Magnets (SC)

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CAS - Introduction to Accelerator Physics

Grand Hotel Varna, Varna, Bulgaria
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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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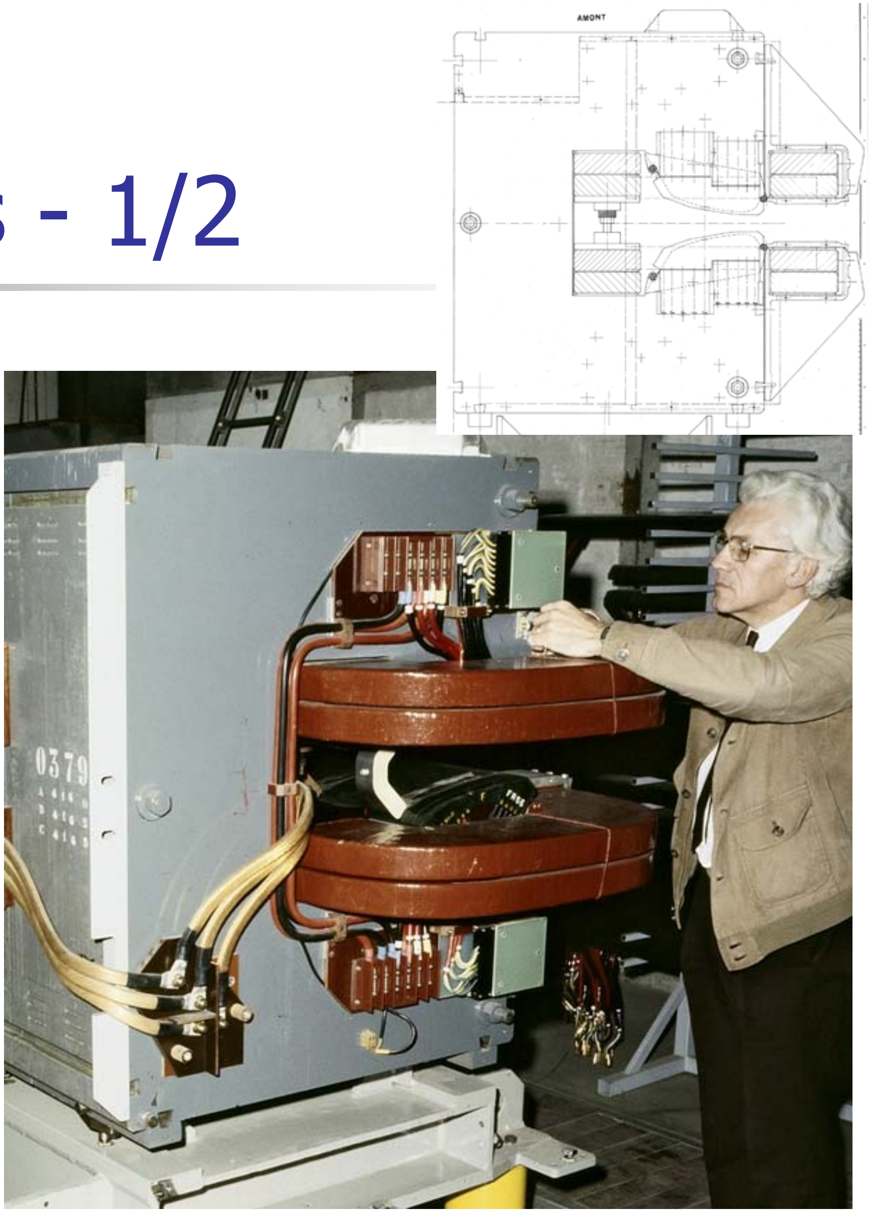
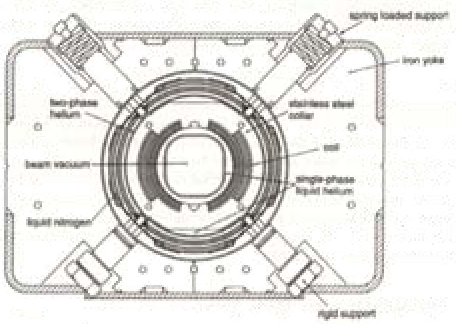
NC vs. SC Magnets - 1/2

- *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)

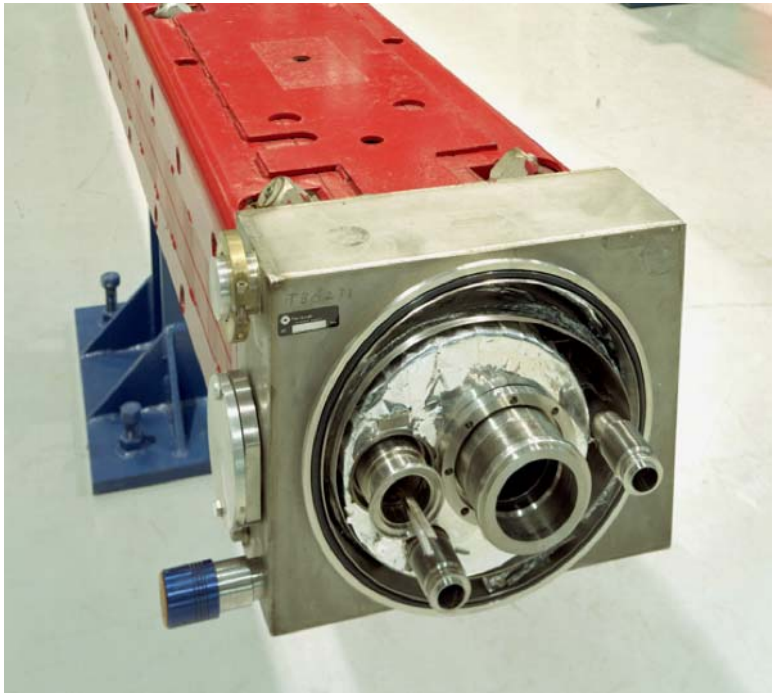


One of the dipole magnets of the PS, in operation at CERN since 51 years

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)

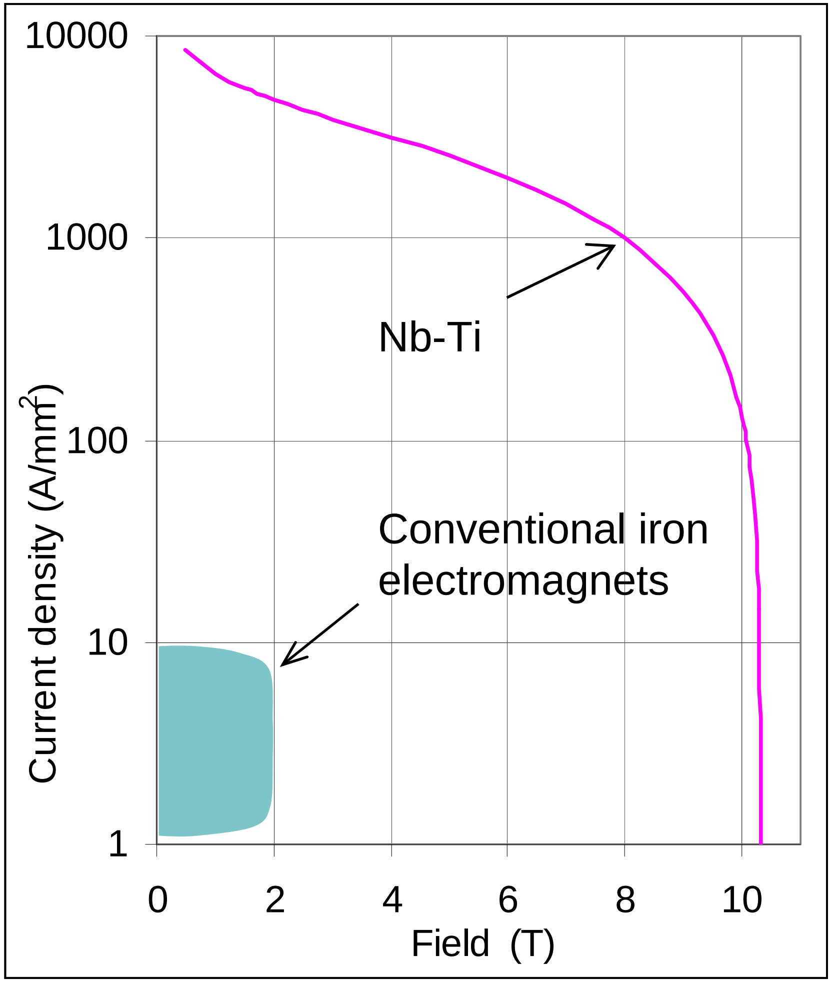


A superconducting dipole magnet of the Tevatron at FNAL, the first superconducting synchrotron, 1983

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 ⇒ new commercial possibilities
  - energy savings
  - high current density ⇒ smaller, lighter, cheaper magnets ⇒ reduced capital cost
  - higher magnetic fields economically feasible ⇒ new research possibilities



jump

Graphics by courtesy of M.N. Wilson

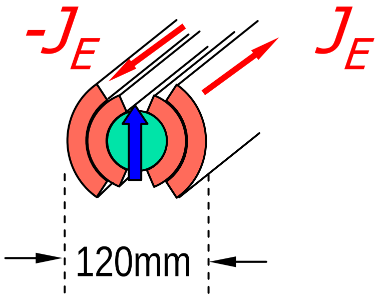
The advantage of high current density

- The field produced by an ideal dipole is:

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

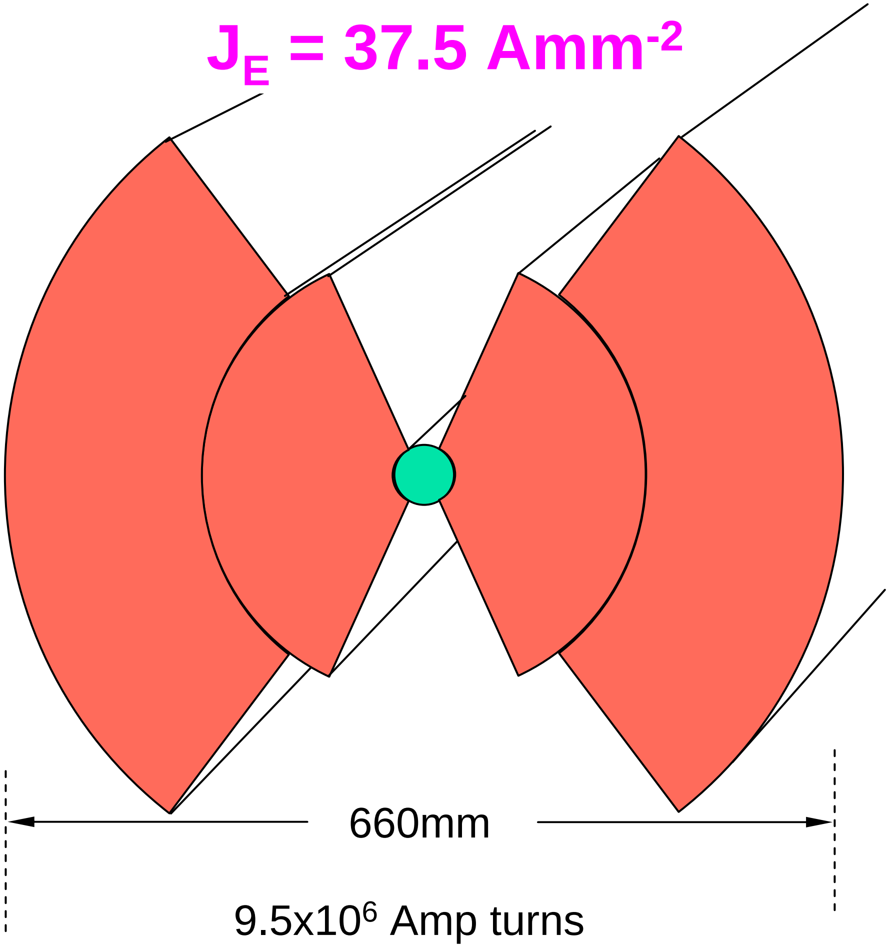
J_E = 375 Amm^{-2}

LHC dipole



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

J_E = 37.5 Amm^{-2}

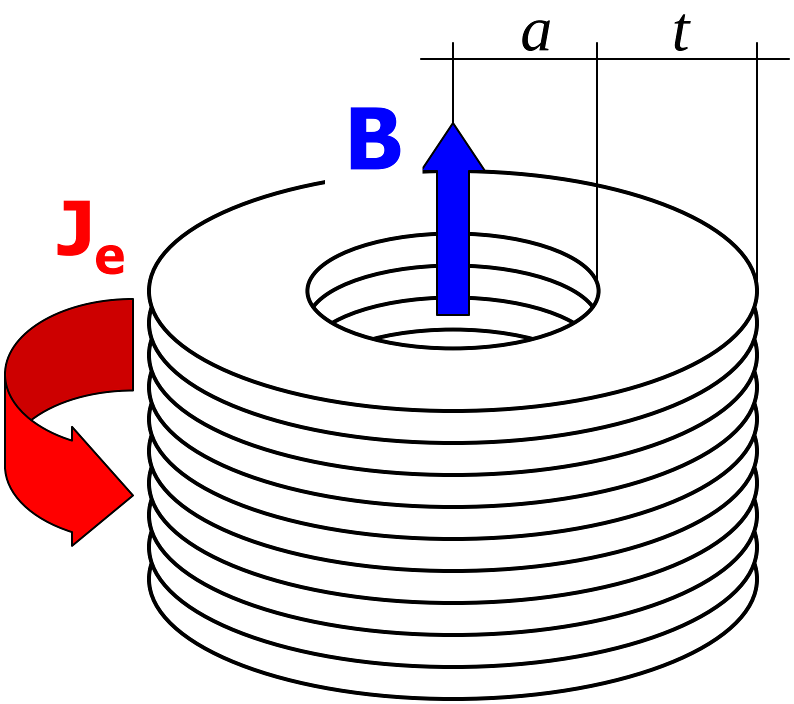


9.5x10^6 Amp turns
=1.9x10^7 A.m per m

High current density: solenoids

- The field produced by an infinitely long solenoid is:

$$B = \mu_o J_e t$$



- In solenoids of finite length the central field is:

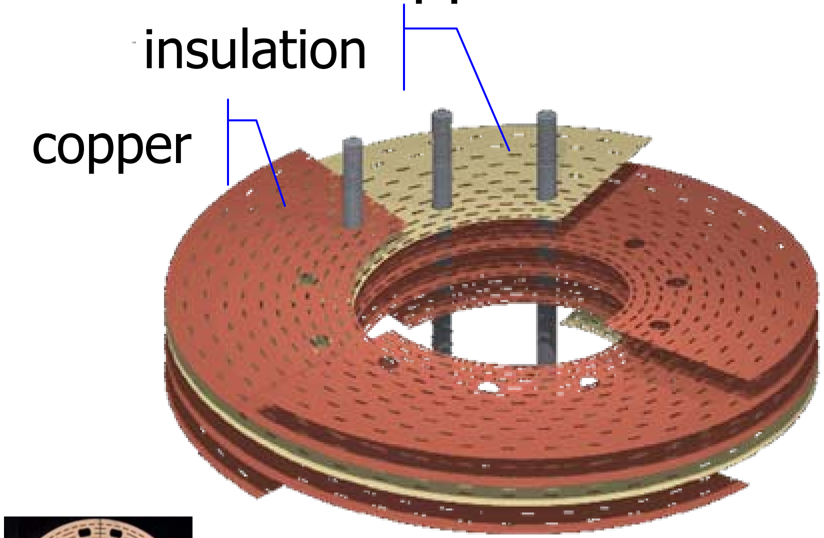
$$B = \mu_o f J_e t$$

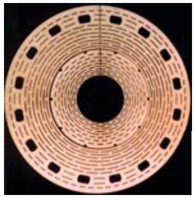
where f is a factor less than 1, typically ~ 0.8

- 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
- Superconducting magnets for *low field* applications





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

ASG Superconductors
Open-Sky MRI

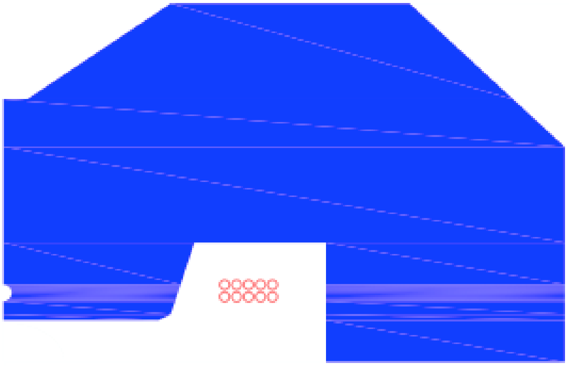
MgB_2 tape

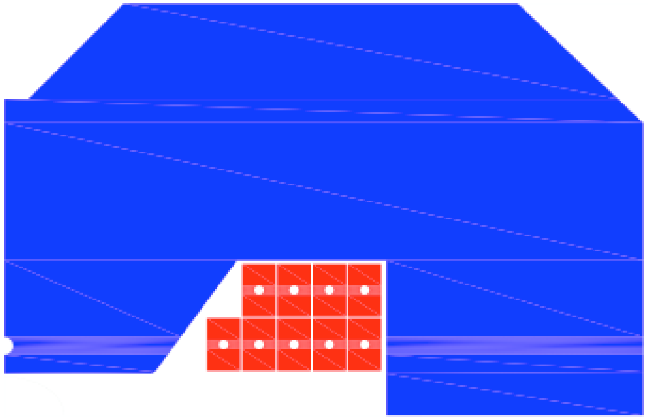
We forget exceptions for the rest of the talk !

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

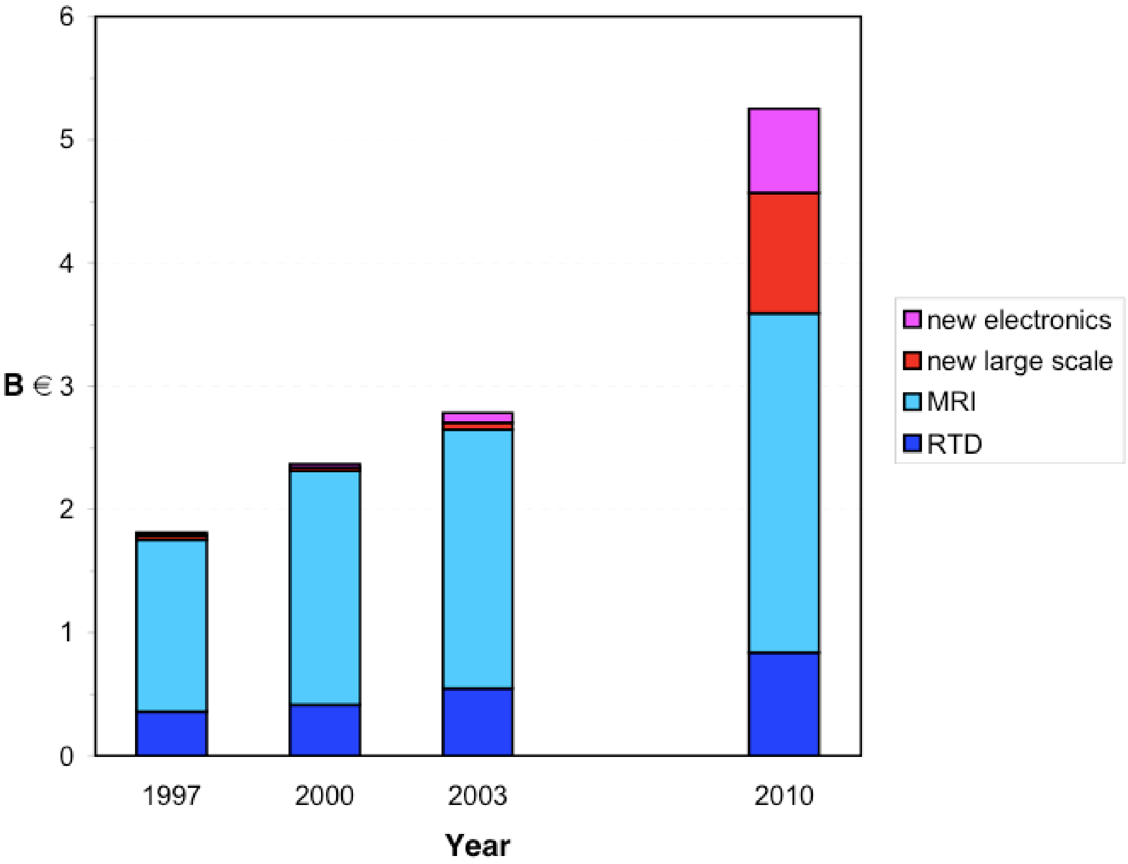
Iron weight [tons]	15
Peak voltage [V]	41
Resistive power [W]	27000

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



* ***CON**sortium of **E**uropean **C**ompanies (determined) **T**o **U**se **S**uperconductivity*

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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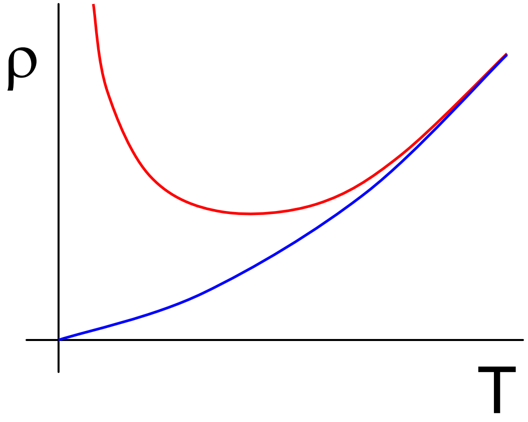
A great physics problem in 1900

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



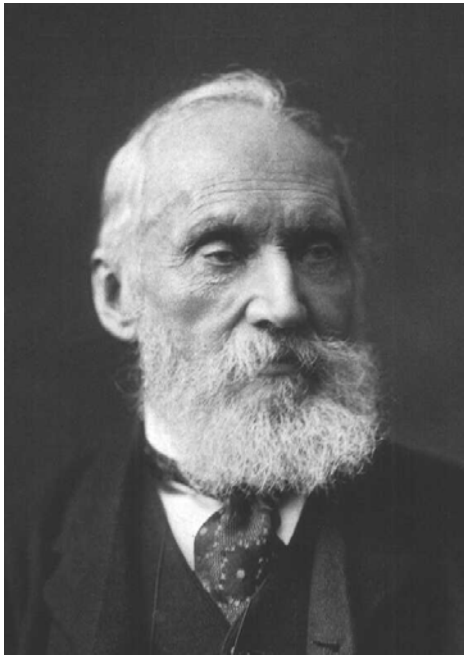
… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

X-rays are an hoax

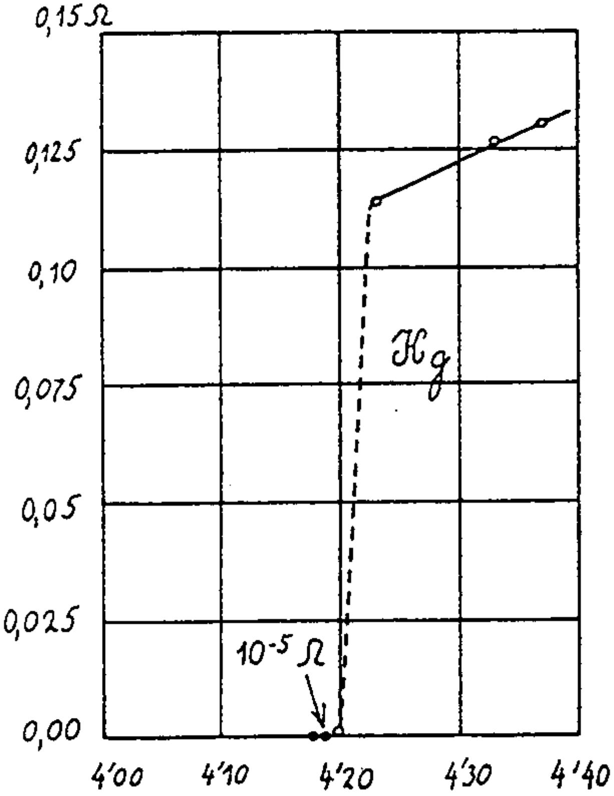
“I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of”

"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



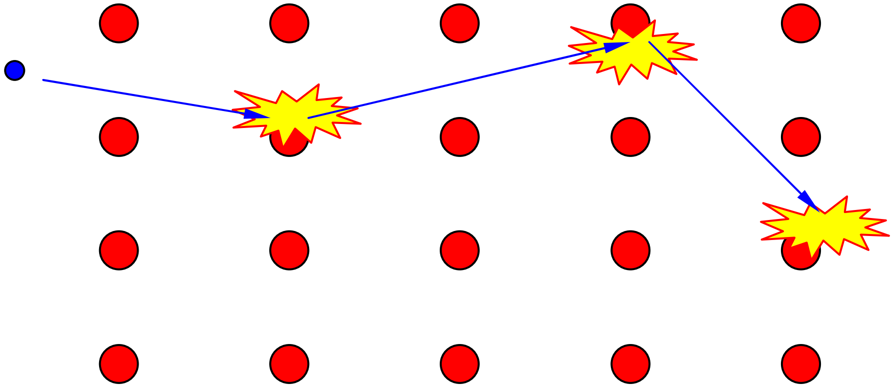
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)

Cooper Pairs

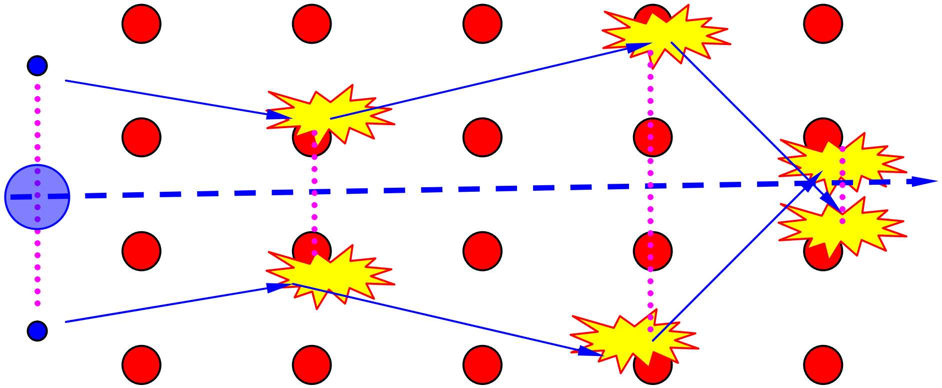
Bardeen, Cooper and Schrieffer

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



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

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



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

Pairing mechanism

Lattice displacement

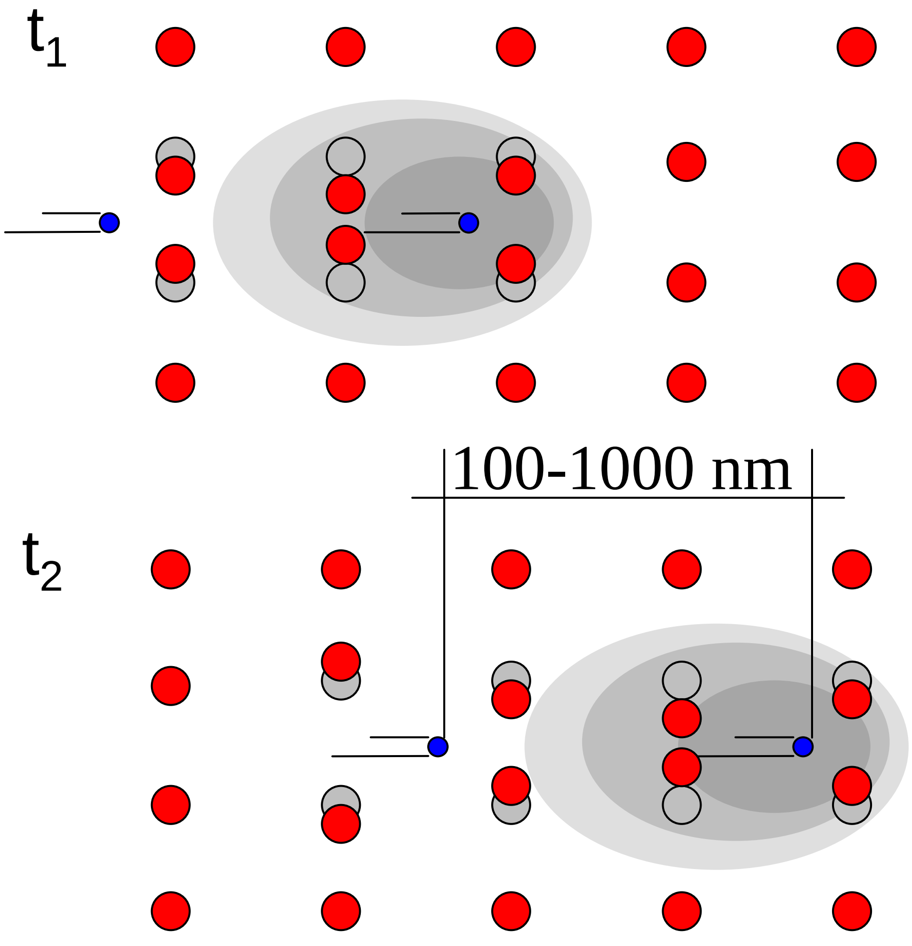
⇓

phonons (sound)

⇓

coupling of charge carriers

Only works at low temperature



Bardeen, Cooper, Schrieffer (BCS) - 1957

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

First (not last) superconducting magnet project cancelled

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

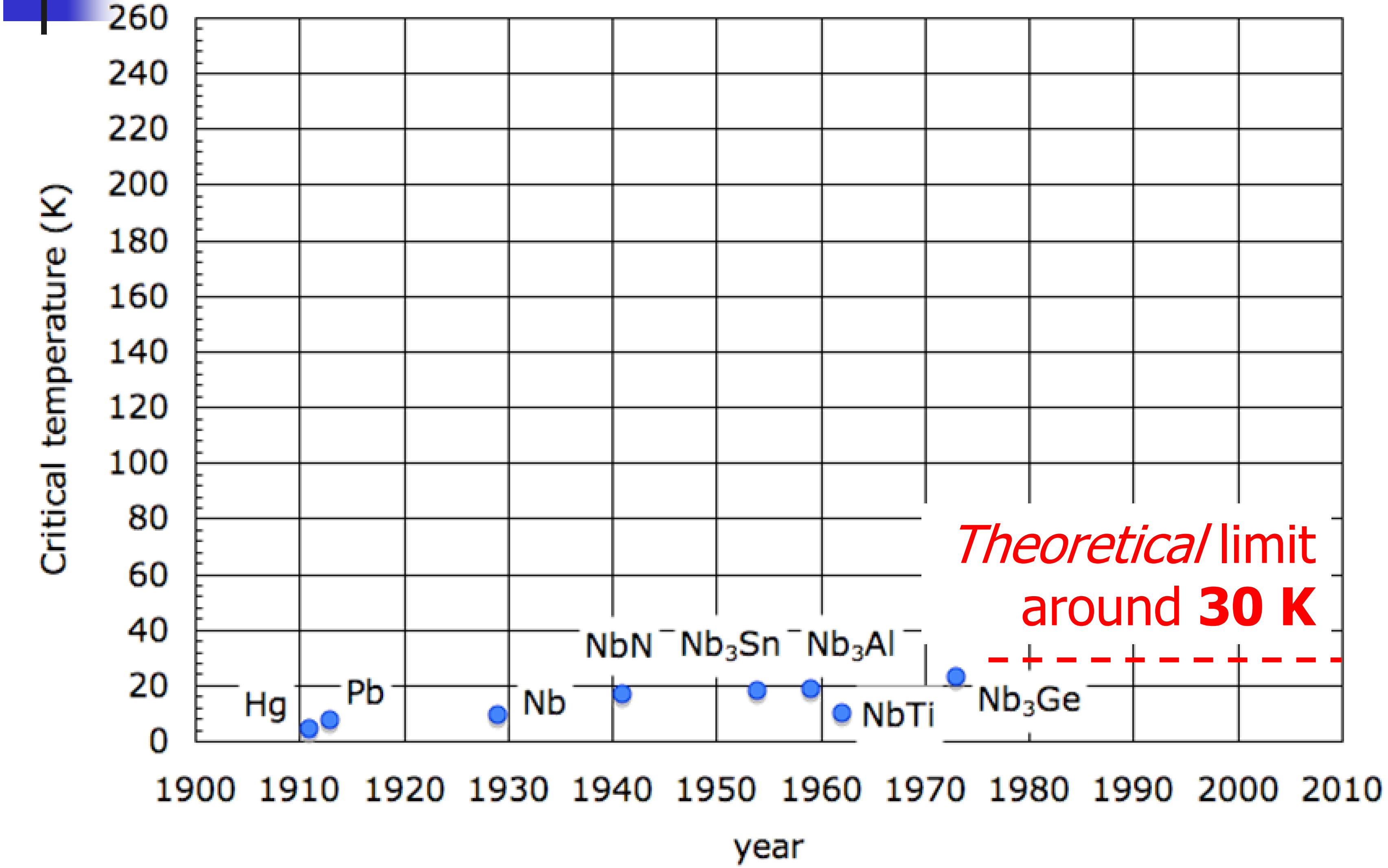
Third International Congress of Refrigeration, Chicago (1913)

Solvay conference (1914)

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

Superconductivity languished for 40 years..

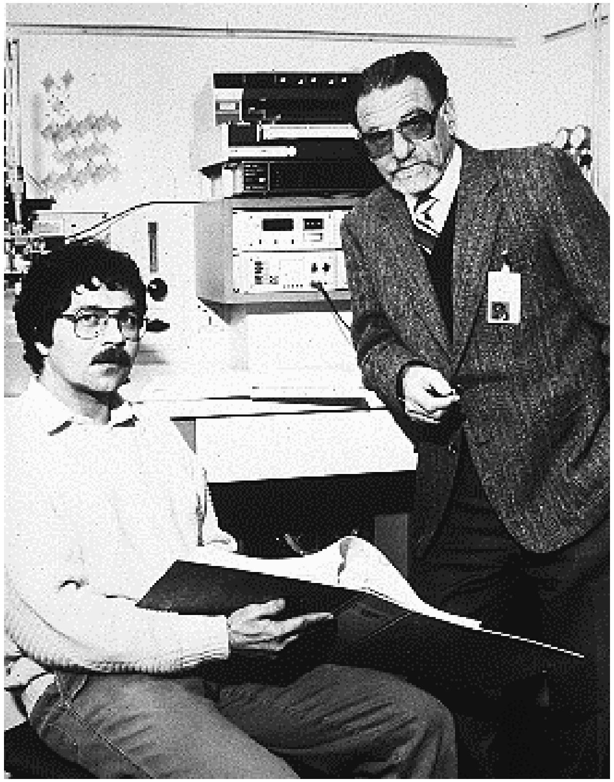
Low-Tc timeline - depressing…



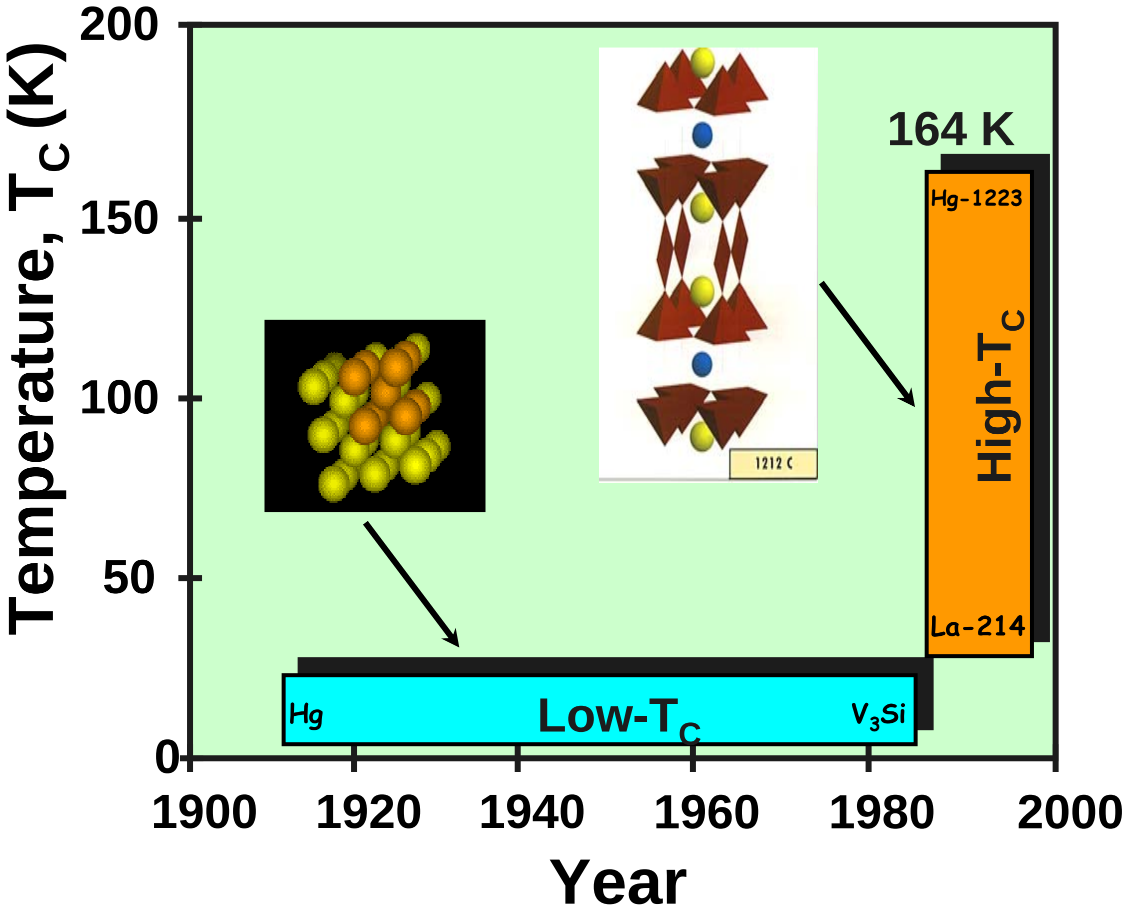
Theoretical limit
around **30 K**

Graphics by courtesy of P. Grant

1986 - A Big Surprise



Bednorz and Mueller
IBM Zuerich, 1986



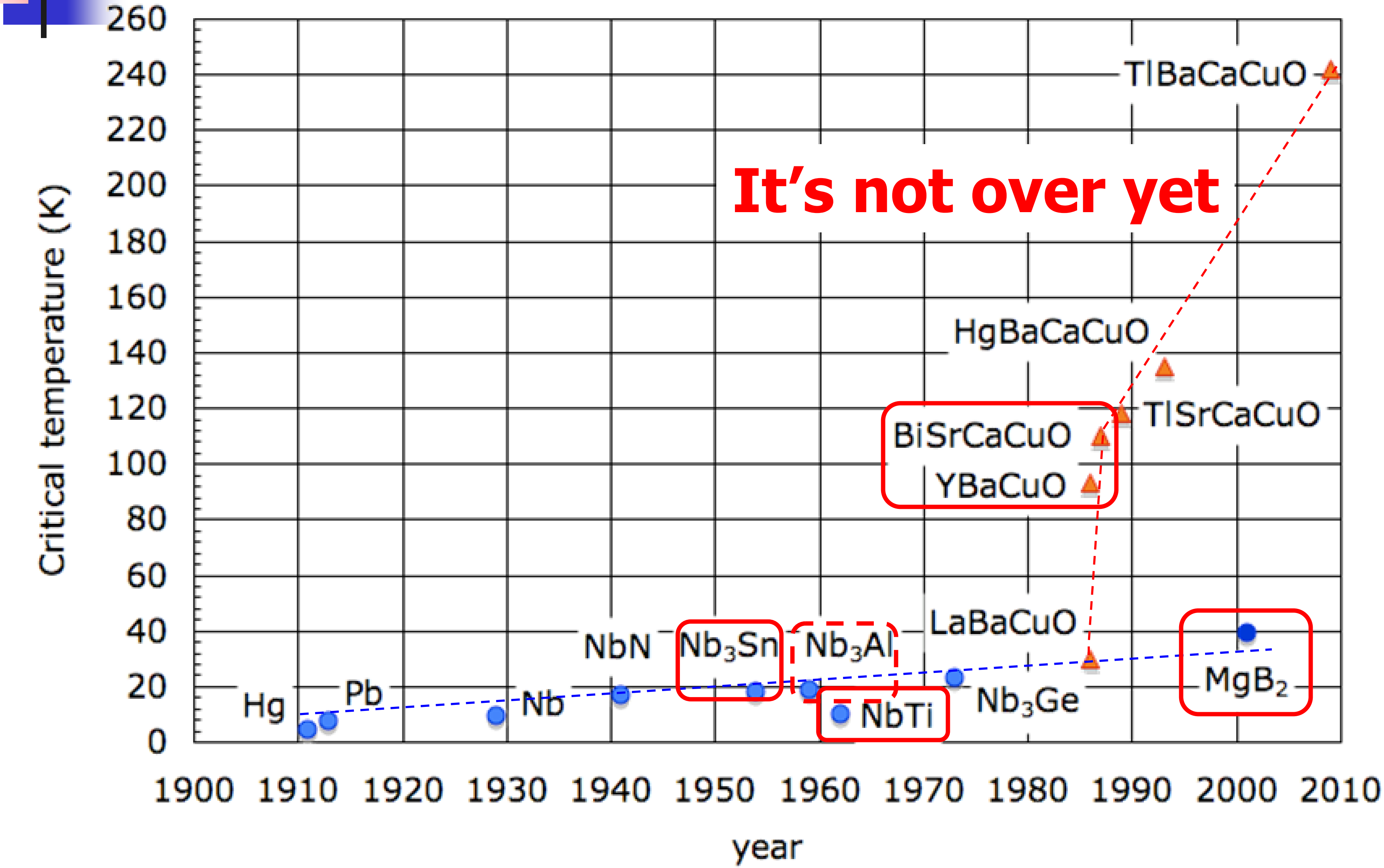
1987 - The prize !

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 !!!

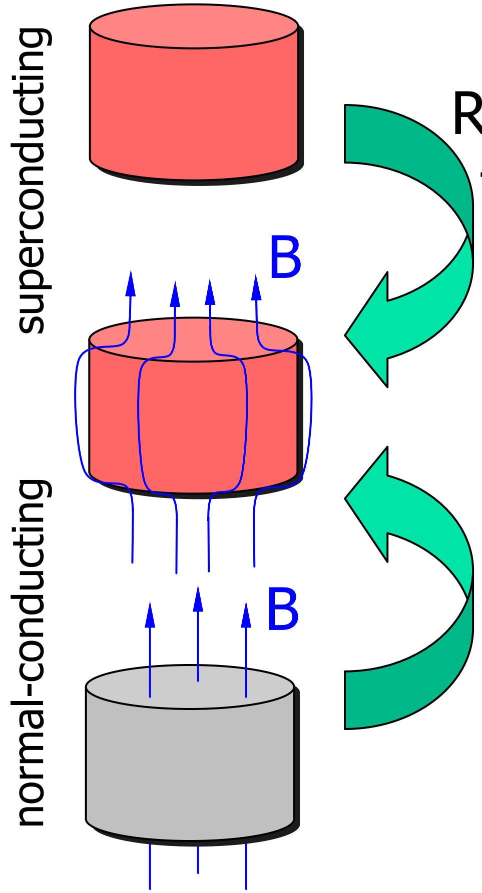


jump

$\kappa=\lambda_L/\xi$

Hey, what about field ?

Landau, Ginzburg and Abrikosov

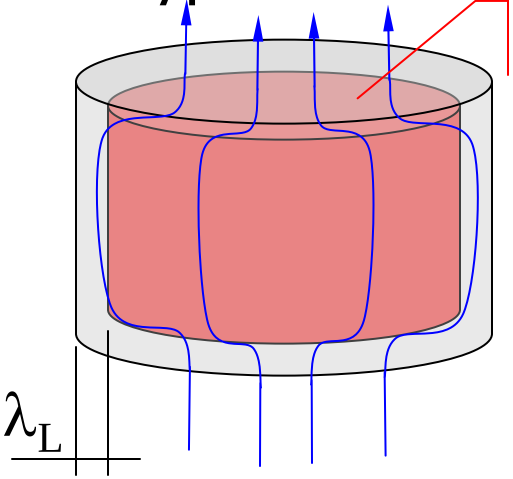


Raise field

Cool down

Meissner & Ochsenfeld, 1933

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

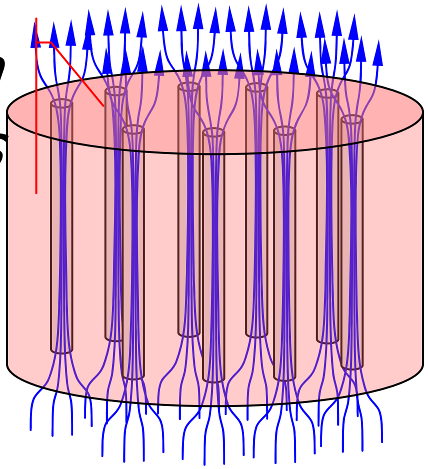


Complete field exclusion

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

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: $G_{sup}(H=0) < G_{normal}$
- The material will reach critical conditions when the energy of the field will equal the jump in free energy:

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

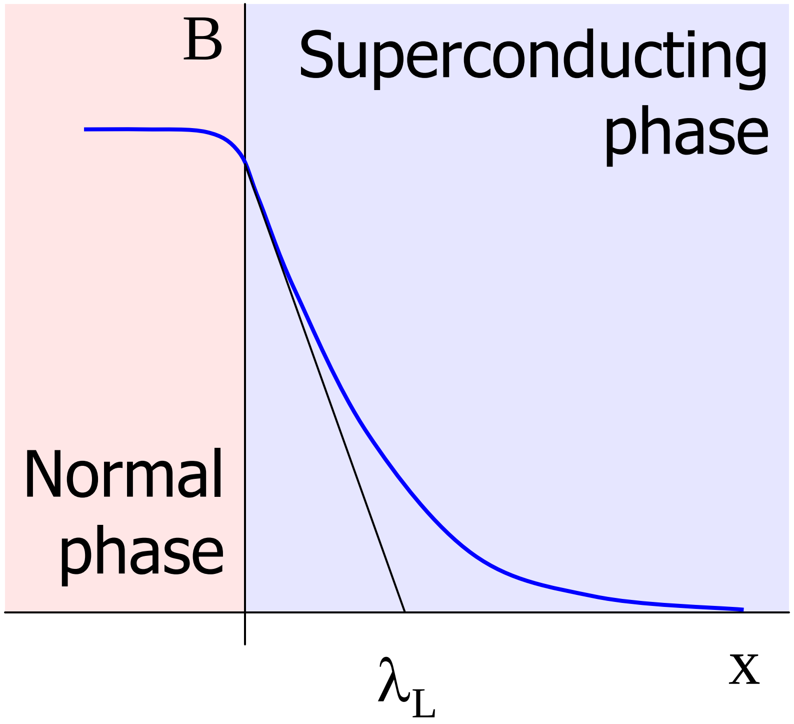
London penetration length λ_L

- Field profile

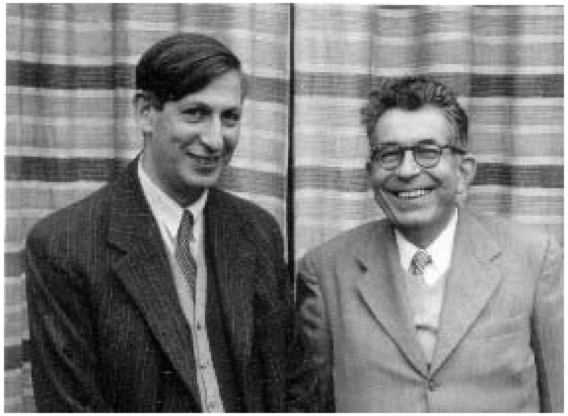
$$B(x) = B_0 \exp\left(-\frac{x}{\lambda_L}\right),$$

- *London* penetration length

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



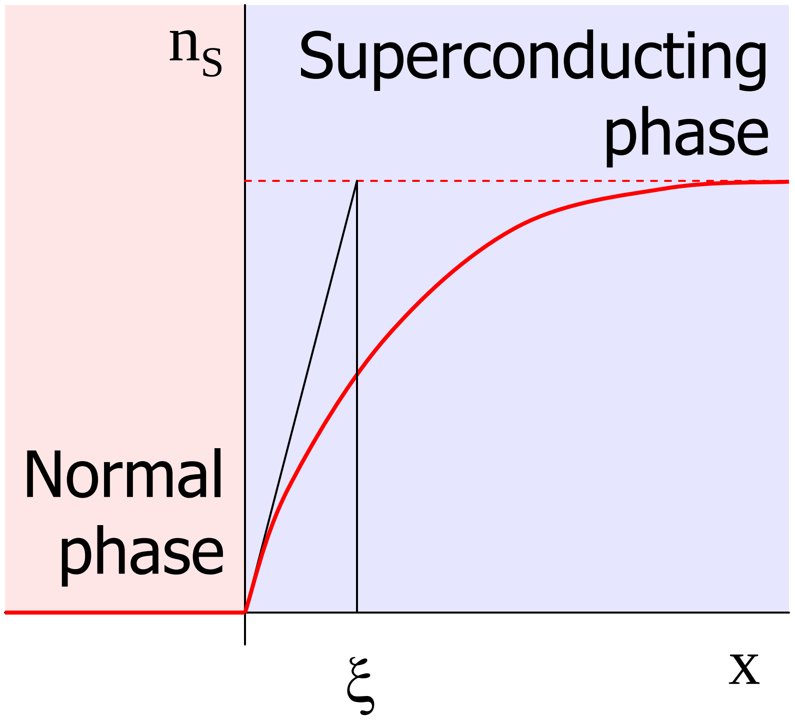
λ_L is of the order of 20 to 100 nm in typical superconducting materials



H. and F. London, 1935

Coherence length ξ

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



Fermi velocity

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

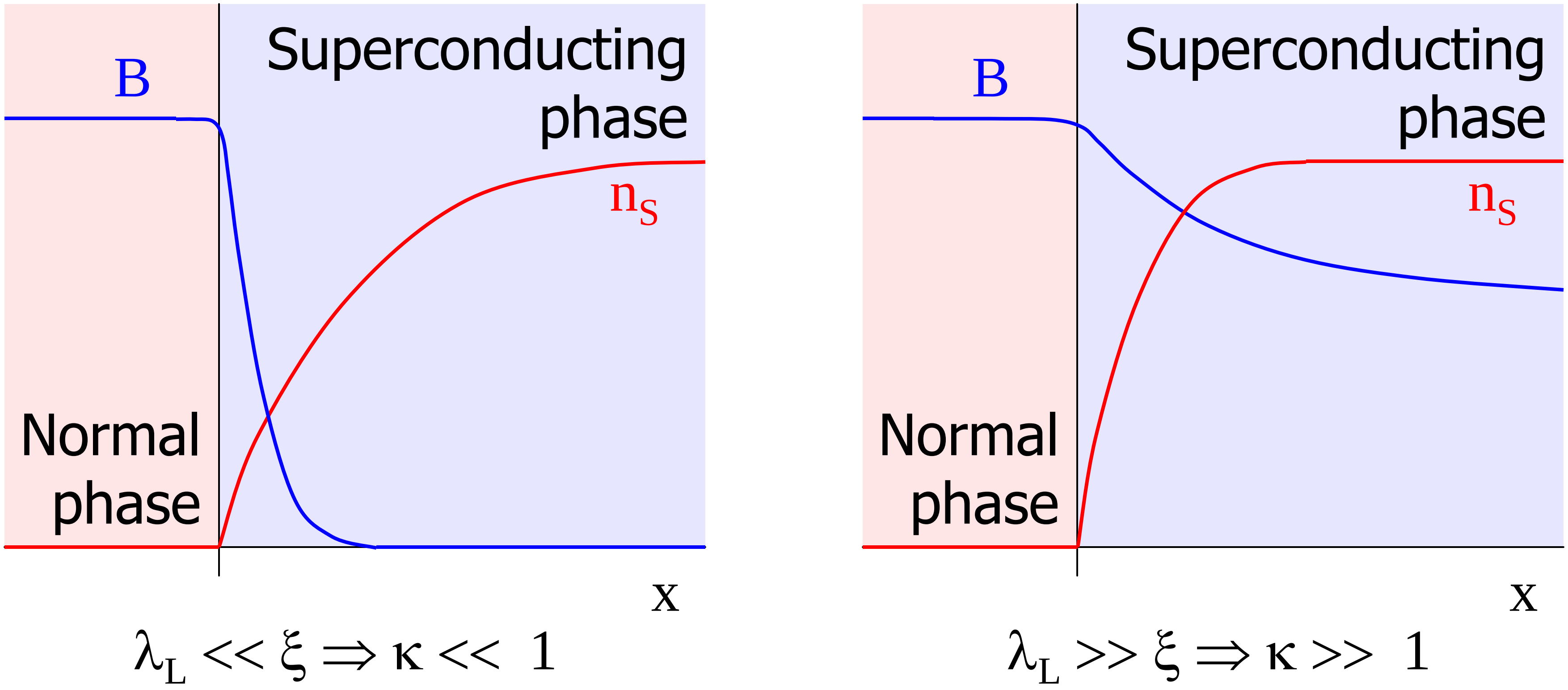
SC energy gap

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 $\kappa = \lambda_L / \xi$



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

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

Ginzburg–Landau, 1950

Values of λ_L , ξ and κ

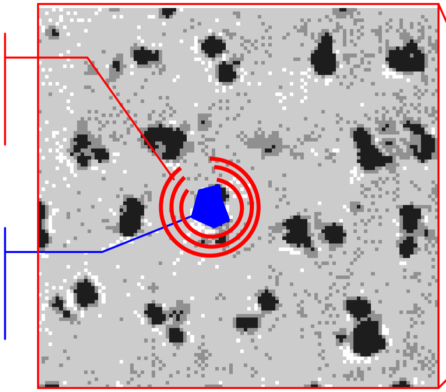
Material	λ_L (nm)	$\xi(B=0)$ (nm)	κ (-)
Al	16	1600	0.01
Pb	32	510	0.06
In	24	360	0.07
Cd	110	760	0.15
Sn	30	170	0.18
Nb	32	39	0.82
Nb_3Sn			≈ 30

Type I

Type II

Graphics by courtesy of Superconductor Lab, Oslo

Lattice of quantum flux lines



Supercurrent

Flux quantum

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

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

Essmann & Träuble, 1967

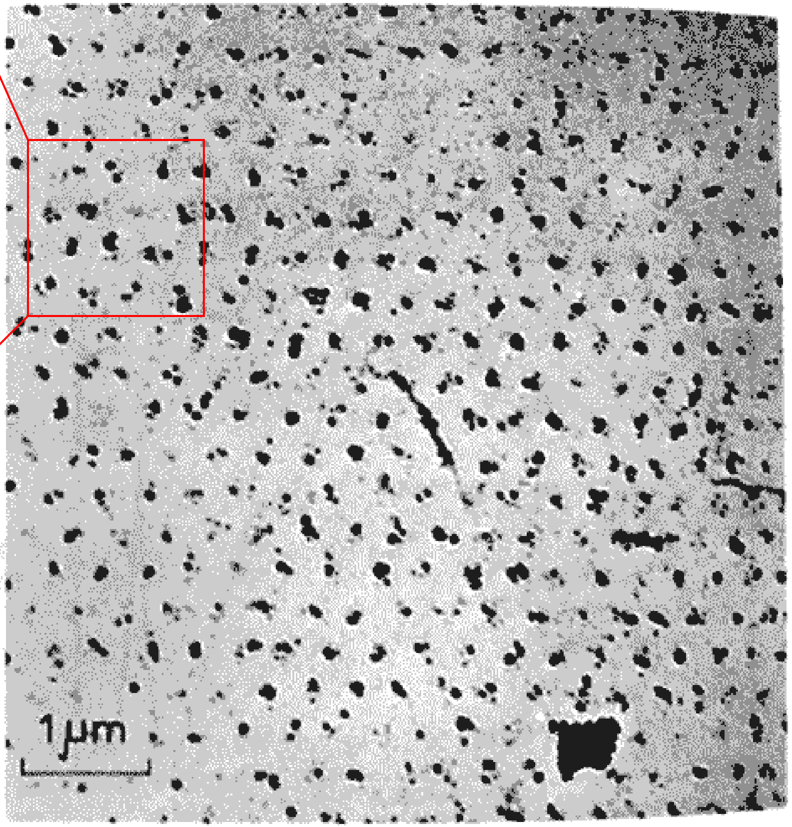
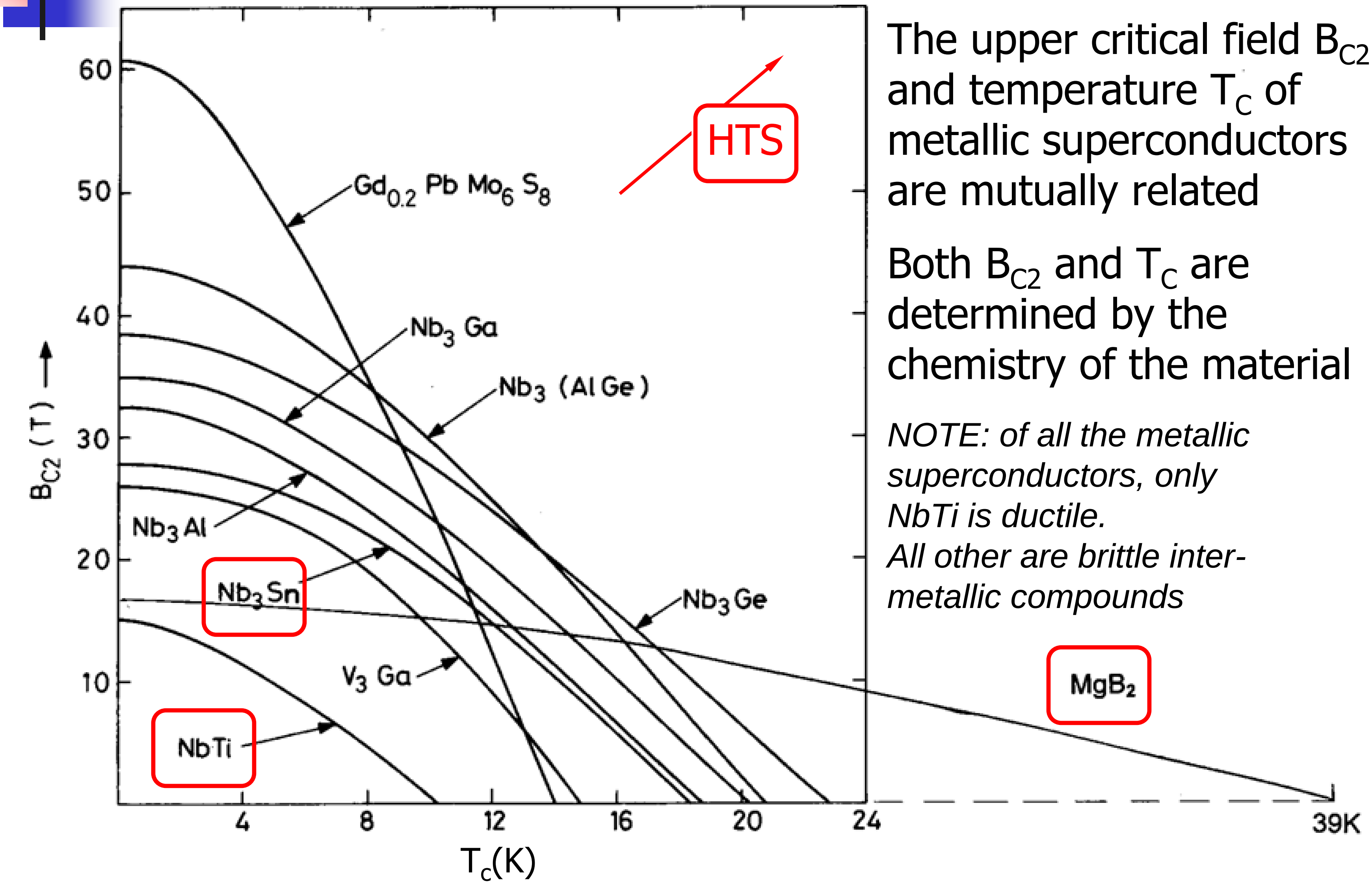


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Graphics by courtesy of M.N. Wilson

Critical temperature and field



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

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

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

Hey, what about current ?

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

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

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

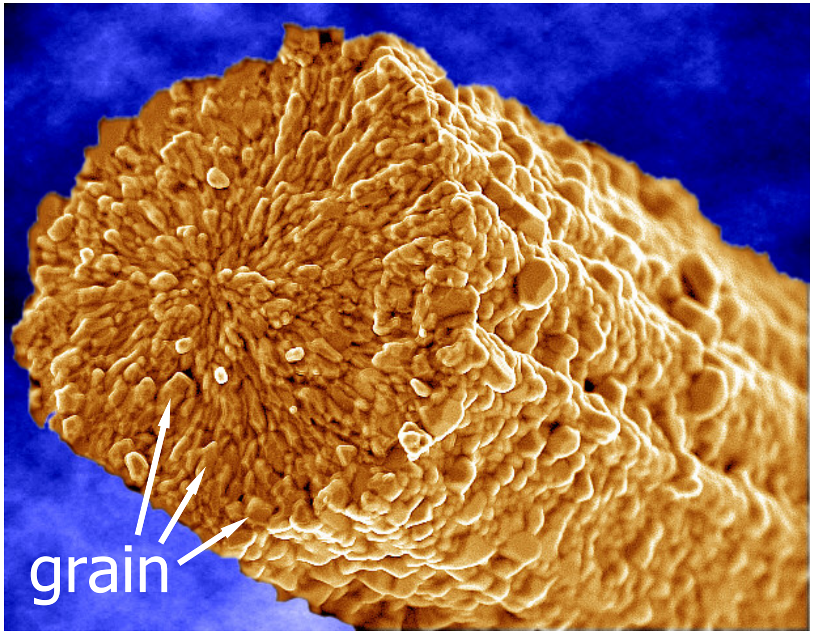
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning mechanisms

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds



Microstructure of Nb_3Sn

Jc(B,T,…)

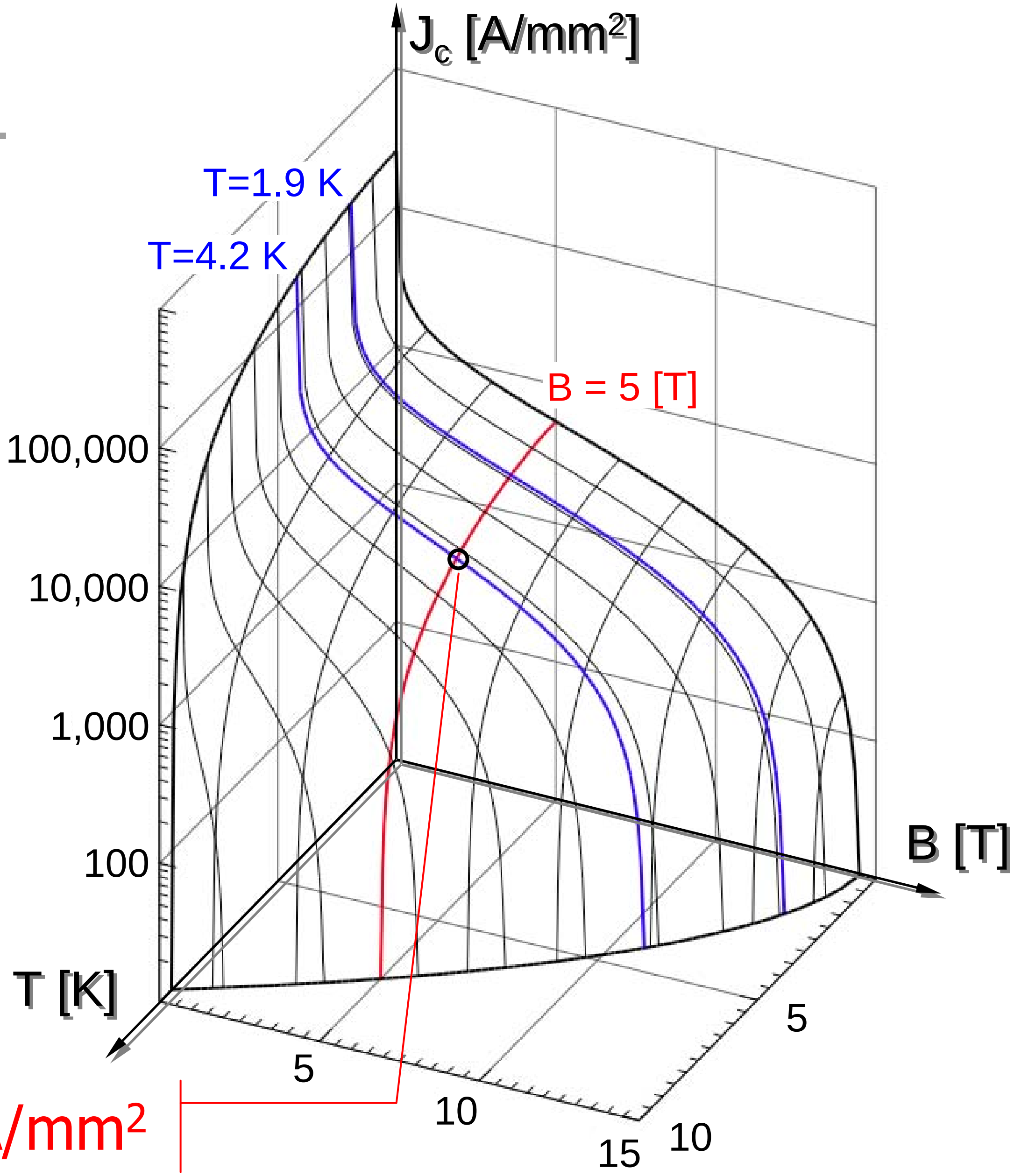
- The maximum current that can be carried by the superconductor is the current at which:

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

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

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

Critical surface of a LHC NbTi wire



Jc (5 T, 4.2 K) ≈ 3000 A/mm²

Superconductors physics - Re-cap

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

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From materials to magnets

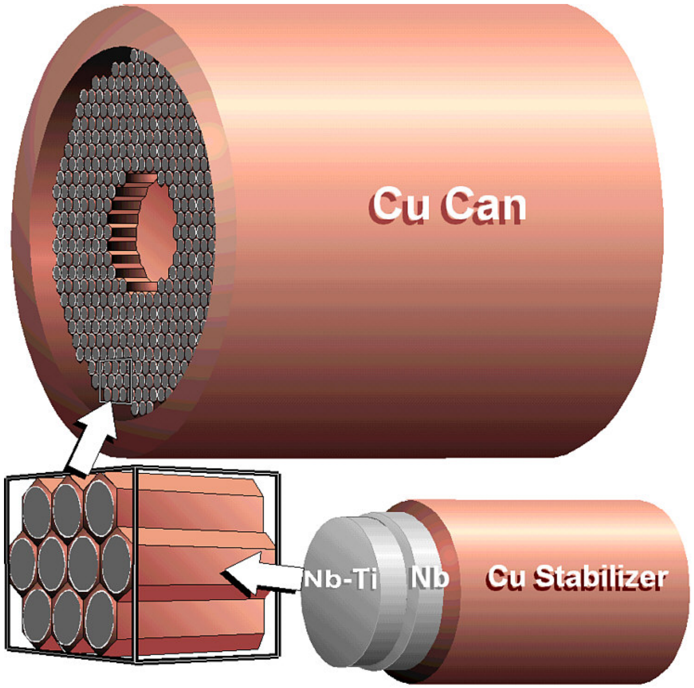
- Materials must be made in high-current wires, tapes and cables(1) for use in magnets
- The manufacturing route depends, among others on:
  - The material (e.g. alloy or chemical compound),
  - The material synthesis (e.g. reaction conditions or a crystal growth method)
  - The material mechanical properties (e.g. ductile or fragile)
  - The compatibility with other materials involved (e.g. precursors or mechanical supports)

(1) See: Stability, quench and protection

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb-Ti manufacturing route

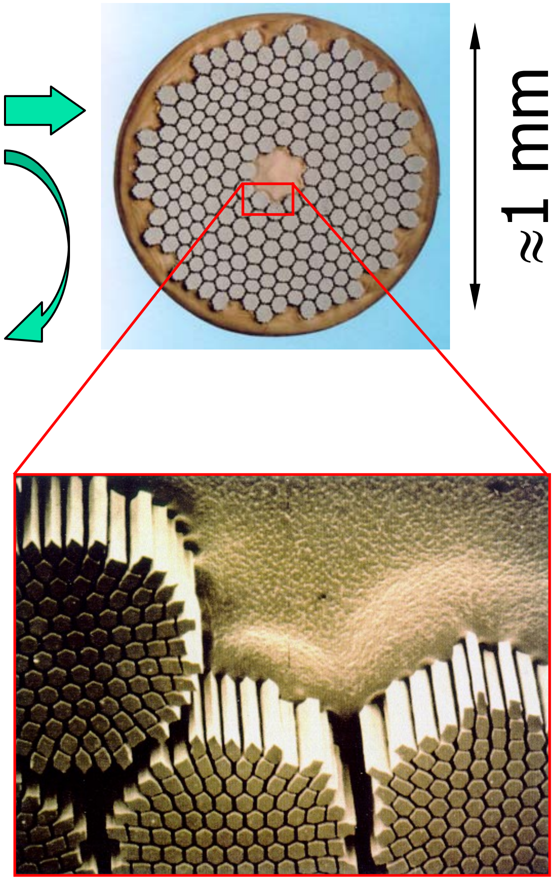
NbTi billet



I_C(5 T, 4.2 K) ≈ 1 kA

extrusion
cold drawing

heat
treatments



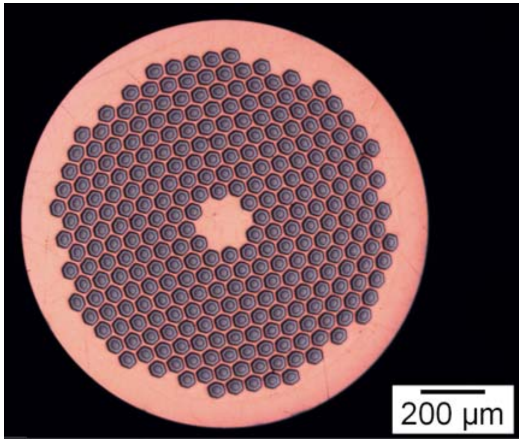
LHC wire

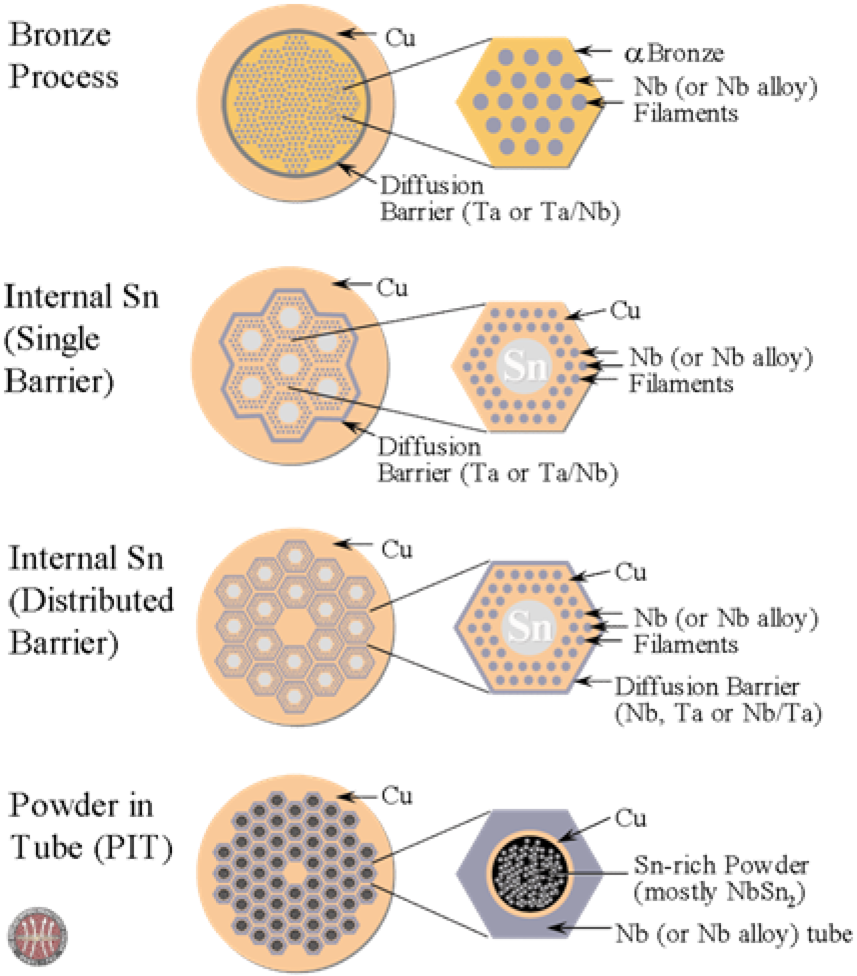
NbTi is a ductile alloy that can sustain large deformations

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 the wire is heat-treated at about 650 C for several hours, to form the Nb_3Sn phase





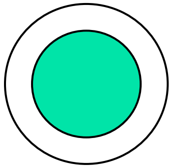
$I_C(12\ T, 4.2\ K) \approx 1.5\ kA$

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

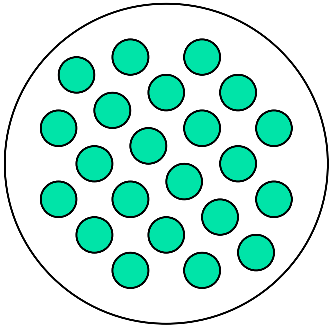
BSCCO manufacturing routes

Oxide powder in tube OPIT

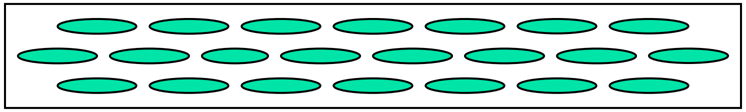
1) draw down BSCCO powder in a silver tube



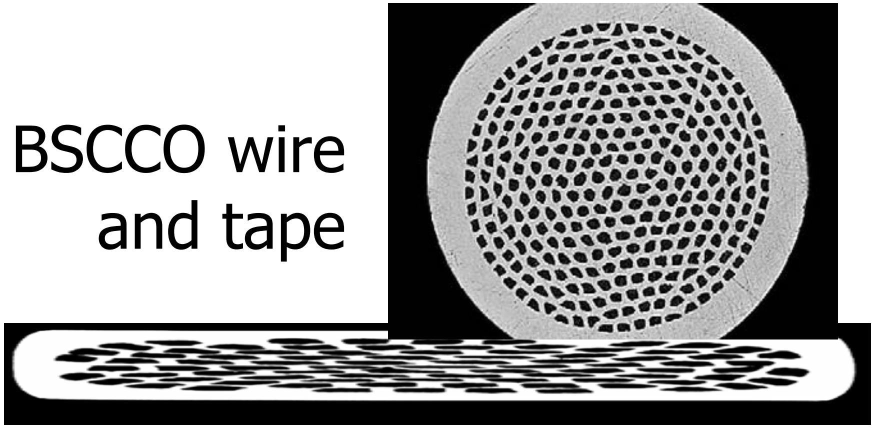
2) stack many drawn wires in another silver tube and draw down again



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

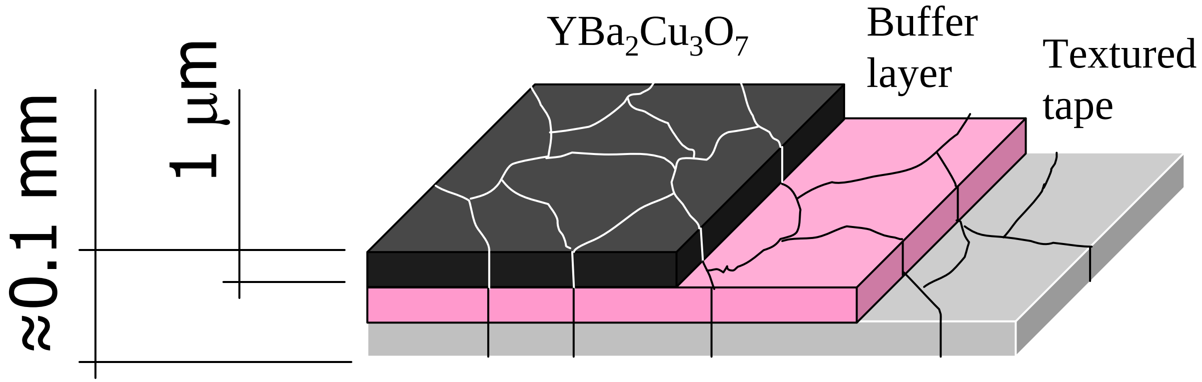


BSCCO wire and tape

YBCO tape

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



Engineering current density

- All wires, tapes and cables 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*:

$$J_E = J_C \times \lambda$$

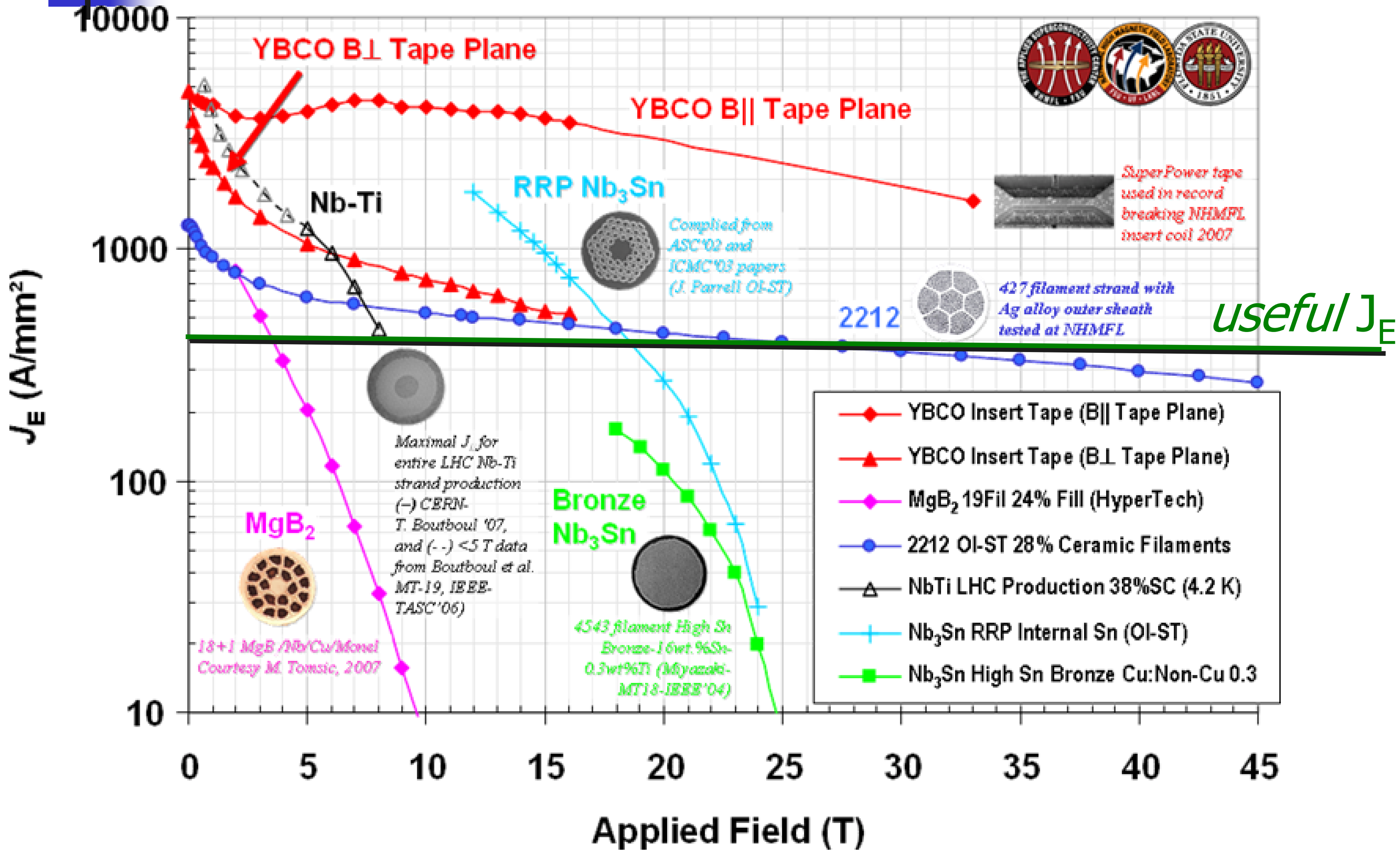
---

(1) See: Magnetization and AC loss

(2) See: Stability, quench and protection

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Best of Superconductors J_E



SuperPower tape used in record breaking NHMFL insert coil 2007

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

427 filament strand with Ag alloy outer sheath tested at NHMFL

Maximal J_c 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)

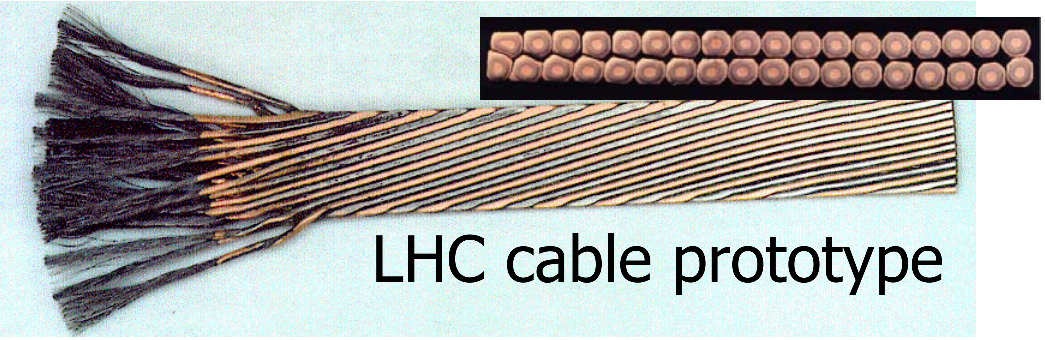
jump

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

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

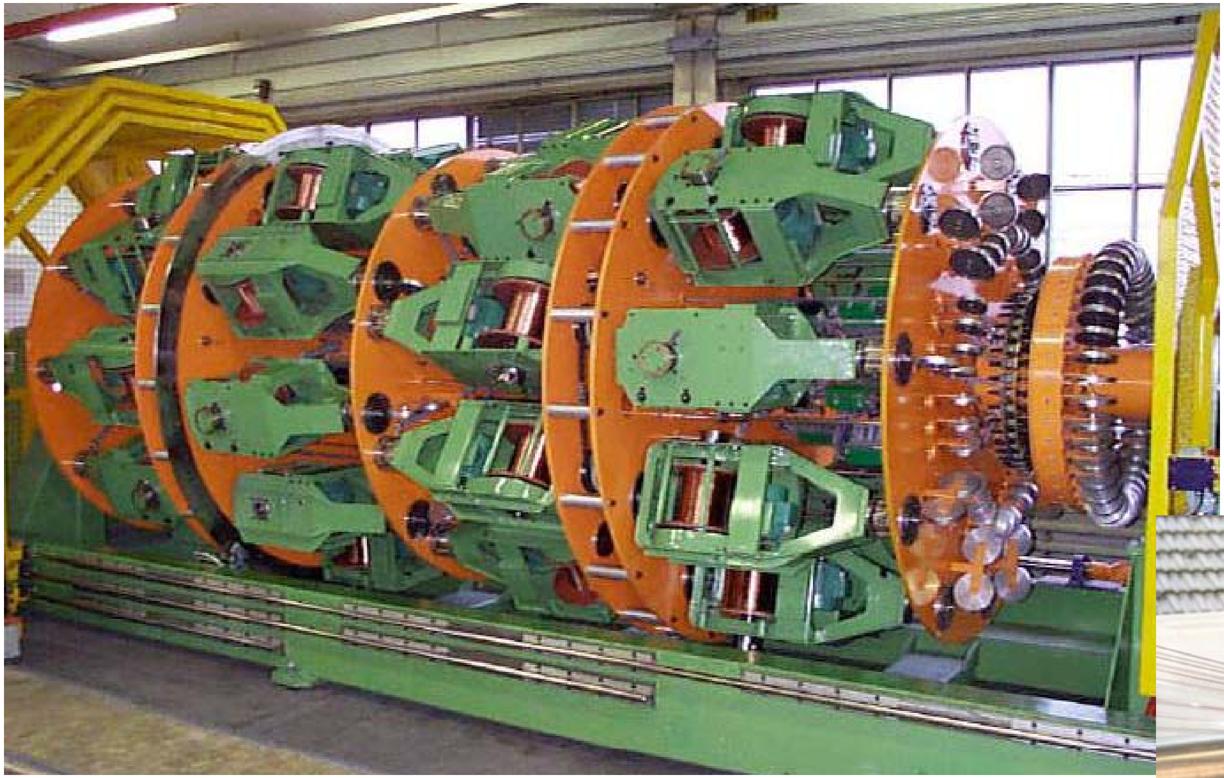
- Large size magnets (e.g. LHC dipoles) need large operating currents (10 to 100 kA) to:
  - Decrease inductance,
  - Lower the operating voltage,
  - Ease magnet protection(1)
- Rutherford cables are ideally suited for this task



LHC cable prototype

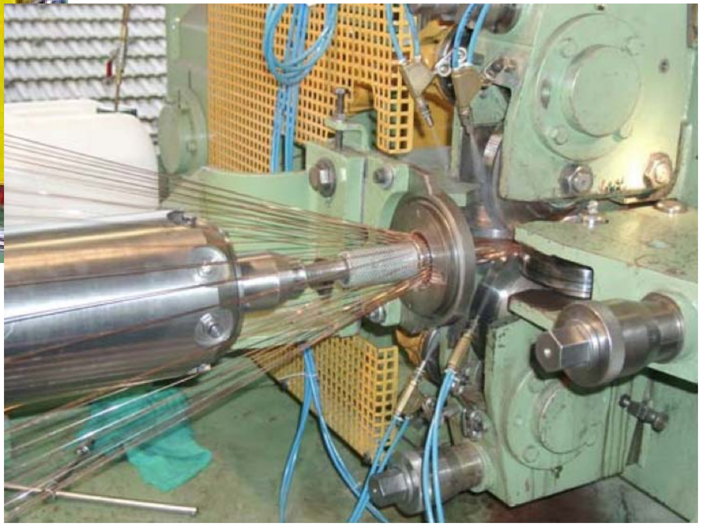
(1) See: Stability, quench and protection

Rutherford cable machine @ CERN



Strand spools on rotating tables

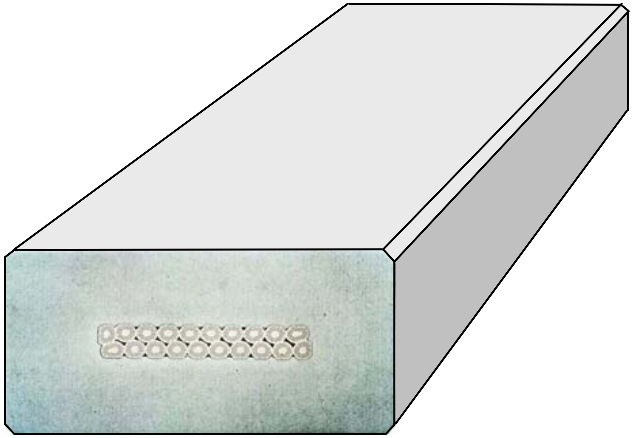
Strands fed through a cabling tongue to shaping rollers



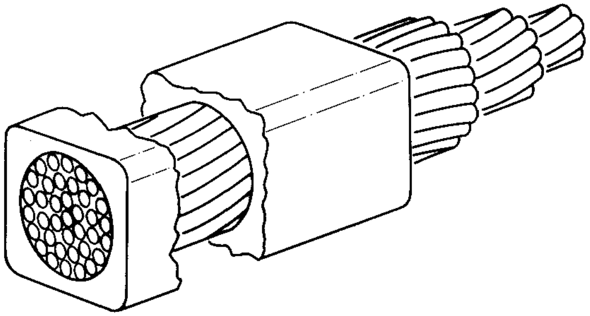
$J_E \approx 50\ \mathrm{A/mm^2}$

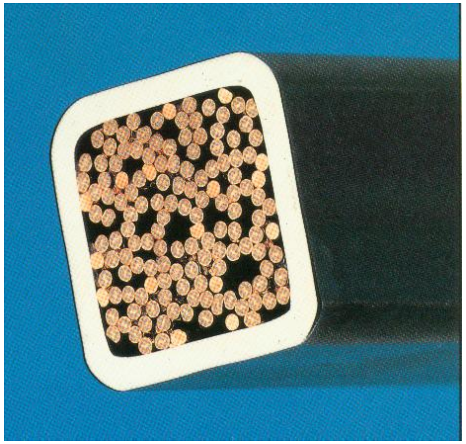
Practical conductors: low J_E

- Super-stabilized conductor, a superconducting cable (e.g. Rutherford) backed by a large amount of good normal conductor (e.g. Al)



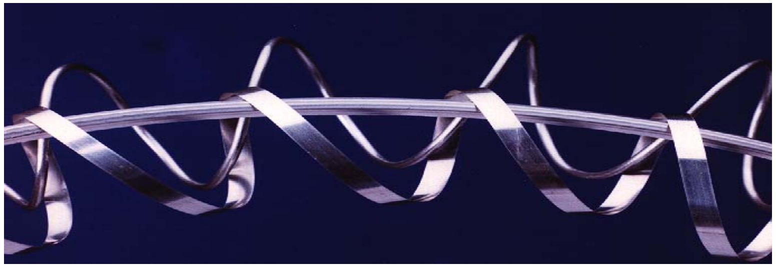
- Internally-cooled conductor, e.g. Cable-In-Conduit Conductor (CICC), a rope of wires inserted in a robust conduit that provides a channel for cooling



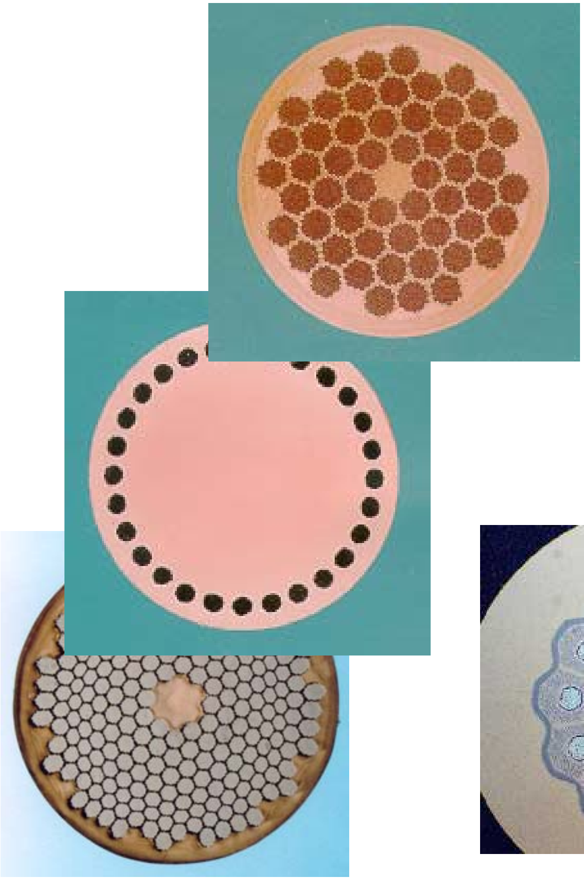


Superconducting wires and tapes for all taste…

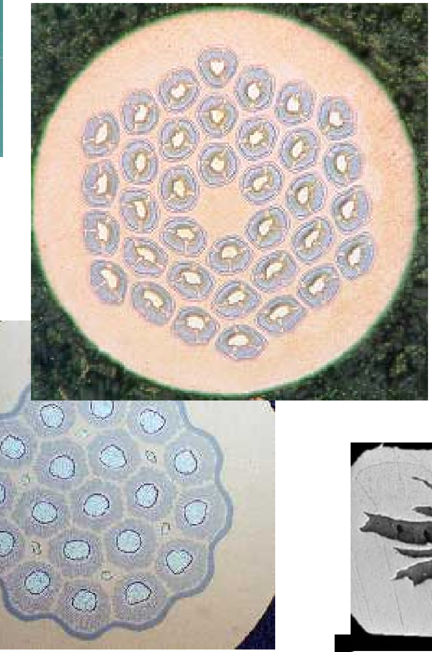
YBCO



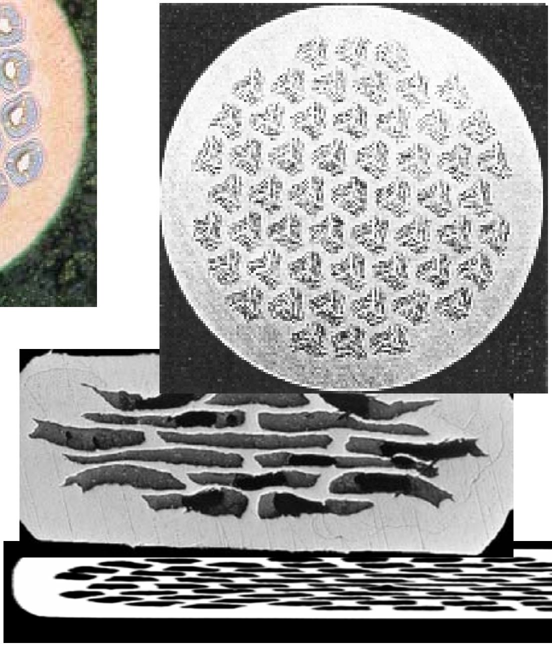
NbTi



Nb_3Sn, Nb_3Al



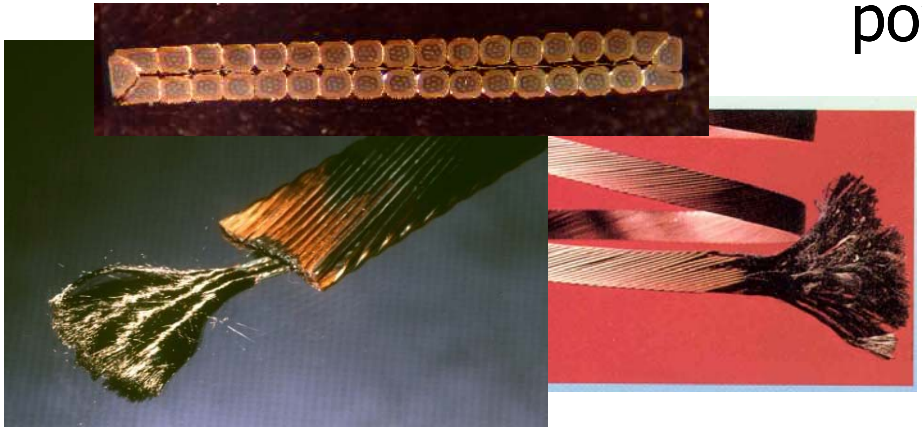
BSCCO



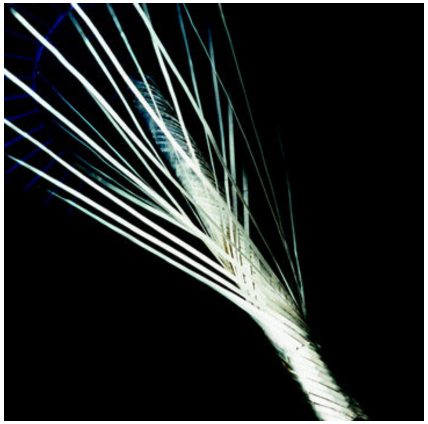
MgB_2

… and superconducting cables

Rutherford

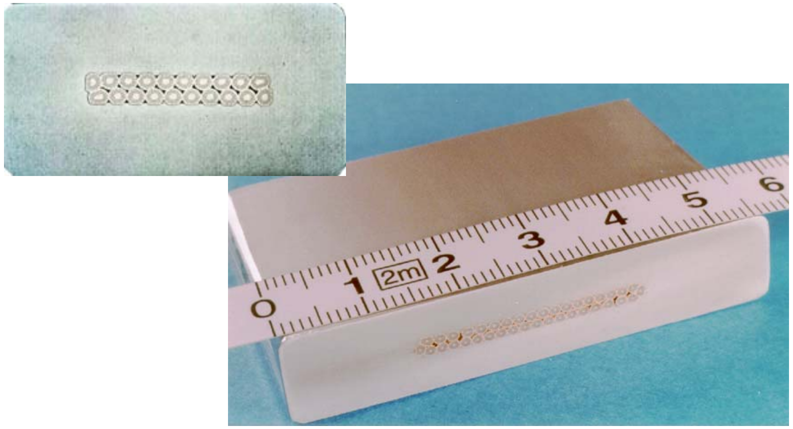


Braids for
power transmission



CICC

Super-stabilized



Internally cooled

Overview

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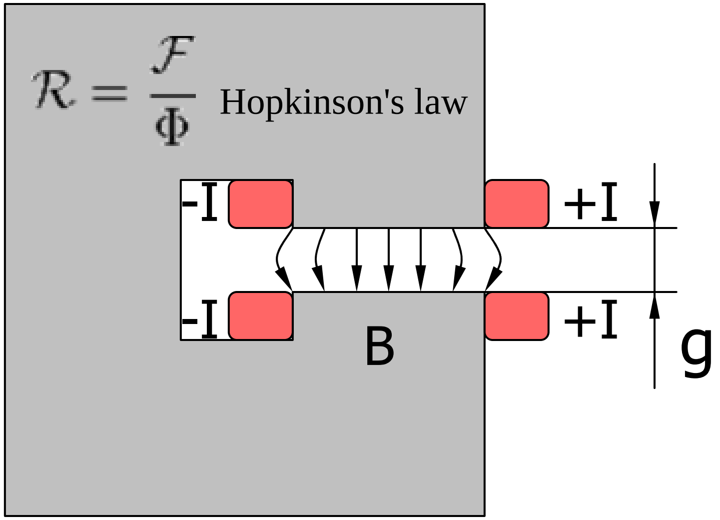
Magnetic design

- NC: magneto motive force, reluctance and pole shapes



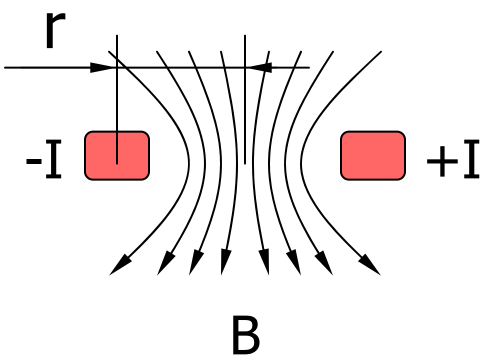
$$\mathcal{R} = \frac{\mathcal{F}}{\Phi}$$ Hopkinson's law

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

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

- SC: Biot-Savart law and coil shapes

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

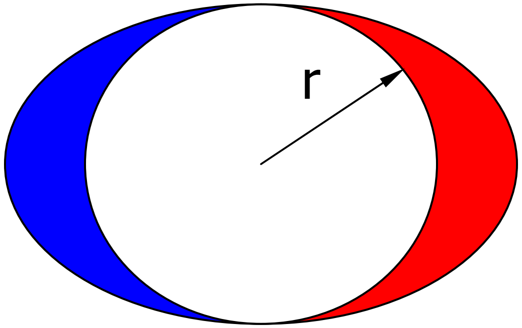


$$B \approx \mu_0 NI / \pi r$$

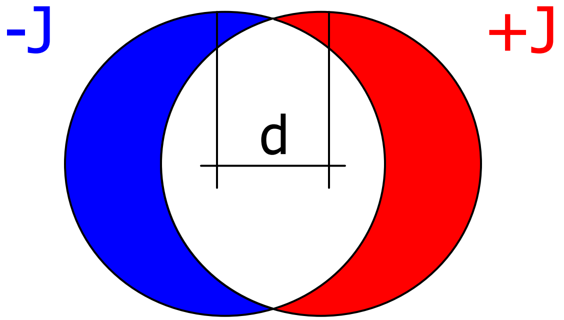
r =45 mm
NI =1 MAturn
B =8.84 T

Design of an ideal dipole magnet

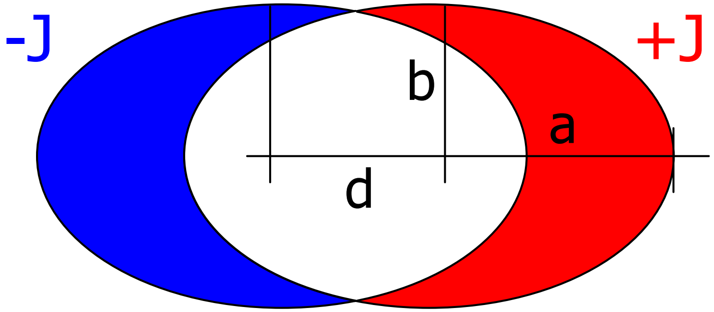
$I=I_0 \cos(\theta)$ ⇨ $B_1=-\mu_0 I_0/2\,r$



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



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

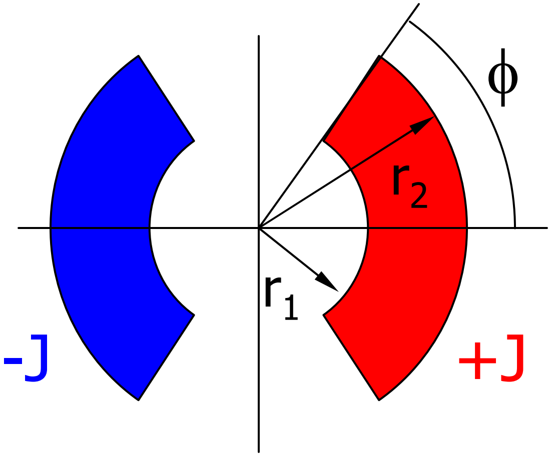


Several solutions are possible and can be extended to higher order multi-pole magnets

None of them is practical !

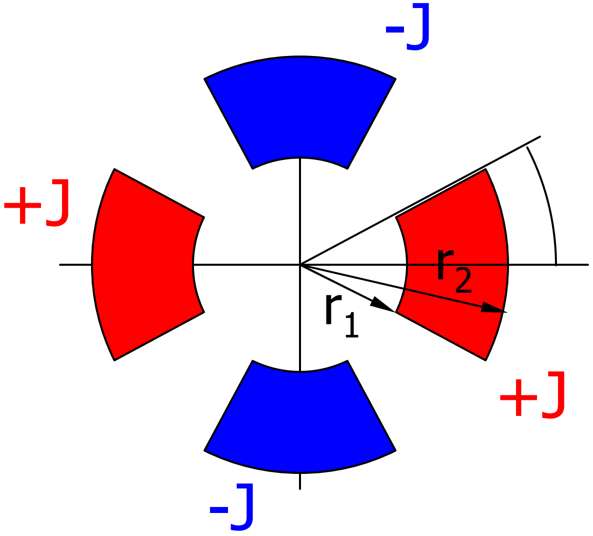
Magnetic design - sector coils

- Dipole coil



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

- Quadrupole coil



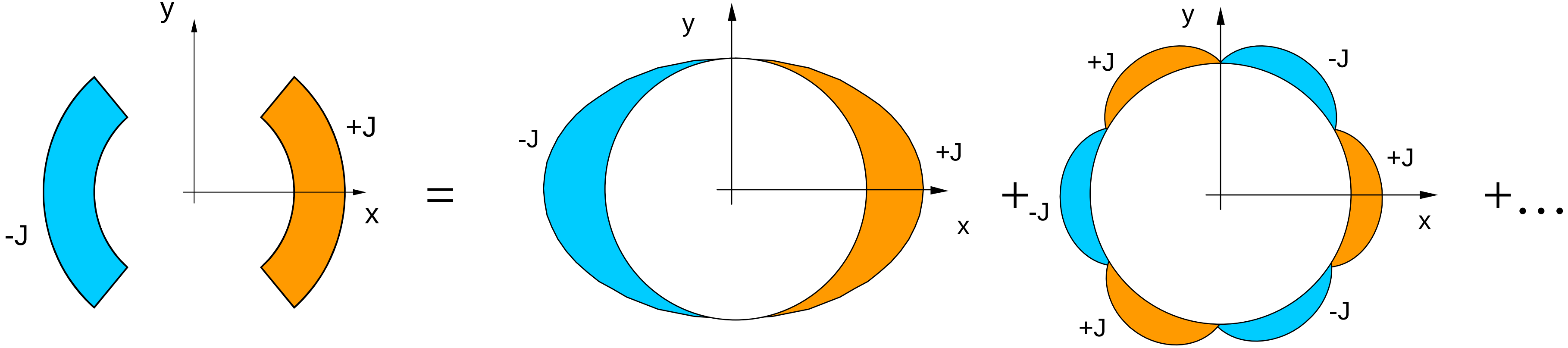
$B_2 = -2\mu_0/\pi \ J \ \ln(r_2/r_1) \ \sin(2\phi)$

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:

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

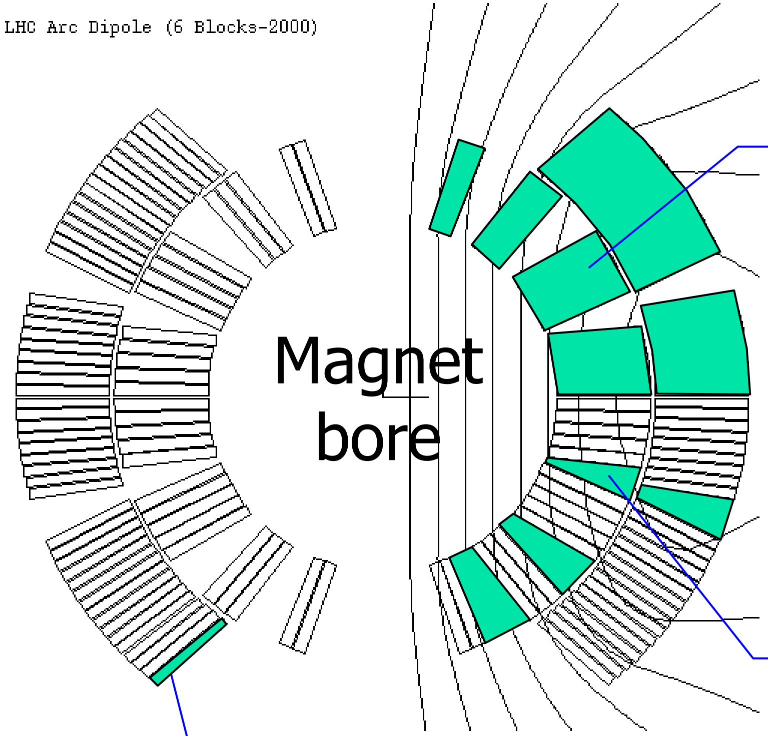


$$\mathbf{B} = B_1 + B_3 + \dots$$

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

jump

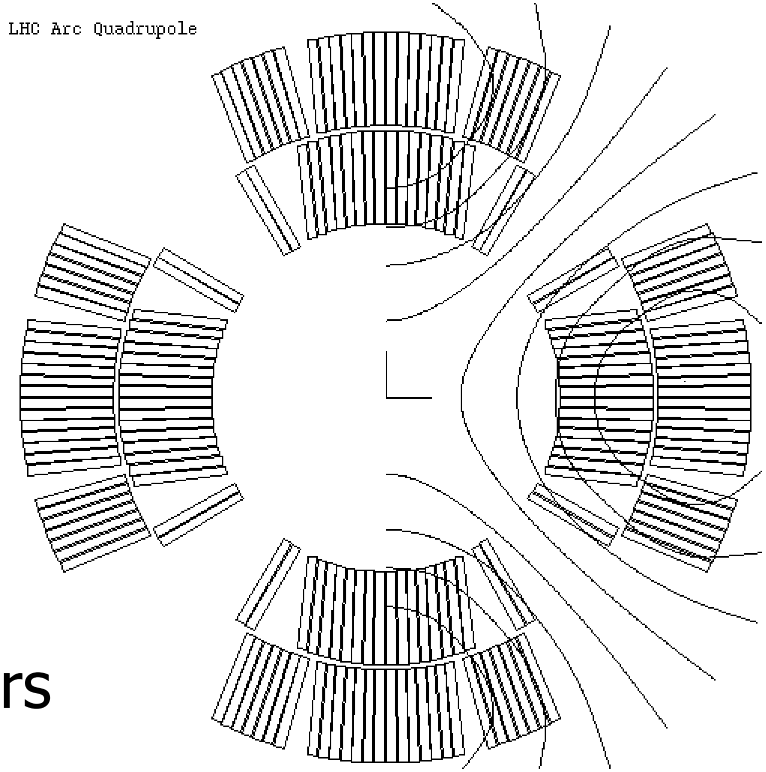
Technical coil windings



Coil blocks

Magnet bore

Spacers



Superconducting cable

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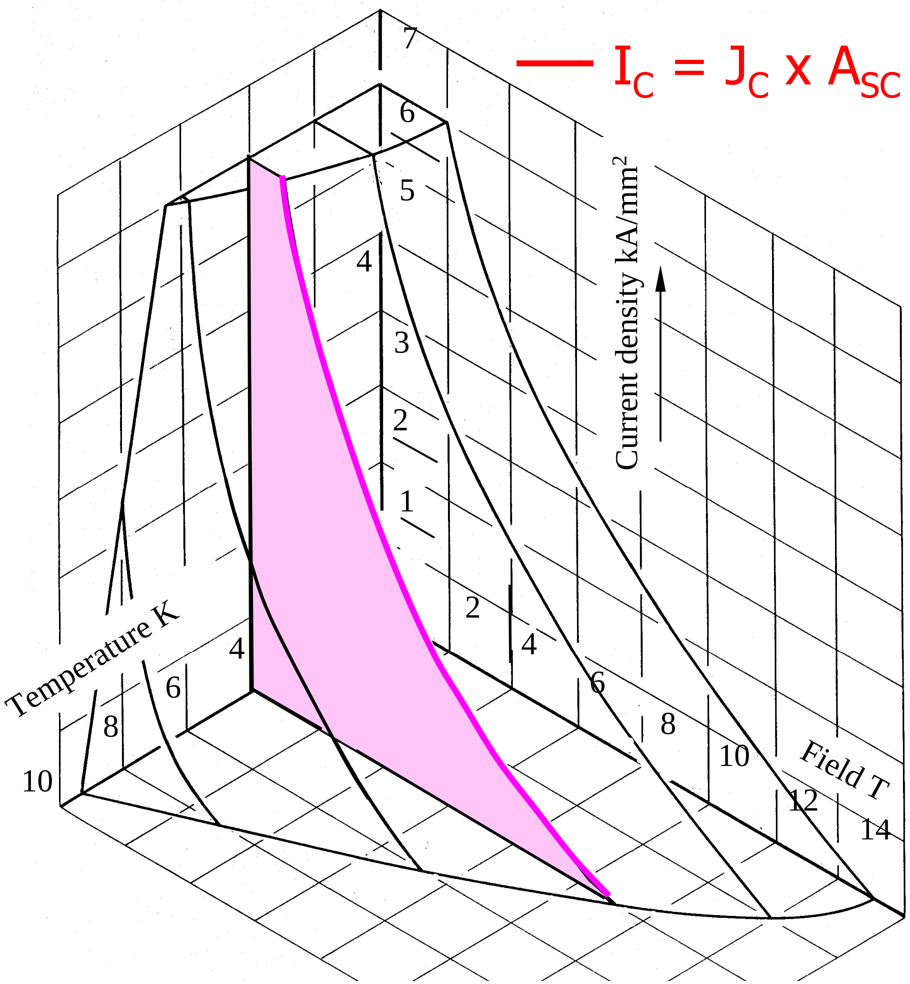
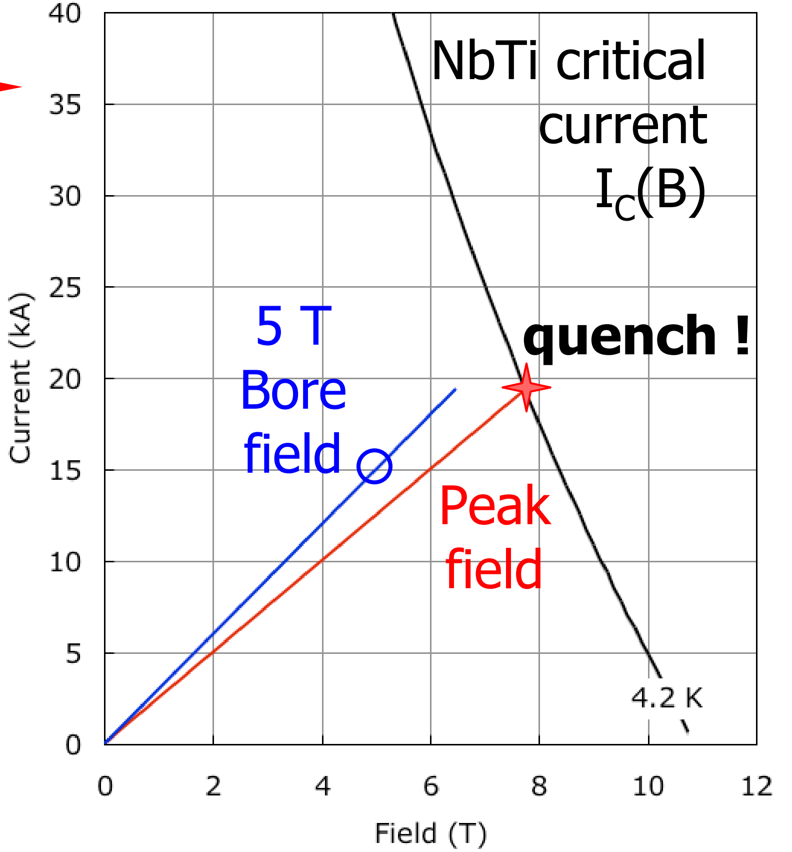
Critical line and magnet load lines

NbTi critical surface



$I_C = J_C \times A_{SC}$

e.g. a 5 T magnet design

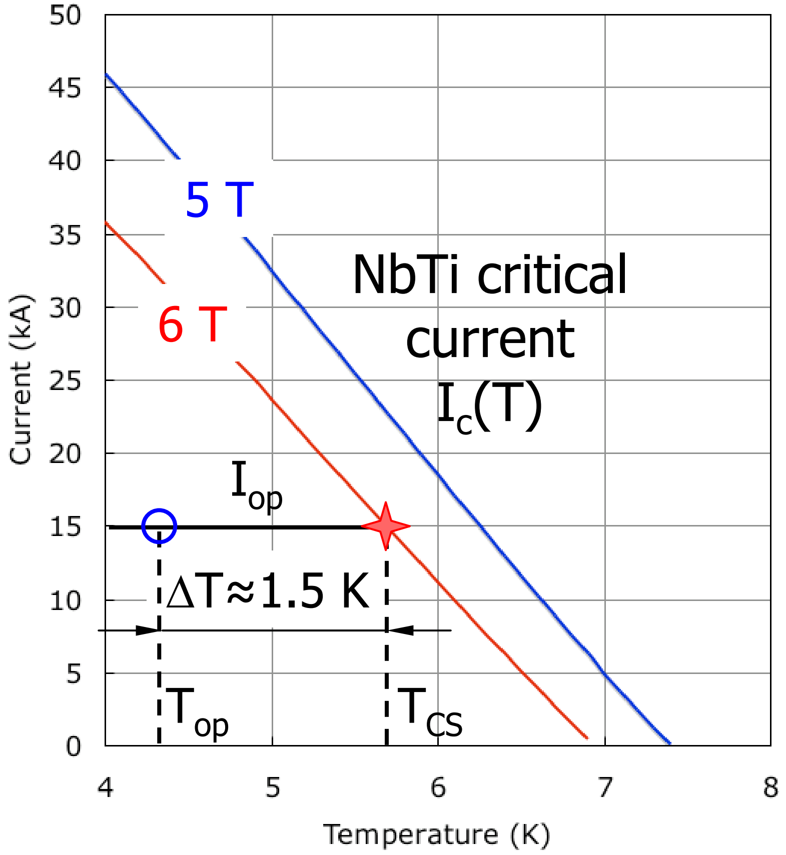


we expect the magnet to go resistive i.e. to **'quench',** where the peak field load line crosses the critical current line

Temperature margin

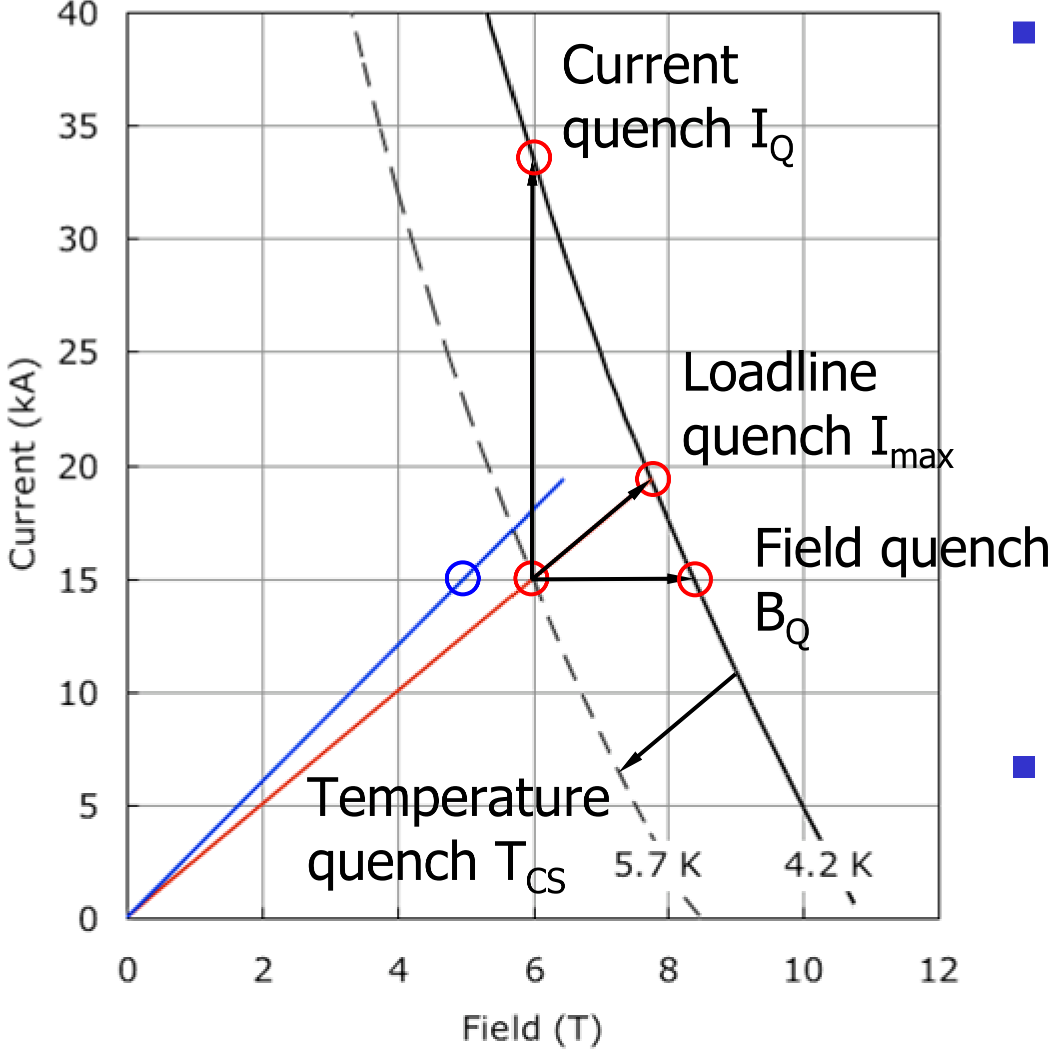
- Temperature rise may be caused by
  - sudden mechanical energy release
  - AC losses
  - Resistive heat at joints
  - Beams, neutrons, etc.
- We should allow *temperature headroom* for all foreseeable and unforeseeable events(1), i.e. a temperature margin:

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



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

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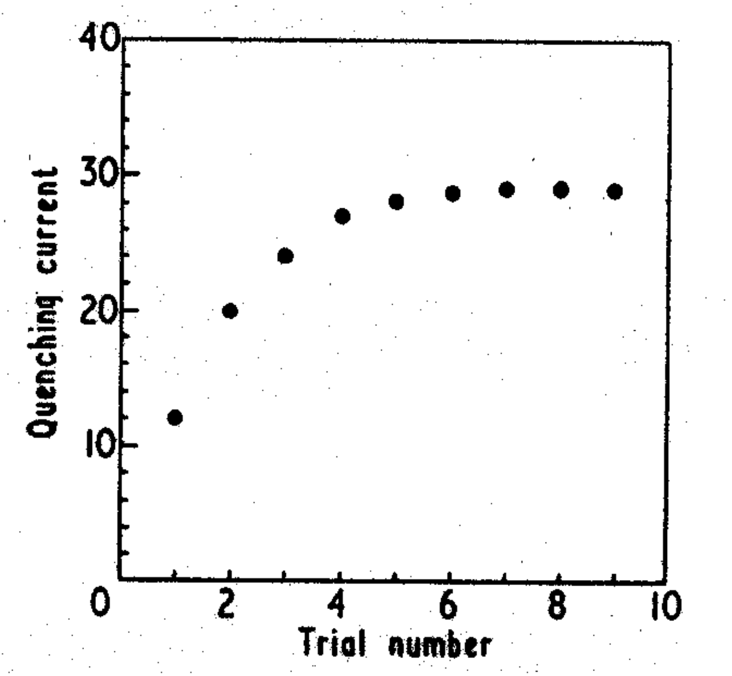
Training…

- Superconducting solenoids built from NbZr and Nb_3Sn in the early 60’s quenched much below the rated current …

- … the quench current increased gradually quench after quench: training

NbZr solenoid
Chester, 1967



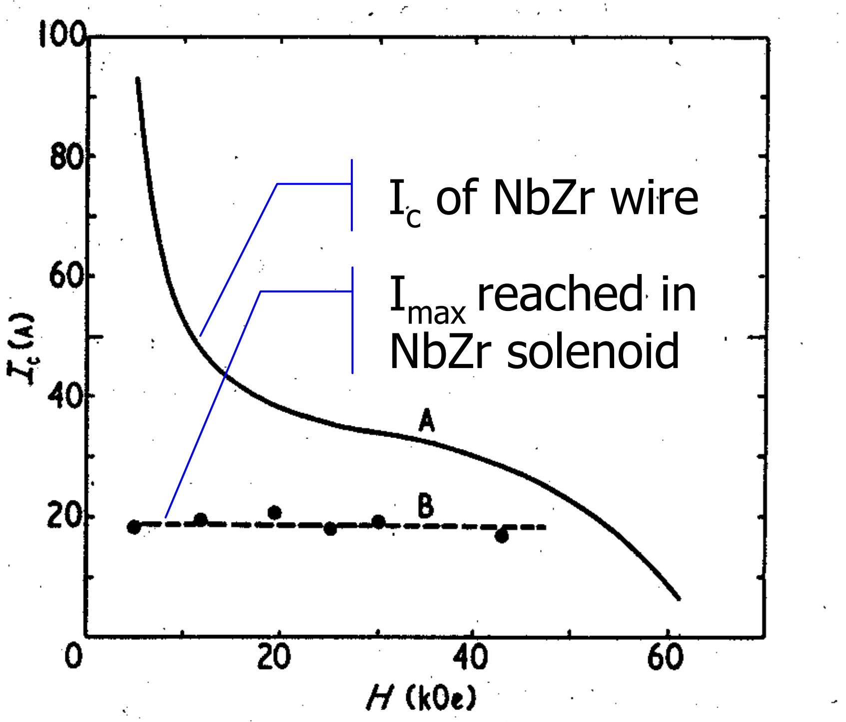
M.A.R. LeBlanc, Phys. Rev., **124**, 1423, 1961.

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 !

NbZr solenoid vs. wire
Chester, 1967

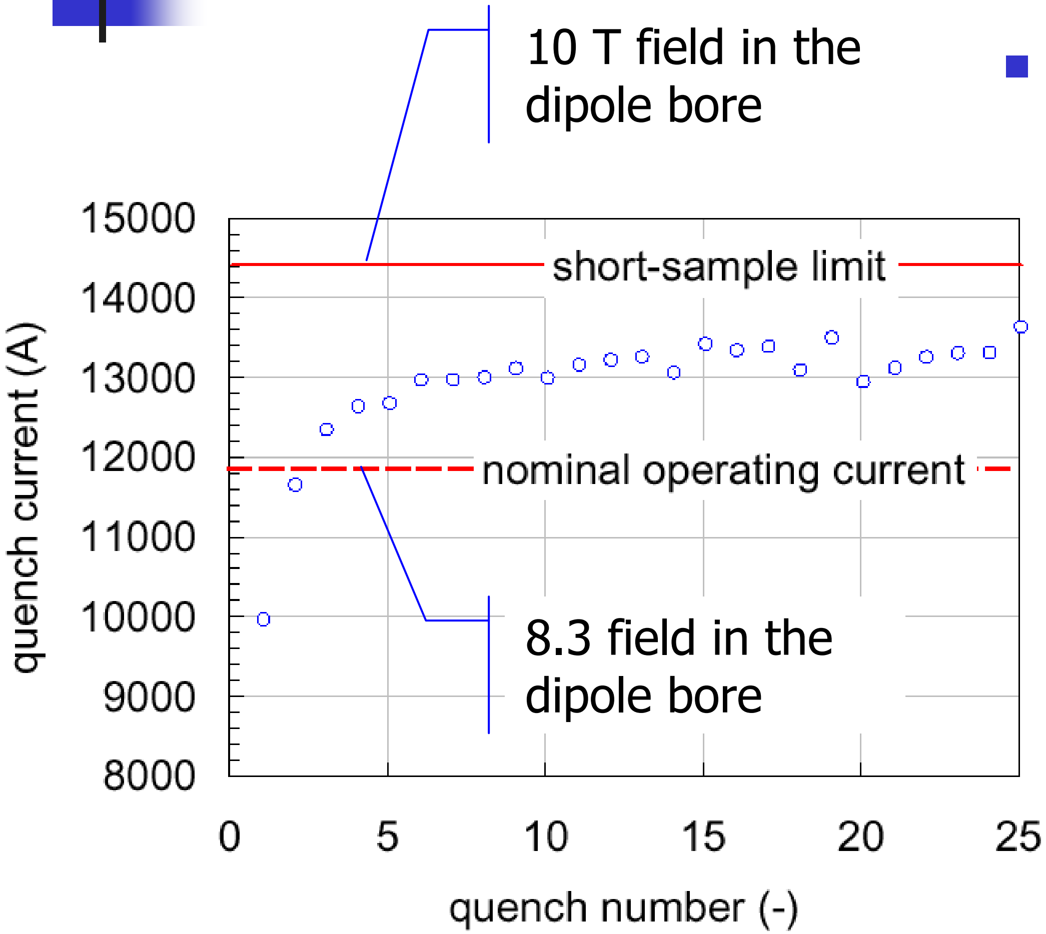


I_c of NbZr wire

I_{max} reached in NbZr solenoid

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

Training today



Courtesy of A. Siemko, CERN, 2002

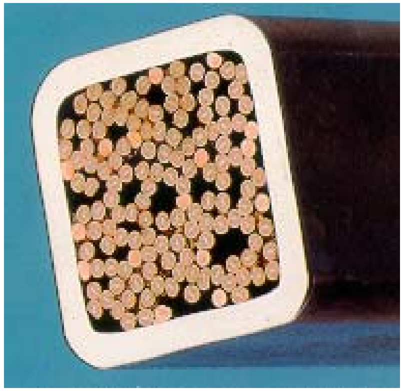
- training of an LHC short dipole model at superfluid helium
  - still (limited) training may be necessary to reach nominal operating current
  - short sample limit is not reached, even after a long training sequence

stability is (still) important !

Stability and quench: a heat balance

perturbation

Joule heating



superconducting cable

heat capacity

conduction

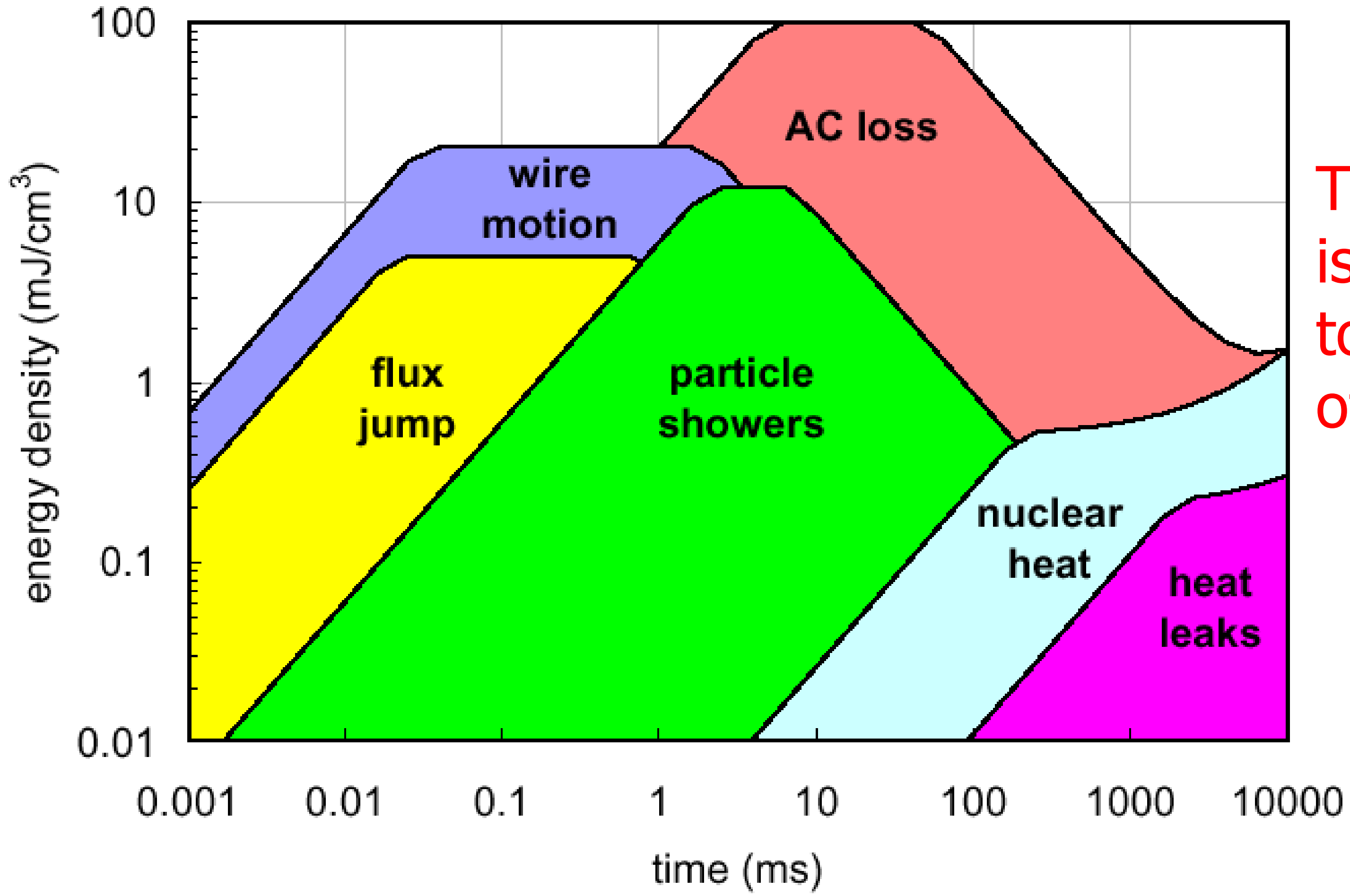
cooling

Heating < Cooling ↓ recovery

Heating > Cooling ↓ quench

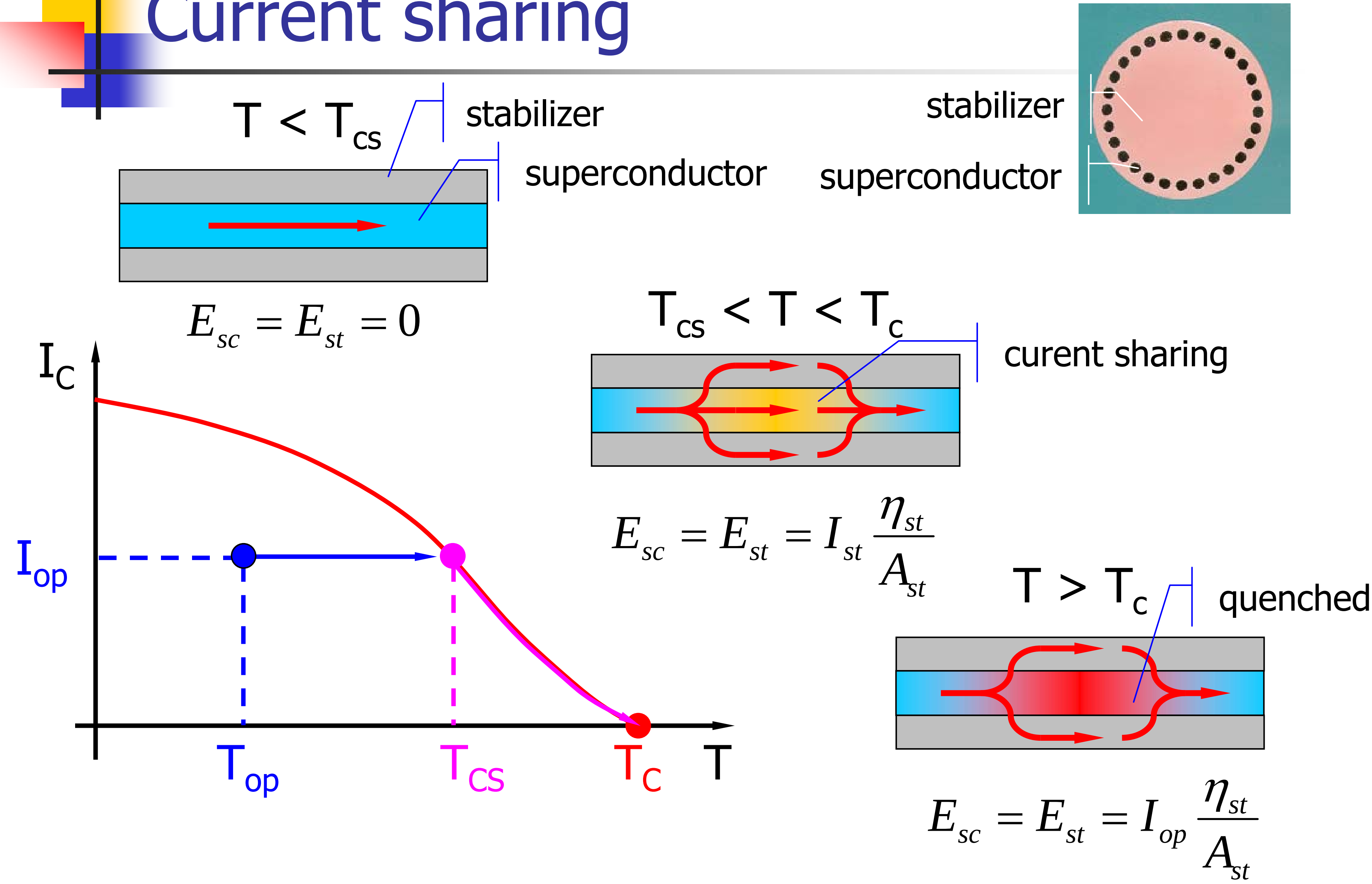
jump

Perturbation overview



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

Current sharing



T < T_{cs}

stabilizer

superconductor

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

stabilizer

superconductor

T_{cs} < T < T_c

curent sharing

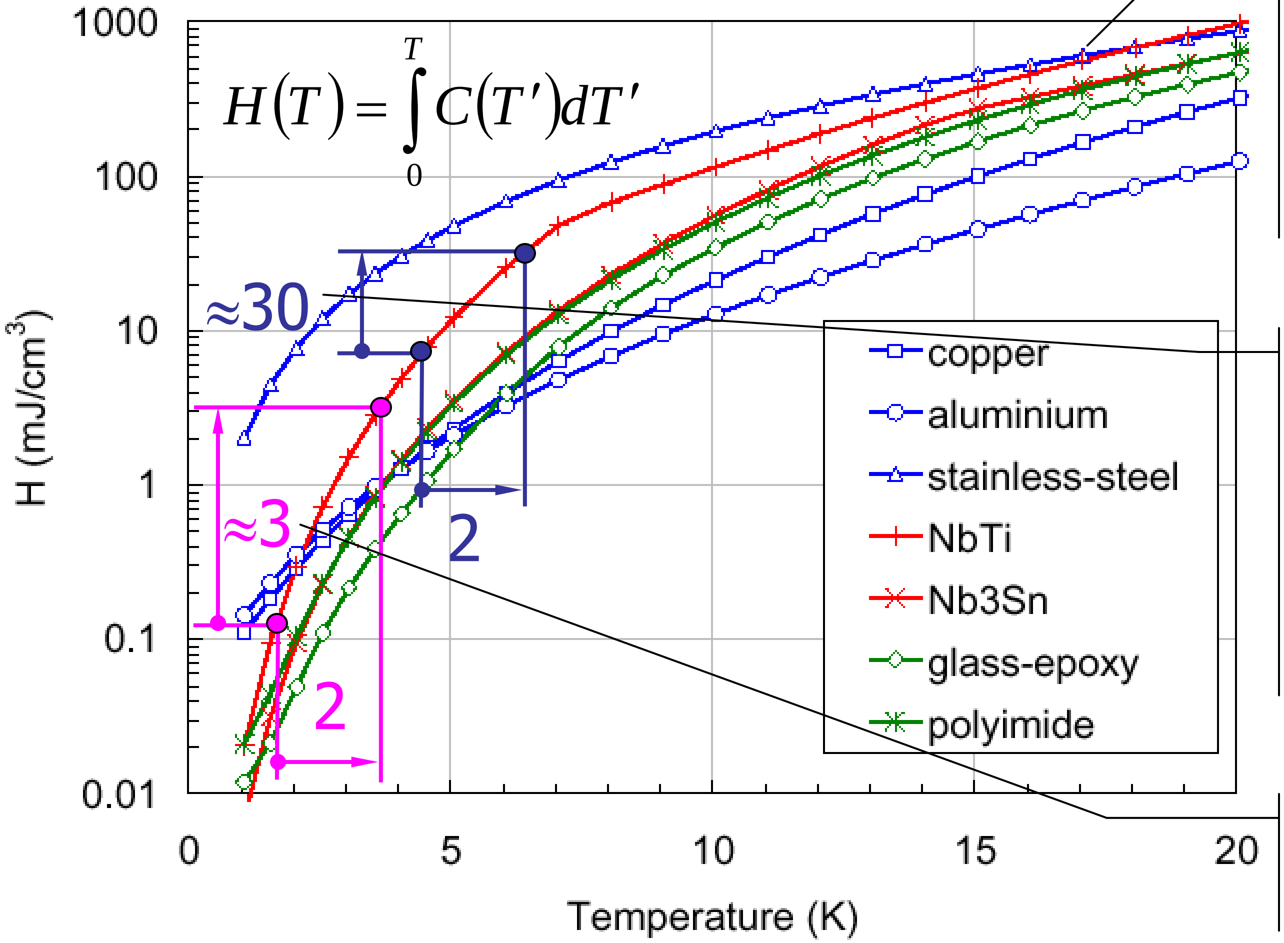
$$E_{sc} = E_{st} = I_{st}\frac{\eta_{st}}{A_{st}}$$

T > T_c

quenched

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

Enthalpy reserve

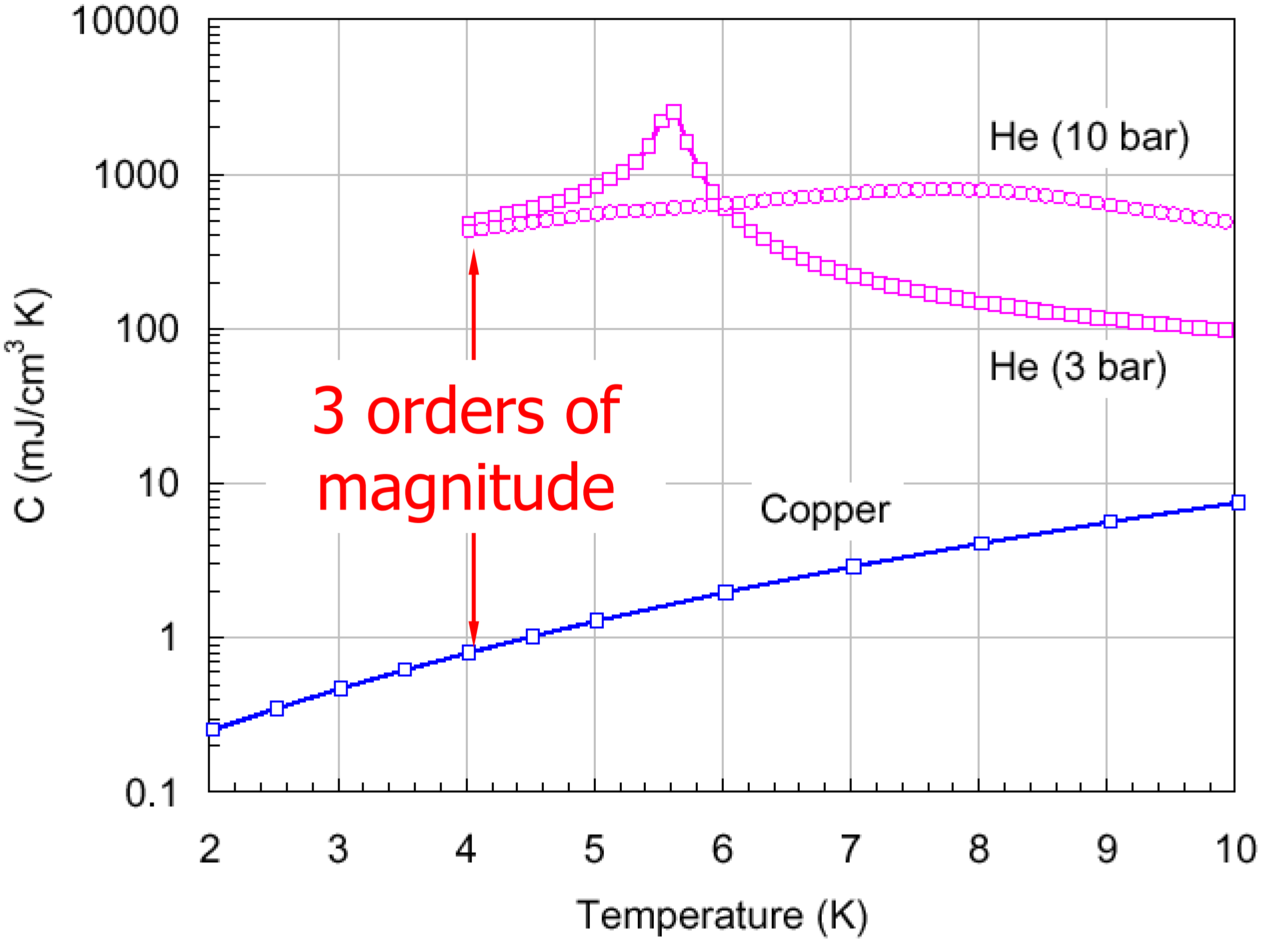


Enthalpy reserve increases massively at increasing T: stability is not an issue for HTS materials

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:

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

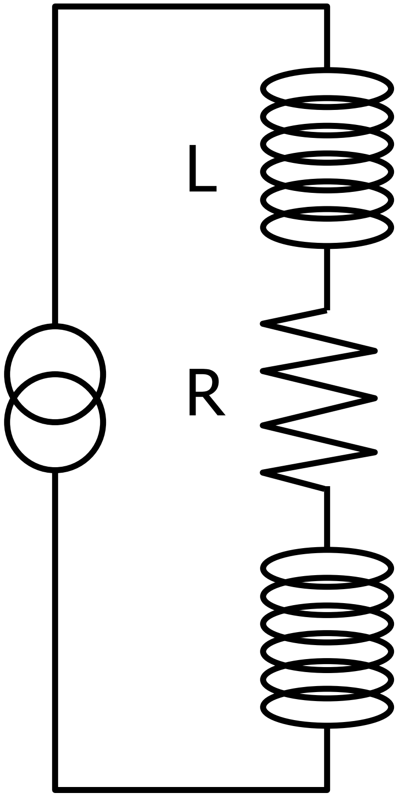
is converted to heat through Joule heating RI^2. *If this process happened uniformly* in the winding pack:

  - 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)



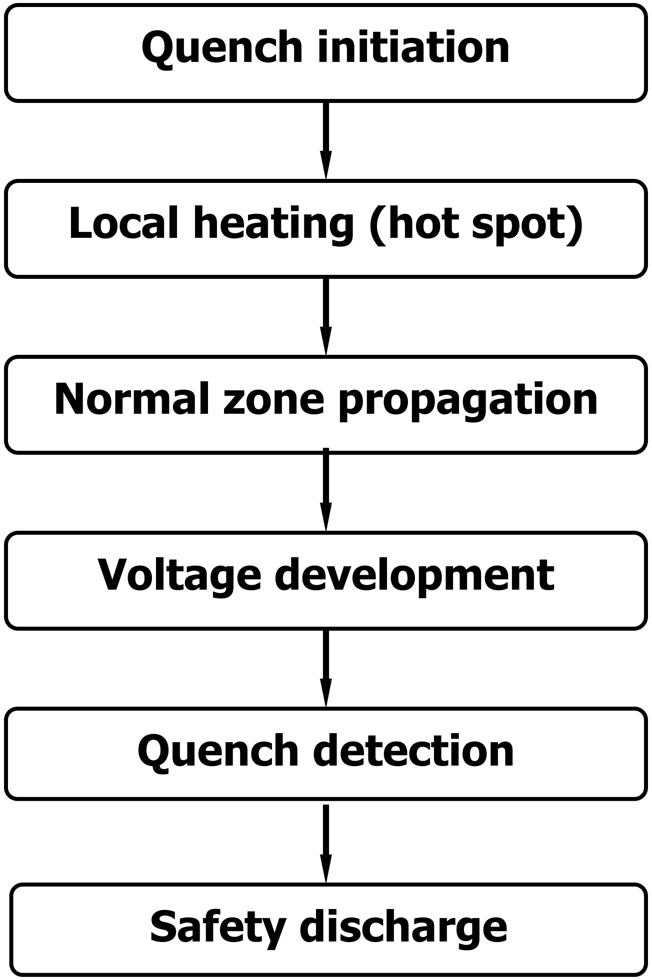
Courtesy of A. Siemko, CERN

Lots of energy !

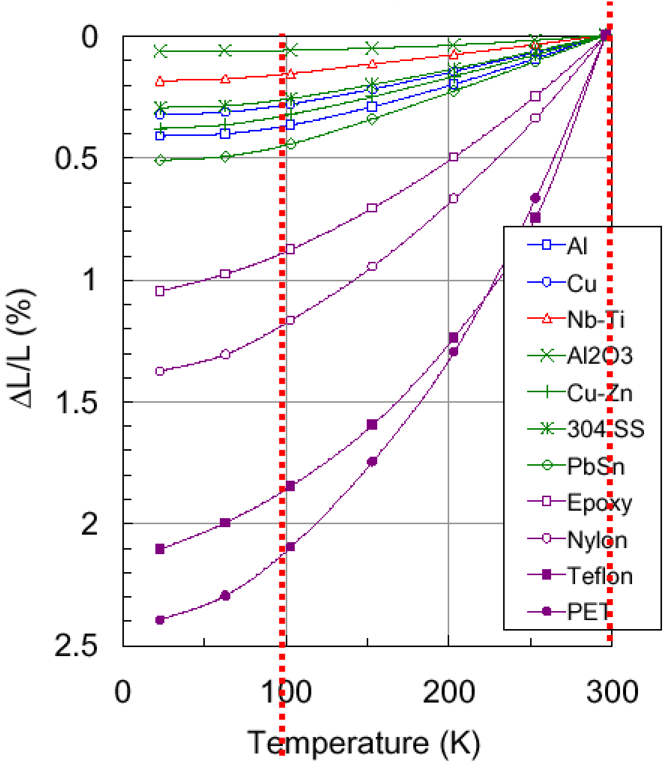
jump

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



T_{max} < 300 K for highly supported coils (e.g. accelerator magnets)

T_{max} < 100 K for negligible effect

- 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)

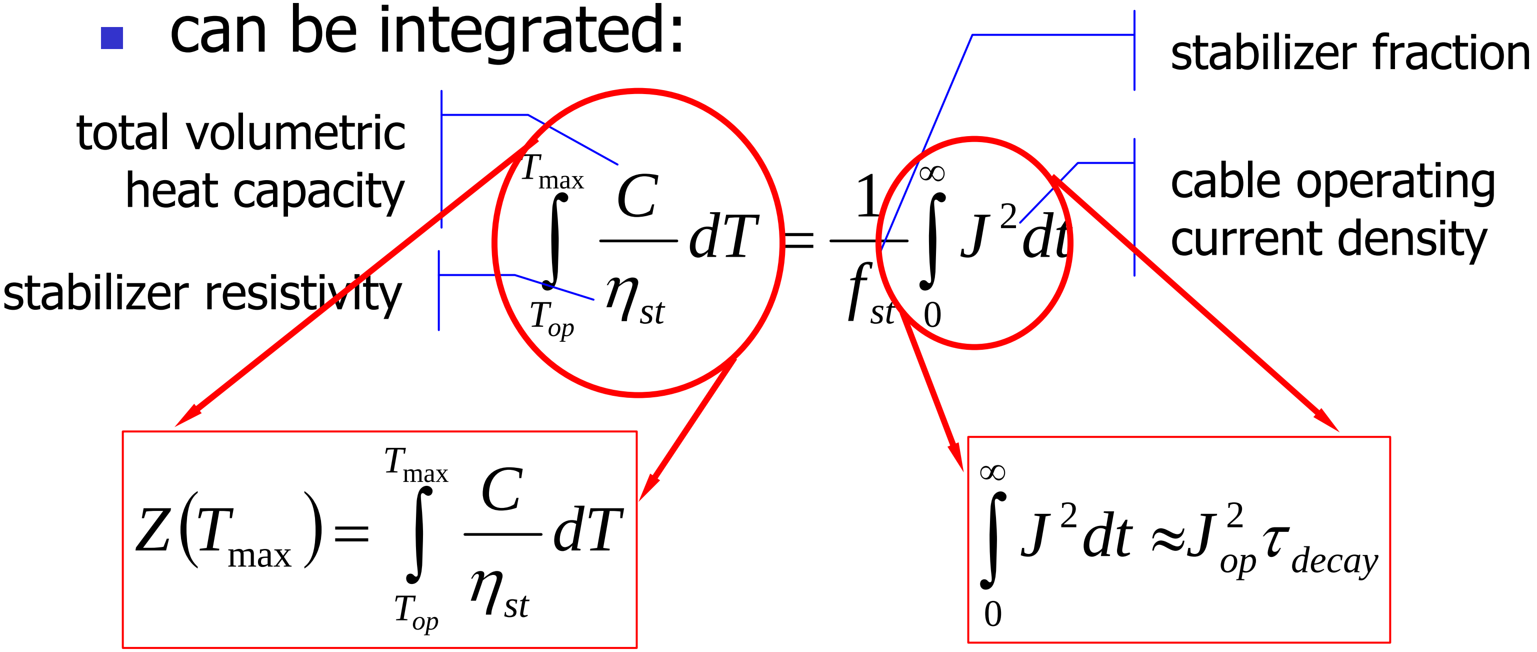
B.J. Maddock, G.B. James, Proc. IEE, **115** (4), 543, 1968

Adiabatic hot spot temperature

- adiabatic conditions at the hot spot :

$$C\frac{\partial T}{\partial t} = q'''_J \qquad \text{where:} \qquad q'''_J = \frac{\eta_{st}}{A_{st}}\frac{I^2}{A}$$

- can be integrated:



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

total volumetric heat capacity

stabilizer resistivity

stabilizer fraction

cable operating current density

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

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

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

How to limit T_{max}

stabilizer material property

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

electrical operation of the coil (energy, voltage)

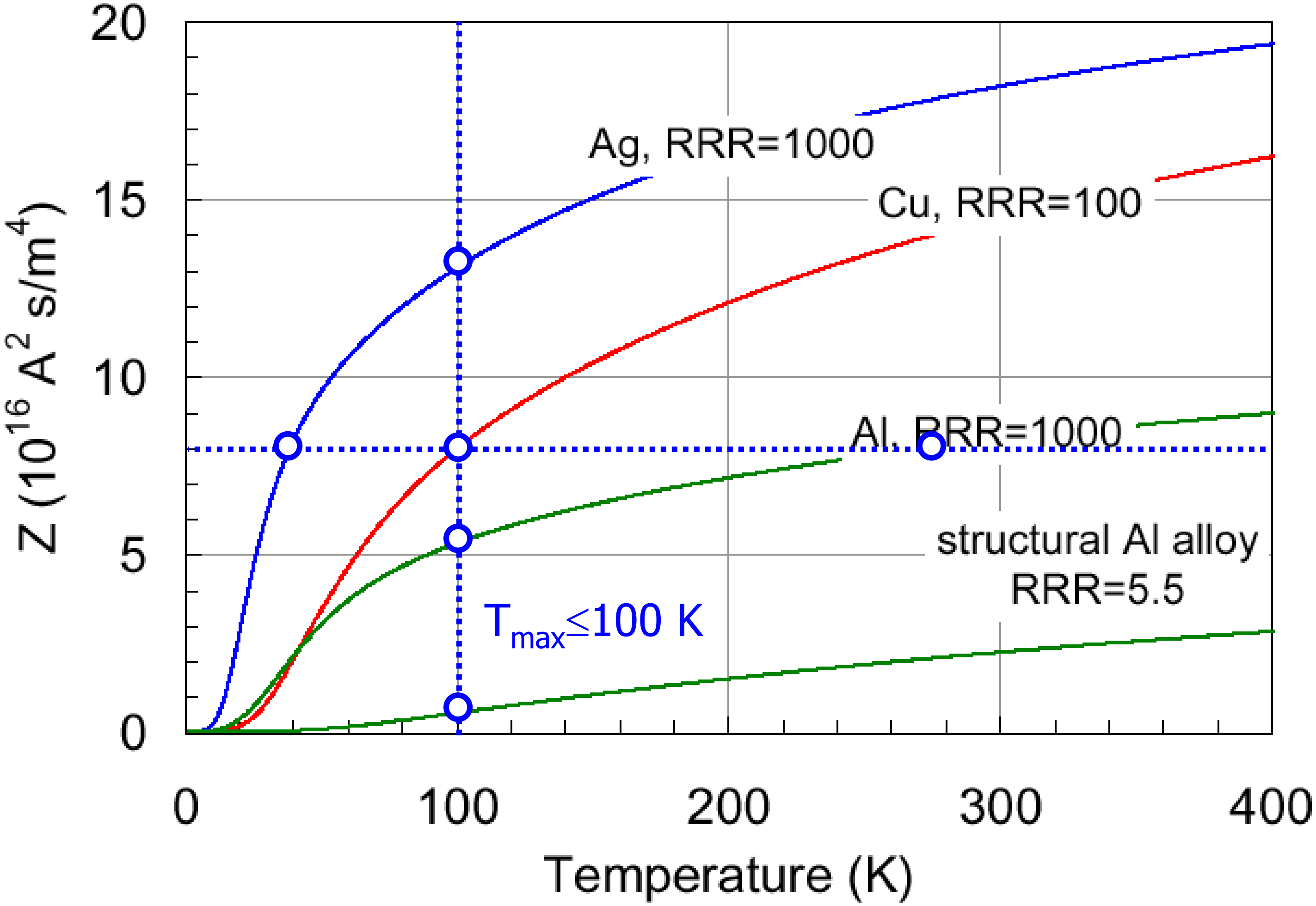
cable fractions design

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 $Z(T_{max}) \Uparrow$

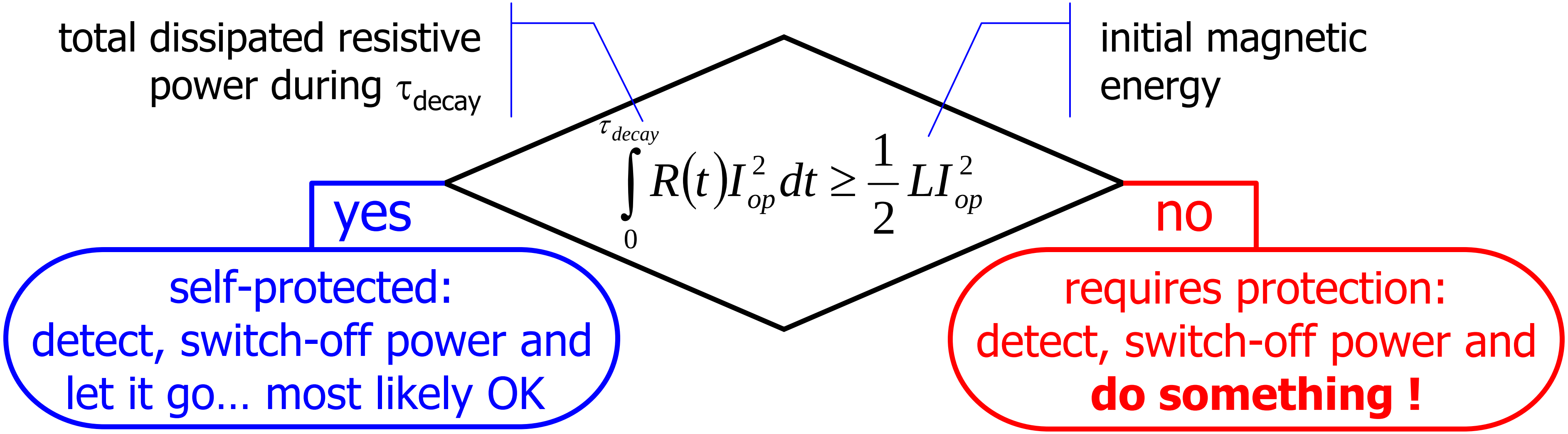
$$Z(T_{\max}) \approx \frac{1}{f_{st}} J_{op}^2 \tau_{decay}$$

Z(T_{max}) for typical stabilizers



Quench protection

- The magnet stores a magnetic energy 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



total dissipated resistive power during τ_{decay}

initial magnetic energy

$$\int_0^{\tau_{decay}} R(t) I_{op}^2 \, dt \geq \frac{1}{2} L I_{op}^2$$

yes

self-protected:
detect, switch-off power and let it go… most likely OK

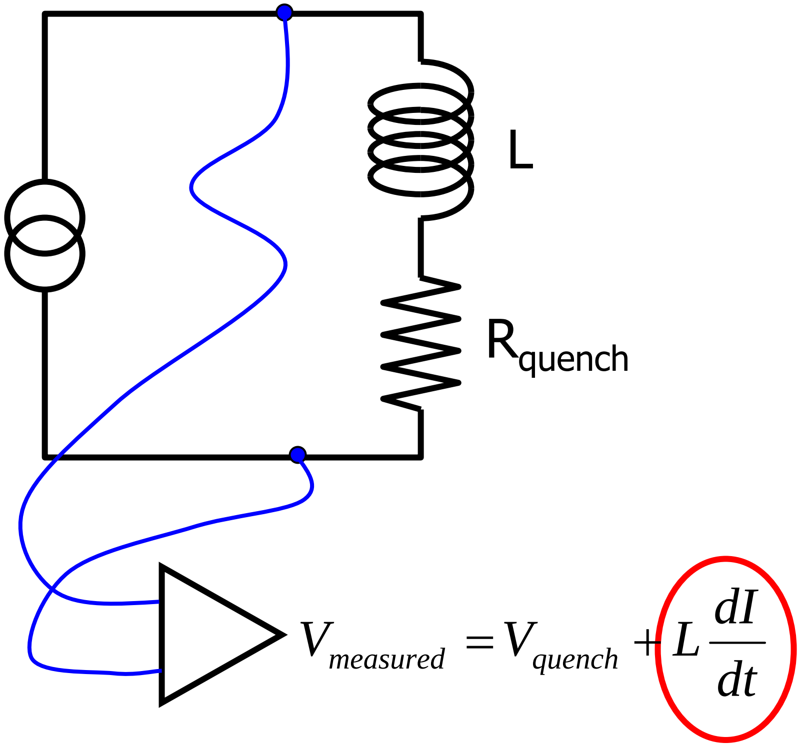
no

requires protection:
detect, switch-off power and **do something !**

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

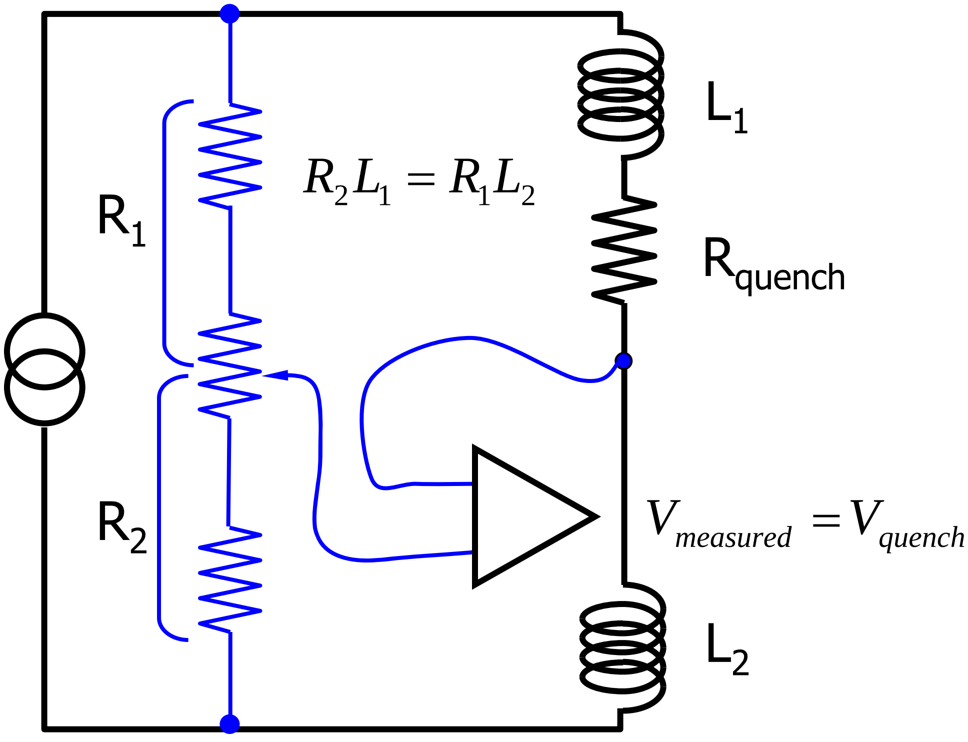
Quench detection: voltage

- a direct quench voltage measurement is subject to inductive pick-up (ripple, ramps)



$$V_{measured} = V_{quench} + L\frac{dI}{dt}$$

- immunity to inductive voltages (and noise rejection) is achieved by *compensation*

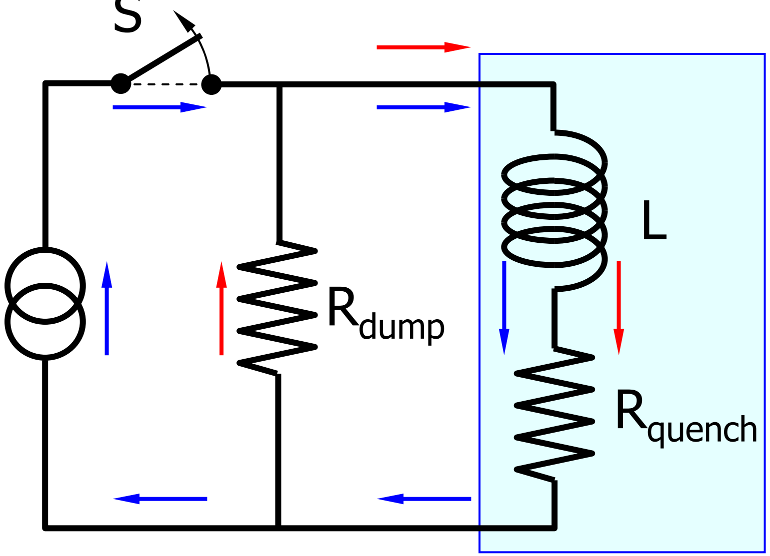


$$R_2 L_1 = R_1 L_2$$

$$V_{measured} = V_{quench}$$

B.J. Maddock, G.B. James, Proc. Inst. Electr. Eng., **115**, 543, 1968

Strategy 1: energy dump



$$R_{dump} >> R_{quench}$$

normal operation

quench

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

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

- 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:

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

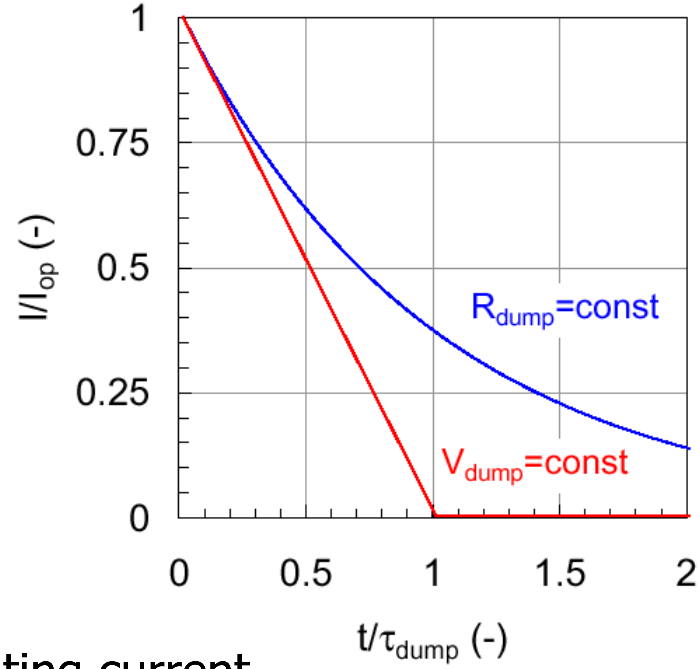
- dump time constant:

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

maximum terminal voltage

operating current

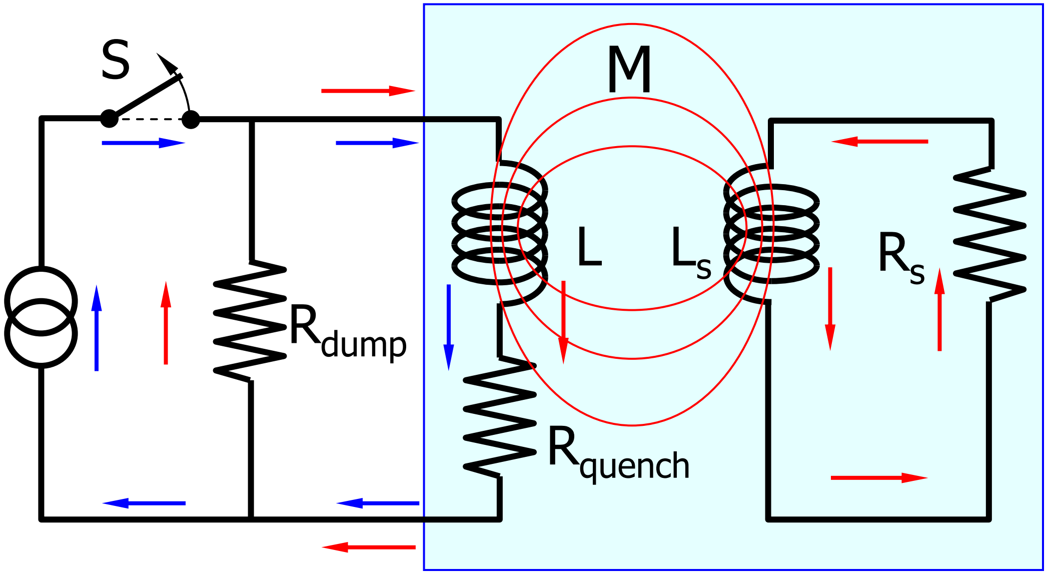
interesting alternative:
non-linear R_{dump} or voltage source



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

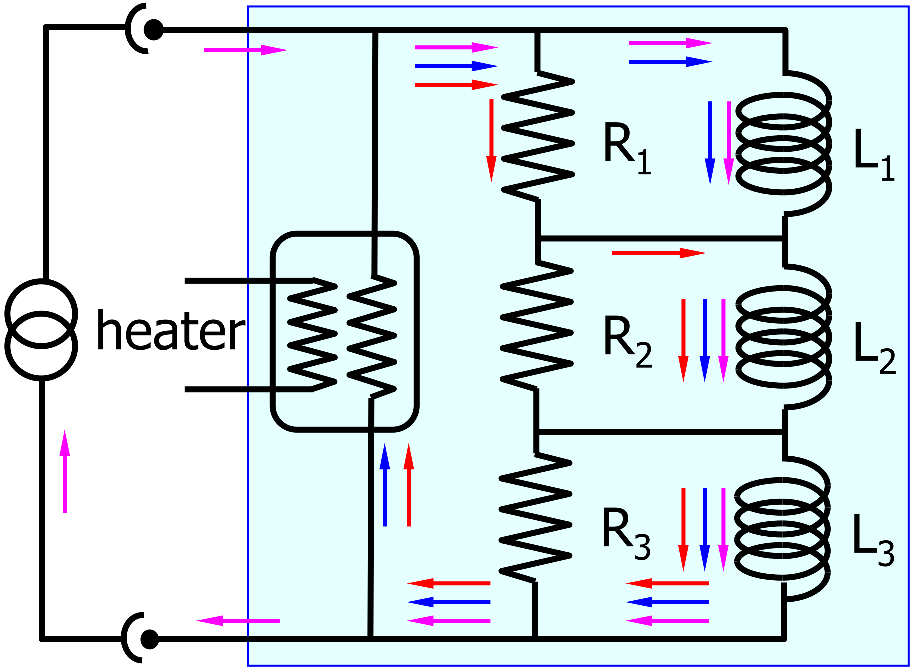
← normal operation

← 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

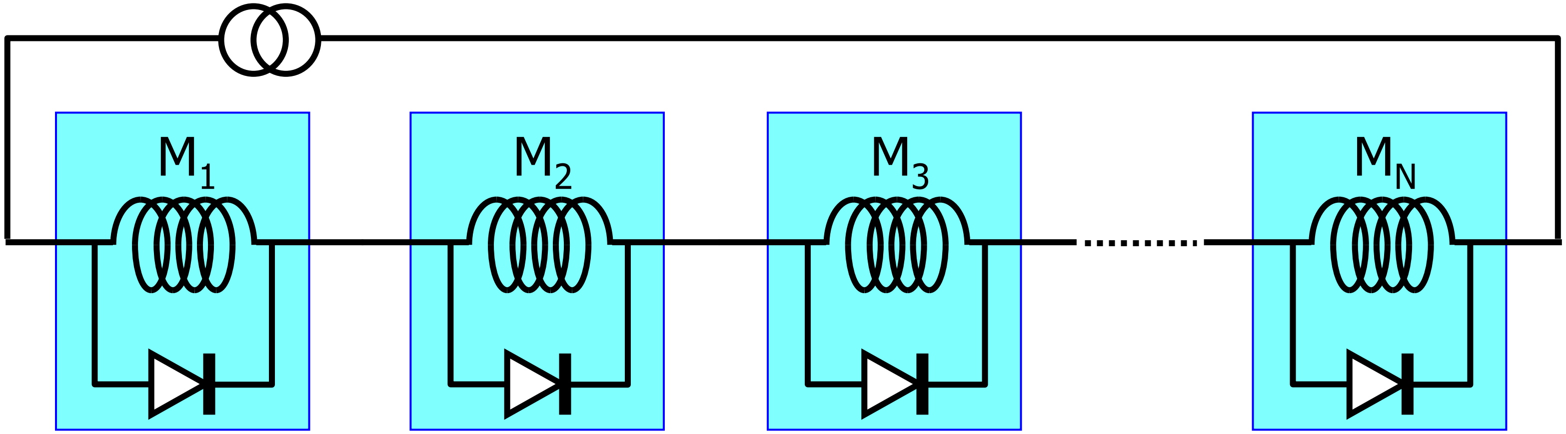
← charge

← normal operation

← quench

Magnet strings

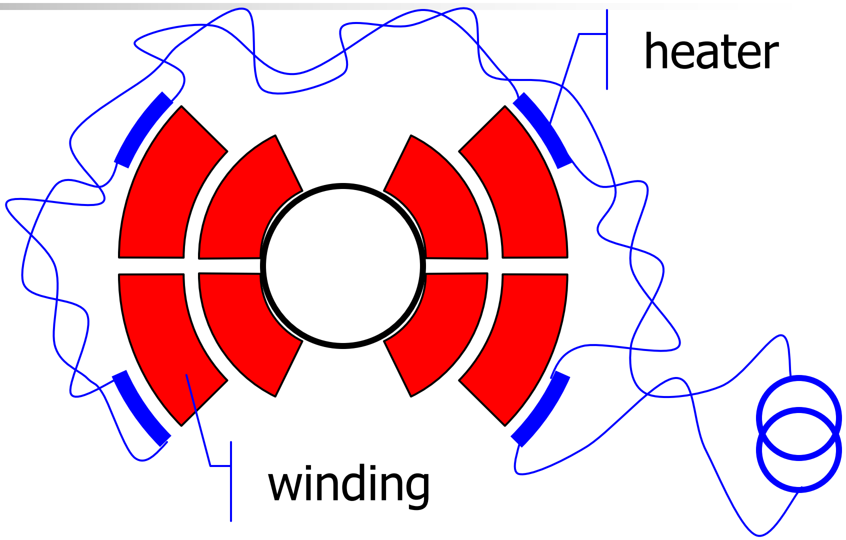
- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10’s of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the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



Strategy 4: heaters

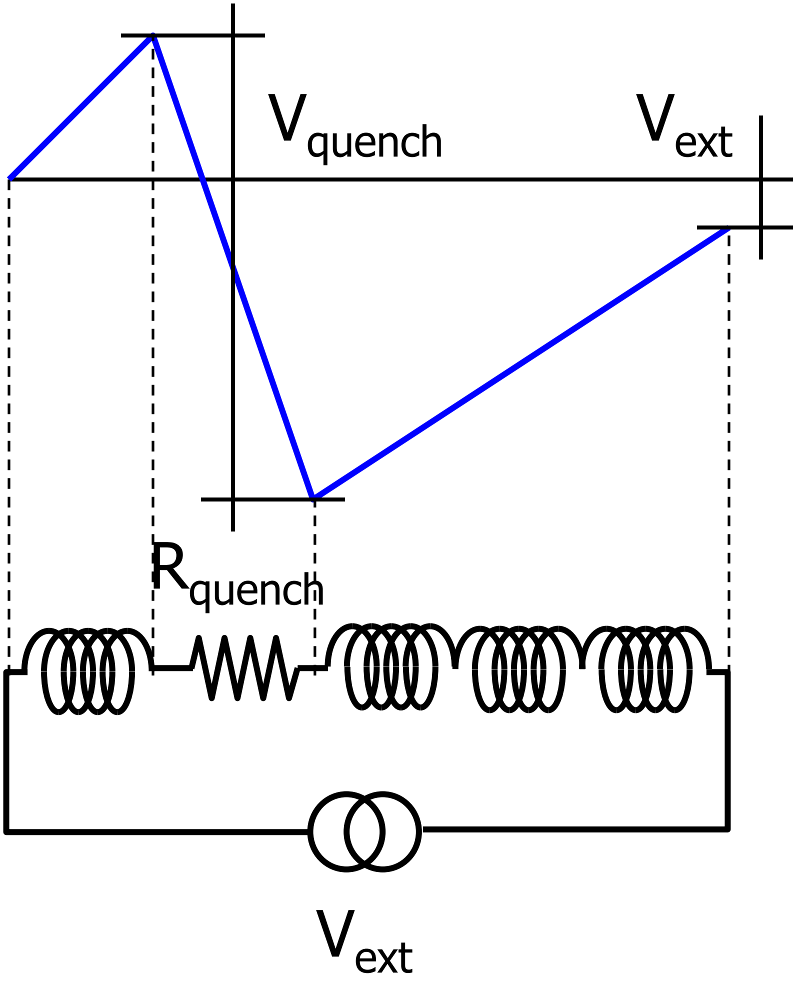
- the quench is spread actively by firing heaters embedded in the winding pack, in close vicinity to the conductor

- 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 (⇔ 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

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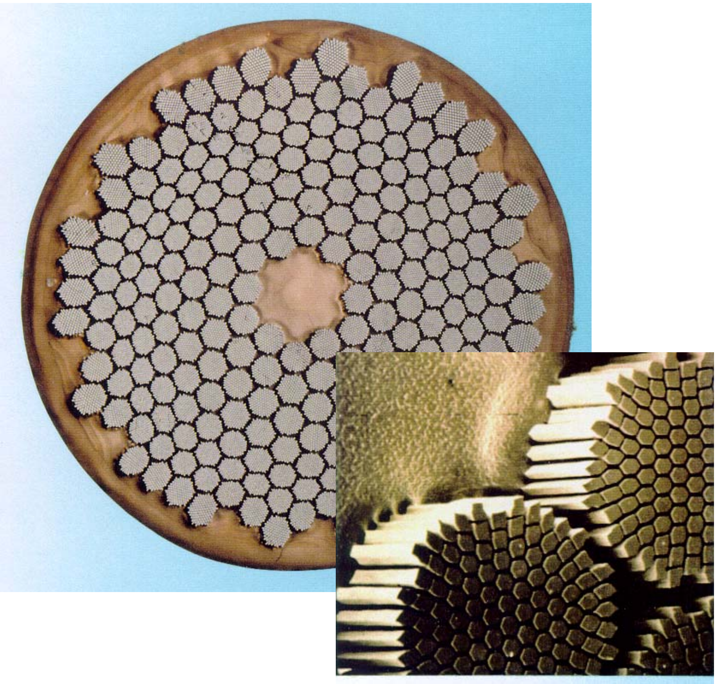
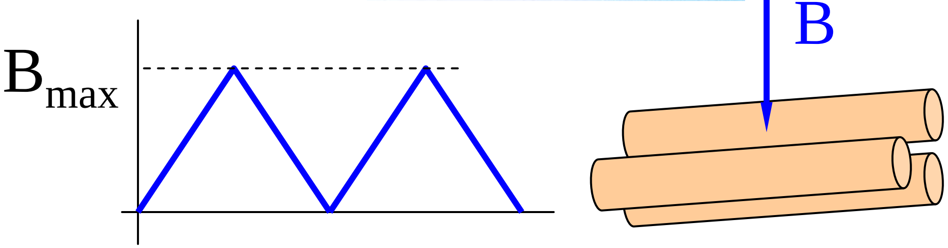
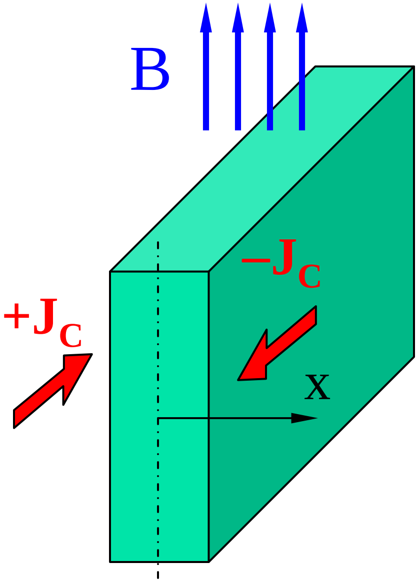
A superconductor in varying field



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



A filament in a time-variable field



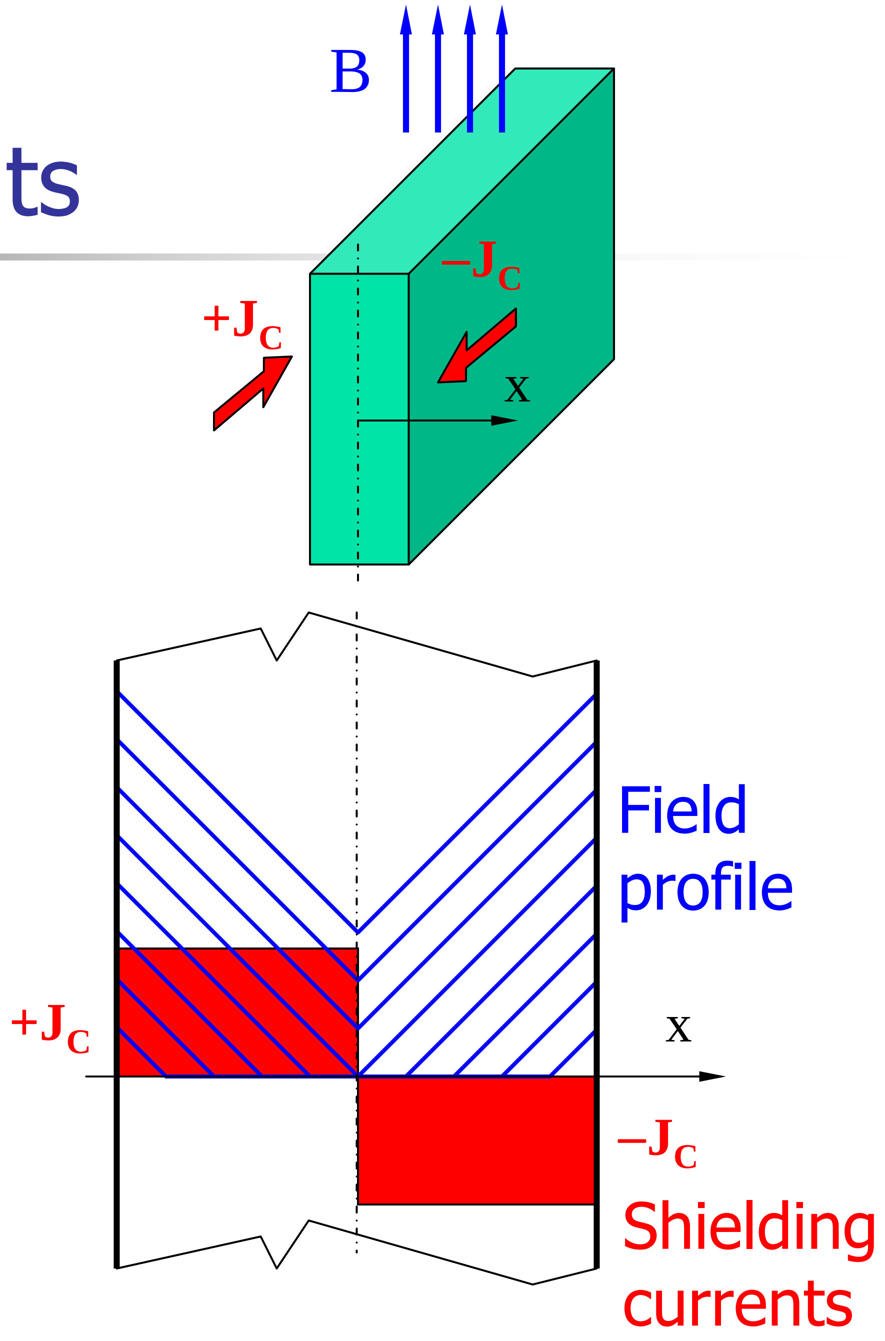
Shielding currents

Quiz: how much is J ?

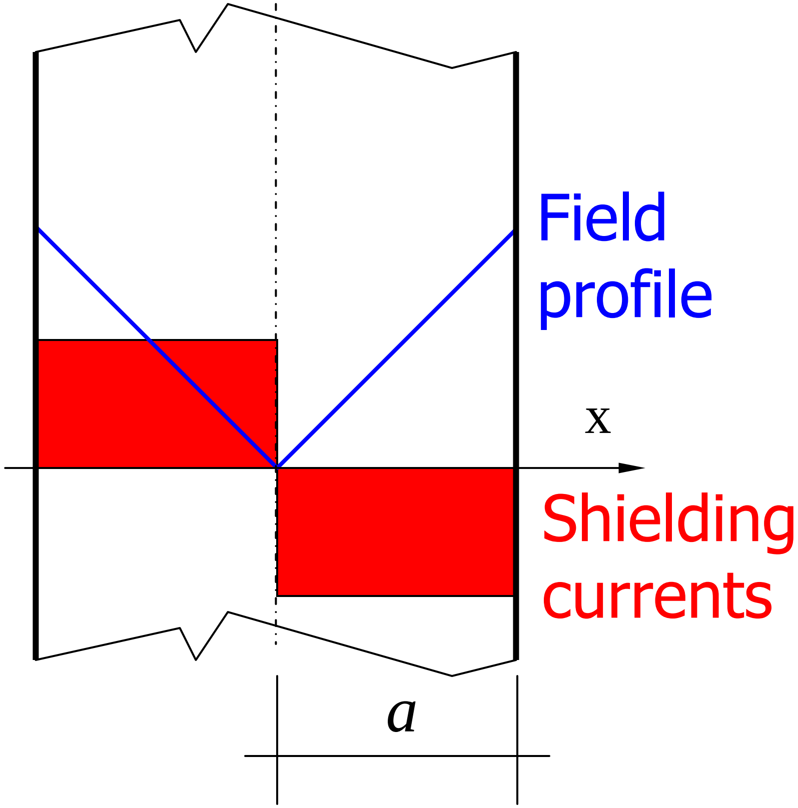
Persistent currents

- 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 ⇒ 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*:

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

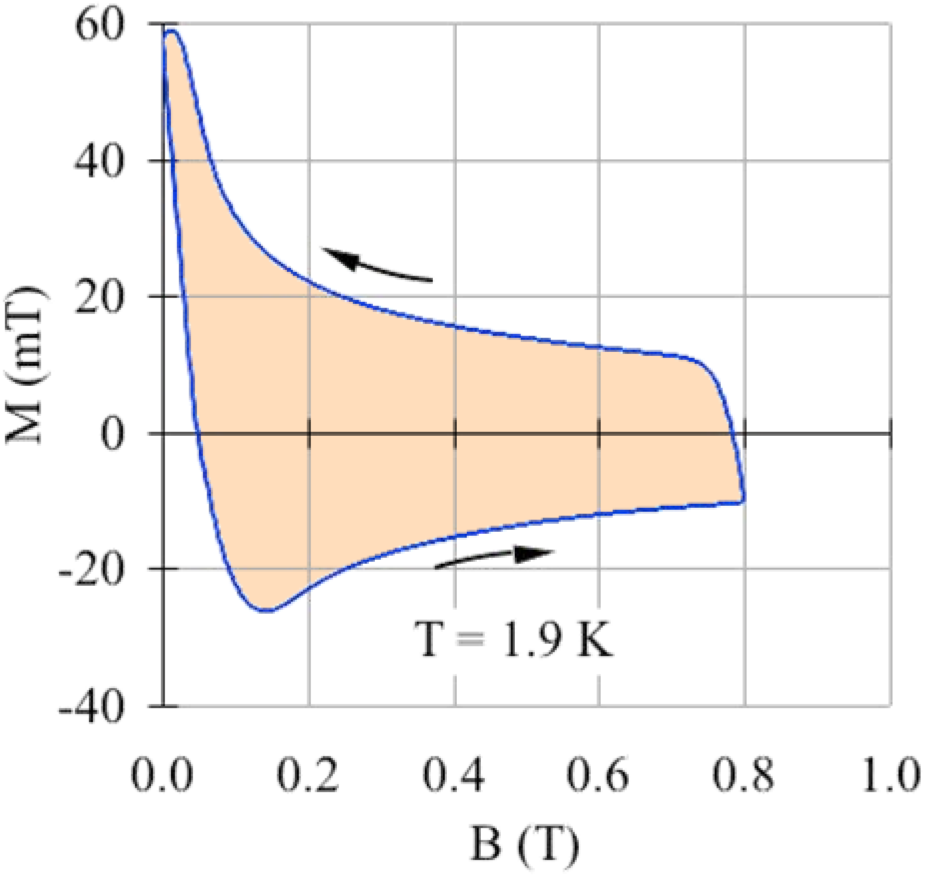
- The magnetization is proportional to the critical current density and to the size of the superconducting slab **(filament diameter !)**

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:

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

i.e. the area of the magnetization loop



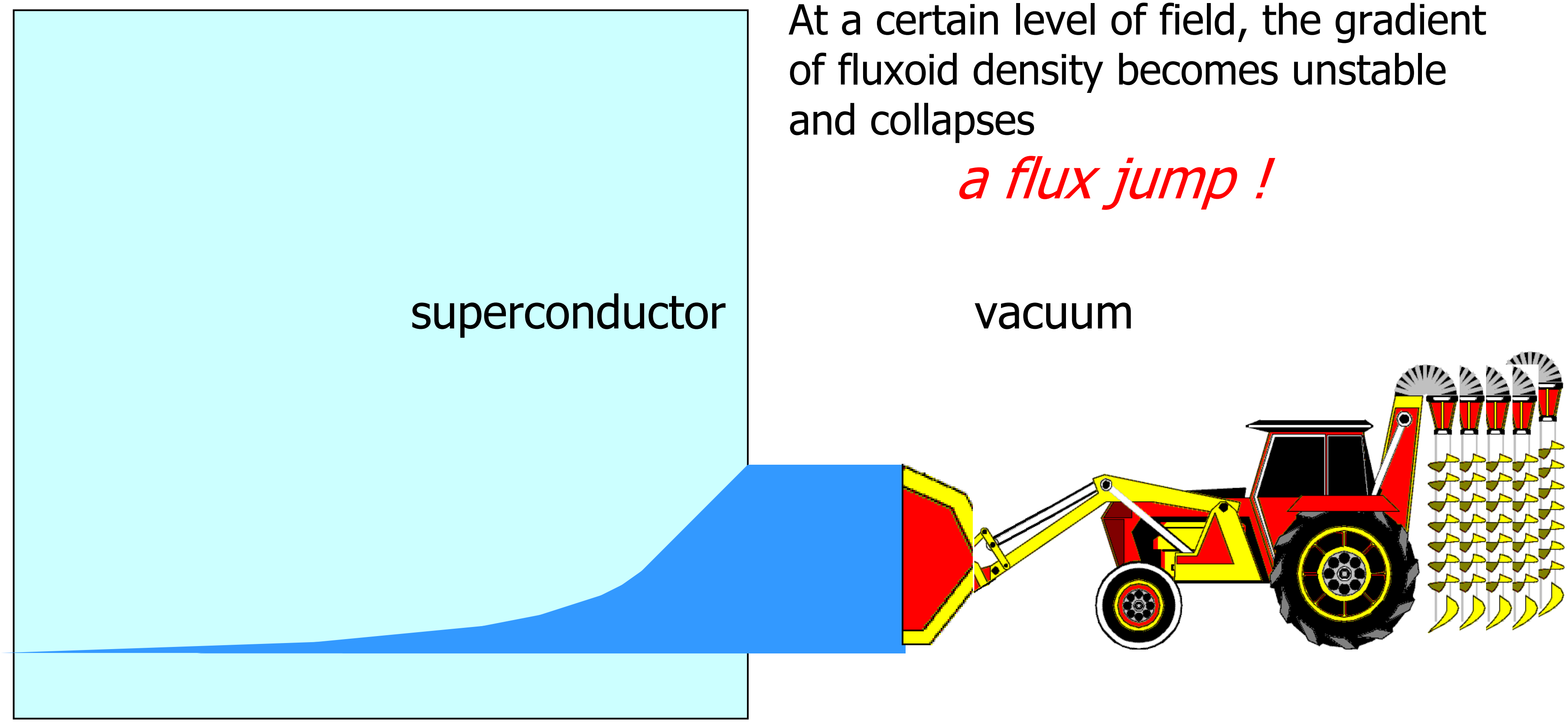
Graphics by courtesy of M.N. Wilson

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)

At a certain level of field, the gradient of fluxoid density becomes unstable and collapses

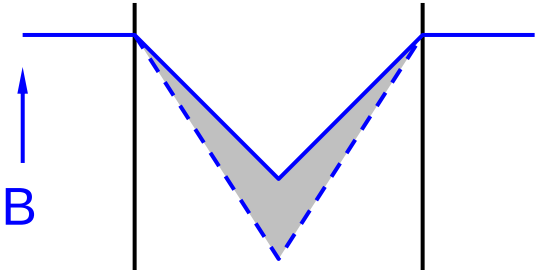
a flux jump !

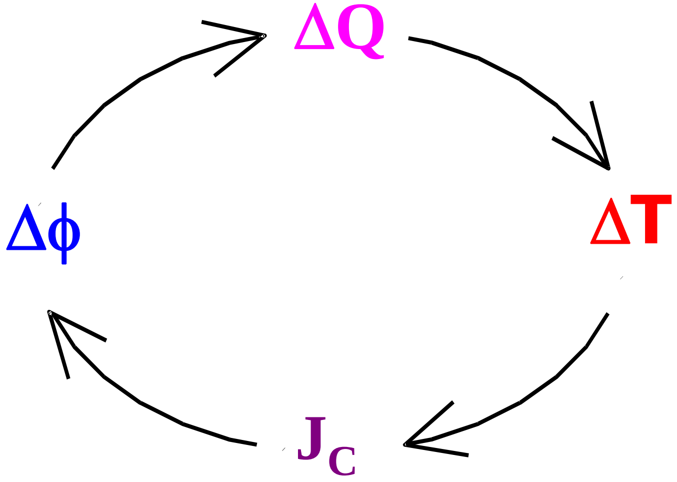


Graphics by courtesy of M.N. Wilson

Flux jumps

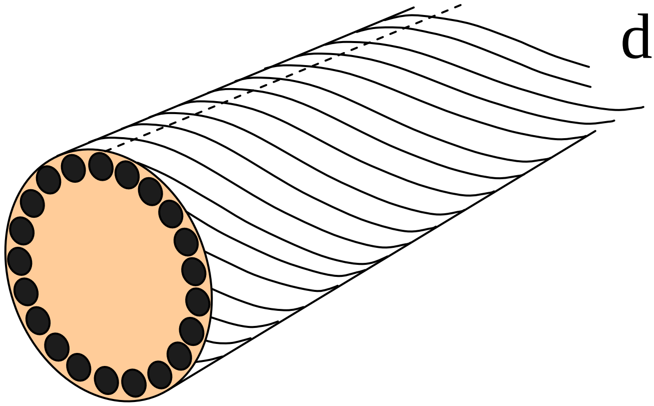
- Unstable behaviour is shown by all superconductors when subjected to a magnetic field:
  - B induces screening currents, flowing at critical density J_C
  - A change in screening currents allows flux to move into the superconductor
  - The flux motion dissipates energy
  - The energy dissipation causes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



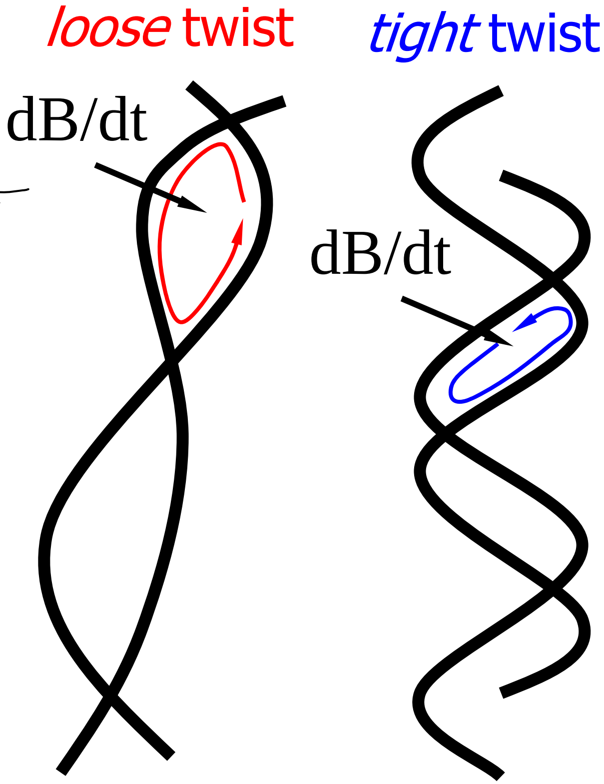


Flux jumping is cured by making superconductor in the form of fine filaments. This weakens the effect of $\Delta\phi$ on ΔQ

Filaments coupling



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



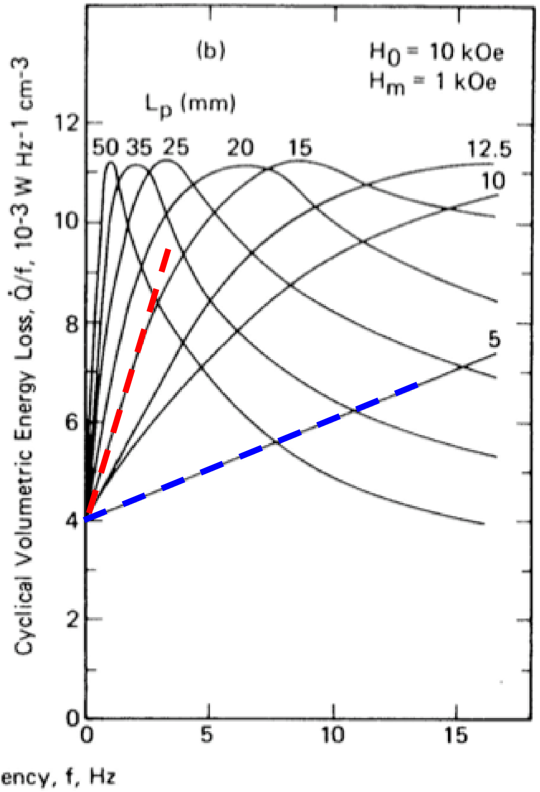
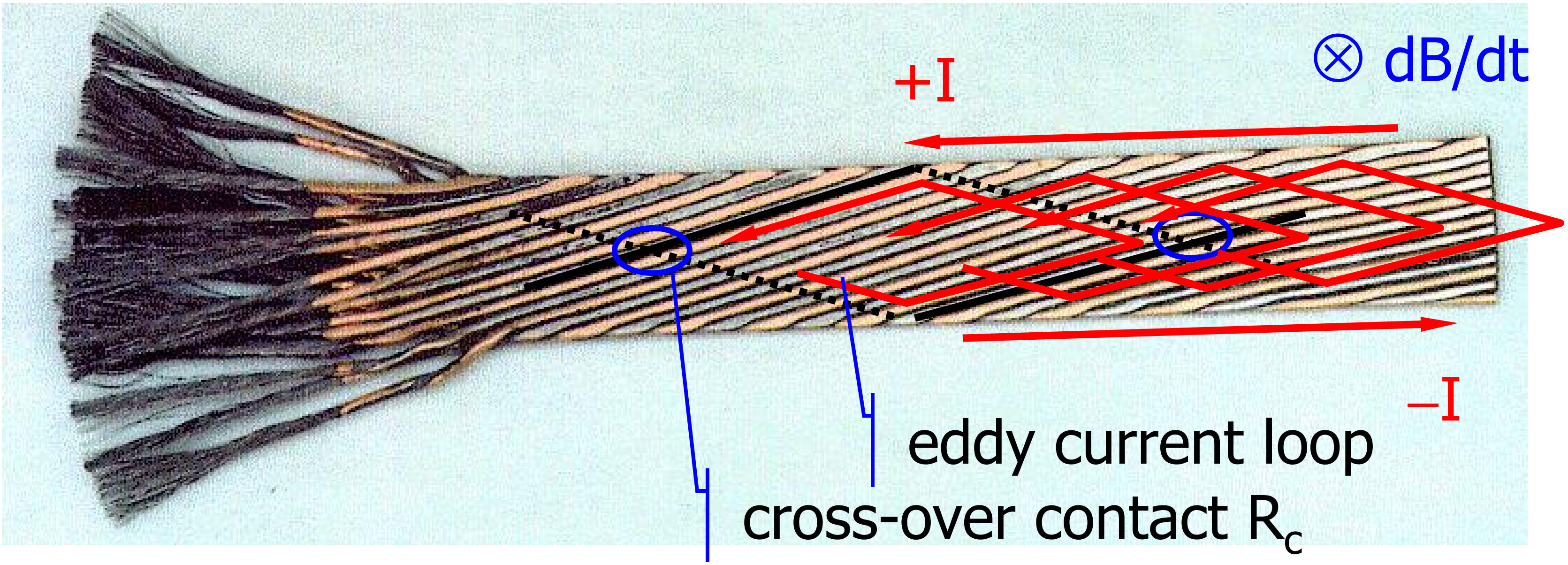


Figure 26-8. Energy loss per cycle ($\equiv \dot{Q}/f$) plotted *versus* frequency of the alternating component of an applied field $H_a(\omega) = H_0 + H_m \sin \omega t$. (a) The per-cycle *coil* loss is plotted for six values of H_m between 0.25 and 1.25 kOe at $H_0 = 10$ kOe; (b) the per-cycle *volumetric* 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 μm 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

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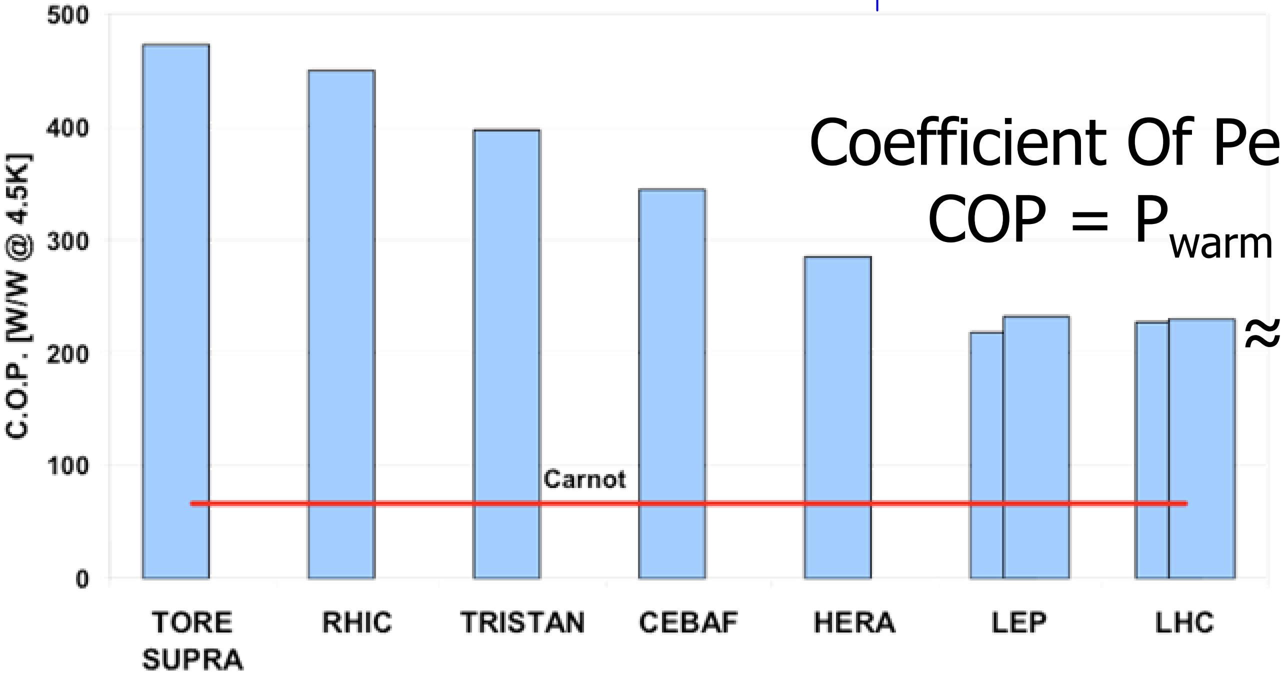
Basic thermodynamics

- 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

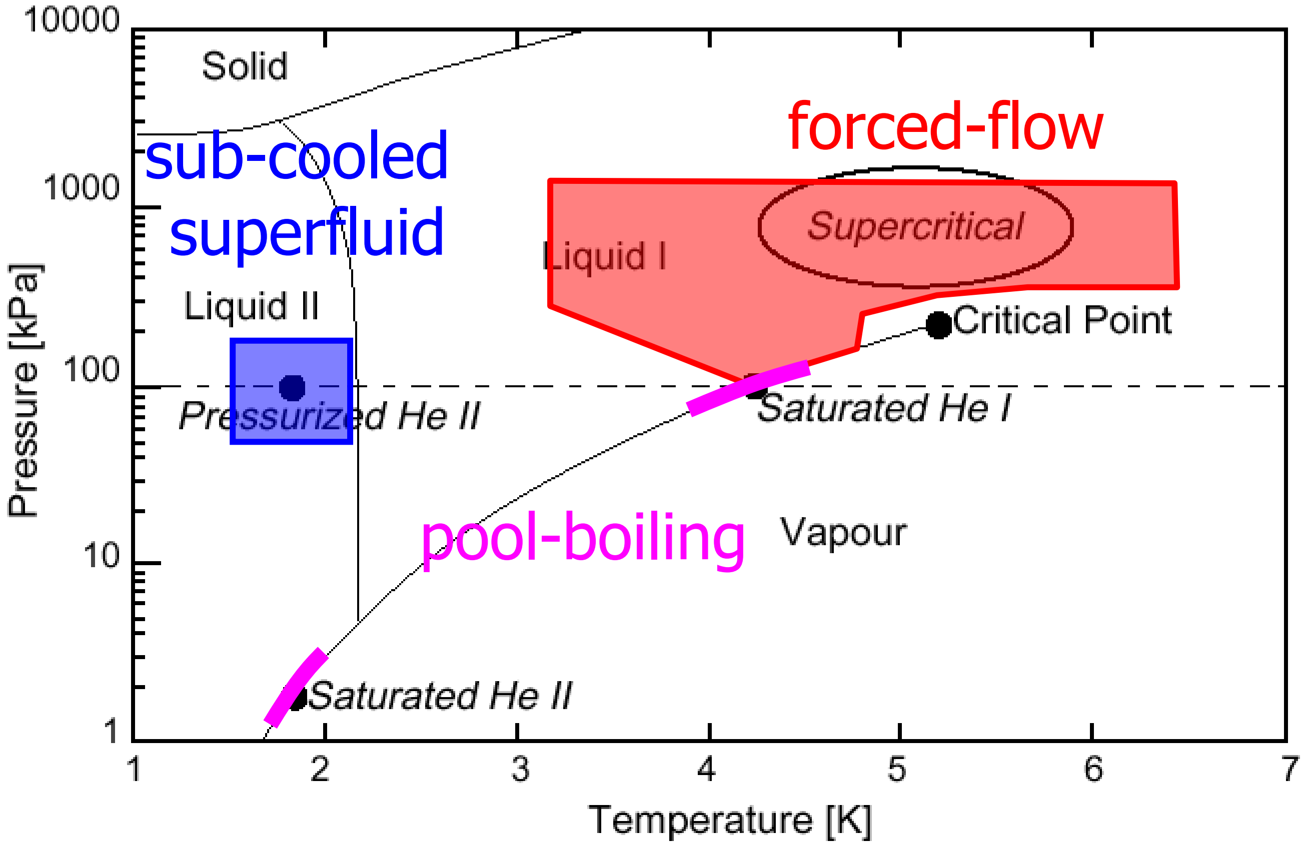


Coefficient Of Performance

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

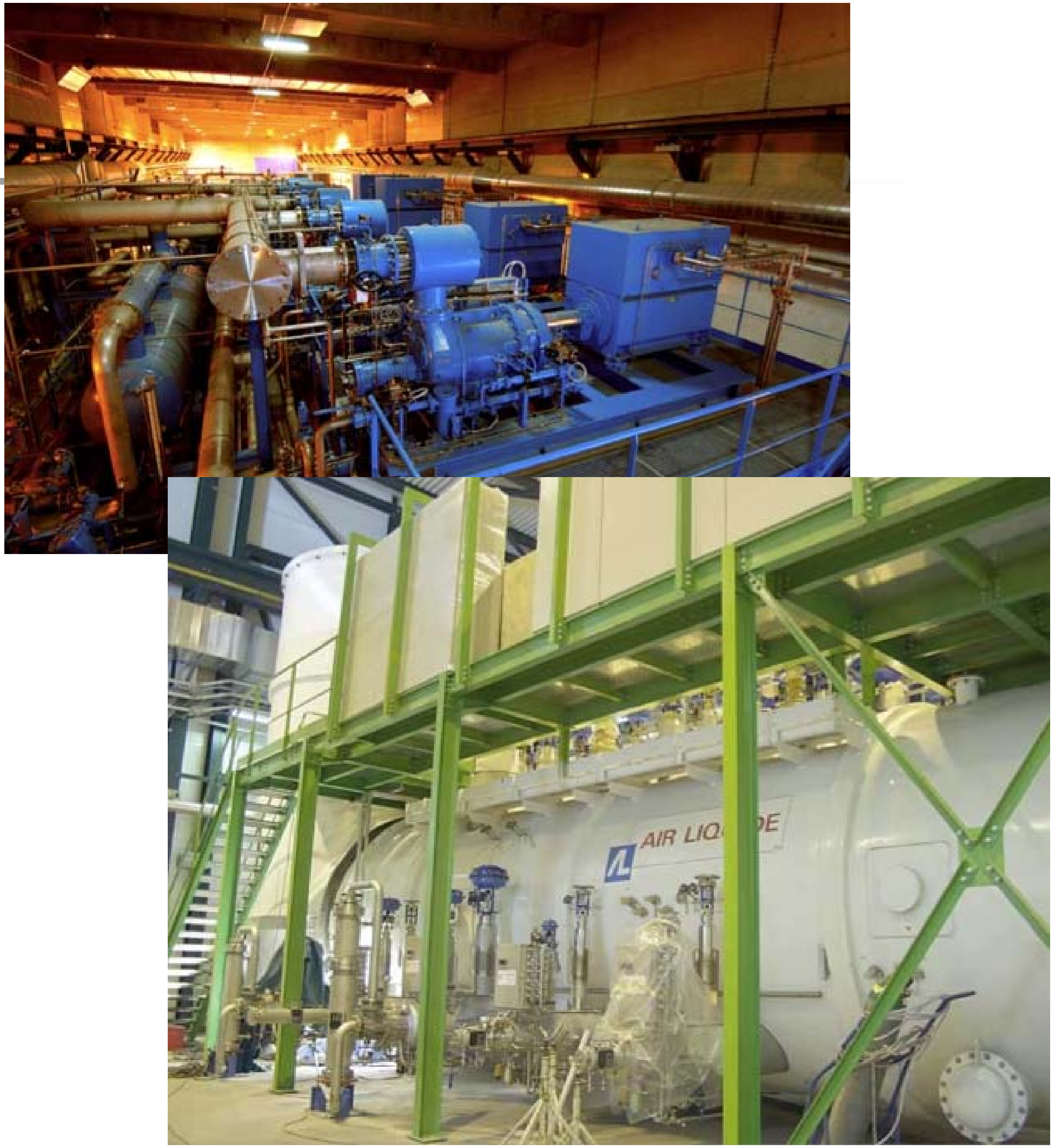
≈ 250

Helium as a low-temperature coolant



Fridge's

Cryocoolers: ≈1.5 W @ 4.2 K



LHC refrigerators: ≈140 kW @ 4.2 K

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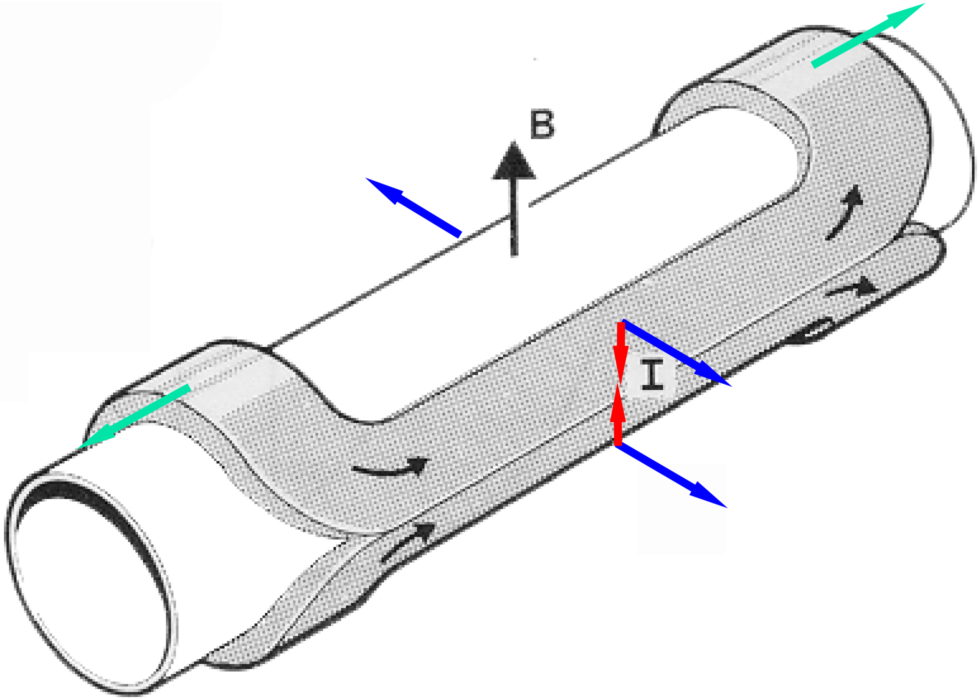
jump

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

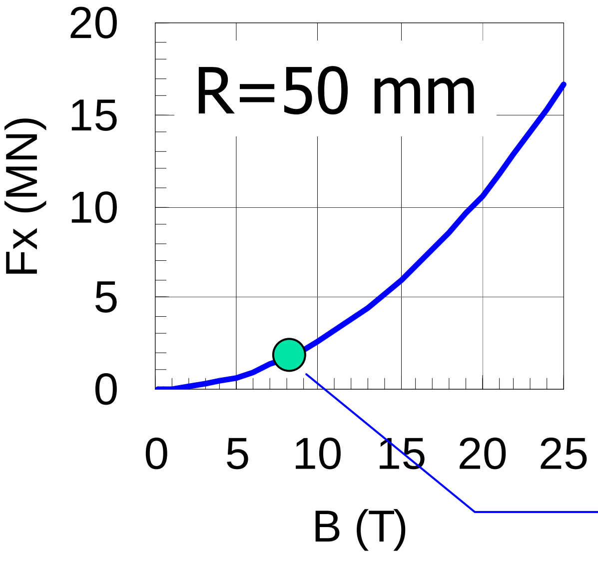


- Remember:
  - Material properties are (sometimes strong) function of temperature
  - Thermal contraction is very different among the various components of a magnet (e.g. metals vs. insulators)
  - Field quality and stability depends on reliable coil dimension to the μm

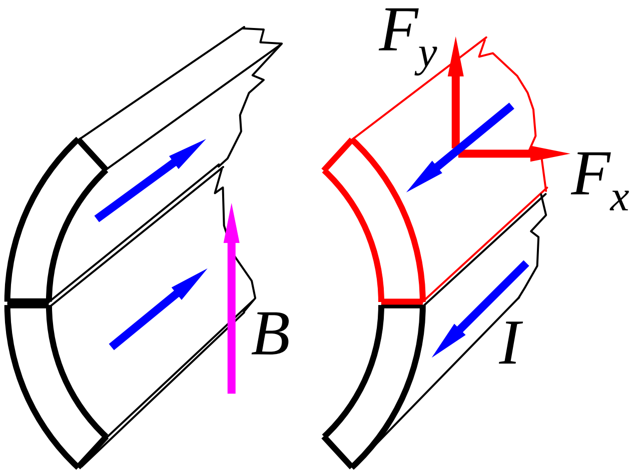
Orders of magnitude of the force

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

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



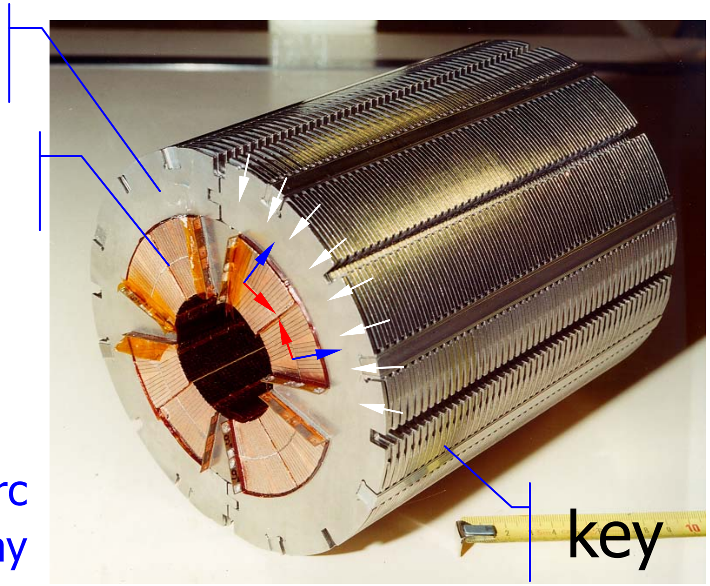
LHC ≈ 2 MN/m



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:



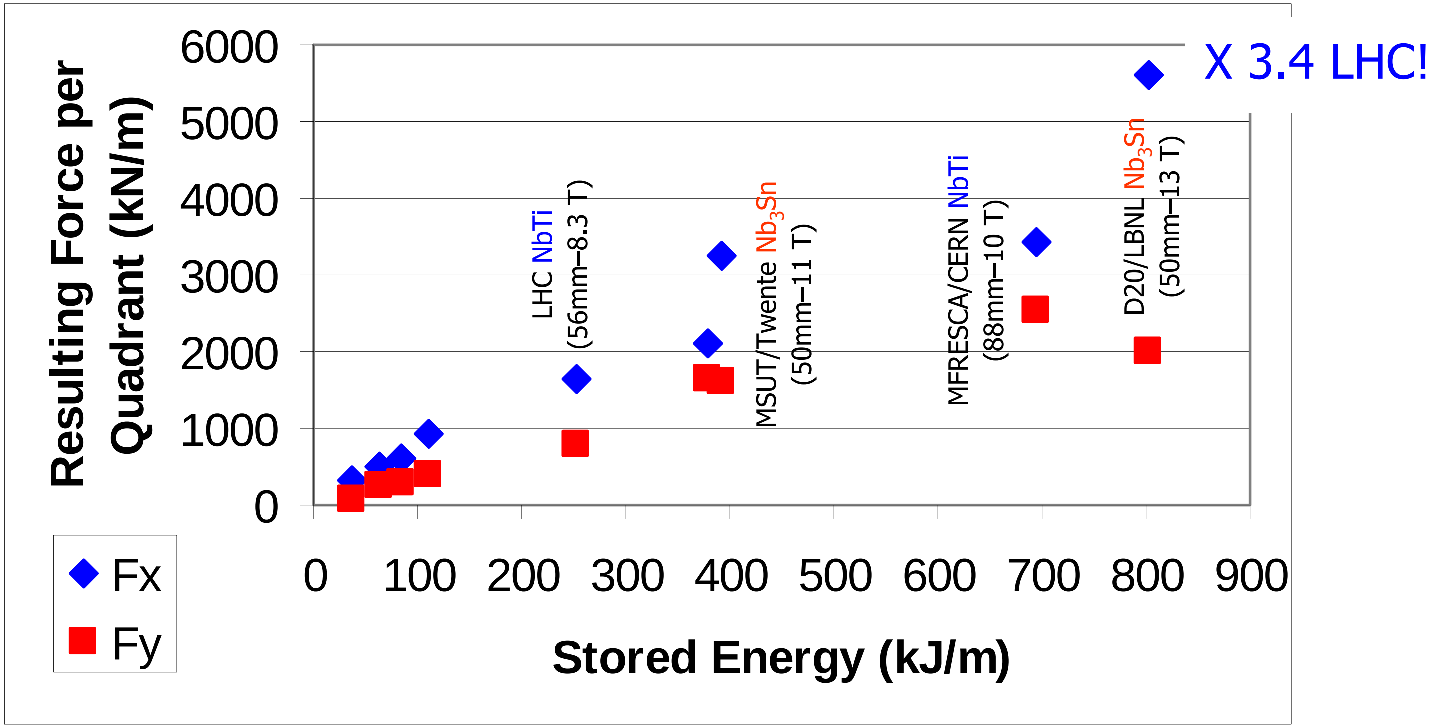
***Roman arch* principle**

promulgated by R. Perin (CERN)

Collared-coil assembly section of LHC arc quadrupole magnet at CEA/Saclay *by courtesy of A. Devred*

Towards higher fields (HE-LHC)

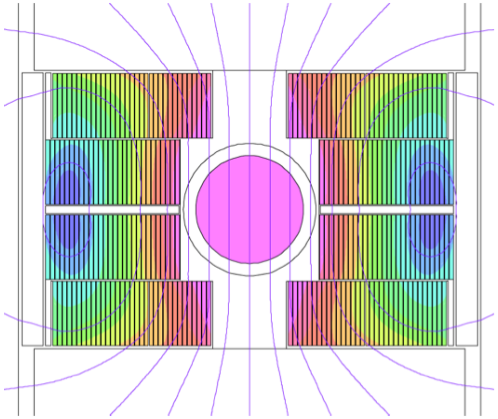
- Several R&D programs are underway to demonstrate the feasibility of magnets with Lorentz force levels far exceeding those of LHC.

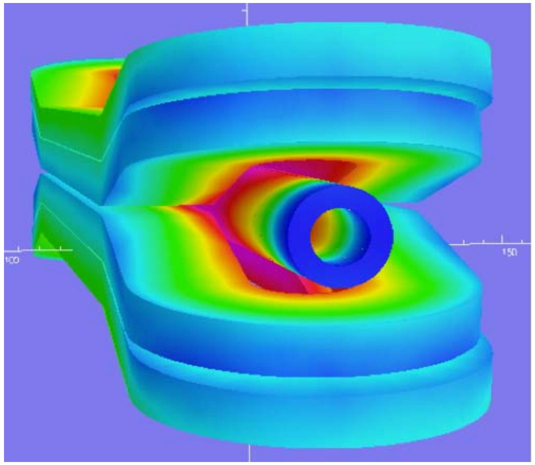


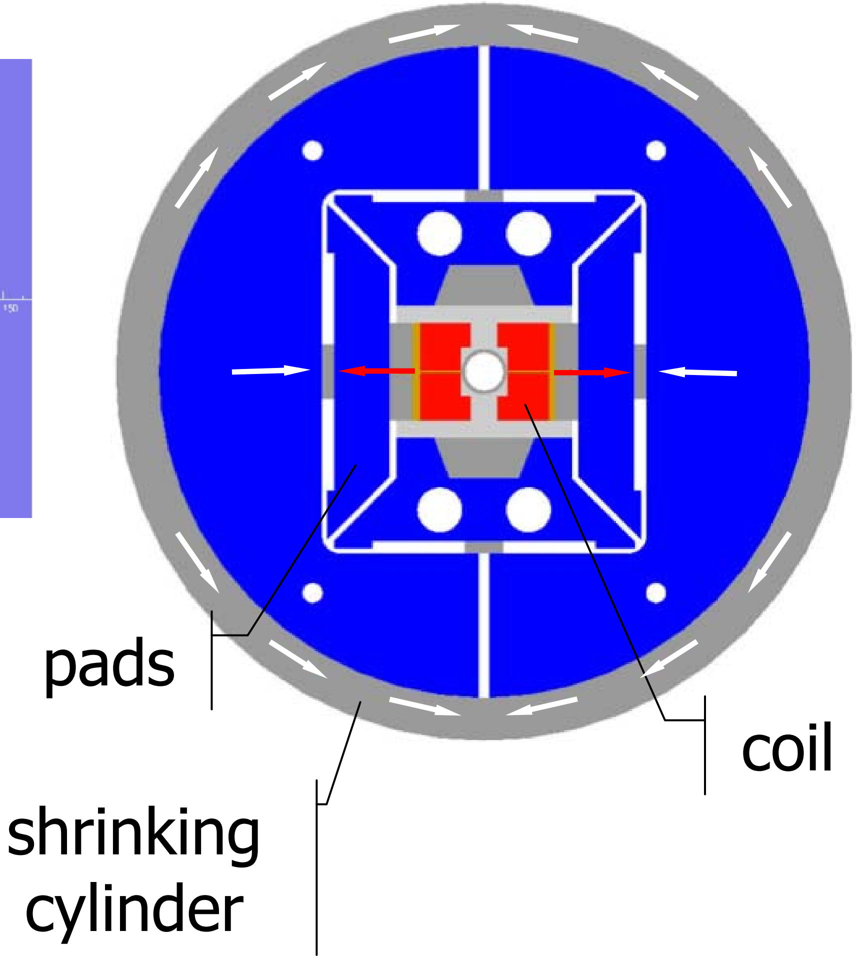
by courtesy of G. Sabbi

New force containment principles

Example: the bladder and key concept from LBNL







Coil wound in *blocks* to manage the distribution of stress in the cross section

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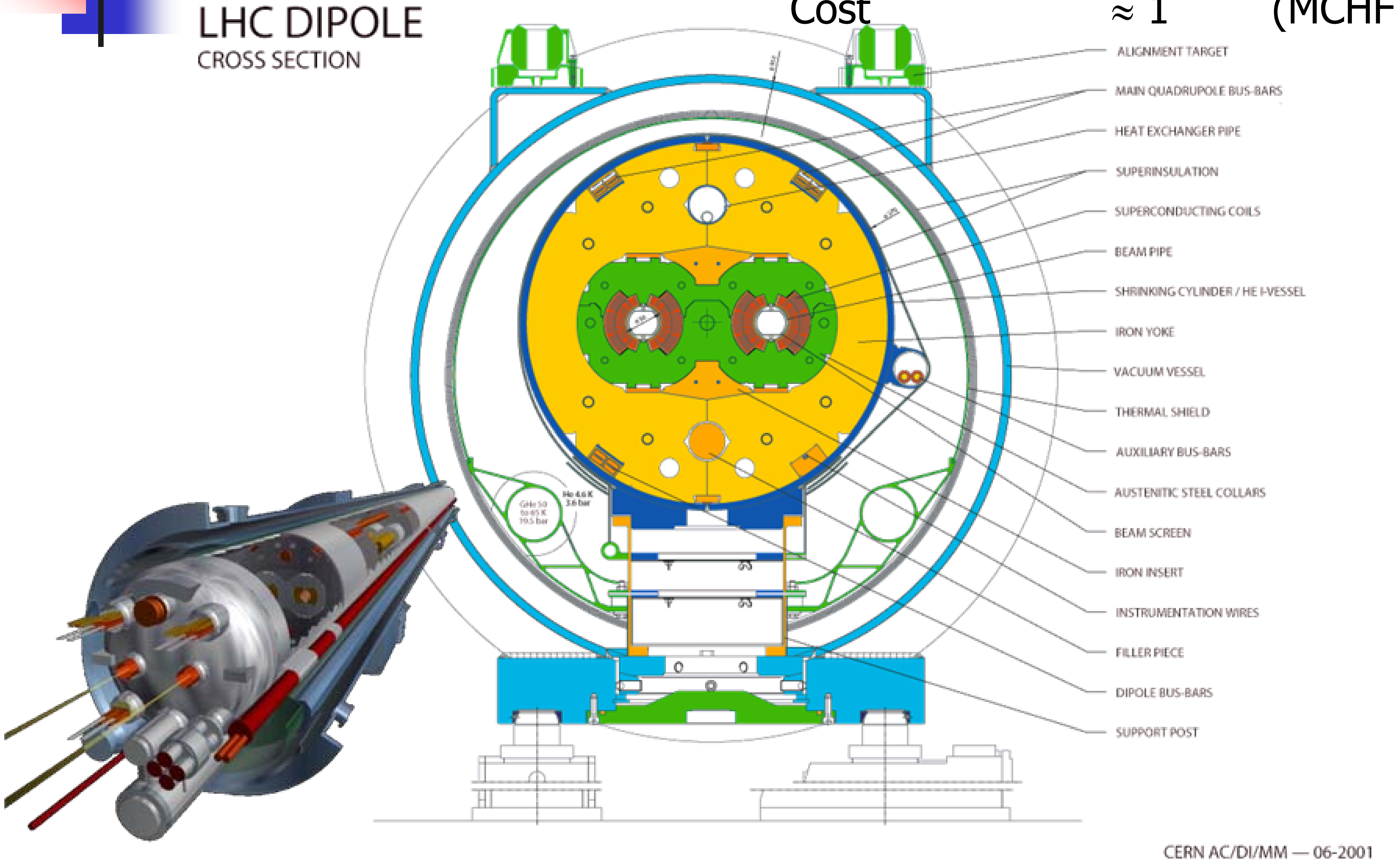
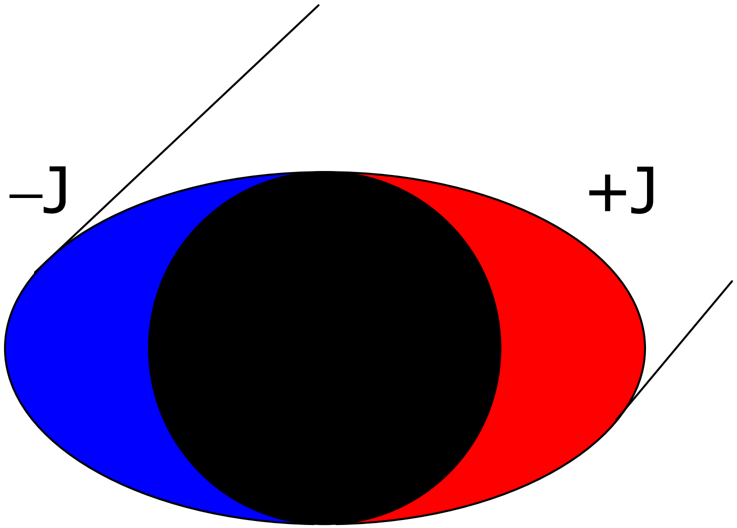
LHC dipole

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

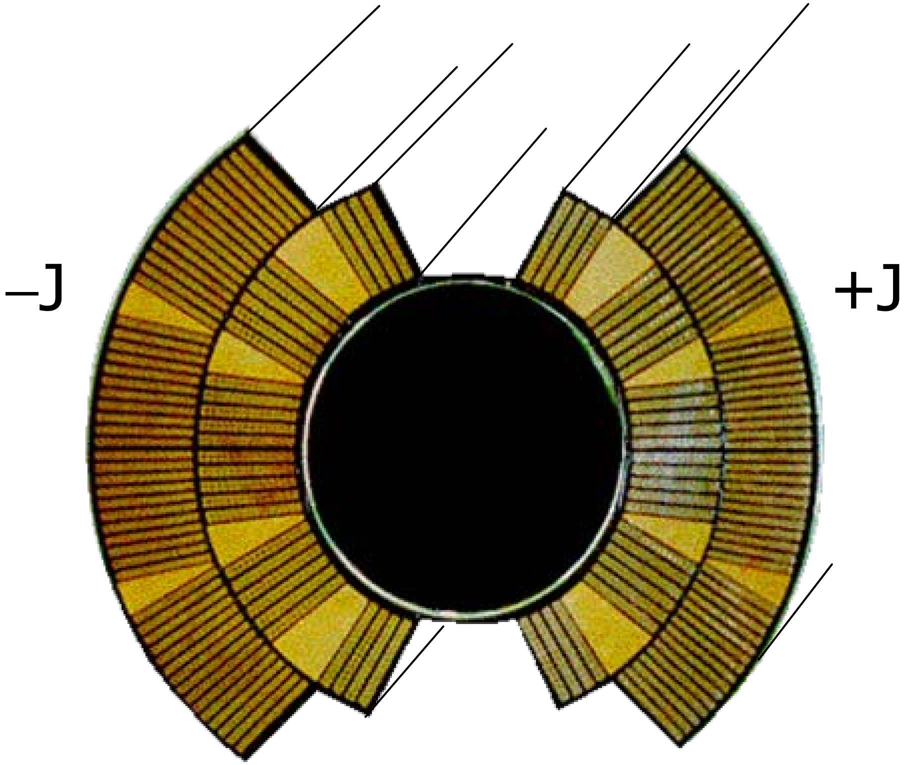


CERN AC/DI/MM — 06-2001

Superconducting dipole magnet coil

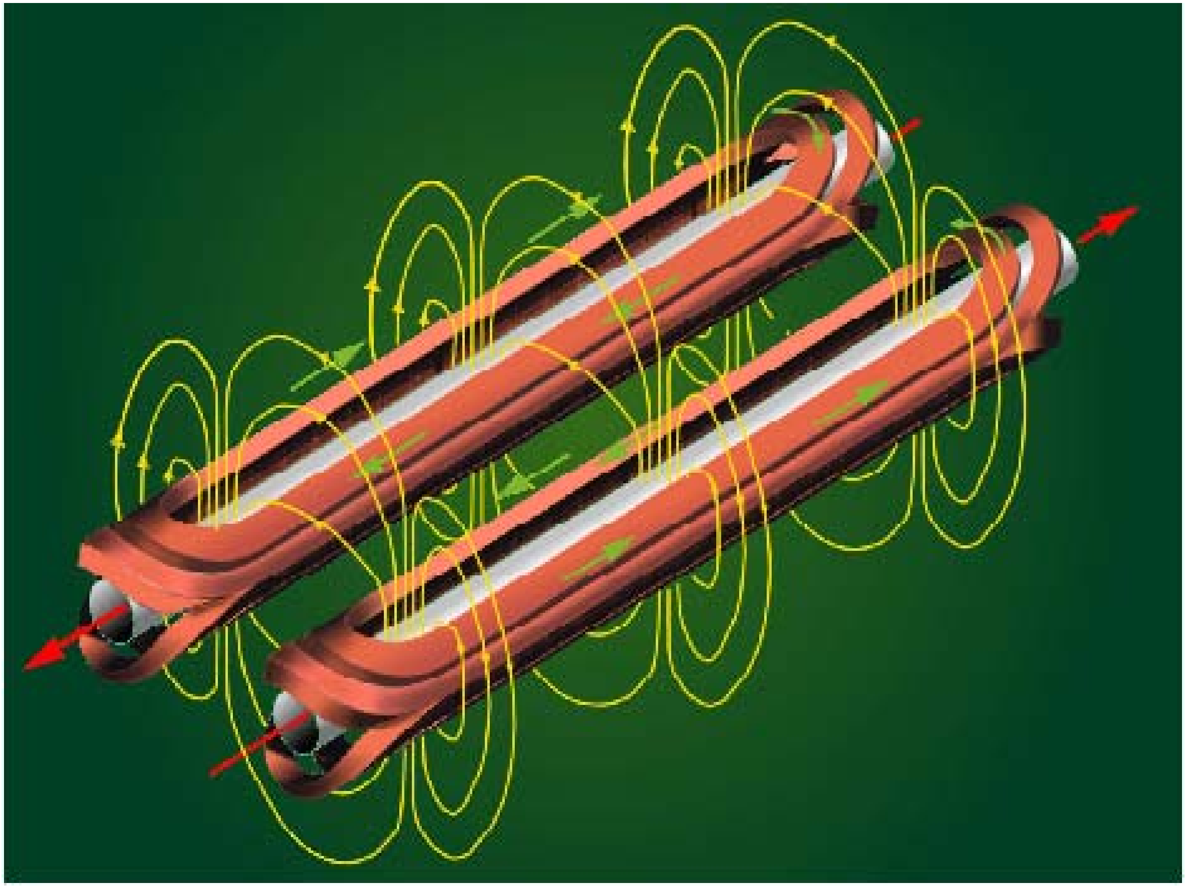


Ideal current distribution that generates a perfect dipole



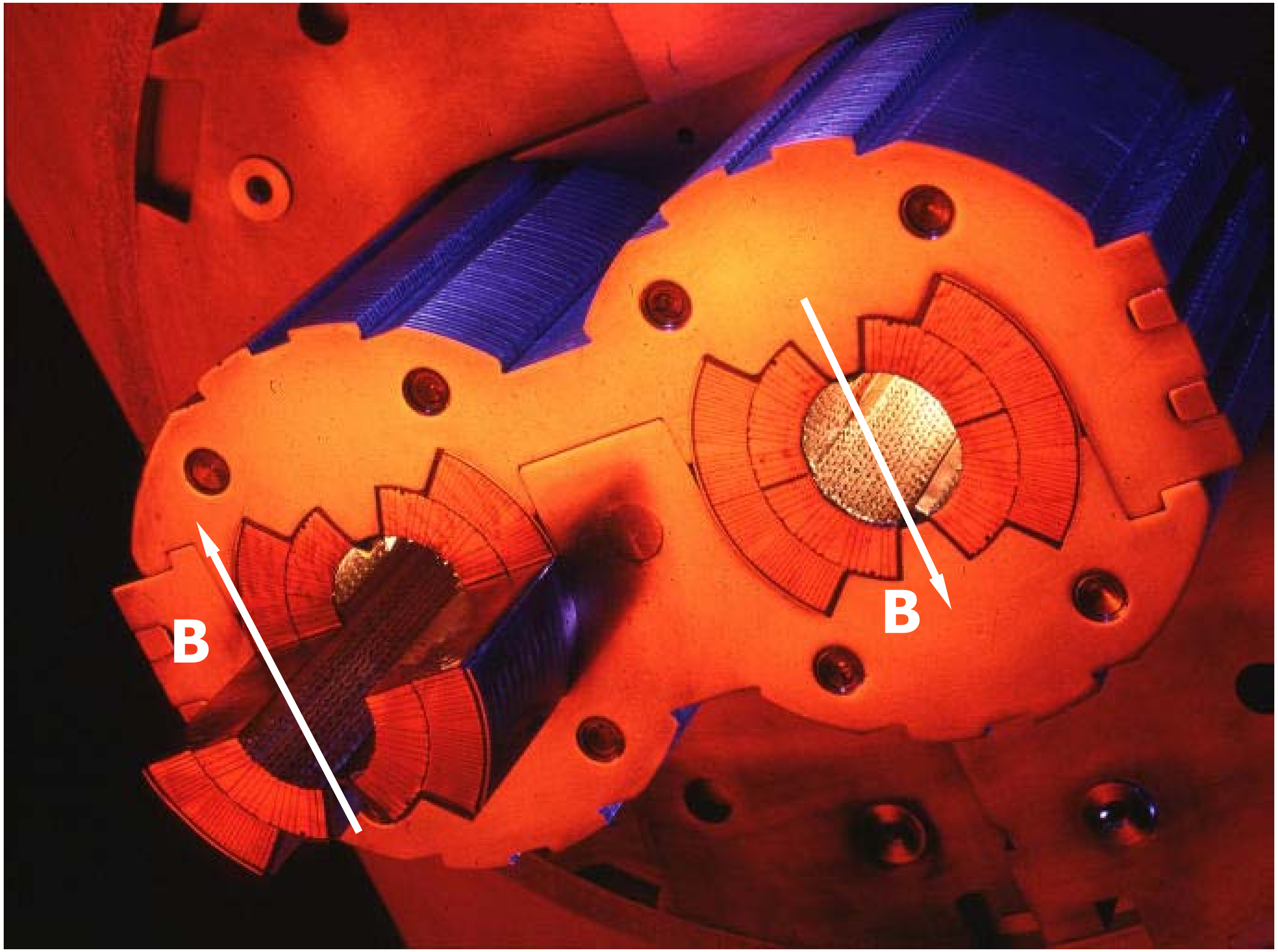
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle



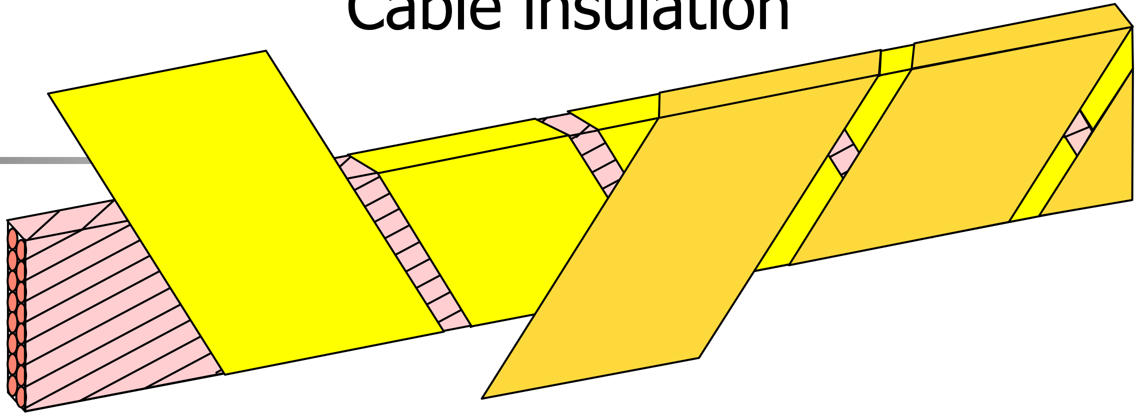
Combine two magnets in one
Save volume, material, cost

LHC dipole coils

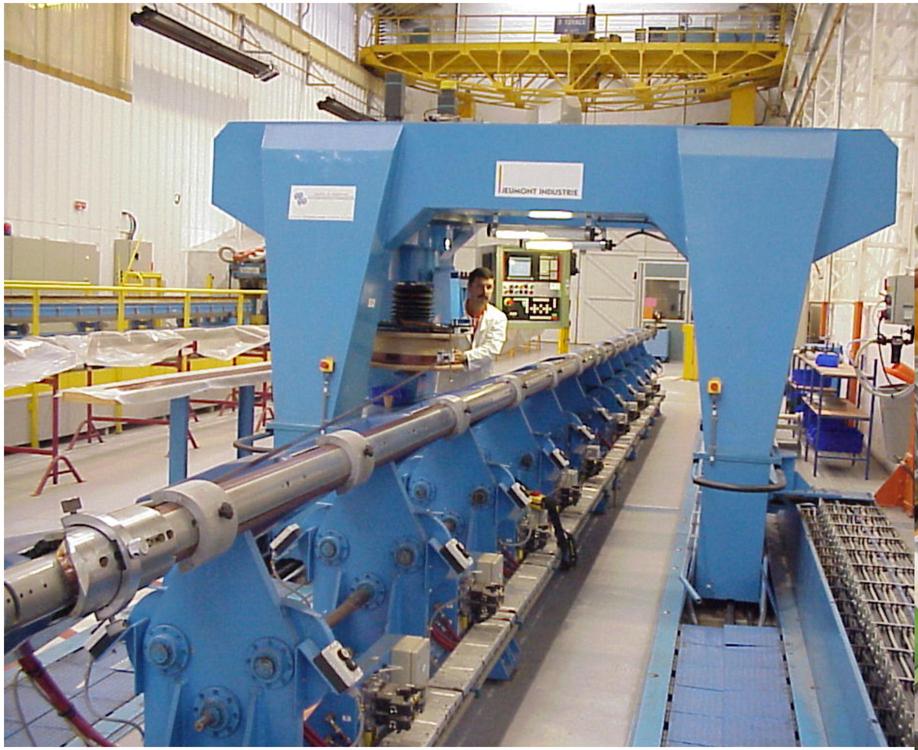


Coil winding

Cable insulation



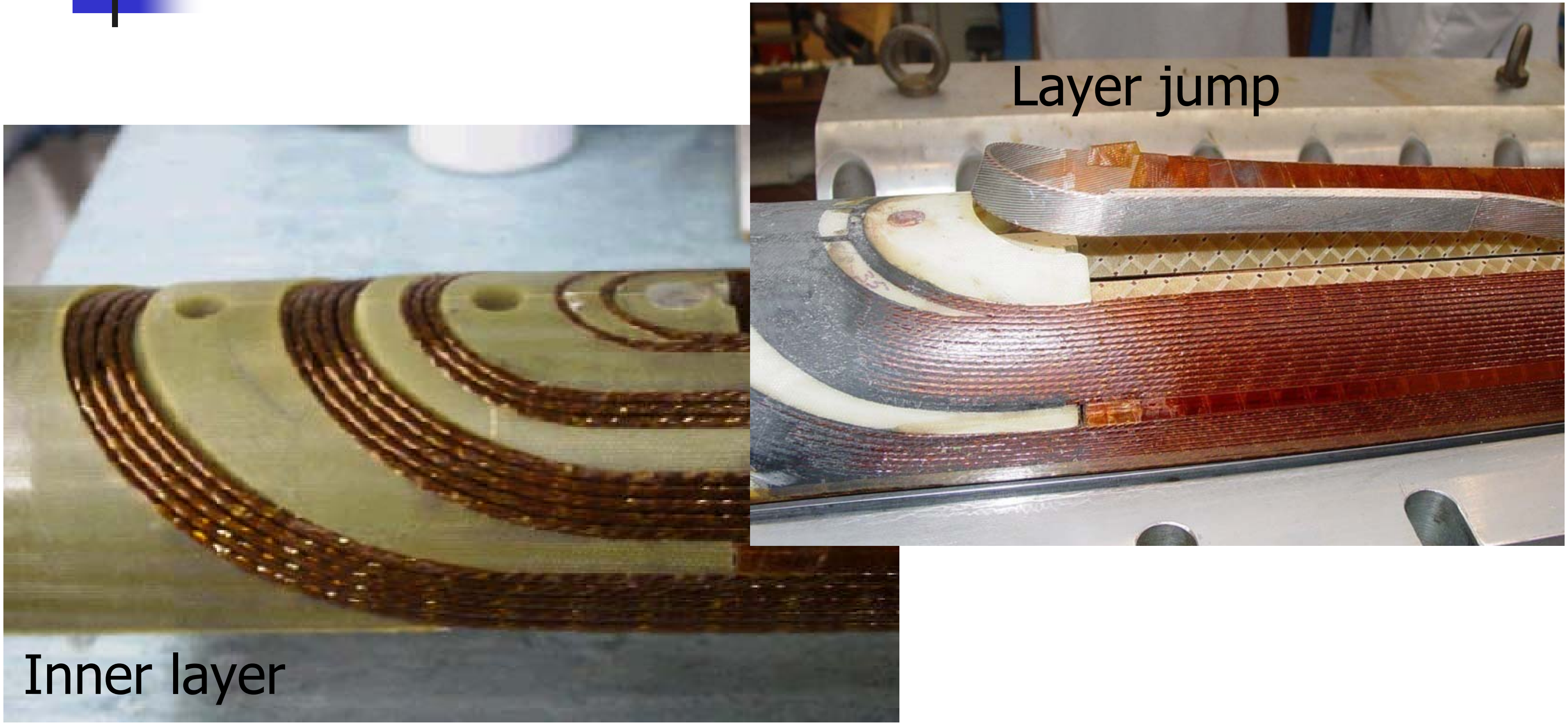
10 μm precision !



Coil winding machine

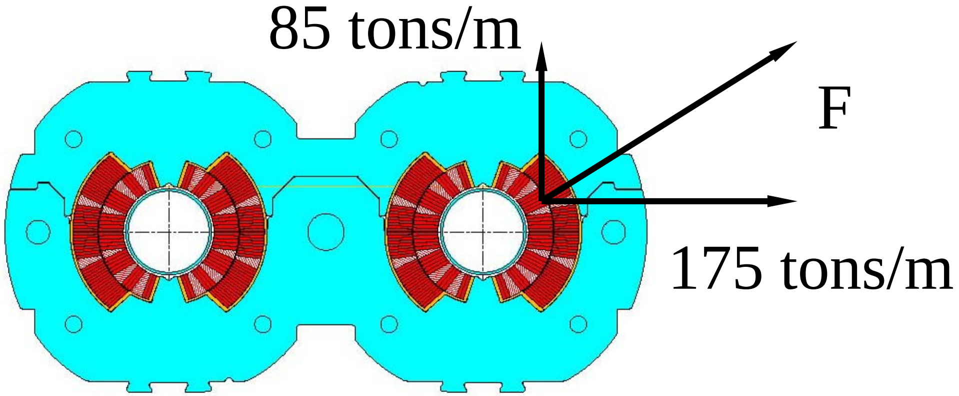
Stored coils

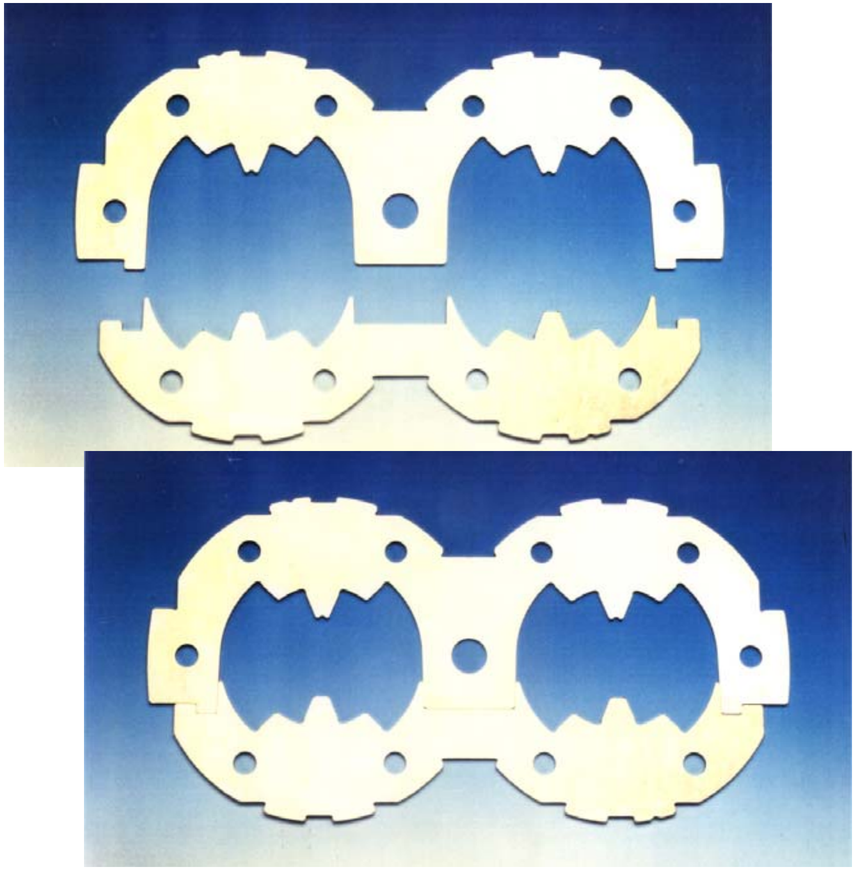
Ends



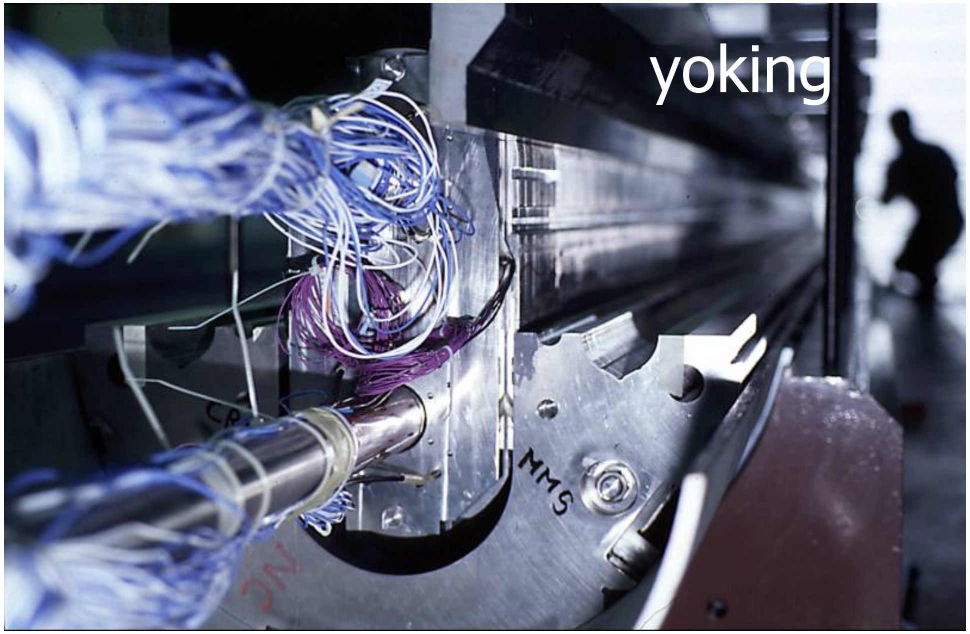
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking





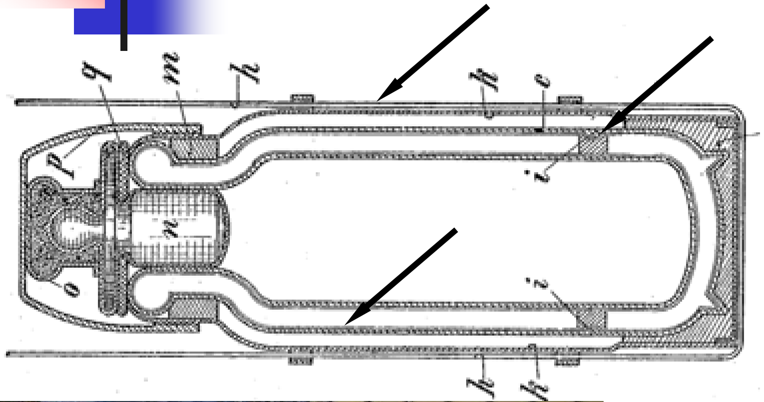
collaring



yoking

Cold mass

Cryostat



Thermal screens

Low conduction foot

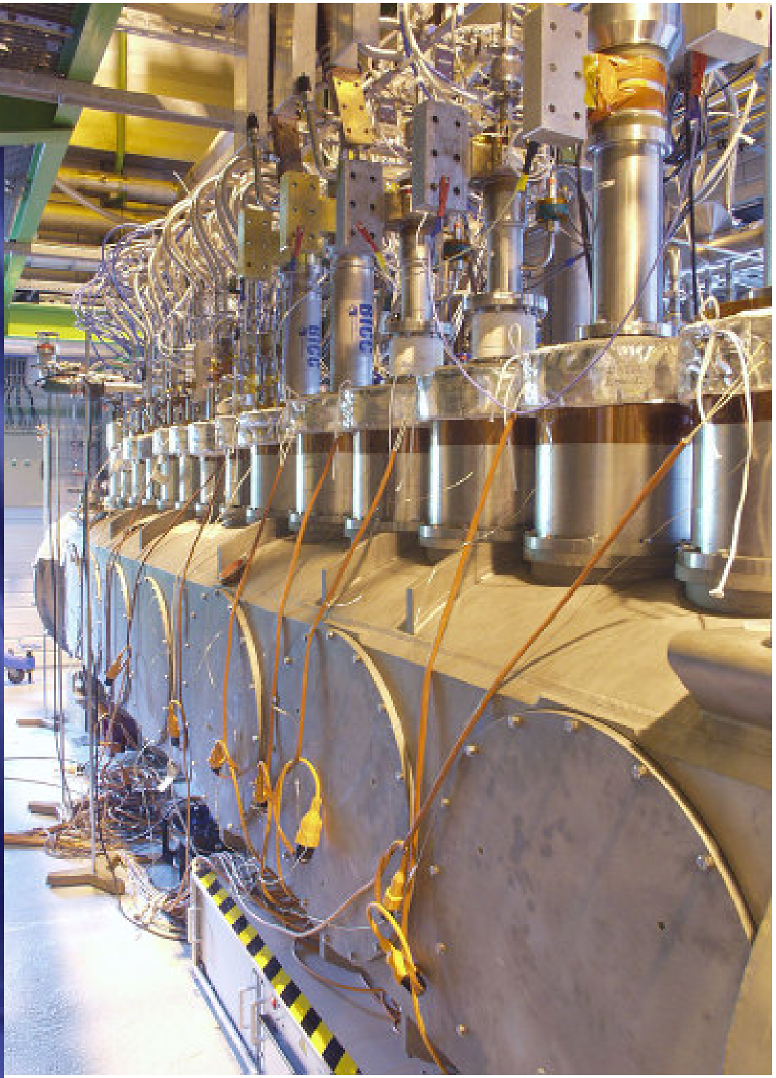
Current leads

Warm end (300K)

Intermediate
temperature (50K)

HTS

Cold end (4K)

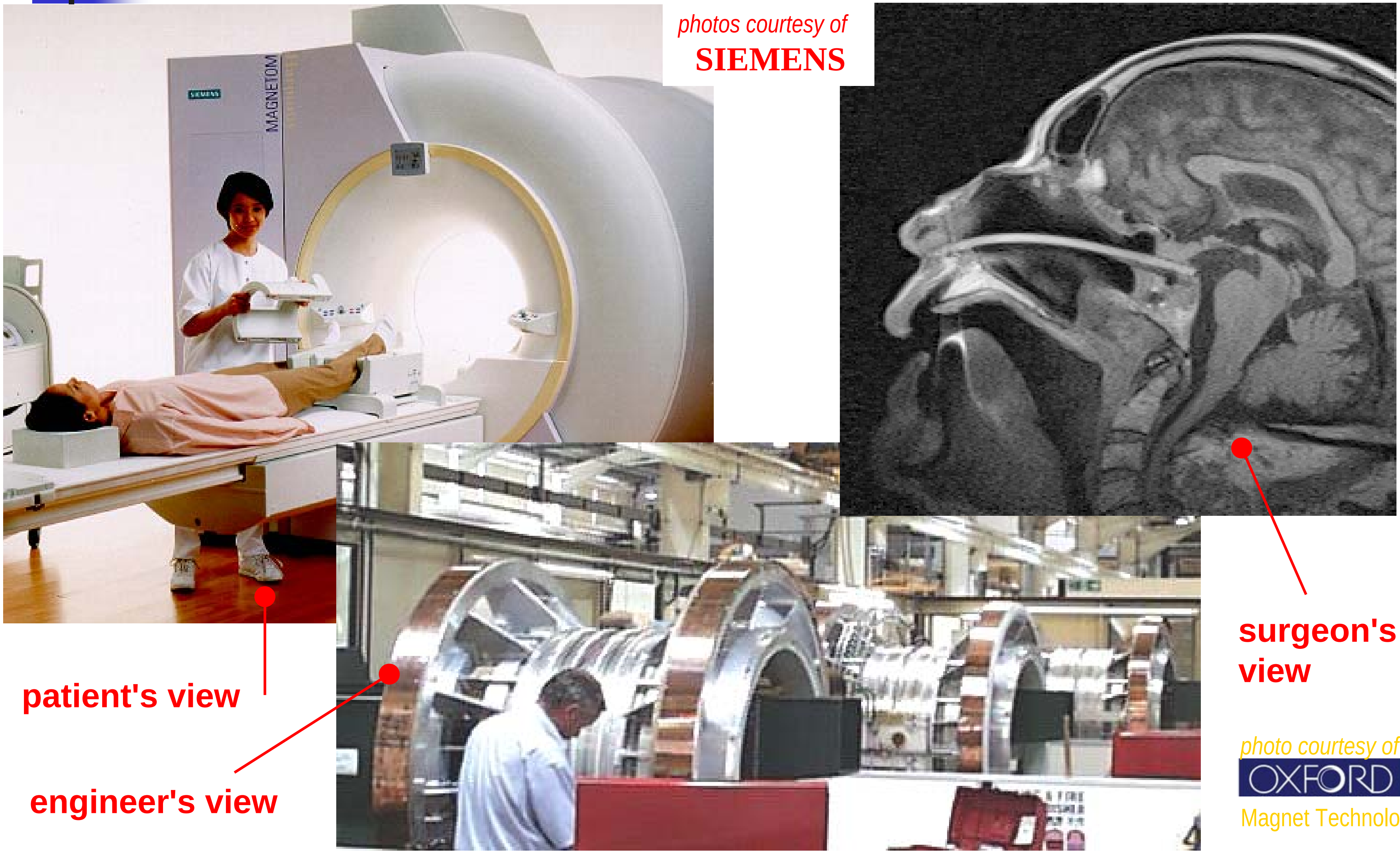


Finally, in the tunnel !

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 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

First 1 GHz (23.5 T) commercial NMR system

©Eric.Le Roux/Communication/UCBL

Motors & generators

Motor with HTS rotor

American Superconductor and Reliance

700 MW generator

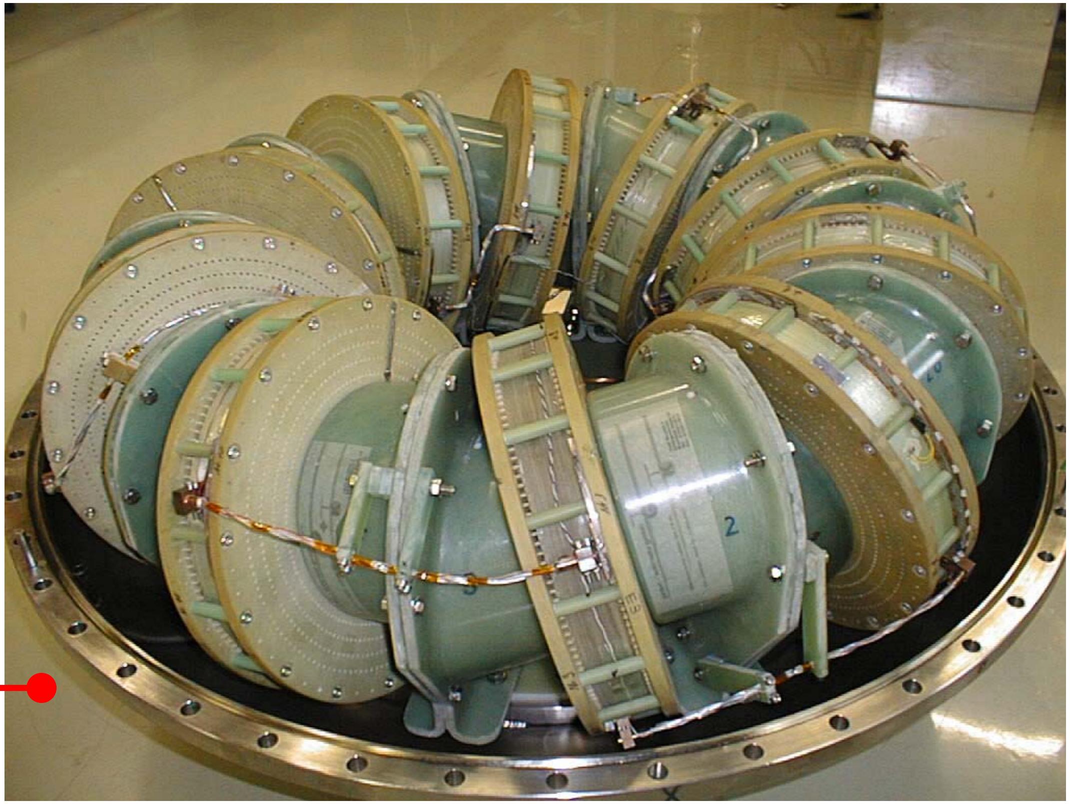
NbTi rotor

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

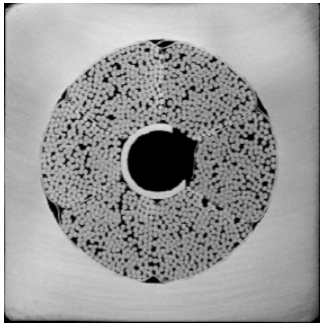
photo courtesy of **Carpco**

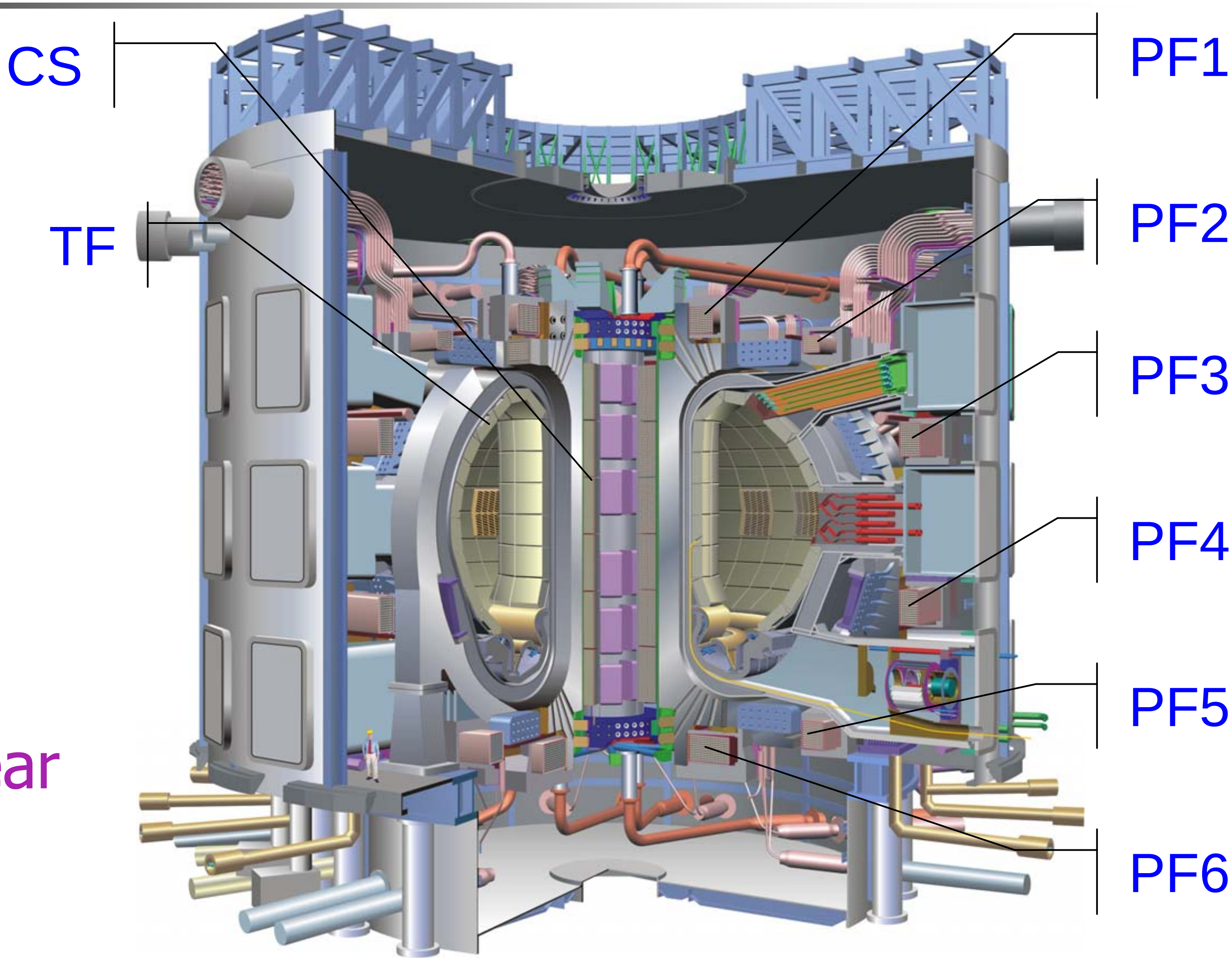
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

Thermonuclear fusion

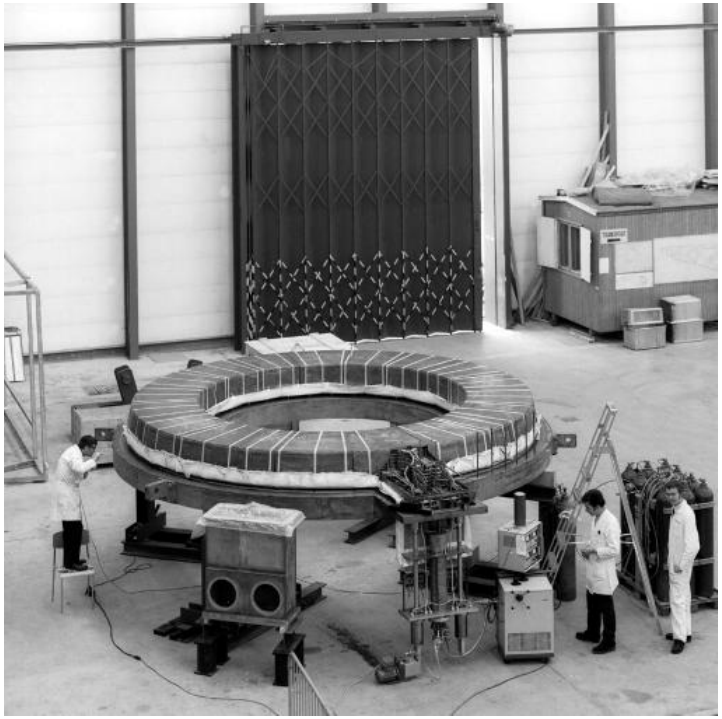




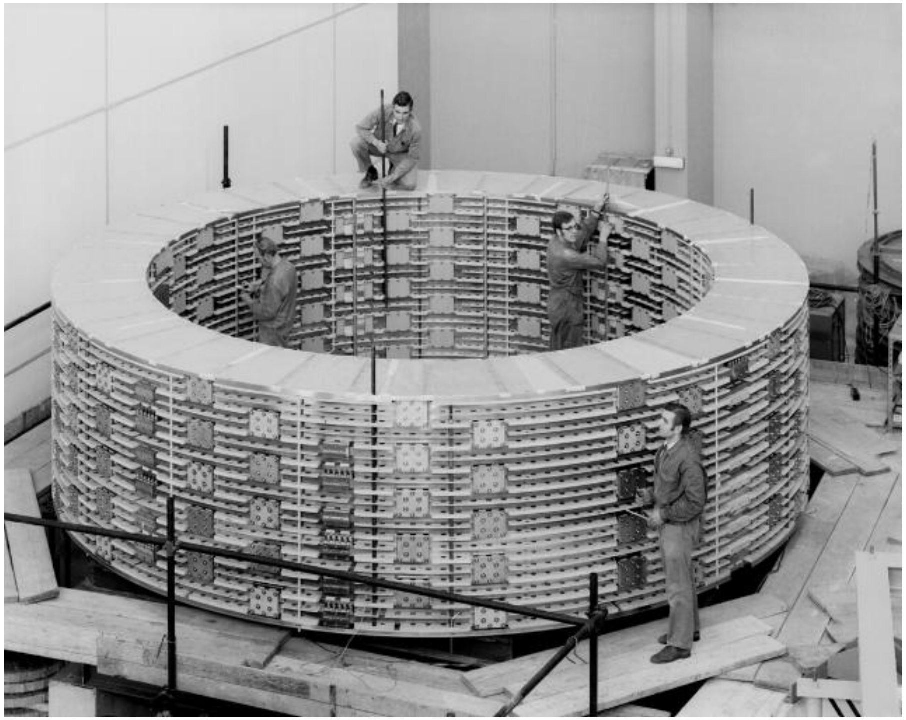
ITER

International
Thermonuclear
Experimental
Reactor

HEP detectors of the past...

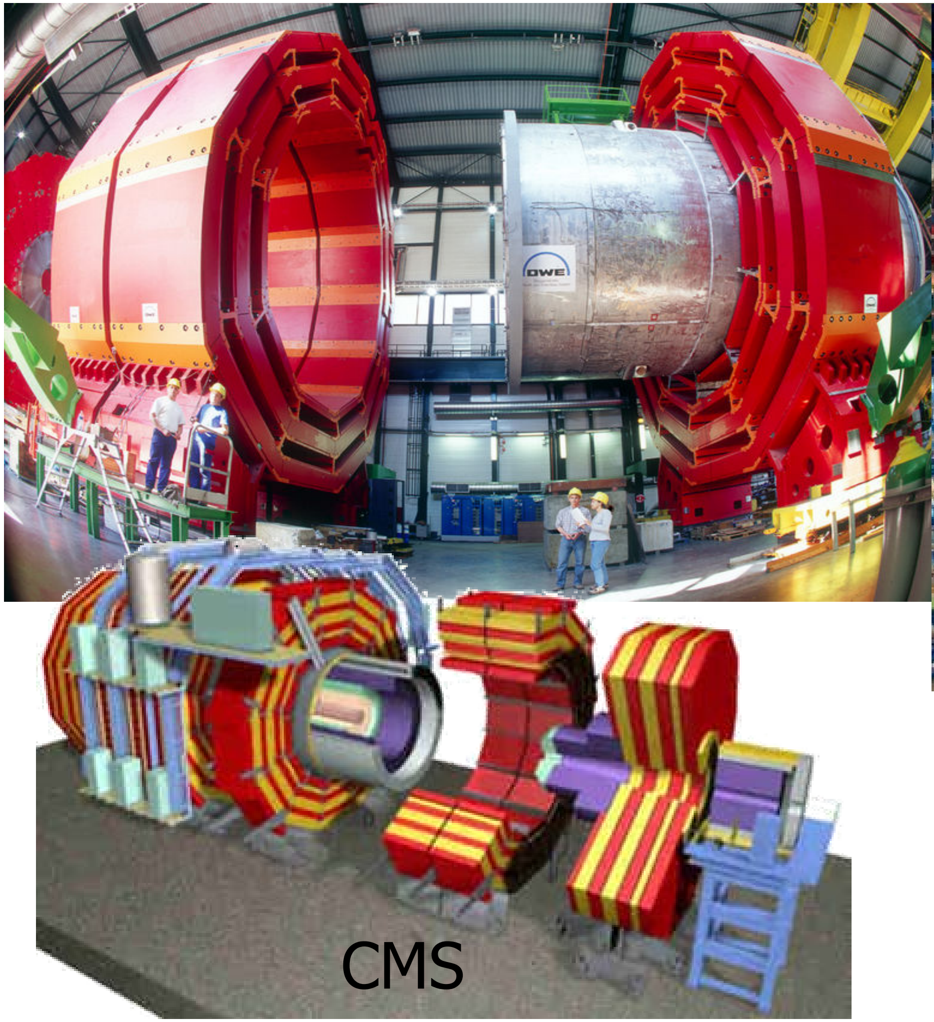


Omega

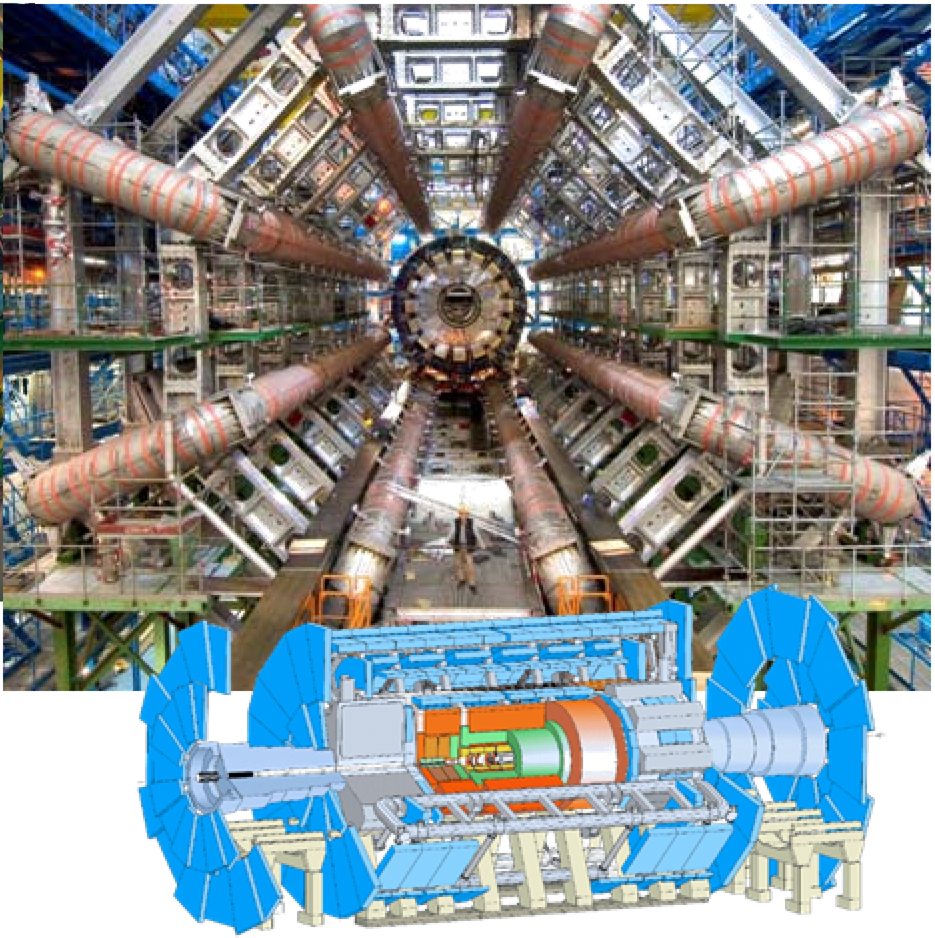


BEBC

… and HEP of the present (CMS and ATLAS)



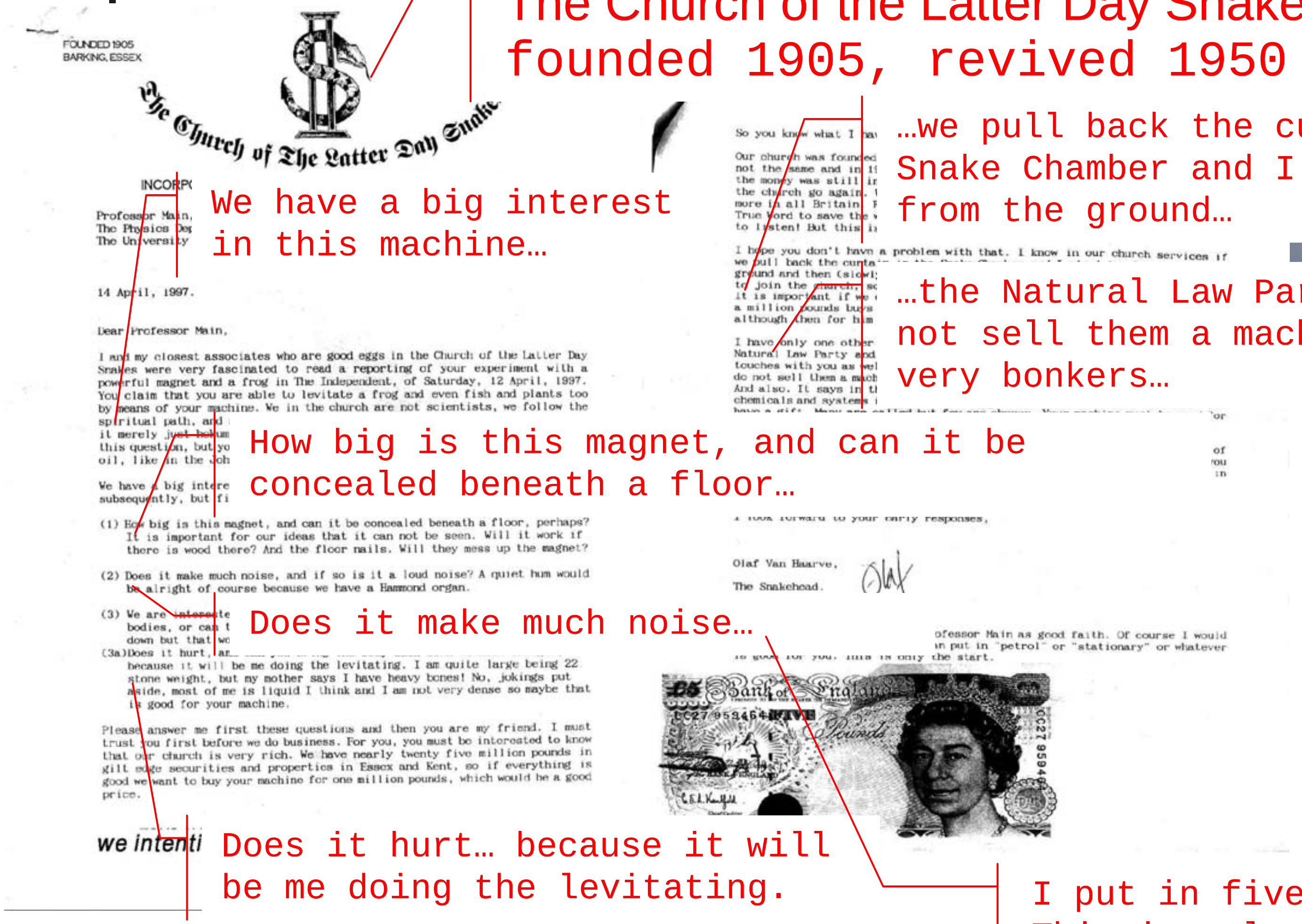
CMS



ATLAS

Other uses of superconductivity

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



FOUNDED 1905
BARKING, ESSEX

The Church of The Latter Day Snakes

INCORPO

Professor Main,
The Physics Dep
The University

14 April, 1997.

Dear Professor Main,

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

We have a big intere
subsequently, but fi

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

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

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

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

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

we intenti

So you know what I hav

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

I hope you don't have a problem with that. I know in our church services if we pull back the curta
ground and then (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

Olaf Van Haarve,

The Snakehead.

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

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.

g

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 ⇒ 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

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