency of the alternating component of an applied field $H_a(\omega) = H_0 + H_m \sin \omega t$. (a) The per-cycle coil loss is plotted for six values of H_m between 0.25 and 1.25 kOe at $H_0 = 10$ kOe; (b) the per-cycle volumetric loss of the composite is plotted for eight values of the twist pitch, L_p , at $H_0 = 10$ kOe, $H_m = 1$ kOe—after KWASNITZA and HORVATH [KWA74, KWA76].

Coupling in cables



The strands in a cable are coupled (as the filaments in a strand). To decouple them we require to twist (**transpose**) the cable and to control the **contact resistances**

AC loss - Re-cap

- AC loss is usually the **major source of internal heat** in pulsed and cycled superconducting magnets
- The magnetic moment associated to DC (persistent) and AC (coupling) currents perturbs the field quality of the magnet
- To reduce loss
 - Use **fine superconducting filaments**, and in any case $< 50 \mu\text{m}$ to avoid flux-jump instability
 - Use **tight twist pitch**, and small cable dimensions
 - Include **resistive barriers** in the wires and cables
- The theory and calculation of AC loss is a **complicated matter !** Rely heavily on measurements

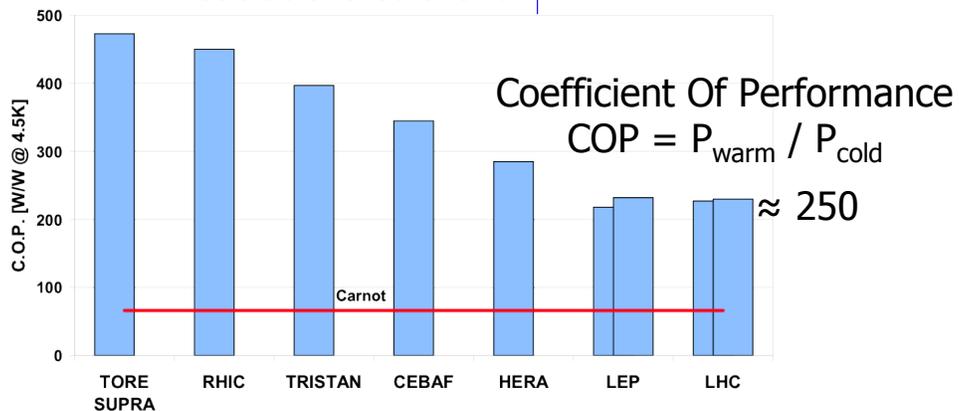
Overview

- Magnets NC vs. SC - a motivation
- A superconductor physics primer
- From material physics to magnet engineering
- **Superconducting magnet design**
 - Magnetic design
 - Operating margins
 - Stability, quench and protection
 - Magnetization and AC loss
 - **Cooling of superconducting magnets**
 - Low-temperature mechanics
- The making of a superconducting magnet
- Other examples of superconducting magnet systems

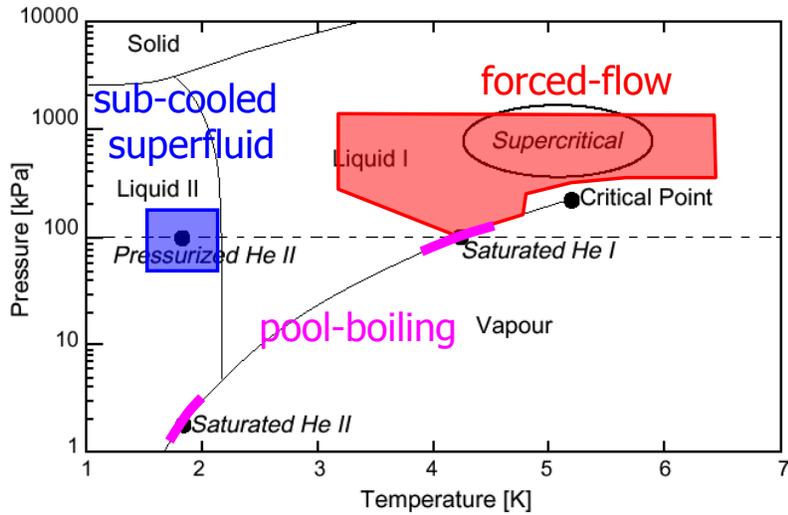
Basic thermodynamics

- 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



Helium as a low-temperature coolant



Fridge's



Cryocoolers: $\approx 1.5 \text{ W @ } 4.2 \text{ K}$



LHC refrigerators: $\approx 140 \text{ kW @ } 4.2 \text{ K}$

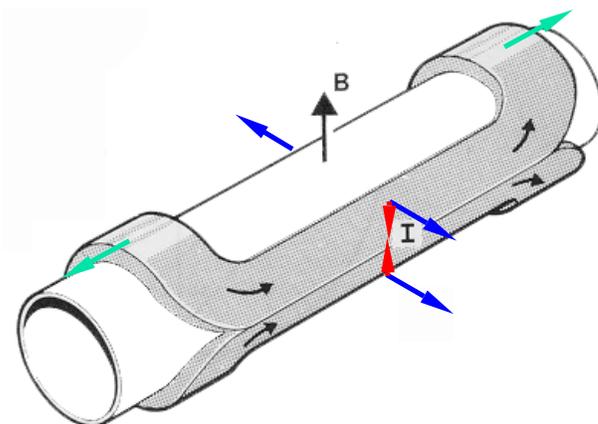
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jump

Mechanical issues in accelerator magnets (e.g. a dipole)

- Electromagnetic forces are exerted in all directions, **radially**, **azimuthally**, and **axially**, and need to be contained to guarantee mechanical integrity

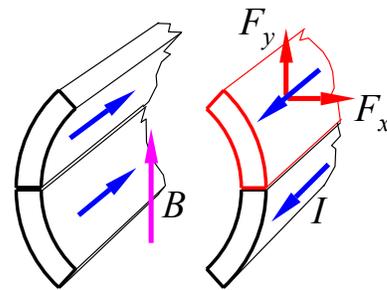
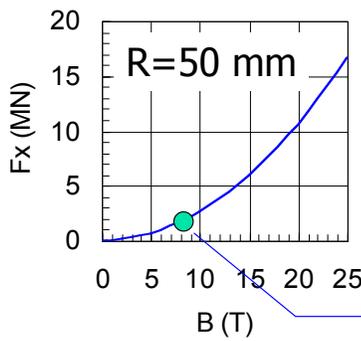


- Remember:
 - Material properties are (sometimes strong) function of temperature
 - Thermal contraction is very different among the various components of a magnet (e.g. metals vs. insulators)
 - Field quality and stability depends on reliable coil dimension to the μm

Orders of magnitude of the force

- Dipole magnet with field B in a bore radius R
 - Approximation of the force on a *quadrant* per unit length:

$$F_x = -F_y = \frac{4}{3} R \frac{B^2}{2\mu_0}$$



LHC ≈ 2 MN/m

Photograph by courtesy of A. Devred

Design principle

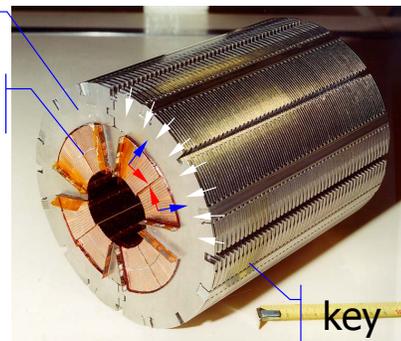
- Stick-slip or frictional motions (at the μm level) are undesirable and can lead to quench or affect the field quality
- In accelerator magnets the coils are (generally) blocked inside a rigid support structure:

locked-in collar pack

coil

Roman arch principle

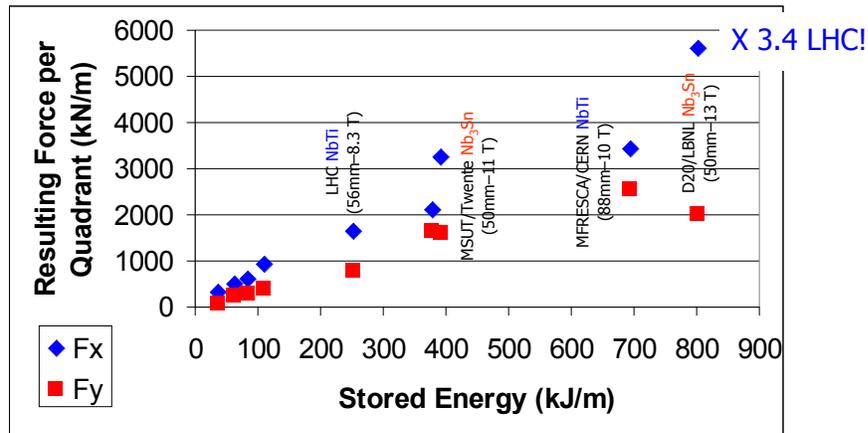
promulgated by R. Perin (CERN)



Collared-coil assembly section of LHC arc quadrupole magnet at CEA/Saclay

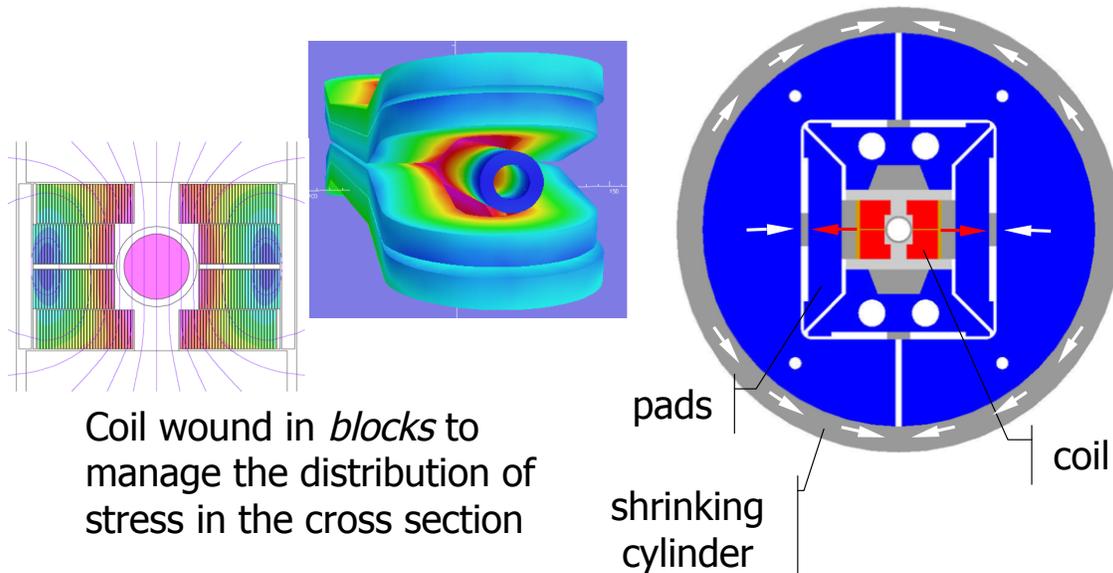
Towards higher fields (HE-LHC)

- Several R&D programs are underway to demonstrate the feasibility of magnets with **Lorentz force levels far exceeding those of LHC.**



New force containment principles

Example: the bladder and key concept from LBNL



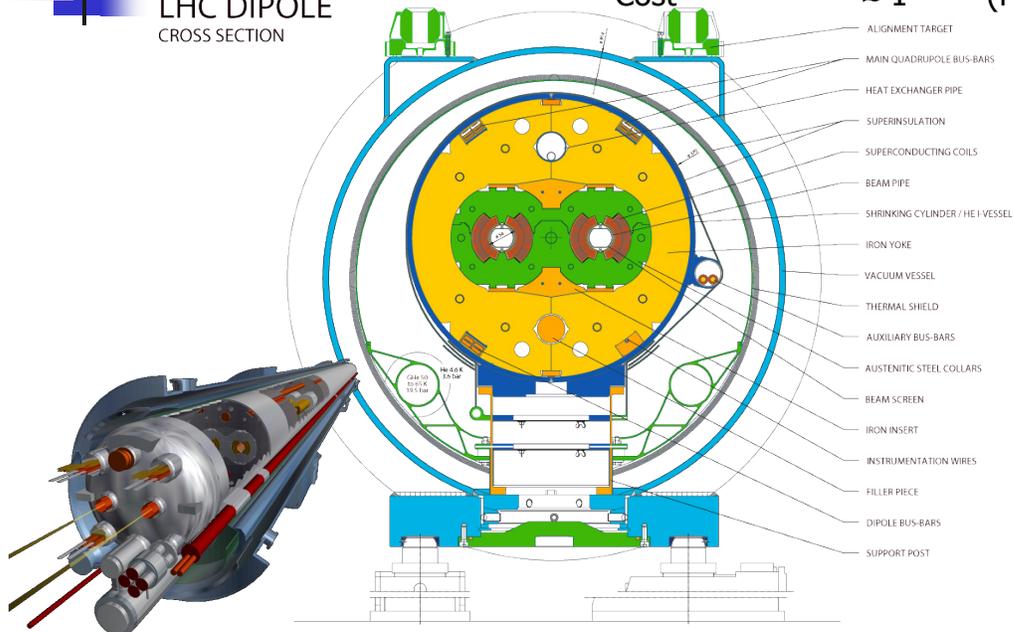
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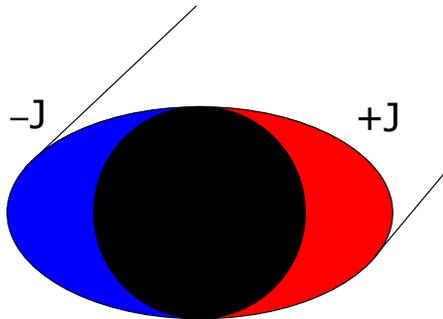
LHC dipole

LHC DIPOLE
CROSS SECTION

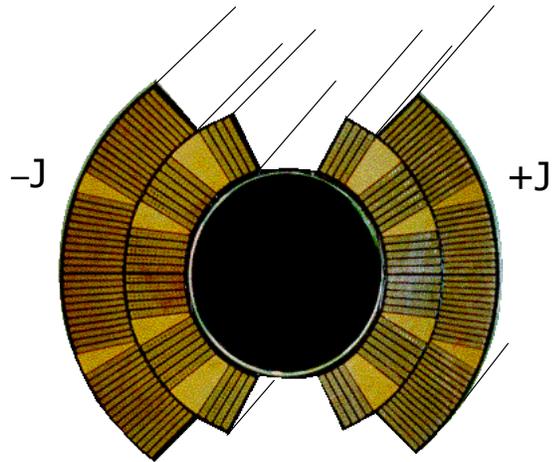
B_{nominal}	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)
Cost	≈ 1	(MCHF)



Superconducting dipole magnet coil

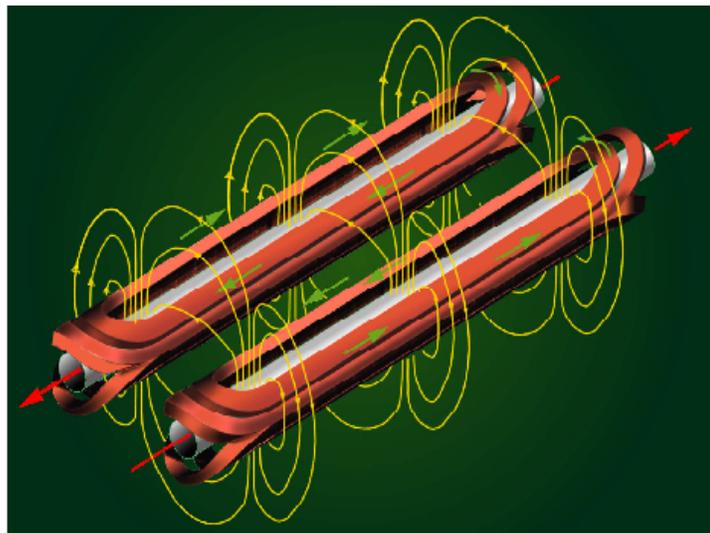


Ideal current distribution that generates a perfect dipole



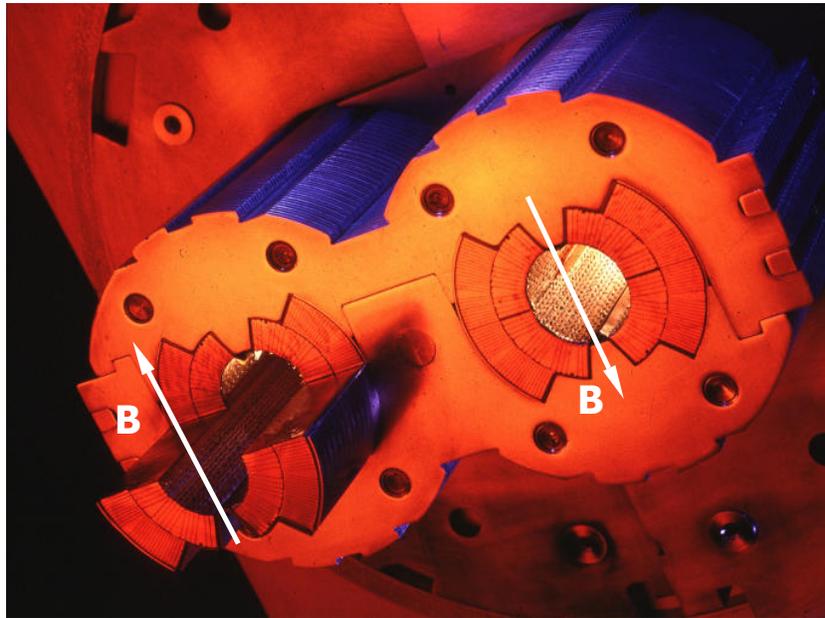
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle

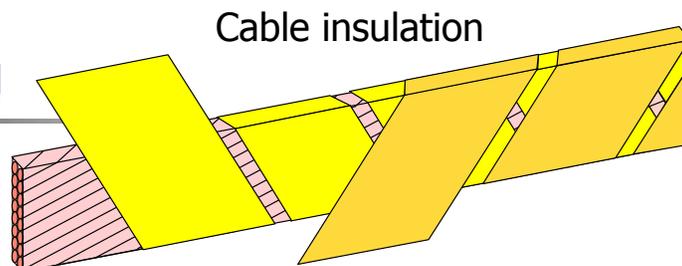


Combine two magnets in one
Save volume, material, cost

LHC dipole coils



Coil winding



10 μm precision !

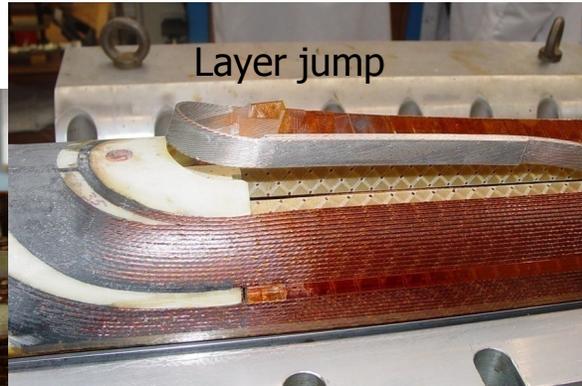
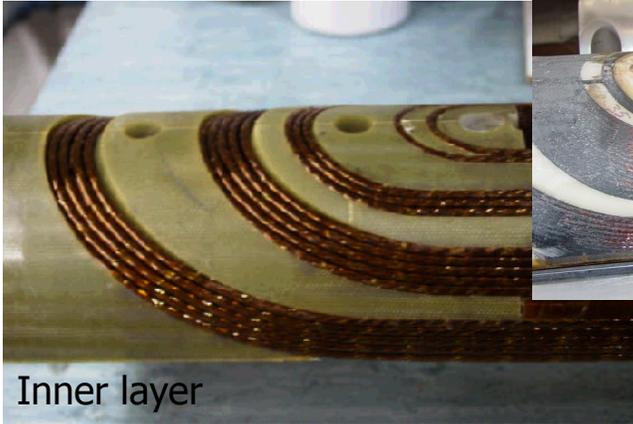


Coil winding machine



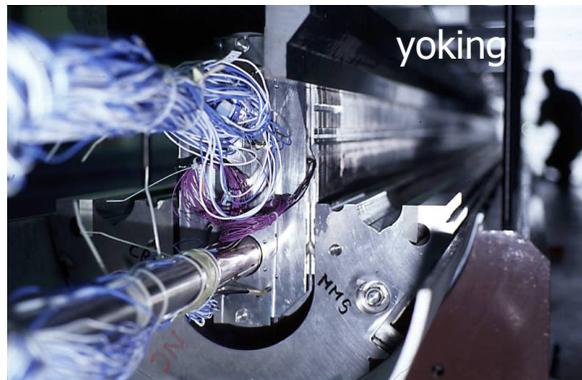
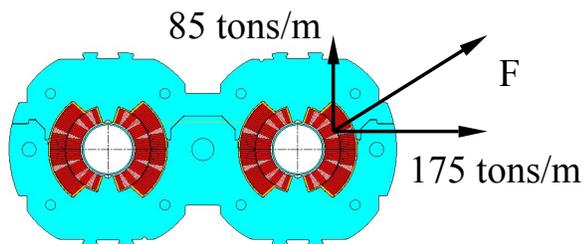
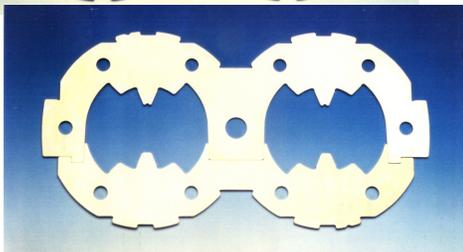
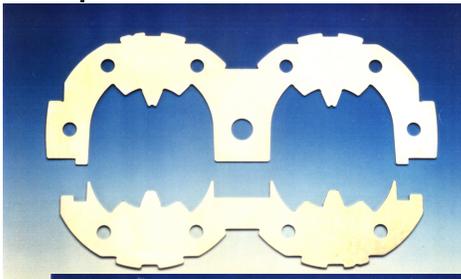
Stored coils

Ends



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

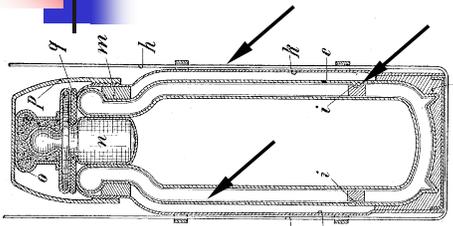
Collaring and yoking



Cold mass



Cryostat



Thermal screens



Low conduction foot

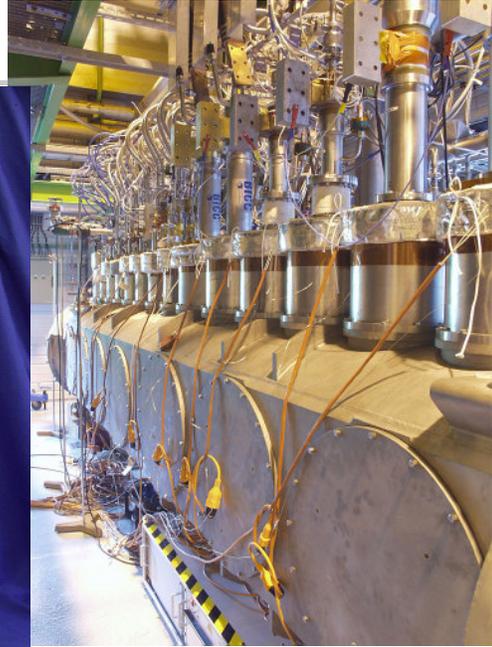
Current leads

Warm end (300K)

Intermediate temperature (50K)

HTS

Cold end (4K)



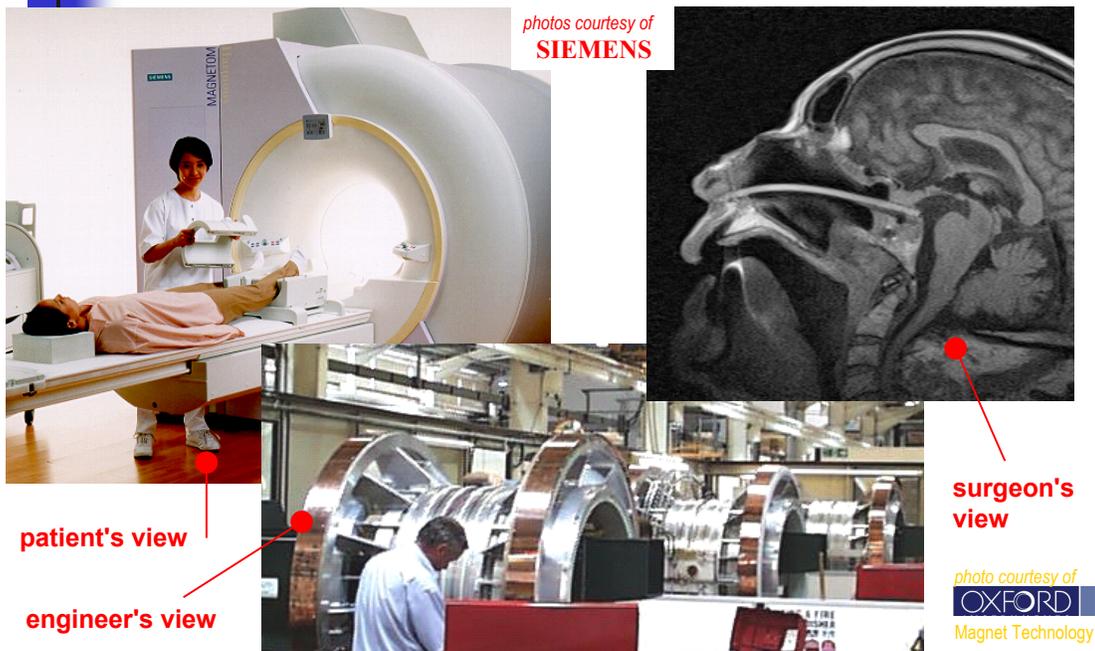
Finally, in the tunnel !



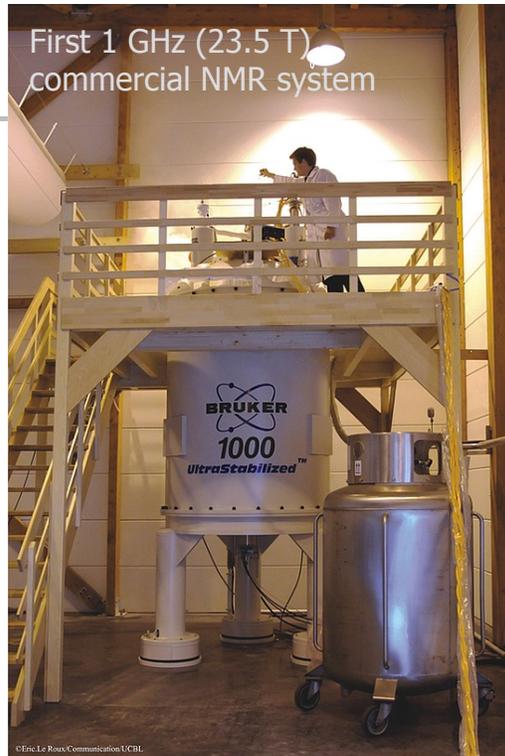
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Magnetic Resonance Imaging (MRI)

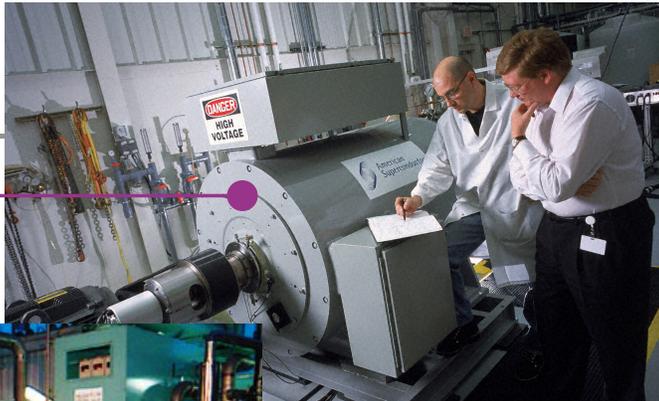


NMR spectroscopy



Motors & generators

Motor with HTS rotor
American Superconductor and Reliance

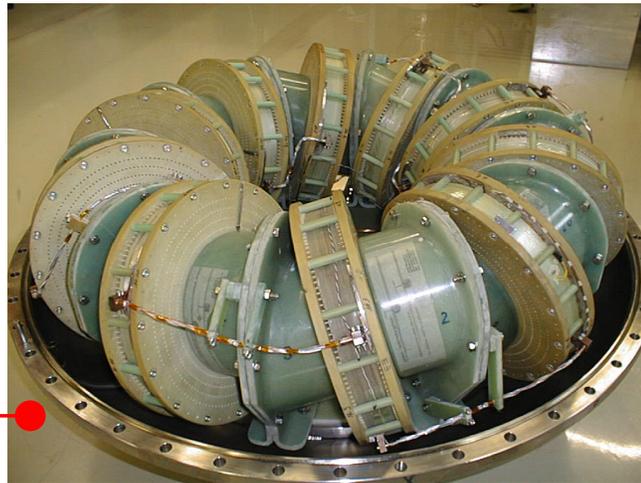


Transformers & energy storage



HTS Transformer
630 kVA, 18.7kV to 0.42 kV

ABB



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

KfZ Karlsruhe

Magnetic separation



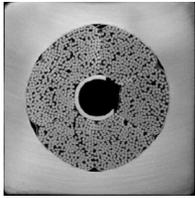
superconducting
solenoid,
enclosed within
iron shield

stainless steel
canister
containing
ferromagnetic
mesh

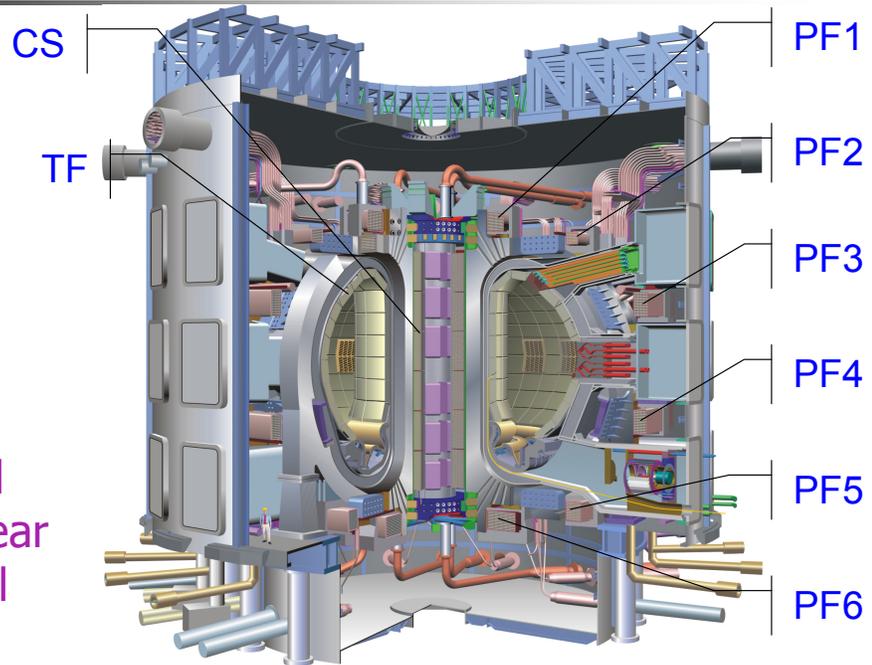
pipes feeding
the kaolin slurry
for separation

photo courtesy of
Carpco

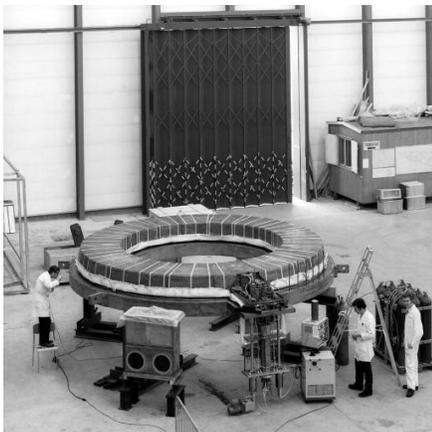
Thermonuclear fusion



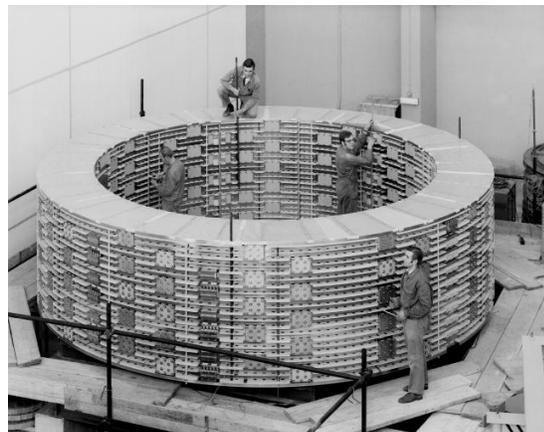
ITER
International
Thermonuclear
Experimental
Reactor



HEP detectors of the past...

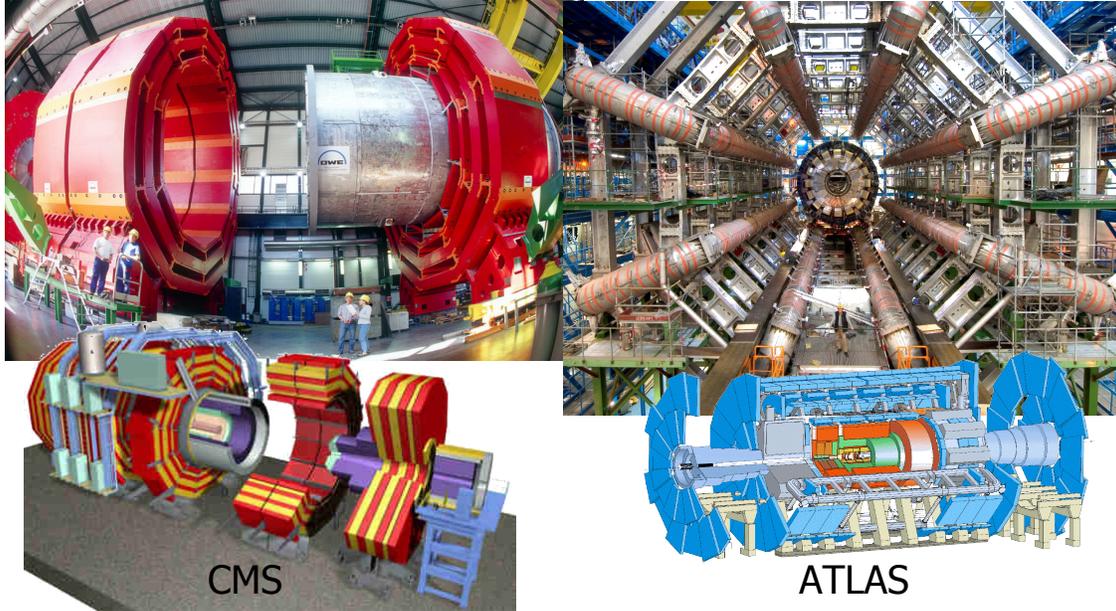


Omega



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 Snakes

INCORP
Professor Main,
The Physics Dept,
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 rats and plants too by means of your machine. We in the church are not scientists, we follow the spiritual path, and it merely coincides that quantum levitation, like the job we have a big interest subsequently, not it.

(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 rails. Will they sense up the magnet?

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

(3) We are interested in bodies, or each of them but that we (3) does it hurt, Ian. 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, joking 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 gold, silver securities and properties in France and Kent, so if everything is good we want to buy your machine for one million pounds, which would be a good price.

we intend

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

So you know what I have... we pull back the curtain in the Snake Chamber and I start to rise up from the ground...

Our church was founded not the same and so it the words are still in the words of the Bible. I mean it all for faith. I Trust more to save the world than that. Give us...

I hope you don't have a problem with that, I know in our church services if we will look the organization and their faith; if you are present as it is a report, if we a million pounds here although from him.

I have only one other member. The Party and focuses will you be and do not sell them a machine. And also, it says in it chemistry and physics. I have a very good friend...

...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...

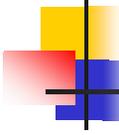
Does it hurt... because it will be me doing the levitating.

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

9

浮いた土佐ノ海

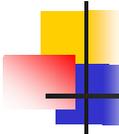
Letter to Prof. Main, University of Nottingham, 14 April 1997



A word of closing

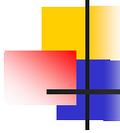
- Superconducting magnet design is **a lot about superconductors** (materials, wires, cables, and their electric and thermal properties)...
- ... but not only !
 - High field & forces bear **mechanical problems** that are tough to solve ($B=10\text{ T} \Rightarrow p_{\text{mag}}=1600\text{ bar !}$)
 - **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

Thank you for your attention



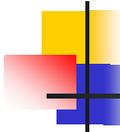
Where to find out more - 1/3

- 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, 1993 to 2008, and as IEEE Trans Magnetics 1975 to 1991
 - Proc European Conference on Applied Superconductivity EUCAS, pub UK Institute of Physics
 - Proc International Conference on Magnet Technology; MT-1 to MT-21 (2009) 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, published 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