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Superconducting Magnets for Accelerator Applications

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June 2021

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SUPERCONDUCTING MAGNETS

Why Superconducting Magnets?

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Main reasons

1. allows **higher particle energy** for given ring size
   - permanent magnet limited by material ~1-2 T
   - normal conducting limited by iron ~2 T
   - superconducting limited by current
     NbTi ~9 T (4.5K), Nb_3Sn ~15 T (4.5 K)

   Note: pulsed magnets up to ~100 T (for ms only)

2. substantial **savings in operating** costs
   - normal conducting requires water cooling
     e.g. 52 MW for CERN SPS at 315 GeV
   - superconducting requires cryogenic cooling
     e.g. 6 MW for DESY HERA at 800 GeV

The Long Way to Superconducting Magnets

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1908: helium liquefaction

1911: discovery superconductivity
in mercury (~4 K)
by Kammerlingh-Onnes

1960s: practical superconductors
(magnet grade) NbZr, Nb_3Sn

1969: first large scale SC magnet
CERN BEBC (800 MJ)

1970s: commercial NMR systems

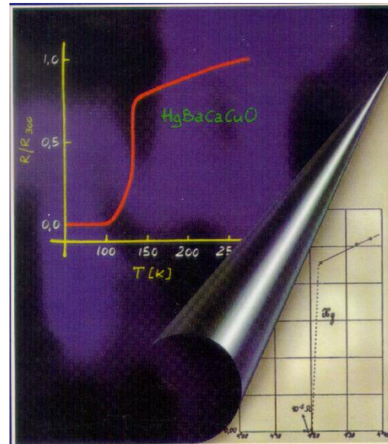
1984: Tevatron: 1st SC accelerator:
520 GeV; 900 GeV in 1987

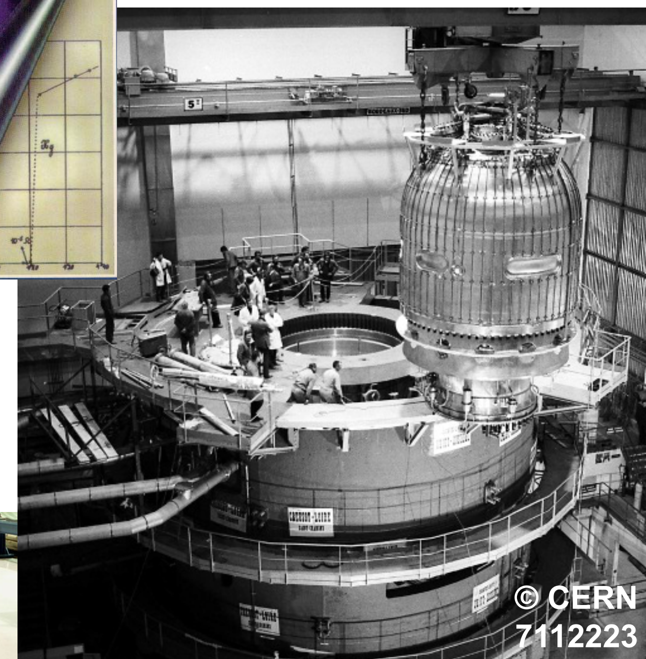
1986: Cu-oxide superconductors
by Bednorz and Müller

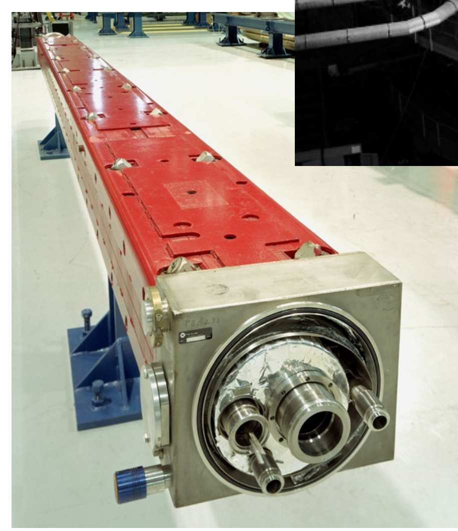
1988: 110 K BSCCO (BiSrCaCuO)

1994: record 150 K, HgBaCaCuO

2001: MgB_2 at 30 K (new type)







The Superconducting Phase

Must operate below the critical surface:

- critical current J_c
- critical temperature T_c
- magnetic field B_{c2}

For NbTi:

- **$T_c(0) = 9.2$ K ; $B_{c2}(0) = 14.5$ T**
- Critical area boundary

  $T_c(B) = T_c(0)\ \{1-\{B/14.5\}\}^{0.59}$

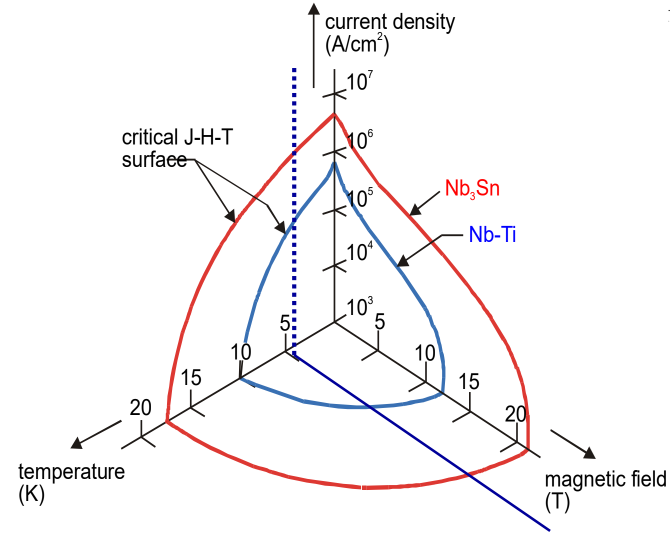
  $B_{c2}(T) = B_{c2}(0)\ \{1-\{T/9.2\}^{1.7}\}$

- Typical operation at 4.2 K and 5 T

  $T_c(5T) = 7.16$ K ; $B_{c2}(4.2K) = 10.7$ T

Similar relations exist for Nb_3Sn and

BSCCO 2212 and 2223



- *all* metallic superconductors are brittle, *except* NbTi
- critical current density depends on processing

Iwasa table on the long route	
Criterion	Number
superconducting	~10'000
$T_c \approx 10$ K and $B_{c2} \approx 10$ T	~100
$J_c \approx 1000$ Amm^{-2} at B > 5 T	~10
magnet grade superconductor	~1

Temperature Margin

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When a transport current flows, the onset of resistance is further reduced from T_c to T_{cs}, the current sharing temperature

$T_{cs}(B,I) = T_b+\{T_c(B)-T_b\}\{1-I/I_c\}$

$T_{cs}(5\ T,0.5I_c) = 5.7\ K$

So we lost a lot of margin from 9.2 K → 7.2 K → 5.7 K

- 50% I_c and 5 T → 1.5 K margin for T_b =4.2 K
- 75% I_c and 5 T → 0.8 K,

→ ***so we never can operate very near to I_c !***

- Following $\Delta T = Q / c(T)$

  release of energy (heat) from various sources will cause a temperature rise and thus the superconducting state is very seriously in danger
- Increased temperature drops I_c; causing flux motion, generates heat

  → ***stability problem***
- The heat that can be absorbed without reaching T_{cs} is the enthalpy difference $\Delta H = \int c(T)\, dT$ between T_{cs} and T_o

Release of Heat and Heat Capacity

Why is release of heat so critical at 4 K ?

- **Heat capacity is strongly T-dependant and extremely low below 10 K for all materials**

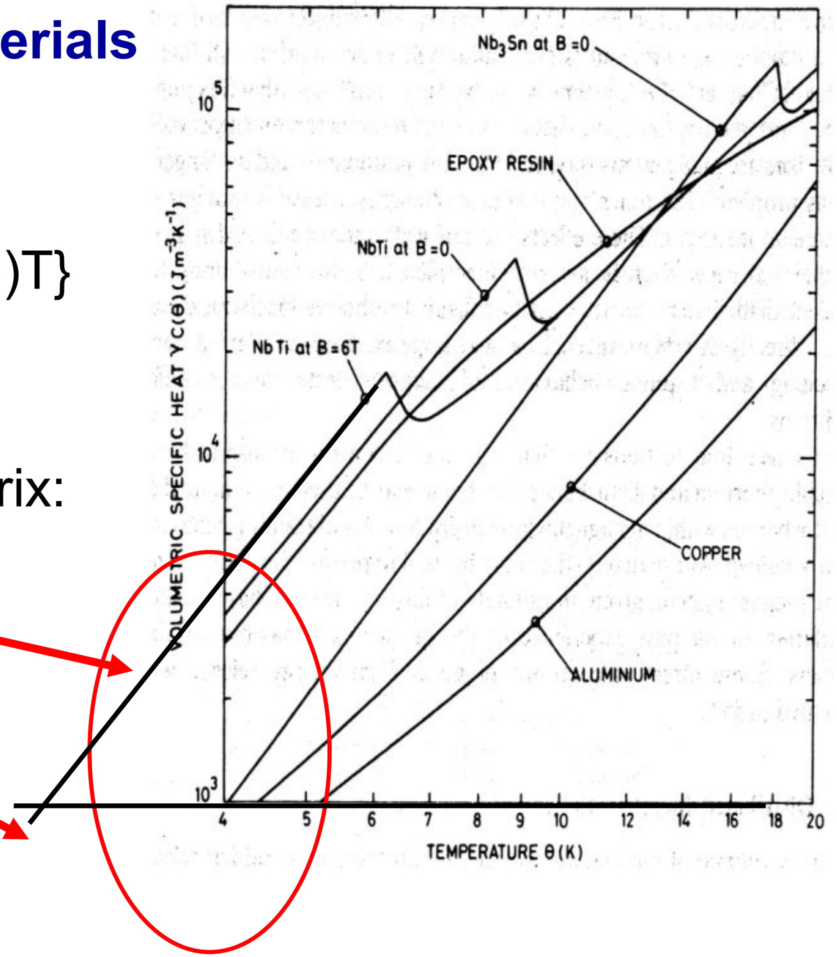
Copper-NbTi composite:

- $C_p(T) = \eta\{(6.8/\eta+43.8)T^3 + (97.4+69.8B)T\}$ [μJ/mm^{3}K]

Which is at 5 T and 40% NbTi in Cu matrix:

- 2.5 μJ/mm^{3}K at 4.2 K and
- 0.5 μJ/mm^{3}K at 1.9 K !

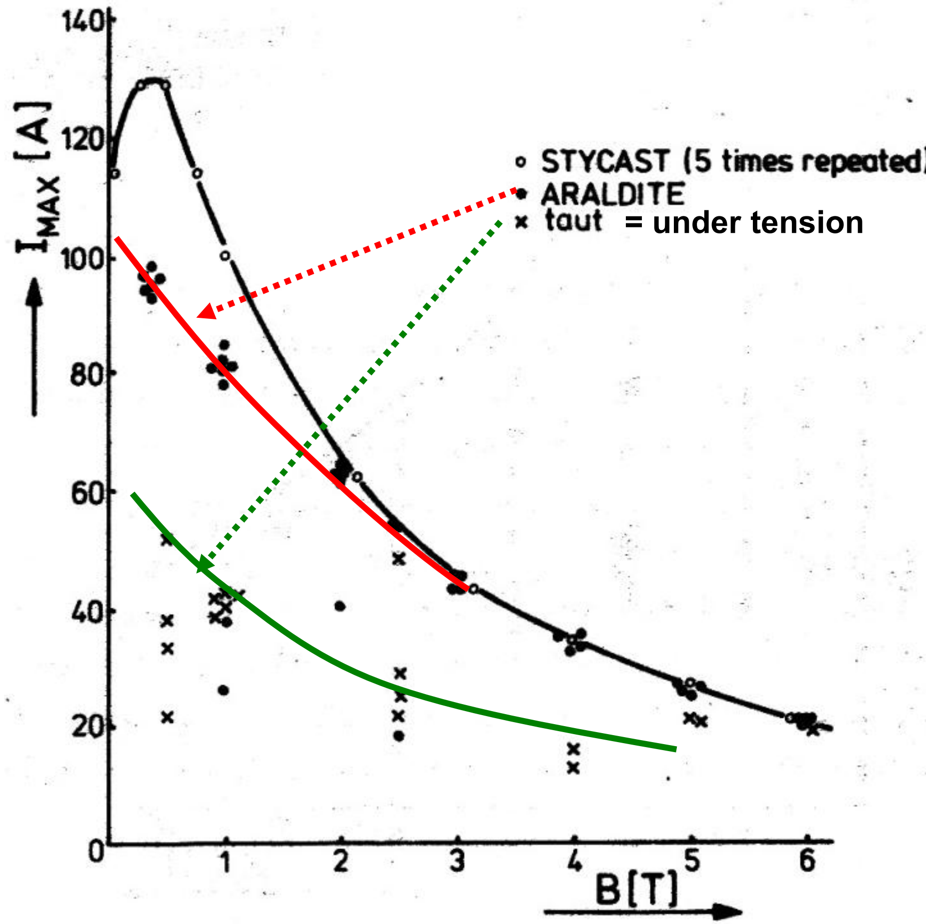
- 2.5 μJ/mm corresponds to a movement in a 1 mm wire at 5 T and 500 A of 1 μm only !



Example Wire Movement

- 2.5 μJ corresponds to
  a movement of 1 μm only
  in a 1 mm wire
  at 5 T and 500 A!

- NbTi/CuNi wire on sample holder, see picture:
  - The critical current of badly stable wires (no Cu matrix but CuNi for use in SC switches) can hardly be measured, resin cracking causes wires to quench.
  - A clear demonstration of how crucial suppression of cracking and wire movements is.



Stabilizing the Superconducting Wire

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Wire and windings displacements

- Heat release of μJ/mm3 has to be avoided,
  - since otherwise the superconducting wires will go to the normal state

Two solutions:

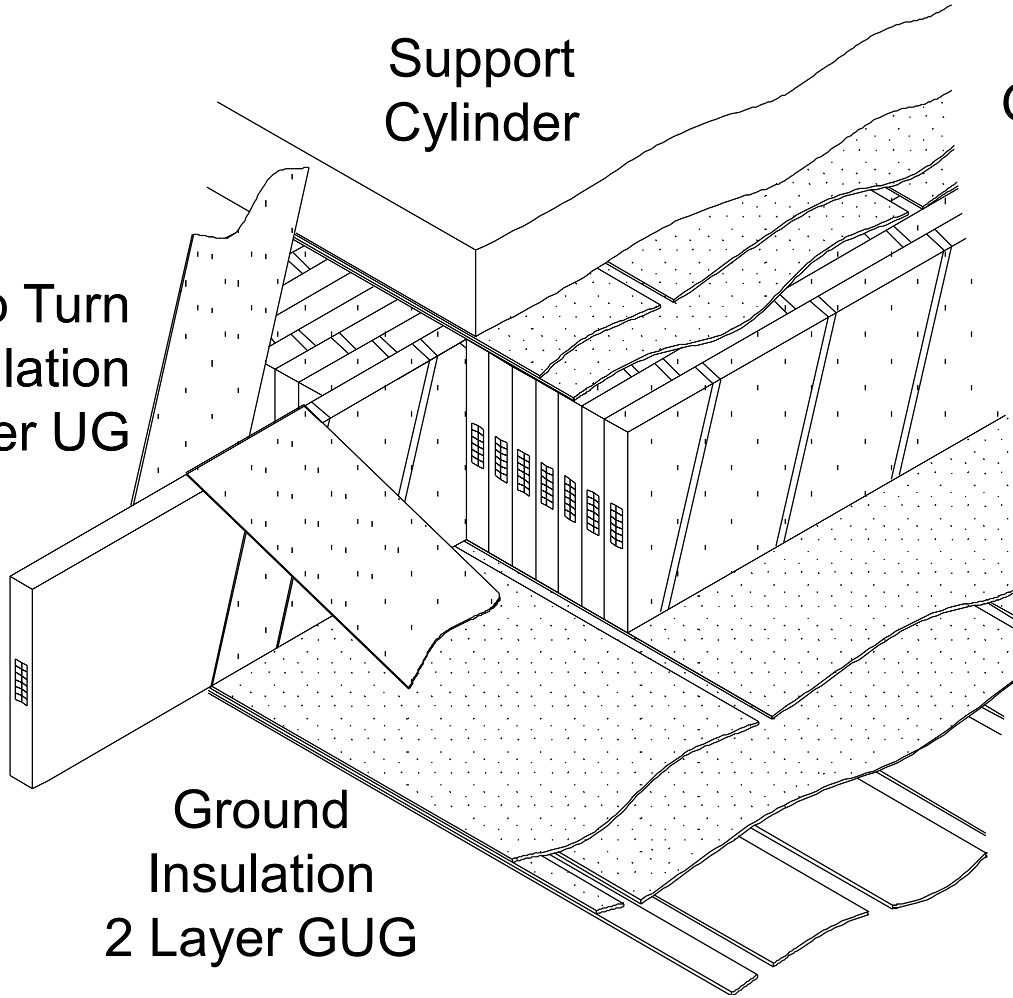
- accept displacements but avoid friction and slip-stick
  - introducing low friction sliding (kapton films wrapped around wires and cables)
- avoid any displacement by fully bonding conductors together
  - requiring vacuum impregnation of coils by a resin/glue

Cracking and de-bonding

- However, resin/glue can break and cracks will release heat too,
  - careful design is required for optimum gluing, vacuum impregnation of coils, and avoiding local stress concentrations at bonded surfaces.
- Good and bad examples of both strategies exist
  - it really depends on the quality of the design and procedures maintained

Example Coil Winding

ATLAS Central Solenoid



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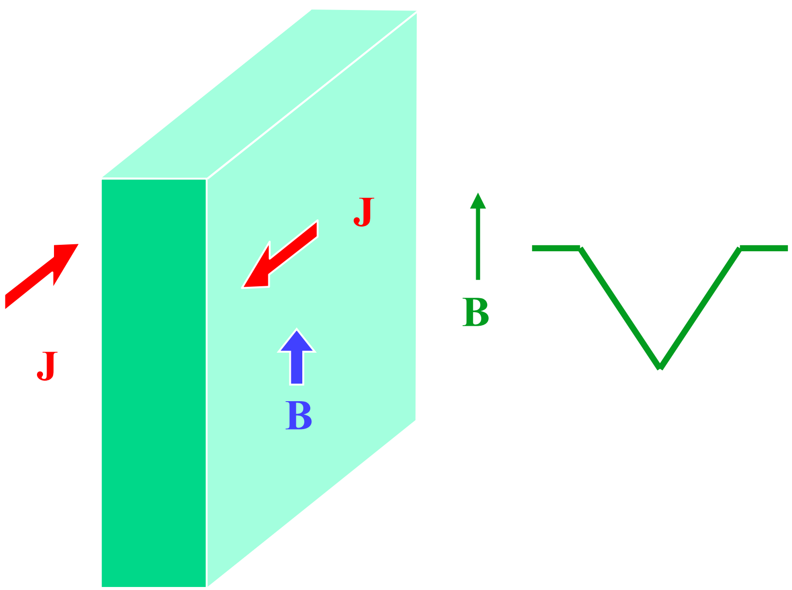
PERSISTENT CURRENTS

Screening Currents and Magnetization

- screening currents are induced when a superconductor is subjected to changing field (like eddy currents)
- ***screening currents*** are in addition to the ***transport current***



- currents don't decay
  → ***persistent currents***

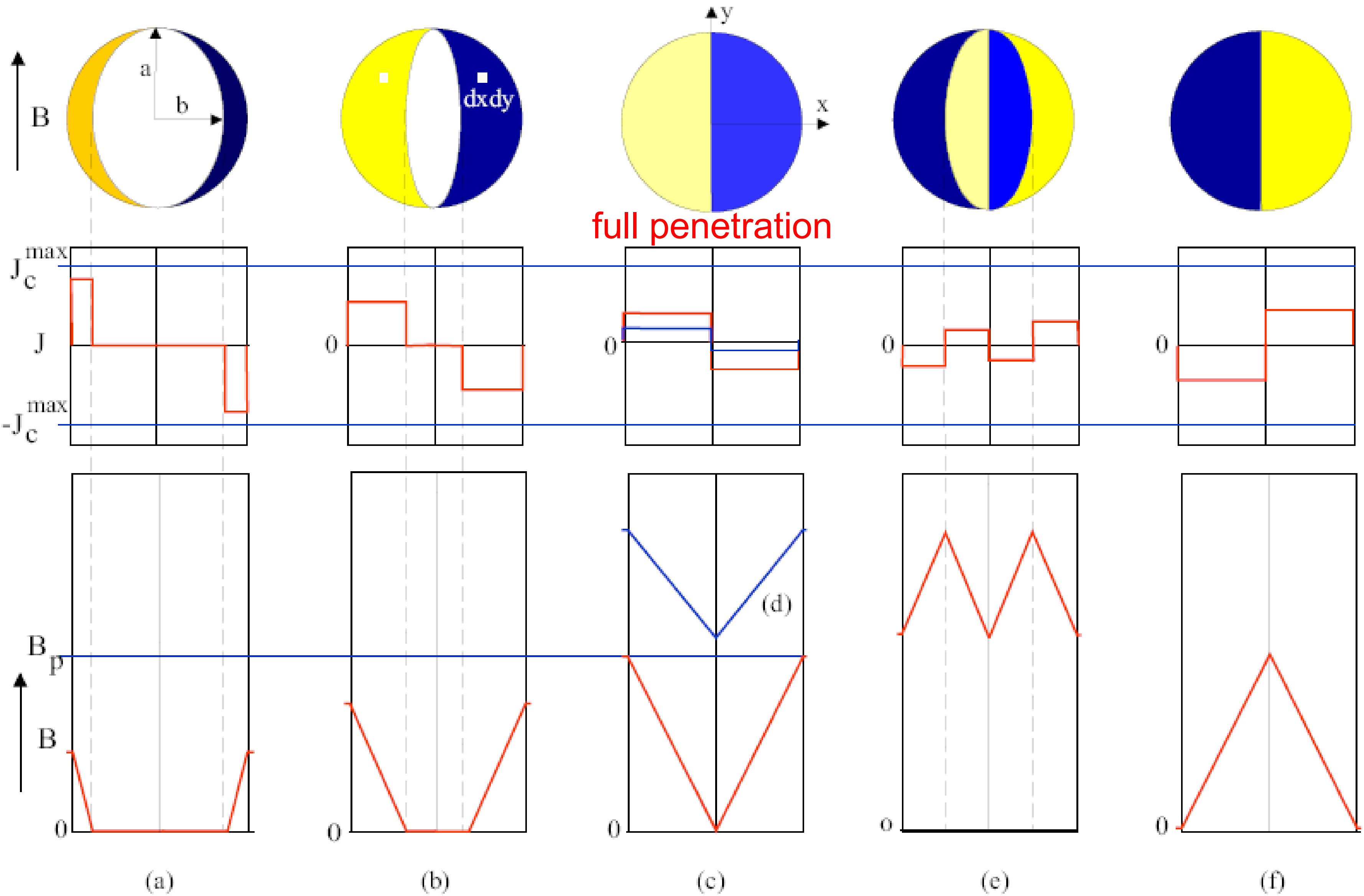
- viewed from outside, looks like magnetization

$$M = \int_{\frac{d}{2}(1-q^*)}^{\frac{d}{2}} -\frac{J_c \, 2x}{d} \mathrm{d}x$$

- at full penetration: q* = 1

$$M_p = -J_c \frac{d}{4}$$

Critical State Model for Full Magnetization



Magnetization as Function of the Field

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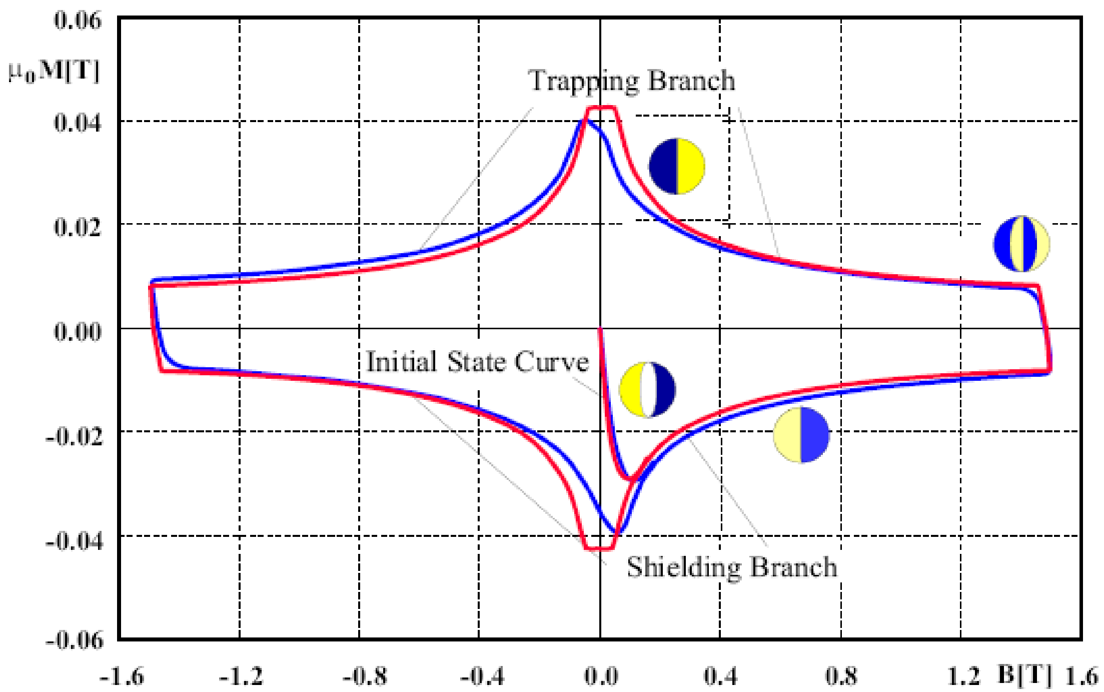

measured (blue) and calculated (red) magnetization of a LHC type strand

Synchrotron injects at low field, ramps to high field and then back down again

relative magnetization error is worst at injection because $\mu_o M/B$ is largest

magnetization changes rapidly at start of ramp

Best to inject beam at higher current!

Multi-filament Wires

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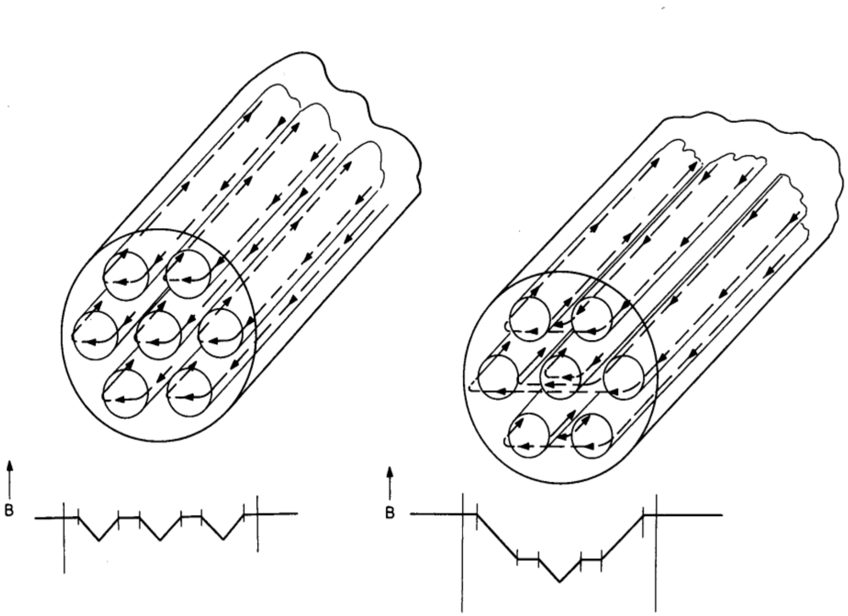
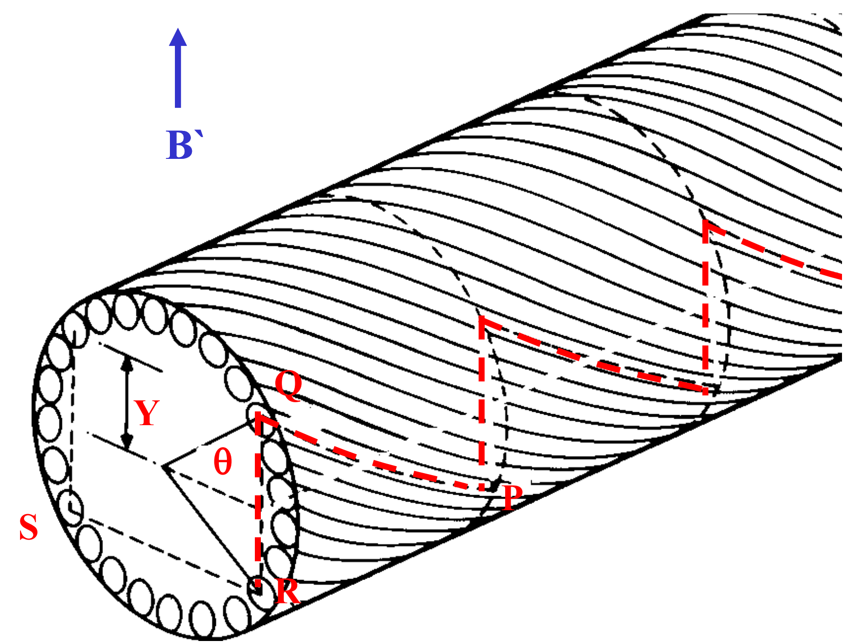
- Reduce magnetization by making the superconductor from **fine filaments**
- Straight filaments couple in changing field → advantage lost



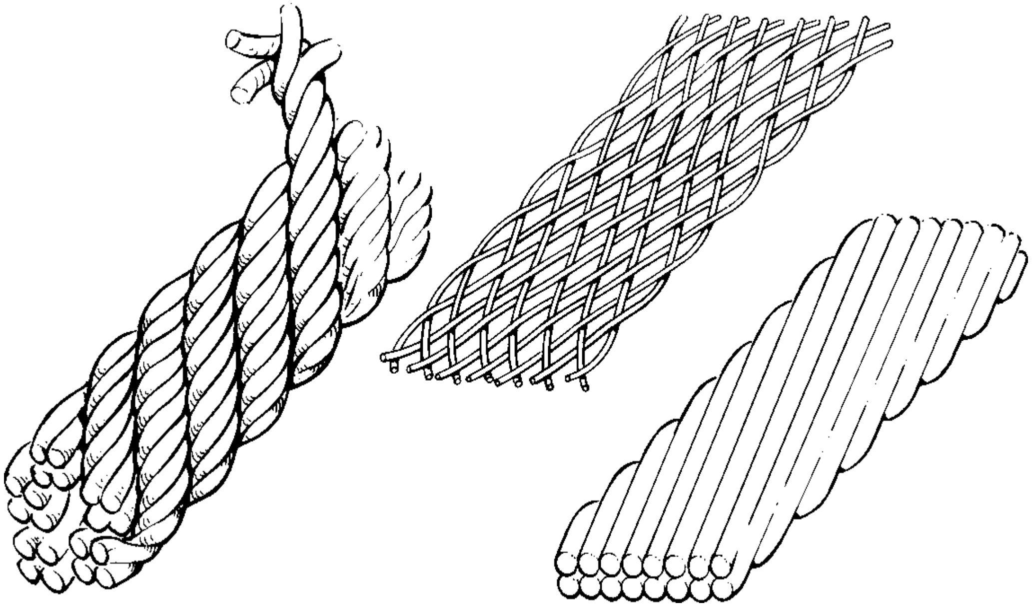
- Reduce coupling by **twisting**
- Matrix crossing currents flow parallel to changing field
- Decay time constant determined by twist pitch



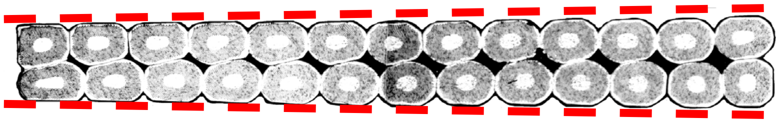
Cable Types

3 twisting types in which each wire is fully **transposed**:

- rope
- braid
- Rutherford
  - Rutherford cable can be compacted (~90%) without damage.

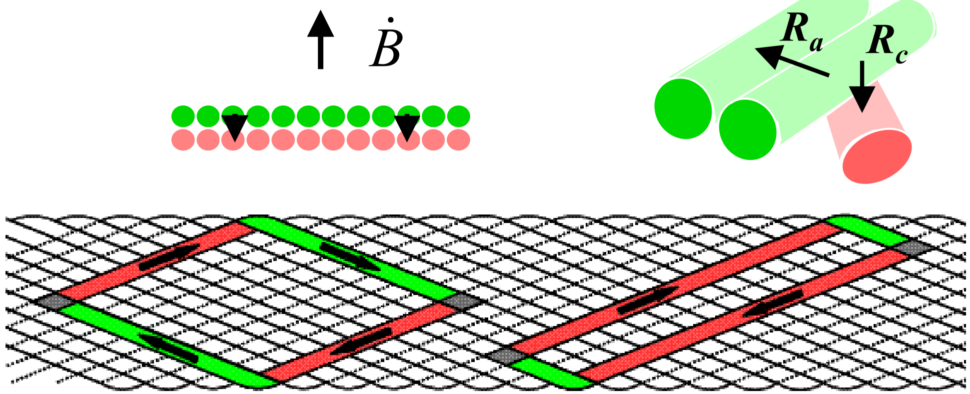


- **Keystone angle** allows stacking around circular aperture.



- induced eddy current $\propto$ -dB/dt and 1/Rc

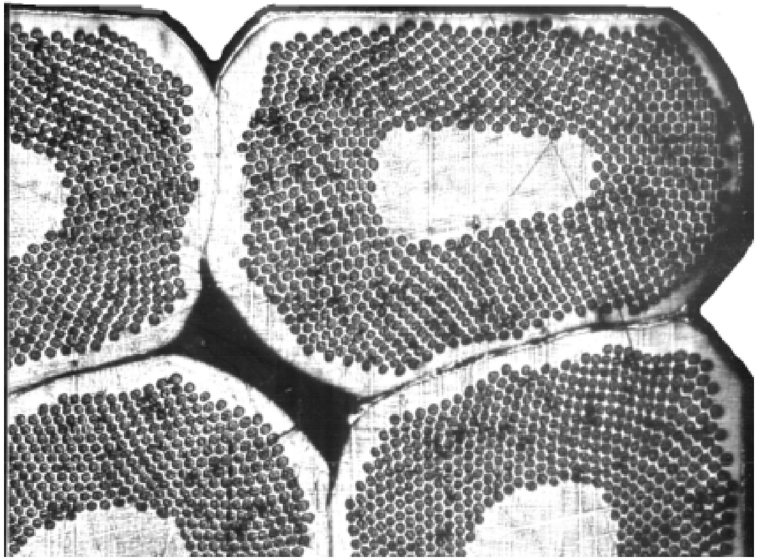
current coupling via **cross-over resistance**



Rutherford Cables

- cable insulated by 2 or 3 layers Kapton
- gaps may be left to allow penetration of liquid helium
- the outer layer is treated with an adhesive layer for bonding to adjacent turns.

- main reason why Rutherford cable succeeded was that it could be compacted to a high density (88 - 94%) without damaging the wires
- furthermore it can be rolled to a good dimensional accuracy (~10mm).



Superconducting Cables

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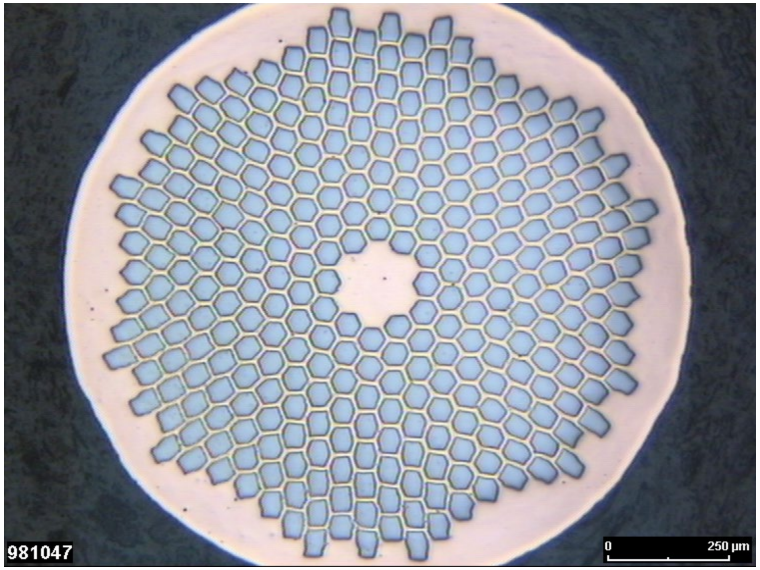
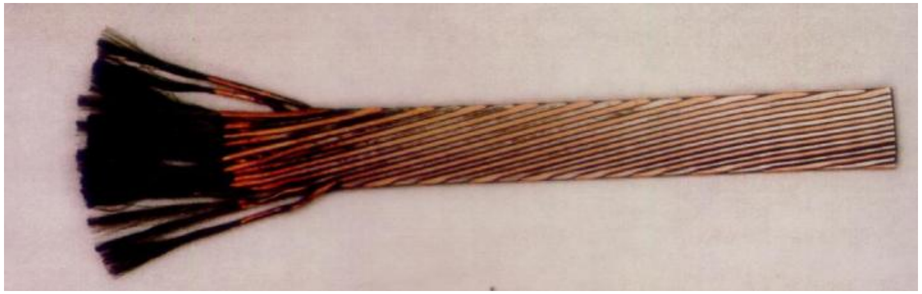
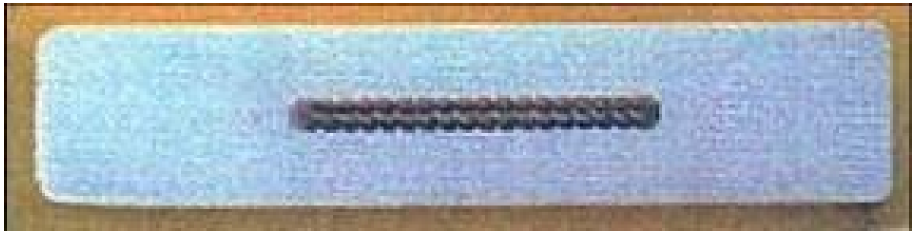
- superconductors made as **multi-filament wires** (strand)
- filaments embedded in **stabilizing copper matrix**
- combined in strongly twisted **multi-strand cable**
- imbedded in **aluminium stabilizer** for enhanced stability & yield strength (mostly detector magnets)







AIR CORE MAGNET EXAMPLES

Coil Winding

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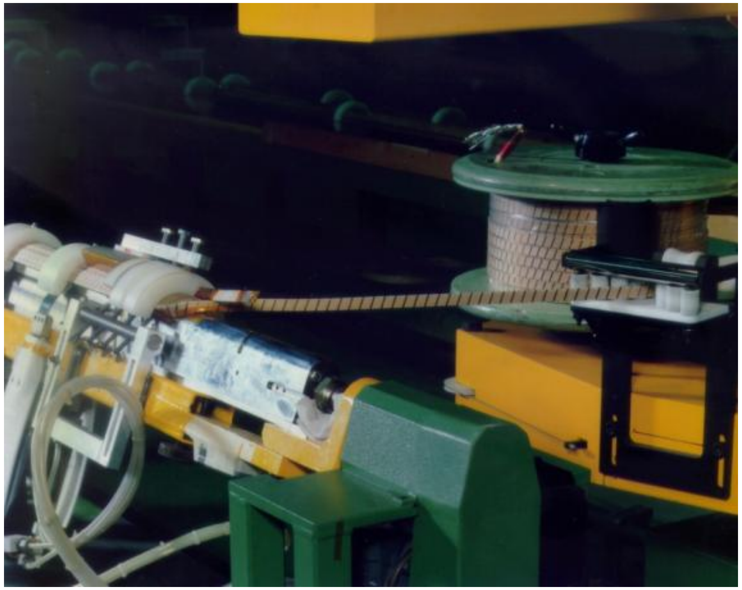

LHC prototype


JPARC

Winding End Spacers

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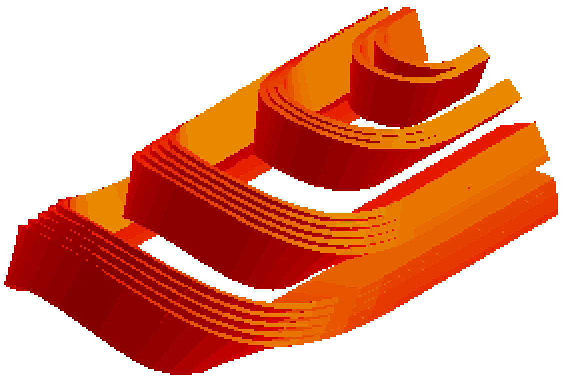
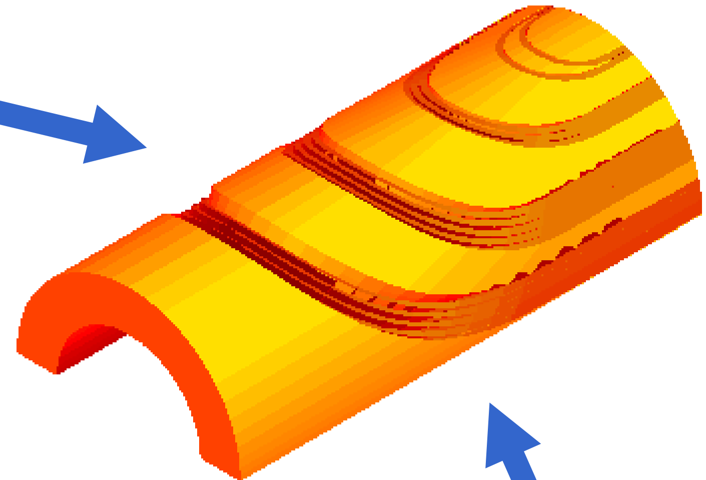
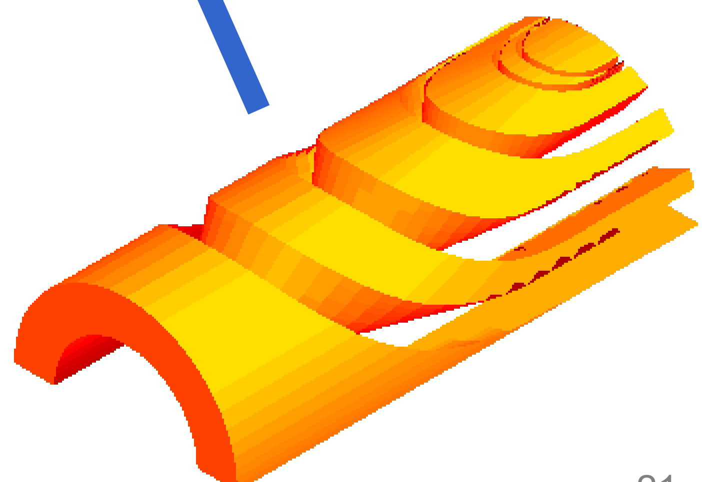




End spacers have a complicated 3D topology.

Their optimization is critical for mechanical stability.



Magnet Assembly

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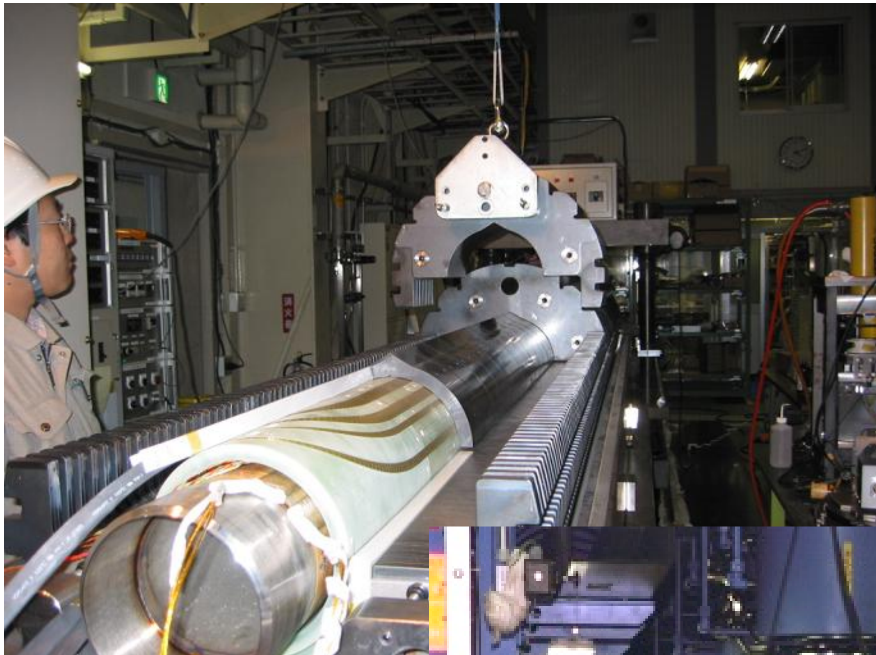
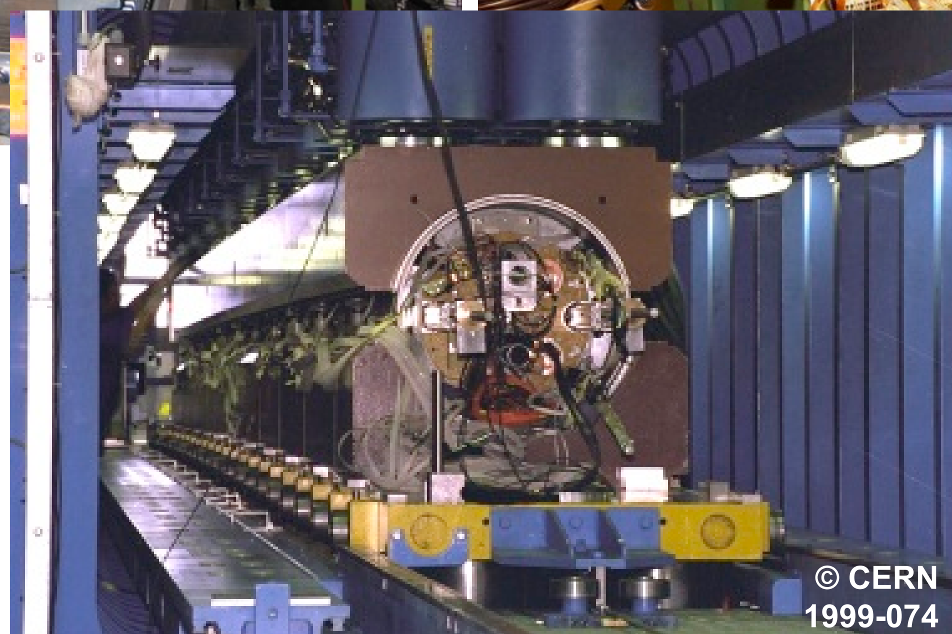


JPARC: collar & yoke

LHC: finishing cold mass



LHC: cylindering under press

Tevatron Dipole Magnet

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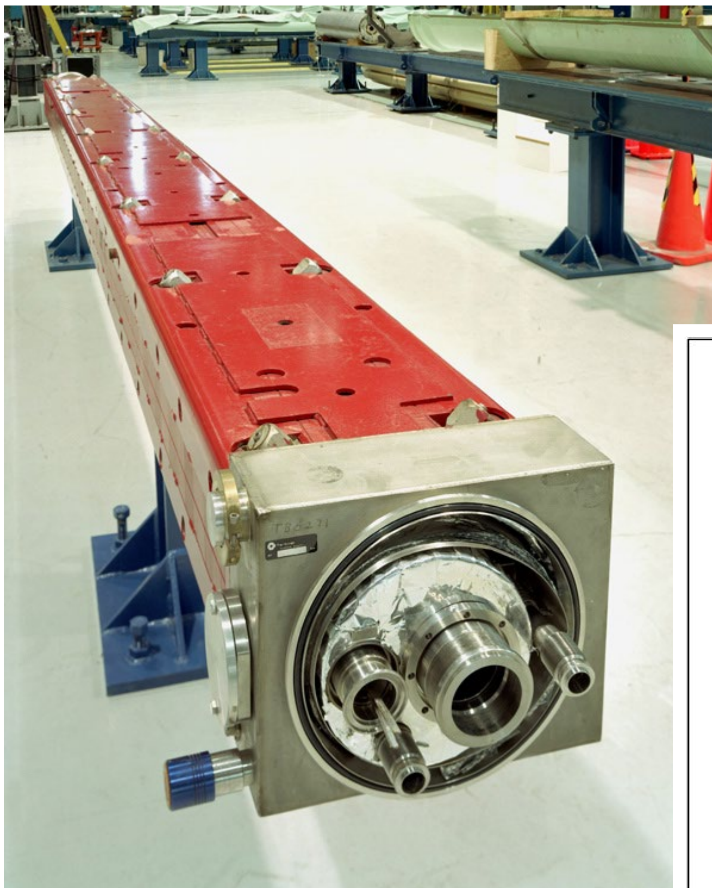
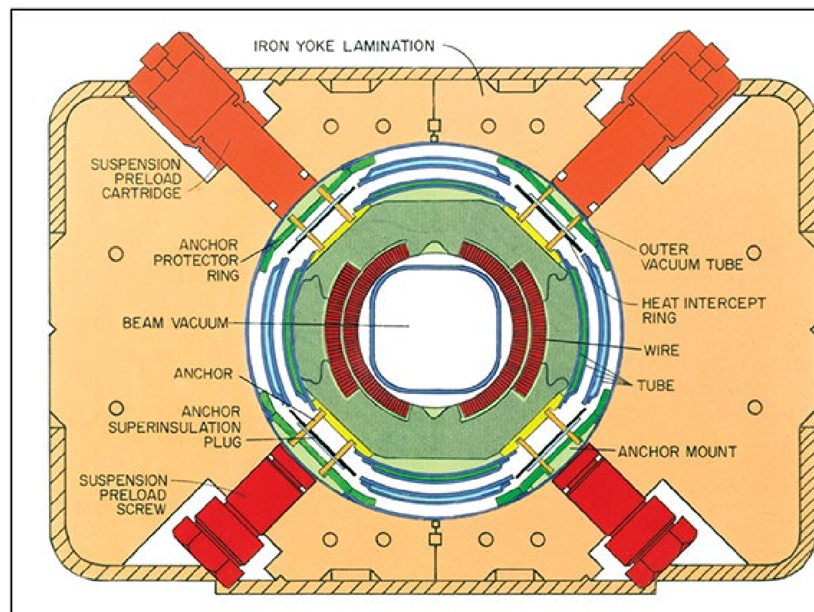
4.5 T at 4’333 A
76 mm bore
warm iron
6.1 m long





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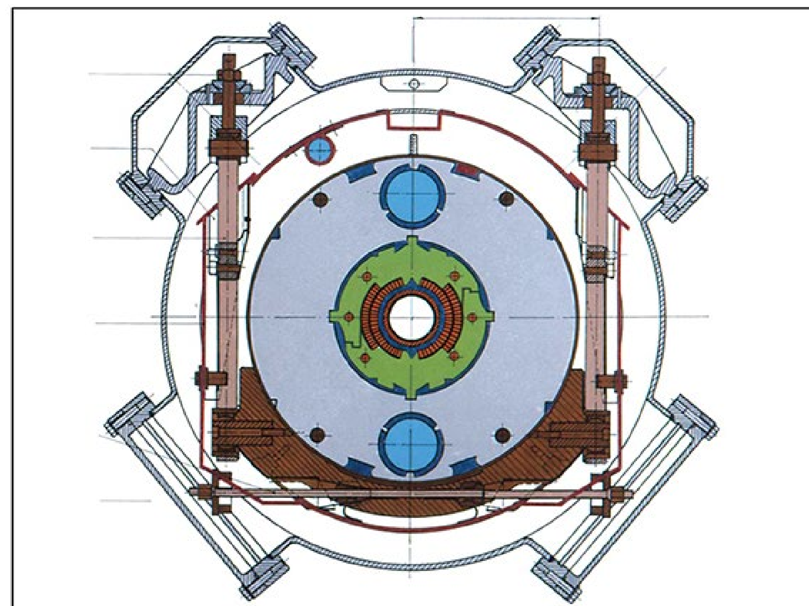
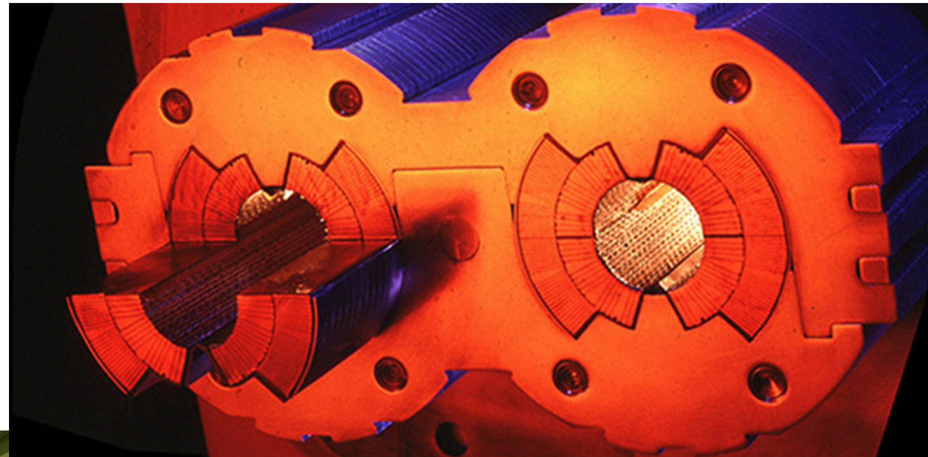
HERA Dipole Magnet

6.05 T at 6'540 A
75 mm bore
cold iron
9 m long

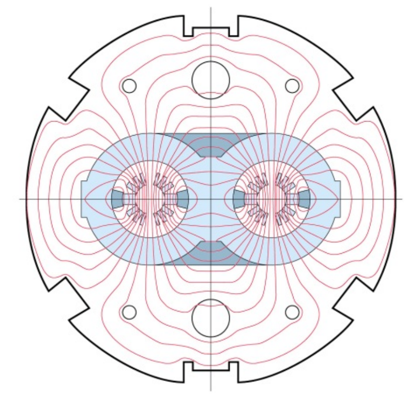


LHC Dipole Magnets

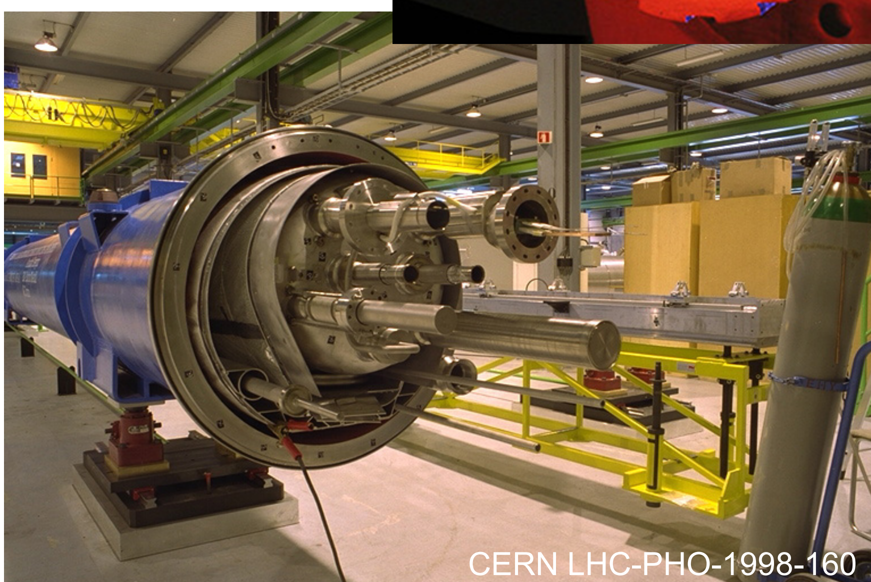
8.33 T at 11’800 A
double aperture
50 mm bore
cold iron
14.3 m long



LHC dipole

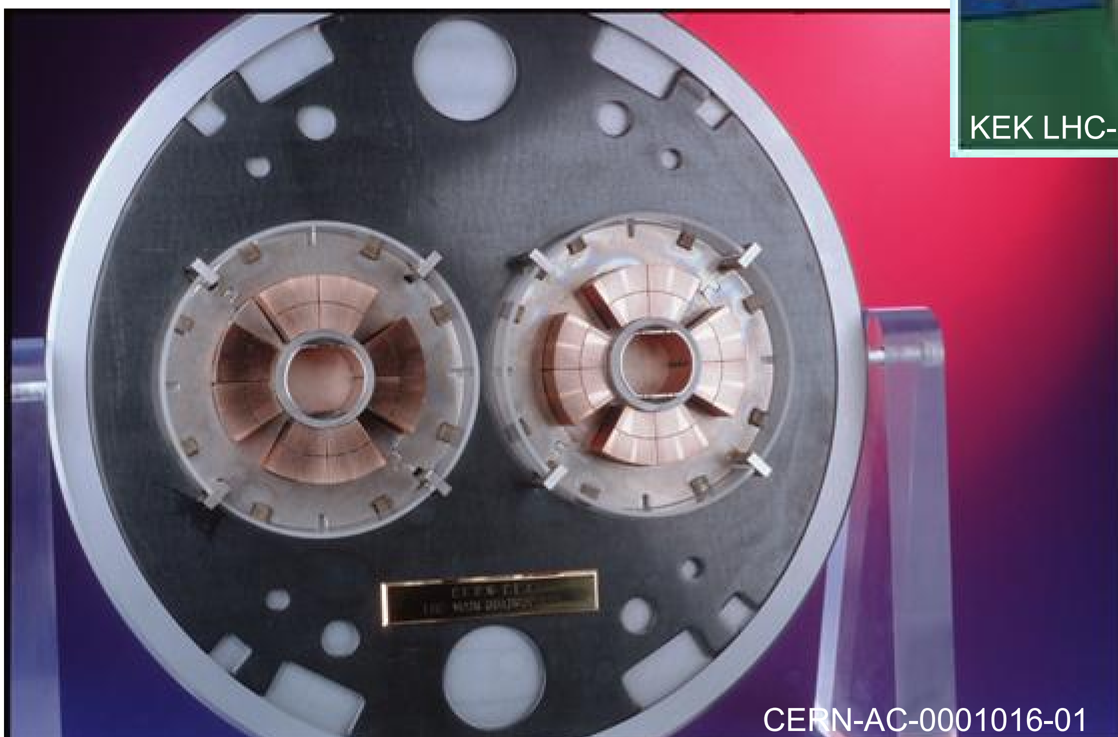


Computed magnetic flux map at B_0=10 Tesla



CERN AC - HE110 - 10/10/95

LHC Quadrupole Magnet



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QUENCH PROPAGATION AND PROTECTION

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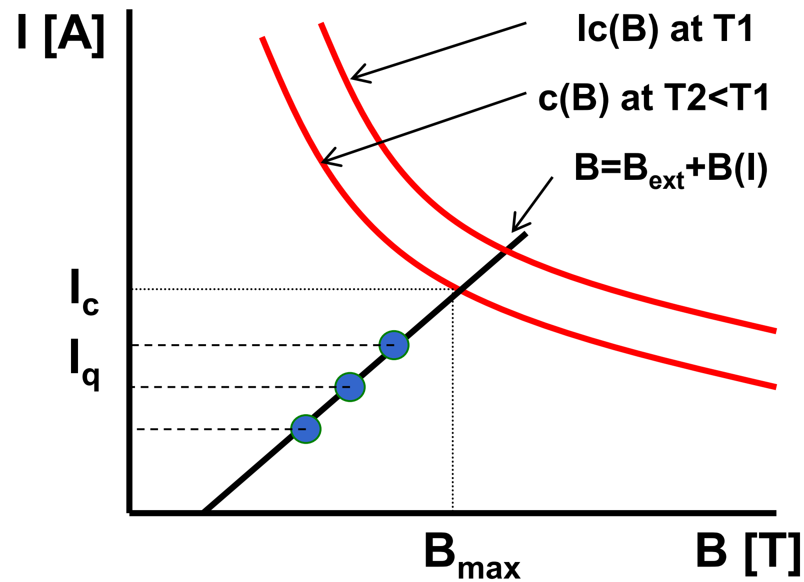
Quench

- sudden and unexpected transition to the normal state

Training

- The maximum attainable current, the quench current so to say, increases step by step after every quench and saturates hopefully near I_c, but often less
- This is highly undesirable, so we need proper design to avoid training!



I vs B, showing premature quenches

Training Quenches

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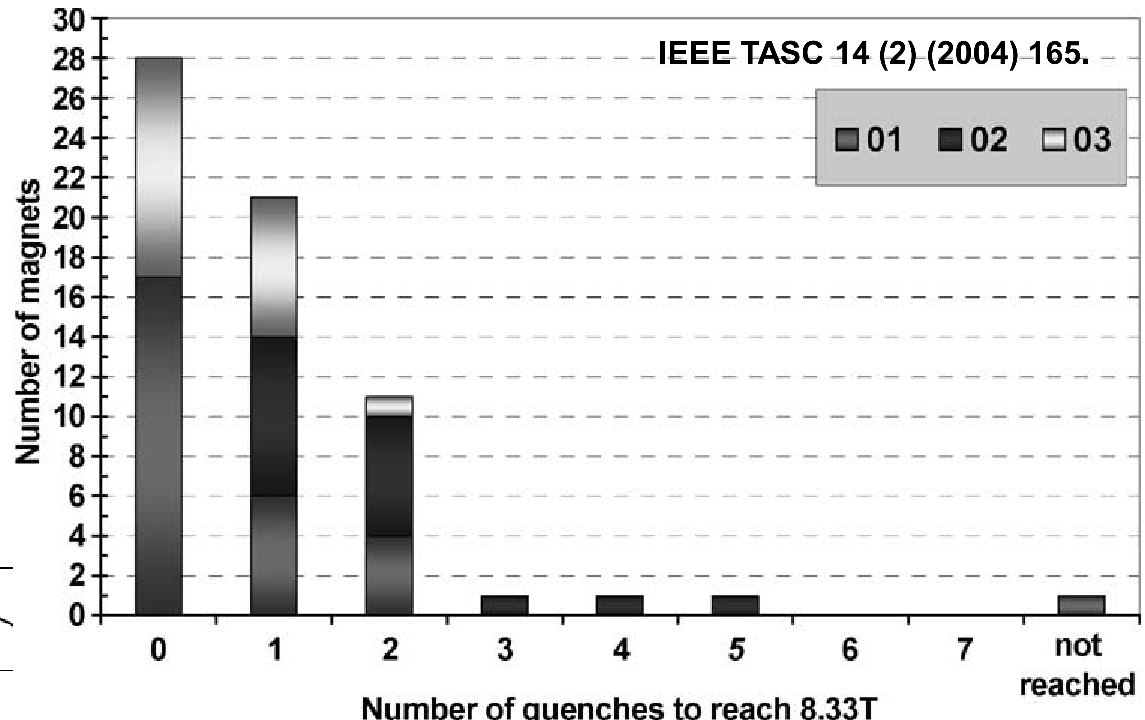
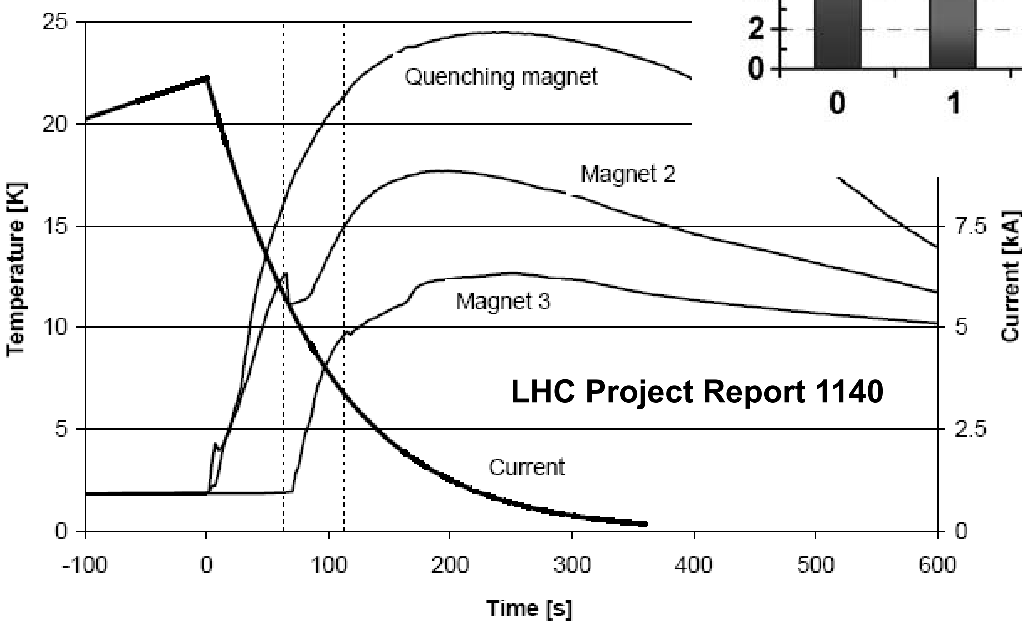
- Number of quenches for LHC dipole to reach nominal field





- Temperature profile of a quenching and 2 adjacent magnets in LHC dipole string

Quench Propagation

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Quench = transition to normal state

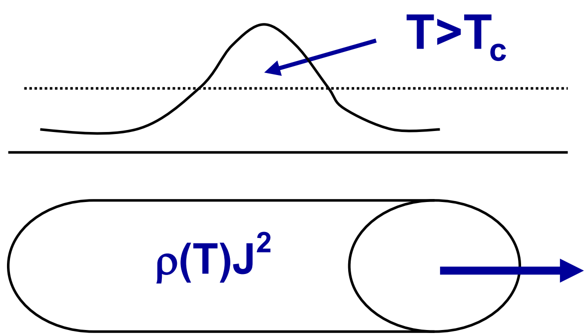
a hot spot larger than the **Minimal Propagation Zone** (MPZ)

- Ohmic heating larger than cooling power
- temperature rise, hot spot expansion … resistance increase

Adiabatic heating in the normal zone ρJ^2:

$\rho(T)\, J^2(t)\, dt = c(T)\, dT$

${}_{o}\int^{t} J^2(t)\, dt = {}_{4}\int^{T} c(T)/\rho(T)\, dT = F(T_{max})$



Stored energy

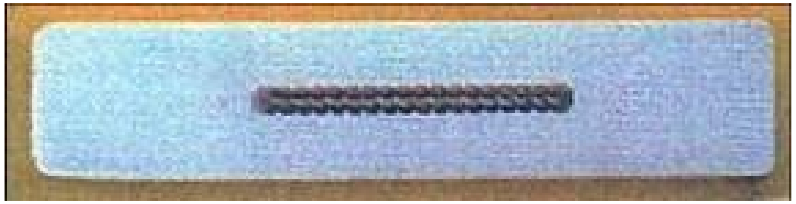
$W_L = ½\, L\, I^2\, [J] = ½ \int BH\, dV$

this energy can be absorbed by the magnet cold mass,

assuming a **safe hot spot temperature T_{max} <150 K** (20kJ/kg)

Limiting the Hot Spot Temperature

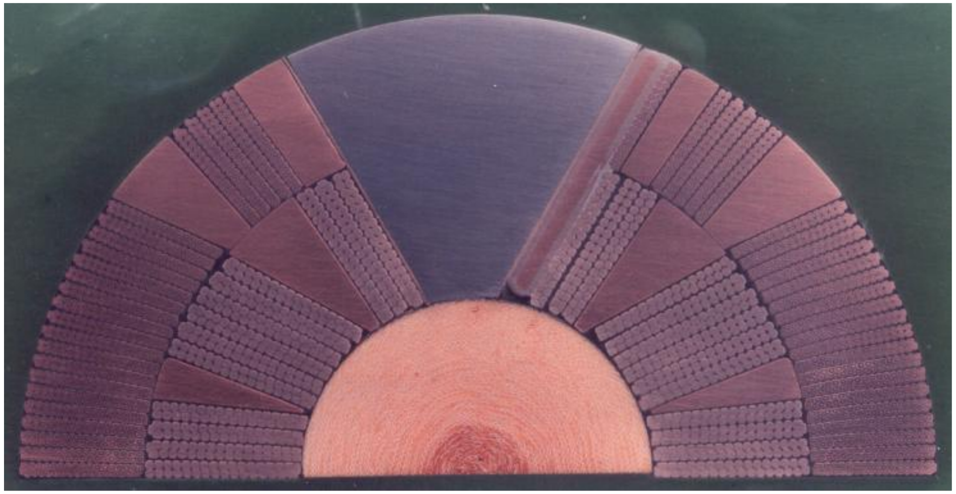
- heat diffusion into
  - cooling cryogen (bath cooling)
  - conductor material: add aluminium



- transverse propagation (turn-to-turn)
  - heat diffusion through multi layer insulation
  - typical speed:
    $V_{//} = 1\text{-}20$ m/s and $V_{\perp} = 10\text{-}100$ mm/s

- accelerate the propagation
  - thermal short cuts
  - heaters (extra MPZ)

- decrease the current



Quench Protection

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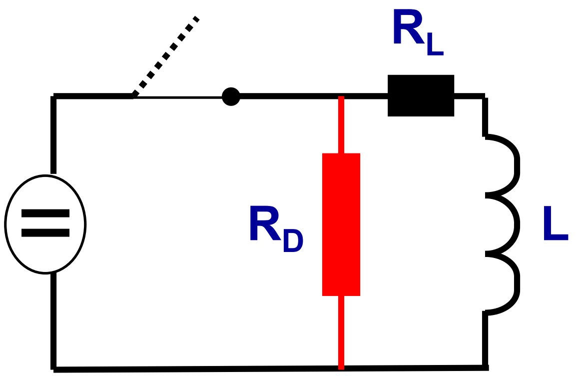
- **Reduction of current**
  - "Time constant" $\tau = L / R$
    can be modified by $R = R_L$ or $(R_D + R_L)$
    - External resistor R_D and
    - Internal resistance of coil after quench R_L



- **External dump, $R_L << R_D$**
  - after *quench detection*, open switch S and the current flows through R_D
  - inclusion R_D decreases the time constant (seconds to minutes range)
  - NOTE: possibly high peak voltage $V = I \cdot R$
- **Internal dump, use of coil resistance $R_L >> R_D$**
  - maximize R_L by artificially heating the coil → create multiple normal zones
  - the time constant is controlled by velocity of normal zone propagation and number of normal zones propagating at the same time
    (e.g. improved heat conductivity)

Quench Detection

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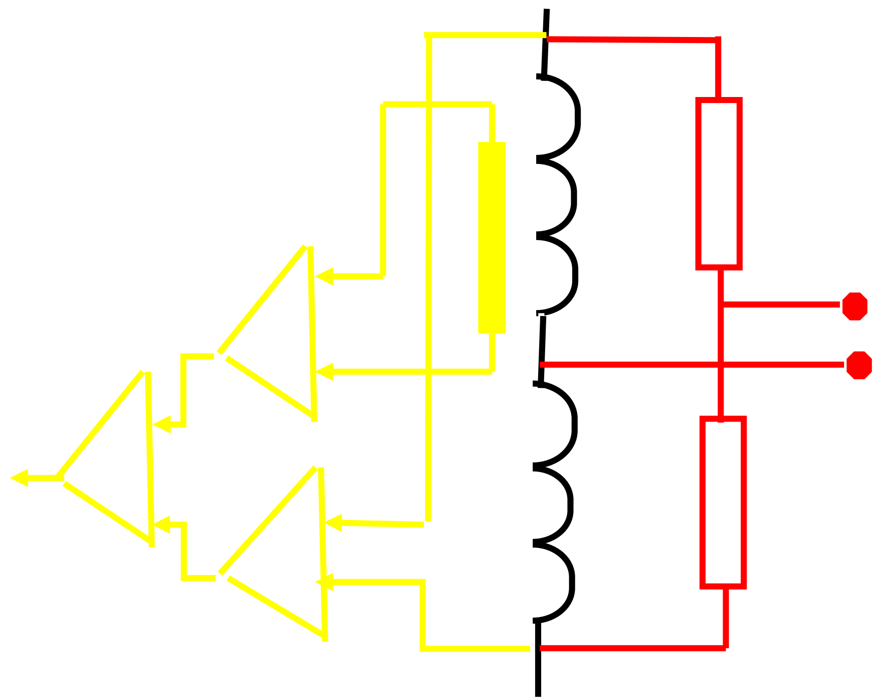
- **Bridge method**
  - detects the resistance in any branch of the coils, very robust, simple and proven
  - commonly used for large magnets
- **Voltage across coil**
  - total voltage across the coil
    - compensated for the inductive component.
  - requires differential amplifiers,
    - more complicated, more electronics
- **Other methods**
  - small superconducting wire or coil (= temperature switch!)
  - temperature
  - pressure, pickup coils, strain sensor, field sensors etc.



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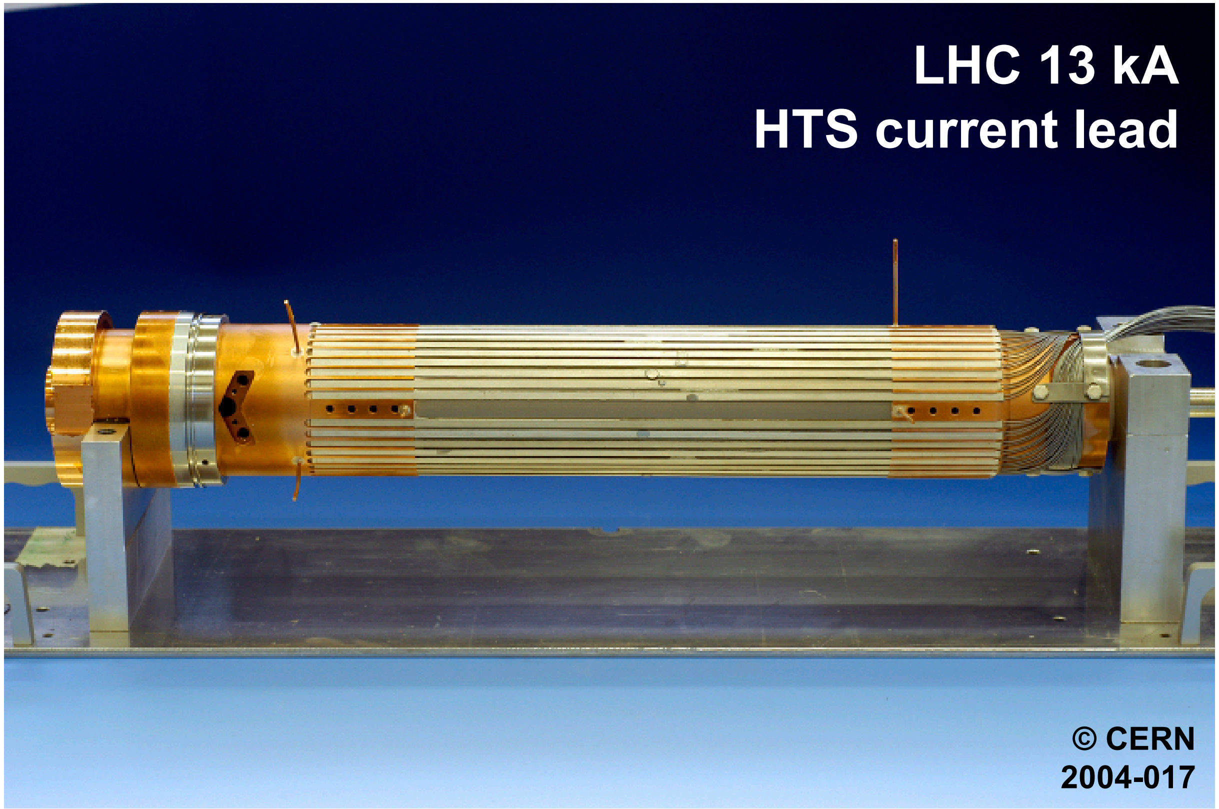
CURRENT LEADS

Current Leads

- connect cold mass (4K) to power converter (300 K)
- copper current lead
  - 1.1 W/kA heat load into liquid helium
- 3x reduction using HTS (10x for HTS part)



LHC Current Distribution Box

- 1182 HTS leads: 600 – 13,000 A
- 2104 copper leads: 60 – 120 A

SUPERCONDUCTING JOINTS

LHC Magnet Interconnection

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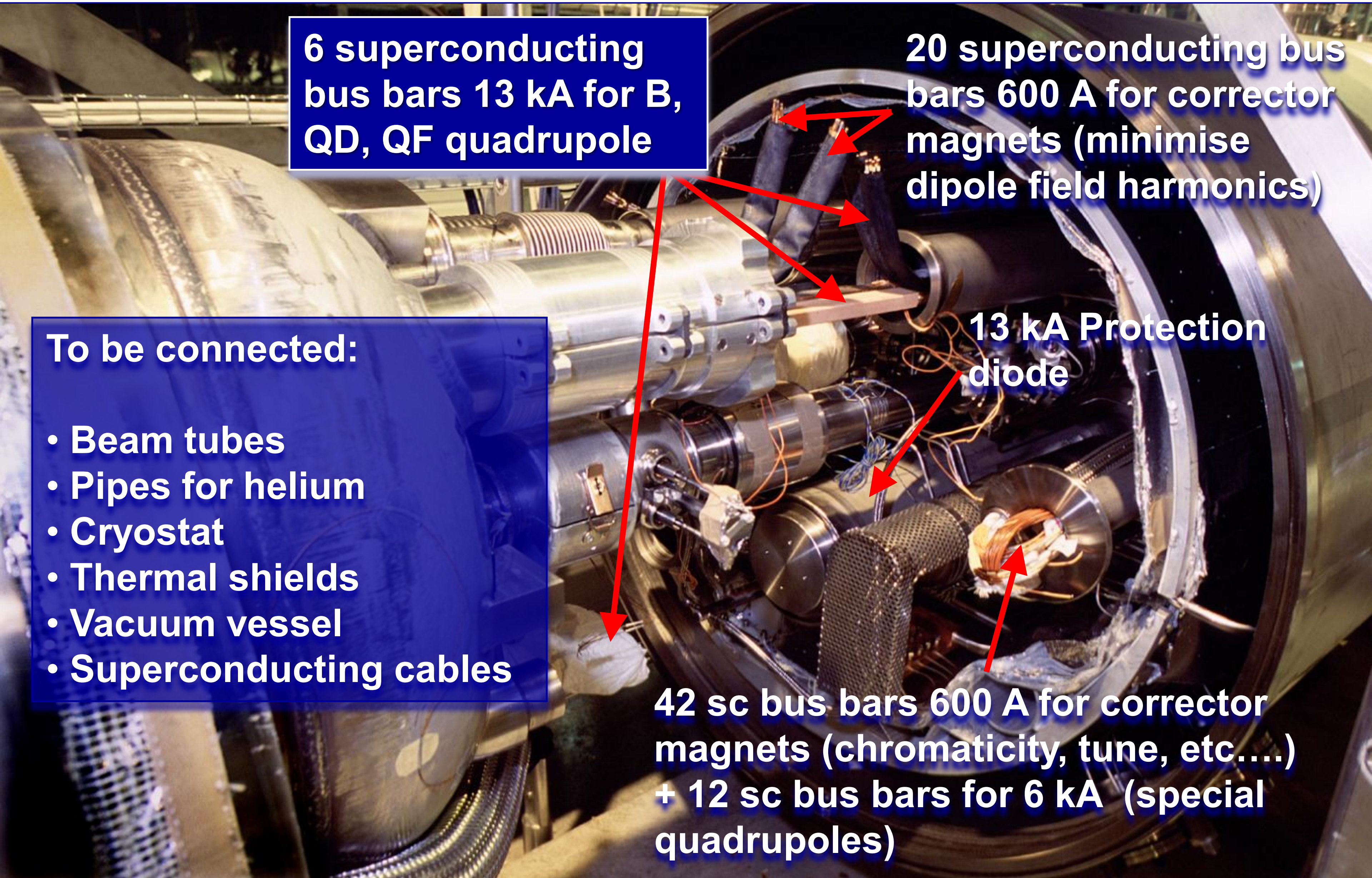
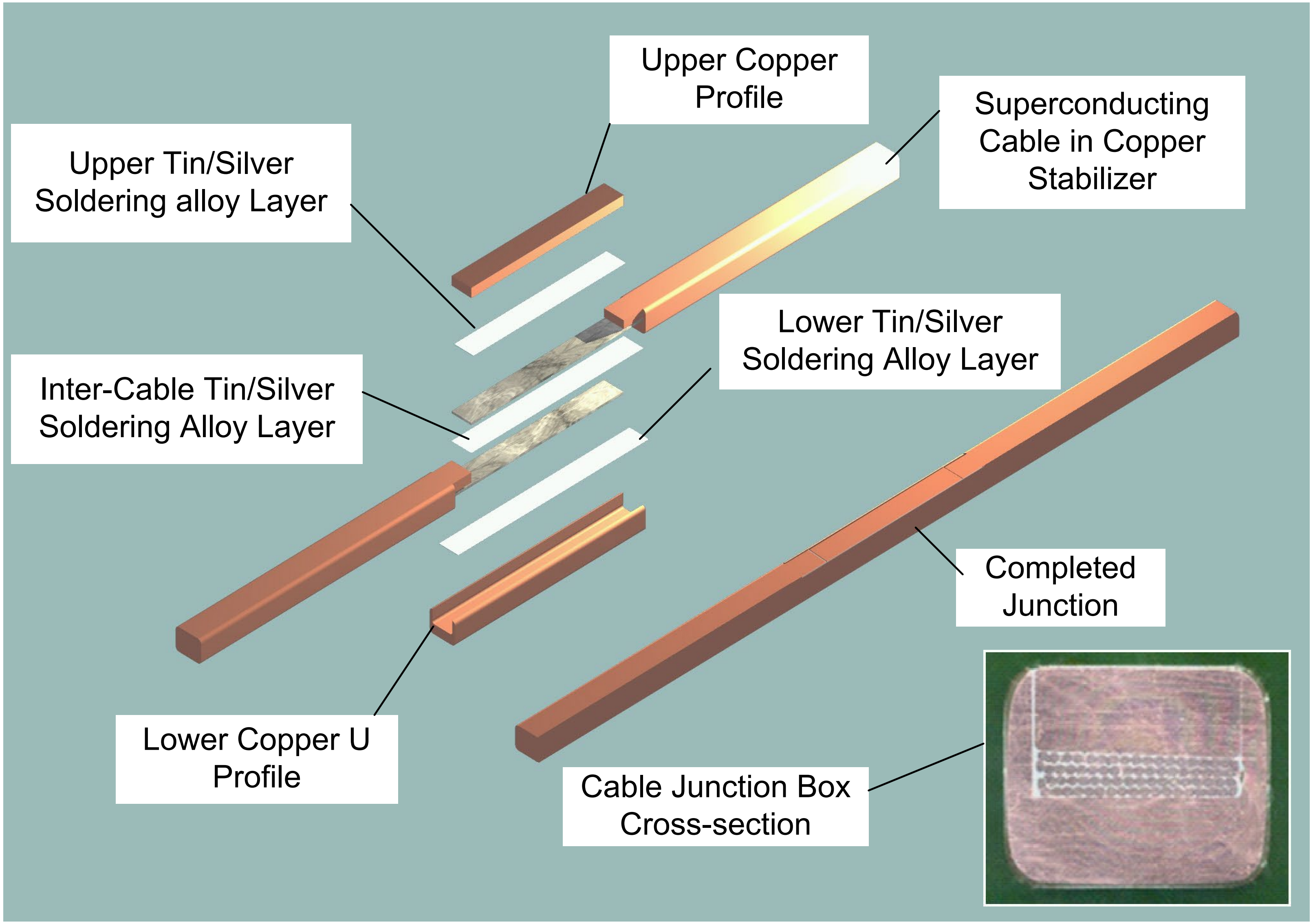


LHC Bus-bar Splice



LHC Bus-bar Splices

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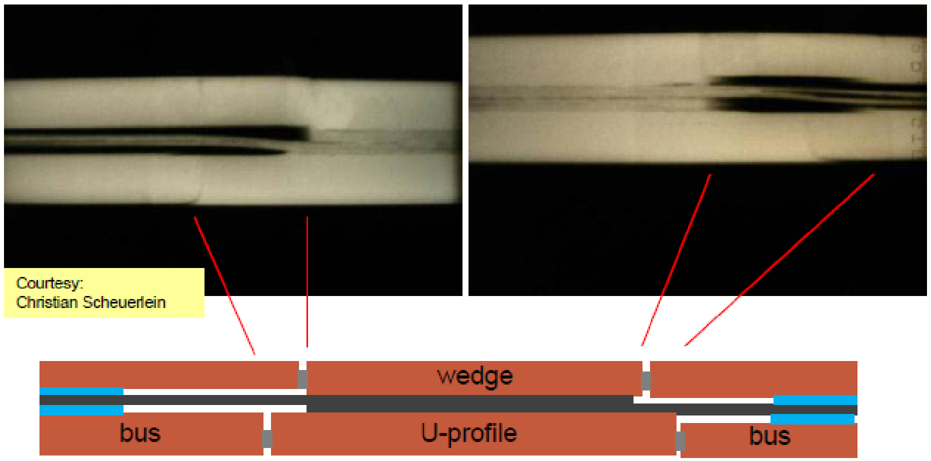
Gamma rays QBBI.B25R3-M3 before disconnection (QRL connection & QRL lyra sides)



A. Verweij, TE-MPE. 28 April 2009, TE-TM meeting

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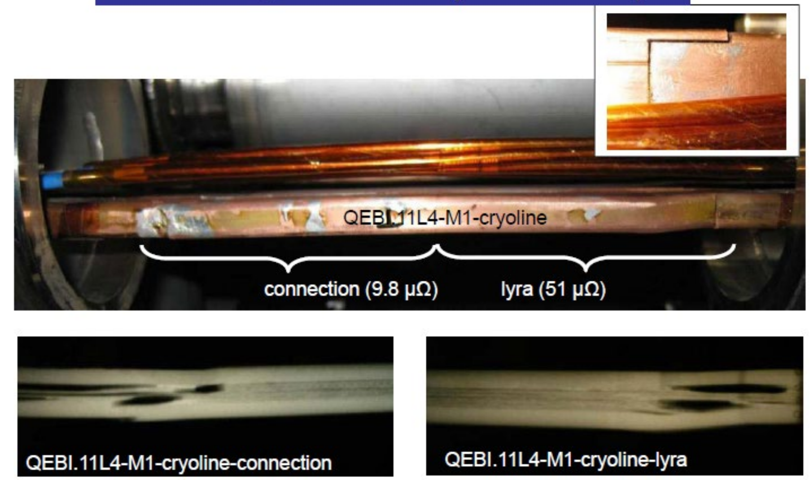
Sector 3-4 : QEBI.11L4-M1-cryoline before repair



C. Scheuerlein TE-MSC

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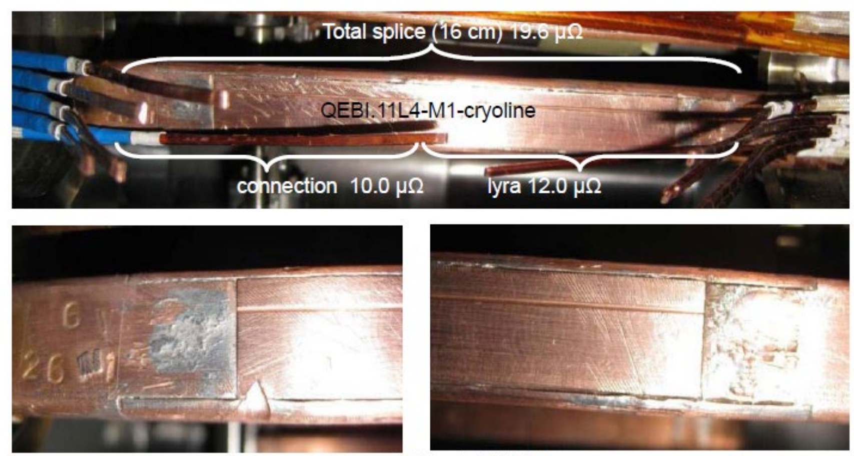
Sector 3-4 : QEBI.11L4-M1-cryoline repaired



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Bad surprise:

- void found in bus extremities
- because SnAg flows out during soldering of the joint

SUMMARY AND INFO

Normal or Superconducting Magnets?

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		Normal Conducting	Superconducting
Field	definition	iron core pole shape	current distribution
	quality	high, defined by iron pole	requires accurate modelling
	errors and hysteresis	iron saturation	filament magnetization
	design soft.	standard commercial	specialized tools
Forces		large	enormous
Operation	cooling	water	cryogenic
	protection	on cooling flow/temperature	specialized system, quench protection
	interconnect	easy	specialized

Conclusions

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- It is not always straight forward to build a (working) magnet.

- Superconducting magnets require extra attention due to the stability criteria and operating margins.
- Quench protection requirements must be strictly observed. If not, the magnet will degrade or die…
- Other aspects, not discussed here, as cooling and insulation, also form an important part.

- The best way to success is to

keep it simple, robust and redundant.

Thanks to many colleagues for text and figures!

Amalia Ballarino, Herman ten Kate, Glyn Kirby, Lucio Rossi, Stephan Russenschuck, Tom Taylor, Arjan Verweij, Martin Wilson and Akira Yamamoto.

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AIR CORE MAGNET DESIGN

The E-M Design; Uniform Magnetic Fields

Field *inside* two *parallel* cylinders is the sum of the fields

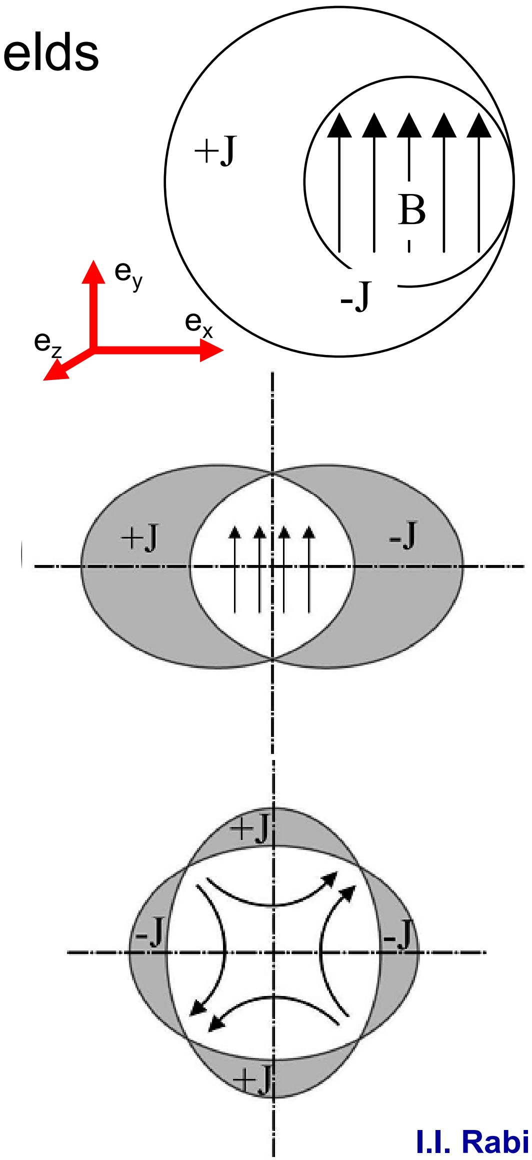
- $\mathbf{B_1} = + \mu_0/2\ \mathbf{J} \times \mathbf{r}_1$
- $\mathbf{B_2} = - \mu_0/2\ \mathbf{J} \times \mathbf{r}_2$

$\mathbf{r_1}, \mathbf{r_2}$ position vector of point relative to origin (on the axis) of each cylinder

Vector $(\mathbf{r_1} - \mathbf{r_2}) = d\mathbf{e_x}$ constant normal to **J**

$\rightarrow$ $\mathbf{B_1} + \mathbf{B_2}$ **uniform field, linear with J**
in current free region (overlap).

$$\mathbf{B} = \frac{\mu_0 J d}{2} \mathbf{e_y}$$



Current distribution $\mathbf{J} \propto \cos n\theta$

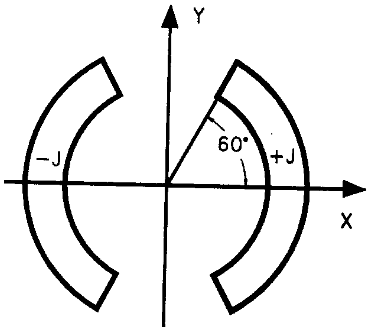
- n = 1: dipole field, 2 ellipses
- n = 2: quadrupole, 2 ellipses
- n = 3: sextupole, 3 ellipses

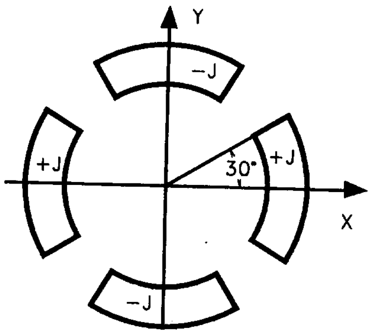
Ideal for high field quality $^{dB}/_{B} < 10^{-4}$

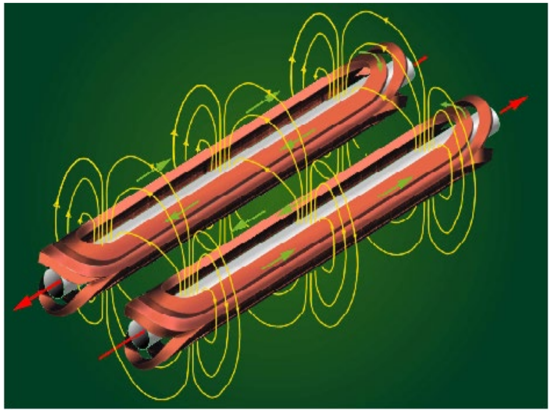
I.I. Rabi, Rev. Sci. Instr. 5 (1934) 78.

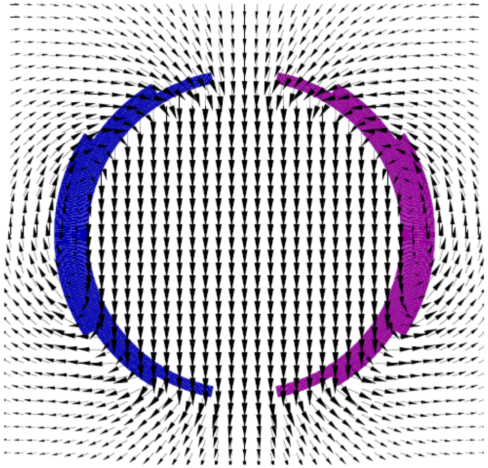
How to Build a cos(θ) Distribution?

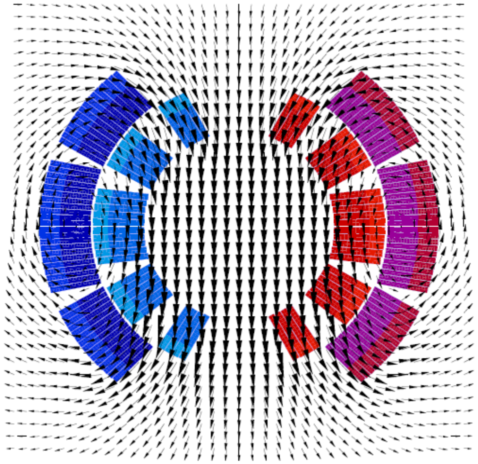
- uniform shell current density will cut the first higher order harmonic
- approximation of cos(θ) distribution with multiple shells (left: b_3=b_5=b_7=0) and coil blocks

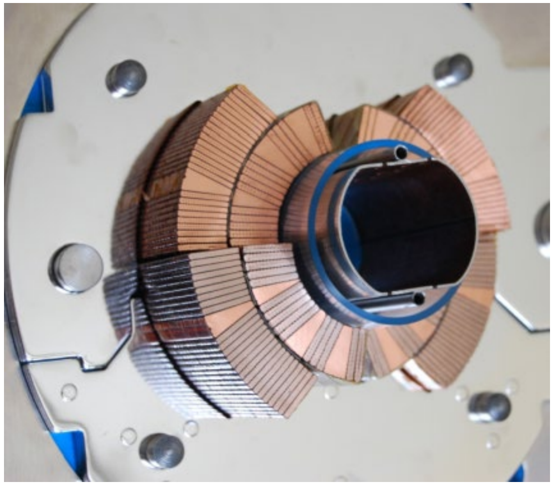












Field Quality Inside the Aperture

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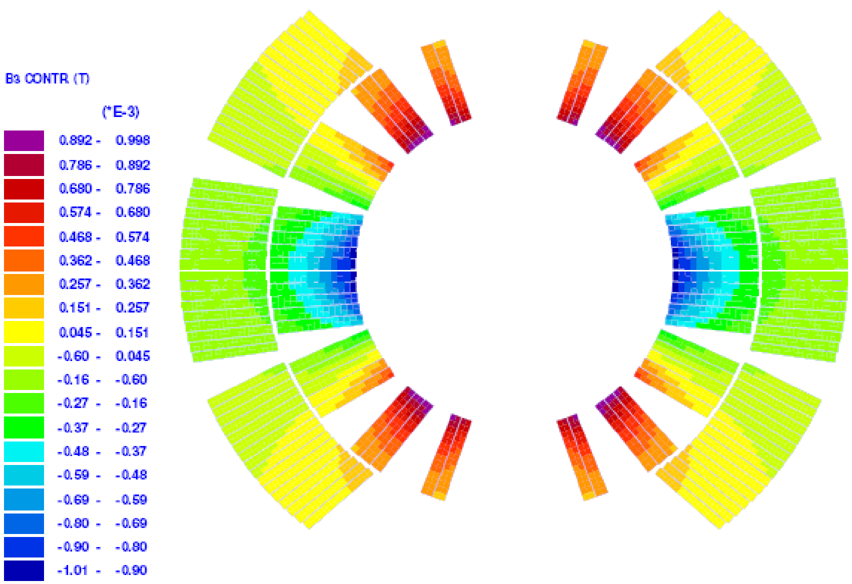
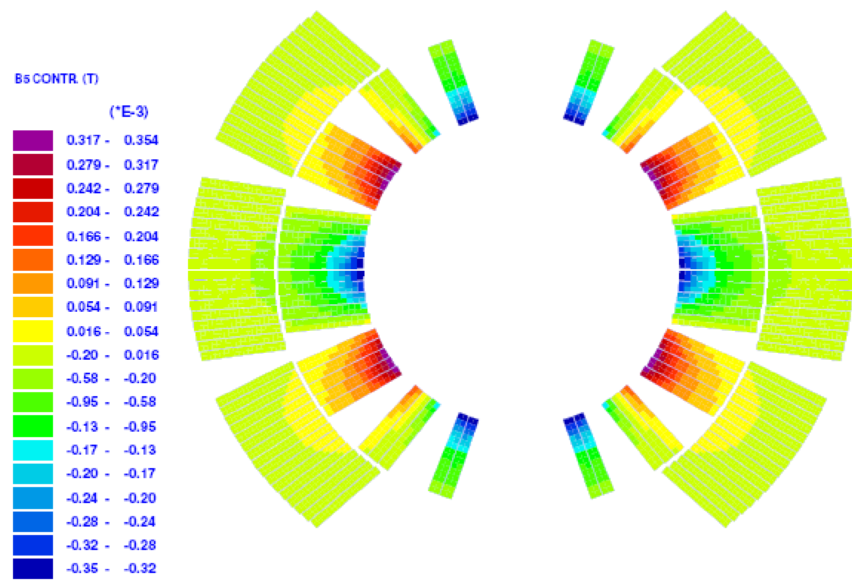
- need high quality field for beam handling ($dB/B < 10^{-4}$)!
- multipole coefficients enable calculation of the field
- higher order multipoles give field "errors"
  - effect shown below as contribution per cable
  - scaling with $1/r^n$ (r = mid radius of the coil)





Coil Fields: Current Dominated Field Shape

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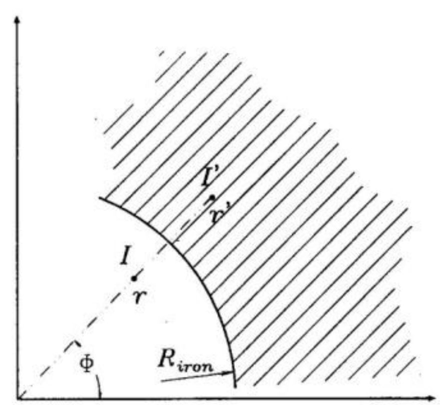
- air core coil (w/o iron) possible direct analytical solution

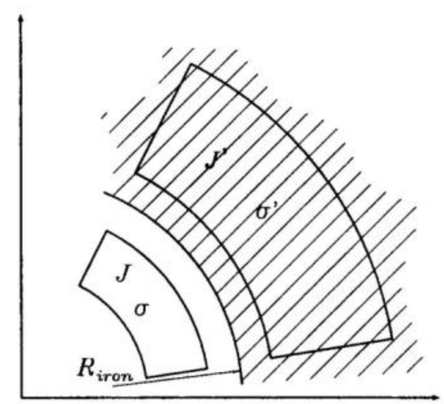
$$\mathbf{B} = \frac{\mu_0}{4\pi} \int_V \mathbf{J} \times \frac{\mathbf{r}}{r^3} \, dv$$

- iron yoke used to contain stray fields, current imaging method (magnetic mirror) may be used (if iron shape respects symmetry of the problem)

$$I' = \frac{\mu_\mathrm{r} - 1}{\mu_\mathrm{r} + 1} I$$

$$r_i' = \frac{R_\mathrm{yoke}^2}{r_i}$$





FIELD MEASUREMENT

Hall Probe Field Measurement

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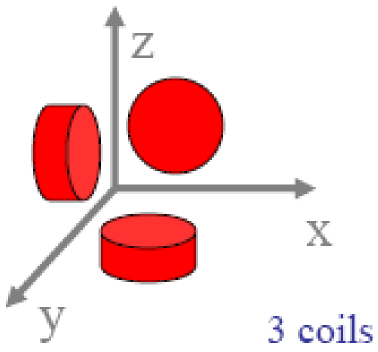
Hall Probe

- semiconductor, uses Hall effect
- change Hall current for different measurement ranges
- potential voltage difference by magnetic field *perpendicular* to current flow

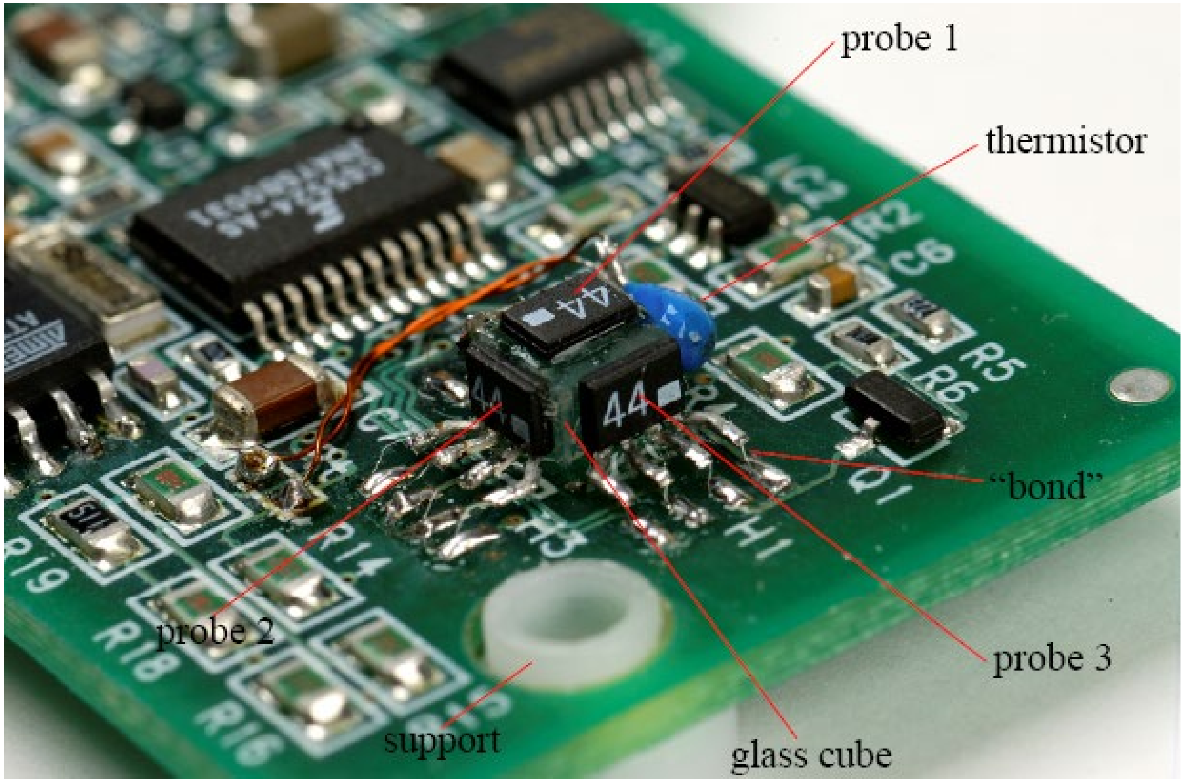


calibration coefficient depends on

- field direction
- material

best achieved

- accuracy ±1 %
- precision ±0.1 mT



Derivation Field in Multipole Coefficients

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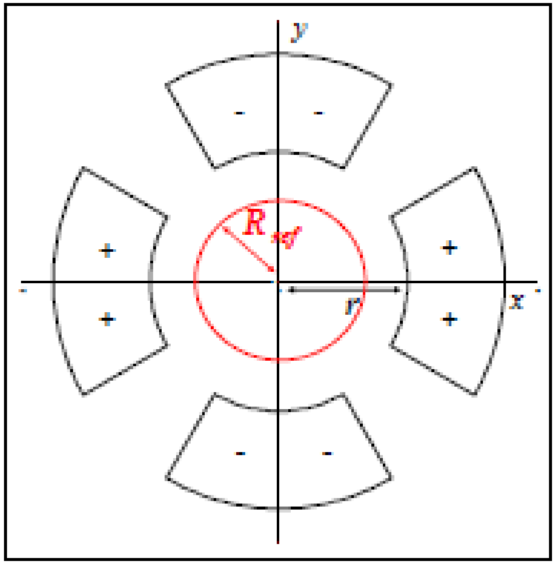
- Hall probe measures x-y-z components
- Dipole, quadrupole, … components are prefered

Derive the multipoles from the field components:

- write coordinates of field components as imaginary number
- Taylor expansion gives a_n and b_n multipole coefficients
  - B_1 = main dipole field
  - a_n = skew component
  - b_n = normal component

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$



Rotating Harmonic Coil

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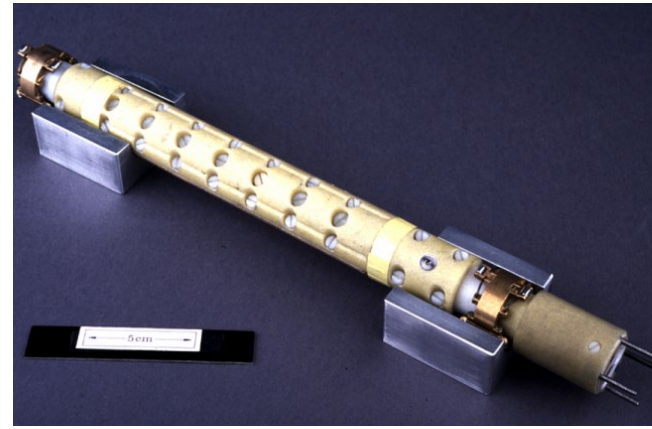
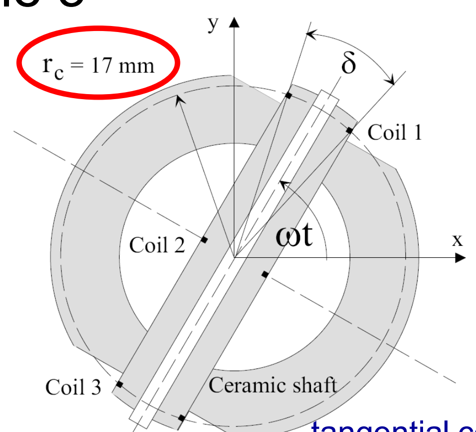
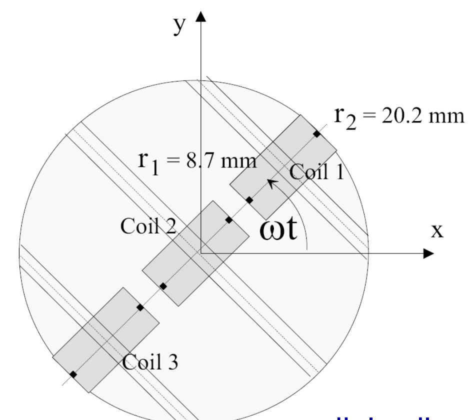
periodic flux variation induces voltage

- measures radial field component B_r
- at *reference radius* r_c
- angular rotation + position Φ = ωt+θ
- tangential coil is blind for multipole n if 2π/n equals the opening angle δ of the measurement coil (use radial coil)





tangential coil



radial coil

Induced voltage:

$$U(t) = -\frac{\mathrm{d}\Phi}{\mathrm{d}t}$$

$$= \sum_{n=1}^{\infty} 2NLr_c\omega \sin(\frac{n\delta}{2})[-B_n(r_c)\underline{\cos(n\omega t + n\Theta)} + A_n(r_c)\underline{\sin(n\omega t + n\Theta)}]$$

- cosinus / sinus shape for normal (θ=0) / skew (θ=π/2) field direction

Normal and Skew Multipoles

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Fourier expansion of field at reference radius r_0 and angle Φ (inside the bore: no currents, no iron)

$$B_r(r_0,\varphi) = \sum_{n=1}^{\infty} (\underbrace{B_n \sin n\varphi}_{\text{normal}} + \underbrace{A_n \cos n\varphi}_{\text{skew}}) = B_N \sum_{n=1}^{\infty} (b_n \sin n\varphi + a_n \cos n\varphi)$$

$$B_\varphi(r_0,\varphi) = \sum_{n=1}^{\infty} (B_n \cos n\varphi - A_n \sin n\varphi) = B_N \sum_{n=1}^{\infty} (b_n \cos n\varphi - a_n \sin n\varphi)$$

Normal multipole $B_n(r_0)$ and *skew* multipole $A_n(r_0)$

Given in units of tesla, at reference radius r_0.

Relative normal $b_n(r_0)$ and skew multipoles $a_n(r_0)$

Relate to the *main field component* $B_N(r_0)$

- N=1,2,… = dipole, quadrupole, …
- Dimensionless, given in *units* of 10^{-4}.