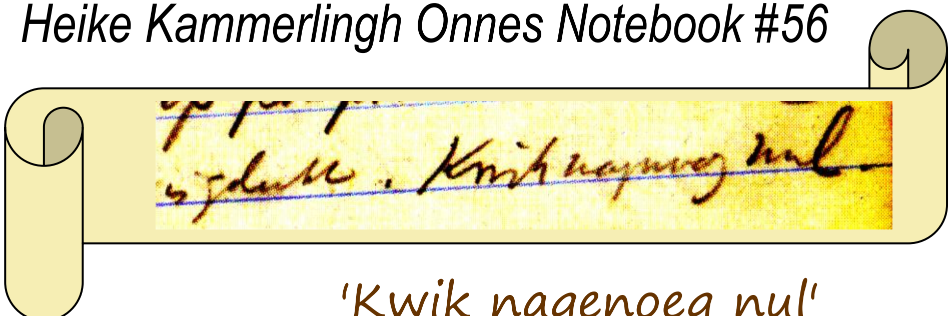
100 Years of Superconductivity
50 Years of Superconducting Magnets

Martin N Wilson

11th April 1911

Heike Kammerlingh Onnes Notebook #56



'Kwik nagenoeg nul'

quick silver near enough zero

1st November 1961

International Conference at MIT on

High Magnetic Fields

sketch of HKO by his brother Menso Kammerlingh Onnes

Serendipity - but only after years of preparation

1882 HKO appointed professor of experimental physics at university of Leiden.
- mission: test Van der Waals molecular theory of gases
- motto: 'through measurement to knowledge'
- cryogenic laboratory - a cold factory ⇒ big science

1892 oxygen liquefier ⇒ 14 litres/hour

1901 Leiden laboratory workshops organized as an instrument makers school
- the 'blue collar boys'
- a modern laboratory

1906 hydrogen liquefier ⇒ 4 litres/hour

1908 helium liquefier ⇒ 0.28 litres/hour

1910 first measurements on resistivity

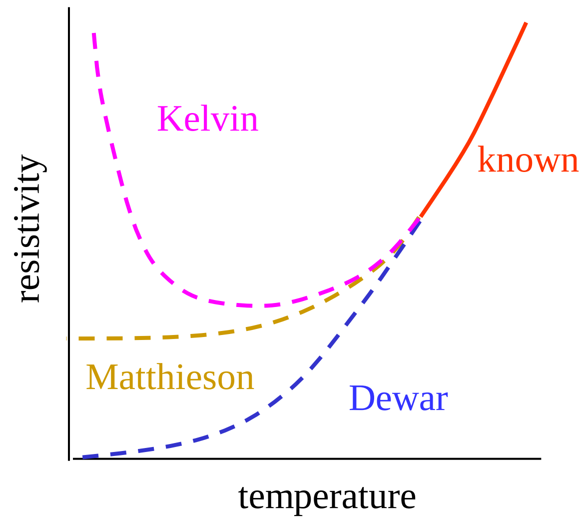
The Leiden helium liquefier

1908 0.28 liquid litres helium per hour

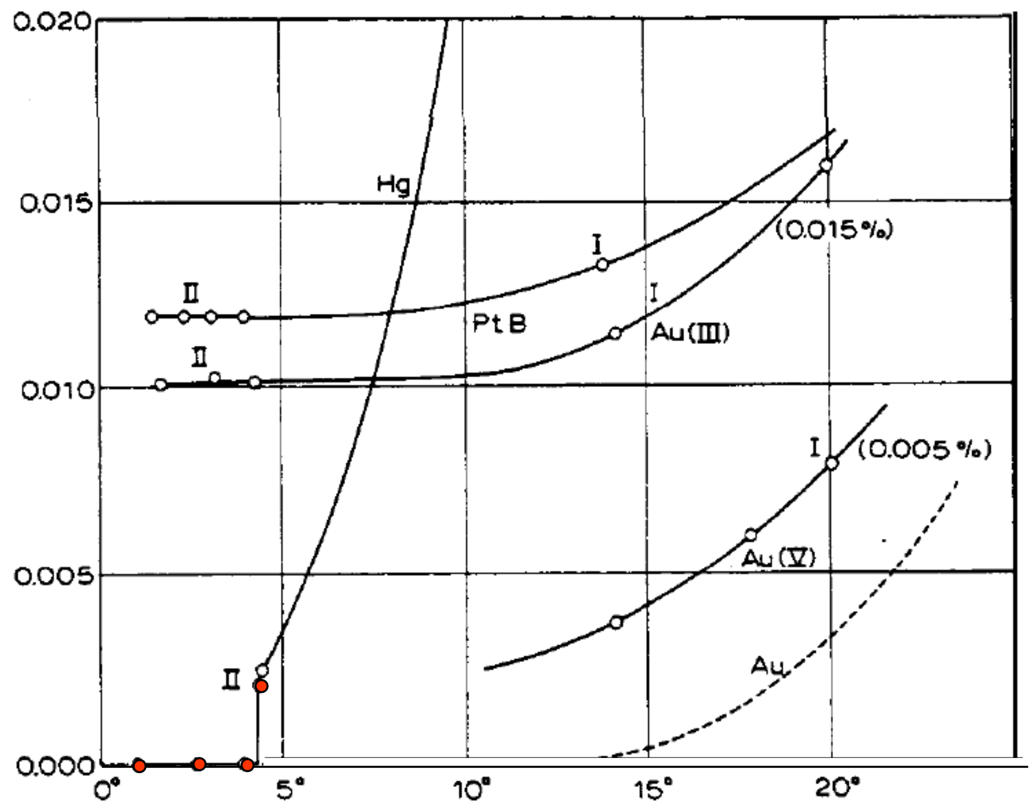
1911 addition of side arm cryostat with stirrer for experiments

1912 improved version liquefies 0.5 litres per hour

1911: Resistivity at low temperature



- very different predictions of what might happen



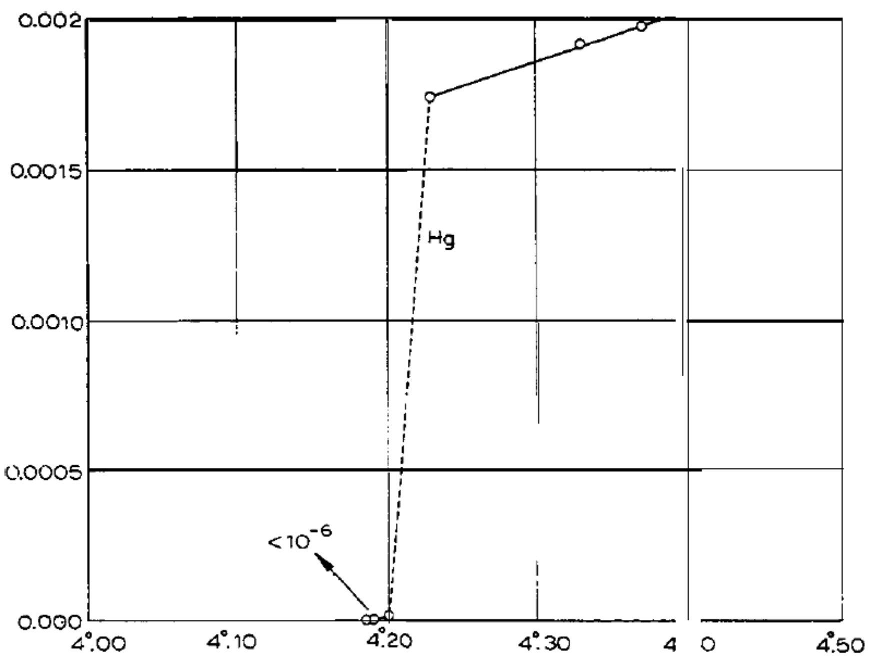
from HKO Nobel lecture

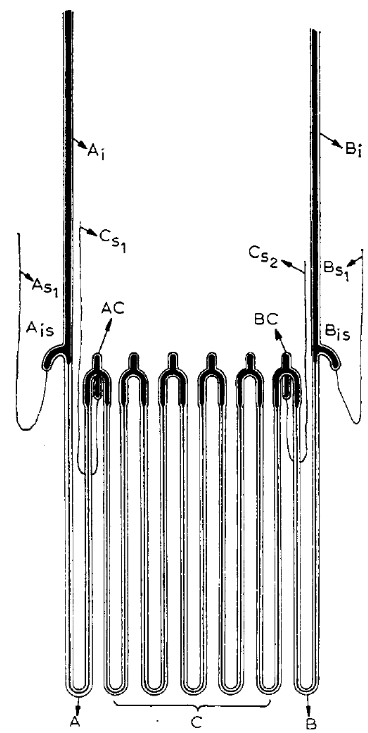
- need high purity to see variations at very low temperature
- Leiden had expertise in purifying Hg by multiple distillation

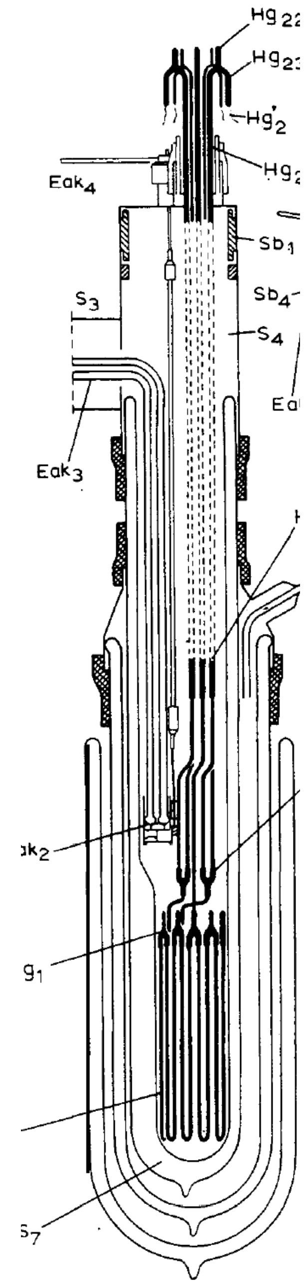
- ***but nobody expected this!***

Superconductivity

'.....something unexpected occurred.
The disappearance did not take place gradually
but abruptly. ...... less than a thousand millionth part'







'......mercury at 4.2 has entered a new state which .... can be called the state of superconductivity' *HKO Nobel Lecture*

Persistent currents

lead coil with shorted terminals

impose magnetic field when warm

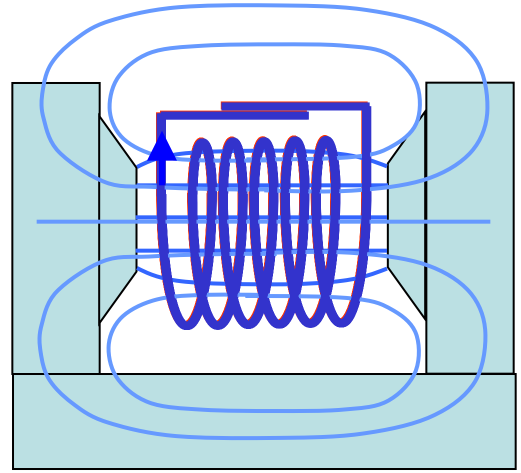
cool the coil

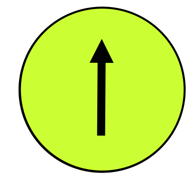
remove field - induces current

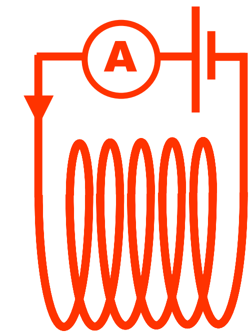
measure field from current

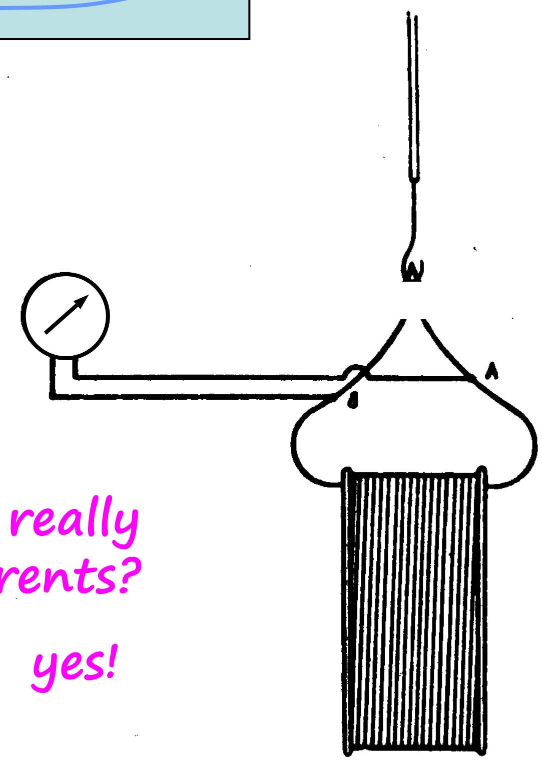
back off with a resistive coil

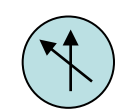
no change for hours - persistent current











> 'It is uncanny to see ……… You can feel, almost tangibly how the ring of electrons in the wire turns around, around, around – slowly and almost without friction'
>
> P Ehrenfest

are they really currents?

yes!

Magnets

' ………. bearing on the problem of producing intense magnetic field ……a great number of Ampere windings can be located in a very small space without …….. heat being developed…..'

Communication from the Physical Laboratory University of Leiden Sept 1913

' ……….. 100,000 Gauss could then be obtained by a coil of say 30 centimetres in diameter and the cooling with helium would require a plant which could be realized in Leiden with a relatively modest support………..'

Third International Congress of Refrigeration, Chicago Sept 1913

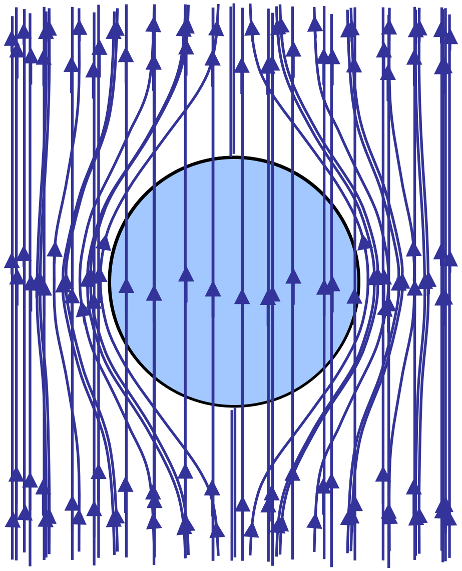
' ……… In field above this threshold value, a relatively large magnetic resistance arises at once…..'

'Thus an unexpected difficulty …………. faced us. The discovery of the strange property which causes this made up for the difficulties involved.'

Nobel Prize Acceptance Lecture, Stockholm Dec 1913

1930s: magnetic properties

1933: Meissner (& Ochsenfeld) effect



- cool down superconductor in magnetic field
- at the critical temperature θ_c the field is pushed out
- increase the field - field is kept out
- increase the field some more - superconductivity is extinguished and the field jumps in
- decrease the field - it's pushed out again

1935: London theory

- within a superconductor

$$\nabla^2 B = B / \lambda$$

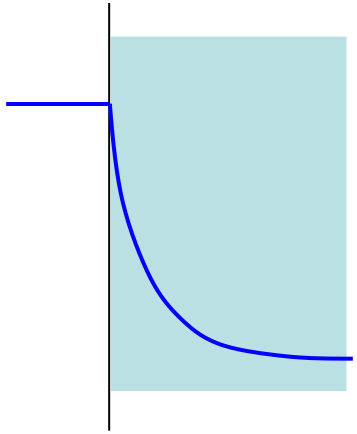
$$\lambda^2 = m / 2e^2 \mu_o n_c$$

where m = mass electron, e = charge electron, n_c *= density of carriers*

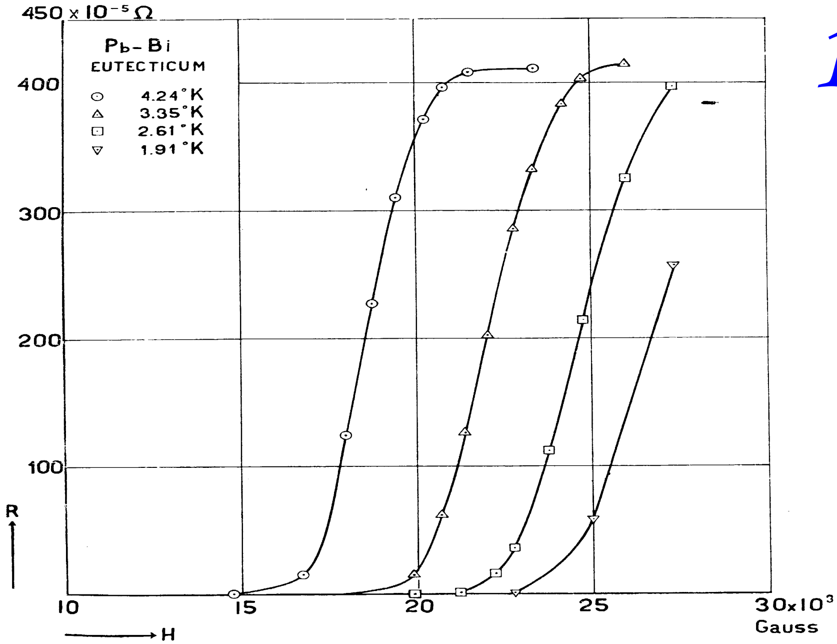
- so at the boundary

$$B = B_o \exp(-x/\lambda)$$

λ = London penetration depth



1930s: magnetic properties

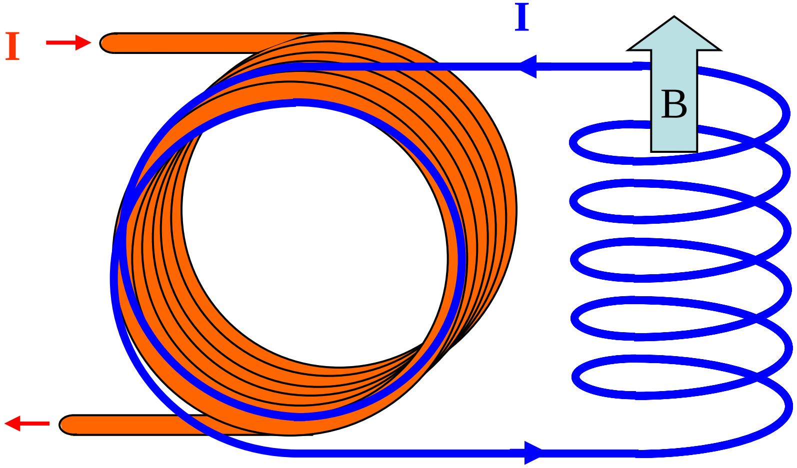


1930: Alloys

- at the Kammerlingh Onnes Laboratory, Keesom and de Haas showed that some alloys, eg PbBi, remain superconducting up to much higher fields than mercury, and lead.

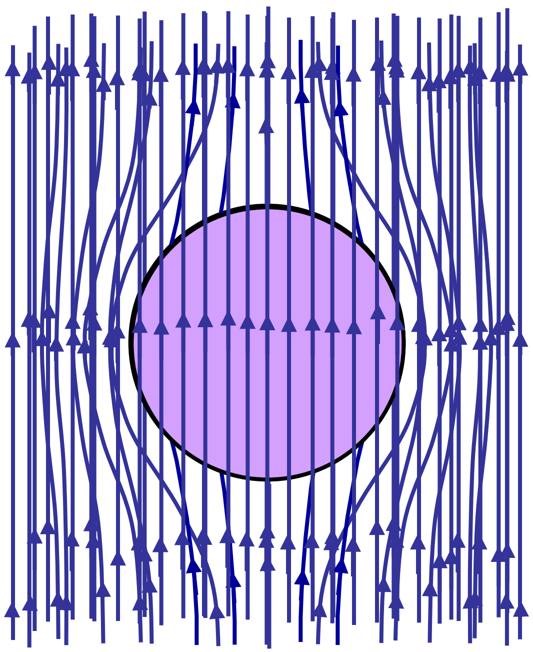
1933: Magnets

- Mendelssohn in Oxford made a small PbBi solenoid for adiabatic demagnetization work
- it didn't work
- in retrospect *'.....the only explanation I can offer is that the solenoid was not made from drawn wire but cut from a cast cylinder.'*



1930s: magnetic properties

1937: Type 2 superconductors



- at Kharkov, Ukraine, Shubnikov showed that some materials show a more complicated Meissner effect
- field expelled at critical temperature
- increasing field penetrates partly at the lower critical field H_{c1}
- superconductivity not destroyed until (much higher) field H_{c2}
- fully reversible - state of thermodynamic equilibrium

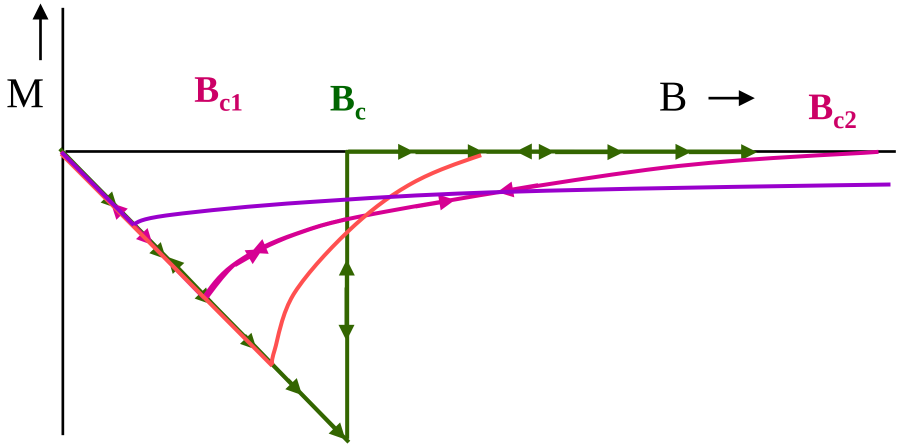
Magnetization

(magnetic moment per unit volume)

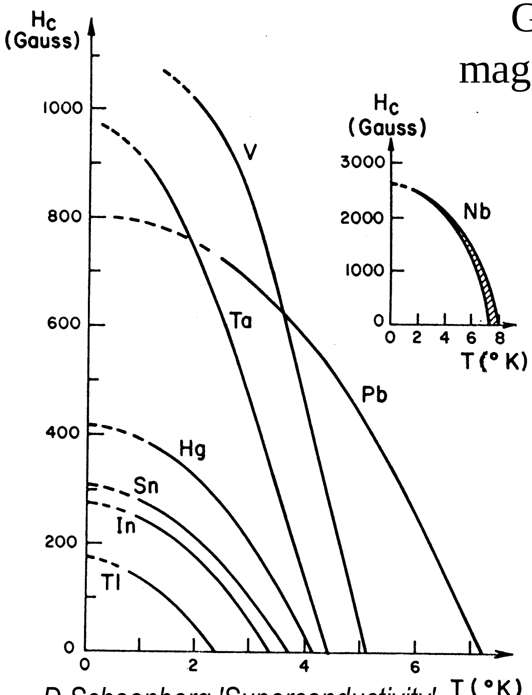
Type 1: diamagnetic up to B_c then resistive

Type 2: diamagnetic up to B_{c1} then partially diamagnetic up to B_{c2} then resistive

more alloy additions ⇒ lower $_{Bc1}$ higher B_{c2}



1954: the first superconducting magnet

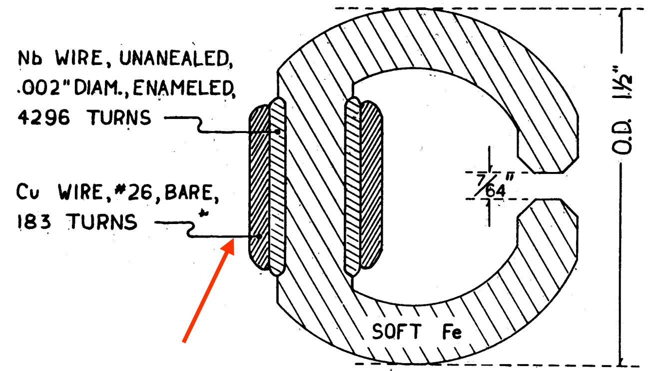


D Schoenberg 'Superconductivity'

George Yntema University Illinois
magnet for adiabatic demagnetization

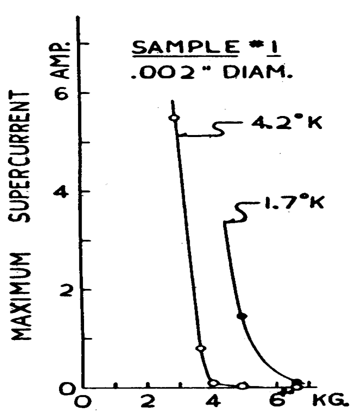
got niobium data from Schoenberg's book

but didn't read
'.......superconducting solenoids....but none of these possibilities could be realized because (high) critical field is characteristic of a very small fraction of the alloy...'

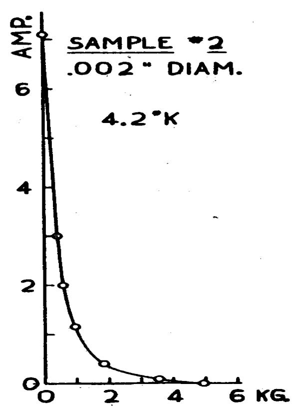


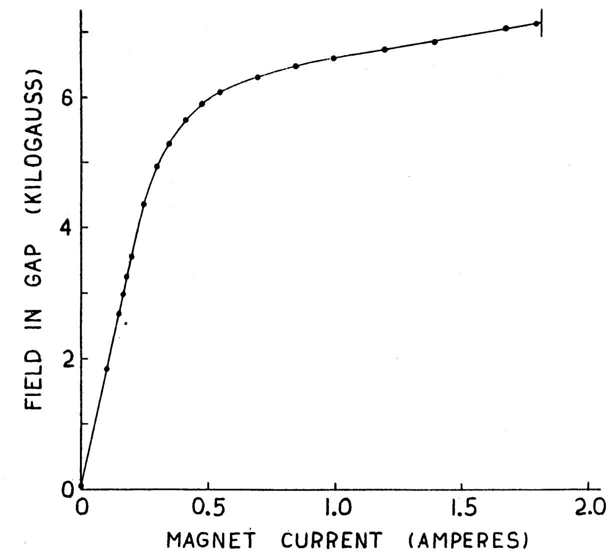
for quench protection

hard



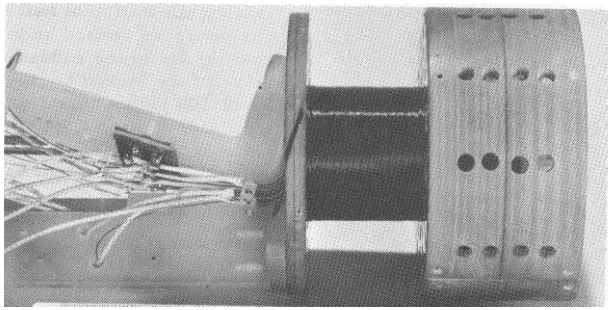
annealed



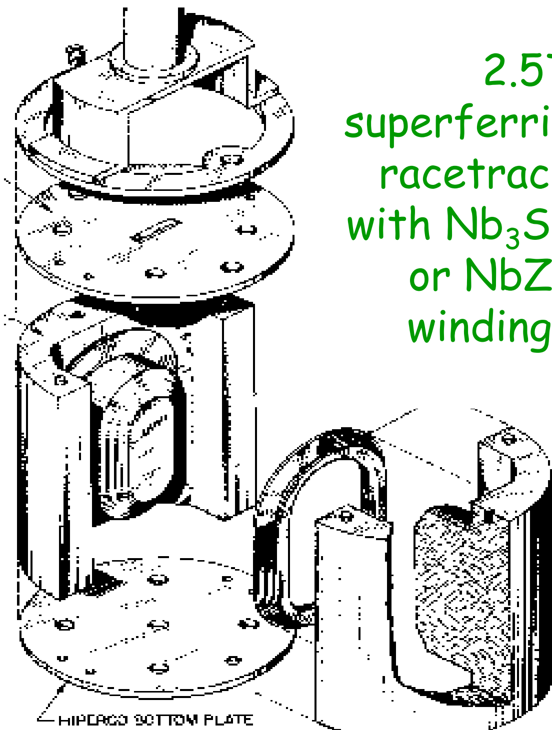


1961: MIT Conference on High Magnetic Fields

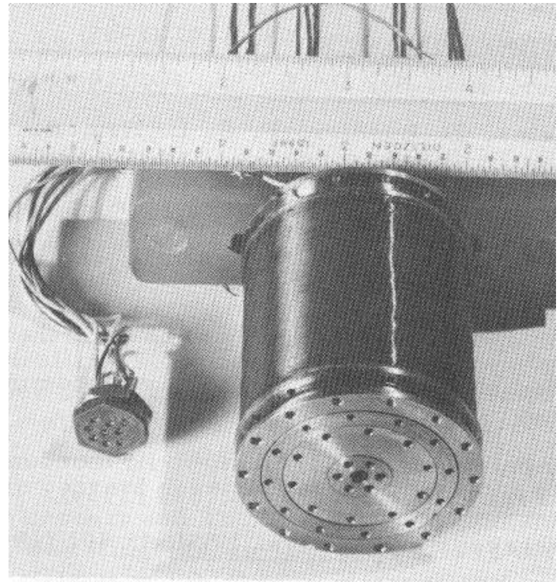
4.3T NbZr solenoid



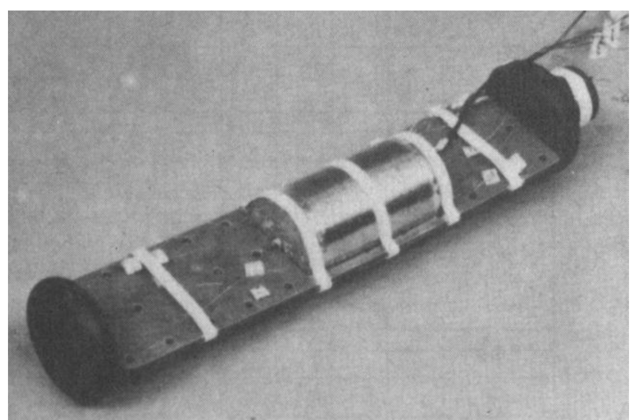
2.5T superferric racetrack with Nb_3Sn or NbZr windings



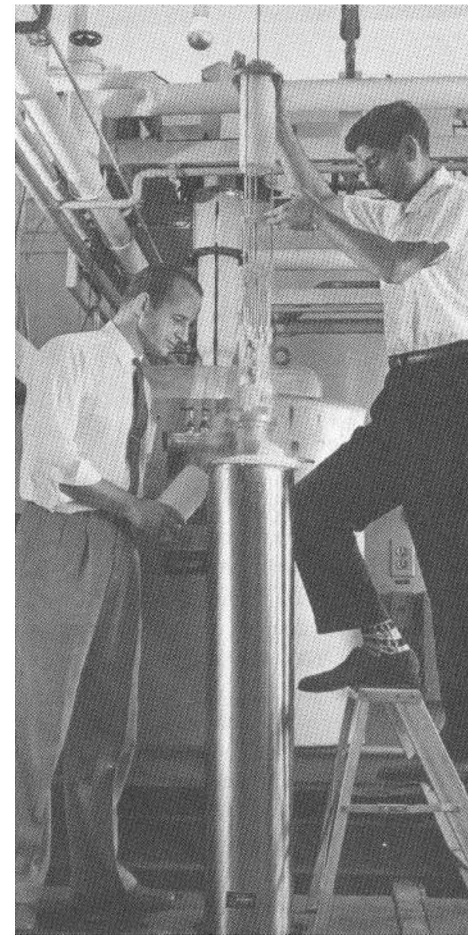
5.5T NbZr solenoid



1.5T MoRe solenoid

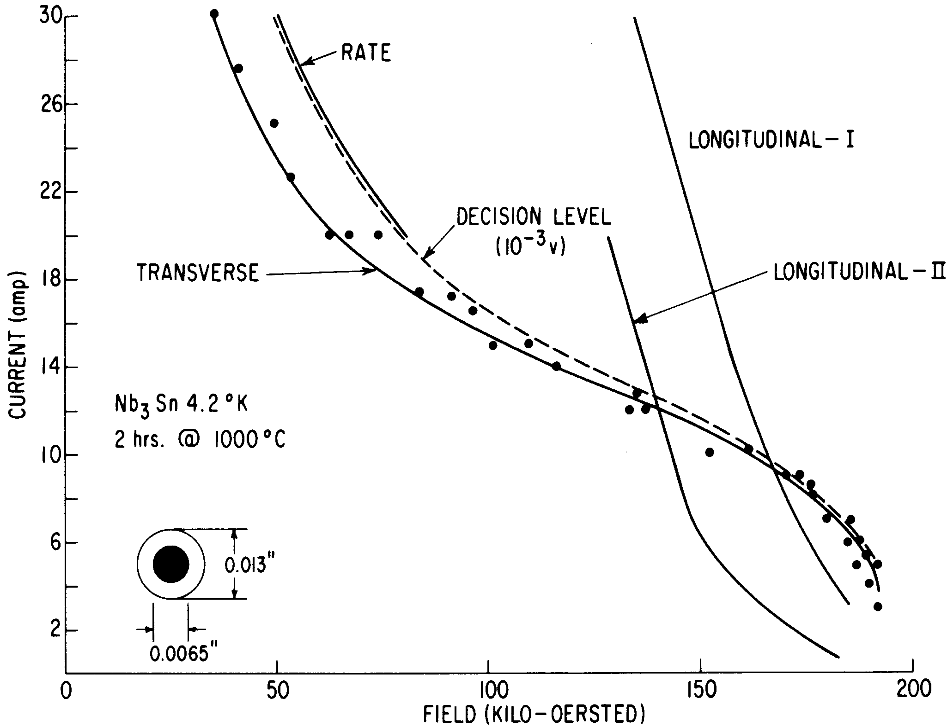


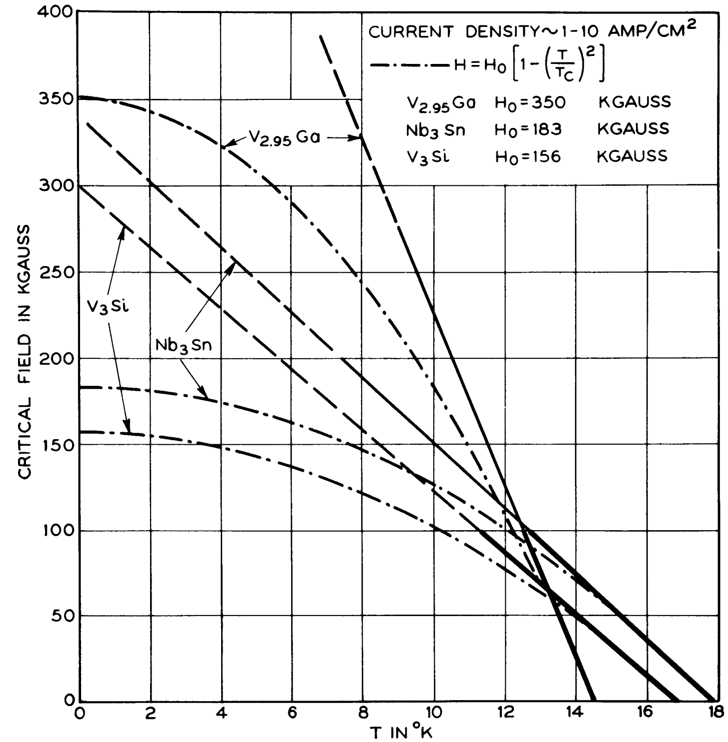
Magnets in cryostats for the first

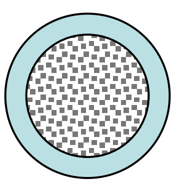


1961: MIT Conference on High Magnetic Fields

Nb_3Sn: a brittle intermetallic compound







- draw down Nb tube filled with Nb & Sn powder then heat to ~1000C
  JE Kunzler, Bell Labs
- measured in pulsed high field
  HR Hart et al GE Research Labs

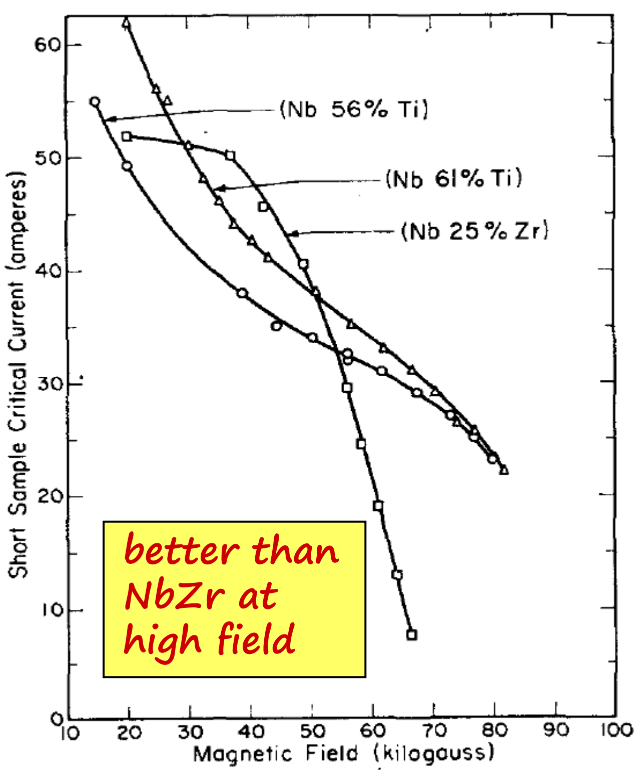
Bernd Matthias found Nb_3Sn and probably more new superconductors than anyone else

NbTi: a ductile alloy

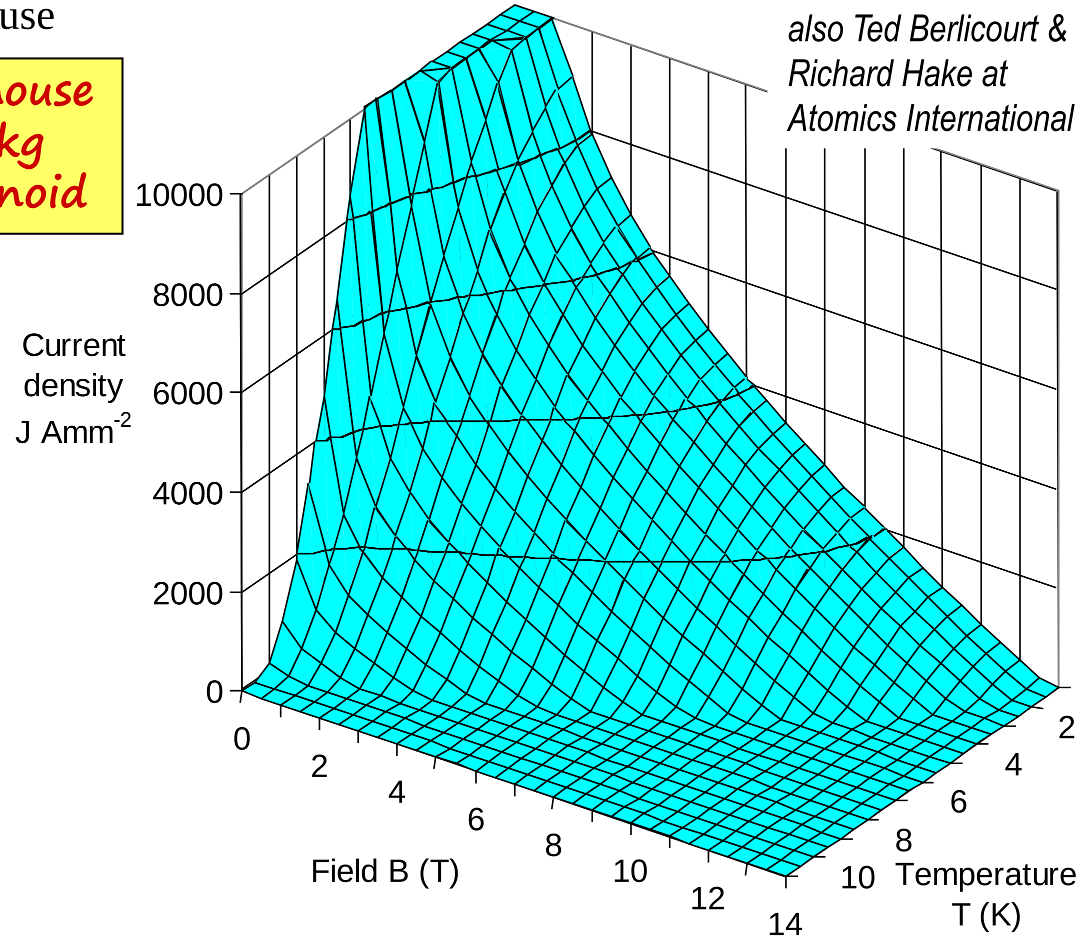
John Hulm
did much of the early work on NbTi at Westinghouse

1965: Westinghouse report a 100kg (10T) NbTi solenoid

also Ted Berlicourt & Richard Hake at Atomics International



better than NbZr at high field



NbTi is now the work horse of the magnet business ~3000 Tonnes pa

Understanding superconductivity

1957 BCS Bardeen Cooper & Schrieffer

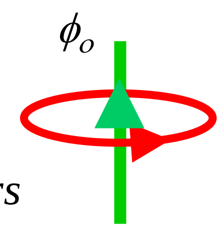
An effective attraction between pairs of electrons via the lattice promotes a condensed state in which the phases of all the individual wave functions are locked together.

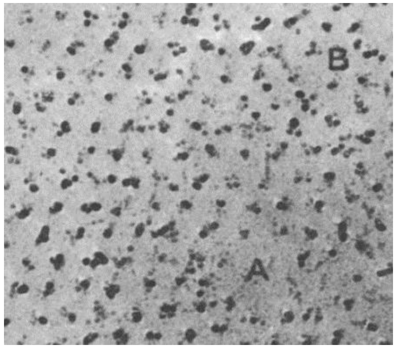
1950 - 1959 GLAG: Ginzburg, Landau, Abrikosov & Gorkov

The behaviour of superconductors is determined by relationship between London penetration depth λ and coherence length ξ (distance over which superconducting state can change).

$\lambda < \xi / \sqrt{2}$ Type 1 behaviour $\Rightarrow$ Meissner effect

$\lambda > \xi / \sqrt{2}$ Type 2 behaviour $\Rightarrow$ Shubnikov state





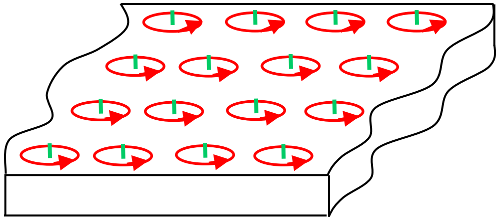
U Essman & H Trauble

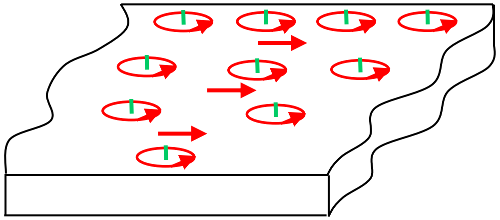
- in type 2 superconductors field enters as quantized fluxoids with

$$\phi_o = \frac{h}{2e} = 2 \times 10^{-15} Webers$$

- fluxoids like to distribute uniformly $\Rightarrow$ zero current density in the bulk

- to get bulk current density must force non uniform distribution - flux pinning



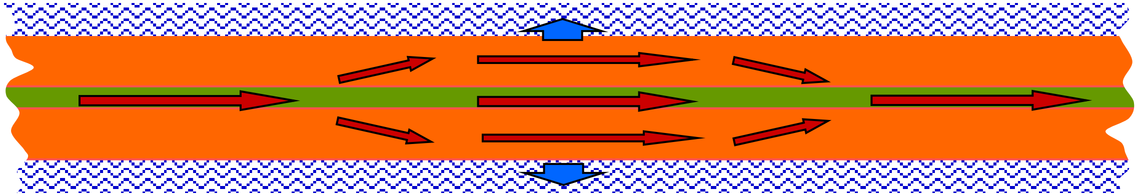


Superconductor engineering

Problem: magnets do not reach field expected from superconductor properties

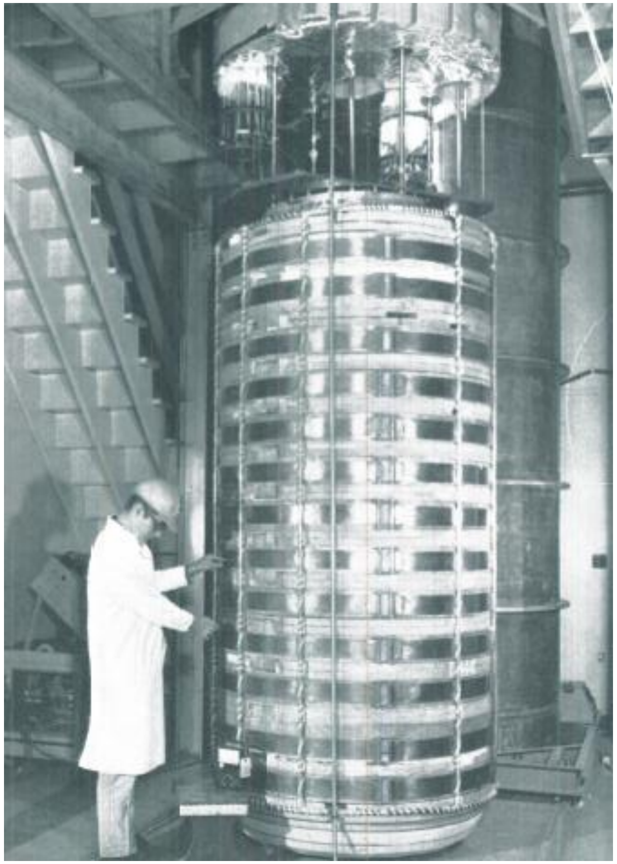
First solution: cryostabilization, devised by John Stekly 1965

- conductor with copper joined in parallel with superconductor
- well cooled by liquid helium



- current normally flows in superconductor
- if superconductor switches off, current diverts to copper
- Ohmic heating in copper
- heat transferred to helium, temperature falls
- current returns to superconductor

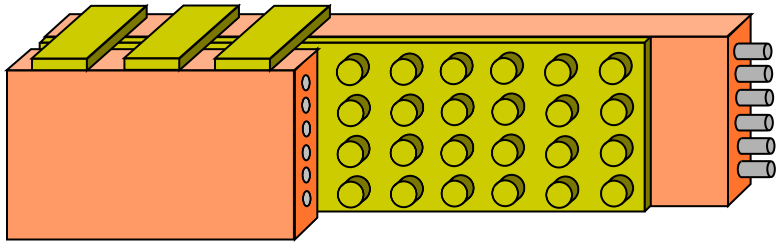
- works well Avco MHD generator ⇒



- *but the large amount of copper dilutes current density too much for accelerators, NMR, MRI etc*

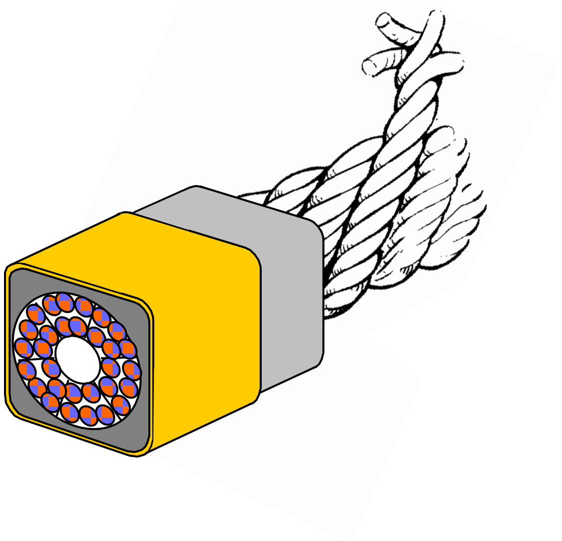
Practical cryostabilization

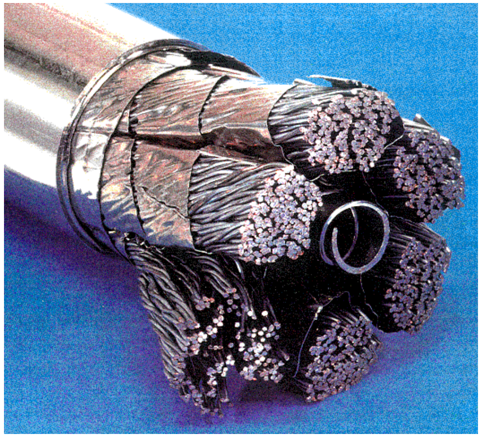
Natural convection cooling

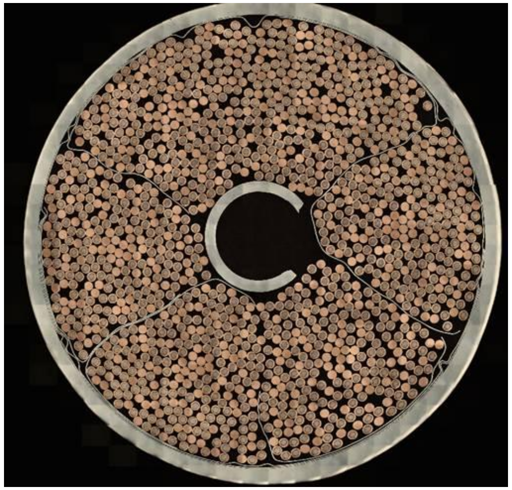


but low engineering current density

Cable in conduit conductor CICC

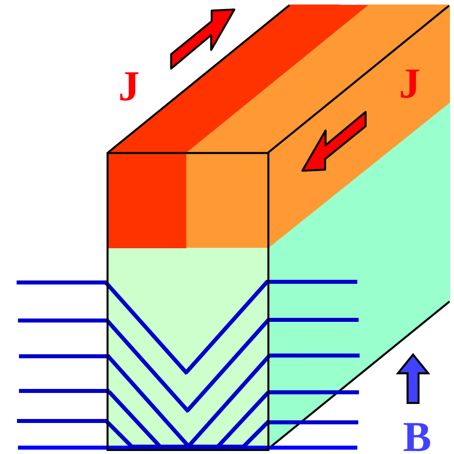






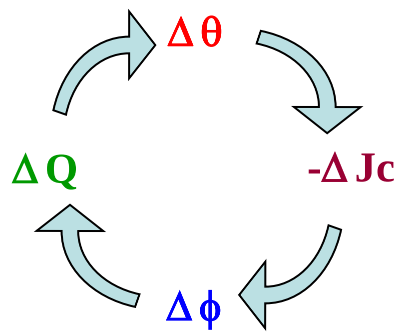
Magnets at high current density

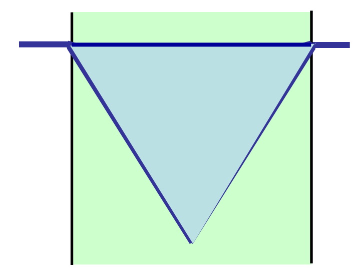
- no need for cryostabilization if we cure the problem of *flux jumping*
- *FJ* is a catastrophic instability of the screening currents which are induced by magnetic field (additional to transport current)



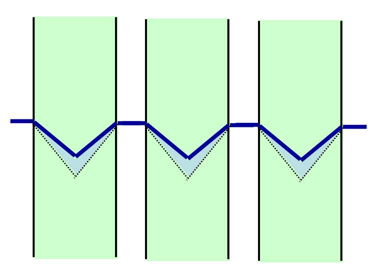
Flux Jumping Instability

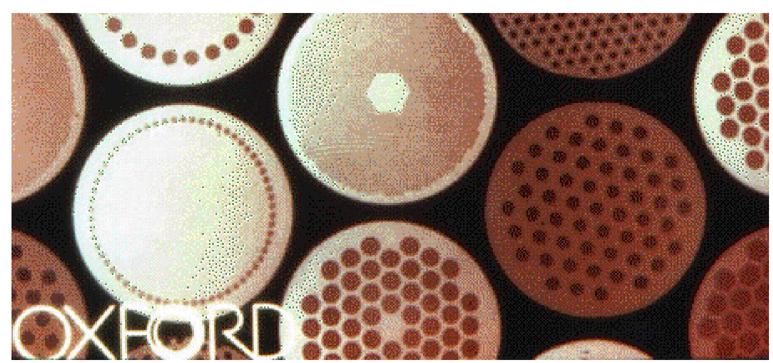
- **screening currents**
- **temperature rise**
- **reduced critical current density**
- **flux motion**
- **energy dissipation**
- **temperature rise**



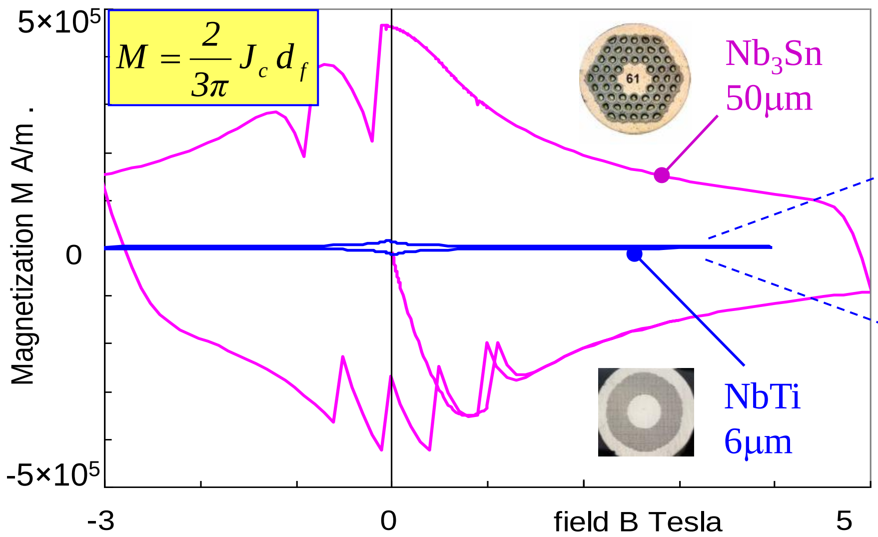


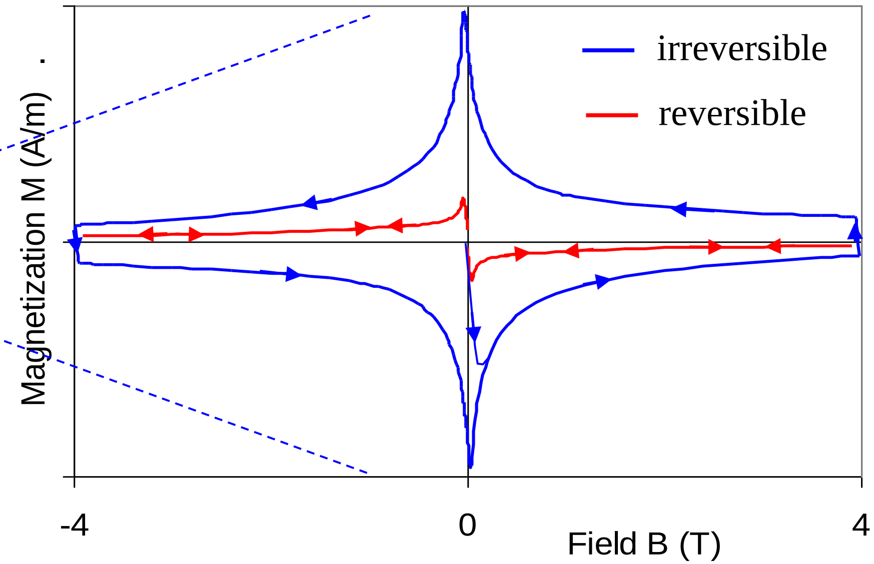
- cure flux jumping by weakening a link in the feedback loop
- fine filaments reduce **Δϕ** for a given **-Δ Jc**
- for NbTi the stable diameter is ~ 50μm

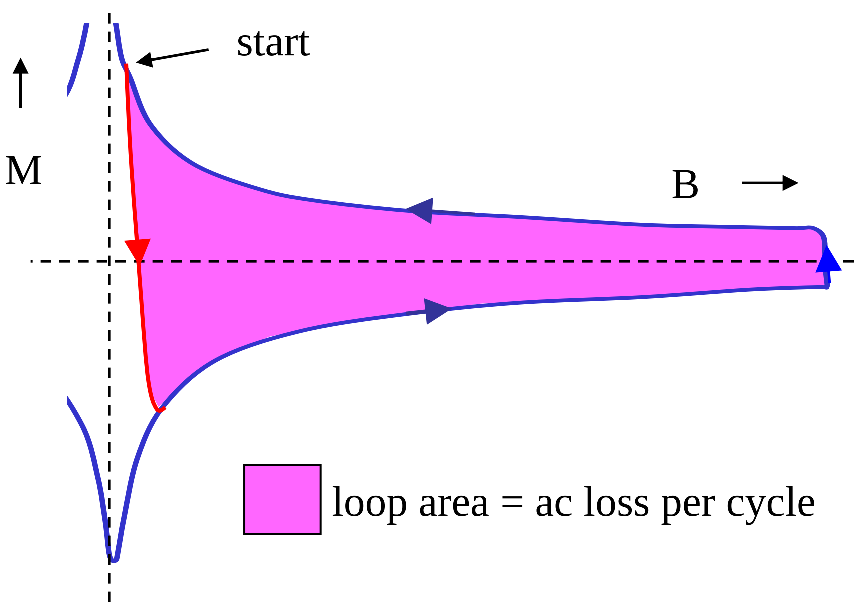


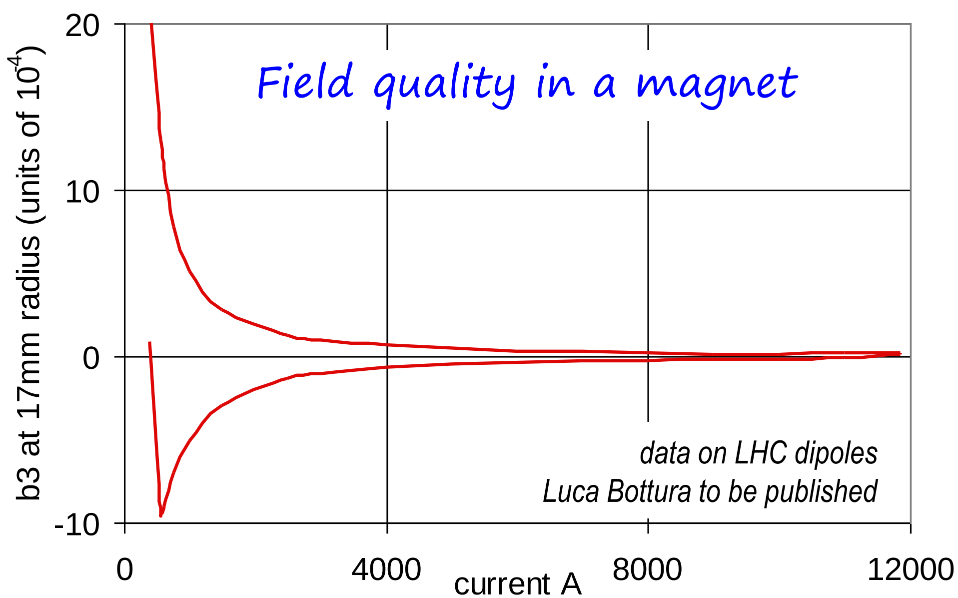


Magnetization, hysteresis and ac loss









1969: *Filamentary composite wires*

- **'Intrinsically' Stable against Flux Jumping**

  high current density in magnets, enables compact windings and high field gradients

- **Low ac Losses**

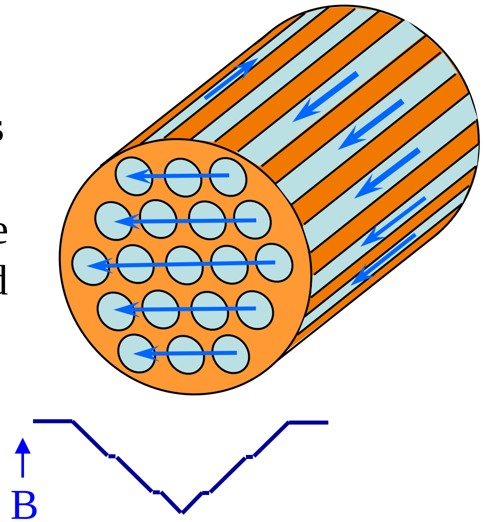
  important for synchrotron accelerators, electrical engineering and any application where the field changes

- **Low Magnetization**

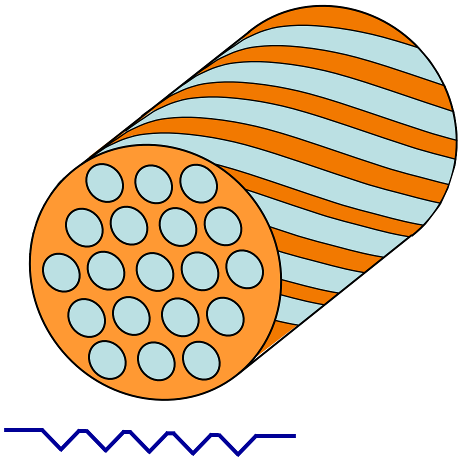
  needed where field quality is important, eg accelerator magnets, NMR spectrometers

- **Twisting is essential**

untwisted filaments are magnetically coupled and behave together like a solid wire

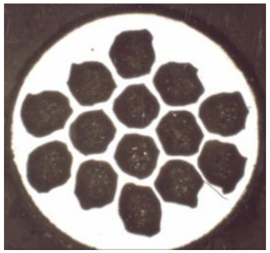


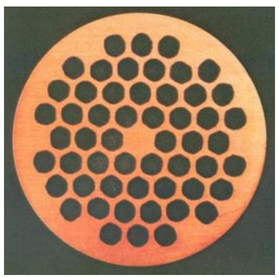
twisted filaments are magnetically decoupled and behave like separate entities

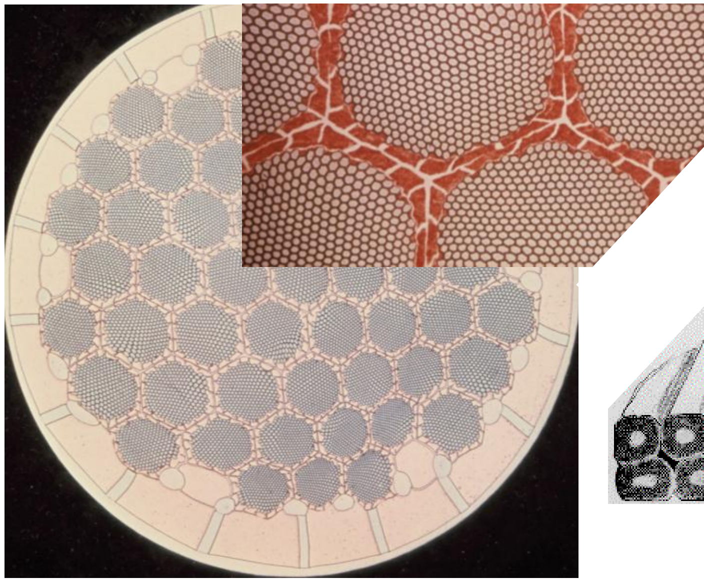


High energy physics: the first technology driver

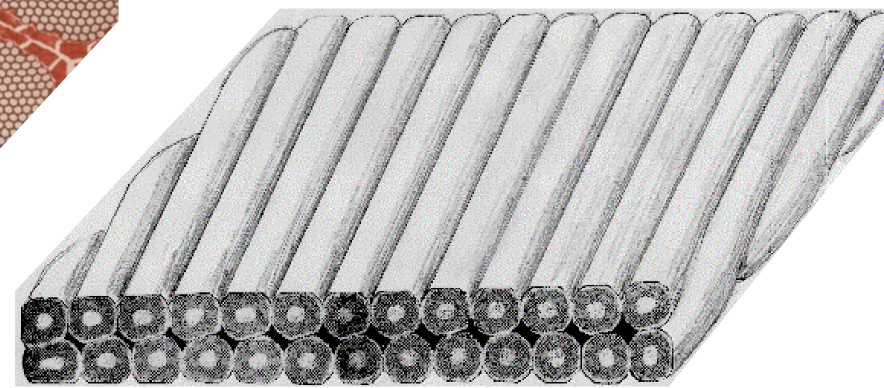
1967: '*…superconductor diameter about 5×10^{-4}cm…' PF Smith JD Lewin: Superconducting Proton Synchrotrons: NIMs* ***52*** *p298*





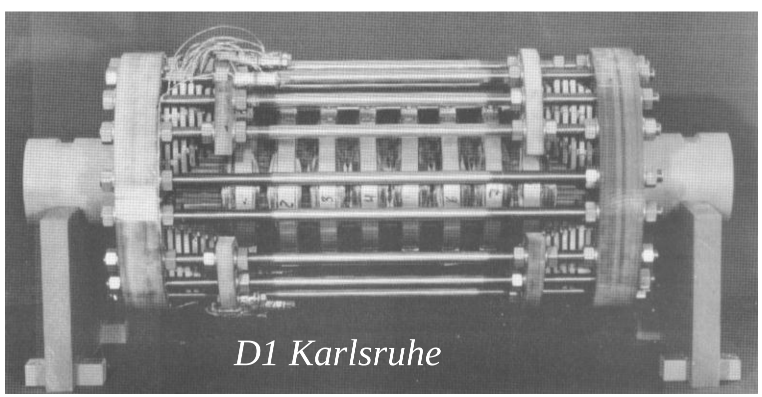


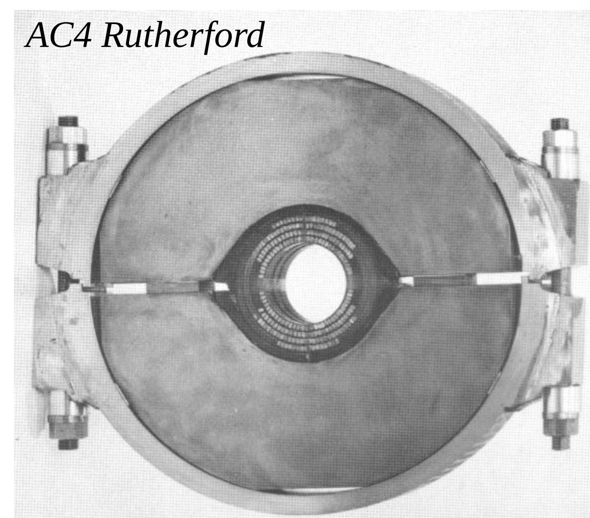
Rutherford cable



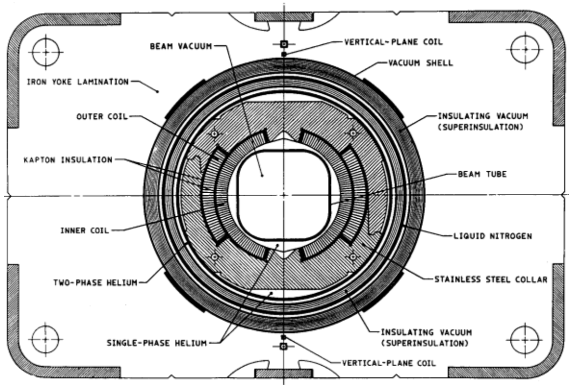
1970s: GESSS collaboration (Karlsruhe, Rutherford, Saclay)

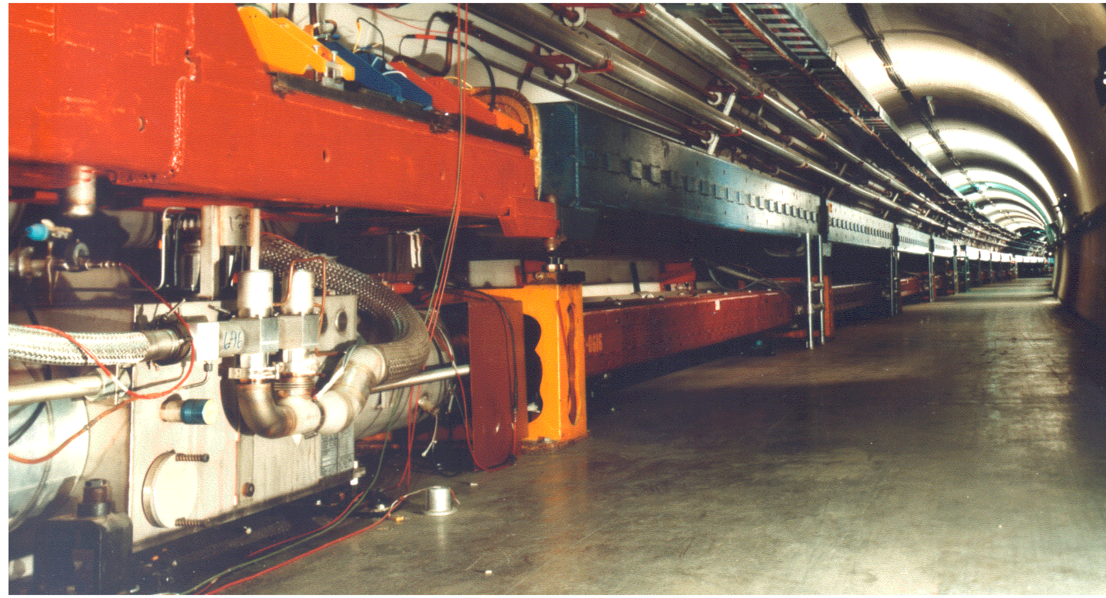
proposed superconducting magnets for the CERN SPS





1984 Tevatron: first superconducting accelerator

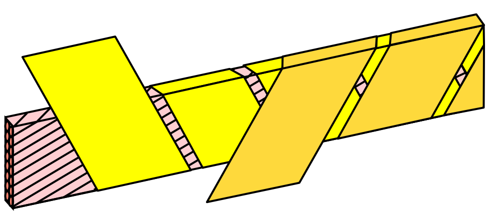




Two gifts for accelerator magnet technology

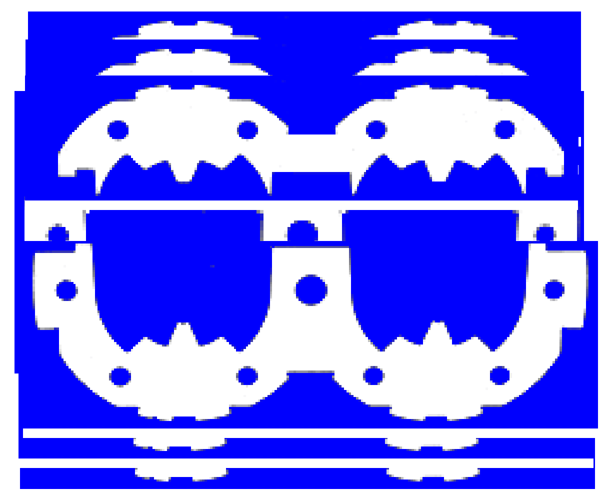
1 porous winding

- Kapton insulation wrap
- no resin against conductor
- liquid helium in contact with wire
- better magnet performance - less training



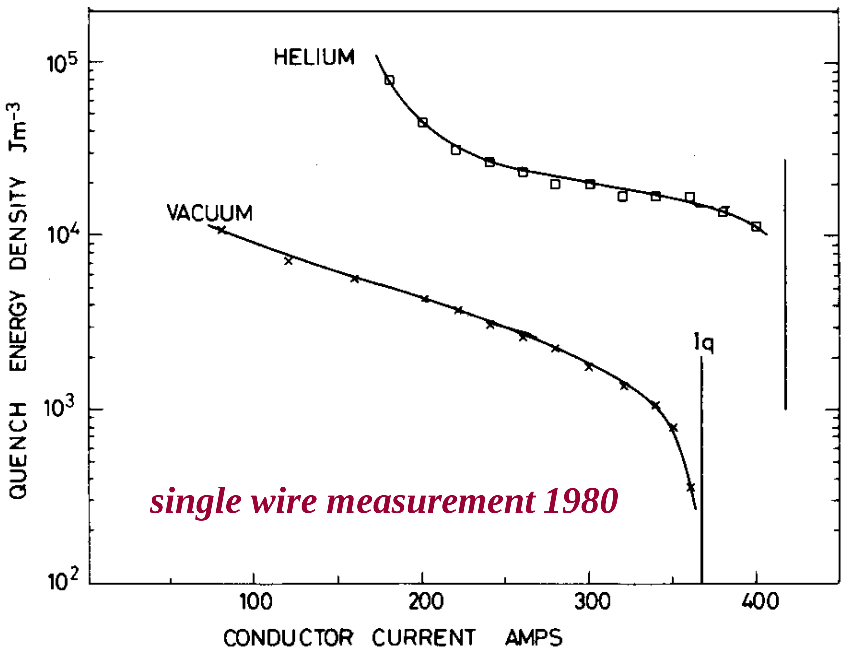
2 collars

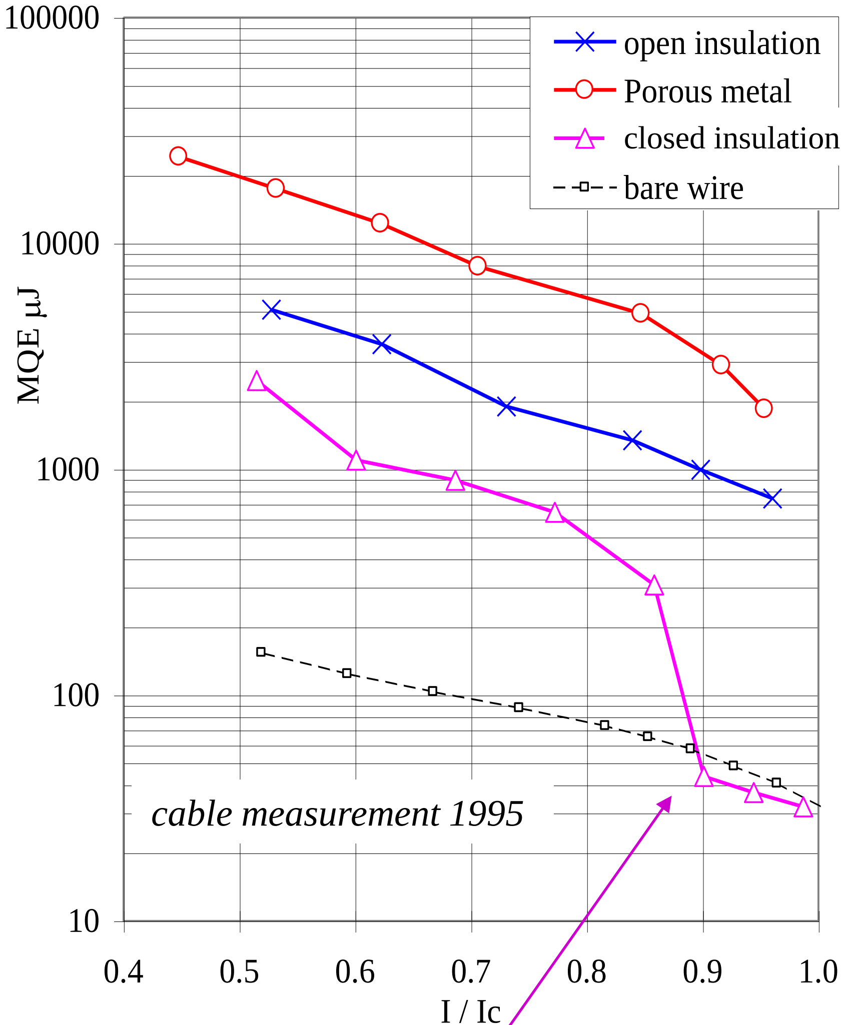
- coils clamped by precision stamped collars, fixed together by rods
- high precision shape
- low eddy currents



Minimum quench energy MQE

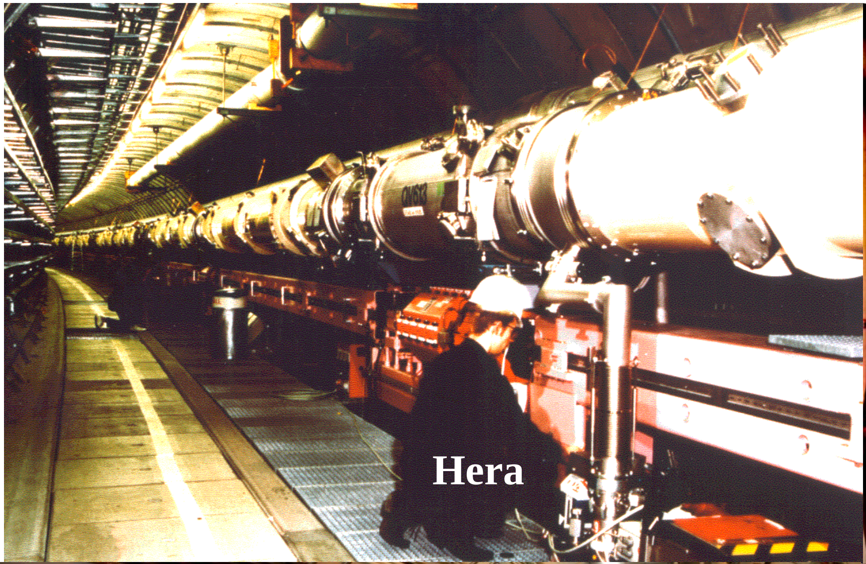
- even when flux jumping is eliminated, still get degraded performance
- mechanical energy release as field raised
- make conductor stable against energy release
- quantify conductor stability as minimum energy pulse needed to quench

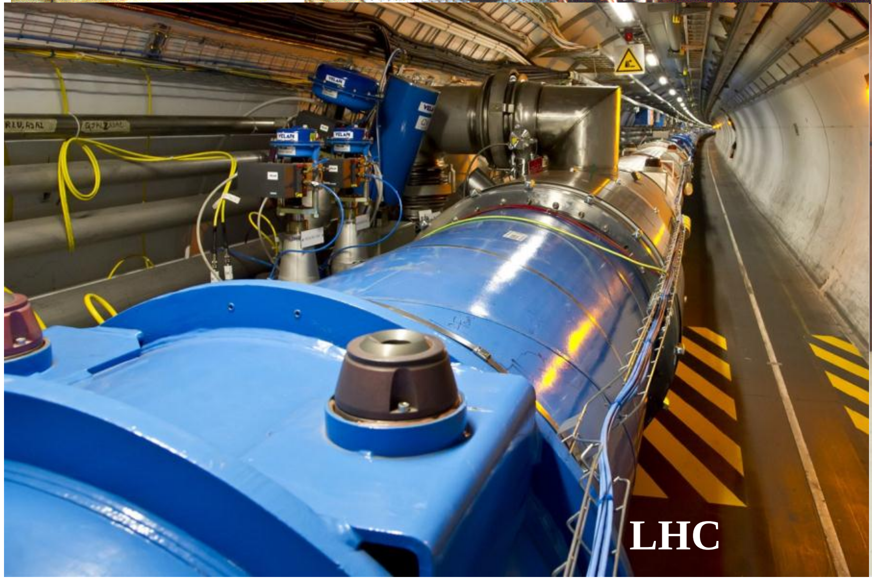


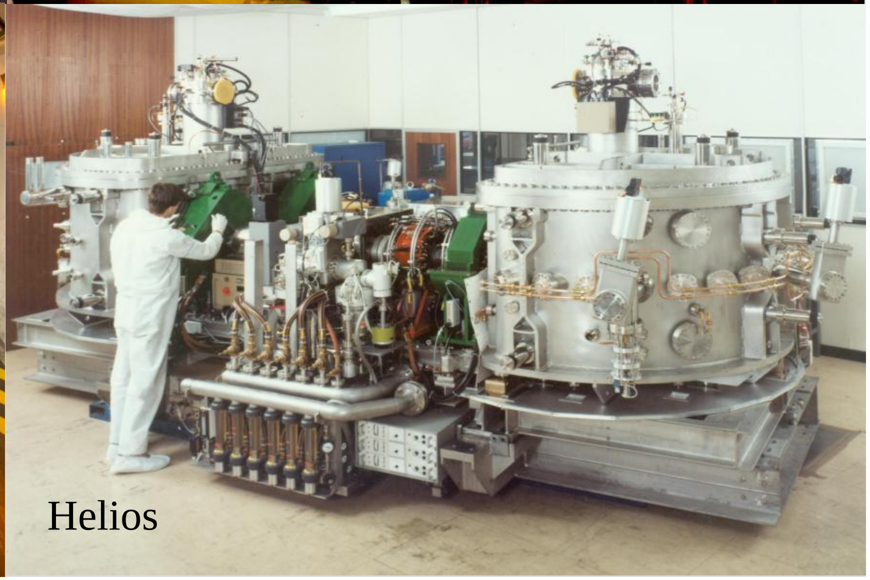


40μJ is a pin dropping 40mm

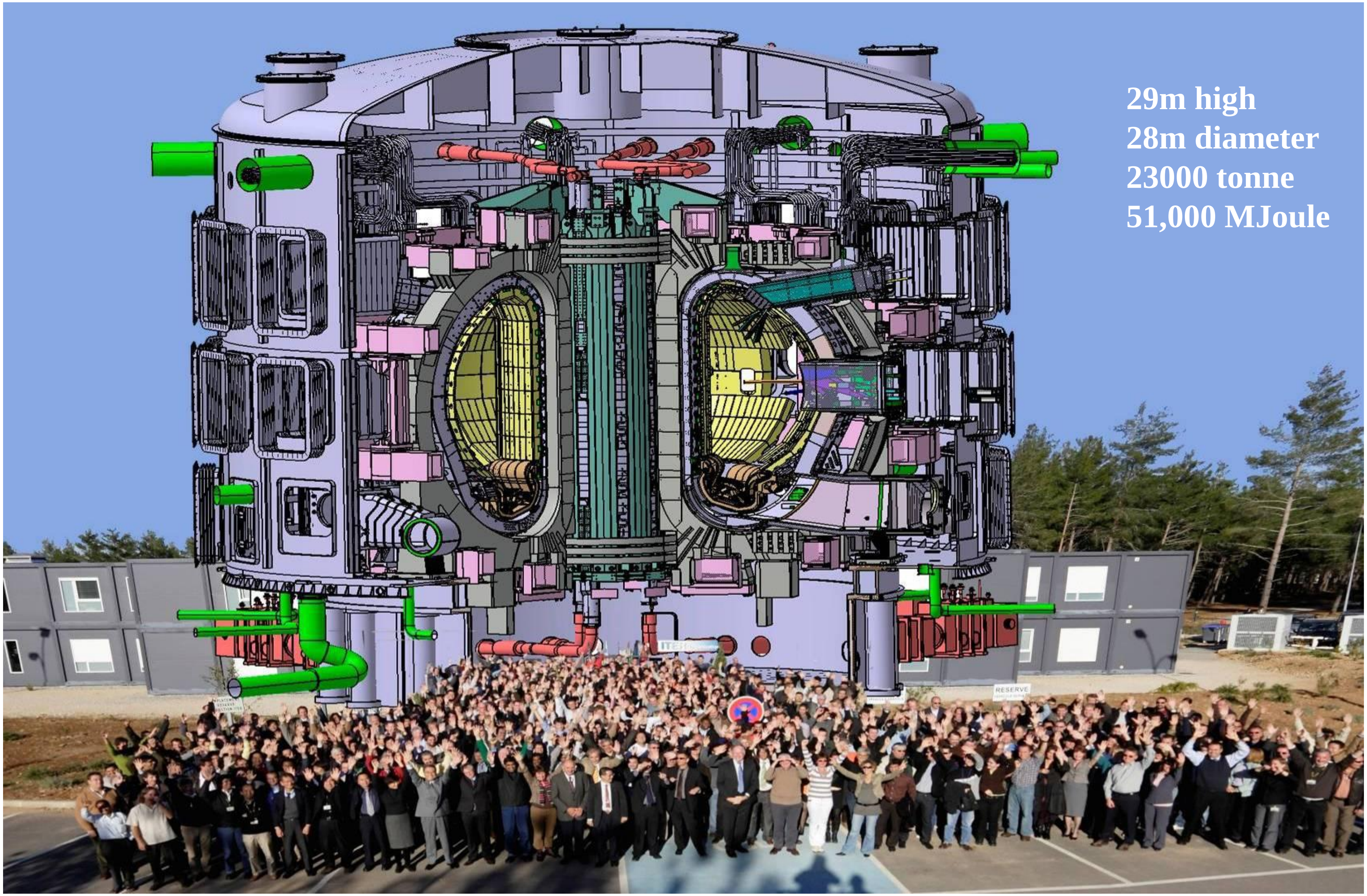
Superconducting accelerators



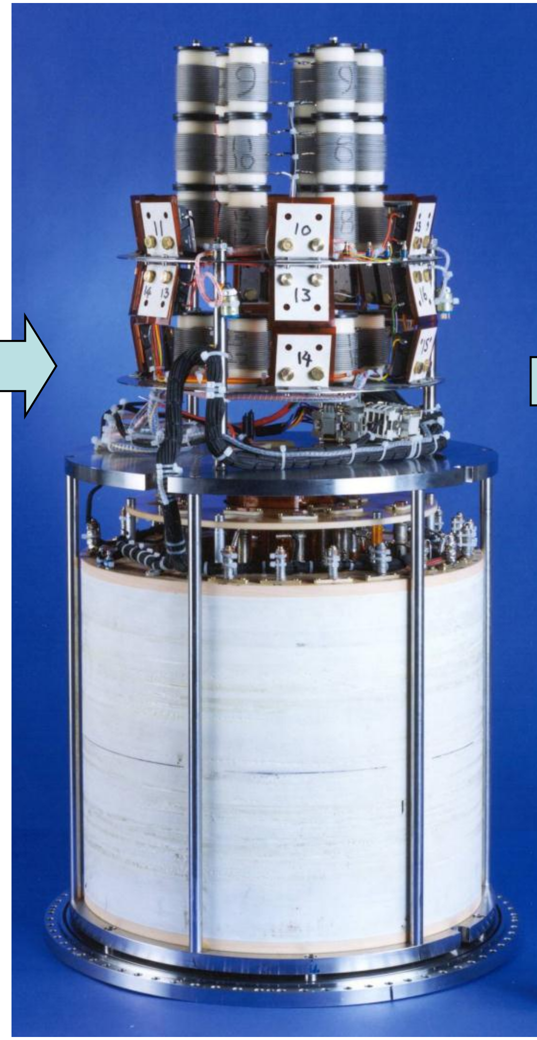




2020: Really big science - ITER



1962: *A new industry*



Research magnets

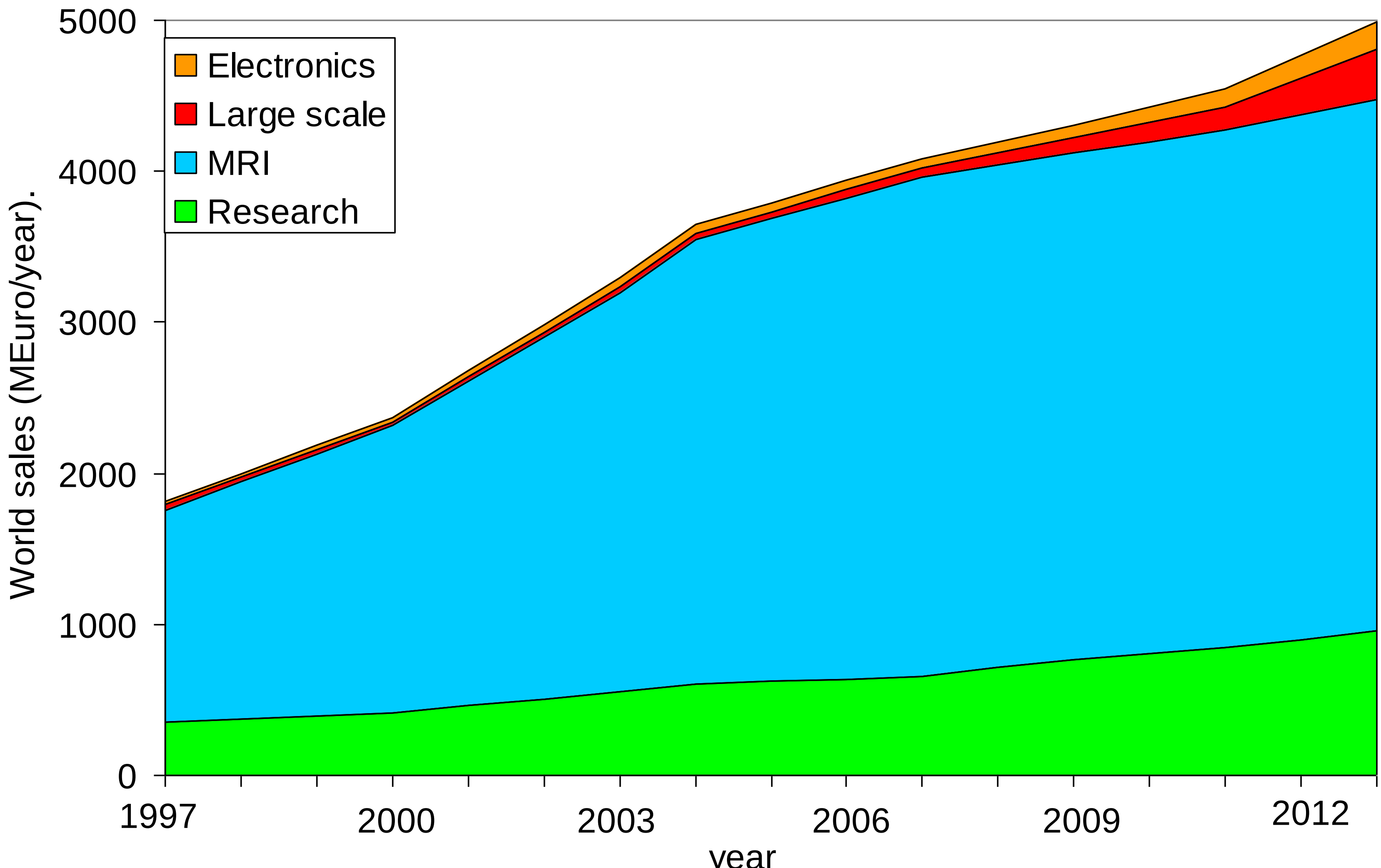
NMR
spectrometers

NMR Imaging

1979 Oxford Instruments build the world's first superconducting NMR imaging magnet

2011 Siemens Skyra MRI

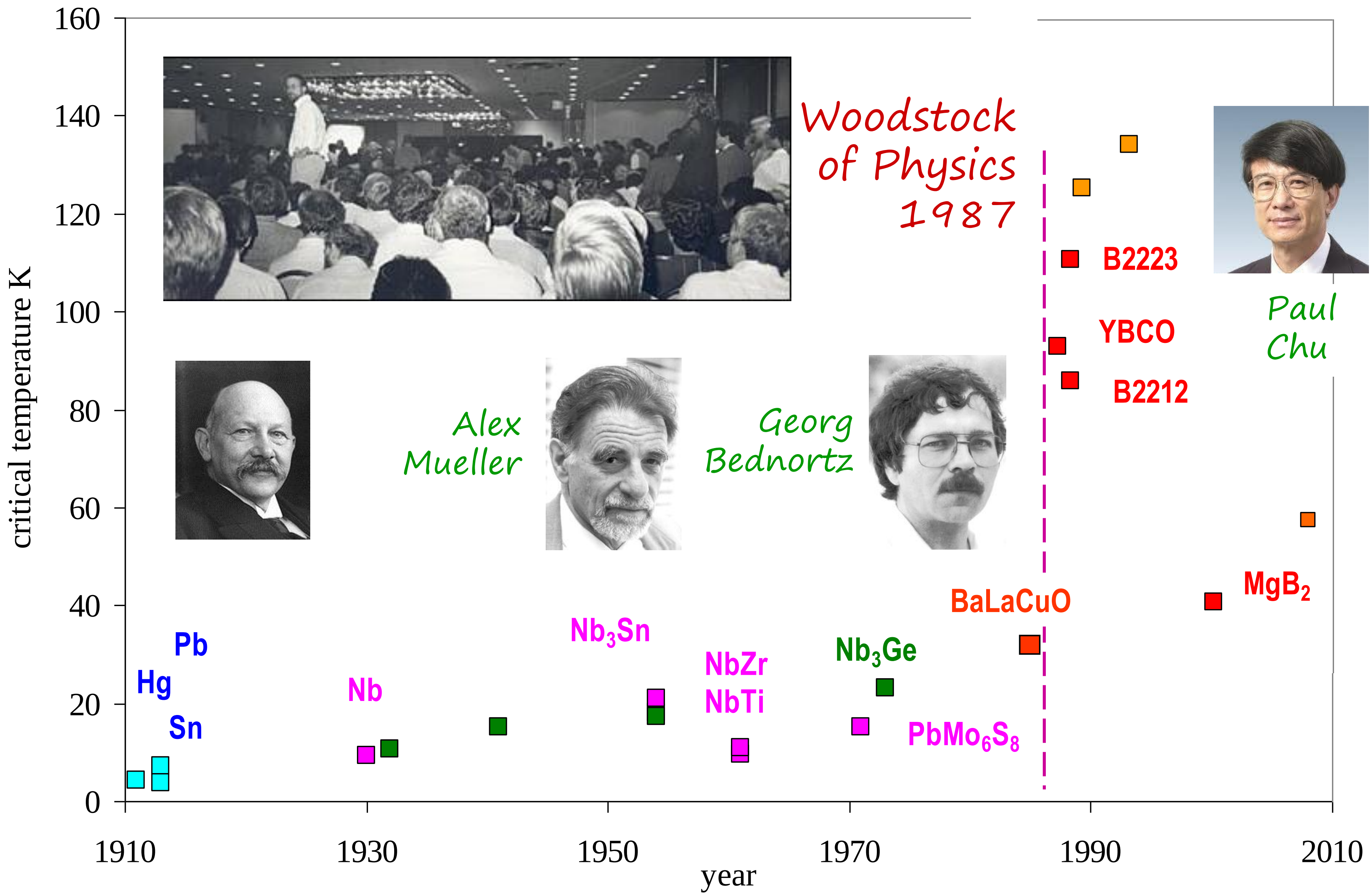
*Market survey by Conectus**



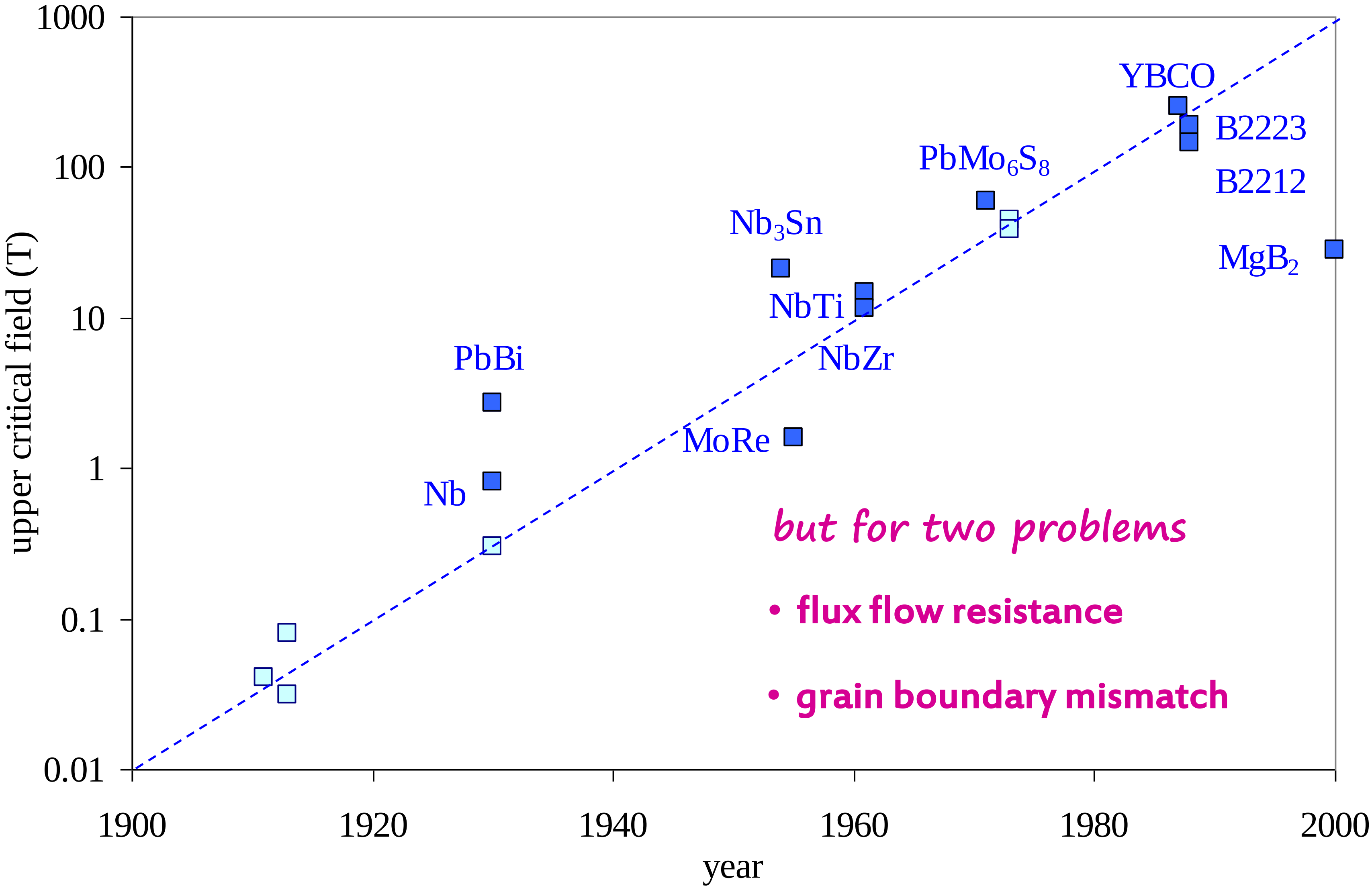
**CONsortium of European Companies (determined) To Use Superconductivity*

Source: **www.conectus.org**

A century of critical temperatures



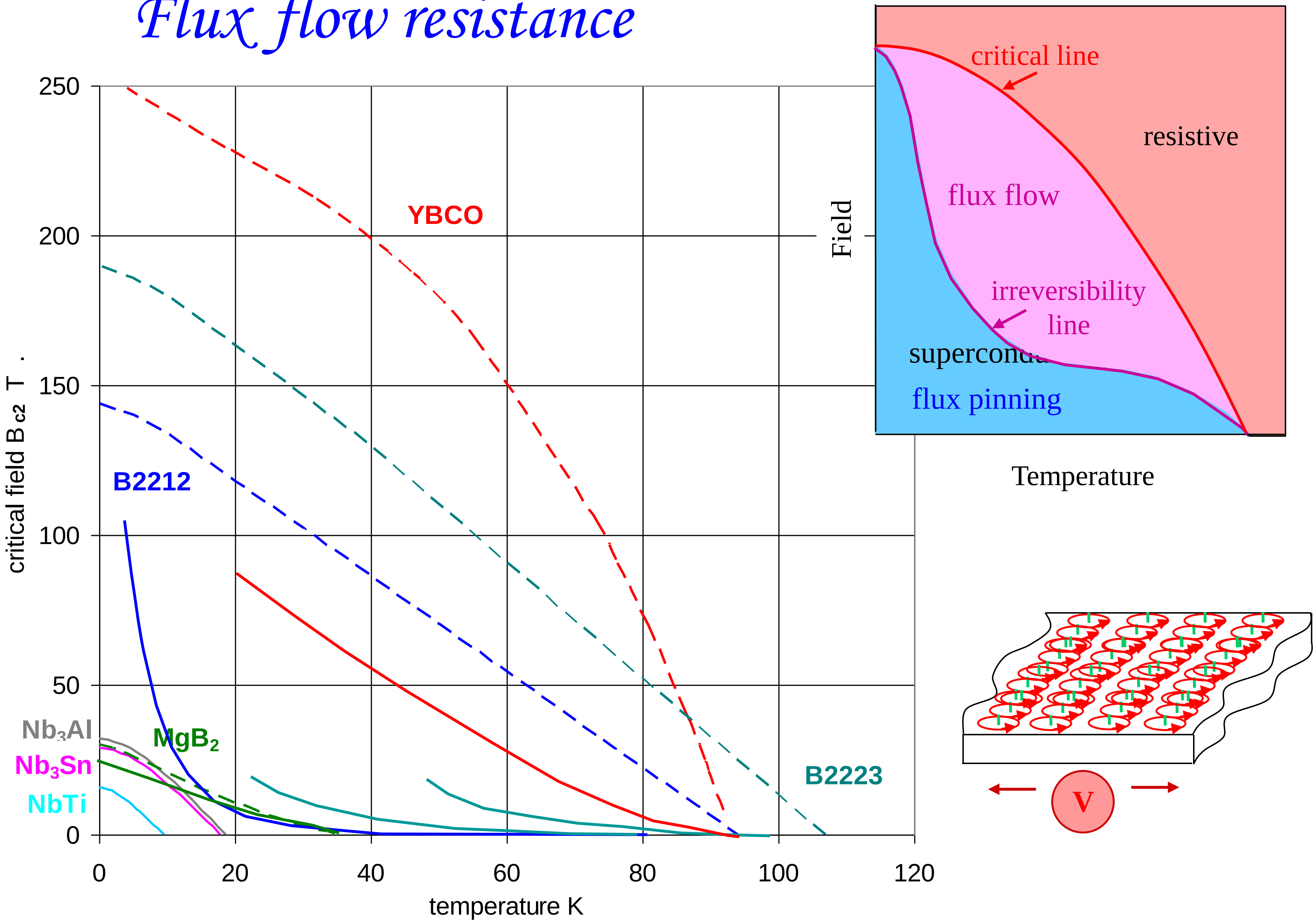
Wonderful materials for magnets



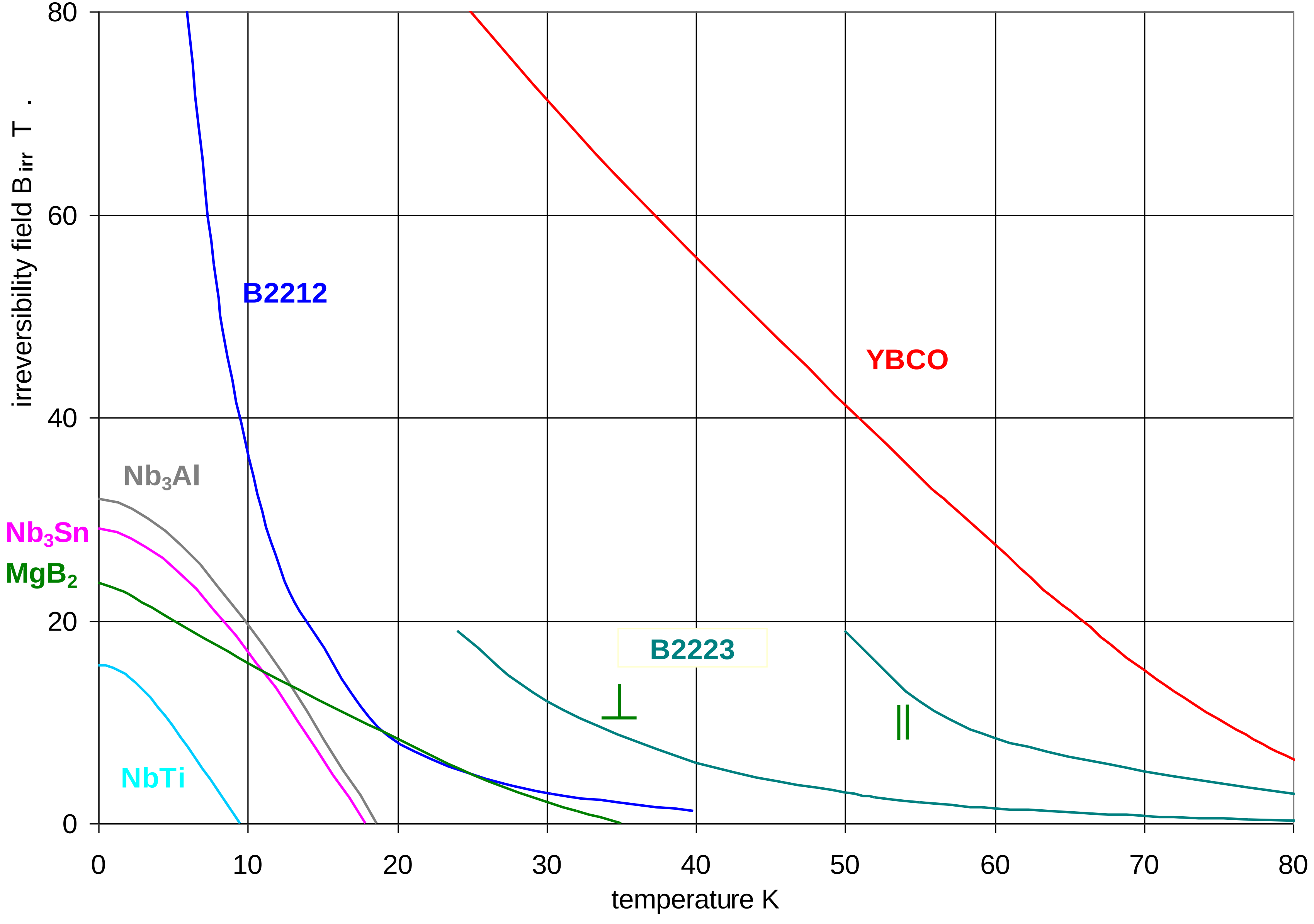
but for two problems

- **flux flow resistance**
- **grain boundary mismatch**

Flux flow resistance

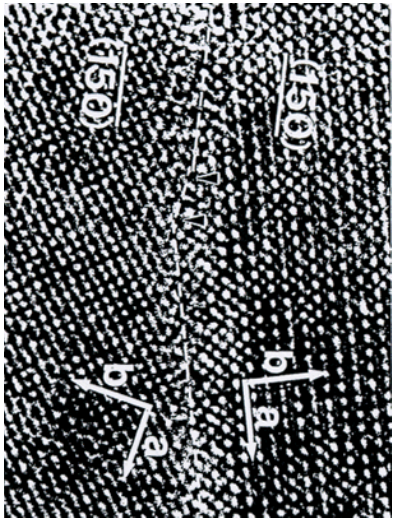


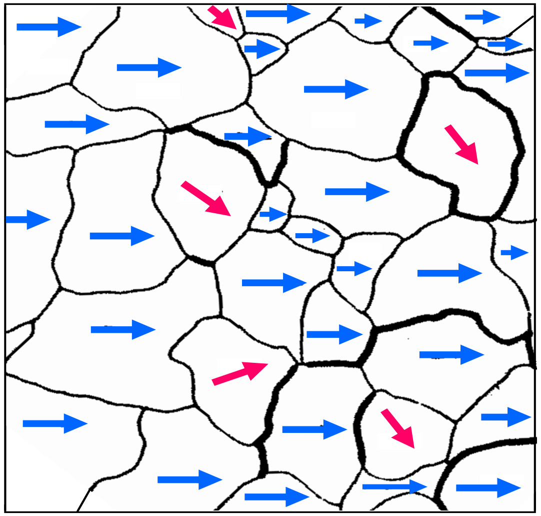
Accessible fields for magnets



HTS grain boundary matching

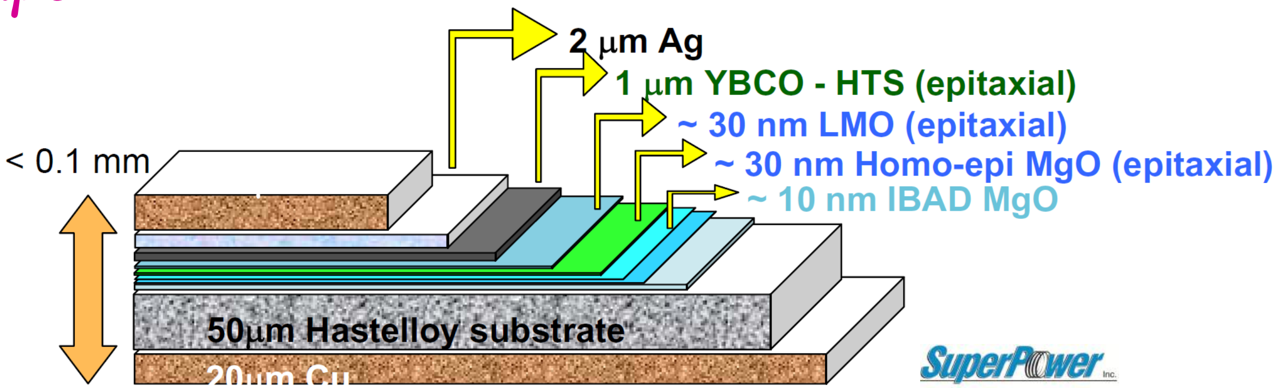
- current can only jump between grains if they are aligned
- must make conductors with all grains aligned to a few degrees
- a single crystal km long!





Textured YBCO tape

- best irreversibility field
- deposit YBCO film on aligned substrate



- OK in high field **and** at high temperature

HTS - where next?

Existing applications? replace LTS

- reduced cost of cryogenics
  - but modern cryogenics are very efficient
  - typical MRI installation cryogenic cost is only 4% of operating budget
- more convenient cryogenics $\Rightarrow$ cryo-free magnet systems
  - but two stage cryocoolers work fine at 4K!
  - no coolant gas: uncooled copper leads $\Rightarrow$ 45 × more heat leak than cooled
  - HTS leads are the essential enabling technology for 4K cryocooler magnets
- current leads: often the largest refrigeration load of a magnet
- High field magnets - research, NMR, HEP?
  - Nb_3Sn $\Rightarrow$ 22T   BSCO & YBCO $\Rightarrow$ 50T

New Applications?

- in rough environments where cryogenics must be very robust and reliable
- where loss is inherent and causes a large refrigeration load - electrical power engineering
  - refrigeration power demand $\frac{CoP(77K)}{CoP(4K)} \approx 25$

Current leads and cryofree systems

13 kA lead for LHC
(photo CERN)

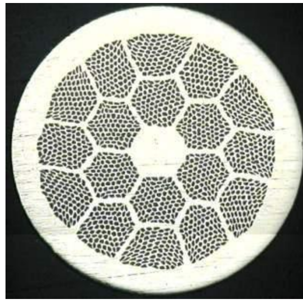
12 T magnet
& dilution
refrigerator

current lead

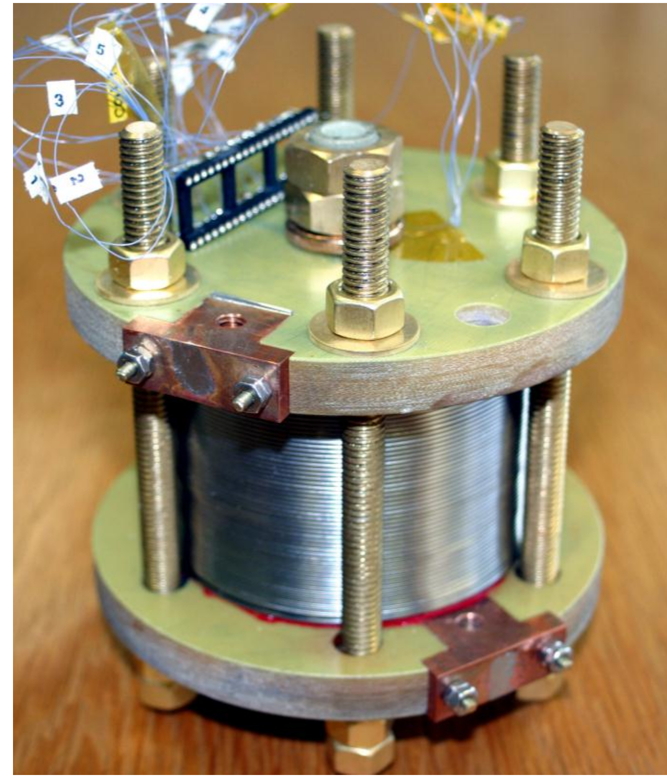
7 T split pair

photos
Oxford Instruments

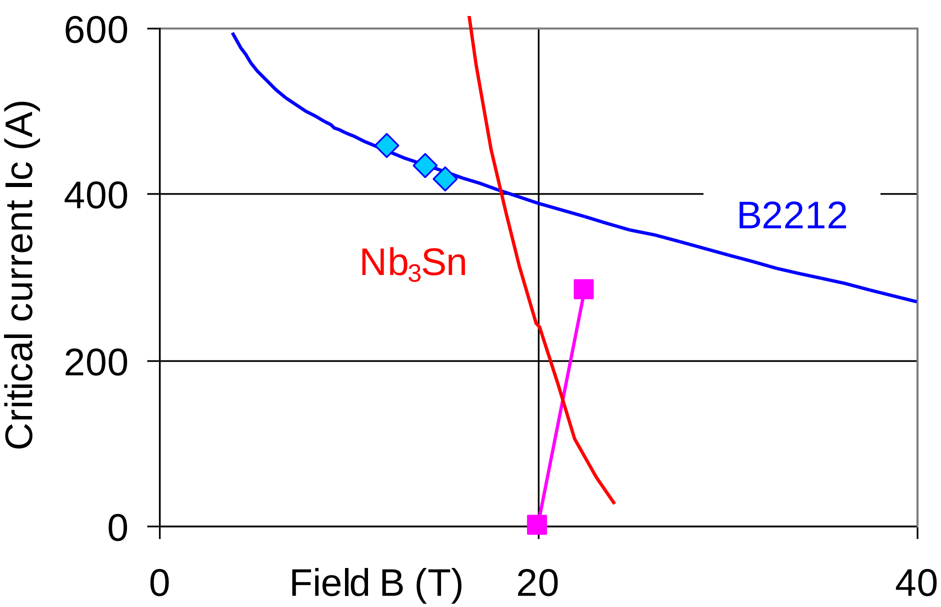
High field inserts



round B2212 wire insert
⇒ 22.5T in 20T background



coated YBCO tape insert
⇒ 33.8T in 31T background



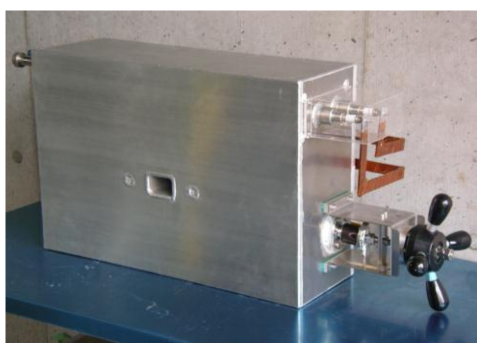
Rough environments

18 May 2011

Japanese Government authorizes Central Japan Railway Co to proceed with high speed Maglev link from Tokyo to Osaka by 2045
speed 580 kph

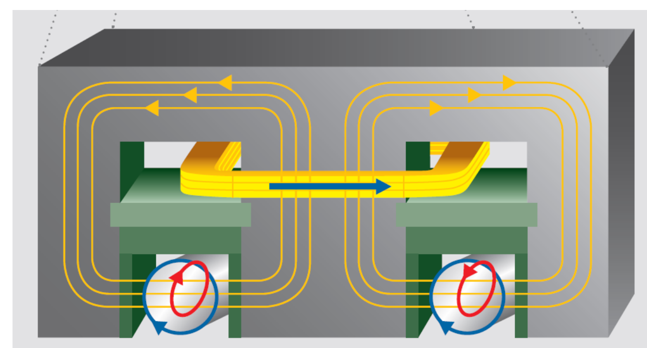
2005 B2223 levitation magnet tested on vehicle

2010 coated YBCO tape model levitation magnet



photos CJR and RTRI

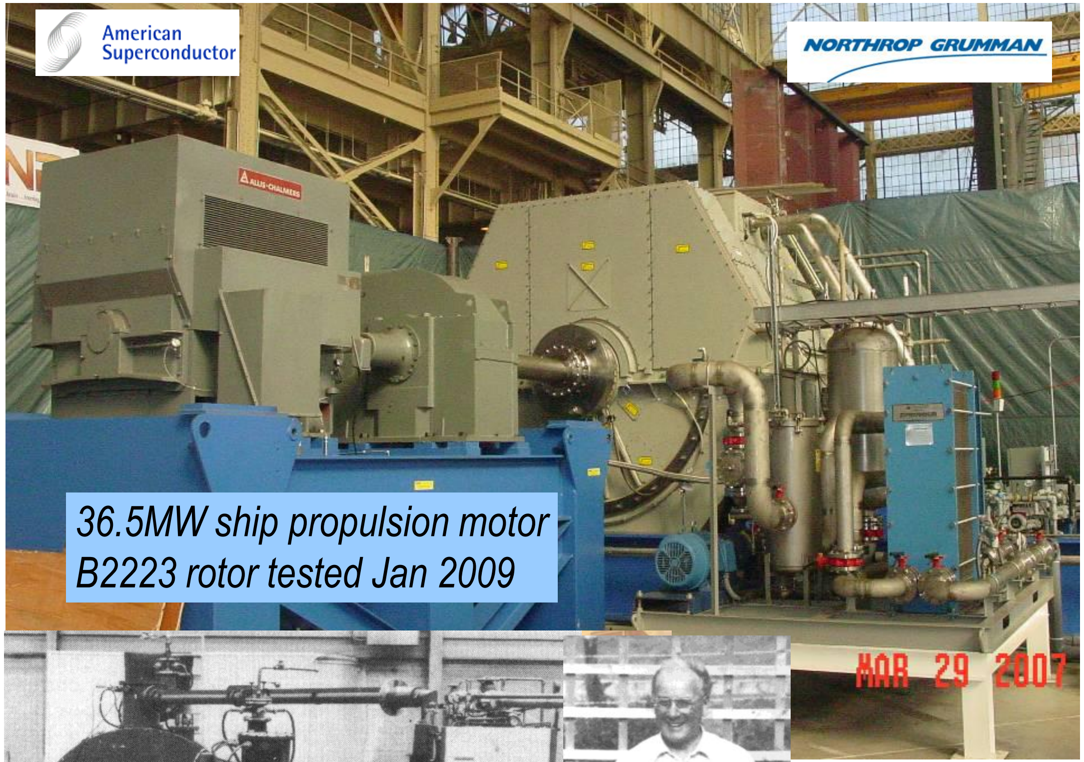
Induction heating of aluminium billets



rotate the billet in a dc field

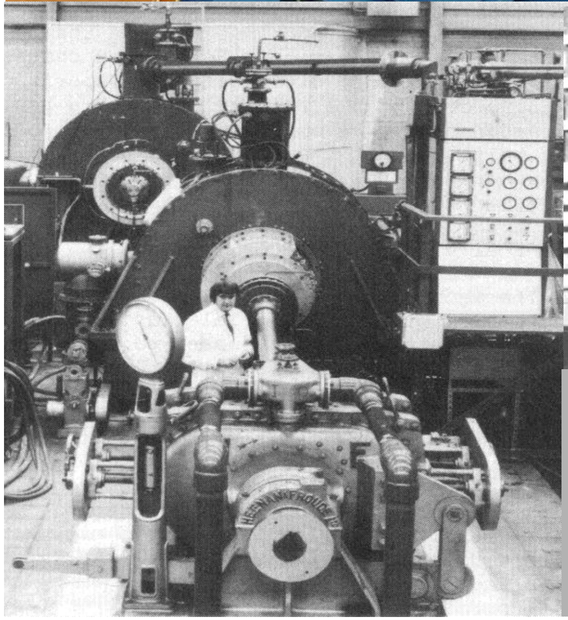
ZENERGY POWER

Motors



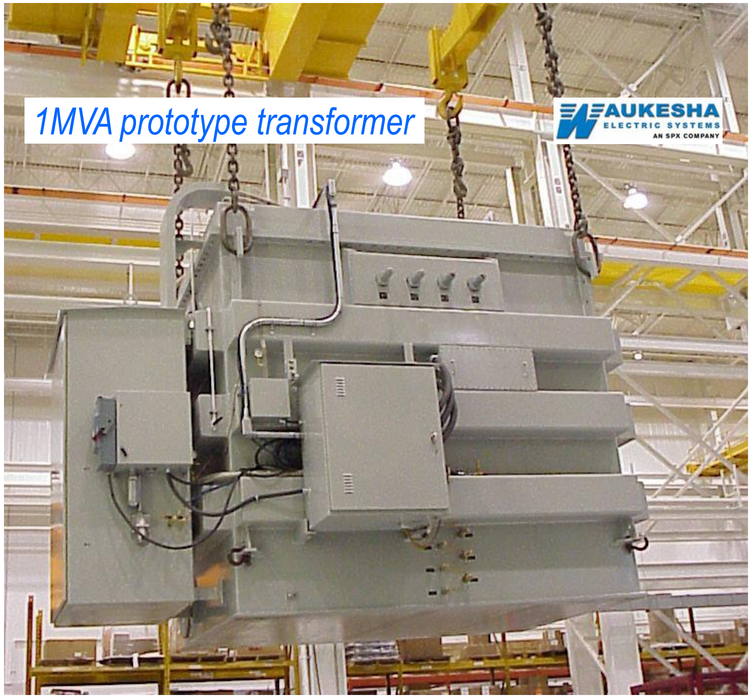
36.5MW ship propulsion motor
B2223 rotor tested Jan 2009

30kW prototype electric car
Sumitomo Electric Industries

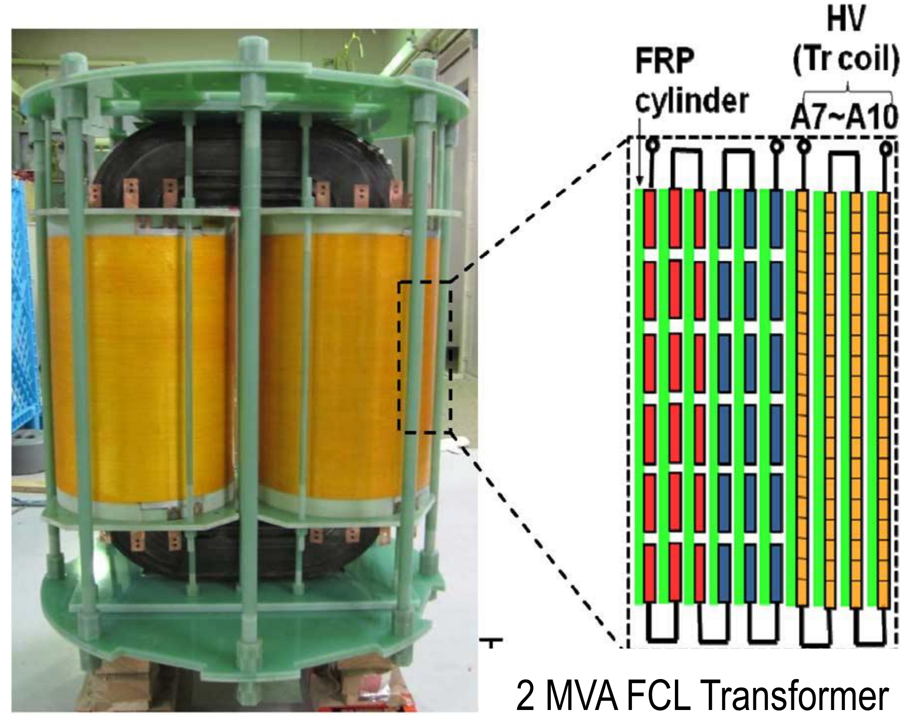


1MW generator
& motor (LTS)
IRD 1975
team leader
Tony Appleton

Power transmission



1MVA prototype transformer



2 MVA FCL Transformer
(Nagoya University)


630kVA 3 phase transformer at Baiyin China

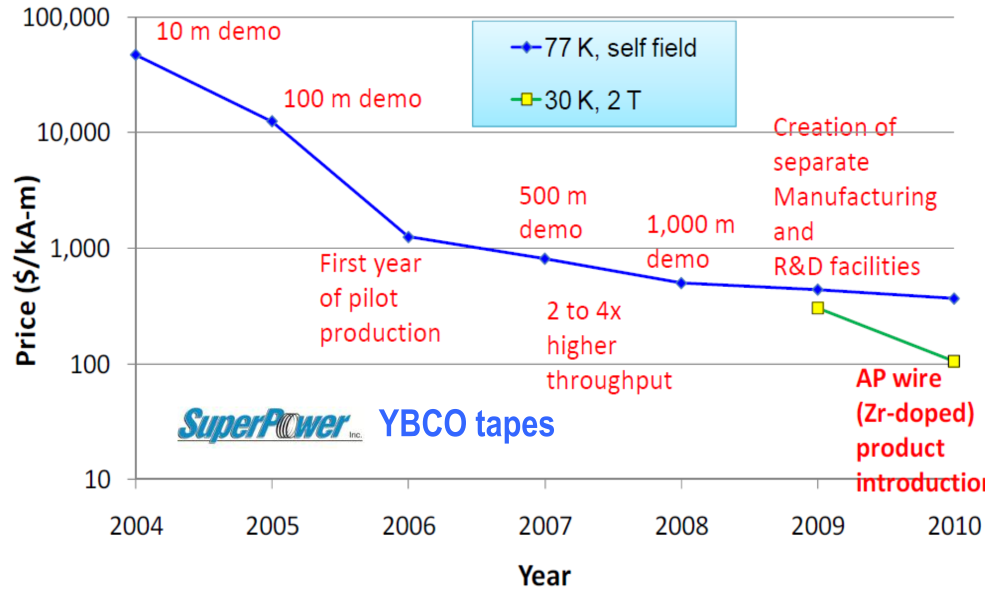
Inductive Fault Current Limiter (Zenergy)

HTS in engineering - things still to do

1) Cost

domestic copper wiring costs ~ 10€ / kA m

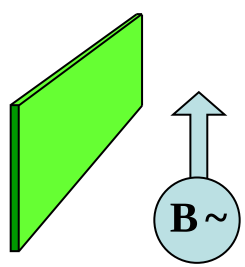
- NbTi or Nb_3Sn at 4.2K 5T ~ 1€ /kA.m
- Nb_3Sn at 4.2K 12T ~ 3€ /kA.m
- B2212 at 4.2K 12T ⇒ ~ 70€ /kA.m

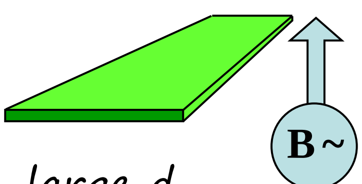


2) AC losses

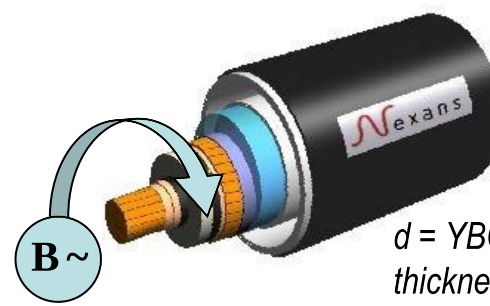
loss power $P = \dot{B} J_c \frac{d}{4}$

d is width ***transverse*** *to field*





small d



d = YBCO layer thickness < 1μm

large d

Refrigeration power demand $\frac{CoP(77K)}{CoP(4K)} \approx 25$

10μm at 4K ⇒ ¼ mm at 77K

1μm at 4K ⇒ 25μm at 77K

A superconducting century