The CERN Accelerator School

Introduction to Accelerator Physics
Superconducting Magnets

Luca.Bottura@cern.ch

Prague, Czech Republic

31 August - 12 September

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

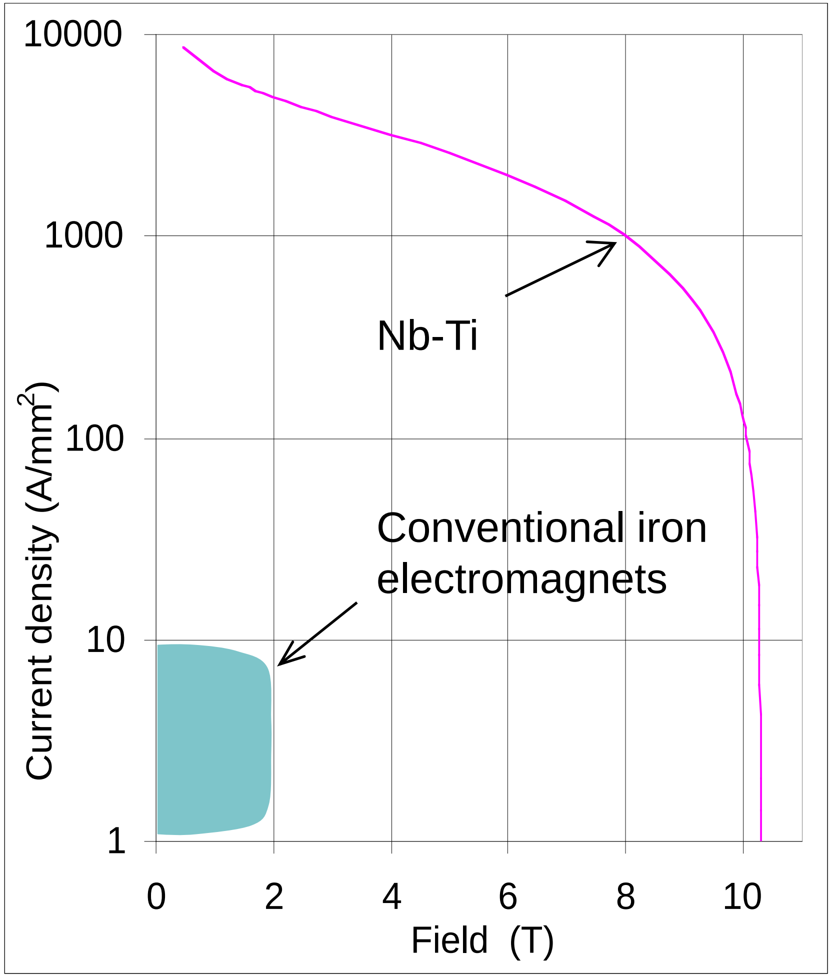
Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

Graphics by courtesy of M.N. Wilson

Why superconductivity anyhow ?

- **Abolish Ohm's law !**
  - no power consumption (although need refrigeration power)
  - high current density
  - ampere turns are cheap, so don't need iron (although often use it for shielding)
- Consequences
  - lower running cost $\Rightarrow$ new commercial possibilities
  - energy savings
  - high current density $\Rightarrow$ smaller, lighter, cheaper magnets $\Rightarrow$ reduced capital cost
  - higher magnetic fields economically feasible $\Rightarrow$ new research possibilities



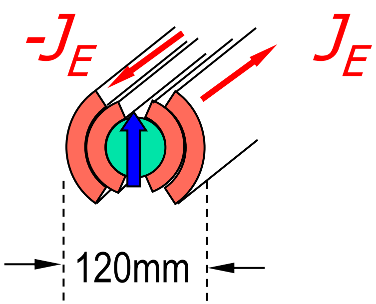
High current density - dipoles

- The field produced by an ideal dipole (see later) is:

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

J_E = 375 Amm^{-2}

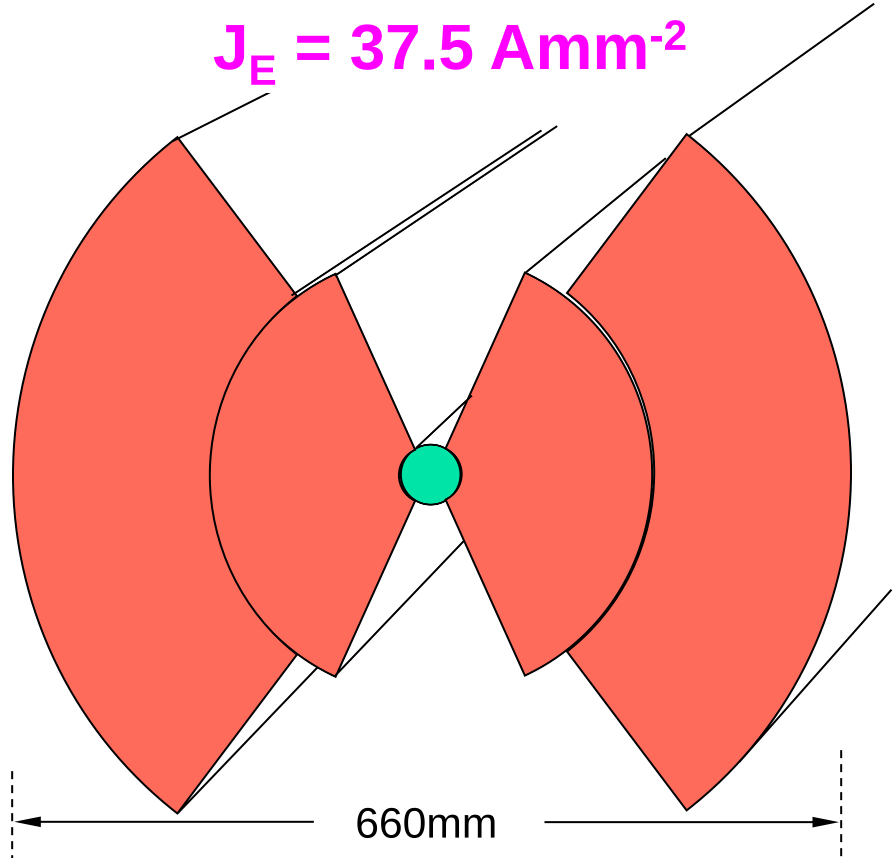
LHC dipole



≈ 1 MA-turn
≈ 2.5 kW/m

all-SC dipole record field: 16 T (LBNL, 2003)

J_E = 37.5 Amm^{-2}



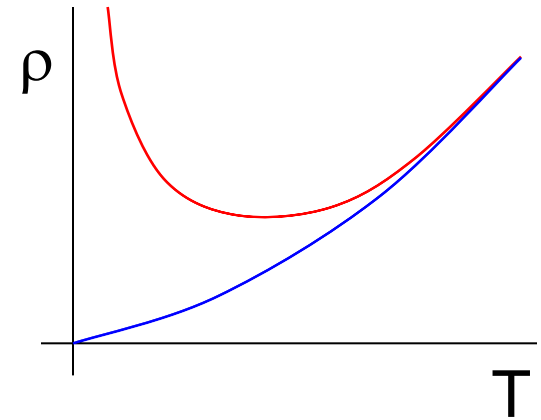
≈ 5x10 MA-turn
≈ 6 MW/m

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

A great physics problem in 1900

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



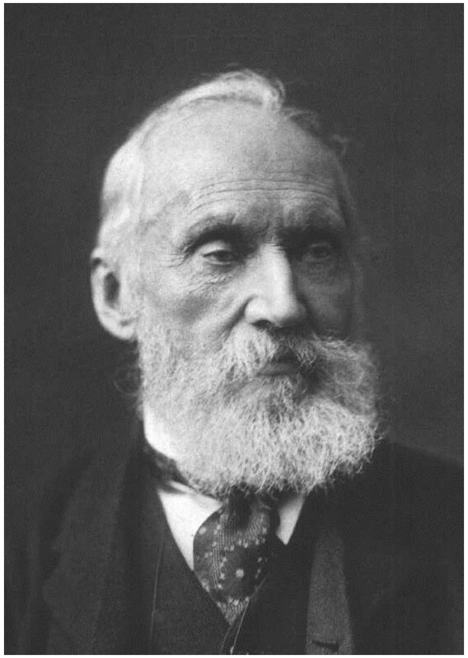
… electrons flowing through a conductor would come to a complete halt or, in other words, metal resistivity will become infinity at absolute zero.

"*X-rays are an hoax*"

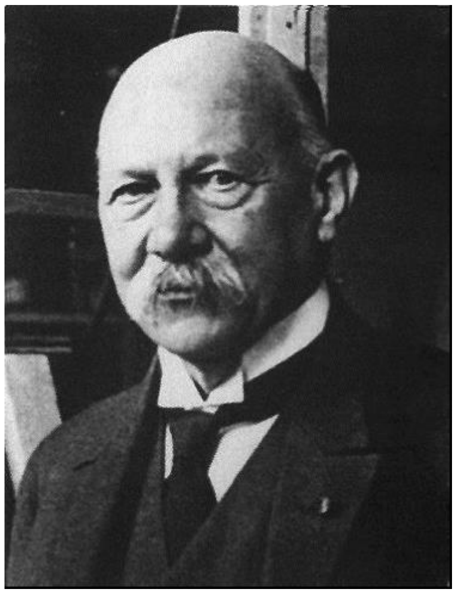
"*I have not the smallest molecule of faith in aerial navigation other than ballooning or of expectation of good results from any of the trials we hear of*"

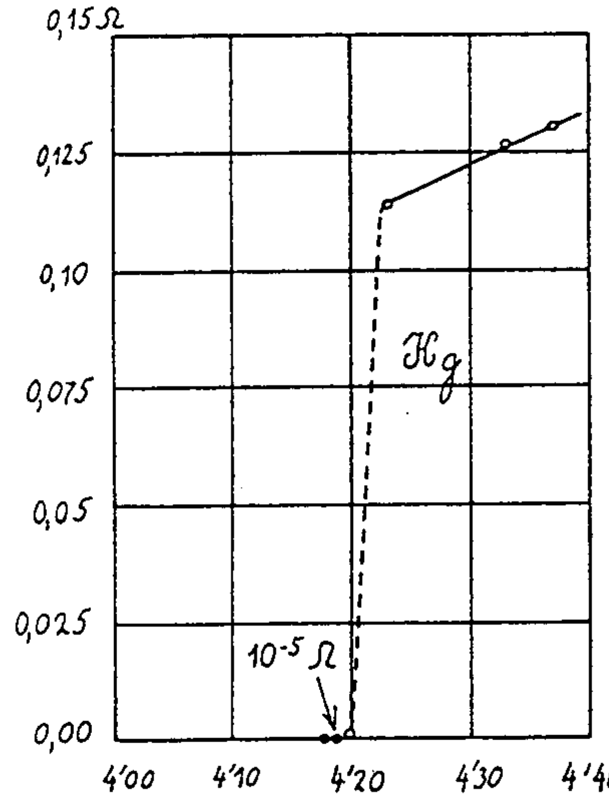
"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement"

W. Thomson (Lord Kelvin)



Superconductors Pre-history





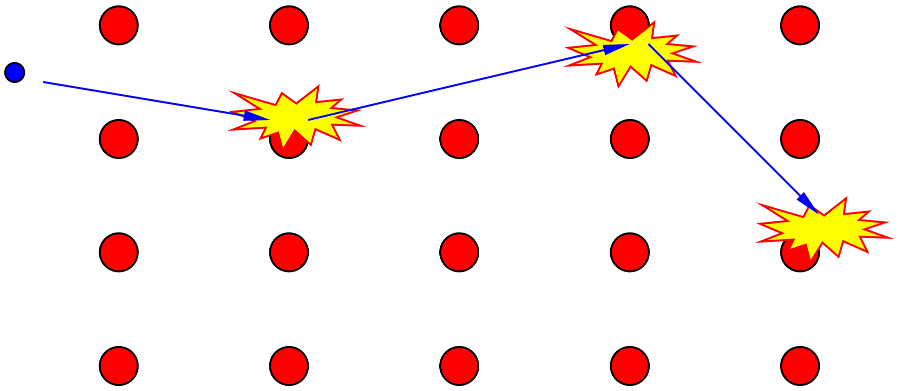
… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

H. Kamerlingh-Onnes (1911)

Cooper Pairs

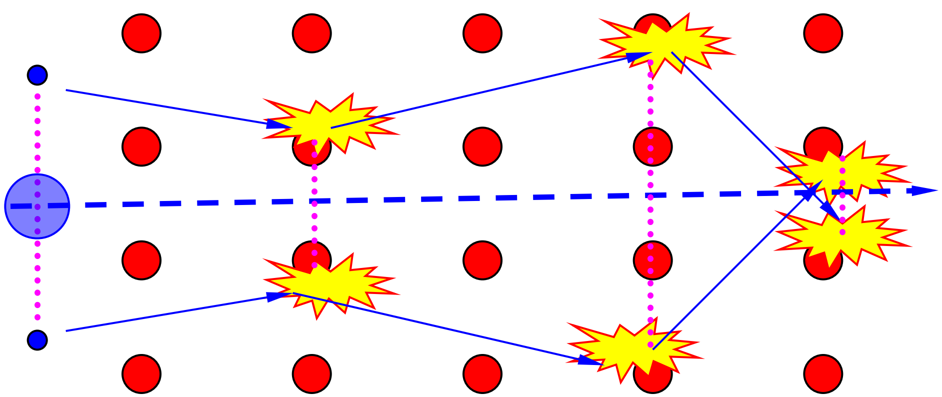
Bardeen, Cooper and Schrieffer

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



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

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



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

Pairing mechanism

Lattice displacement

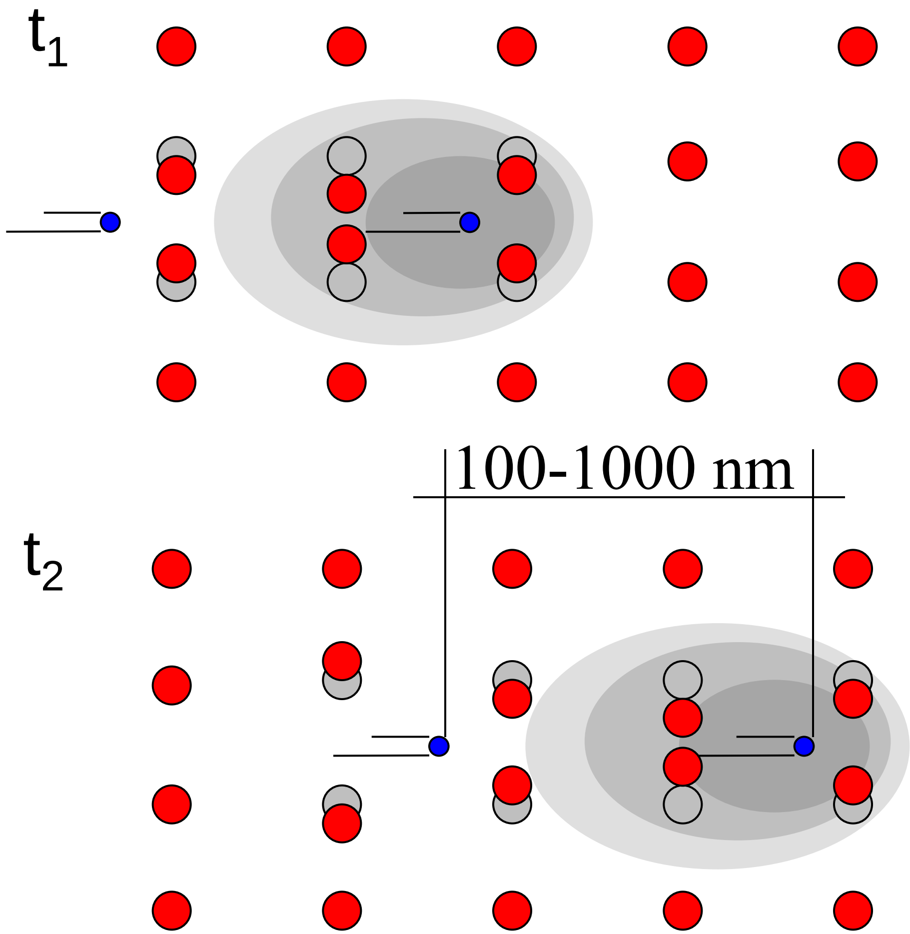
⇓

phonons (sound)

⇓

coupling of charge carriers

Only works at low temperature



Bardeen, Cooper, Schrieffer (BCS) - 1957

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

First (not last) superconducting magnet project cancelled

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

Third International Congress of Refrigeration, Chicago (1913)

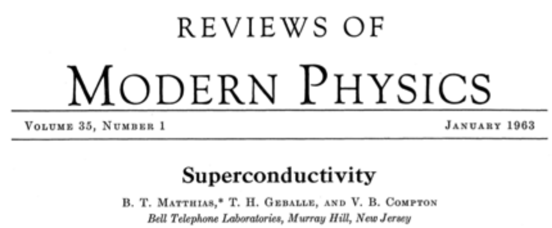
Solvay conference (1914)

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

Superconductivity languished for 40 years…

Flourishing of materials, but depressing Tc…

Theoretical limit around **30 K**



REVIEWS OF

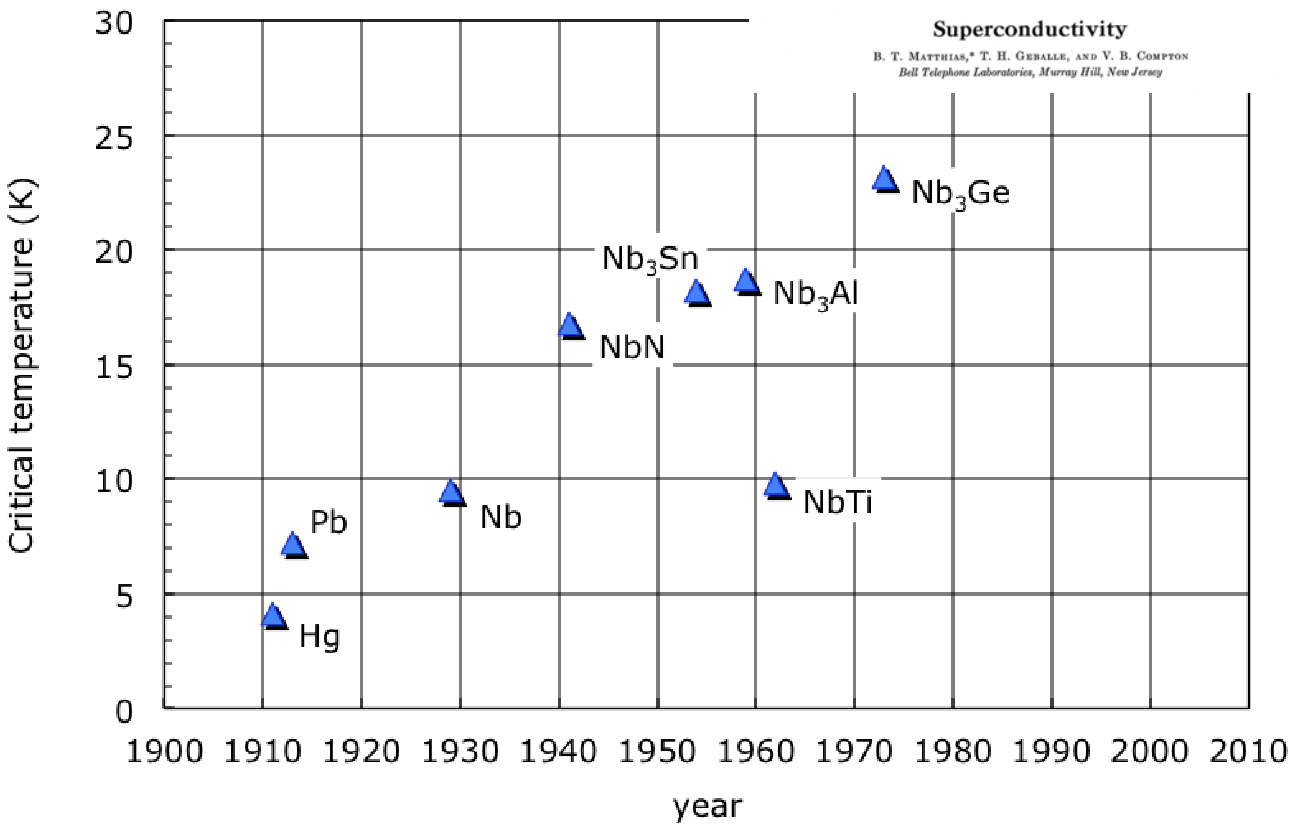
MODERN PHYSICS

VOLUME 35, NUMBER 1 — JANUARY 1963

Superconductivity

B. T. MATTHIAS,* T. H. GEBALLE, AND V. B. COMPTON

Bell Telephone Laboratories, Murray Hill, New Jersey



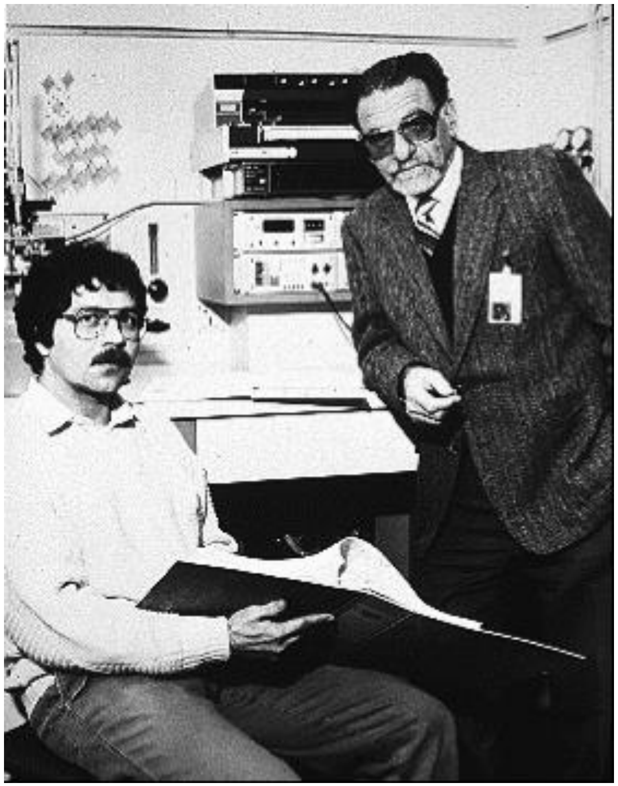
One Thousand and One Superconductors

B. Matthias (1918-1980)

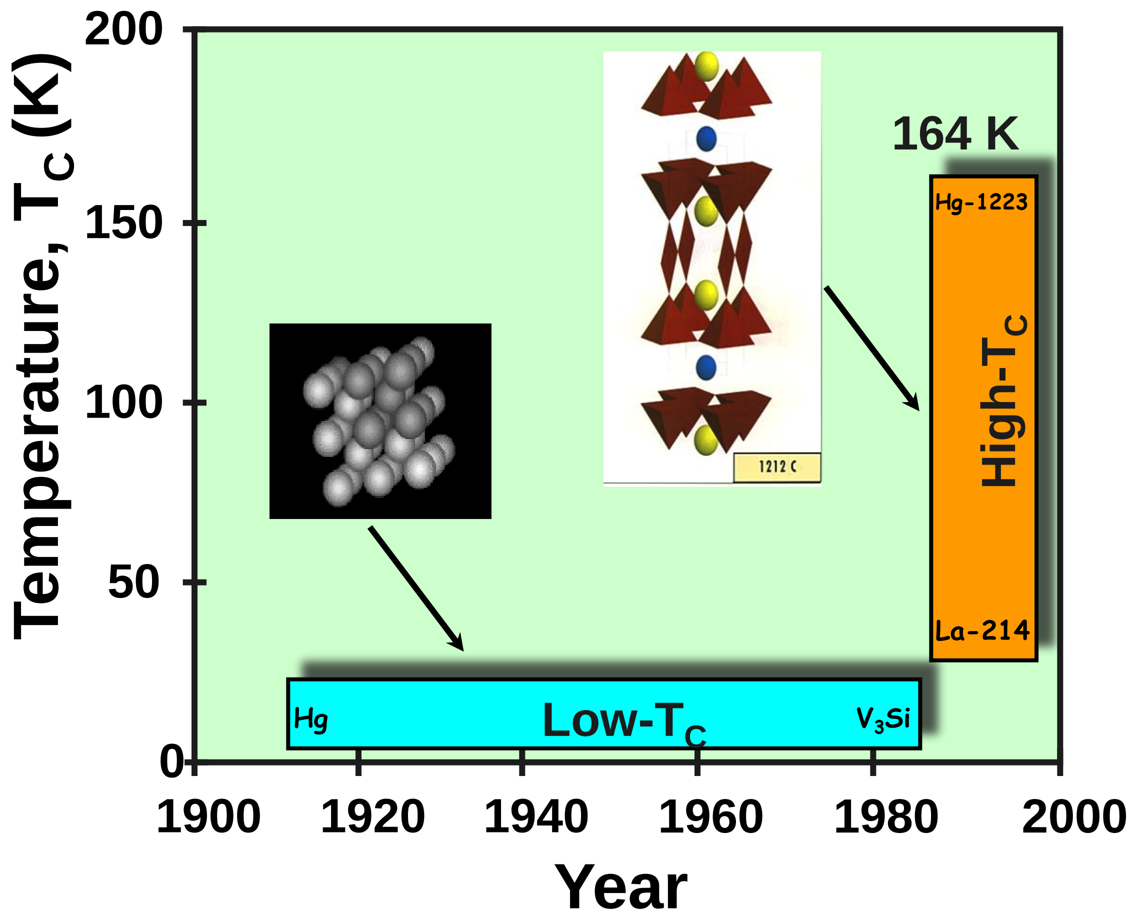
Superconductivity was a *physicist playground* till the late 1950’s

Graphics by courtesy of P. Grant

1986 - A Big Surprise



Bednorz and Mueller
IBM Zuerich, 1986



1987 - The prize !

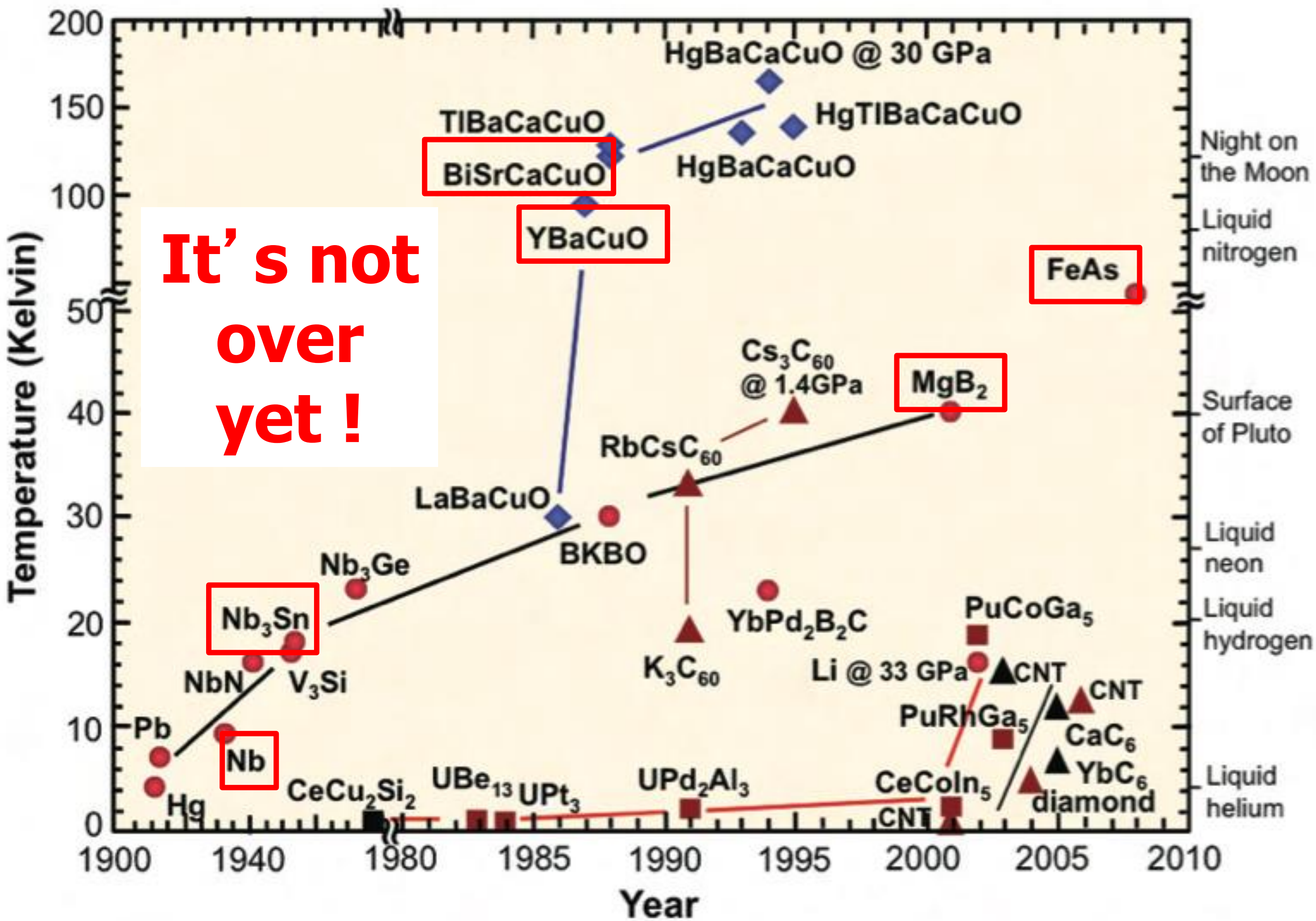
"…for their important break-through in the discovery of superconductivity in ceramic materials"


Associated Press

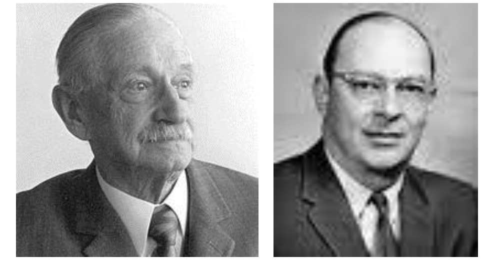
J. Georg Bednorz, left, and K. Alex Müller after learning they had won the Nobel Prize in physics.

2 Get Nobel for Unlocking Superconductor Secret

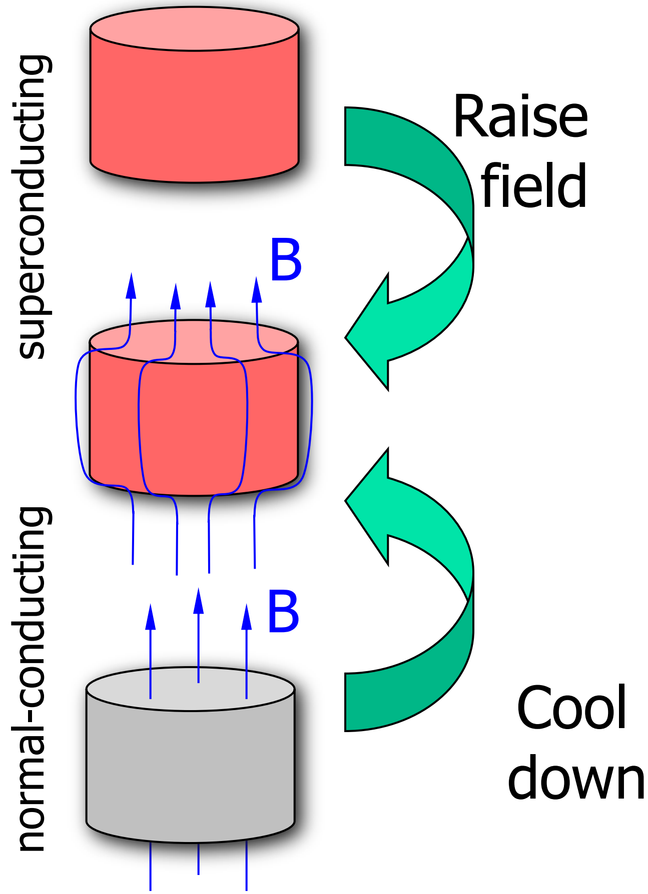
High-Tc timeline - impressive !!!



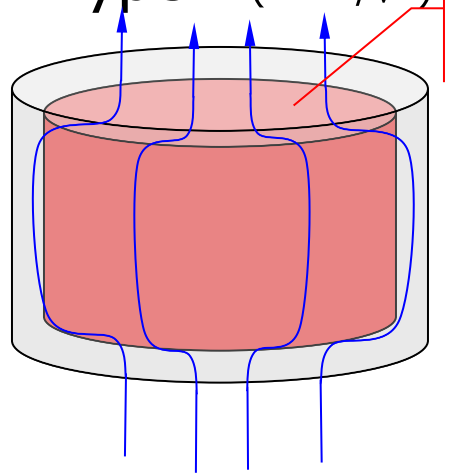
Hey, what about field ?



W. Meissner, R. Ochsenfeld



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



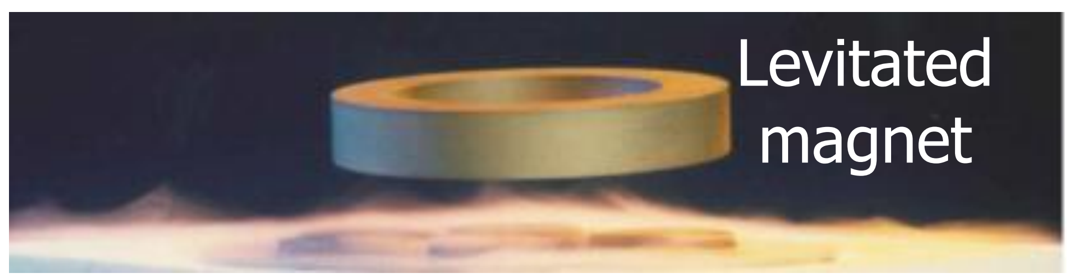
Complete field exclusion

Pure metals

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

Meissner & Ochsenfeld, 1933

Example of magnetic levitation



Superconducting disk

Free energy and critical field

- Let us define the Gibbs free energy of a material in a magnetic field:

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

- A system in equilibrium will tend to a minimum of G
- In zero applied field, the SC phase (being in a condensed state) has lower free energy than the normal phase:

$$G_{sup}(H=0) < G_{normal}(H=0)$$

- The field expulsion ($\mathbf{M}=-\mathbf{H}$) corresponds to a magnetic energy density:

$$-\mu_0\, \mathbf{M} \cdot \mathbf{H} = \mu_0/2\, H^2$$

- The material *prefers* to expel the magnetic field (Meissner effect) until the free energy of the SC phase in field equals the free energy of the normal state:

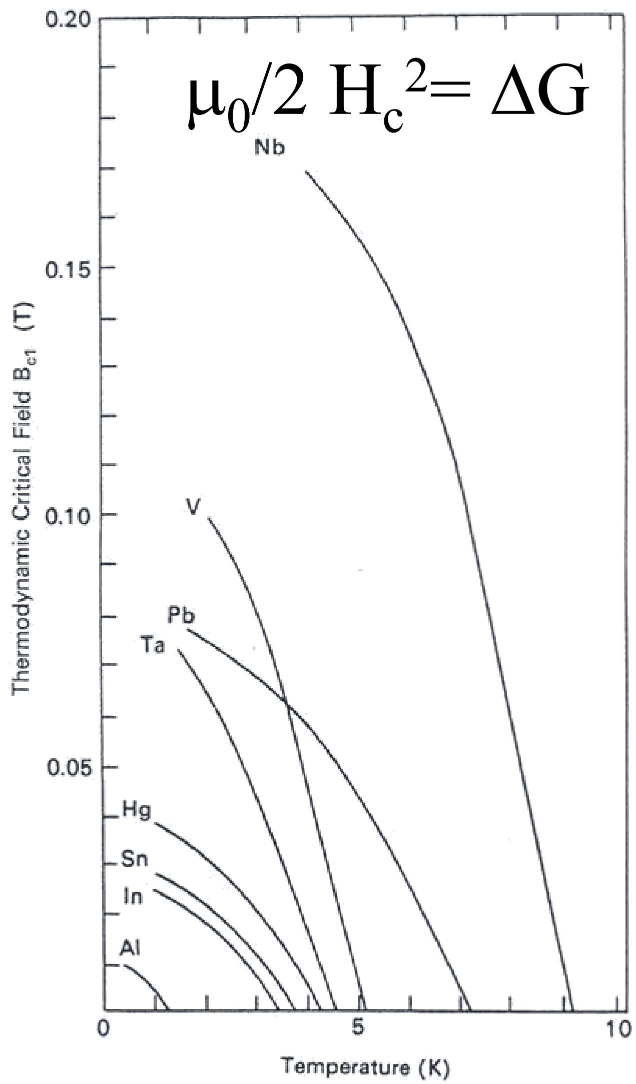
$$\mu_0/2\, H_c^2 = G_{normal} - G_{sup}(H=0)$$

Thermodynamic critical field

Type I – critical field

- The difference in free energy ΔG among the SC and normal state is small
- The corresponding values of the thermodynamic critical field are also small, i.e. in the range of few mT to barely above 100 mT

Not very useful for magnet engineers !



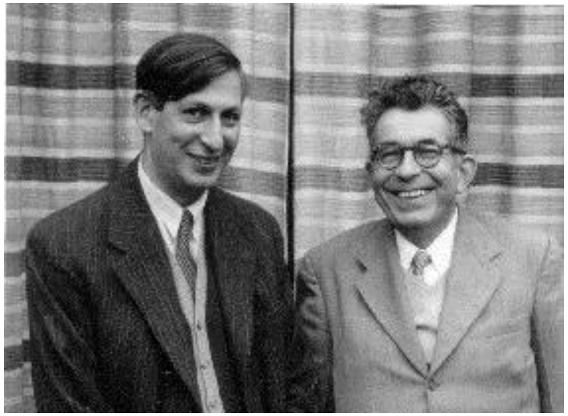
London penetration length λ_L

- Field profile

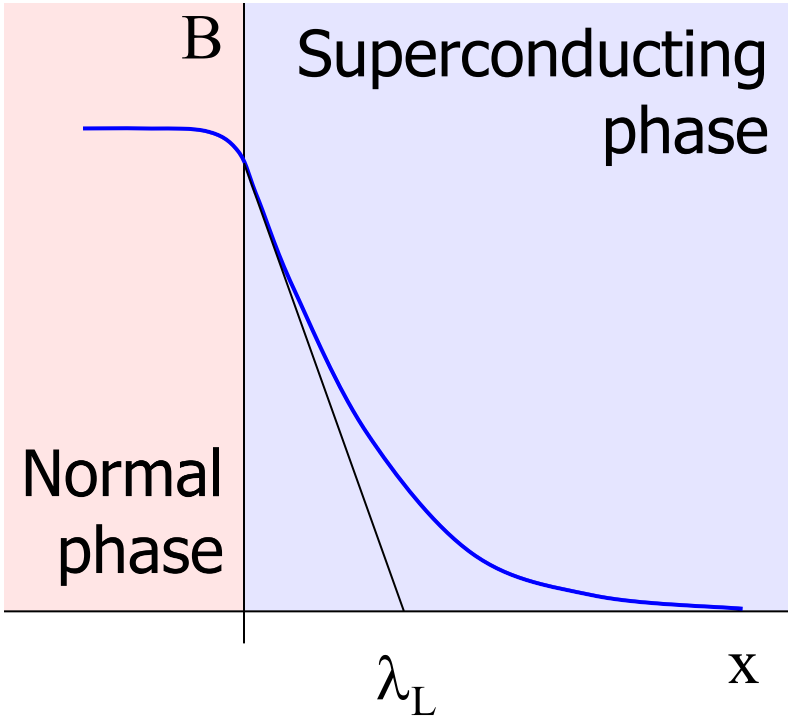
$$B(x) = B_0 \exp\left(-\frac{x}{\lambda_L}\right),$$

- *London* penetration length

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



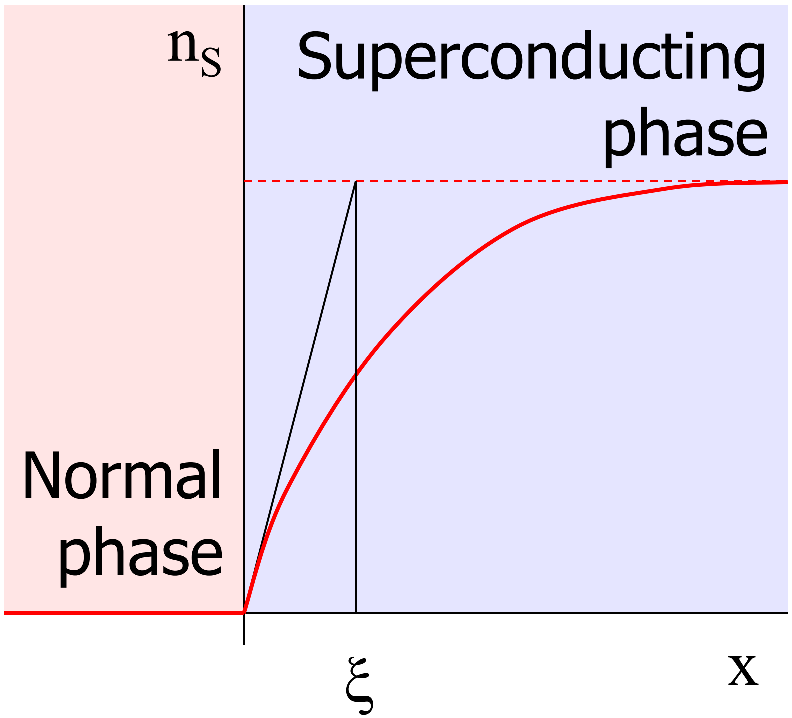
H. and F. London, 1935



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

Coherence length ξ

- At an interface the density of paired electron n_S rises smoothly from zero (at the surface) to the asymptotic value (in the bulk)
- The characteristic length of this transition is the coherence length



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

Fermi velocity

SC energy gap

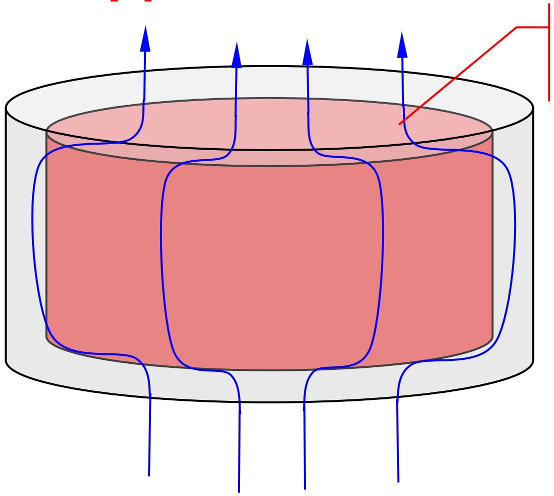
ξ is of the order of 1 to 1000 nm in typical superconducting elements and alloys

Ginzburg–Landau, 1950

Energy efficient fluxons

Landau, Ginzburg and Abrikosov

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



Complete field exclusion

Pure metals

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

Meissner & Ochsenfeld, 1933

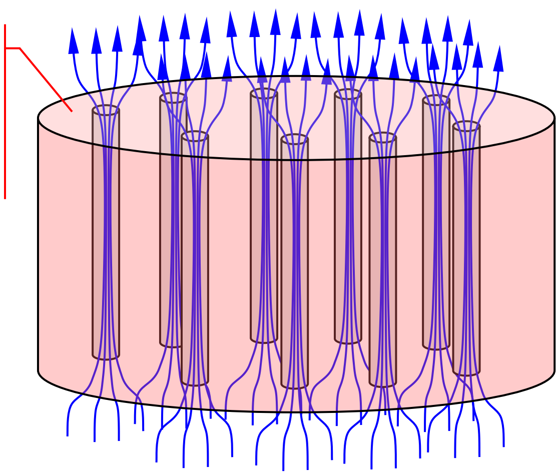
Type II ($\kappa > 1/\sqrt{2}$)

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

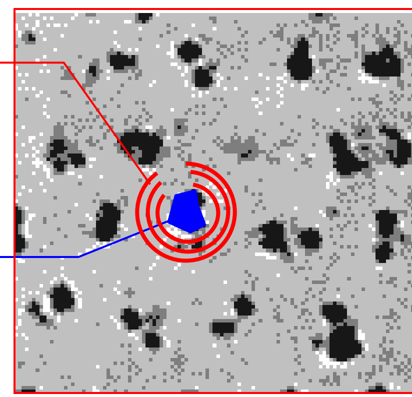
Values of λ_L , ξ and κ

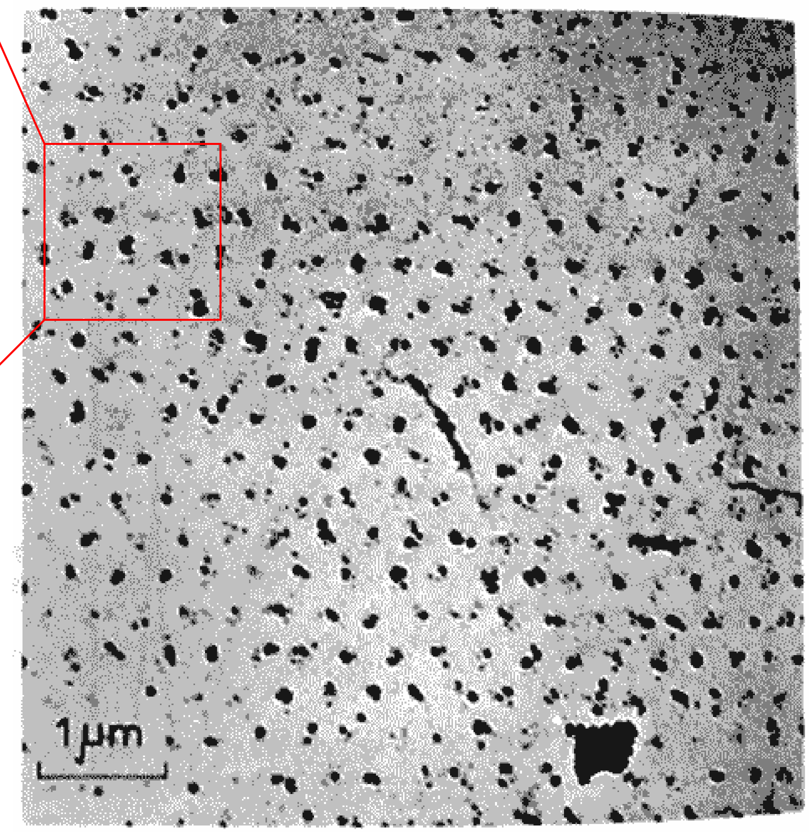
Material	λ_L (nm)	$\xi(B=0)$ (nm)	κ (-)
Al	16	1600	0.01
Pb	32	510	0.06
In	24	360	0.07
Cd	110	760	0.15
Sn	30	170	0.18
Nb	40	39	1
Nb_3Sn	200	12	≈ 20
MgB_2	185	5	≈ 40
YBCO	200	1.5	≈ 75

Type I

Type II

Lattice of quantum flux lines





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

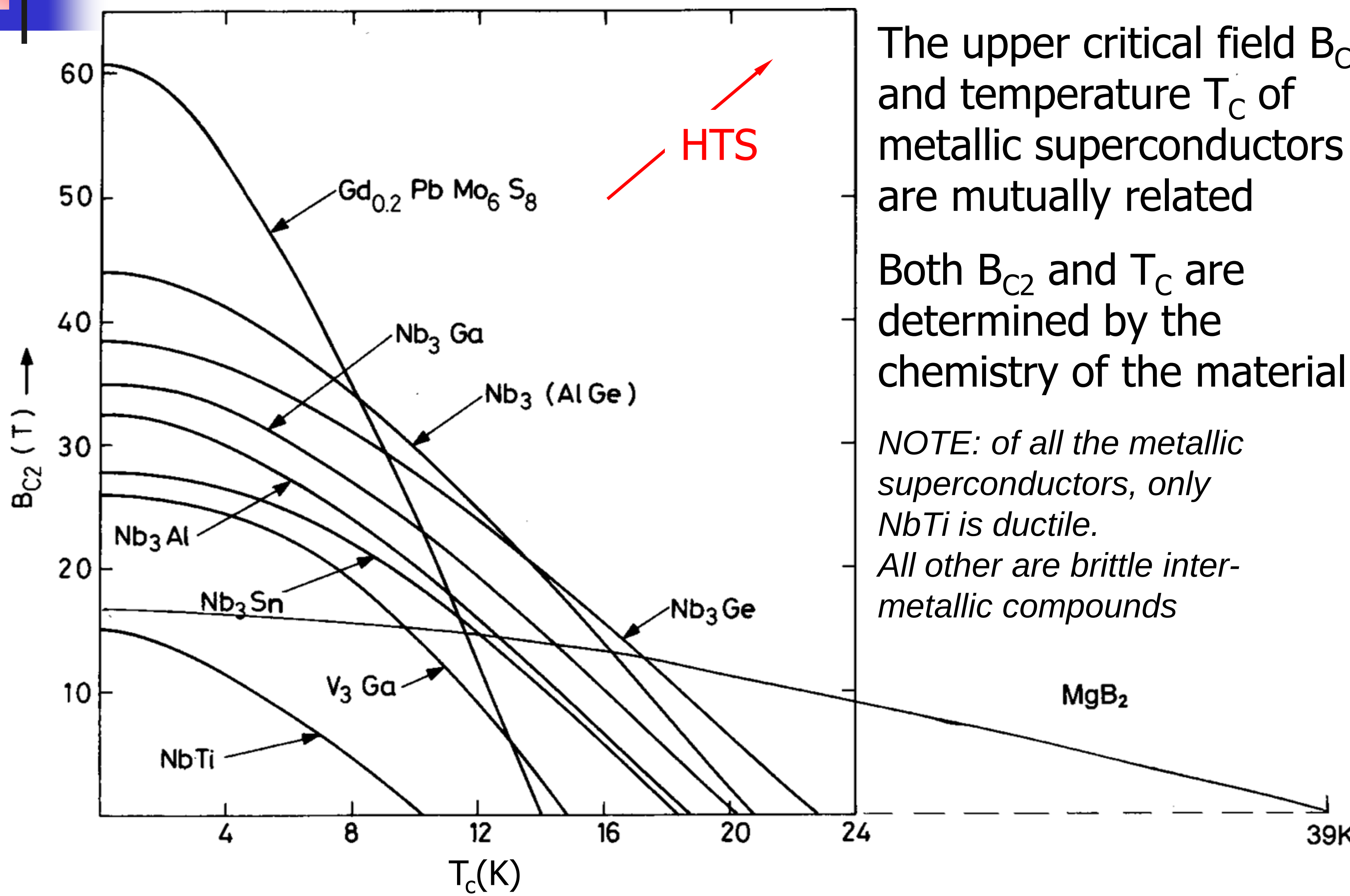
Observation on Pb-4at% In magnetised by a field of 3000 Oe and decorated by Co particles

Essmann & Träuble, 1967

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

Graphics by courtesy of M.N. Wilson

Type II – critical 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 $\Rightarrow$ energy dissipation $\Rightarrow$ loss of superconductivity
- To carry a significant current we need to *lock the fluxoids* so to resist the Lorentz force. For this we mess-up the material and create **pinning centers** that exert a pinning force F_P

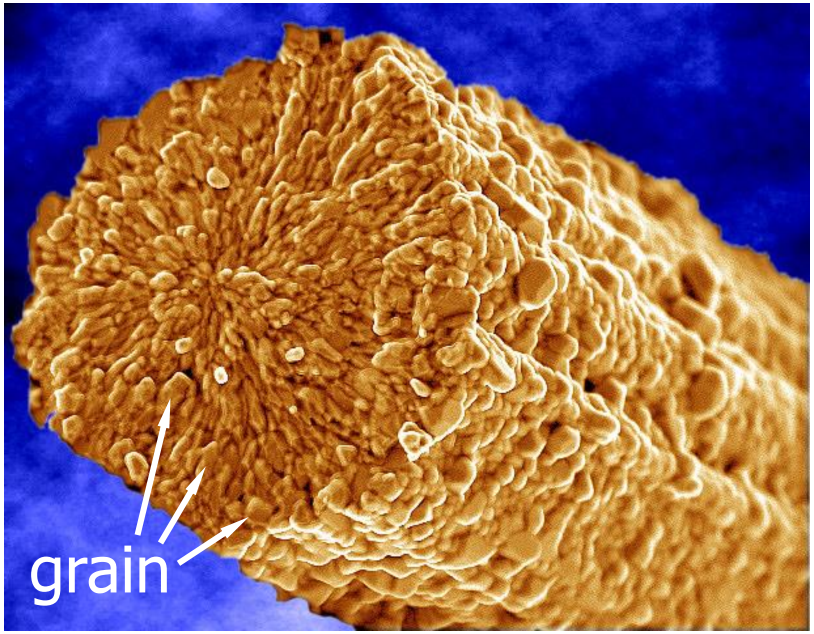
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning centers

Precipitates in alloys

Grain boundaries in inter-metallic compounds

Microstructure of Nb-Ti



Microstructure of Nb_3Sn

Jc(B,T,...)

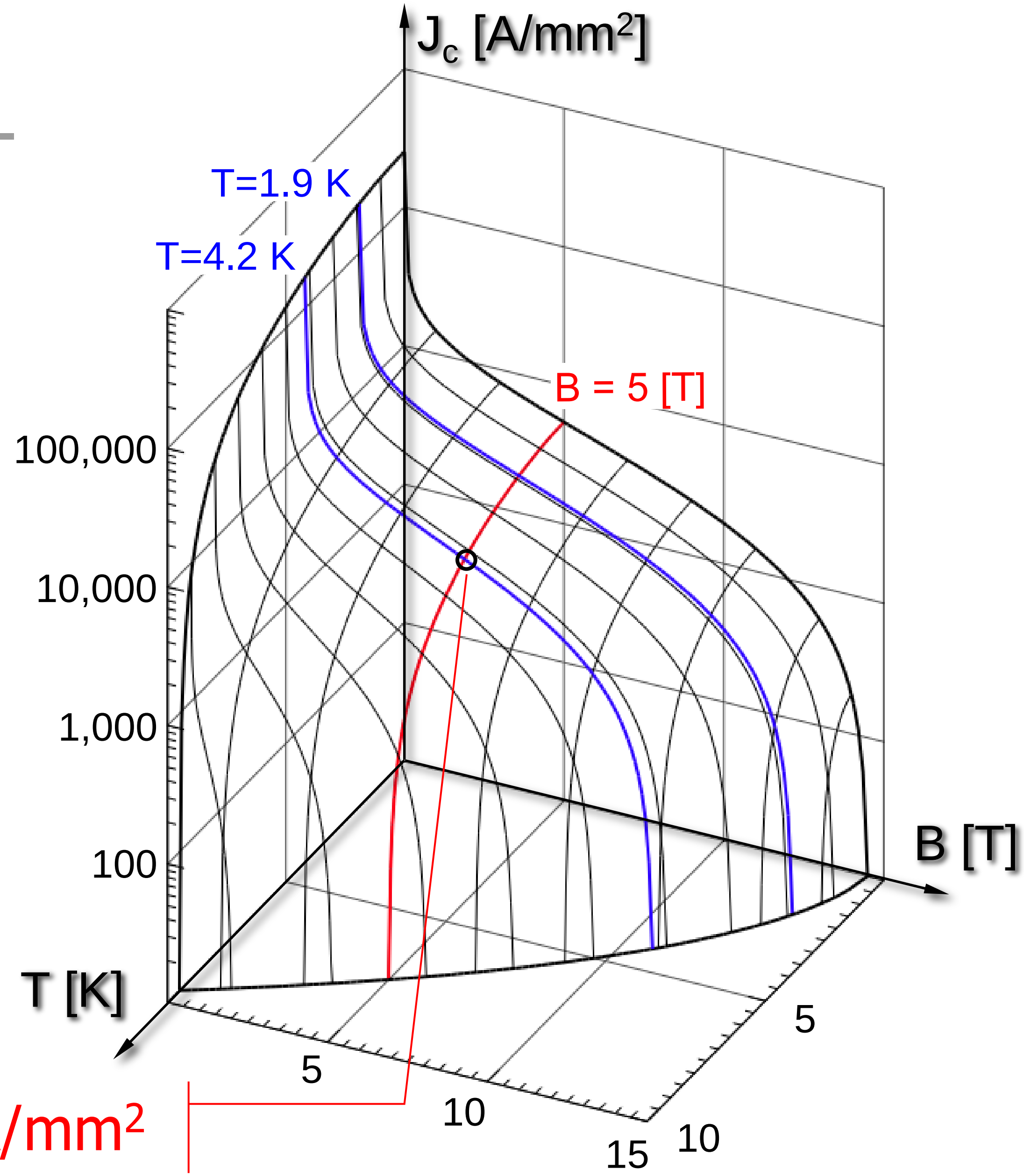
- The maximum current that can be carried by the superconductor is the current at which:

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

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

$$J_C(B,T,...) = F_P / B$$

Critical surface of a LHC NbTi wire



Jc (5 T, 4.2 K) ≈ 3000 A/mm²

Superconductors – the bottom line

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

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

From materials to magnets

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

A summary of technical materials

20 T and beyond !

Material		LTS				HTS	
		Nb-Ti	Nb_3Sn	Nb_3Al	MgB_2	YBCO	BSCCO
Year of discovery		1961	1954	1958	2001	1987	1988
Tc	(K)	9.2	18.2	19.1	39	≈93	$95^{(*)}$ $108^{(\#)}$
Bc	(T)	14.5	≈30	33	36…74	$120^{(\dagger)}$ $250^{(\ddagger)}$	≈200

HL-LHC

Power transmission cables and SC links

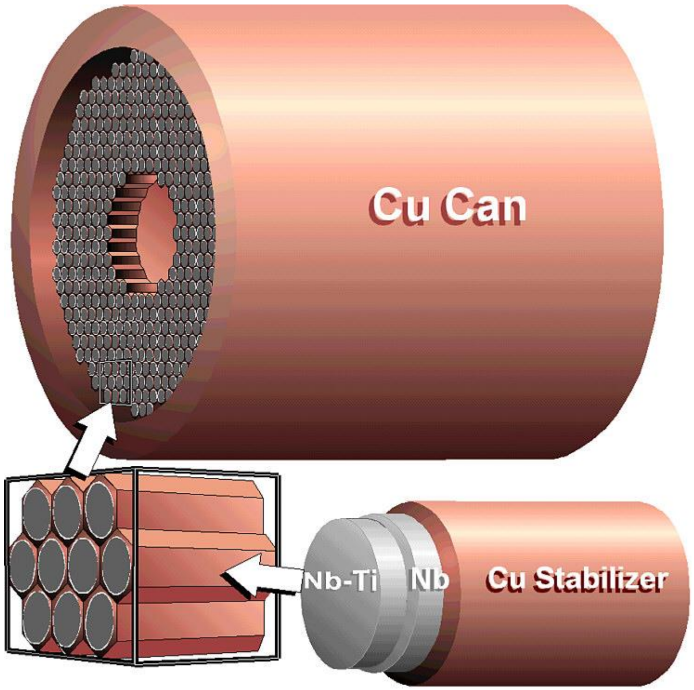
Tevatron
HERA
RHIC
LHC

NOTES:
(†) B parallel to *c*-axis
(‡) B parallel to *ab*-axes
(*) BSCCO-2212
(#) BSCCO-2223

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb-Ti manufacturing route

NbTi billet

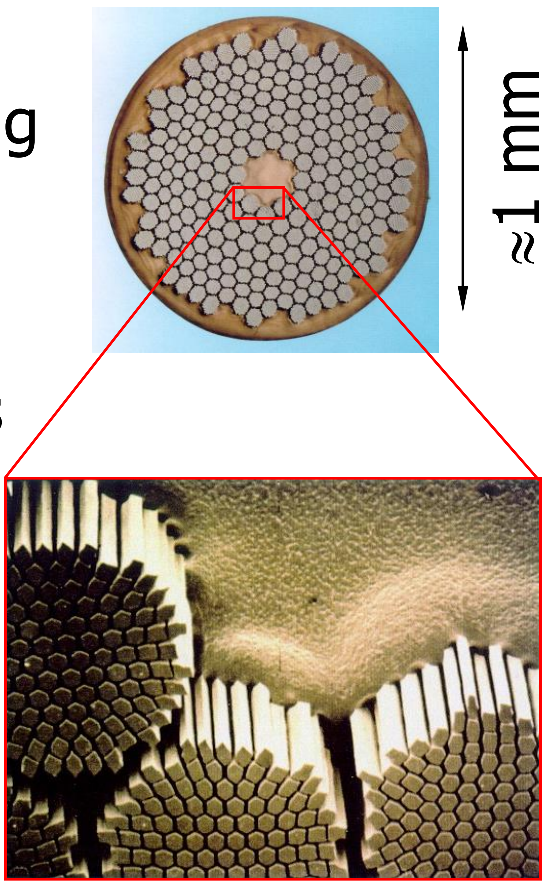


NbTi is a ductile alloy that can sustain large deformations

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

extrusion
cold drawing

heat
treatments

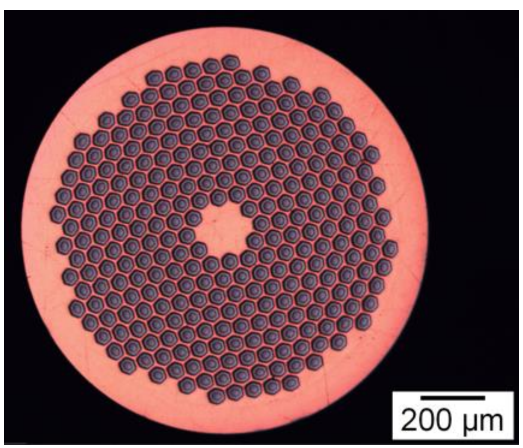


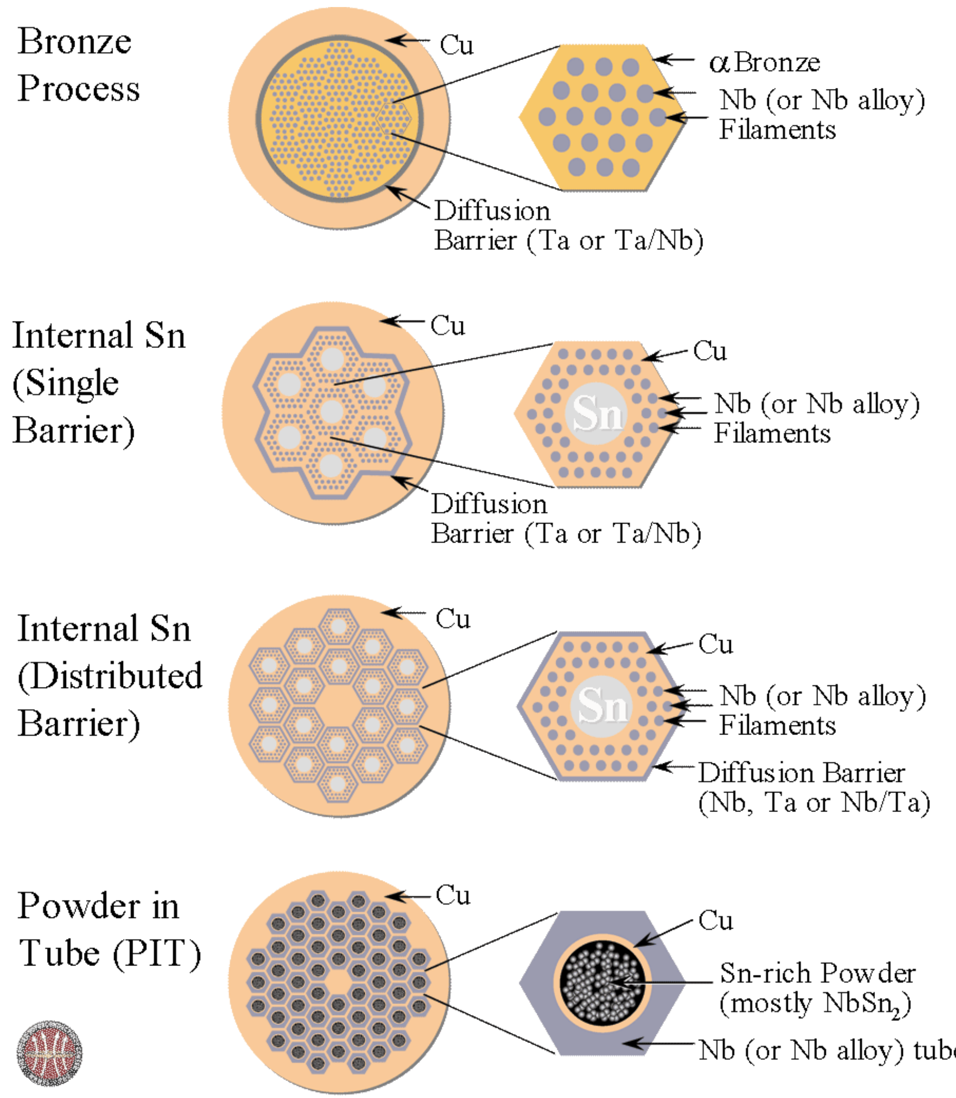
LHC wire

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb_3Sn manufacturing routes

Nb_3Sn is brittle and cannot be drawn in final form. The precursors are drawn and only later the wire is heat-treated to ≈650 C for several hrs, to form the Nb_3Sn phase





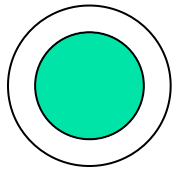
I_C(12 T, 4.2 K) ≈ 1.5 kA

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

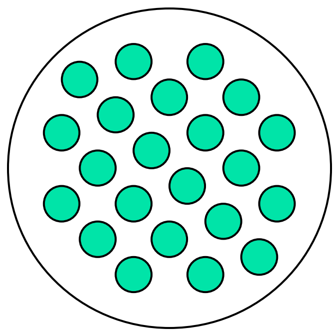
BSCCO manufacturing routes

Oxide powder in tube OPIT

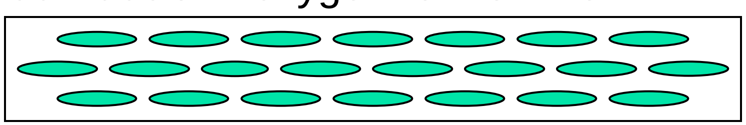
1) draw down BSCCO powder in a silver tube



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

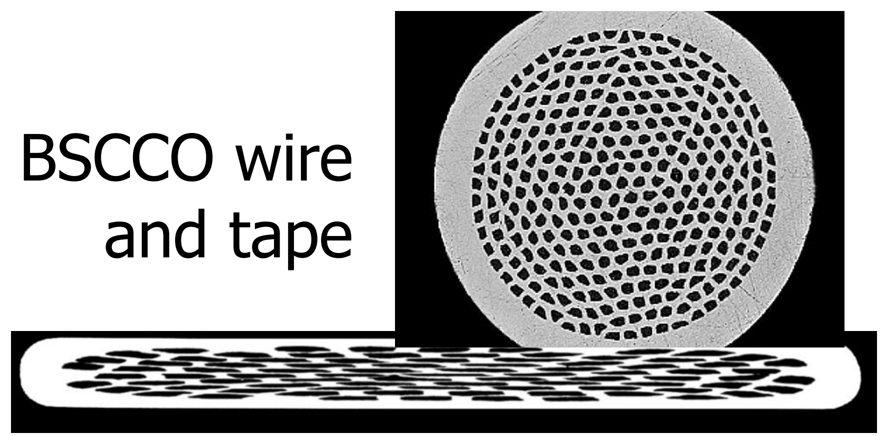


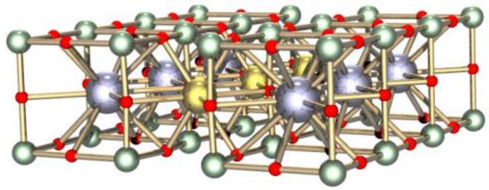
3) roll the final wire to tape and heat treat at 800 - 900C in oxygen to melt the B2212



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



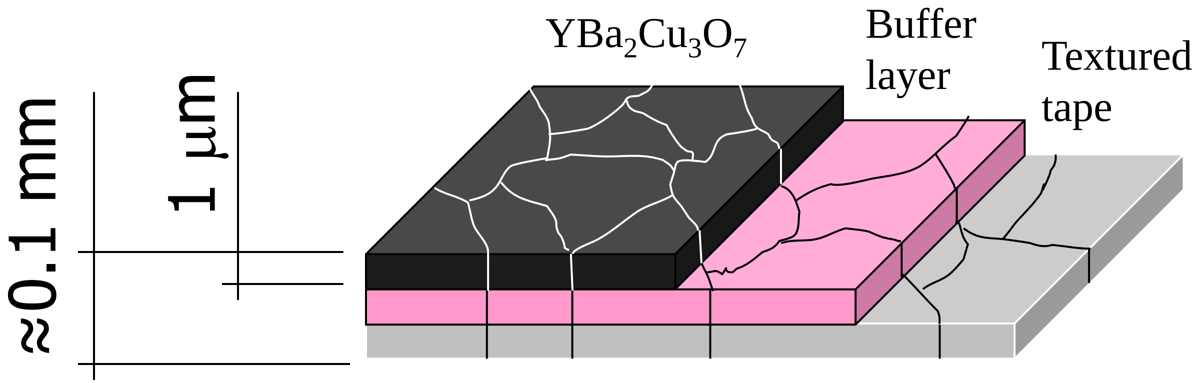


YBCO tape (developmental)

YBCO has excellent critical properties, but grains do not align during processing. If grains are not aligned the supercurrent cannot jump between the grains. All manufacturing processes force a certain degree of alignment in the microstructure

- produce a tape with an aligned texture
- coat the tape with a buffer layer
- coat the buffer with a layer $YBa_2Cu_3O_7$ such that the texture of the YBCO follows that of the buffer and substrate

All routes use a ion deposition techniques (laser, plasma, evaporation) in vacuum (cost & length !)

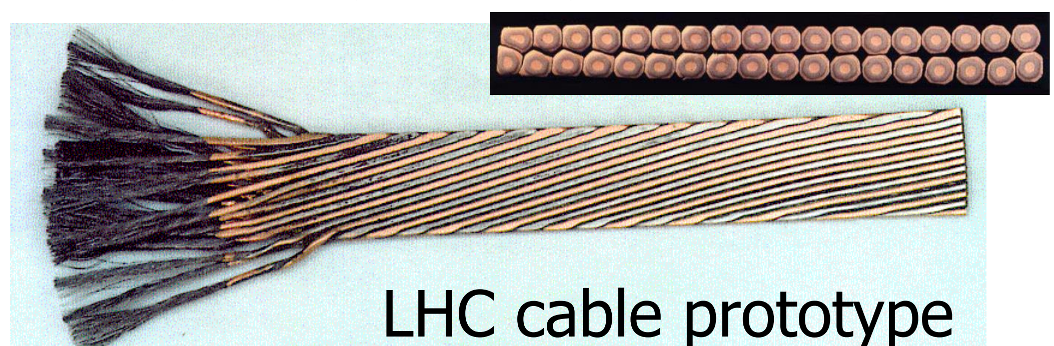


$J_E \approx 500$ A/mm^2

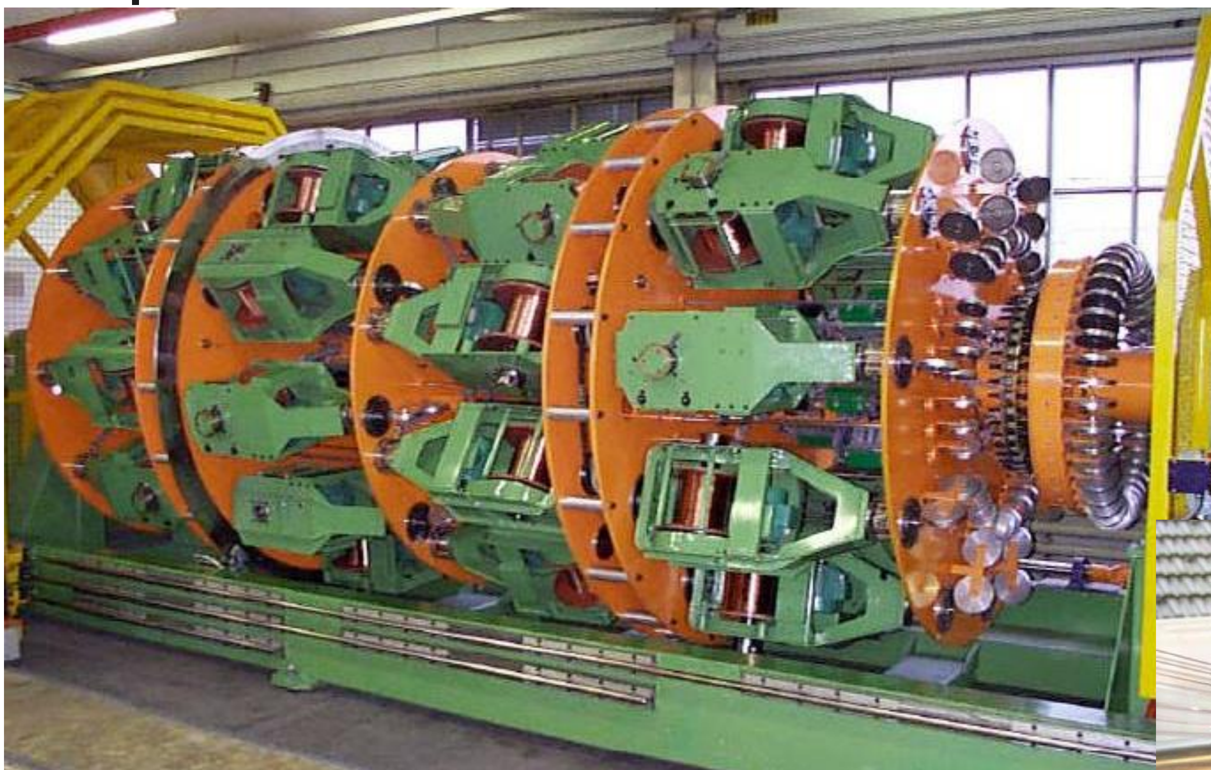
Practical conductors: high J_E

- Multifilamentary wires have current carrying capability of 100… 1000 A
- Insulated with varnish or glass-braids they can be used to make all kind of small size magnets

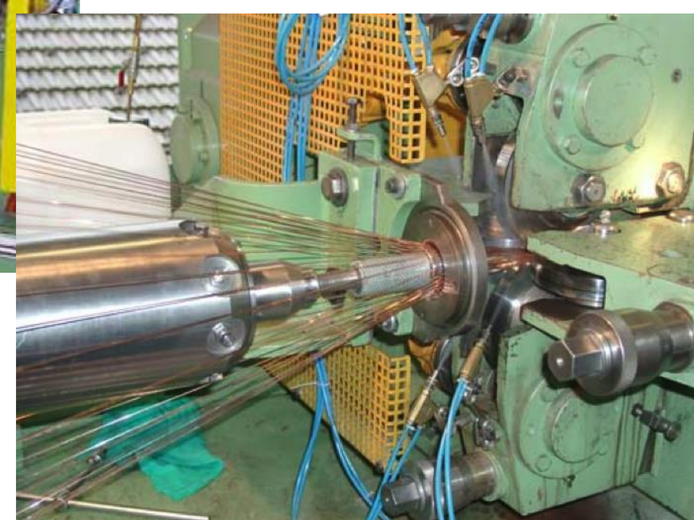
- Large size magnets (e.g. LHC dipoles) require invariably large operating currents (10 to 100 kA) to:
  - Decrease inductance,
  - Lower the operating voltage,
  - Ease magnet protection
- Rutherford cables are ideally suited for this task



Rutherford cable machine @ CERN



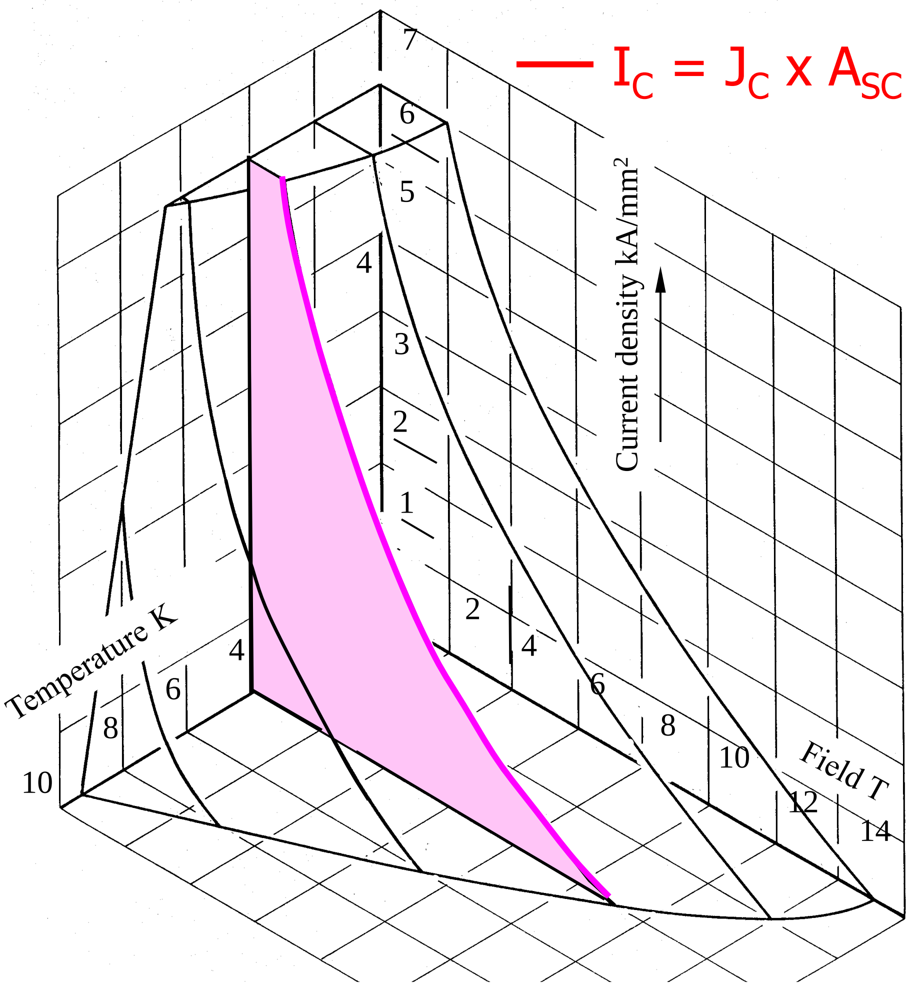
Strands fed through a cabling tongue to shaping rollers



Strand spools on rotating tables

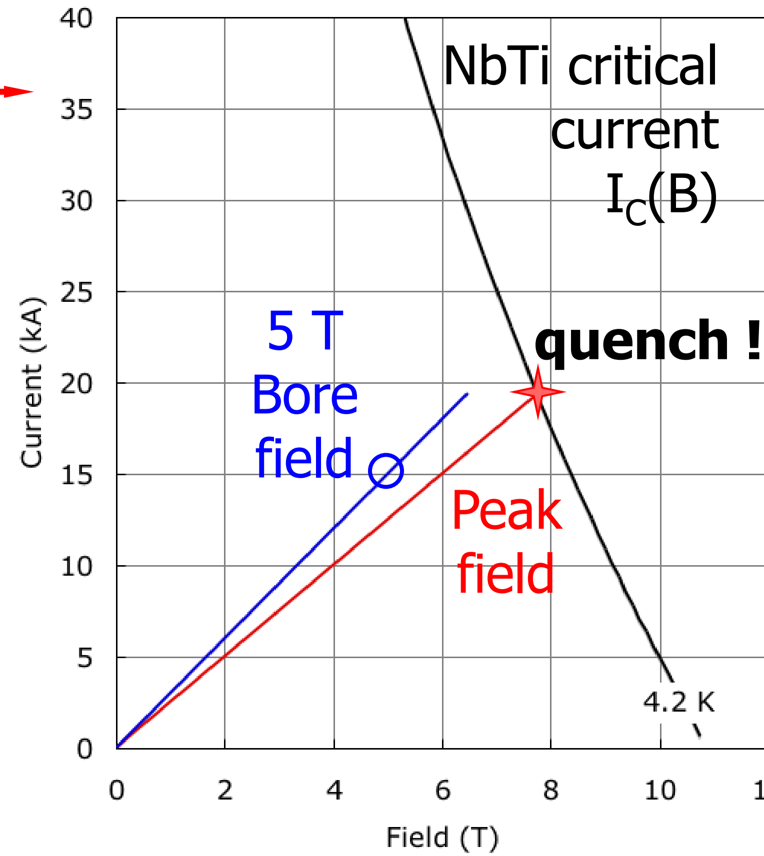
Critical line and magnet load lines

NbTi critical surface



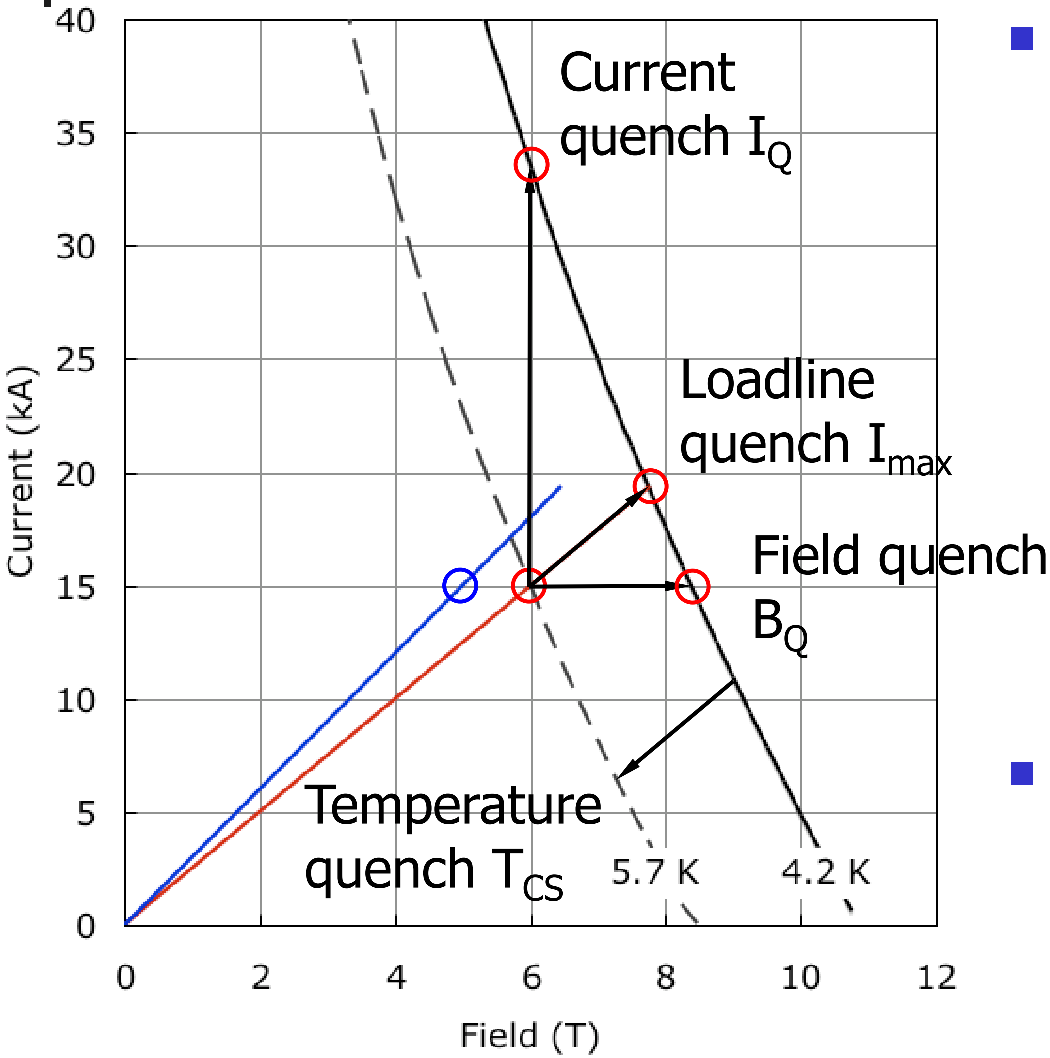
$I_C = J_C \times A_{SC}$

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

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

Engineering current density

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

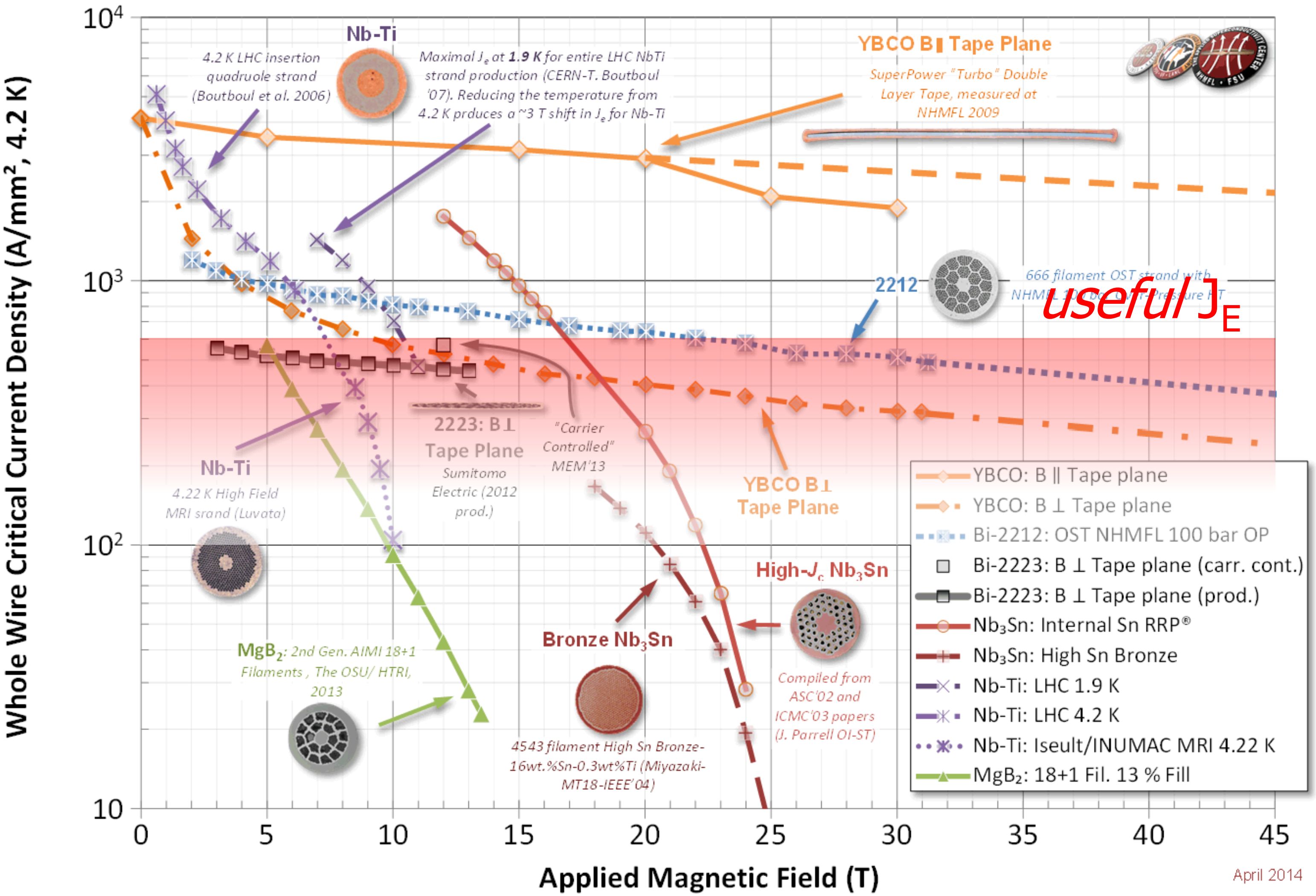
$$\lambda = A_{SC} / A_{total}$$

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

$$J_E = J_C \times \lambda$$

Graphics by courtesy of Applied Superconductivity Center at NHMFL

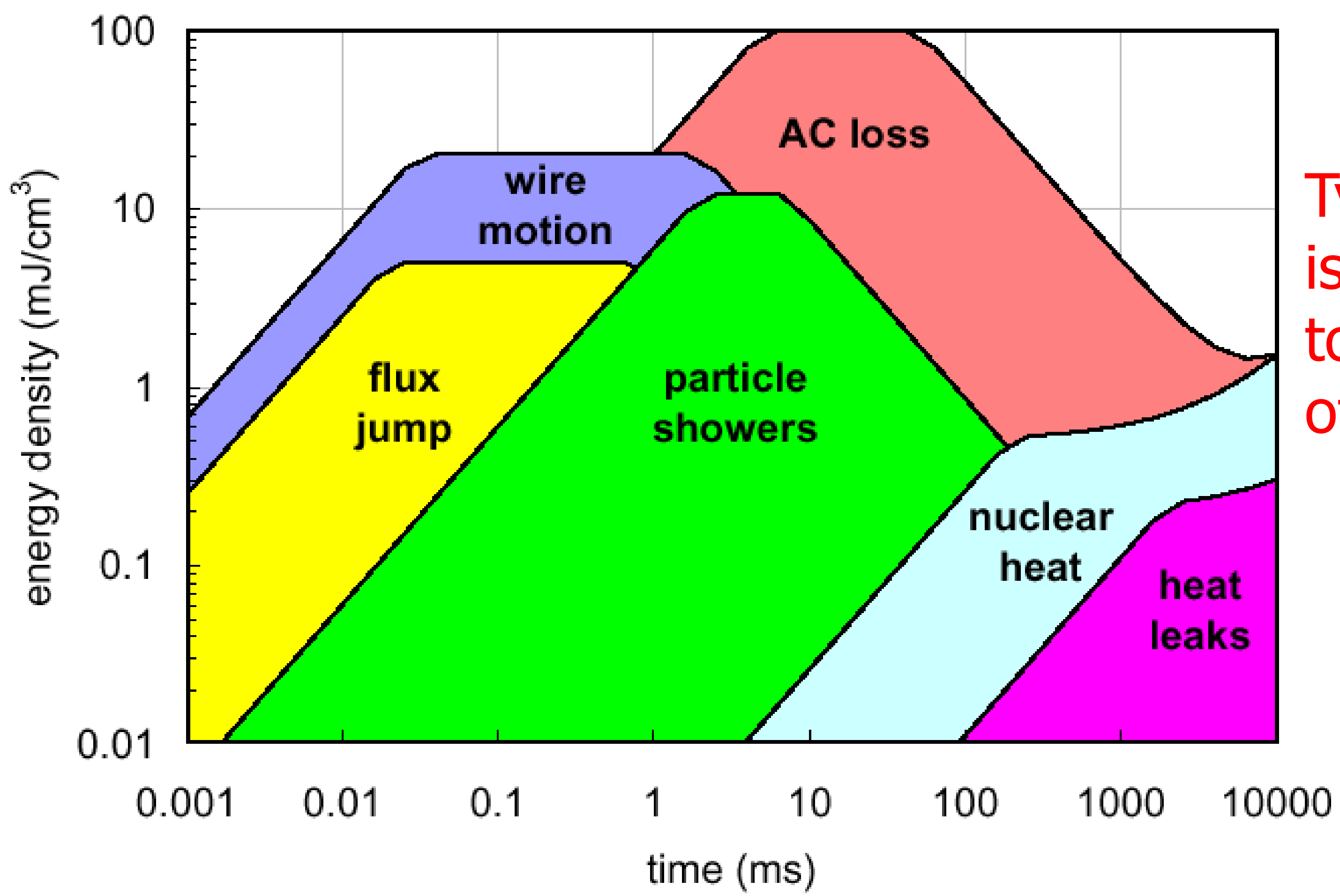
Best of Superconductors J_E



Perturbation spectrum

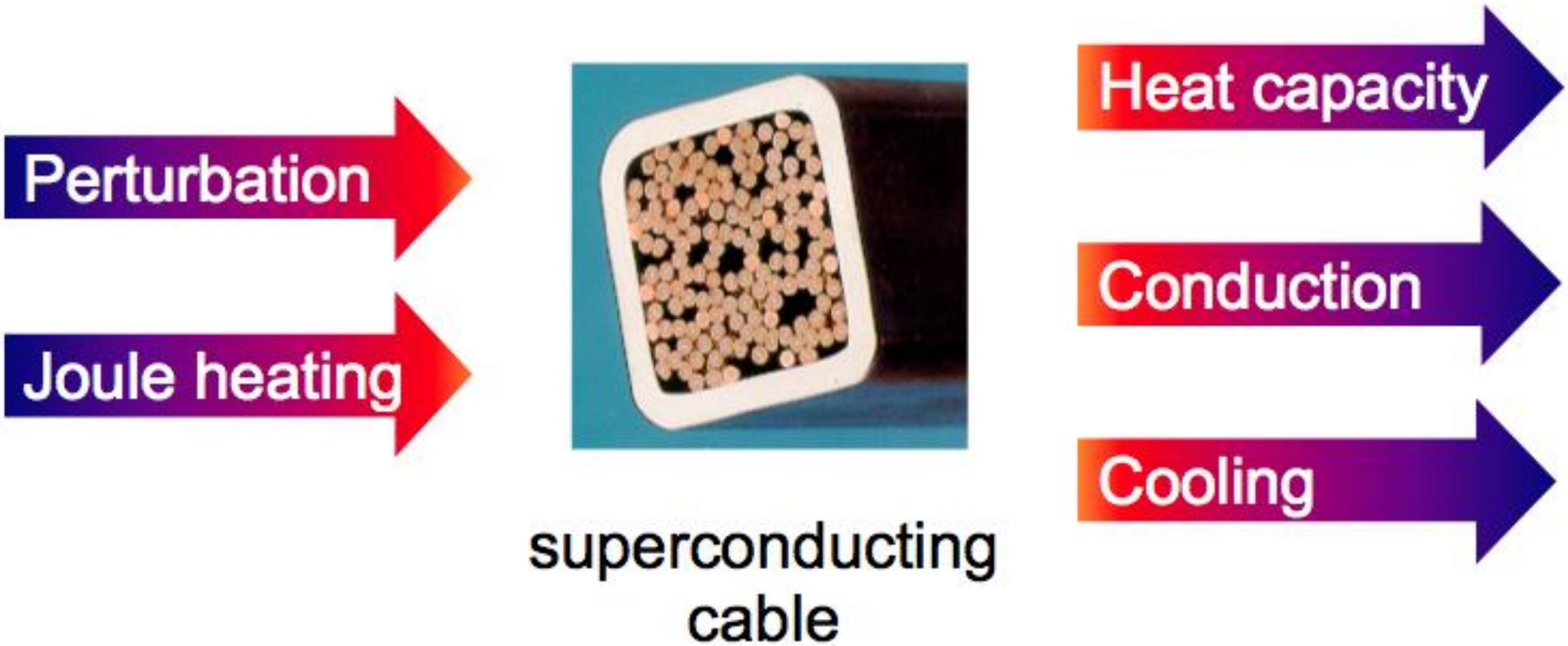
- mechanical *events*
  - wire motion under Lorentz force, micro-slips
  - winding deformations
  - failures (at insulation bonding, material yeld)
- electromagnetic *events*
  - flux-jumps (important for large filaments, old story !)
  - AC loss (most magnet types)
  - current sharing in cables through distribution/redistribution
- thermal *events*
  - current leads, instrumentation wires
  - heat leaks through thermal insulation, degraded cooling
- nuclear *events*
  - particle showers in particle accelerator magnets
  - neutron flux in fusion experiments

Perturbation overview

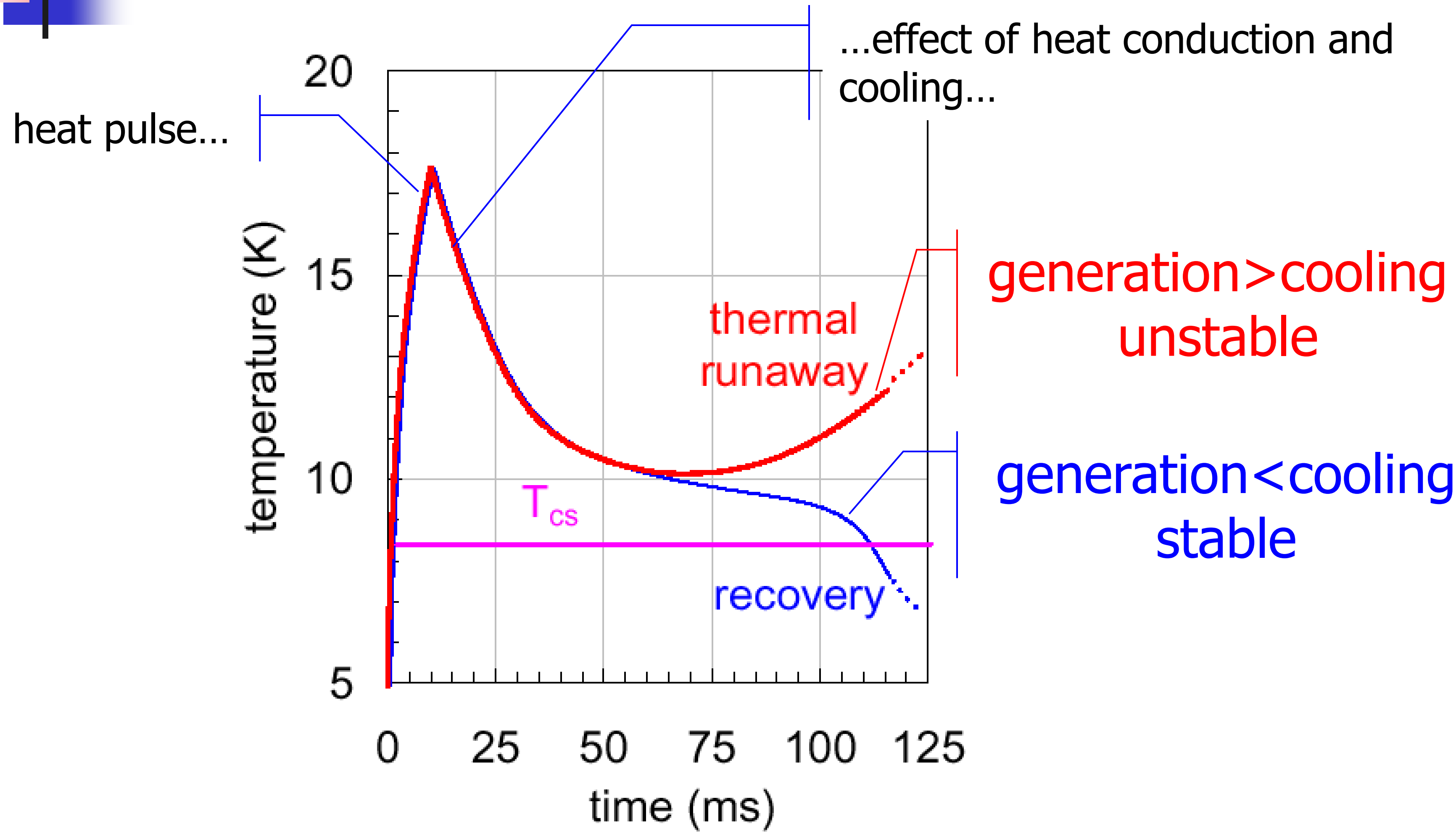


Typical range is from a few to a few tens of mJ/cm^3

Stability as a heat balance



A prototype temperature transient

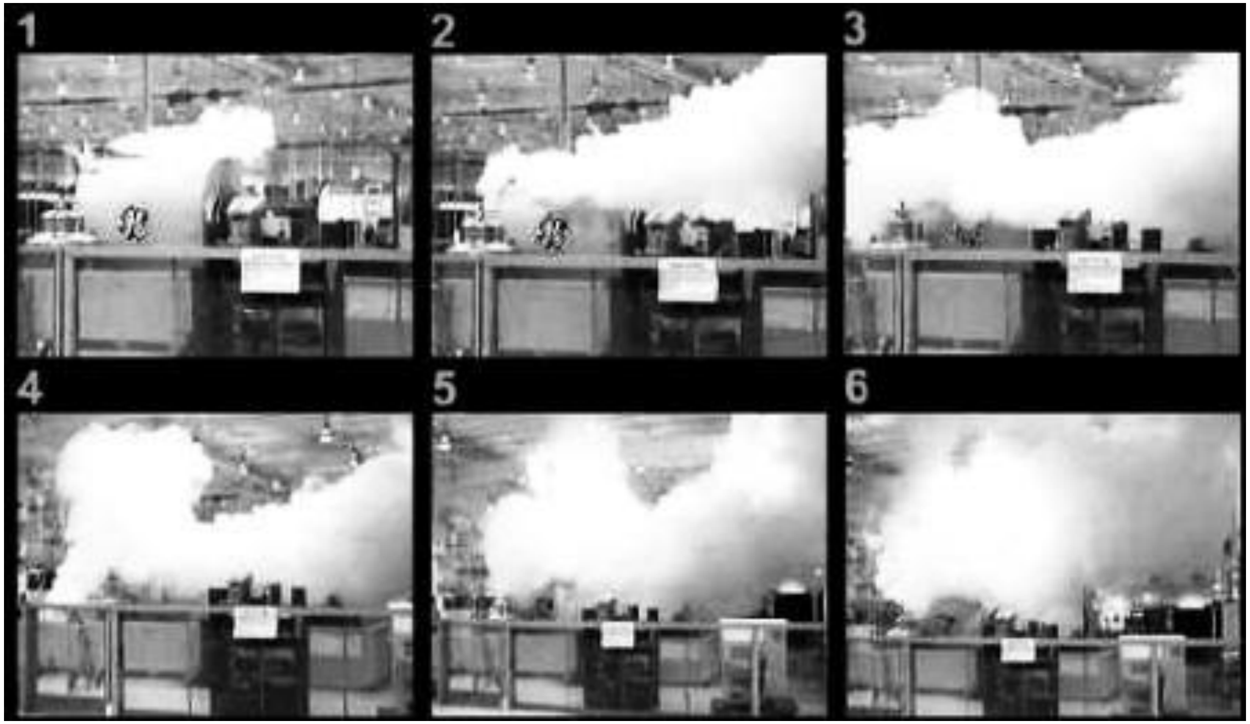


Stability - Re-cap

- 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 we exceed the limits ? Quench !

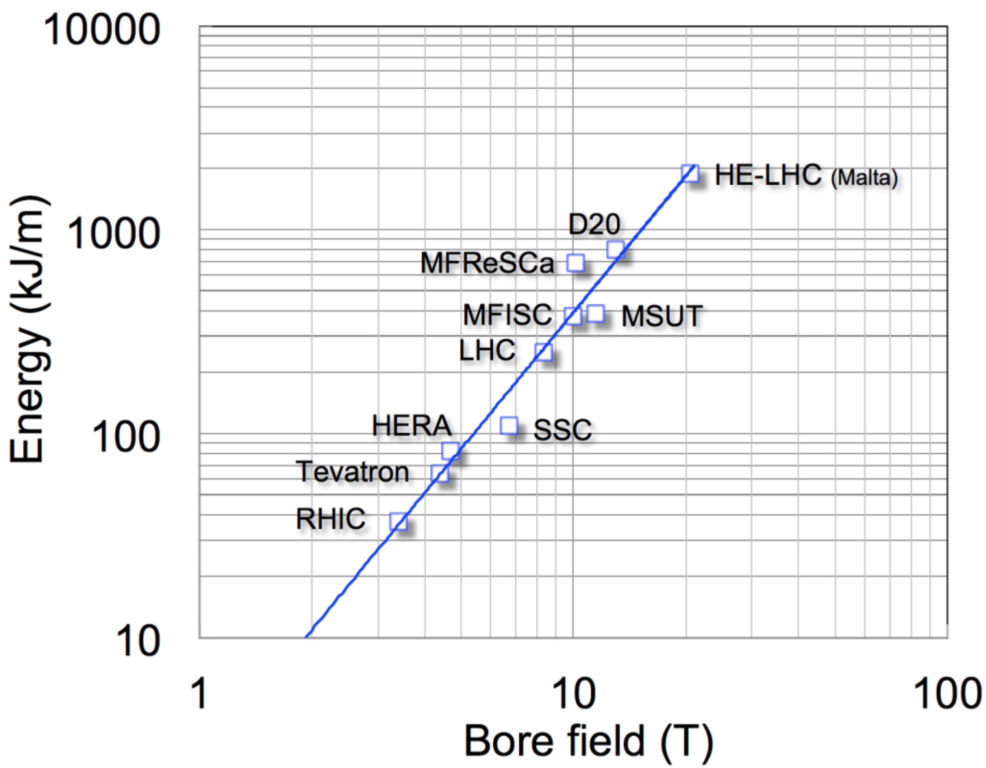
- A resistive transition in a superconducting magnet, leading to appearance of voltage, Joule heating, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion.



This is a quench of a GE MRI magnet during tests at the plant

Stored energy

- The energy stored in the magnetic field of accelerator dipoles scales with the square of the bore field



- A large stored magnetic energy makes the magnet difficult to protect, and requires:
  - Fast detection and dump
  - High terminal voltage and operating current

Energy dissipation

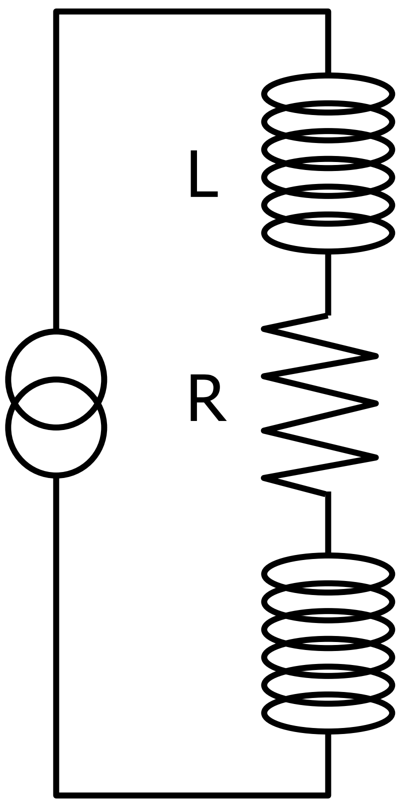
- the magnetic energy stored in the field:

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

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)

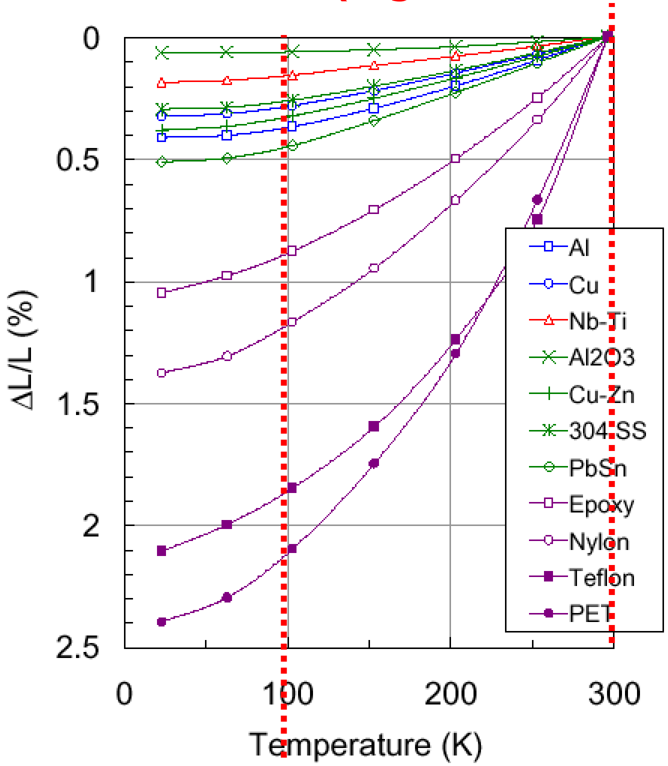
Issues to be considered

- Temperature increase and temperature gradients (thermal stresses)
- Voltages within the magnet, and from the magnet to ground (whole circuit)
- Forces caused by thermal and electromagnetic loads during the magnet discharge transient
- Cryogen pressure increase and expulsion

A quench invariably requires **detection** and may need **actions** to safely turn-off the power supply (possibly more)

Hot-spot limits

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

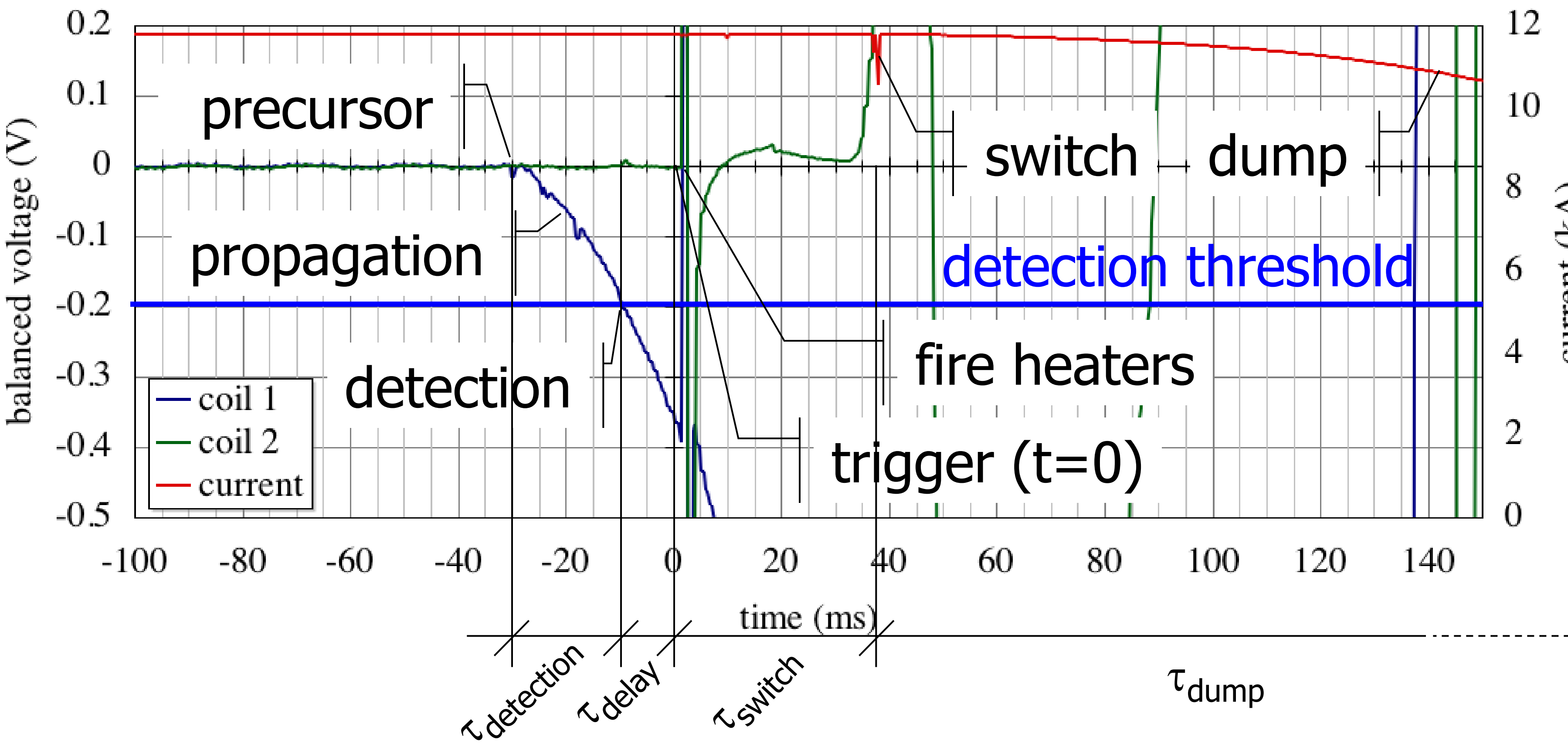


T_{max} < 100 K for negligible effect

- 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)

By courtesy of M. Di Castro, CERN AT-MTM, 2007.

Detection, switch and dump



$$\tau_{discharge} \approx \tau_{detection} + \tau_{delay} + \tau_{switch} + \tau_{dump}$$

Quench resistance

- the quench propagates in the coil at speed v_{quench} longitudinally ($v_{longitudinal}$) and transversely ($v_{transverse}$)…
- …the total resistance of the normal zone $R_{quench}(t)$ grows in time following
  - the temperature increase, and
  - the normal zone evolution…
- …a resistive voltage $V_{quench}(t)$ appears along the normal zone…
- …that dissipates the magnetic energy stored in the field, thus leading to a discharge of the system in a time $\tau_{discharge}$.

the knowledge of $R_{quench}(t)$ is mandatory to verify the protection of the magnetic system !

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

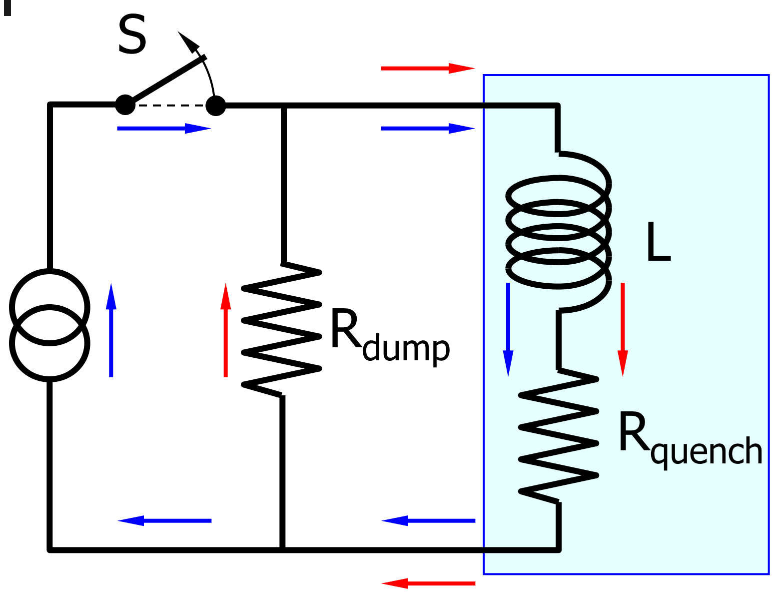
self-protected:
detect, switch-off power and let it go… most likely OK

no

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

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

Energy dump



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

normal operation

quench

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

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

- the integral of the current:

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

- 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:

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

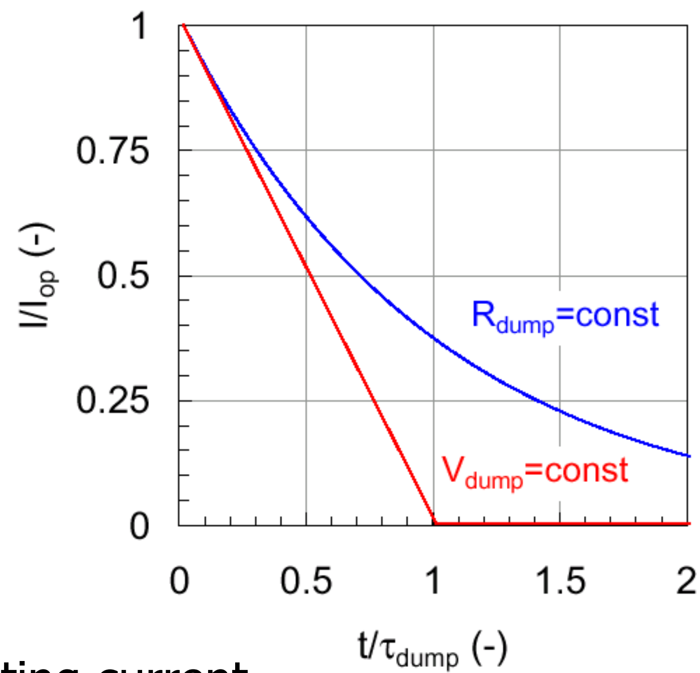
- dump time constant:

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

maximum terminal voltage

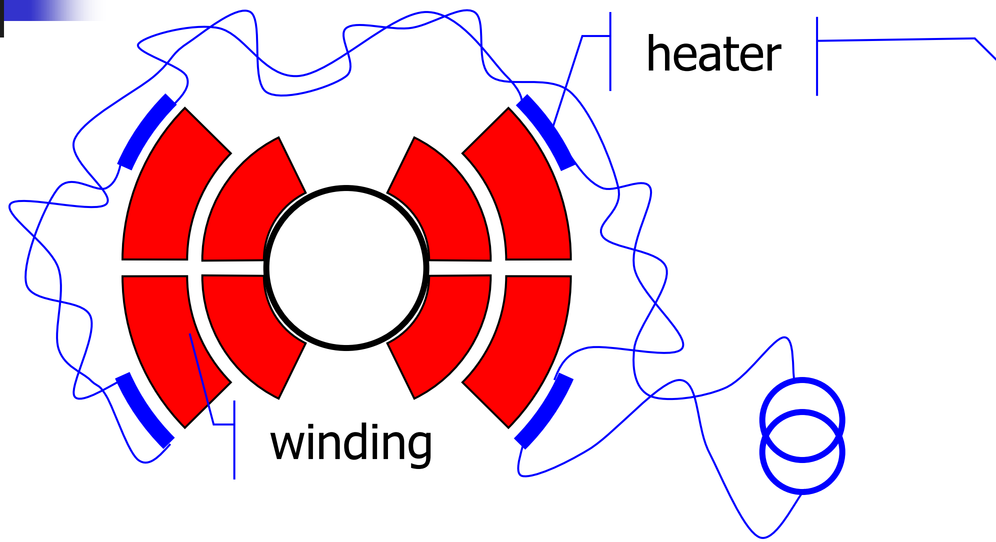
operating current

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



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

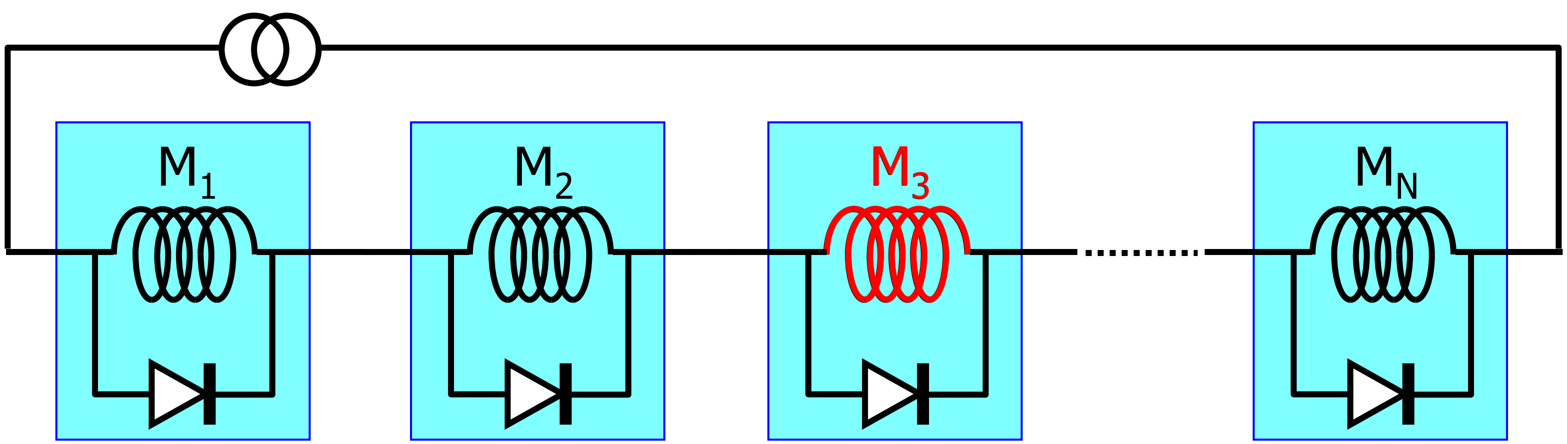
Quench heaters



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

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



Quench - Re-cap

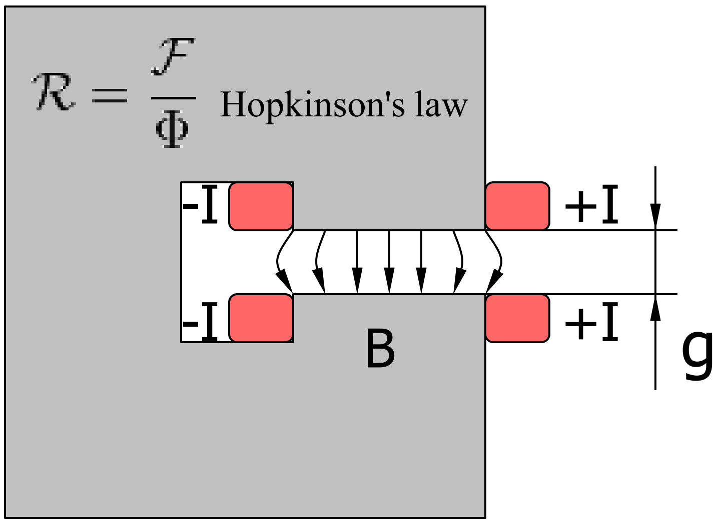
- A good conducting material (Ag, Al, Cu: large $Z(T_{max})$) must be added in parallel to the superconductor to limit the maximum temperature during a quench
- The effect of a quench can be mitigated by
  - Adding stabilizer (⇔ operating margin, stability)
  - Reducing operating current density (⇔ economics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

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

Magnetic design - basics

- NC: magneto motive force, reluctance and pole shapes

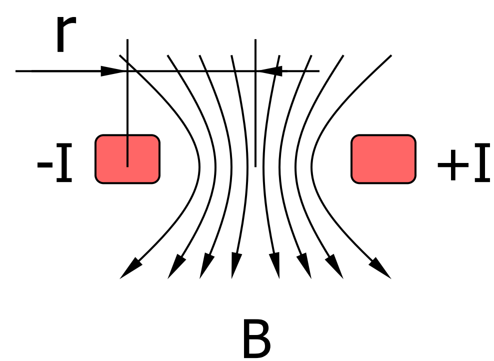


$B \approx \mu_0 NI / g$

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

- SC: Biot-Savart law and coil shapes

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

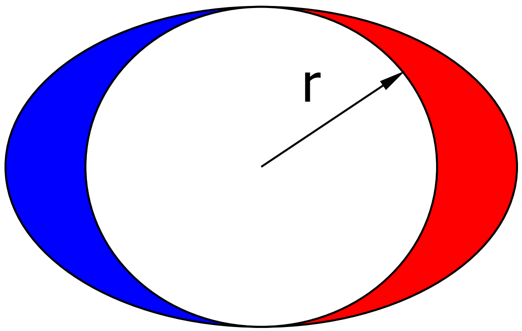


$B \approx \mu_0 NI / \pi r$

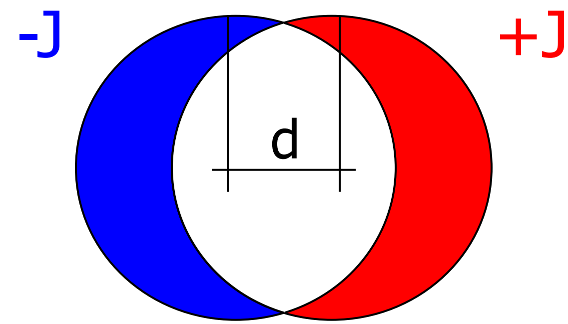
r	=45 mm
NI	=1 MAturn
B	=8.84 T

Design of an ideal dipole magnet

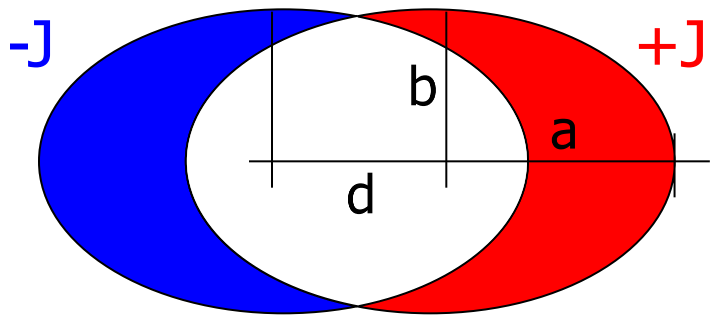
$I=I_0 \cos(\theta)$ ⇨ $B_1=-\mu_0 I_0/2r$



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



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

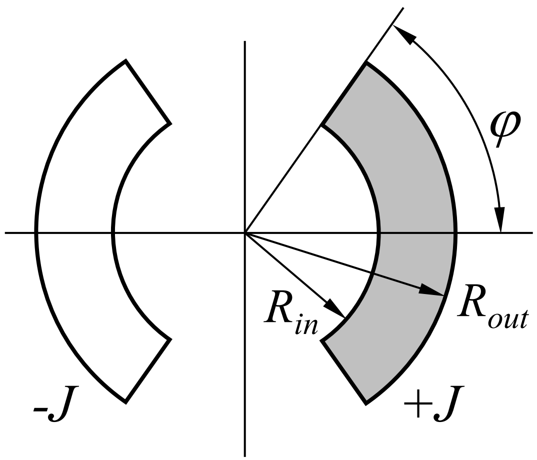


Several solutions are possible and can be extended to higher order multi-pole magnets

None of them is practical !

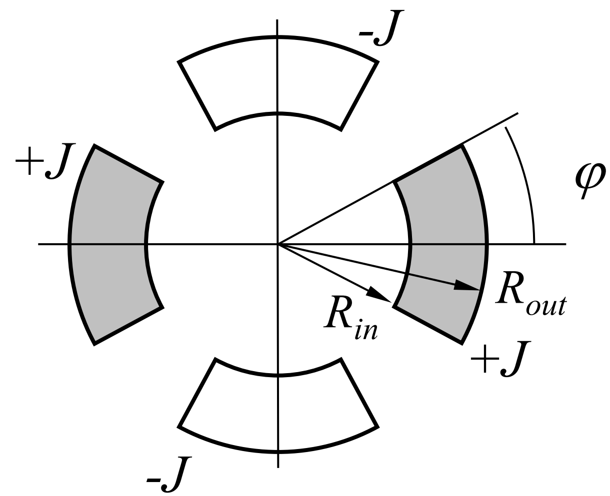
Magnetic design - sector coils

- Dipole coil



$$B=-2\mu_0/\pi \, J \, (R_{out} - R_{in}) \, \sin(\varphi)$$

- Quadrupole coil



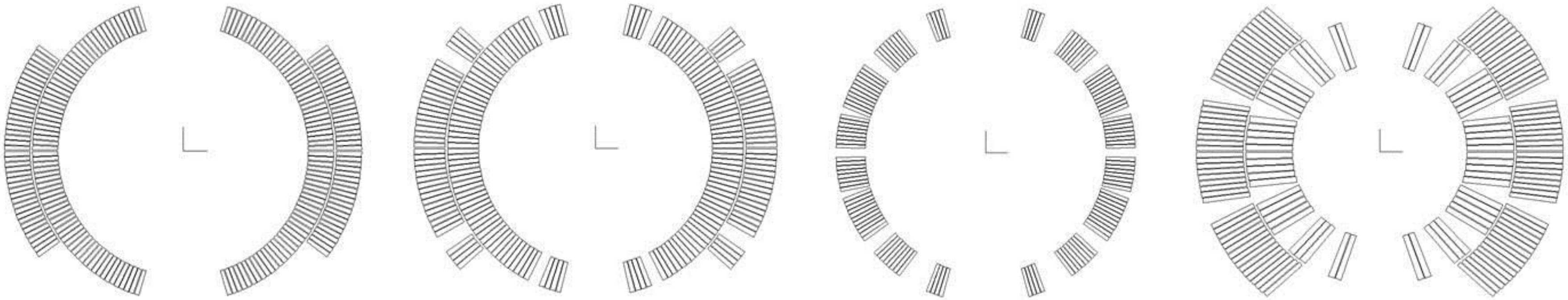
$$G=-2\mu_0/\pi \, J \, \ln(R_{out}/R_{in}) \, \sin(2\varphi)$$

The field is proportional to the current density **J** and the coil width (***R_{out}-R_{in}***)

This is getting much more practical !

Evolution of coil cross sections

- Coil cross sections (to scale) of the four superconducting colliders

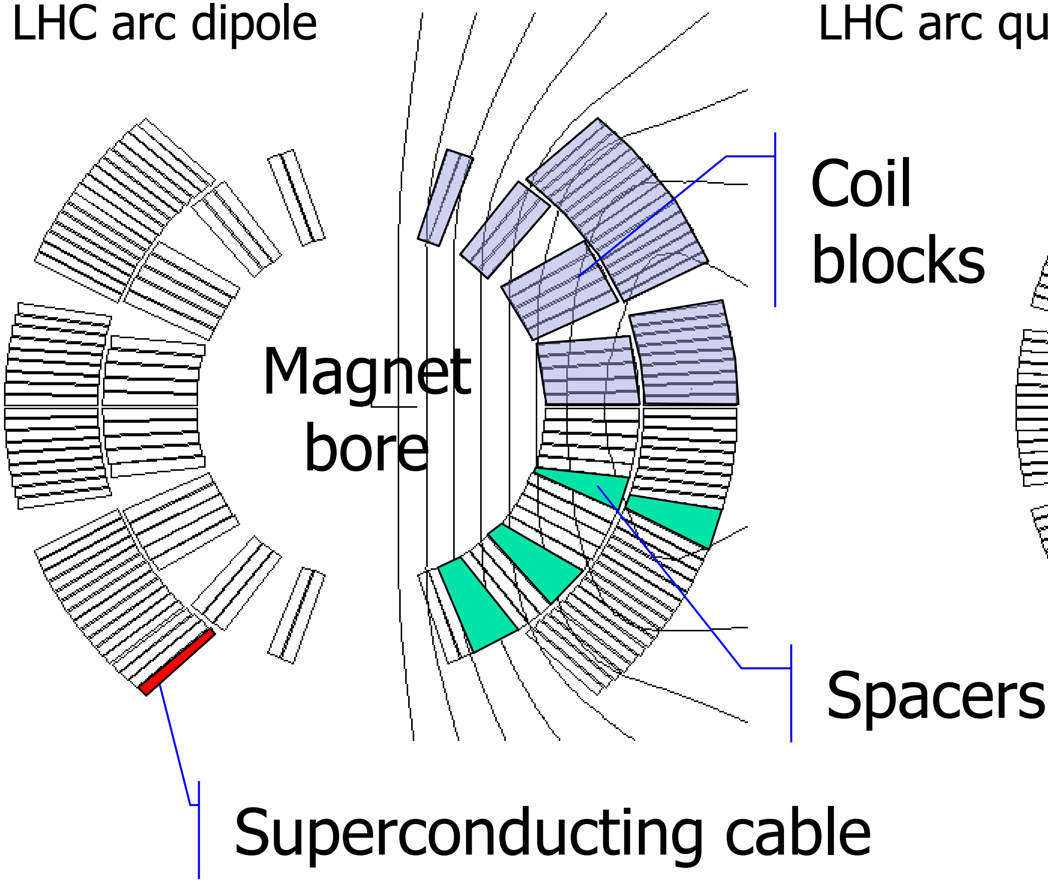


Tevatron **HERA** **RHIC** **LHC**

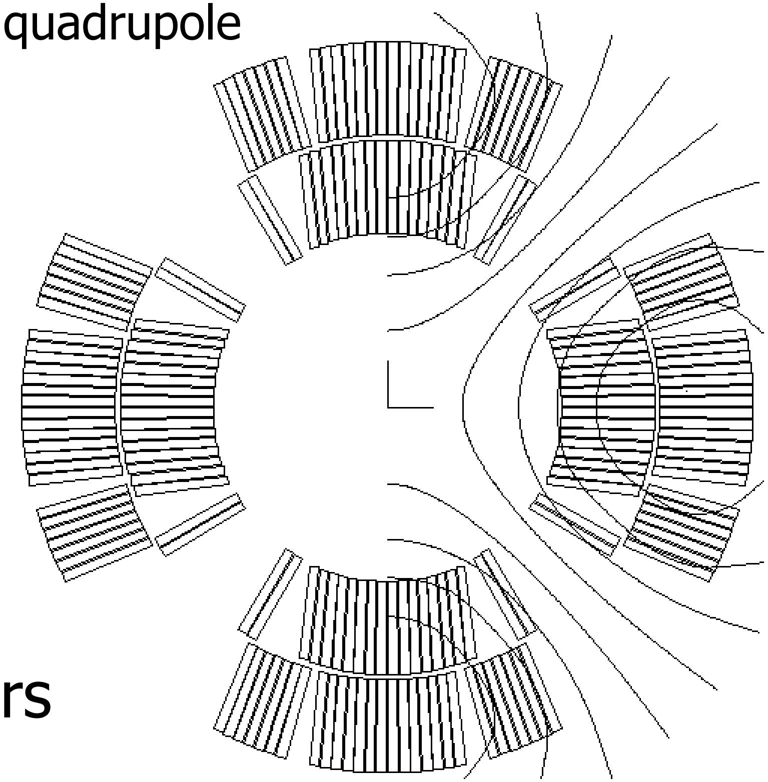
- Increased coil complexity (nested layers, wedges and coil blocks) to achieve higher efficiency and improved field homogeneity

Technical coil windings

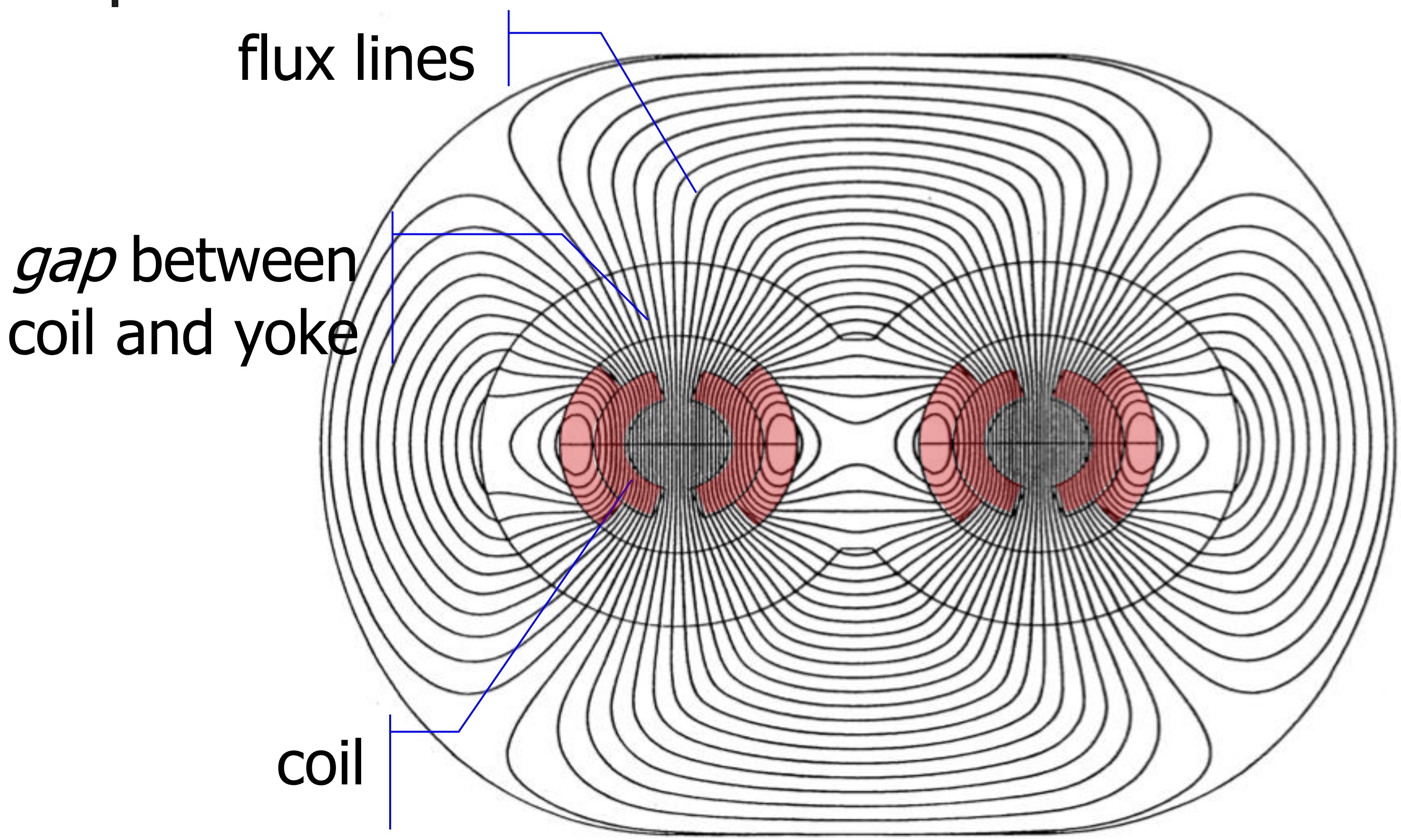
LHC arc dipole



LHC arc quadrupole



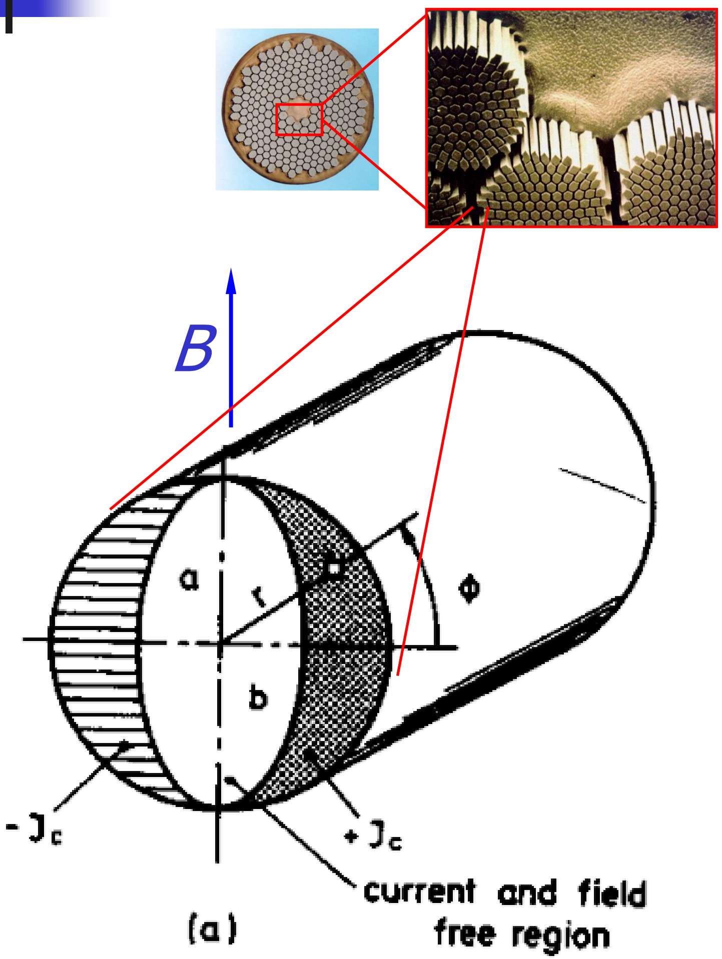
Iron to close the magnetic circuit



CERN 87-05, G. Brianti and K. Hubner Ed.

G. Brianti

Persistent currents - basics



H. Brück, et al., Z. Phys. C, Particles and Fields, 44, pp. 385-392, 1989

- Eddy currents that flow in the superconducting filaments to shield the interior from outer field variations
- For accelerator magnets:
  - Neglect flux-creep and flow
  - Neglect outer field changes (decay at I=const)

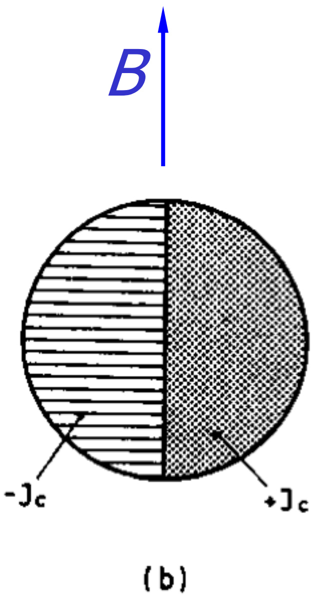
Infinite time constant,
the eddy currents *last forever*

Persistent currents

Persistent currents - basics

The current *doublet* in the filament corresponds to a magnetization:

$$\mathbf{M} = \frac{1}{V}\left\{\frac{1}{2}\int_V \mathbf{r} \times \mathbf{J}\, dV\right\}$$

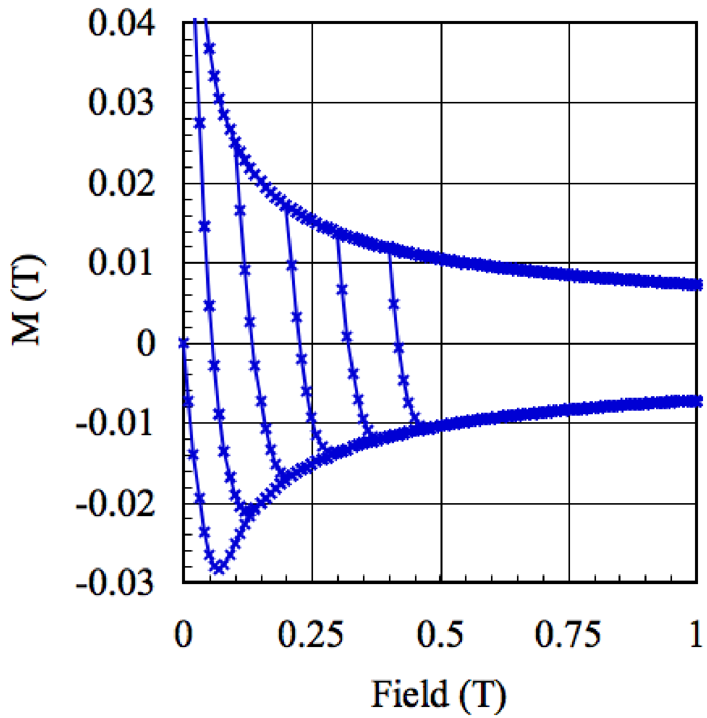


A strand, with round filaments in a resistive matrix ($\lambda = A_{SC}/A_{tot}$), fully penetrated:

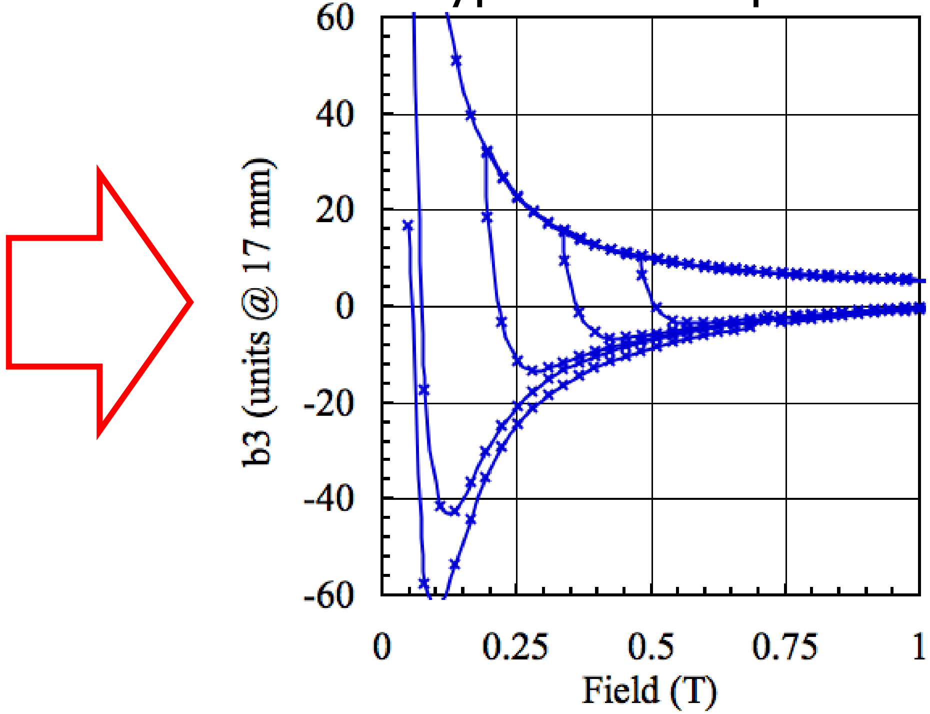
$$M = \pm \frac{2}{3\pi} \mu_0\, J_c\, D\, \lambda$$

Persistent current multipoles

Magnetization of a typical LHC strand



Sextupole in a typical LHC dipole



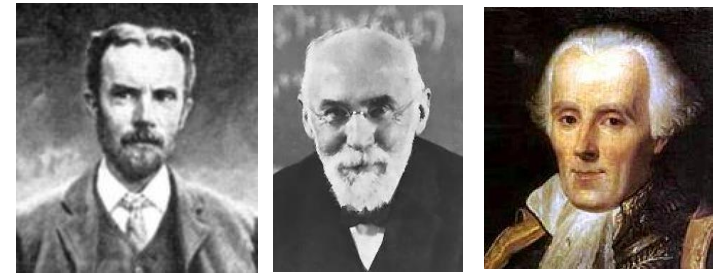
Effects are relatively large, cycle and history dependent and require careful design, measurement and control !

A matter of (field) quality

- The field homogeneity for an accelerator magnet needs to be in the 100 ppm range (at 1 cm from the coil)

Type of error	Origin	Effect on main field	Effect on harmonics	Means to control
geometric	Deviation of conductor from ideal position	10^{-4}	10^{-4}	Respect coil tolerances at 10 μm level
saturation	Iron saturation in vicinity of the coil	10^{-2} to 10^{-3}	10^{-4}	Optimize iron geometry, control permeability to % level
DC magnetization	Diamagnetism of SC filaments and hysteresis	10^{-3} to 10^{-4}	10^{-3} to 10^{-4}	Use small filaments (10...20 μm) and control wire magnetization homogeneity
AC magnetization	*Coupling currents in strands and*	*10^{-3} to 10^{-4}*	*10^{-4}*	*Use resistive matrix in strands (ramped magnets), control strands*

Electromagnetic force



(O. Heaviside) E.A. Lorentz, P.S. Laplace

- An electric charged particle q moving with a velocity v in a field B experiences a force F_L called electromagnetic (Lorentz) force (N):

$$\vec{F}_L = q\vec{v} \times \vec{B}$$

- A conductor carrying current density J (A/mm^2) experiences a (Laplace) force density f_L (N/m^3):

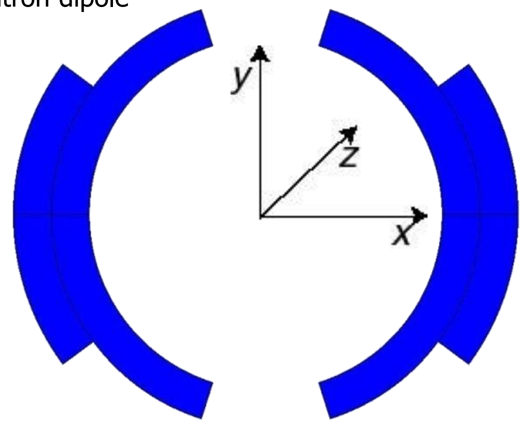
$$\vec{f}_L = \vec{J} \times \vec{B}$$

Graphics by courtesy of P. Ferracin, S. Prestemon, E. Todesco

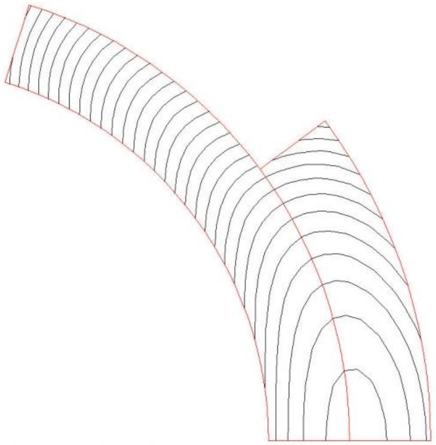
Electromagnetic forces - dipole

- The electromagnetic forces in a dipole magnet tend to push the coil:
  - Vertically, towards the mid plane (Fy < 0)
  - Horizontally, outwards (Fx > 0)

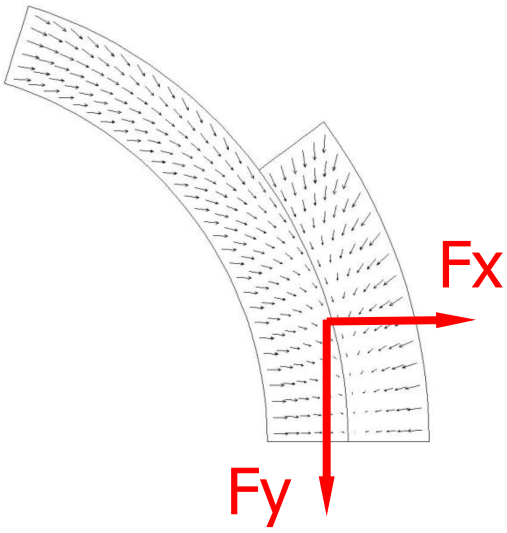
Tevatron dipole



Field



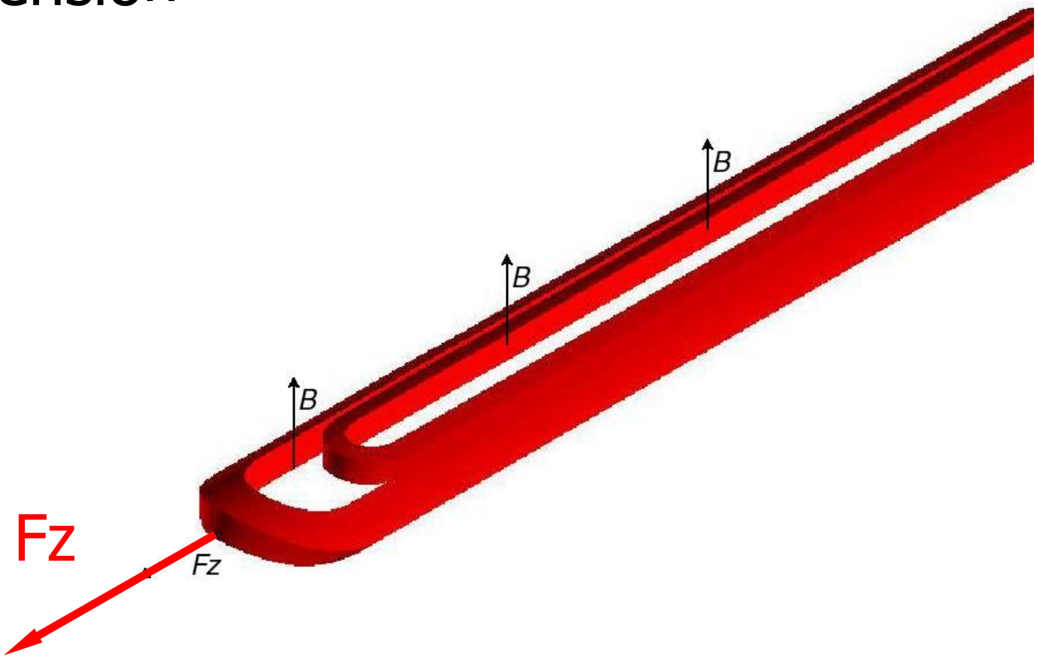
Force



Graphics by courtesy of P. Ferracin, S. Prestemon, E. Todesco

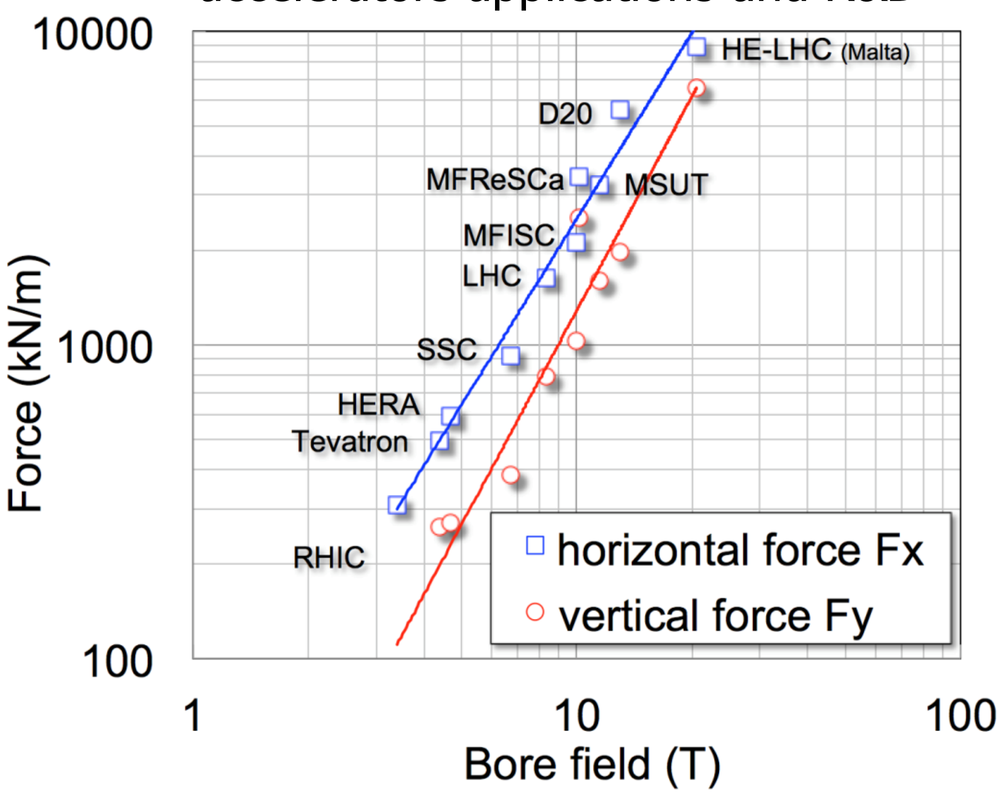
Electromagnetic forces - ends

- In the coil ends the Lorentz forces tend to push the coil:
  - Outwards in the longitudinal direction (Fz > 0), and, similar to solenoids, the coil straight section is in tension



The real challenge of very high fields

Force per coil quadrant in high-field dipoles built or designed for accelerators applications and R&D



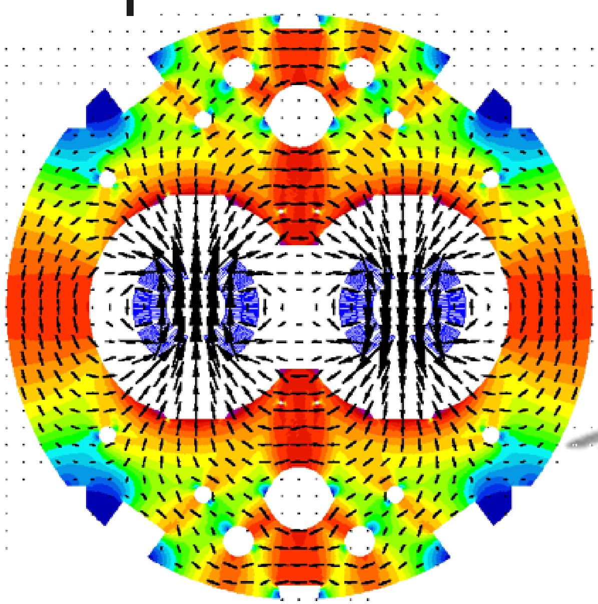
- Force increases **with the square of the bore field**
  - Requires massive structures (high-strength materials, volume, weight)
  - The stress limit is usually in the superconducting coil (superconductor and insulation, mitigated by $J_e \approx 1/B$)
- In practice the design of high field magnets is **limited by mechanics**

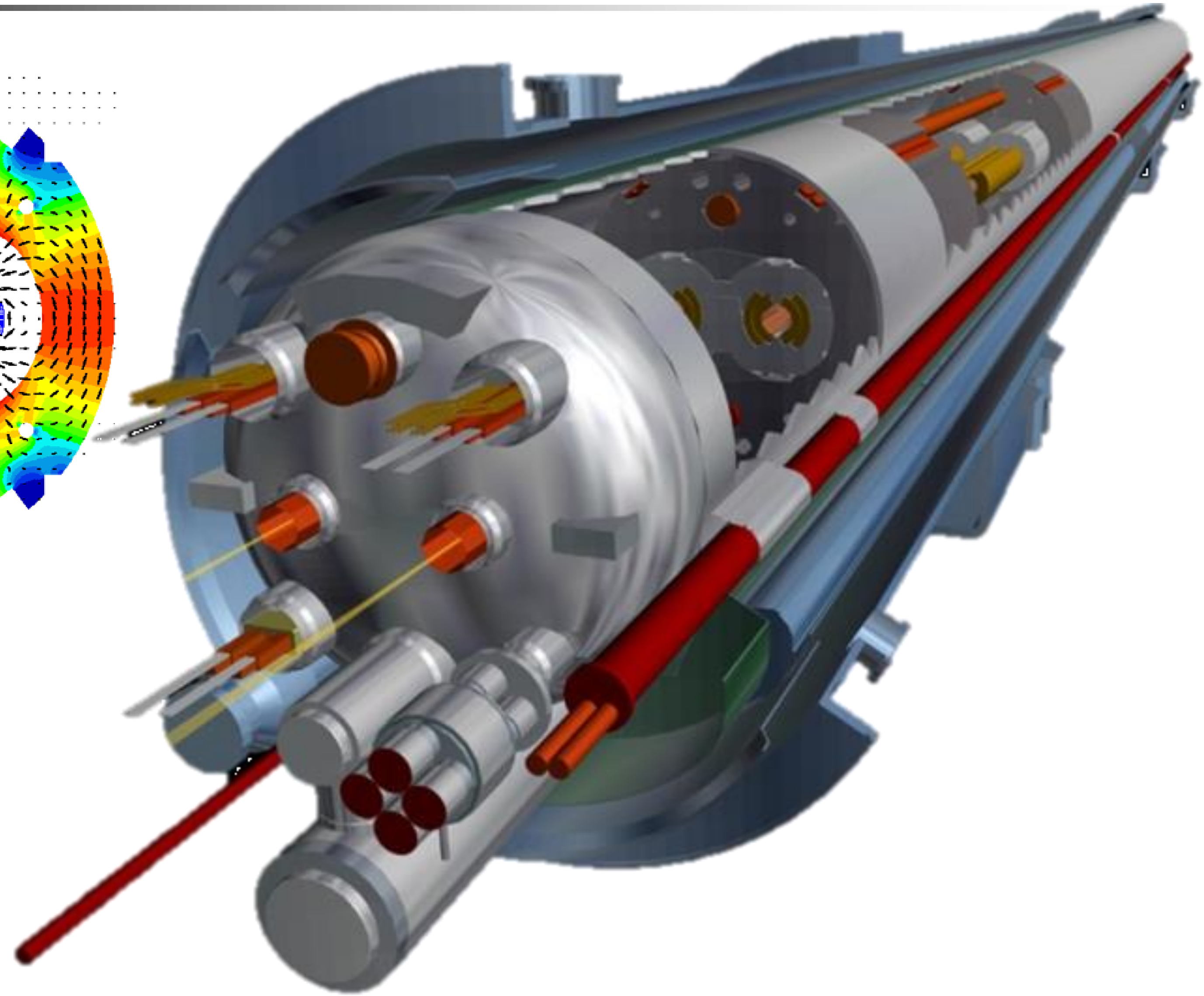
Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

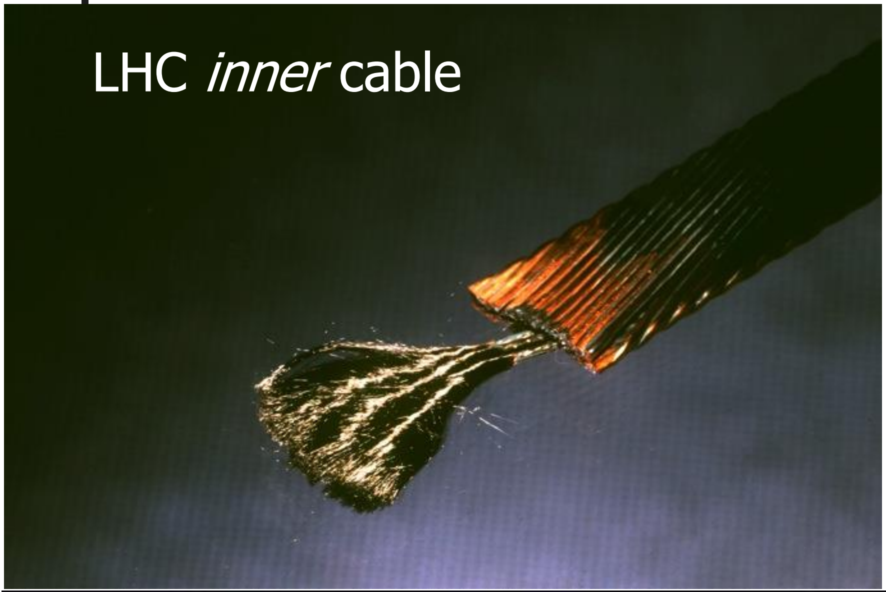
LHC dipole

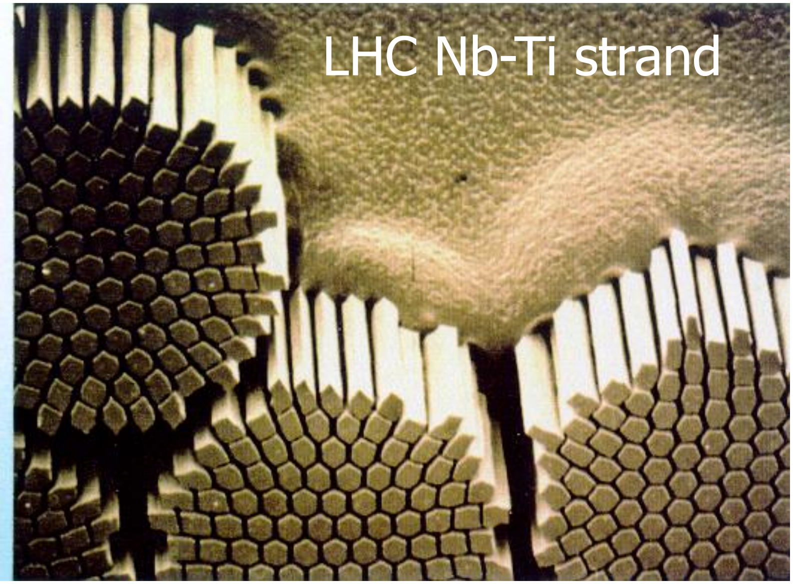
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 10	(MJ)
cold mass	≈ 35	(tonnes)





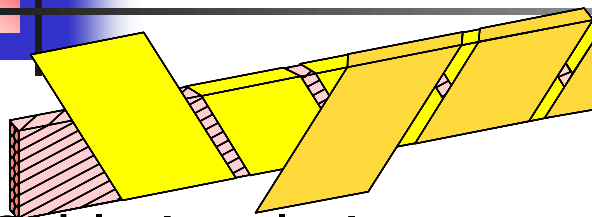
Rutherford cables



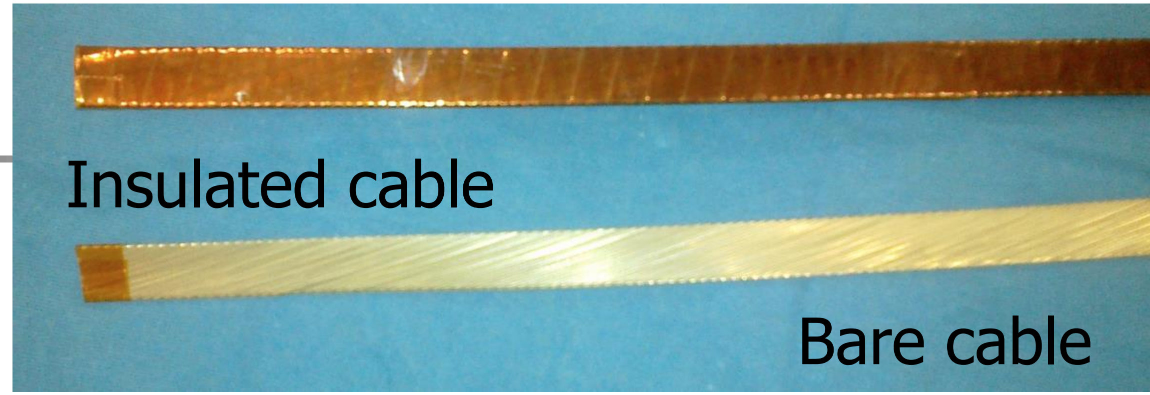


7500 km of superconducting cables with tightly controlled properties (state-of-the-art production)

Coil winding



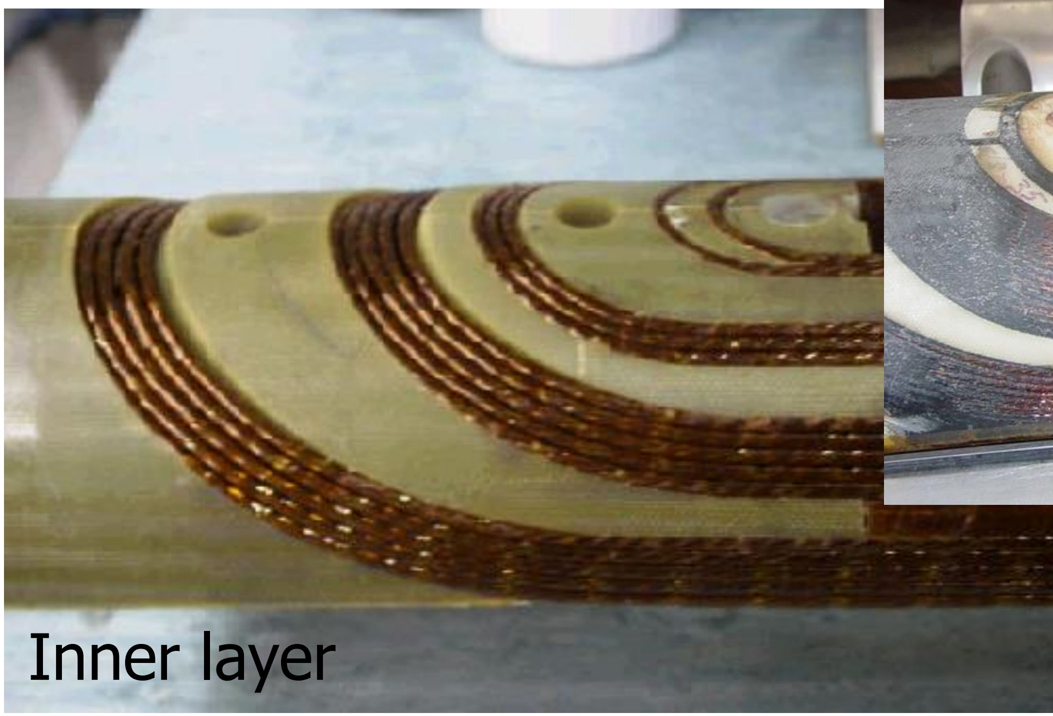
Cable insulation wraps

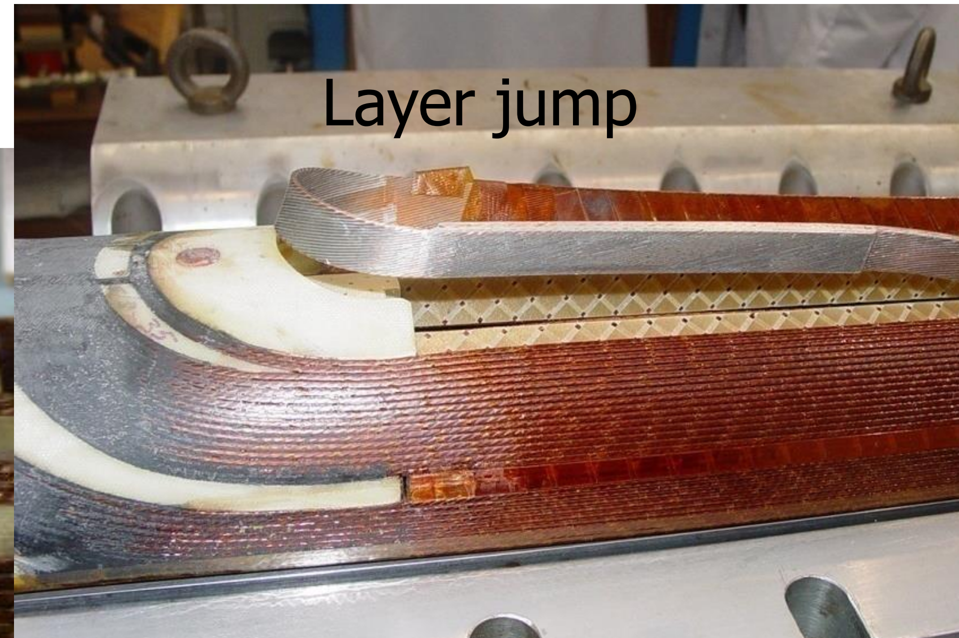


Coil winding machine

Stored coils

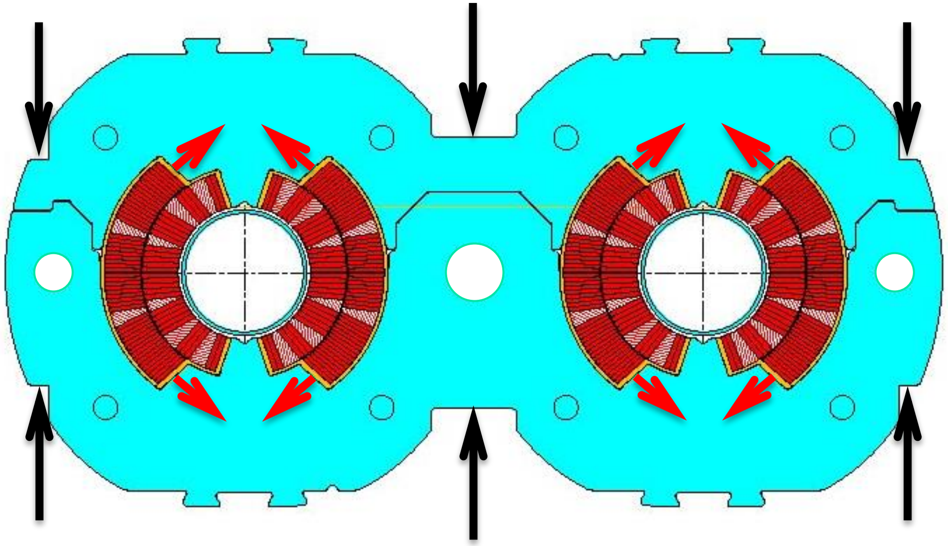
Ends





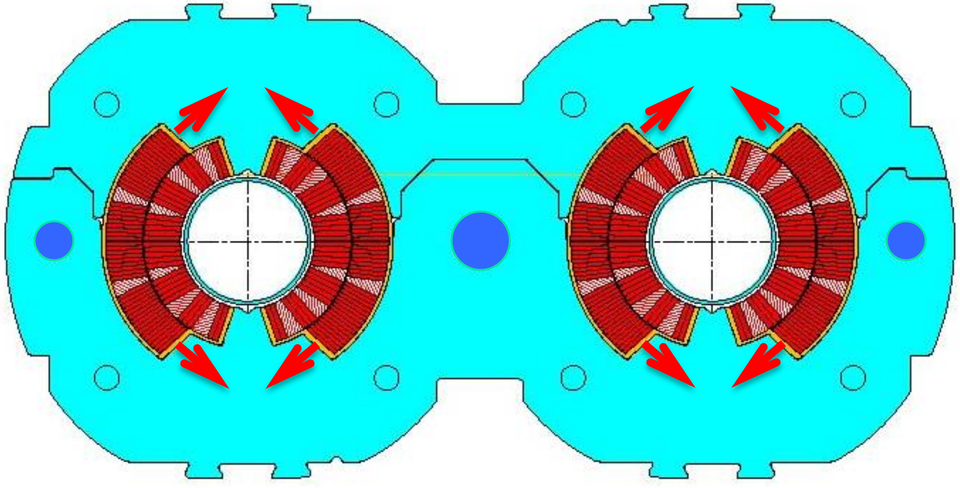
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring operation

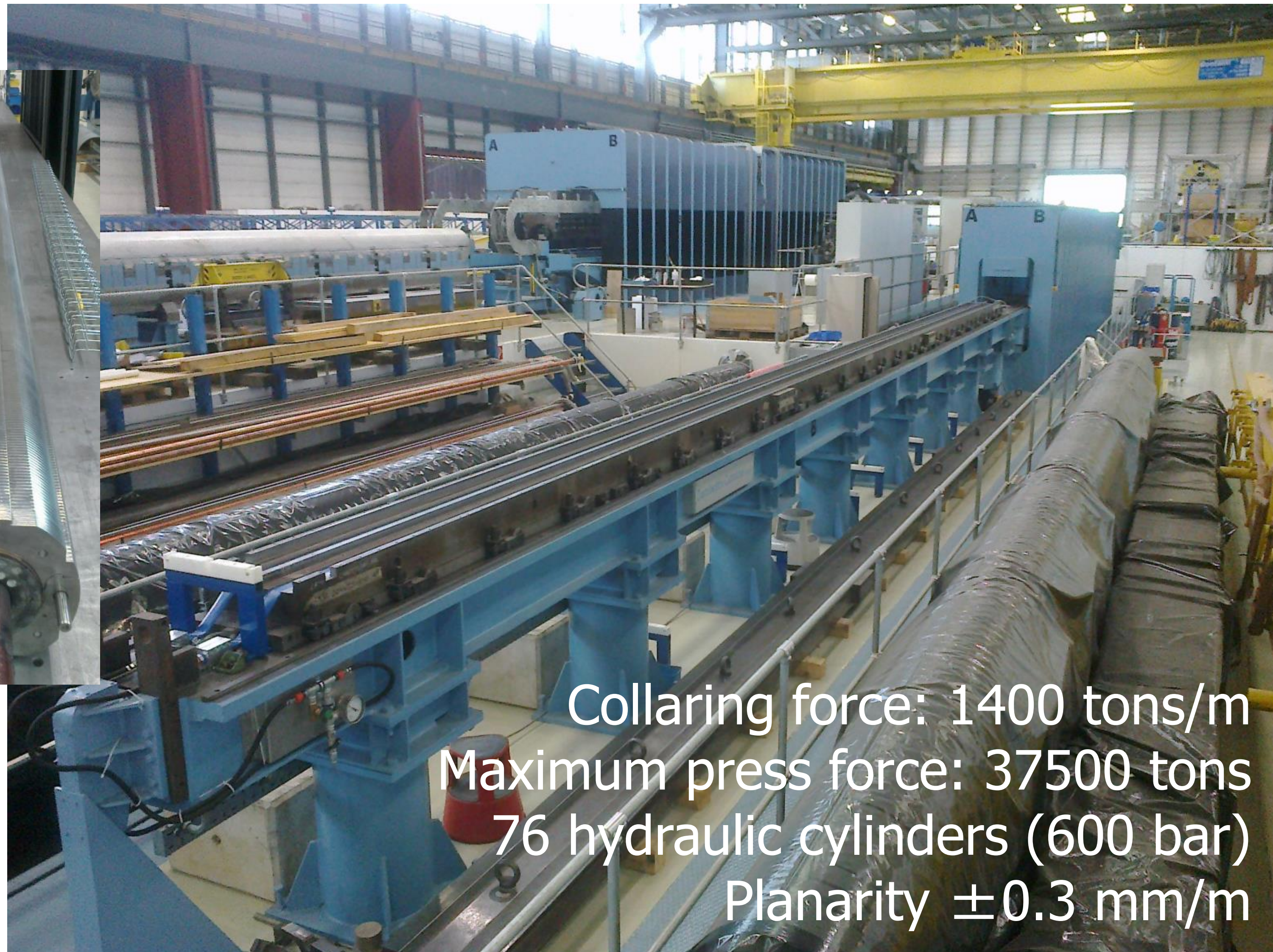


Pre-collared coil assembly under a press, load the coil to the desired pre-stress (in the range of 50…100 MPa)

Insert keys to "lock" the collars, unload the assembly that is now self-supporting and provides the desired pre-load to the coil

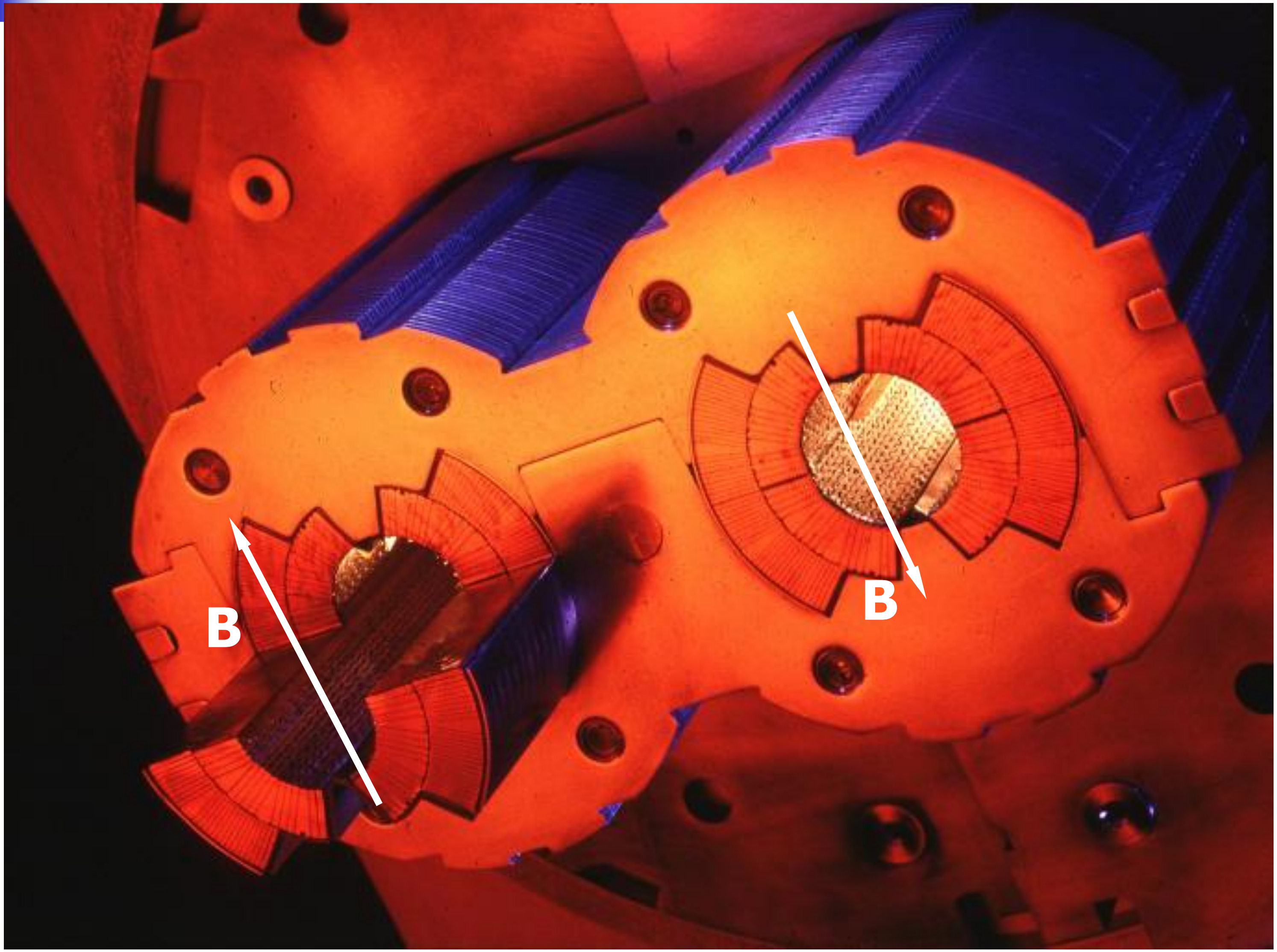


Collaring of an LHC dipole

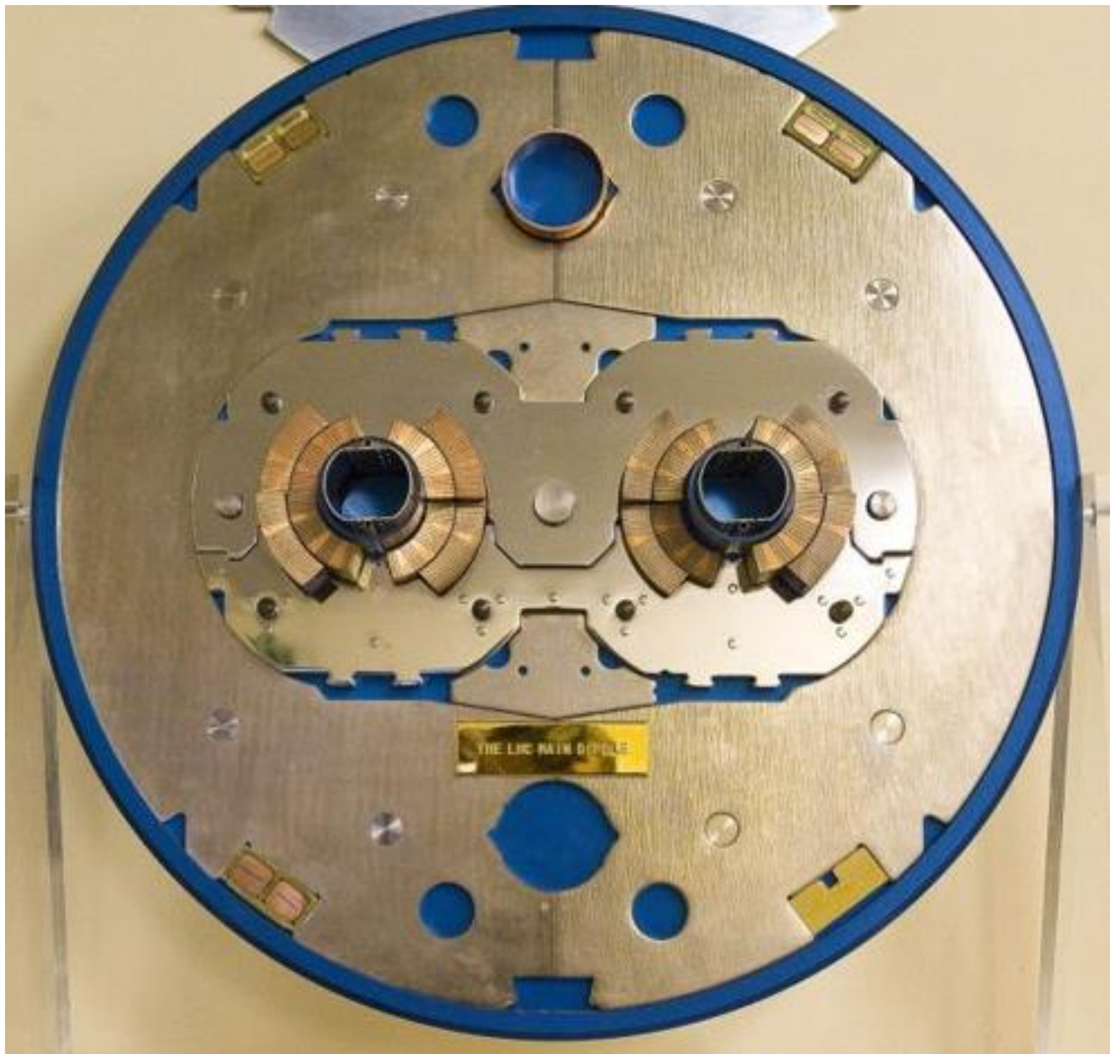


Collaring force: 1400 tons/m
Maximum press force: 37500 tons
76 hydraulic cylinders (600 bar)
Planarity ±0.3 mm/m

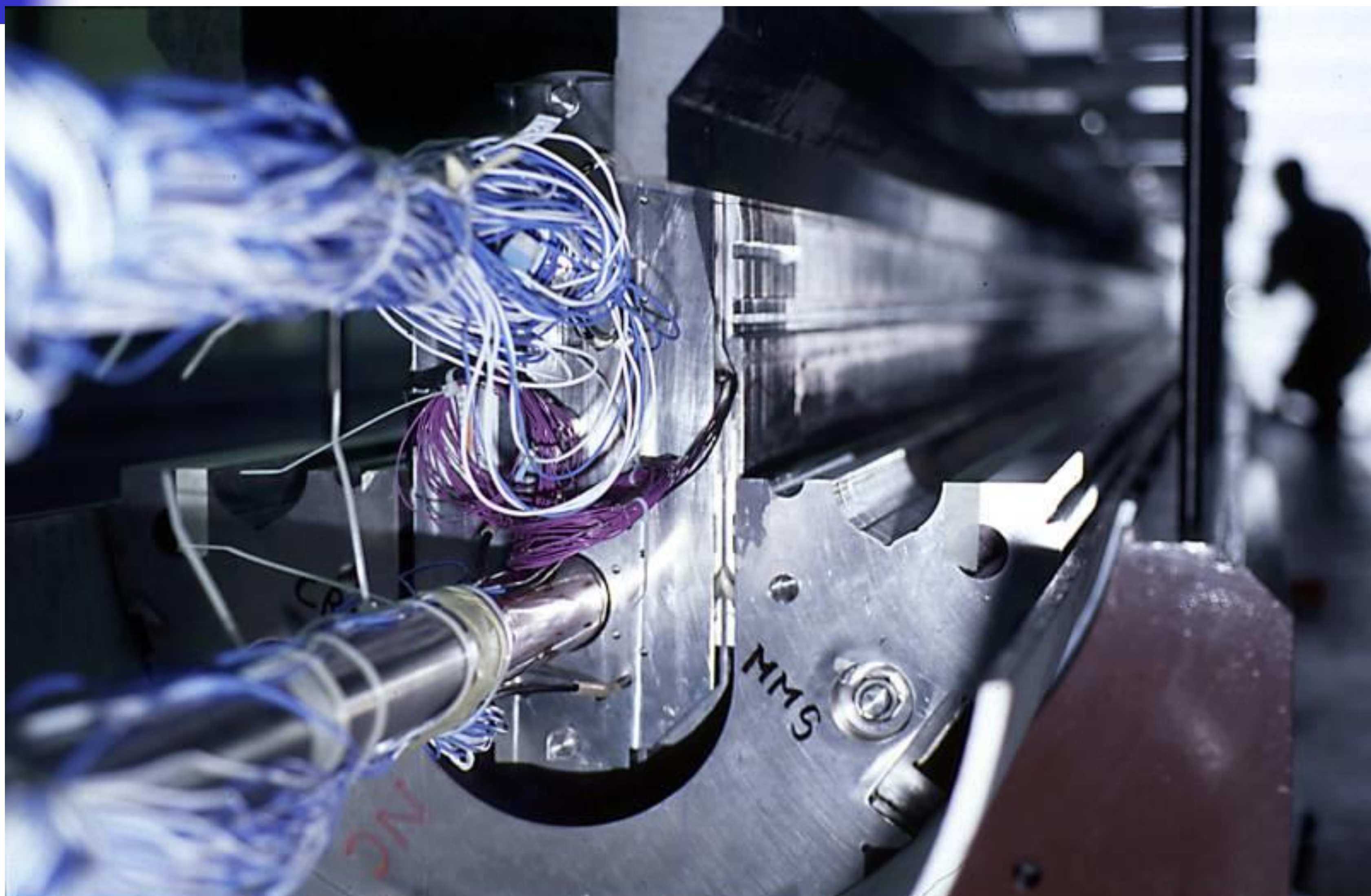
LHC dipole coils



LHC Iron yoke



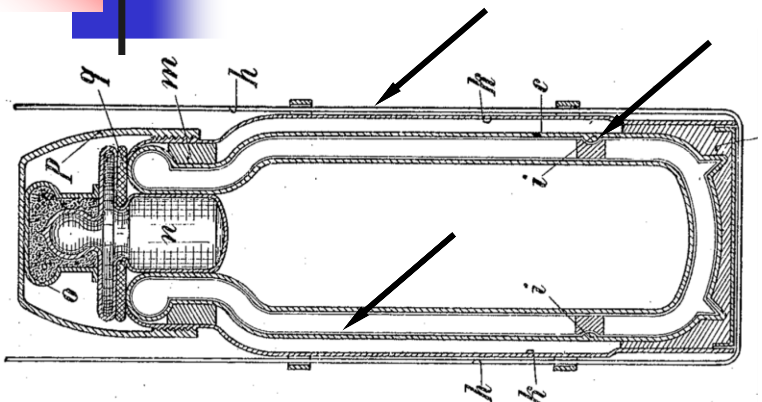
"Yoking" of a dipole magnet



Yoke welding press

Cold mass

Cryostat



Vacuum enclosure

Thermal screens

Low conduction foot

Finally, in the tunnel !

Overview

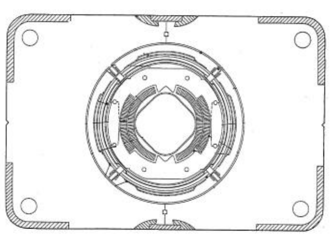
- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

The *Hall of Fame* of SC colliders

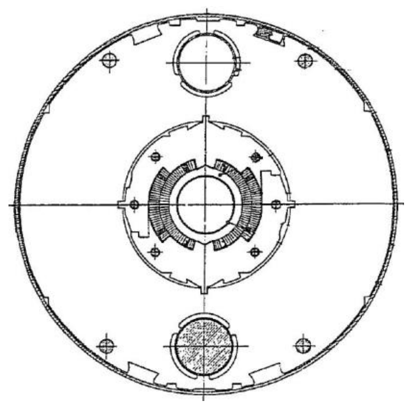
		Tevatron	HERA	RHIC	LHC
Maximum energy	(GeV)	980	920(1)	250(2) 100/n(3)	7000
Injection energy	(GeV)	151	45	12	450
Ring length	(km)	6.3	6.3	3.8	26.7
Dipole field	(T)	4.3	5.0	3.5	8.3
Aperture	(mm)	76	75	80	56
Configuration		Single bore	Single bore	Single bore	Twin bore
Operating temperature	(K)	4.2	4.5	4.3-4.6	1.9
First beam		7-1983	4-1991	6-2000	9-2008

(1) energy of the proton beam, colliding with the 27.5 GeV electron beam
(2) energy for proton beams
(3) energy per nucleon, for ion beams (Au)

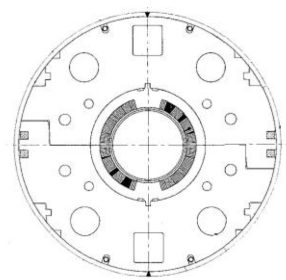
Champion dipoles cross sections



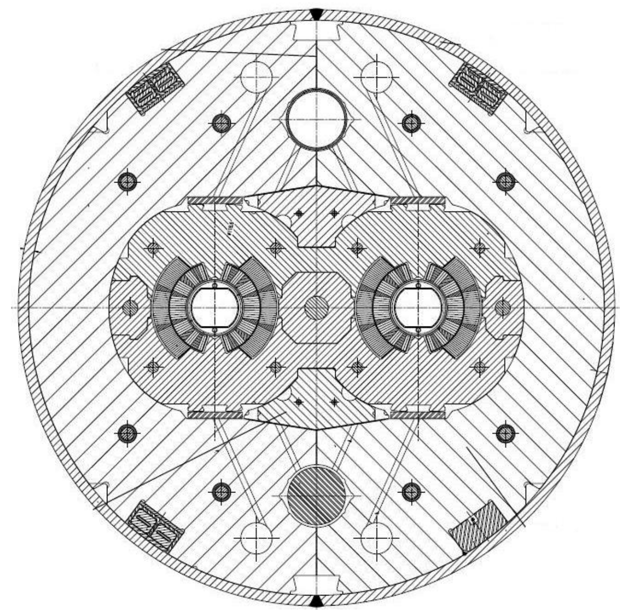
Tevatron
Bore: 76 mm
Field: 4.3 T



HERA
Bore: 75 mm
Field: 5.0 T

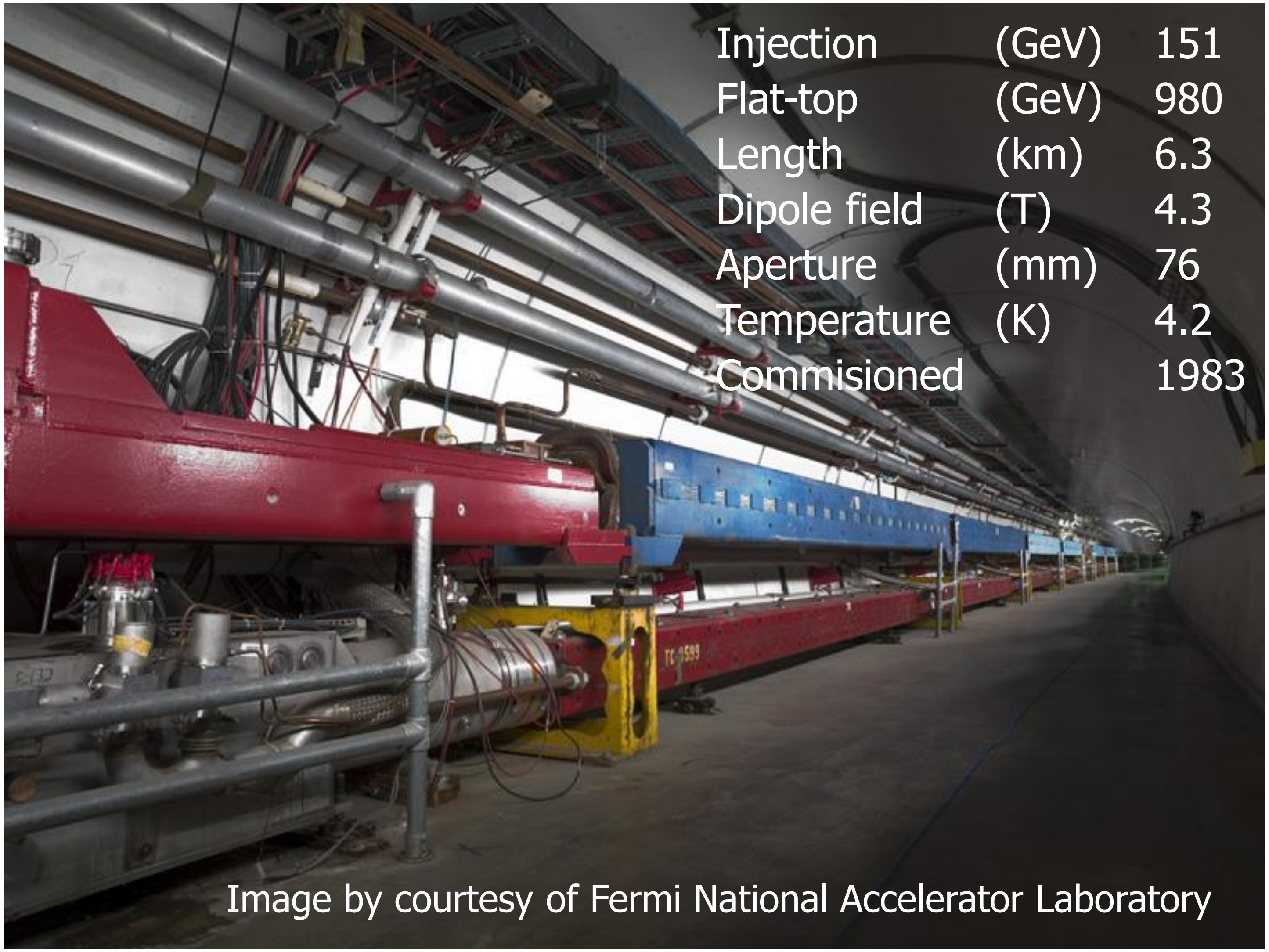


RHIC
Bore: 80 mm
Field: 3.5 T



LHC
Bore: 56 mm
Field: 8.3 T

Tevatron at FNAL (Chicago, IL, USA)



HERA at DESY (Hamburg, D)

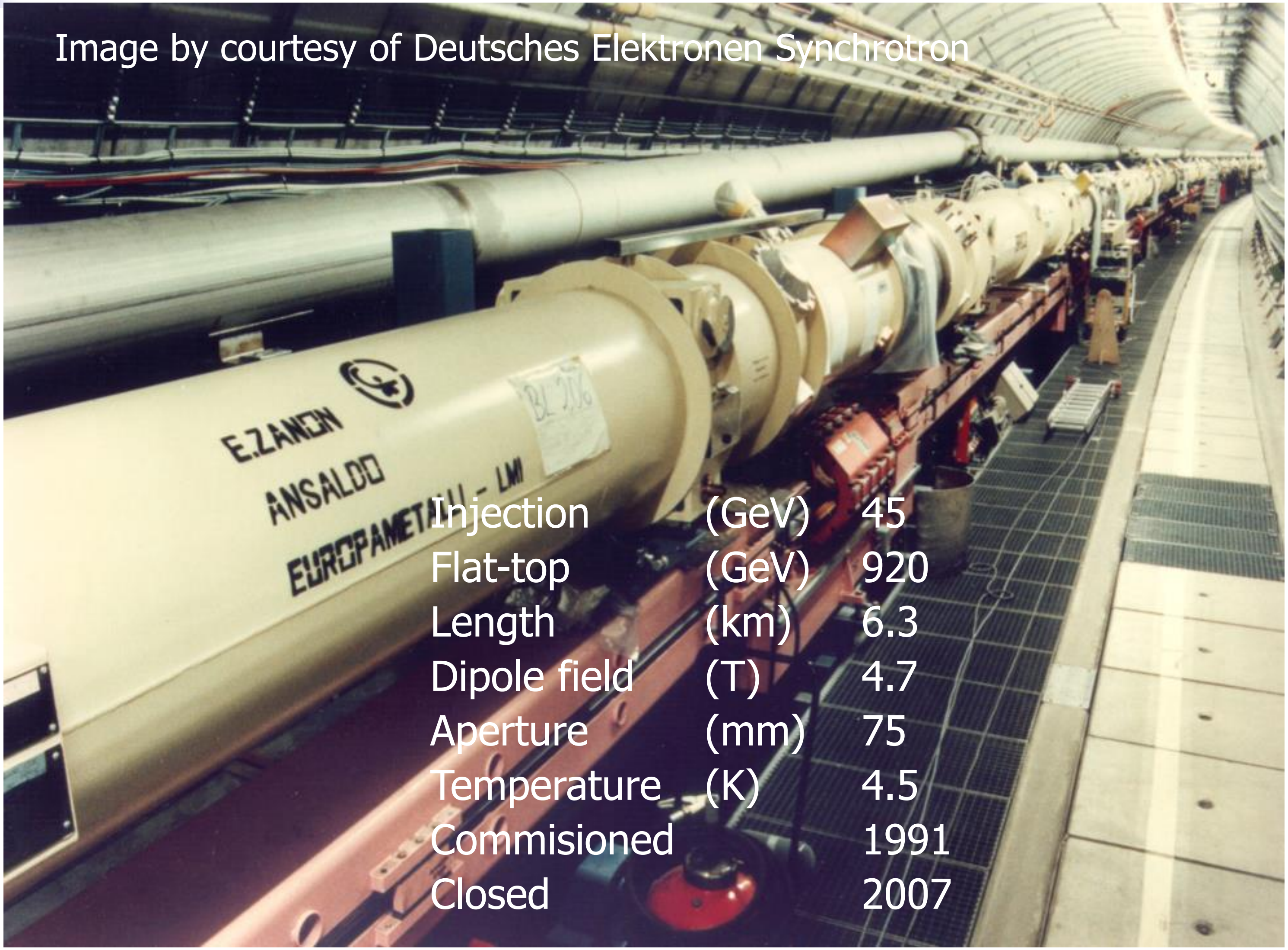


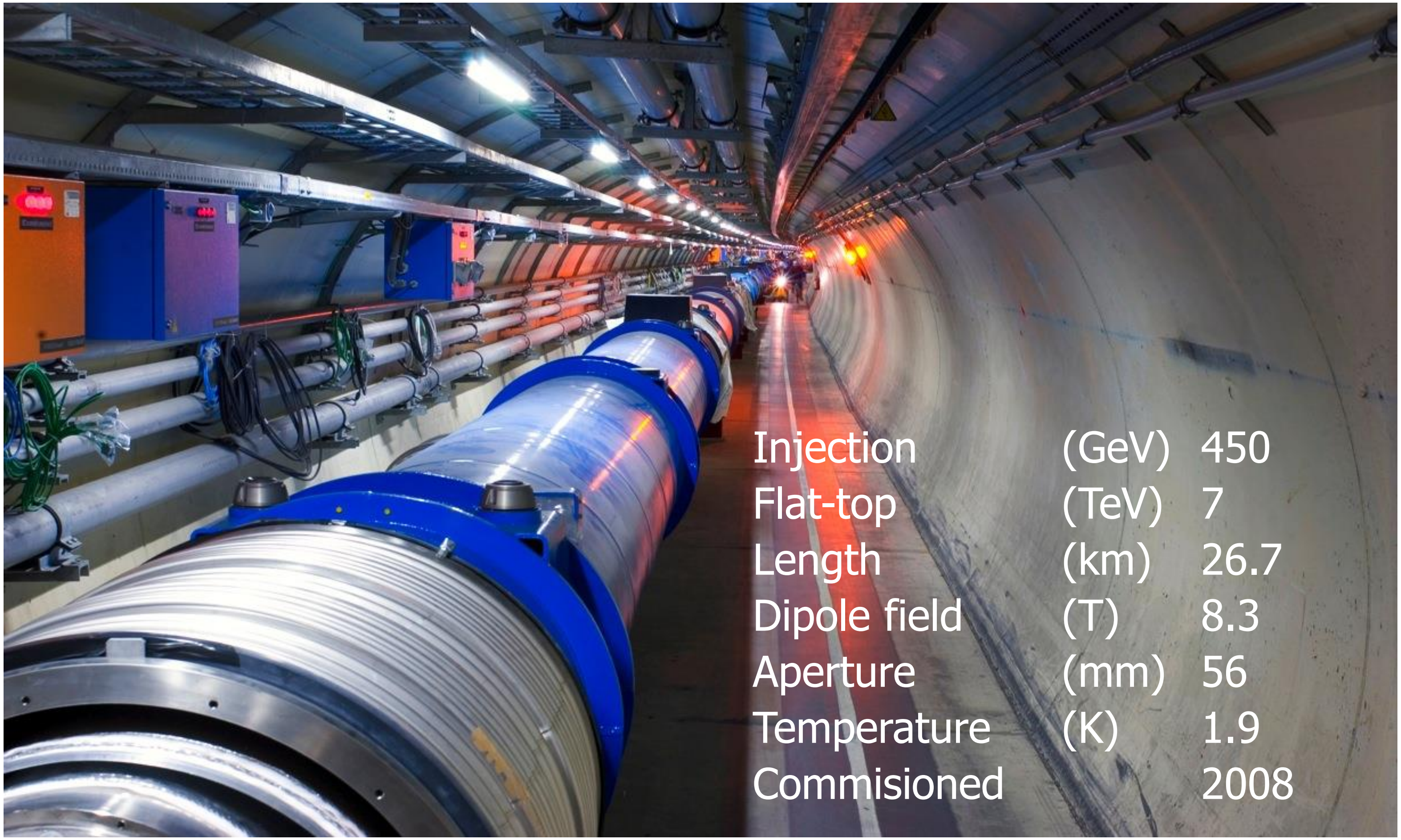
Image by courtesy of Deutsches Elektronen Synchrotron

Injection	(GeV)	45
Flat-top	(GeV)	920
Length	(km)	6.3
Dipole field	(T)	4.7
Aperture	(mm)	75
Temperature	(K)	4.5
Commisioned		1991
Closed		2007

RHIC at BNL (Upton, NY, USA)

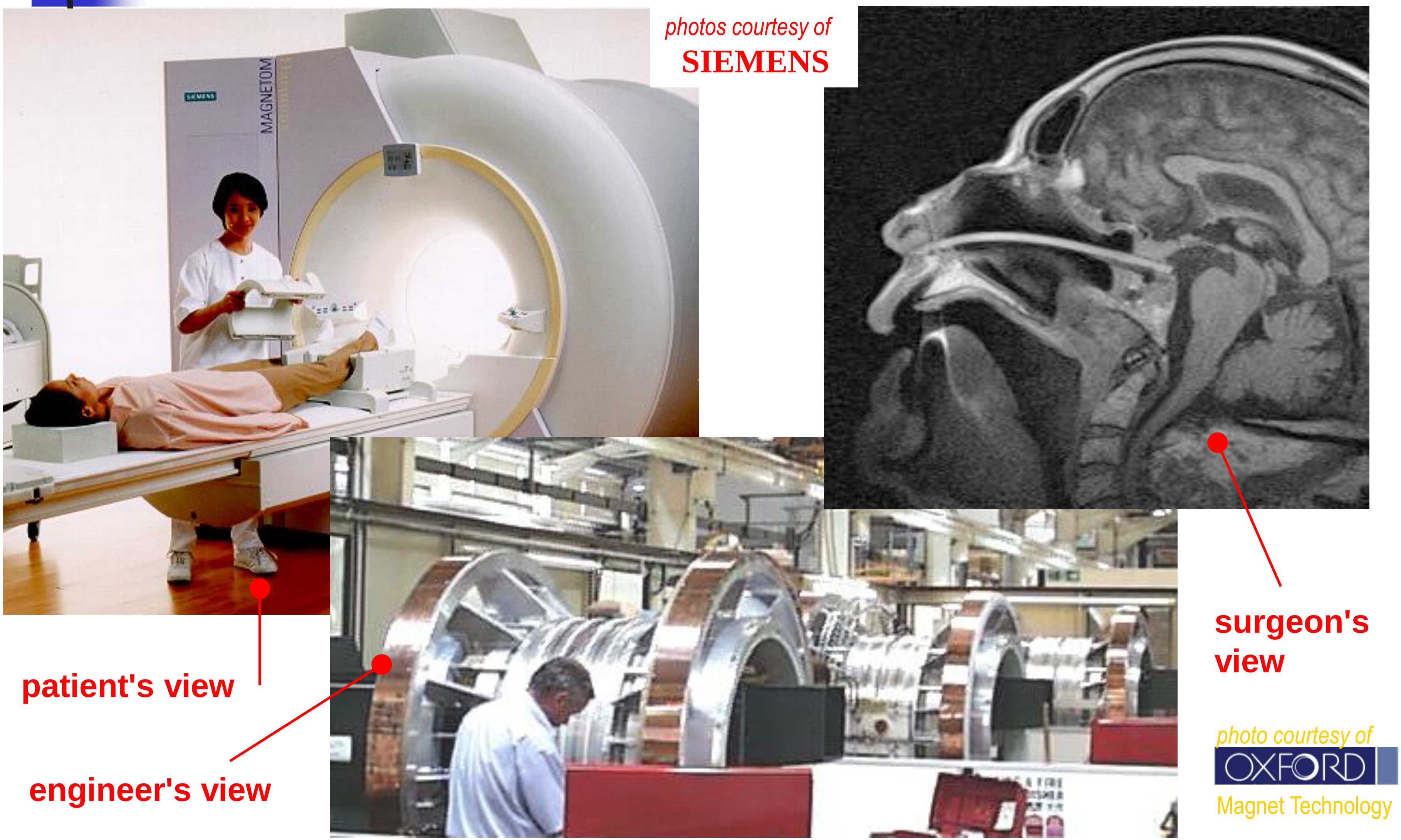
Injection	(GeV)	12/n
Flat-top	(GeV)	100/n
Length	(km)	3.8
Dipole field	(T)	3.5
Aperture	(mm)	80
Temperature	(K)	4.3-4.6
Commisioned		2000

LHC at CERN (Geneva, CH)

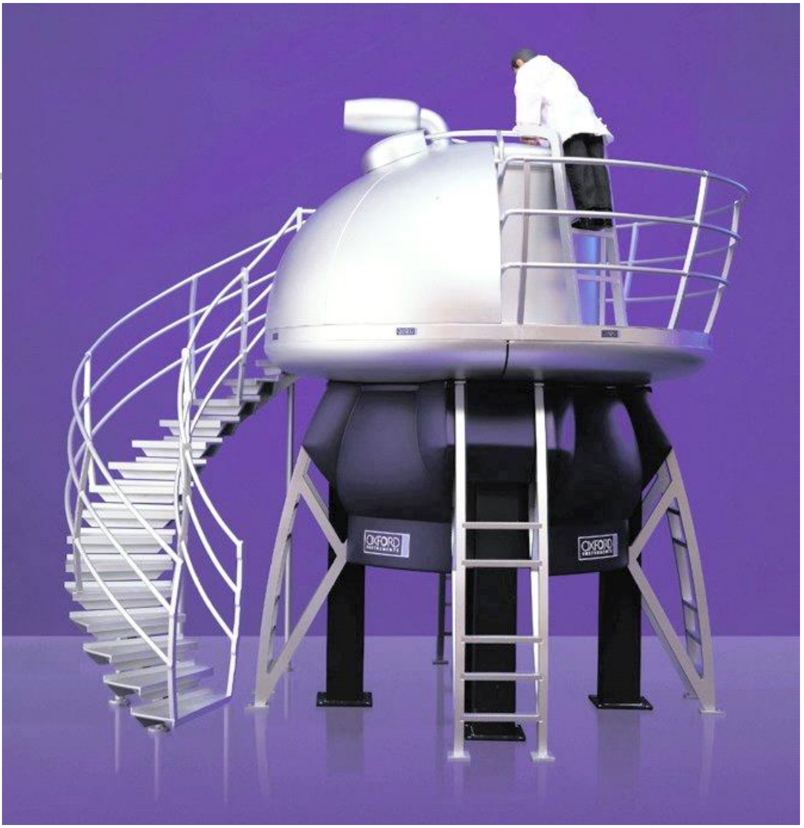


Injection	(GeV)	450
Flat-top	(TeV)	7
Length	(km)	26.7
Dipole field	(T)	8.3
Aperture	(mm)	56
Temperature	(K)	1.9
Commisioned		2008

Magnetic Resonance Imaging (MRI)



NMR spectroscopy



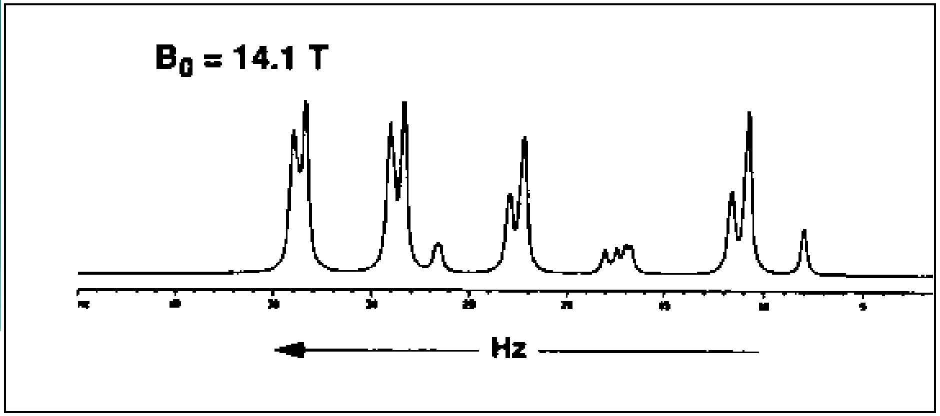
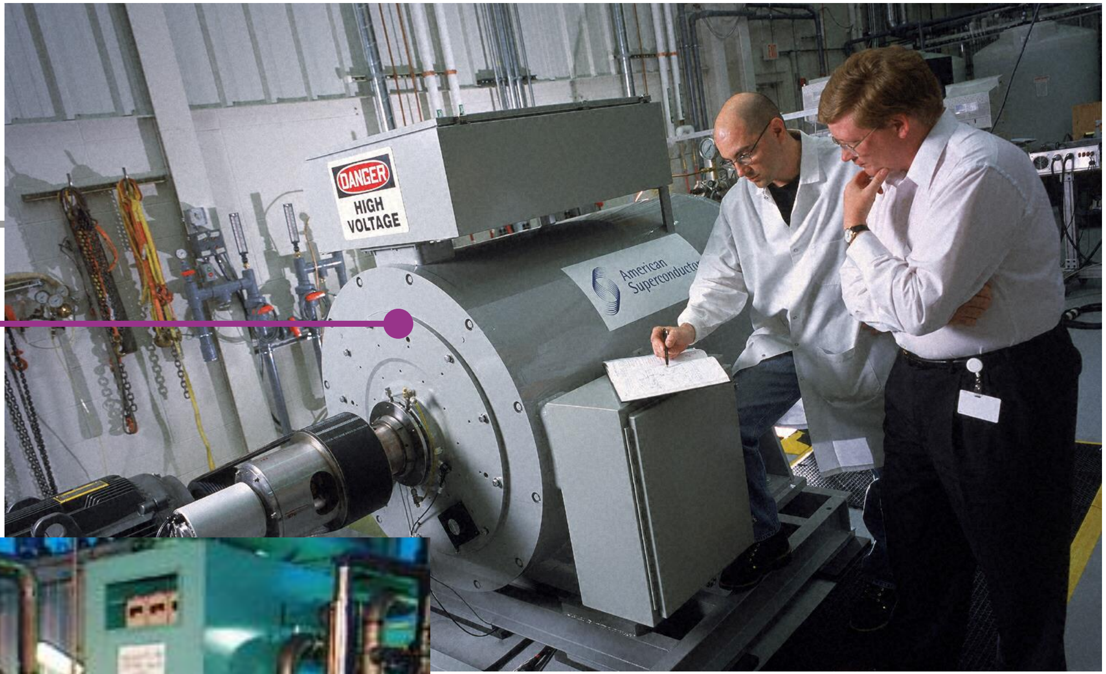


photo courtesy of
OXFORD
Magnet Technology

Motors & generators



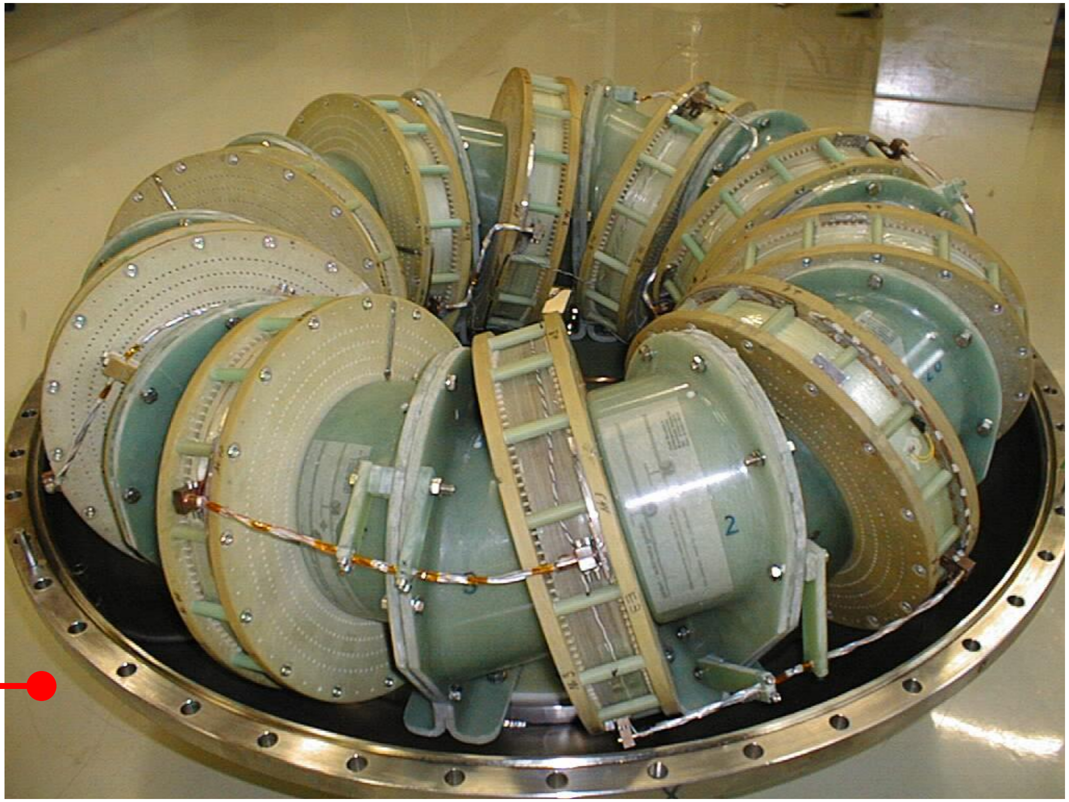
Motor with HTS rotor
American Superconductor and Reliance

700 MW generator
NbTi rotor
Hitachi, Toshiba, Mitsubishi

Transformers & energy storage

HTS Transformer
630 kVA,   18.7kV to 0.42 kV

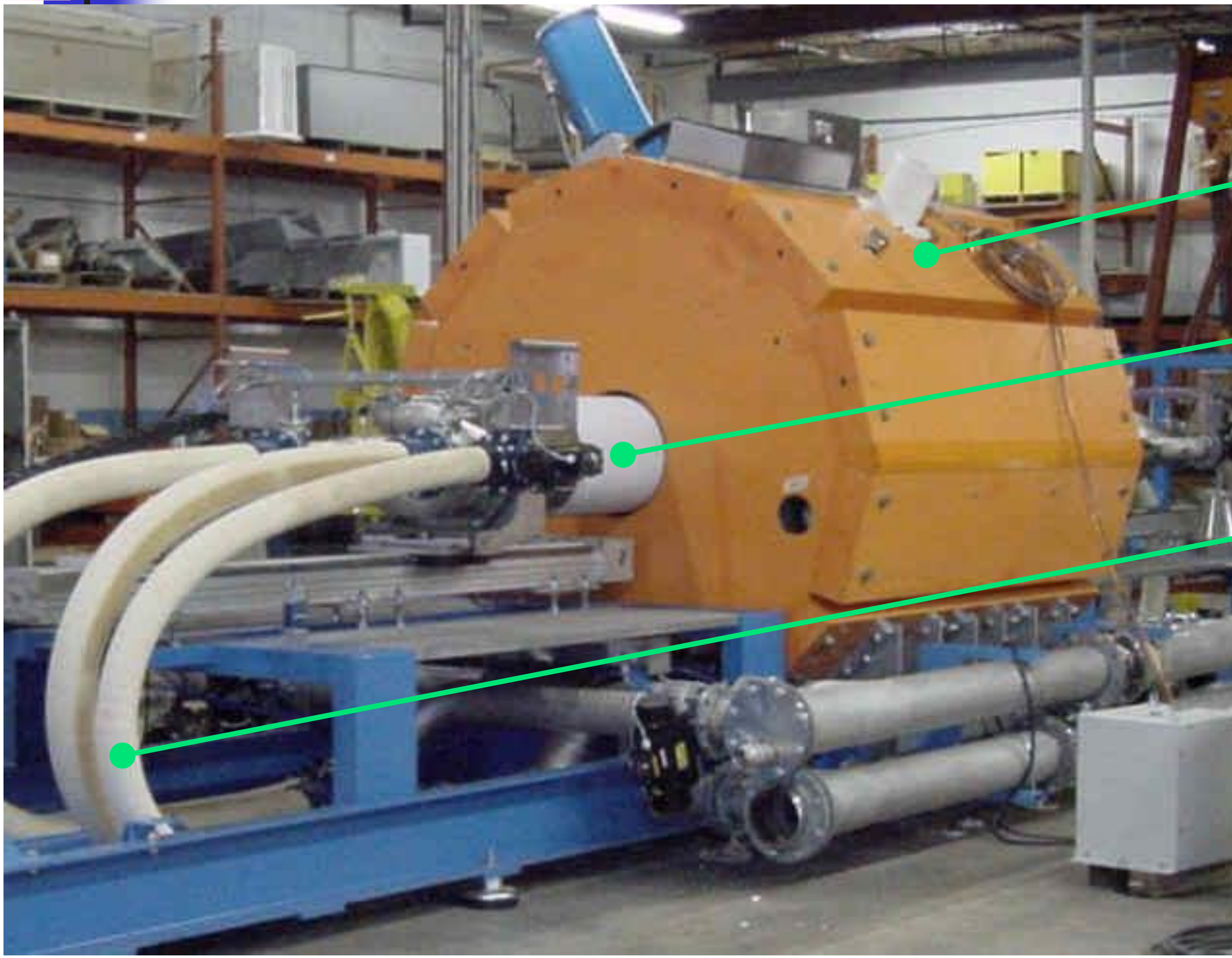
ABB



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

KfZ Karlsruhe

Magnetic separation

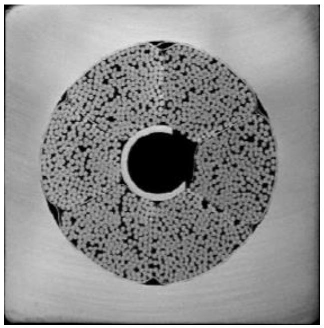


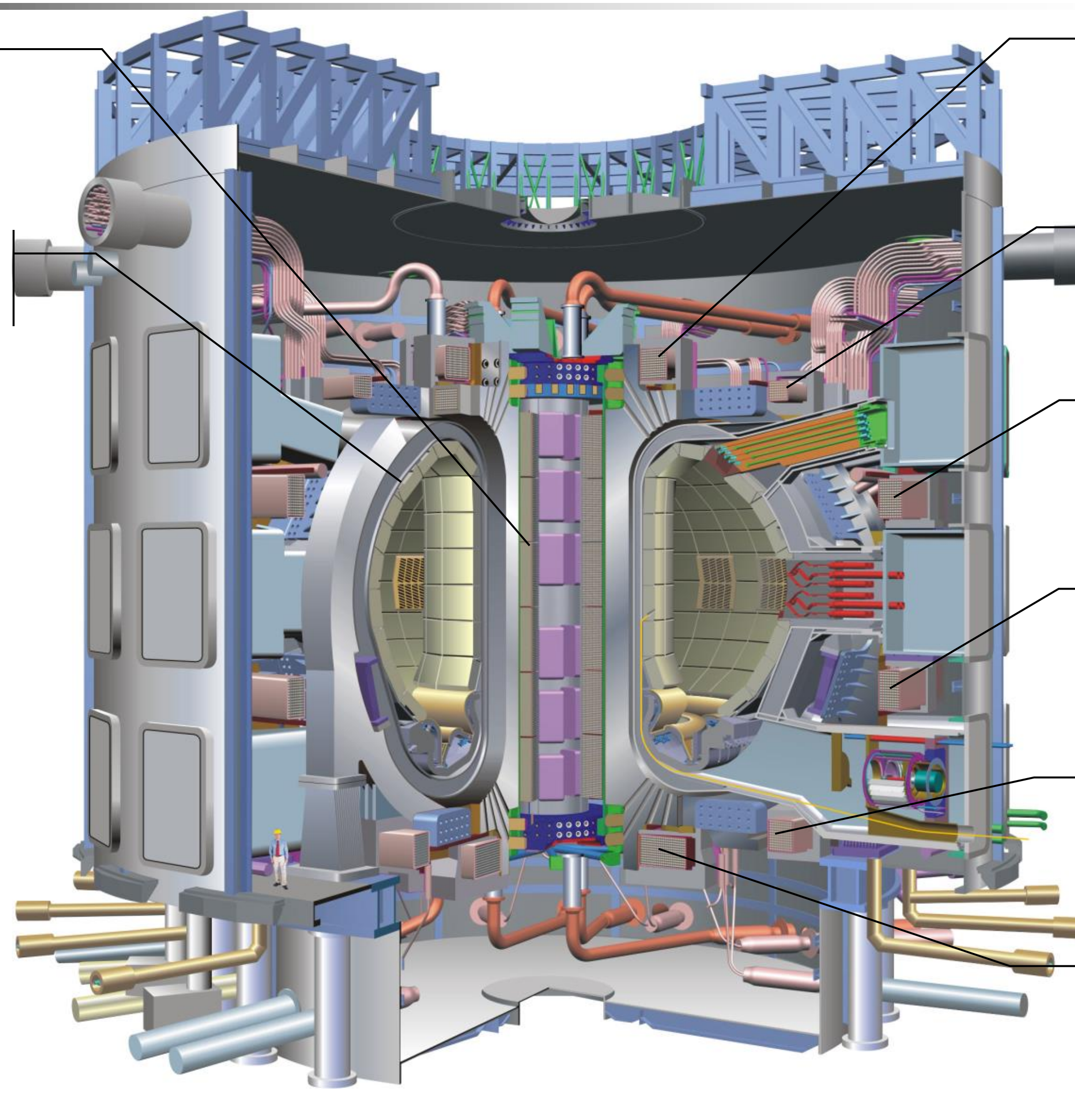
superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

Thermonuclear fusion

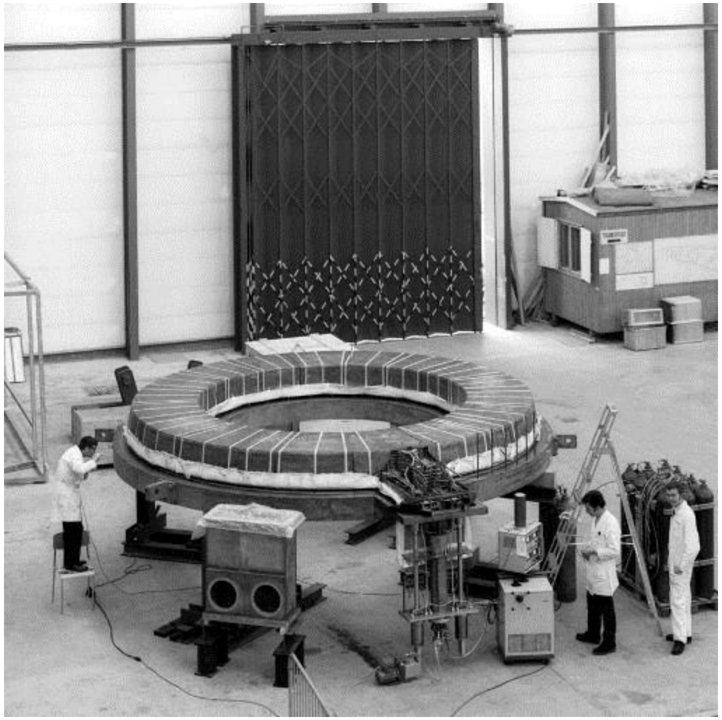




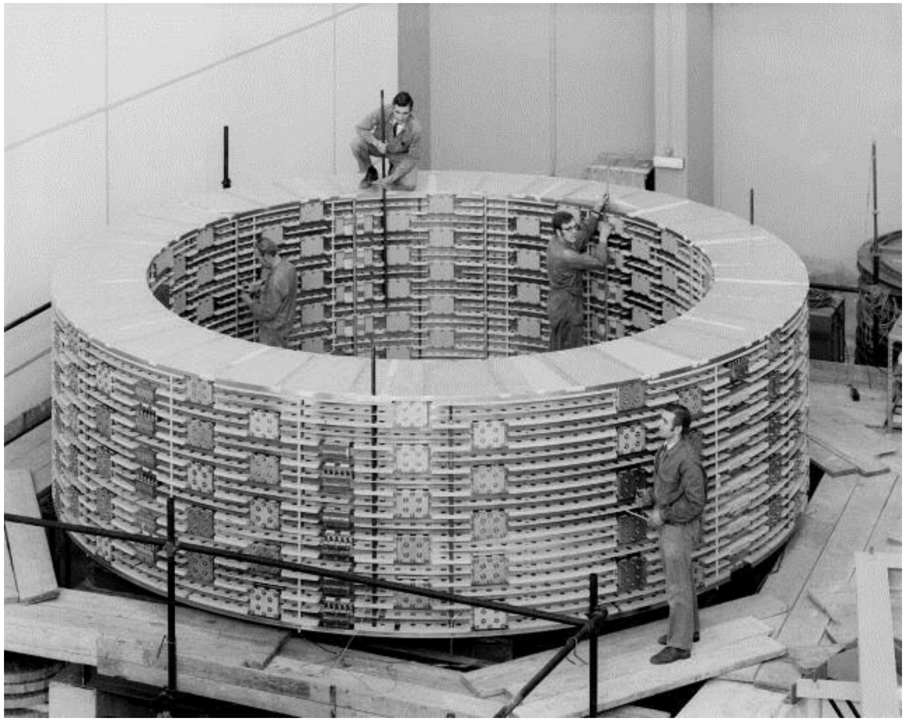
ITER

International
Thermonuclear
Experimental
Reactor

HEP detectors of the past...

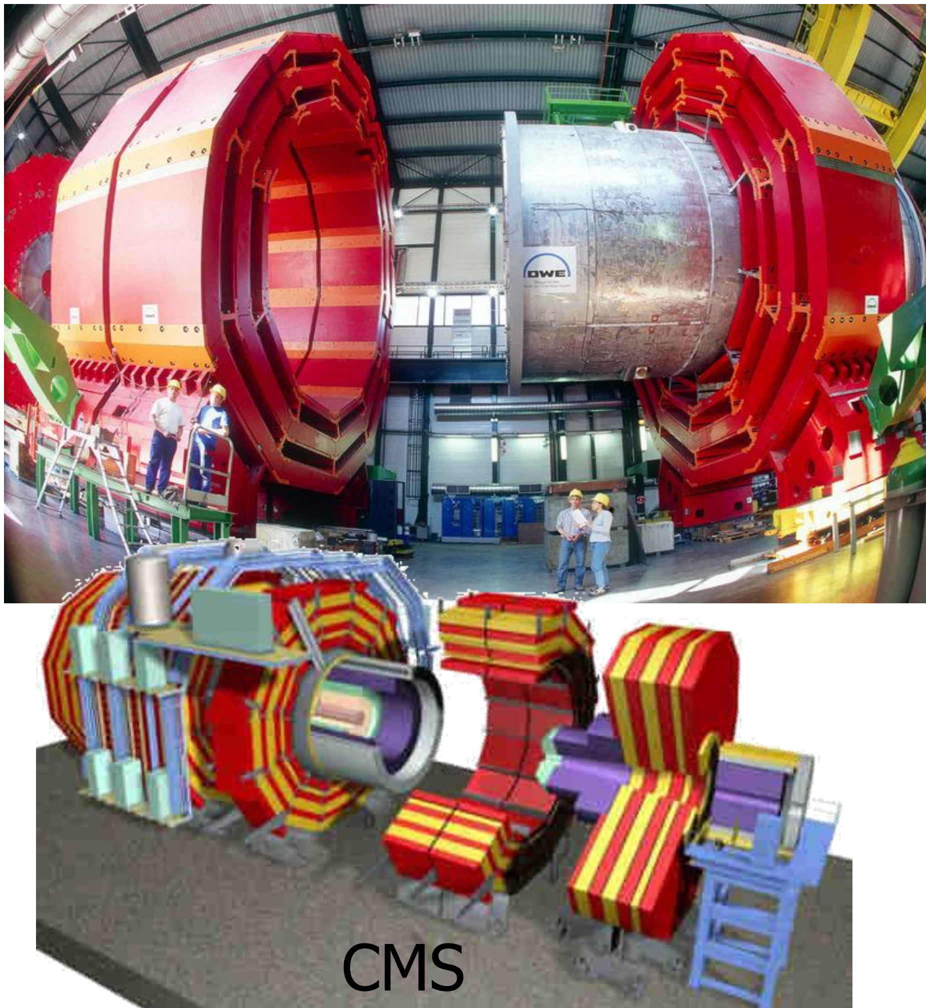


Omega

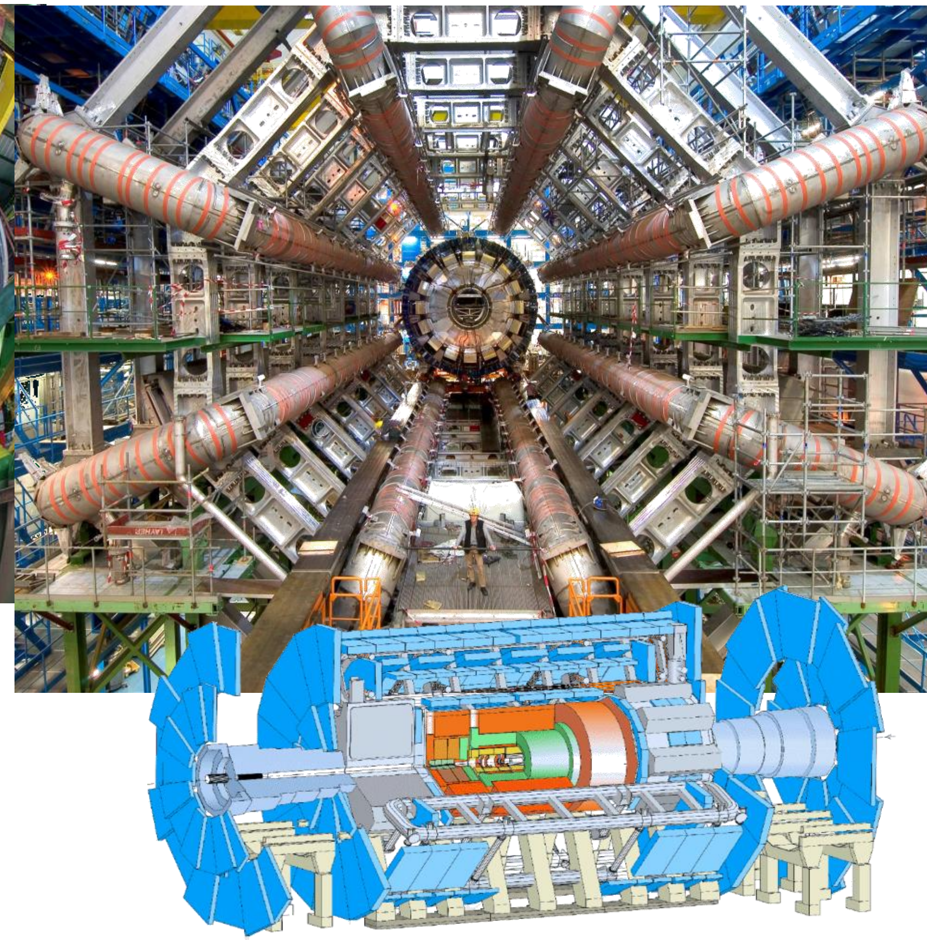


BEBC

… and HEP of the present (CMS and ATLAS)



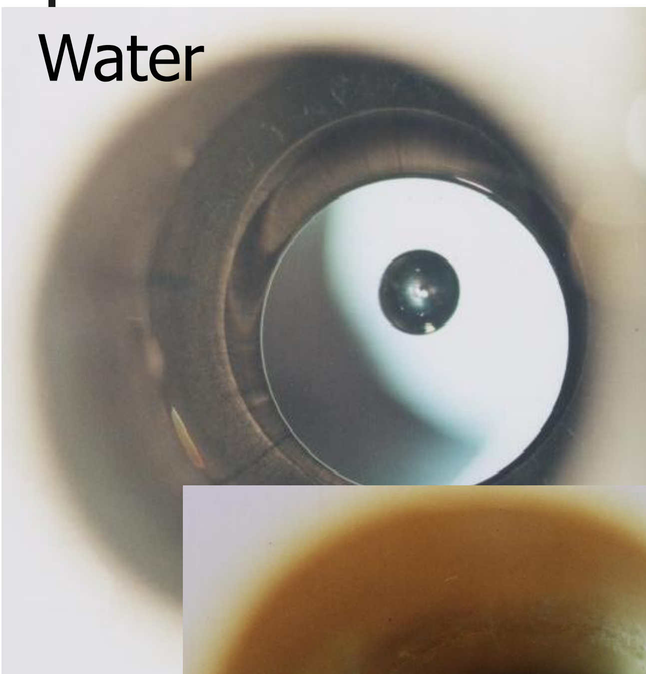
CMS

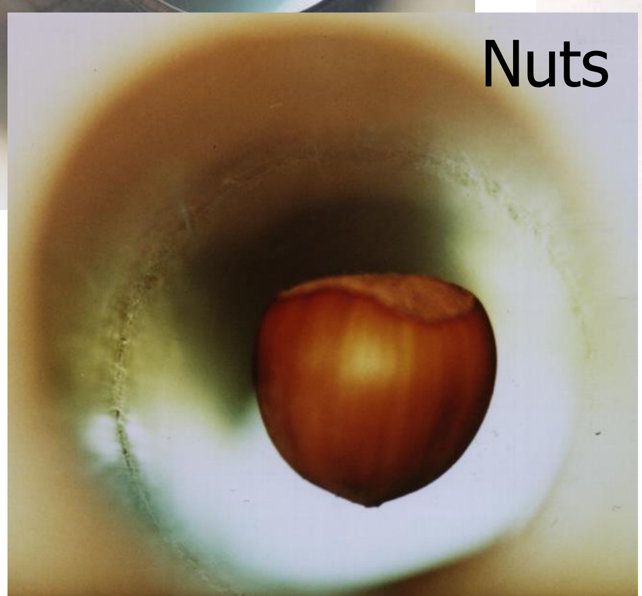


ATLAS

Levitation…

… more levitation

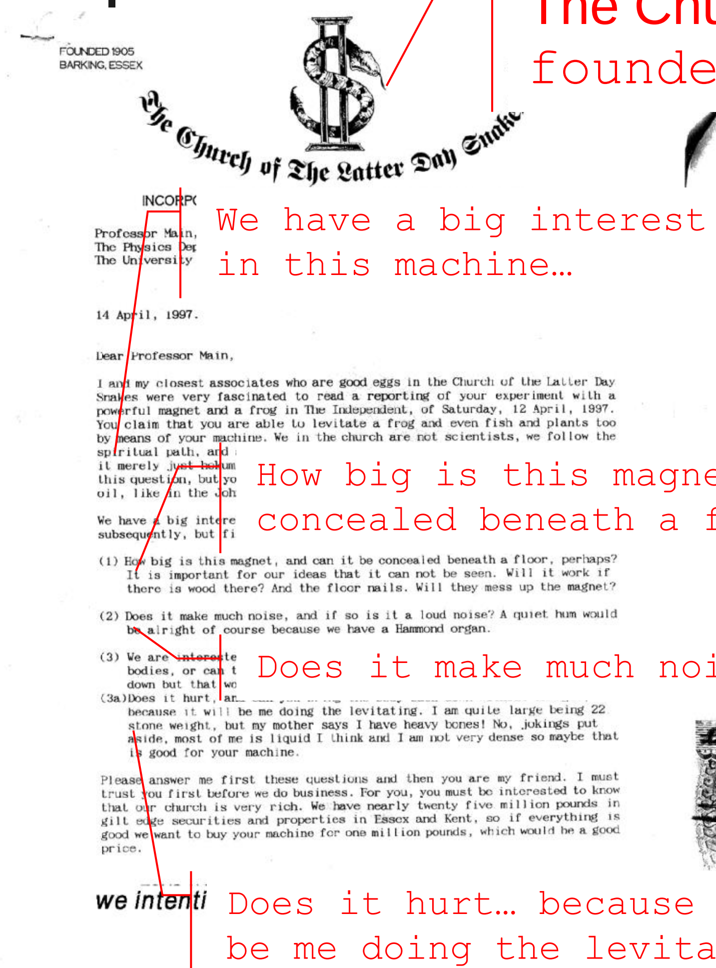




Diamagnetic levitation in strong magnetic fields (16 T) as can be produced by superconductin and hybrid magnets

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

INCORP

Professor Main,
The Physics Dep
The University

14 April, 1997.

Dear Professor Main,

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

We have a big intere
subsequently, but fi

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

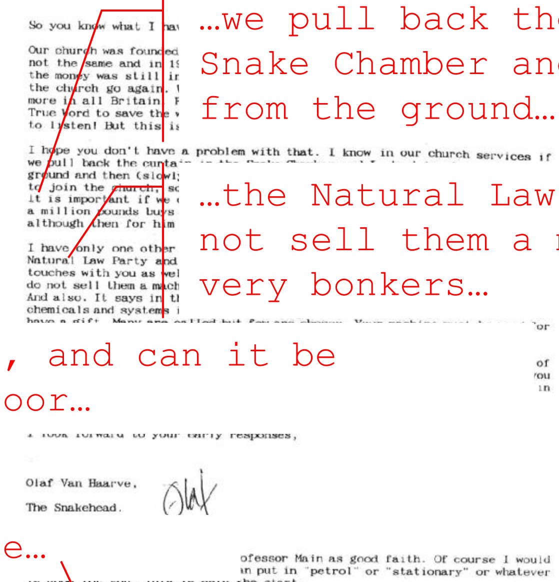
(2) Does it make much noise, and if so is it a loud noise? A quiet hum would be alright of course because we have a Hammond organ.

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

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

we intenti

We have a big interest in this machine…


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

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

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

I look forward to your early responses,

Olaf Van Haarve,
The Snakehead.

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

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

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

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

Does it make much noise…

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

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

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

Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Superconducting cables
  - Superconducting magnets
- The making of a superconducting magnet
- Uses of superconductivity
- A closing word

A word of closing

- Superconducting magnet design is a lot about superconductors (materials, wires, cables, and their electric and thermal properties)…
- … but not only !
  - High field & forces bear mechanical problems that are tough to solve ($B=10$ T $\Rightarrow$ $p_{mag}=400$ bar !)
  - Materials at low temperature are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - Cooling is an applied science by itself

Where to find out more - 1/3

- Superconducting magnets:
  - Case Studies in Superconducting Magnets: Y. Iwasa, Plenum Press, New York (1994), ISBN 0-306-44881-5.
  - Superconducting Magnets: M.N. Wilson, Oxford University Press (1983) ISBN 0-019-854805-2
  - High Field Superconducting Magnets: F.M. Asner, Oxford University Press (1999) ISBN 0 19 851764 5
  - Superconducting Accelerator Magnets: K.H. Mess, P. Schmuser, S. Wolf, World Scientific, (1996) ISBN 981-02-2790-6
  - Stability of Superconductors: L. Dresner, Plenum Press, New York (1994), ISBN 0-306-45030-5
  - Handbook of Applied Superconductivity ed. B. Seeber, UK Institute Physics 1998
  - Proc Applied Superconductivity Conference: IEEE Trans Magnetics, 1975 to 1991, and IEEE Trans Applied Superconductivity, 1993 to 2012,
  - Proc European Conference on Applied Superconductivity EUCAS, UK Institute Physics
  - Proc International Conference on Magnet Technology; MT-1 to MT-20 (2007) mainly as IEEE Trans Applied Superconductivity and IEEE Trans Magnetics

Where to find out more - 2/3

- Cryogenics
  - Helium Cryogenics S.W. Van Sciver, Plenum Press, 86 ISBN 0-0306-42335-9
  - Cryogenic Engineering, B.A. Hands, 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, J.R. Waldram, Institute of Physics Publishing (1996) ISBN 0 85274 337 8
  - High Temperature Superconductors: Processing and Science, A. Bourdillon and N.X. Tan Bourdillon, Academic Press, ISBN 0 12 117680 0

Where to find out more - 3/3

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