Lecture 14
Superconducting Magnets

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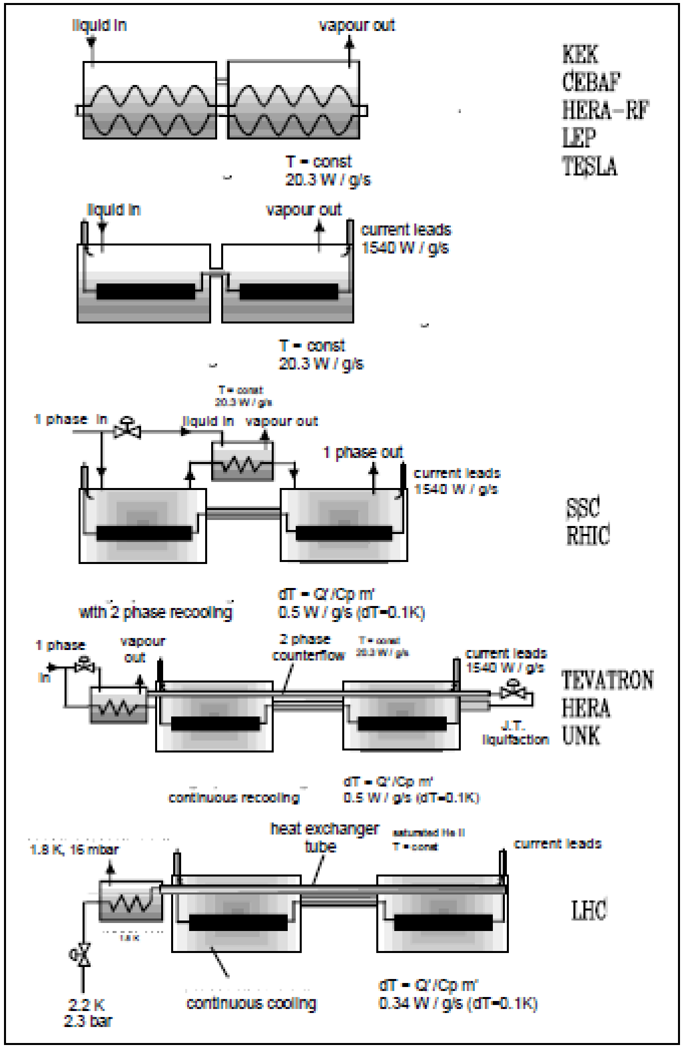
Goals

- Describe the basics of superconducting magnet design
  - Cooling approaches
  - Stability
  - Quench detection & protection
- Illustrate superconducting magnet design by reviewing 2 case studies: The LHC dipole magnets and the BaBar detector solenoid
- Note that many of the slides here have been graciously provided by L. Bottura of CERN.

Magnet Cooling Options

- There are a variety of ways to provide cooling for superconducting magnets. These include:
  - Saturated Bath cooling in He I or He II
  - Subcooled baths of He I (Tevatron) or He II (LHC)
  - Forced flow cooling of Cable-in-Conduit Conductors (CICC) by supercritical helium (many Tokamak magnets)
  - Indirect cooling via conduction from a forced flow of helium through a cooling channel (BaBar solenoid) or by a small cryocooler

Examples of Various Magnet Cooling Options

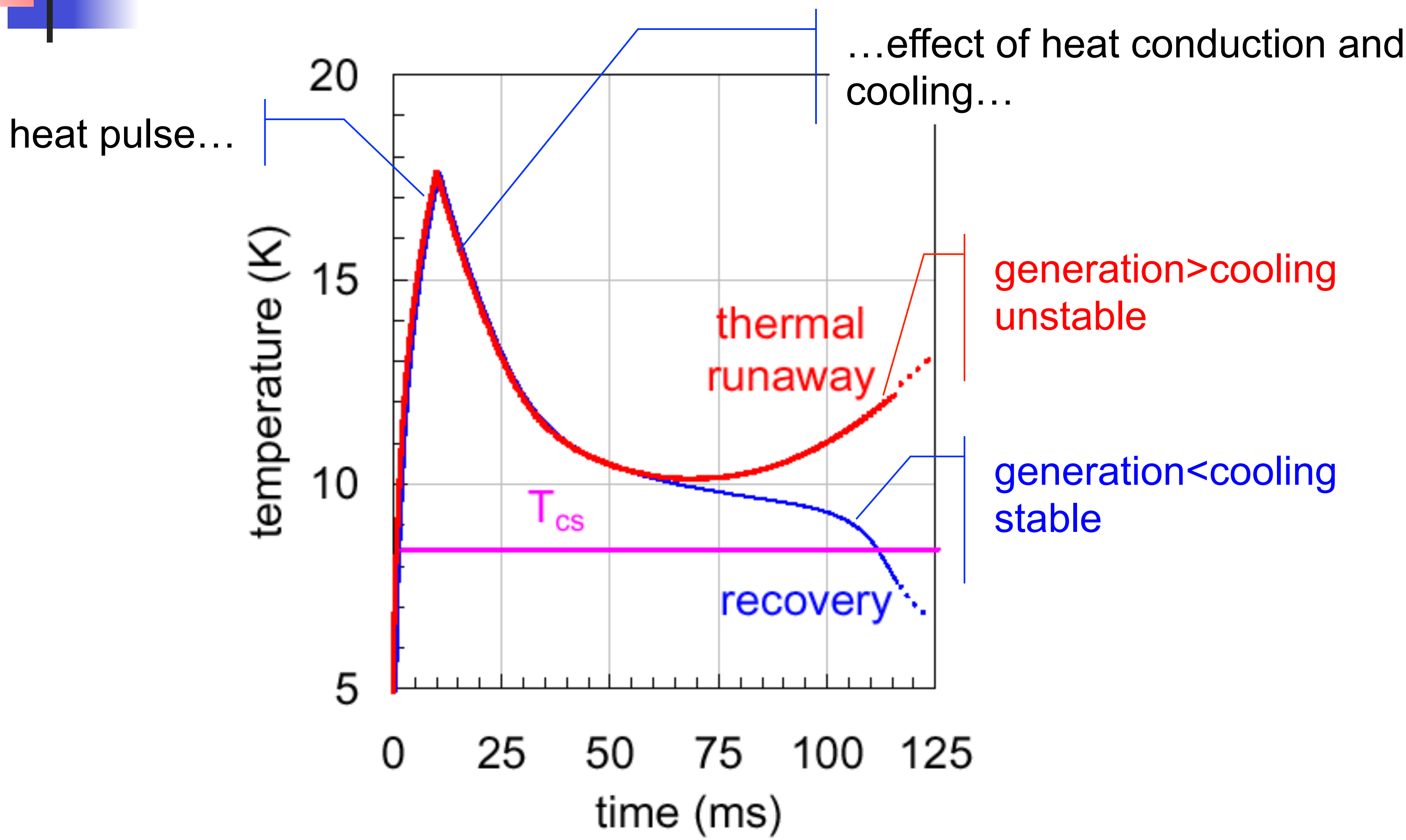


From: "Technology of Cryogenics for Storage Rings"
H. Lierl, EPAC 98

Stability of Superconducting Magnets

- When a wire in a s/c magnet undergoes a temperature rise, there are 2 possibilities:
  - It can cool back down and remain superconducting
  - It can warm up above Tc and “quench” (become normally conducting in all or most of the magnet)
- Which one occurs depends on the amount of heat generation and cooling

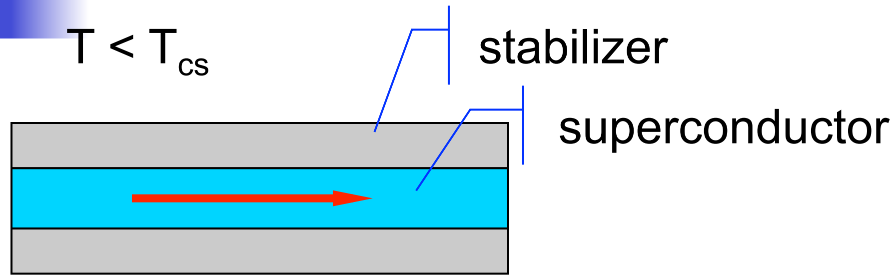
A prototype temperature transient

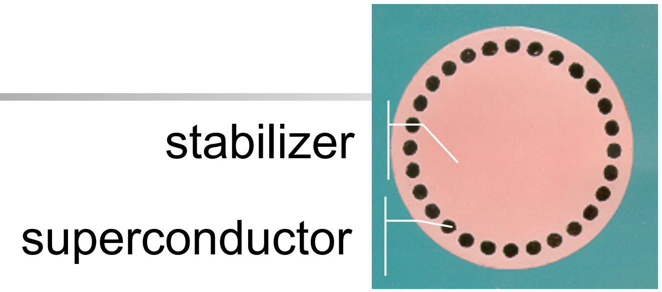


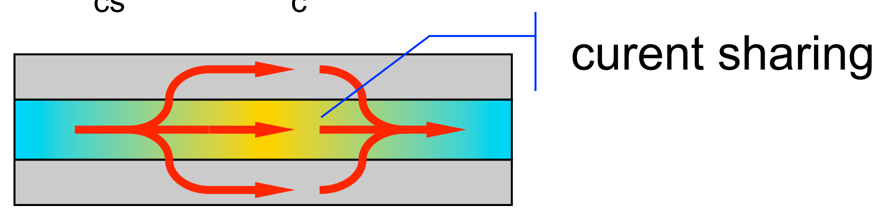
Perturbation spectrum

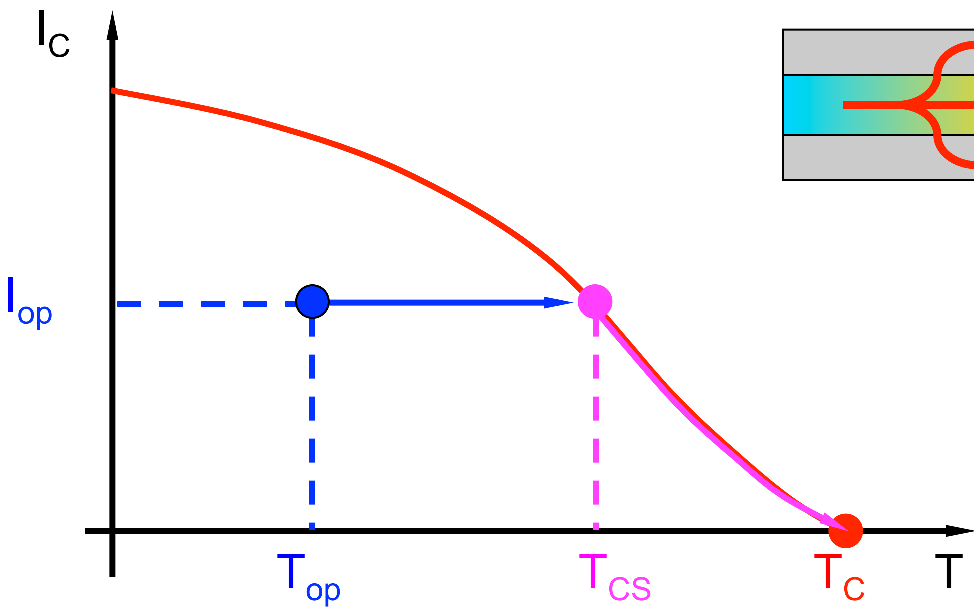
- mechanical *events*
  - wire motion under Lorentz force, micro-slips
  - winding deformations
  - failures (at insulation bonding, material yeld)
- electromagnetic *events*
  - flux-jumps (important for large filaments, old story !)
  - AC loss (most magnet types)
  - current sharing in cables through 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, separator magnets

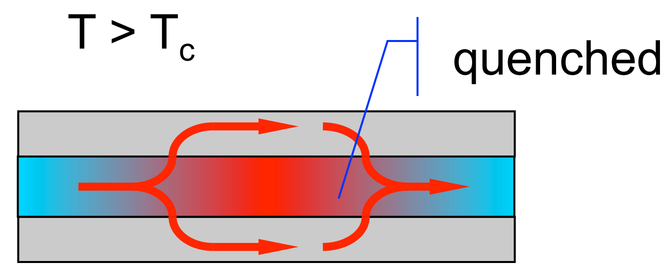
Current sharing







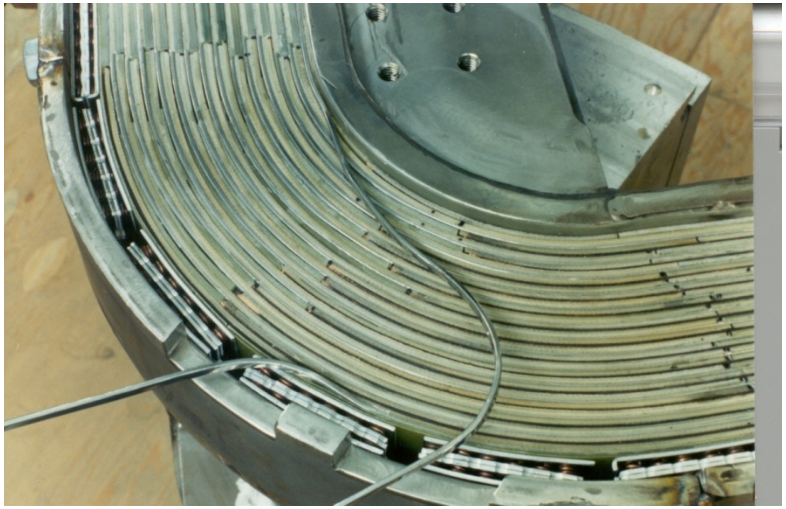




Stability of Superconducting Magnets

- Fully cryostable: magnet will recover regardless of size of normal zone (disturbance) May be true of large detector magnets e.g BaBar detector or MRI magnets, but generally magnets are conditionally stable up to some heat input level.
- Adiabatic stability: magnet will recover if heat input is not too big – more typical of accelerator magnets or potted-coil magnets

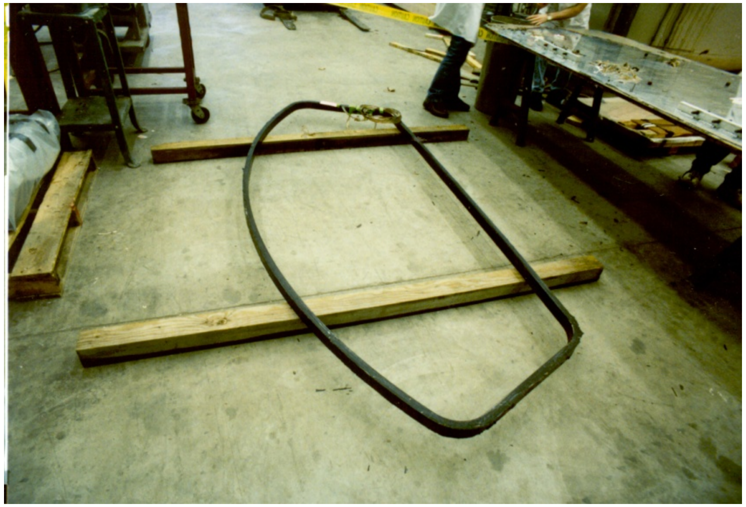
Stability of Superconducting Magnets(2)



Why not make all magnets cryostable?

S800 dipole coil

A1900 dipole coil



S800 dipole coil took 6 weeks to wind
A1900 dipole coil took 2 days

Criteria for Fully Cryostable Magnets

- Stekley Criteria – most conservative, doesn't account for end cooling

$$\alpha = \frac{\rho I^2}{hPA(T_c - T_b)}$$

$\alpha < 1$ magnet is stable

- Equal area theorem
  - Takes into account the cooling of the conductor via conduction at the ends
  - Can be expressed as a graphical solution comparing the areas under the cooling and heating curves (see references)

Lund University

Quench Detection & Protection

European Spallation Source

- Superconducting magnets store large amounts of energy either individually (20 MJ for the Babar detector magnet) or connected in series (10's of GJ)
- If all the energy is deposited in a small volume, bad things happen!

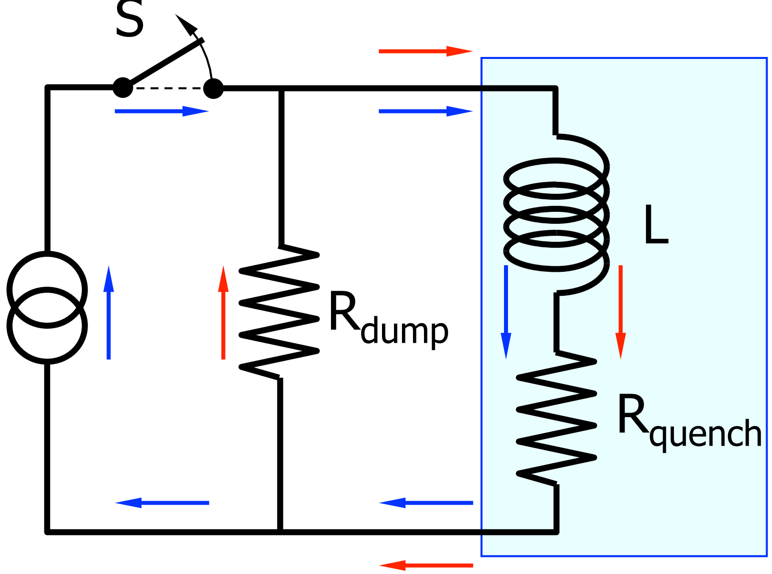
Quench Detection & Protection

- The goal is to rapidly and accurately detect the quench and safely dispose of the energy
  - Spread throughout the magnet
  - In an external dump resistor
  - In a coupled secondary
  - In magnet strings, bypass the energy of the other s/c magnets away from the quenching one
- Remember it's the stored energy in the magnet(s) not the power supply that's problem (S/C magnet power supplies are low voltage, high current, so increased resistance in a quenched magnet prevent further power input)

Detecting Quenches

- Can't just measure voltage directly as magnet ramping causes voltage and give a false signal
- The general approach is to subdivide the magnet with voltage taps and build a bridge circuit that cancels out voltage due to ramping
- Redundant QD systems are necessary
- Other measurements such as temperature, helium level or vacuum level might be used to look for precursors to trouble but take care not to "over interlock the magnet"
- HTS magnets are of special concern due to slow quench propagation, so sensitive QD required

Strategy: energy dump



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

normal operation

quench

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

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

- the integral of the current:

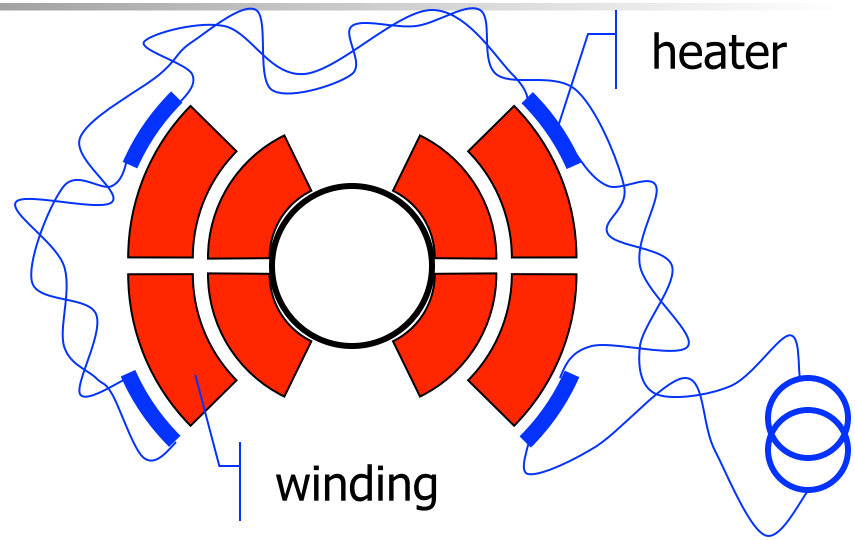
$$\int_0^\infty J^2 dt \approx J_{op}^2 \left(\tau_{detection} + \frac{\tau_{dump}}{2} \right)$$

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

Strategy: heaters

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

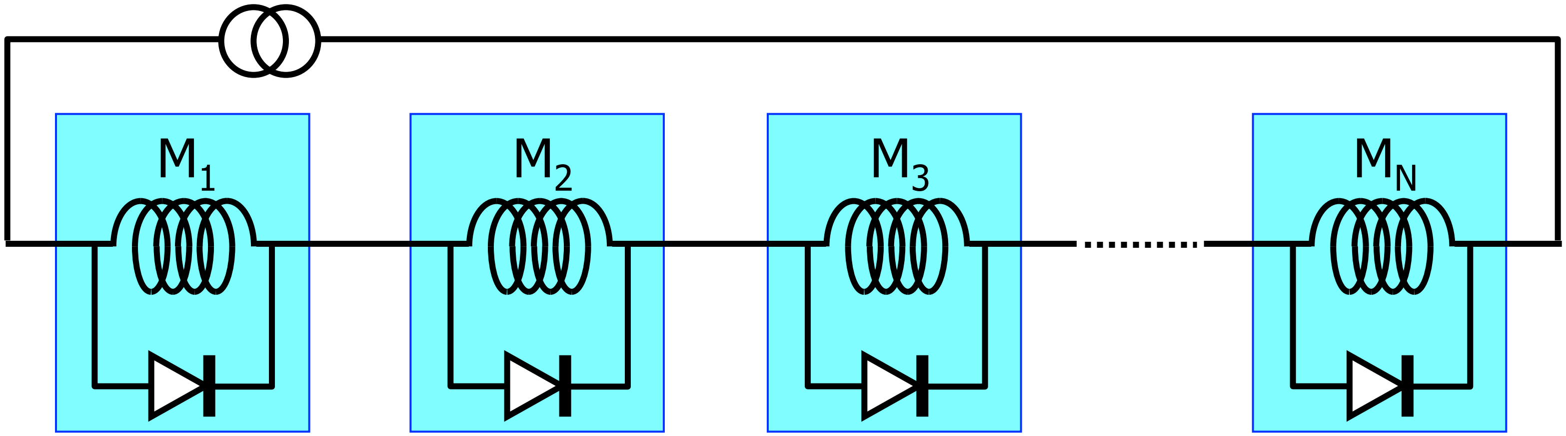
- heaters are mandatory in:
  - high performance, aggressive, cost-effective and highly optimized magnet designs (high current density)…
  - …when you are really desperate



- advantages:
  - homogeneous spread of the magnetic energy within the winding pack
- disadvantages:
  - active
  - high voltages at the heater
  - Doesn’t work well with highly stable magnets

Magnet strings

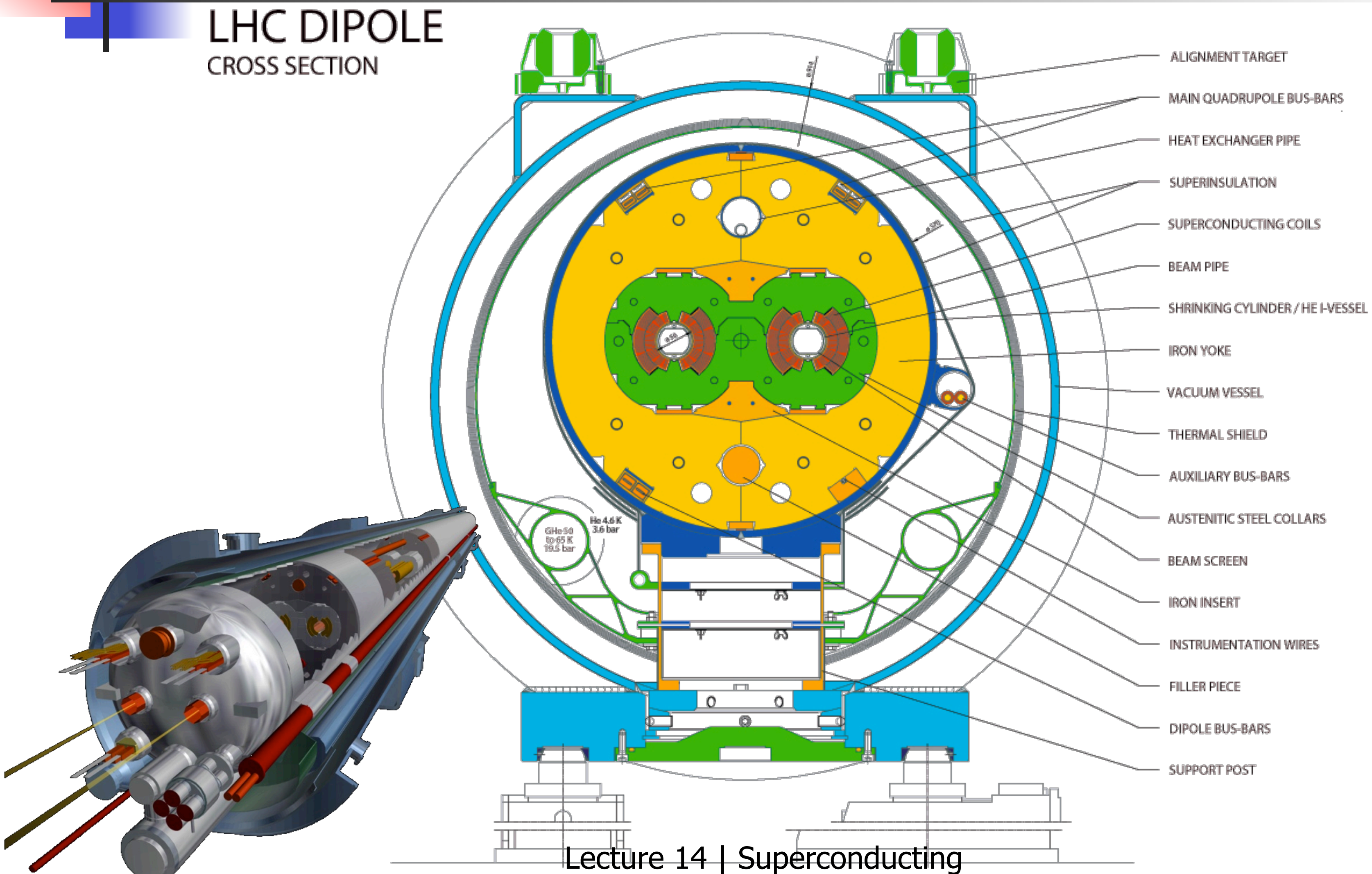
- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
  - energy dump takes very long time (10…100 s)
  - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
  - the diode acts as a shunt during the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



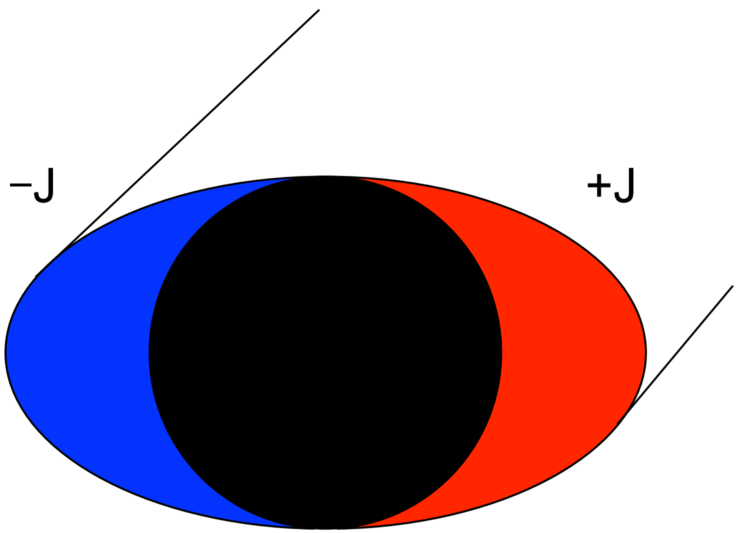
EXAMPLE # 1

LHC dipole

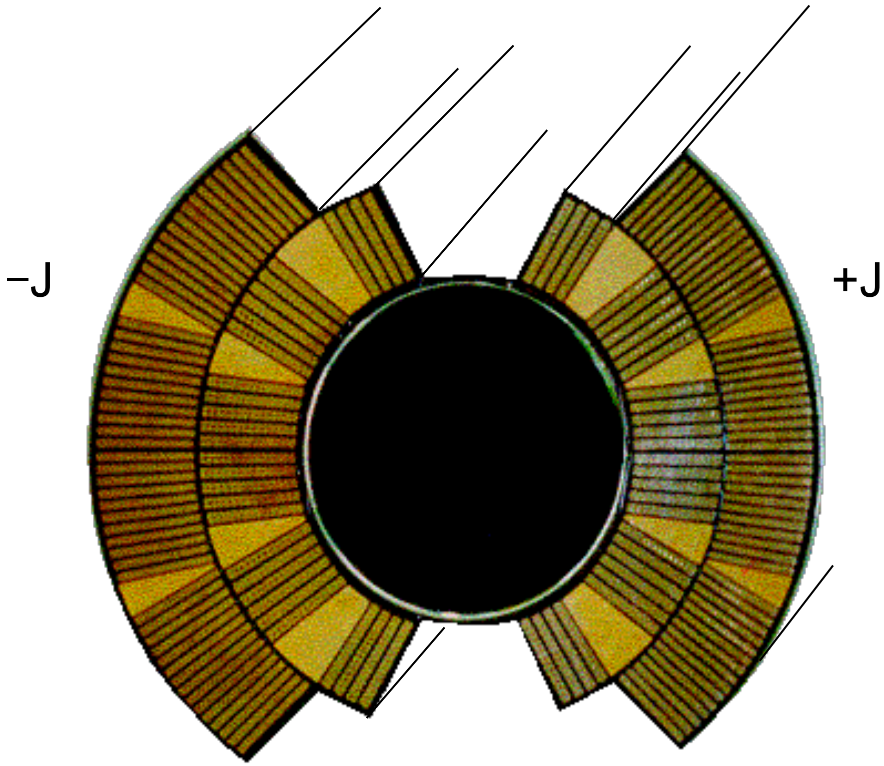
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 8	(MJ)
cold mass	≈ 35	(tonnes)



Superconducting dipole magnet coil

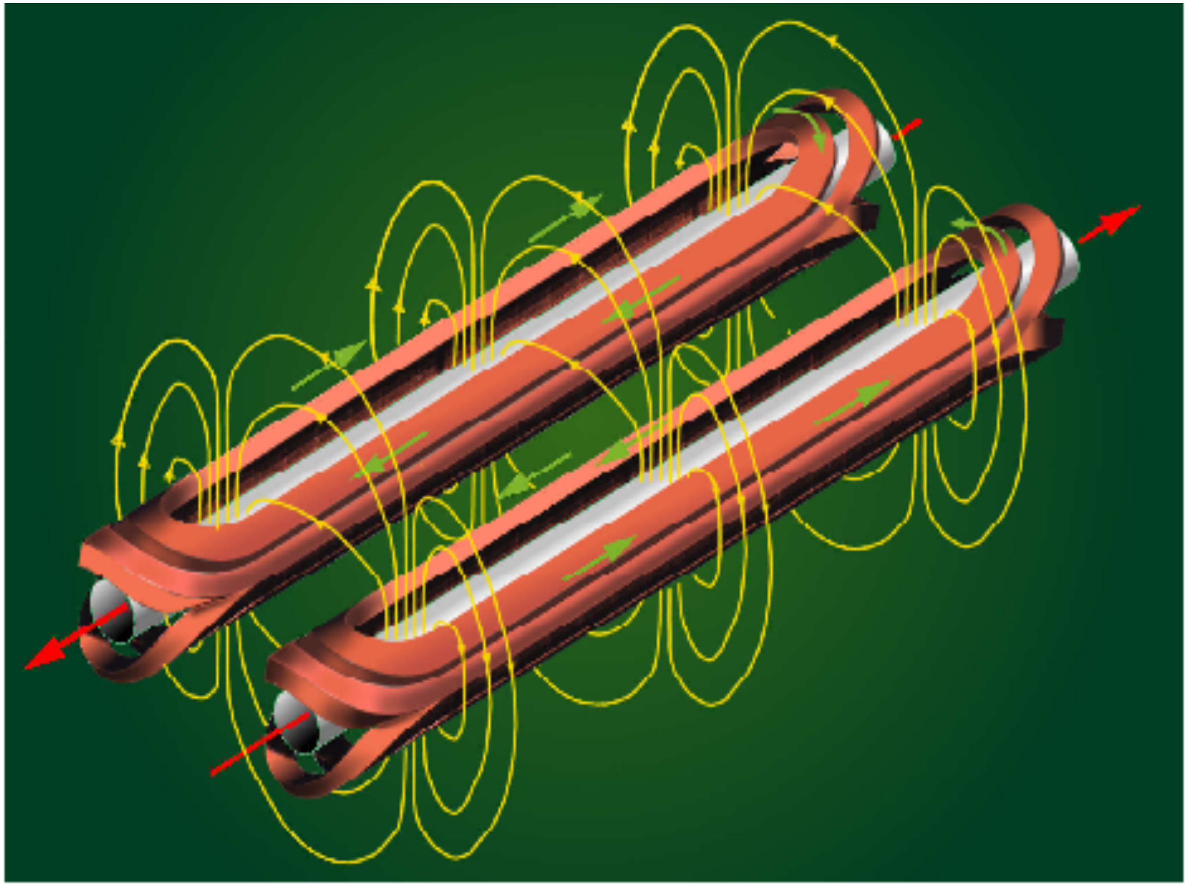


Ideal current distribution that generates a perfect dipole "Cos Θ"



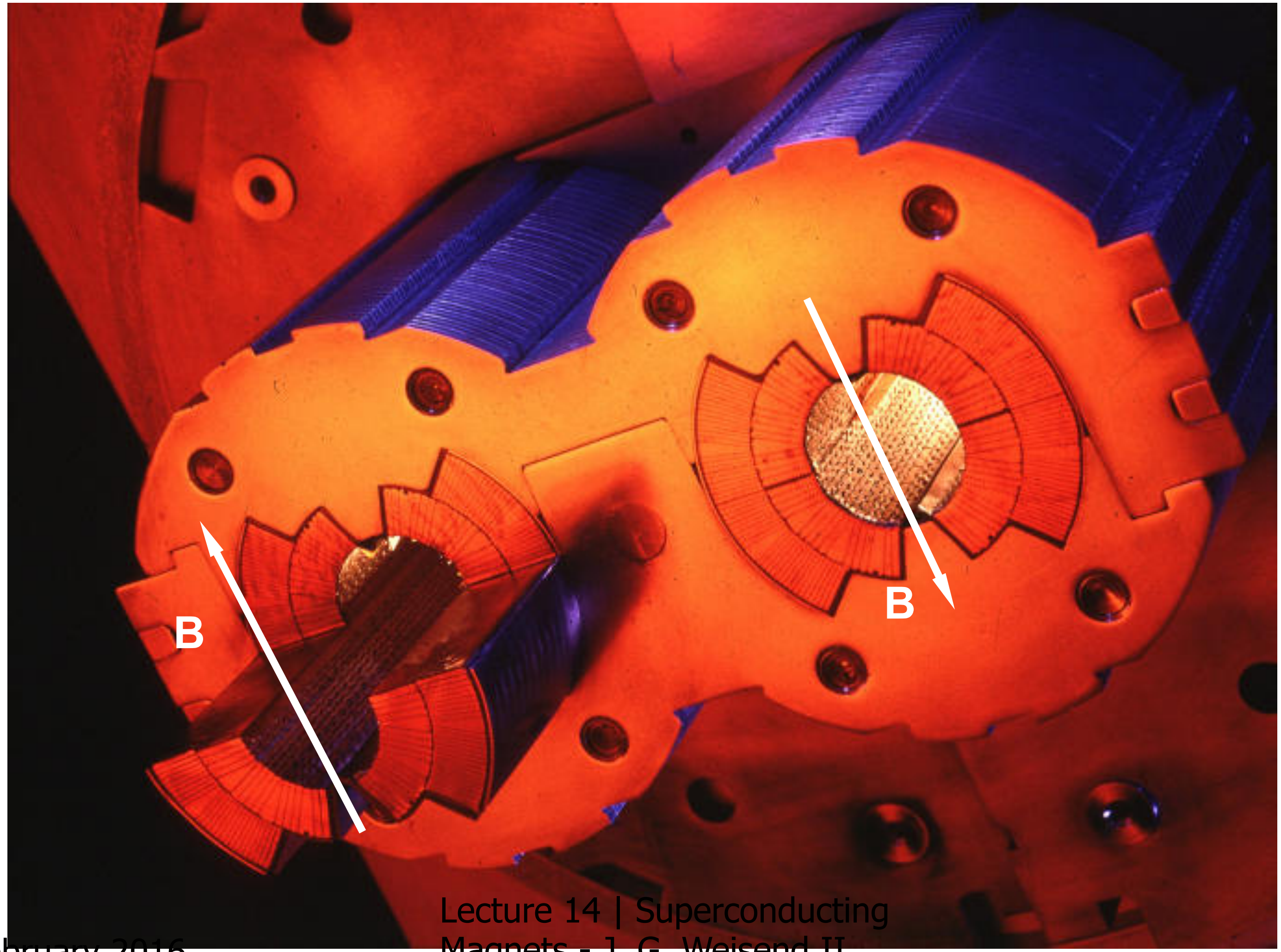
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle



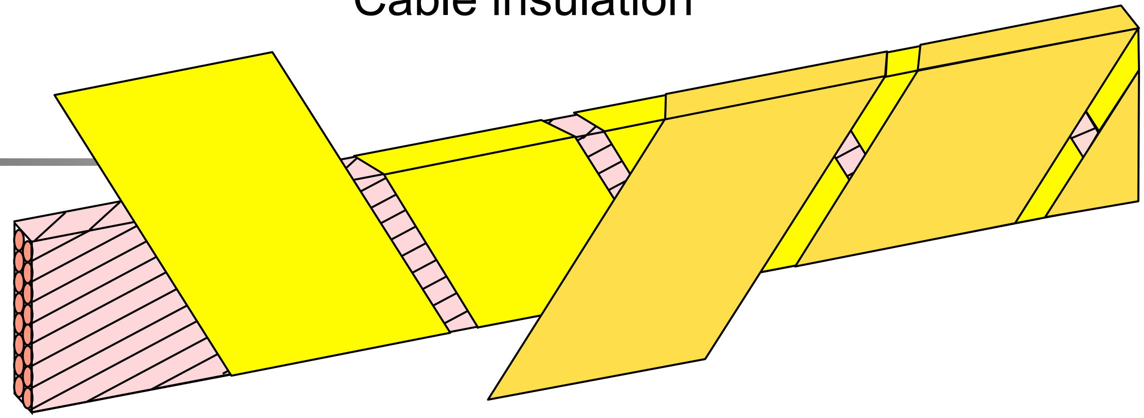
Combine two magnets in one
Save volume, material, cost

LHC dipole coils

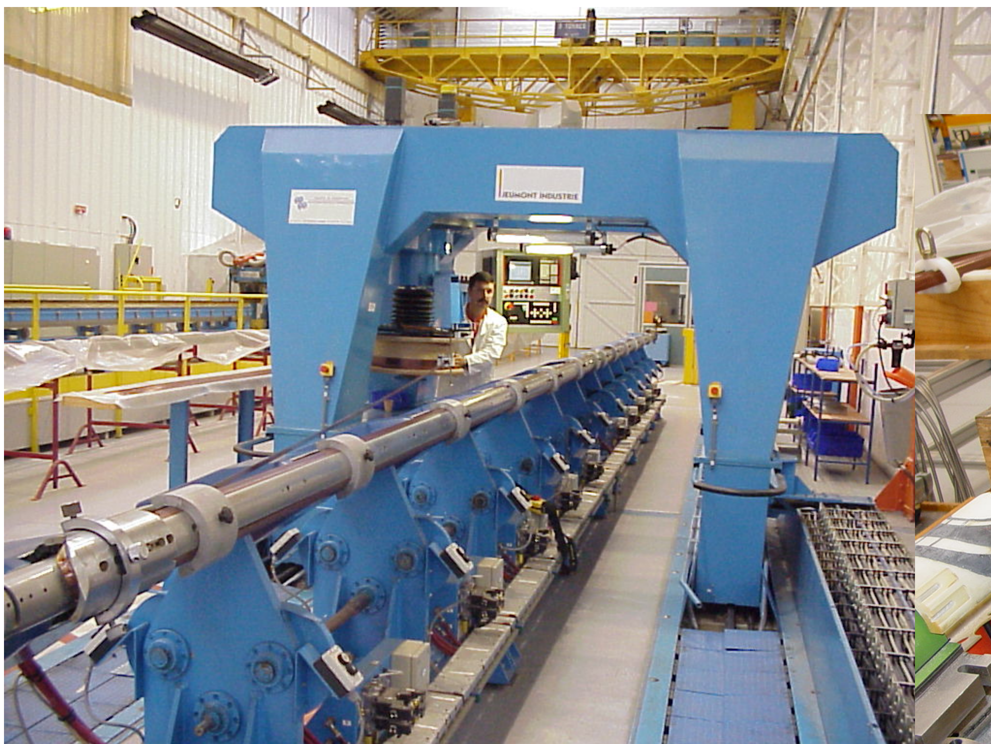


Coil winding

Cable insulation



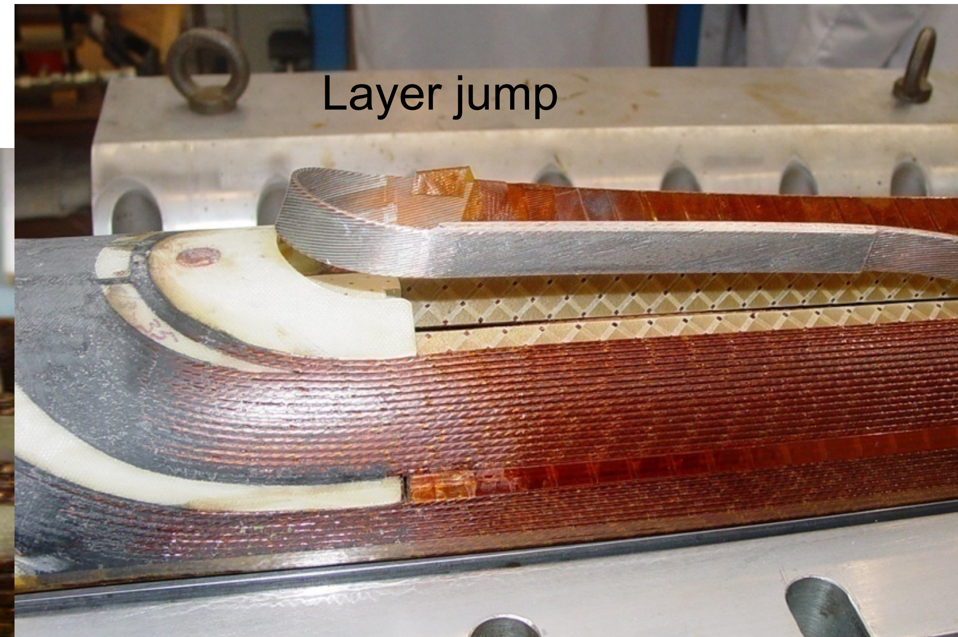
10 μm precision !

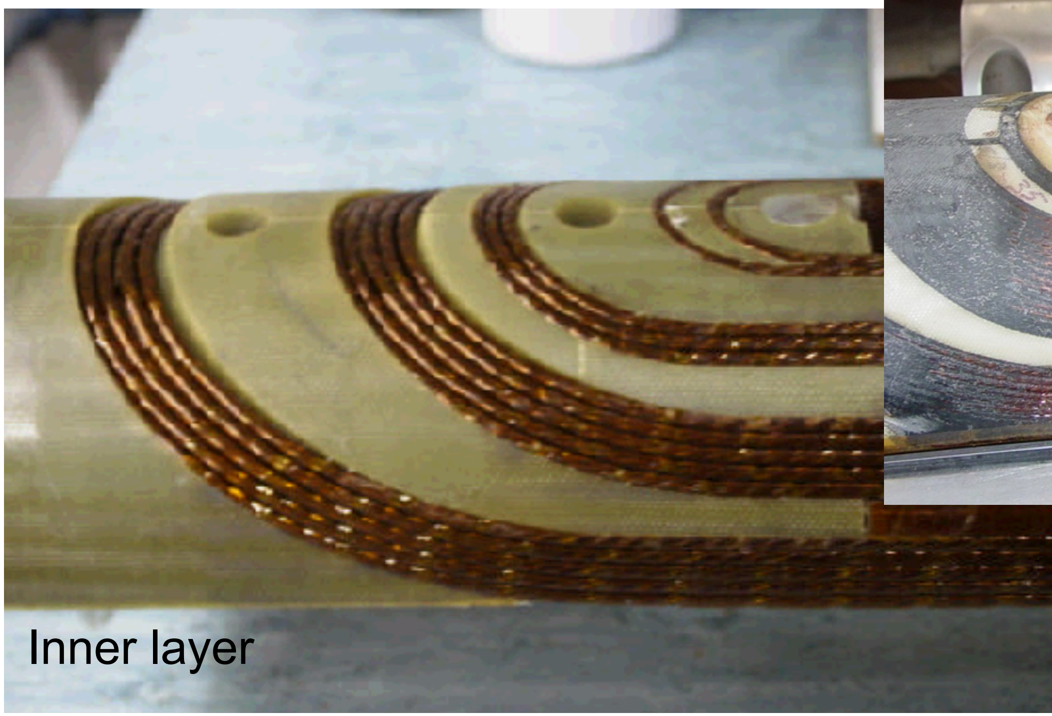


Coil winding machine

Stored coils

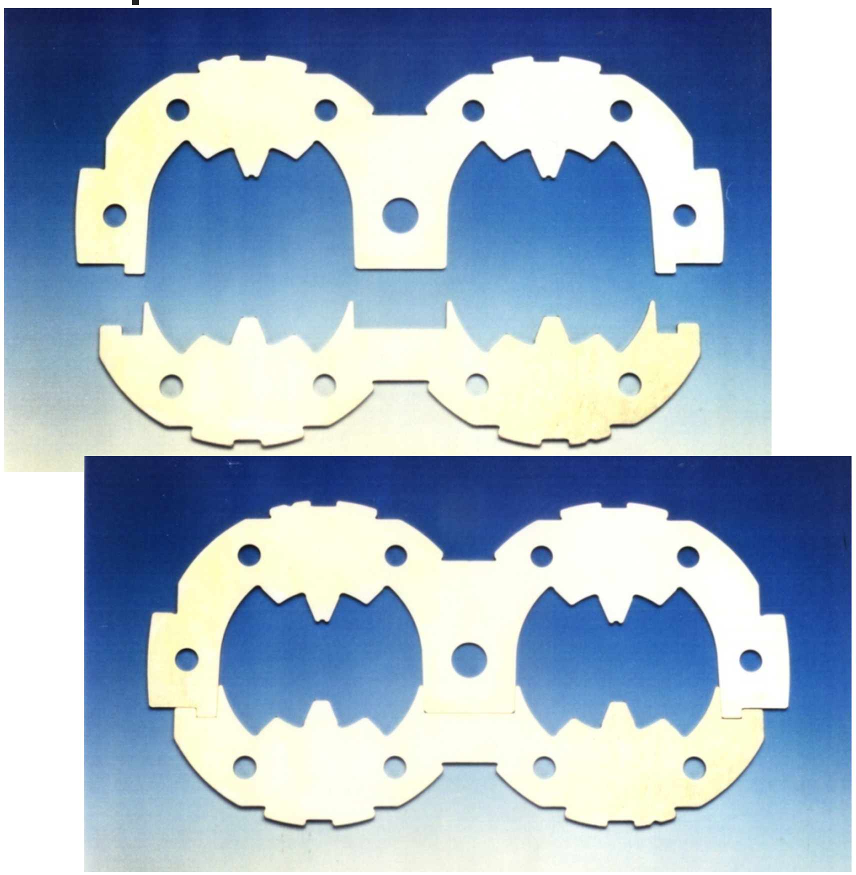
Ends



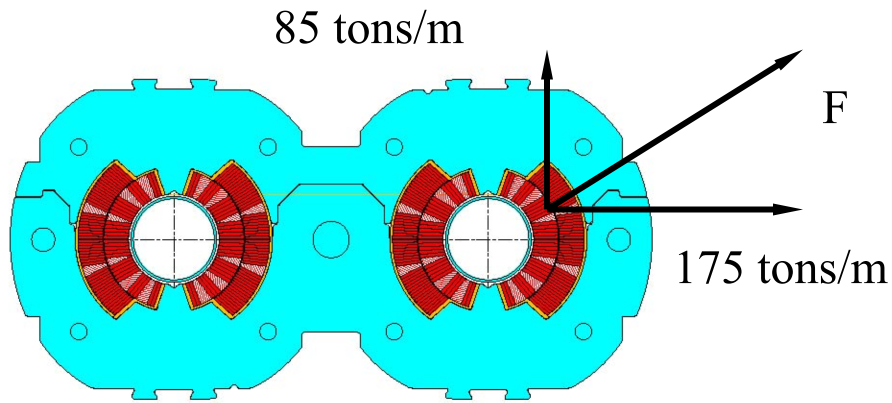


Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking

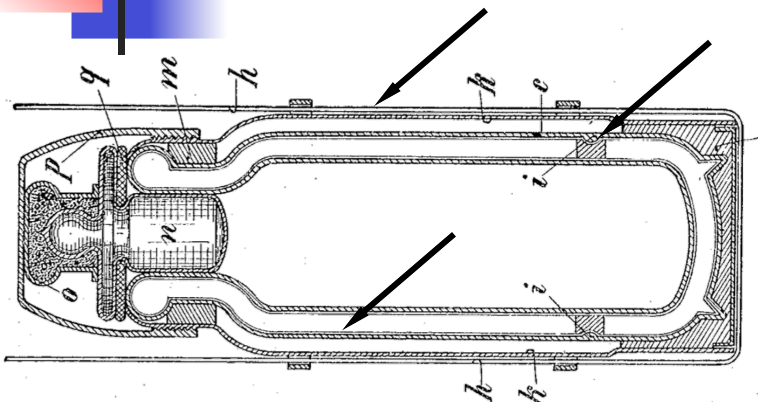


collaring



Cold mass

Cryostat



Vacuum enclosure

Thermal screens

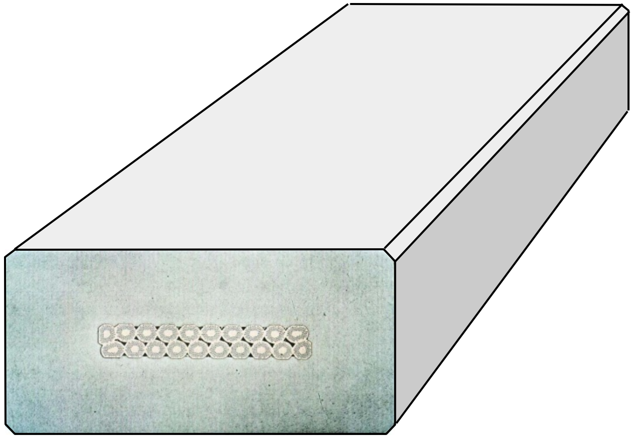
Low conduction foot

Finally, in the tunnel !

Example 2
BaBar Detector S/C Solenoid

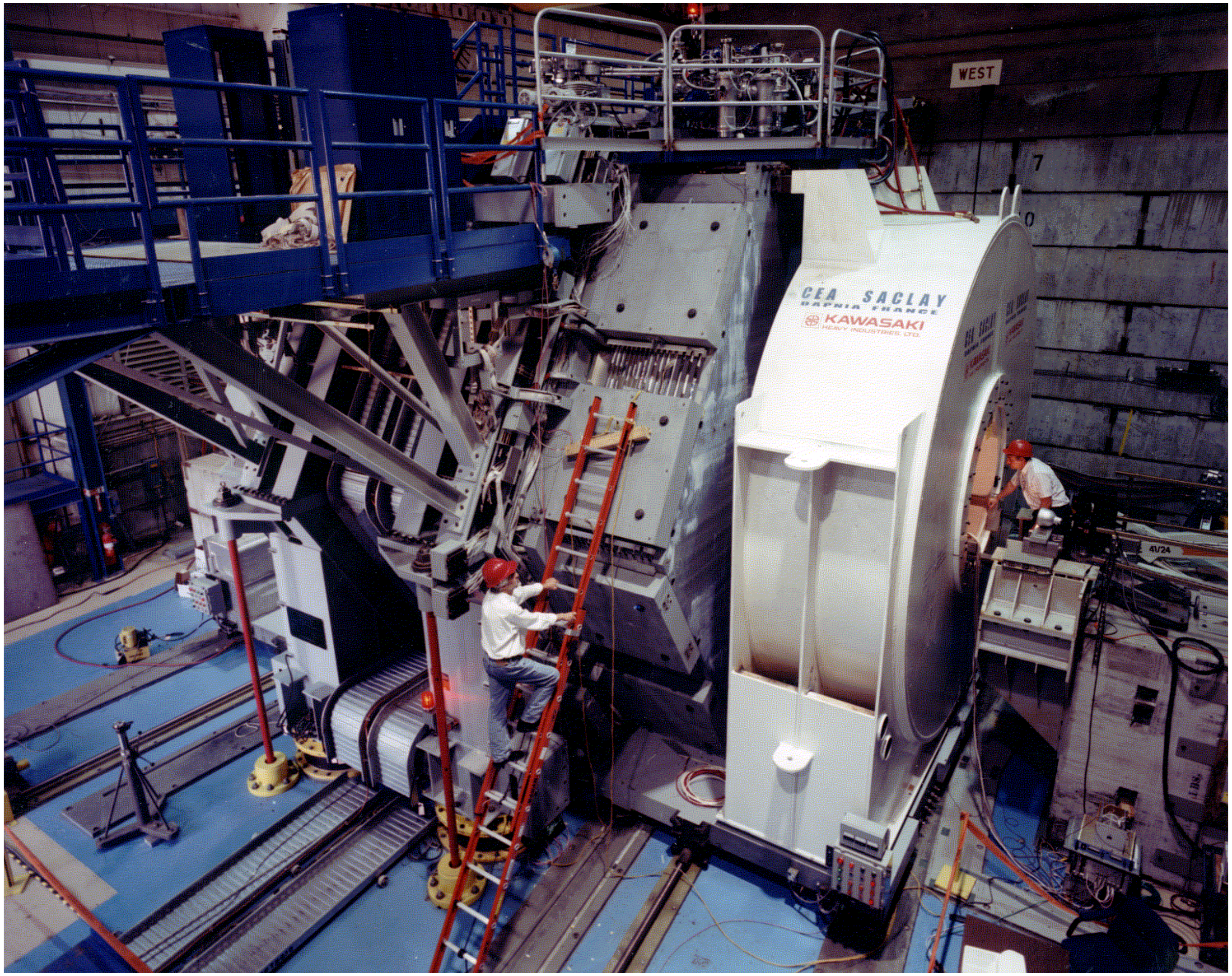
- Provided background field for particle identification for the BaBar detector at SLAC
- Physics requirements dictated a relatively thin solenoid

Properties of BaBar Solenoid

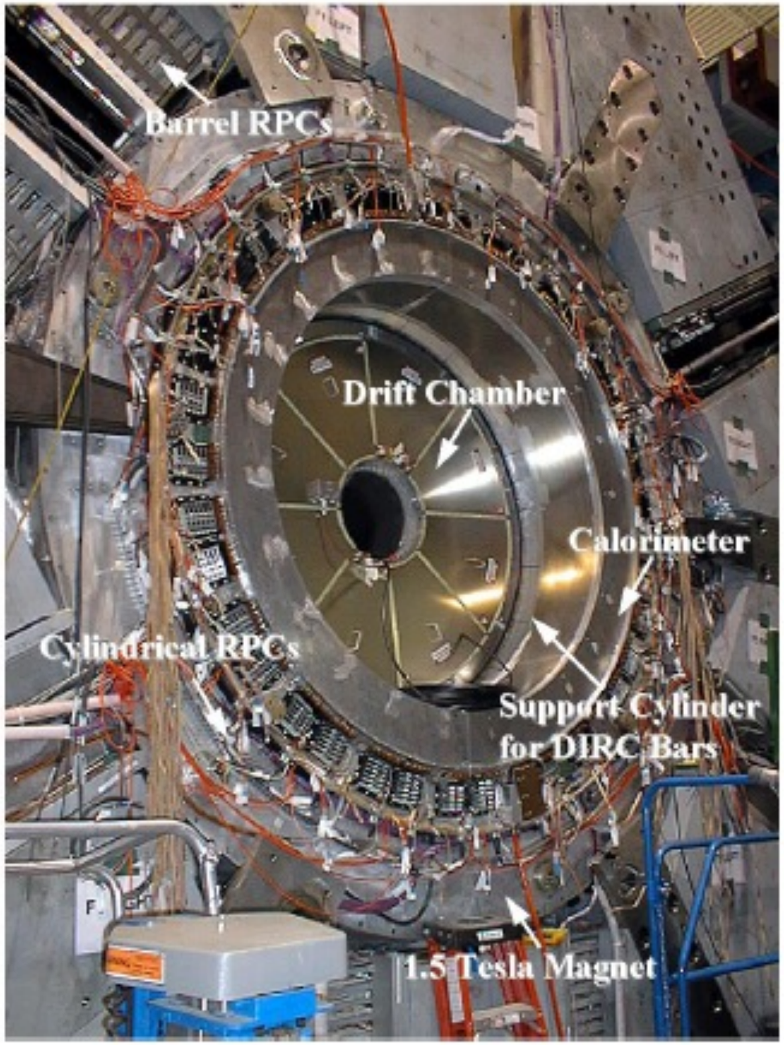


- Field: 1.5 Tesla
- Stored Energy: 27 MJ
- Operating Current: 4596A
- Tc= 8.3K
- Operating Temp: 4.5K
- Total Heat Load at 4.5K: 225liquid-liters/hr
- Cryogenics: indirectly cooled using the force flow technique where the liquid He is circulated in cooling pipes welded to the outside diameter of the support tube
- Uses NbTi highly stabilized by a pure Al conductor

BaBar Detector Under Construction



BaBar Detector



BaBar Solenoid

- Operated almost continuously for ~ 10 years
- Was very stable – only discharged due to loss of power, controls or cooling
  - Availability was > 96% from the start and better than 98% during final 3 years
    - » Improvement due mainly to removing unnecessary interlocks and adding additional utility backups
- May still be used as part of the proposed Super B project in Italy

Conclusions

- Superconducting magnets make possible modern technology including HEP accelerators, MRI Systems and heavy ion machines such as NSCL, FRIB and FAIR.
- Superconducting magnet design involves detailed engineering on a scale from the microscopic (flux pinning) to the immense (multi ton, GJ magnets)
- Superconducting magnet design involves a wide range of disciplines: materials science, electrical engineering, mechanical design, cryogenics etc.
- Superconducting magnet requirements have driven and enabled many advances in s/c materials, wire and ancillary systems