Superconducting Magnets for Accelerators

J. G. Weisend II
National Superconducting Cyclotron Lab
Michigan State University

U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

Introduction

- Superconducting Magnets are highly engineering devices
  - material → wire → cable → magnet
- Want to show examples
- Too much material for a 45 min talk
  - See backup slides & suggested readings for more information
- Won't really cover HTS or SCRF

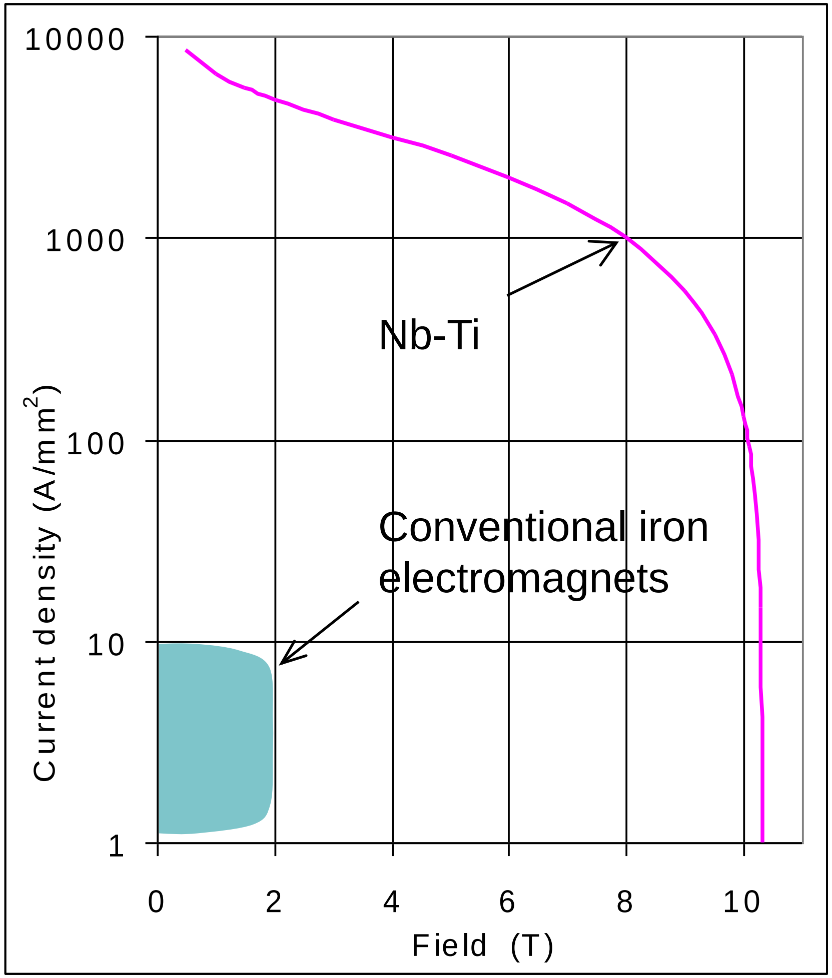
Acknowledgement

- This talk includes many slides graciously provided by Luca Boturra of CERN

Graphics by courtesy of M.N. Wilson

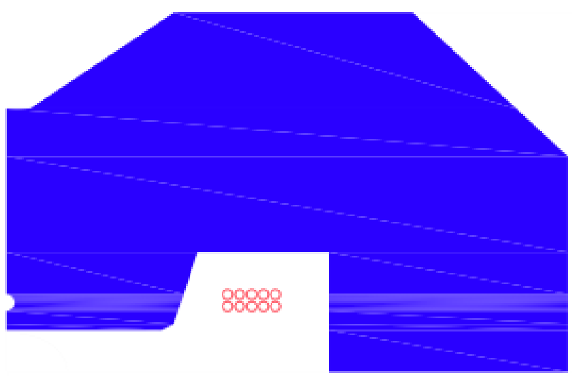
Why superconductivity anyhow ?

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



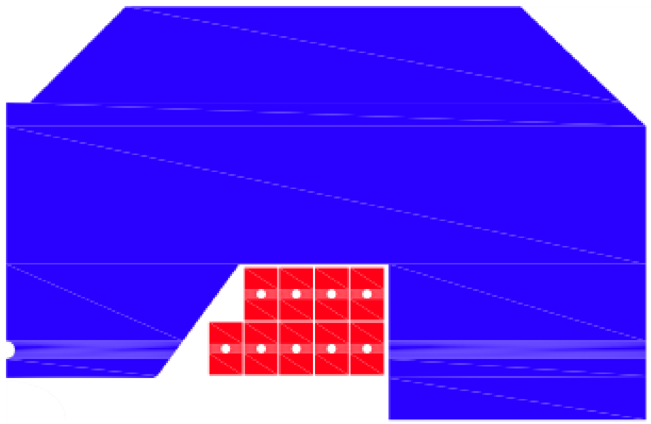
Abolish Ohm's law -

Super-conducting dipole



Iron weight [tons]	10
Peak voltage [V]	34
Average AC loss power [W]	1.3

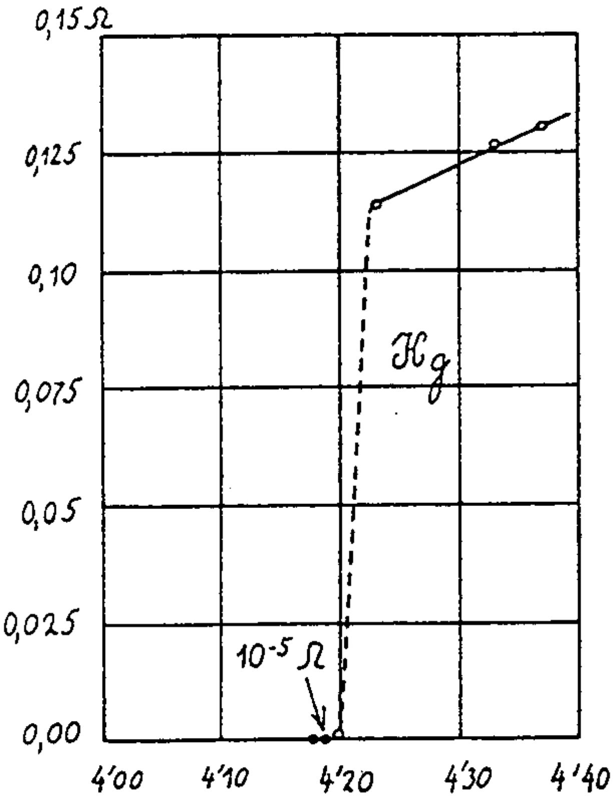
Normal-conducting dipole



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

Potential for saving **7 MW** of the **15 MW** estimated total power consumption of *an accelerator complex*

Superconductors Pre-history

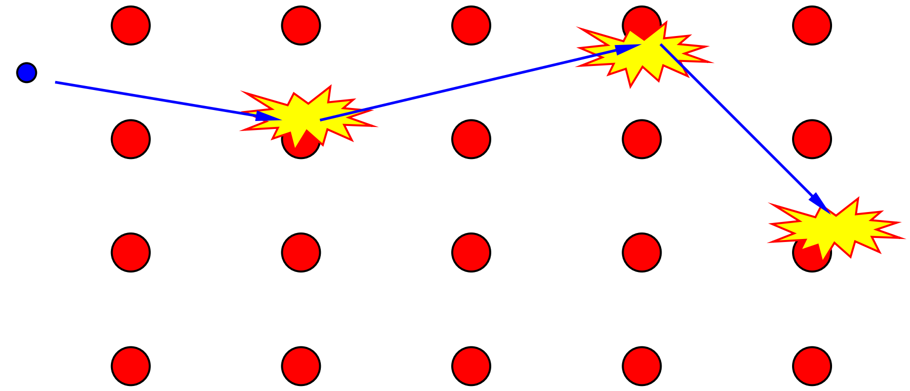


… thus the mercury at 4.2 K has entered a new state, which, owing to its particular electrical properties, can be called the state of *superconductivity*…

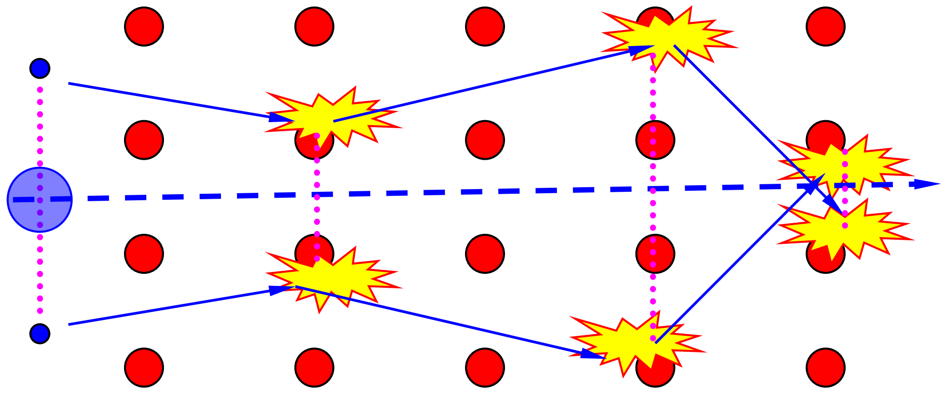
H. Kamerlingh-Onnes (1911)

Cooper Pairs

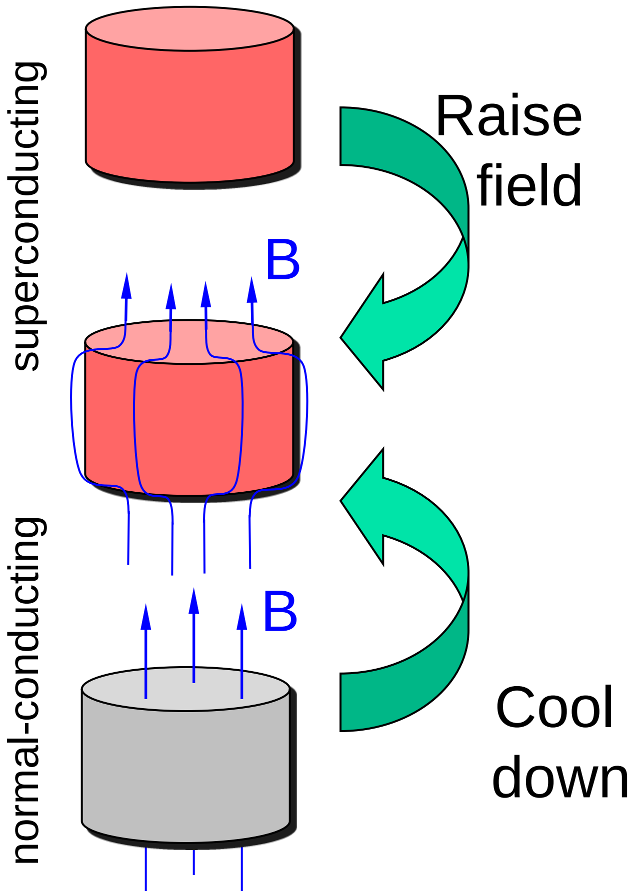
- Normal conductor
  - scattering of e^-
  - finite resistance



- Superconductor
  - paired electrons are bosons, a quasi particle in condensed state
  - zero resistance

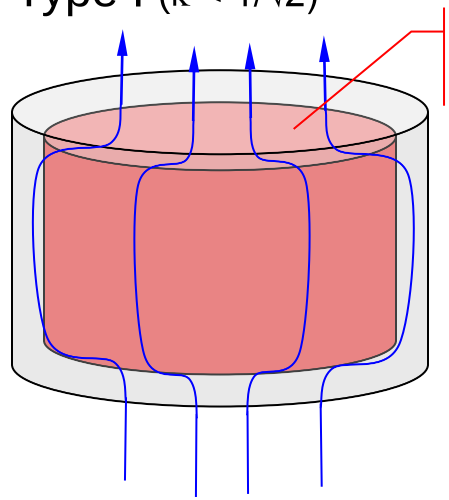


Hey, what about field ?



Meissner & Ochsenfeld, 1933

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



Complete field exclusion

Pure metals

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

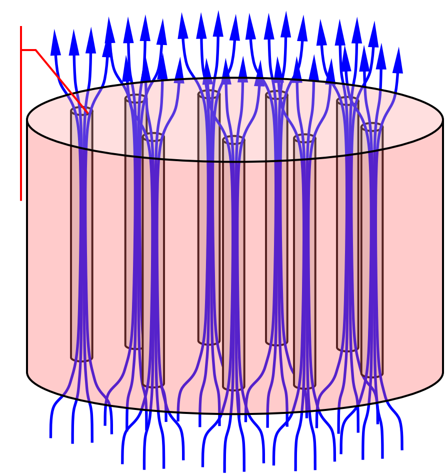
Type II ($\kappa > 1/\sqrt{2}$)

Partial field exclusion

Lattice of fluxons

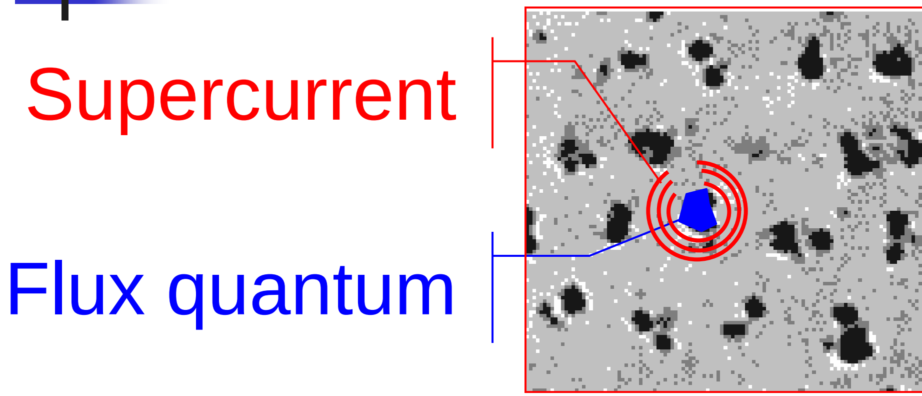
Dirty materials: alloys intermetallic, ceramic

$B_C \approx 10 \ldots 10^2$ T



Ginzburg, Landau, Abrikosov, Gor'kov, 1950…1957

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

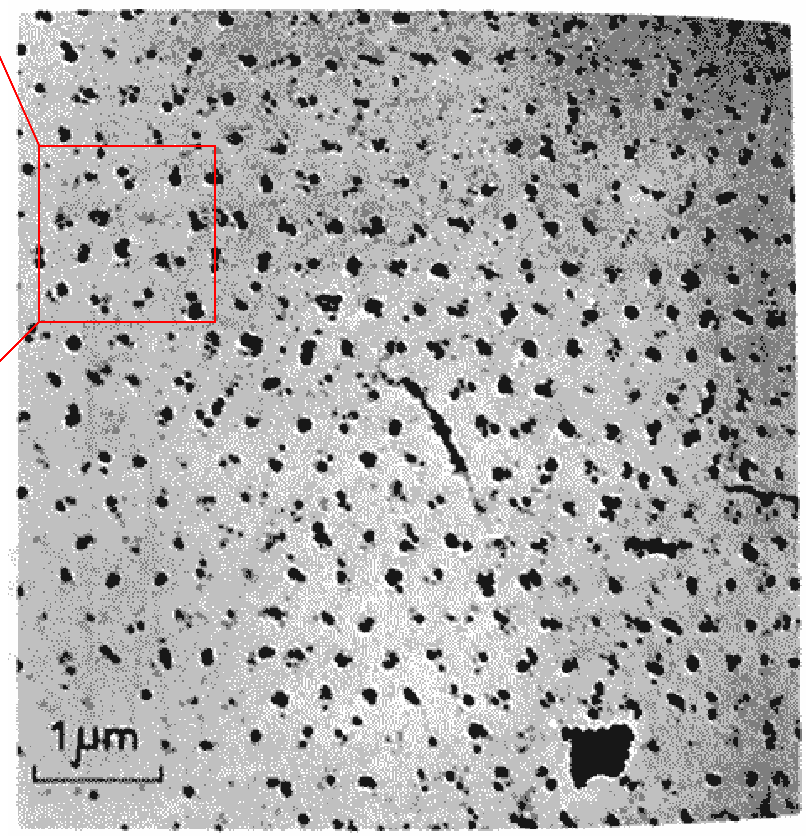
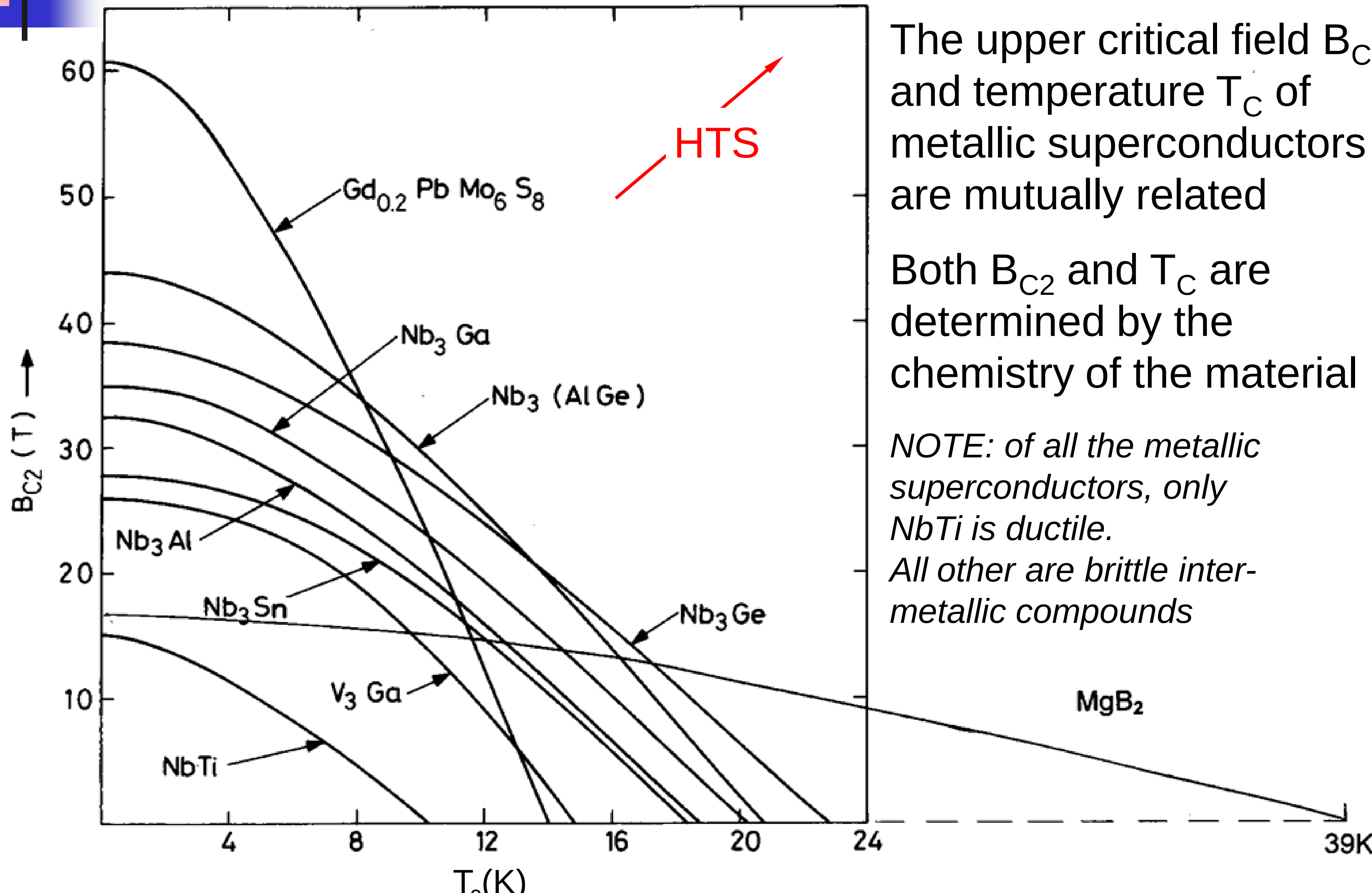


Fig. 1. "Perfect" triangular lattice of flux lines on the surface of a lead-4at% indium rod at 1.1°K. The black dots consist of small cobalt particles which have been stripped from the surface with a carbon replica.

Graphics by courtesy of M.N. Wilson

Critical temperature and field



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

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

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

Hey, what about current ?

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

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

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

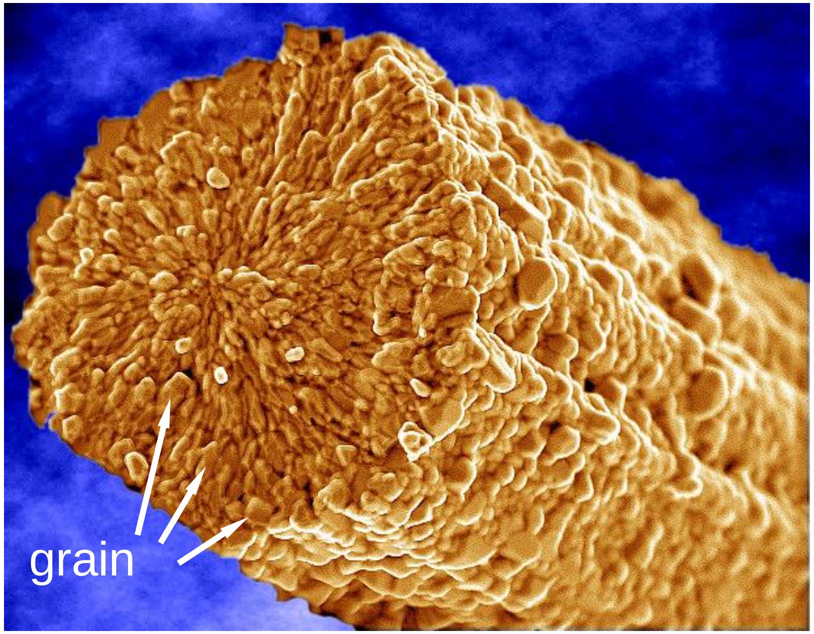
Graphics by courtesy of Applied Superconductivity Center at NHMFL

Pinning mechanisms

Precipitates in alloys

Grain boundaries in inter-metallic compounds

Microstructure of Nb-Ti



Microstructure of Nb_3Sn

Today we are engineering the structure of superconductors at a microscopic scale via heat treating, alloying and cold work

Jc(B,T,…)

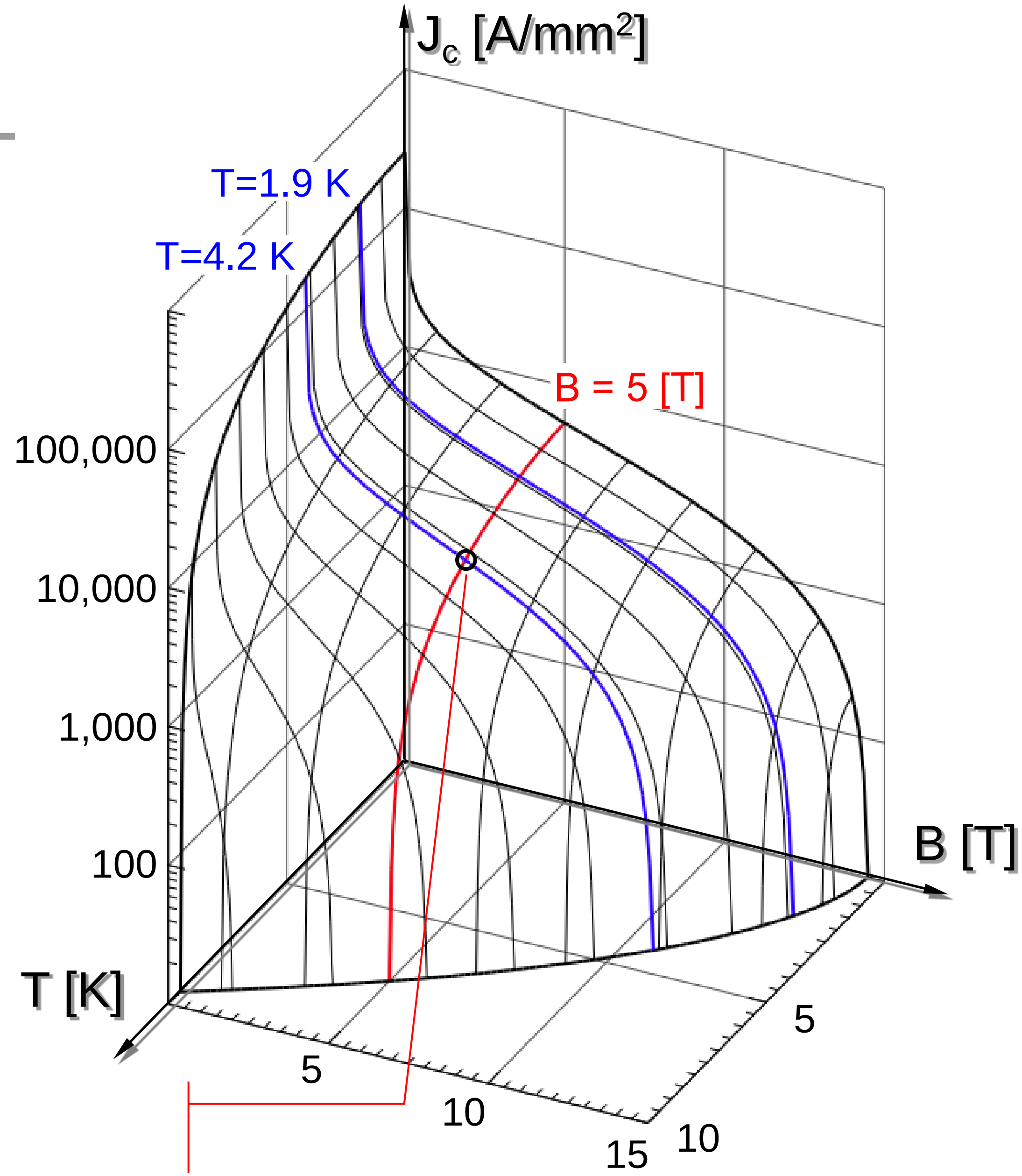
- The maximum current that can be carried by the superconductor is the current at which:

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

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

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

Critical surface of a LHC NbTi wire



Jc (5 T, 4.2 K) ≈ 3000 A/mm²

Practical Superconductor Facts

- Superconductor s are relatively poor conductors when normal
- Superconductors do have resistive losses when the current is varied
- Superconductors can’t generally be used as a bulk material. They are divided into filaments (tens of μm in DIA) housed in a good conductor matrix. This:
  - Prevents flux jumping and heating
  - Increases stability

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:

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

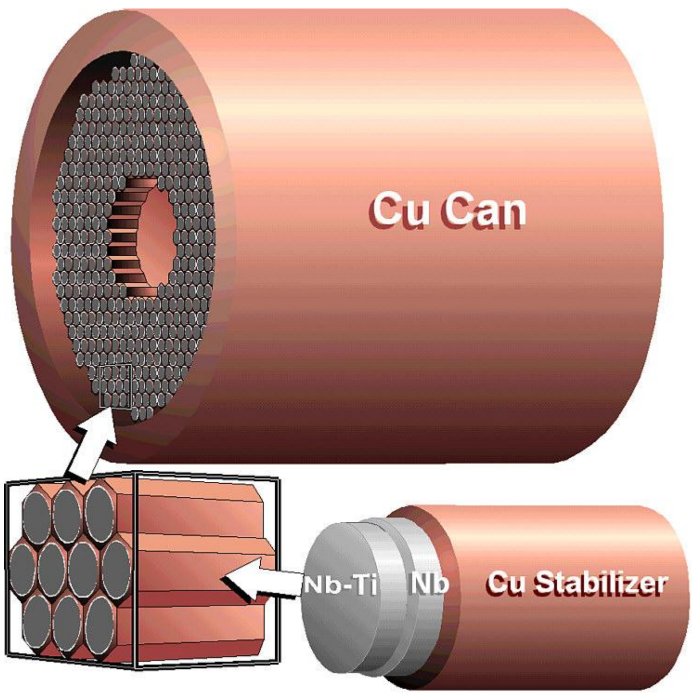
- To compare materials on the same basis, we use an *engineering current density*:

$$J_E = J_C \times \lambda$$

Graphics by courtesy of Applied Superconductivity Center at NHMFL

Nb-Ti manufacturing route

NbTi billet

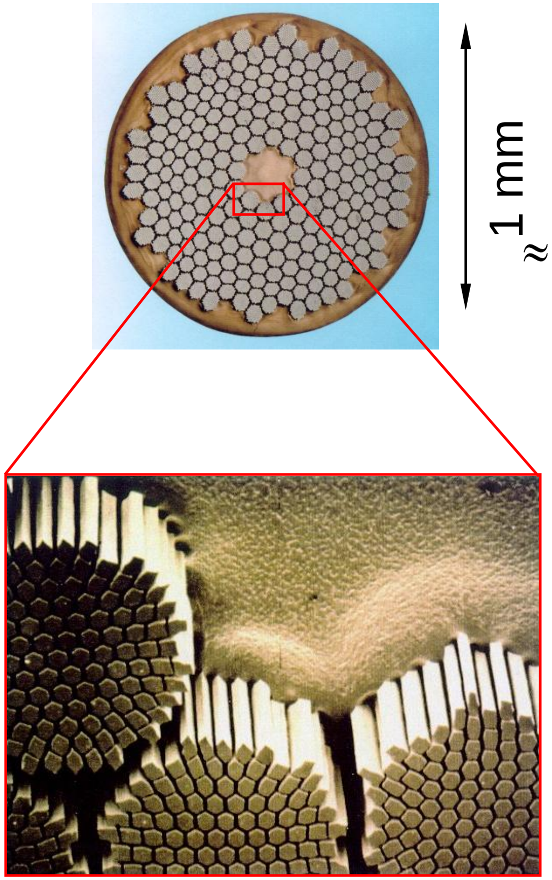


NbTi is a ductile alloy that can sustain large deformations

extrusion
cold drawing

heat
treatments

I_C(5 T, 4.2 K) ≈ 1 kA

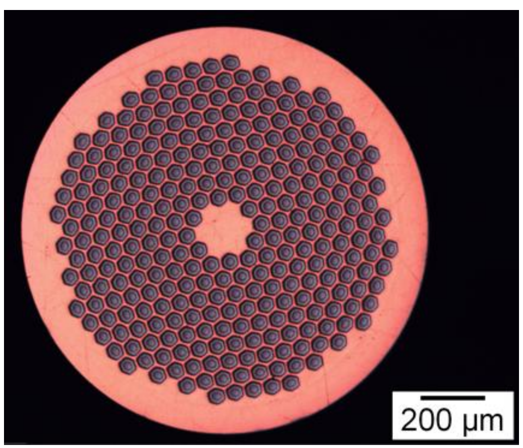


LHC wire

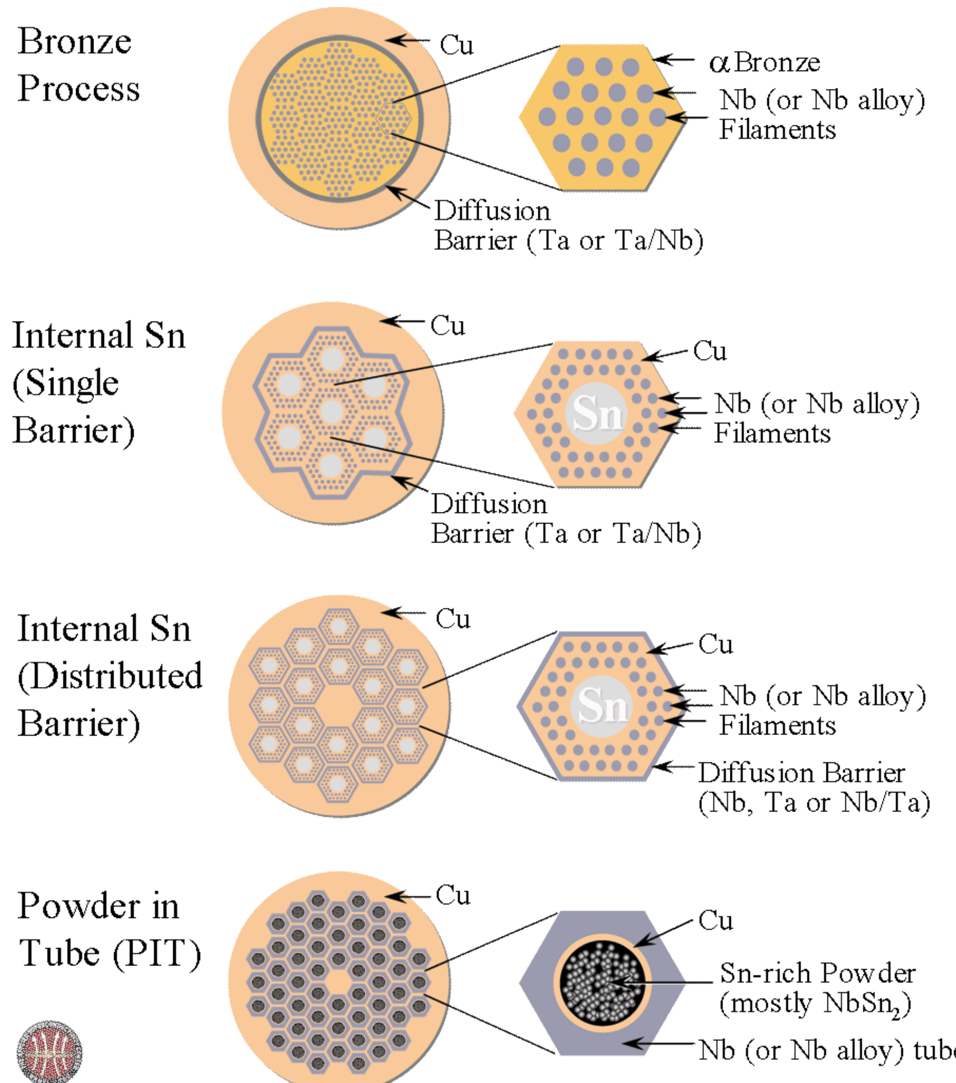
Graphics by courtesy of Applied Superconductivity Center at NHMFL

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, to form the Nb_3Sn phase



I_C(12 T, 4.2 K) ≈ 1.5 kA

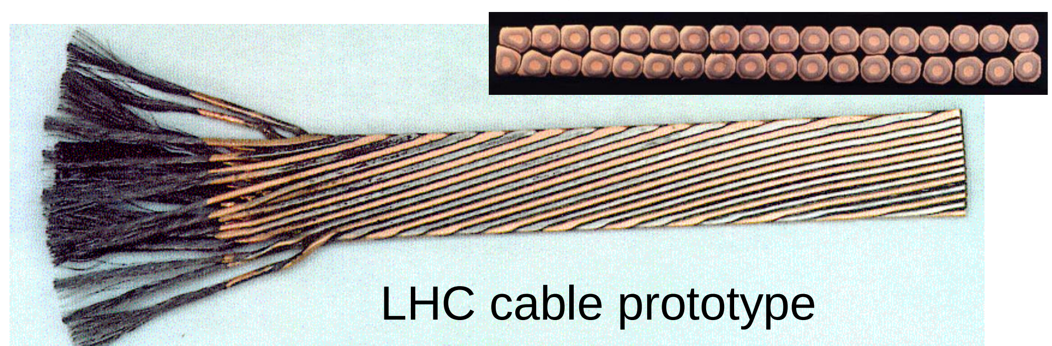


$J_E \approx 500$ A/mm^2

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 the *magnet protection*
- Rutherford cables are ideally suited for this task

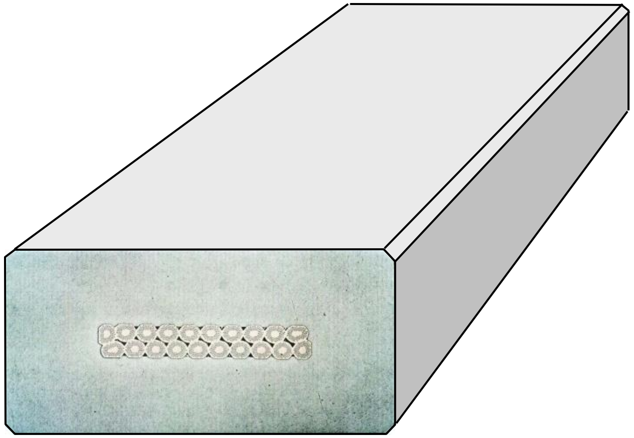


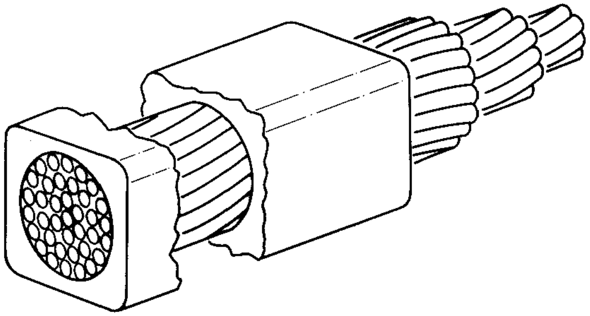
LHC cable prototype

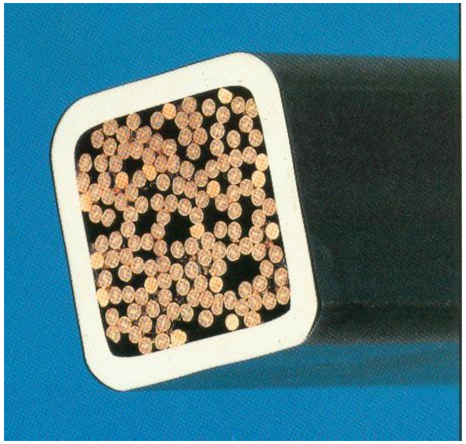
$J_E \approx 50$ A/mm^2

Practical conductors: low J_E

- Super-stabilized conductor, a superconducting cable (e.g. Rutherford) backed by a large amount of good normal conductor (e.g. Al)
- Internally-cooled conductor, e.g. Cable-In-Conduit Conductor (CICC), a rope of wires inserted in a robust conduit that provides a channel for cooling

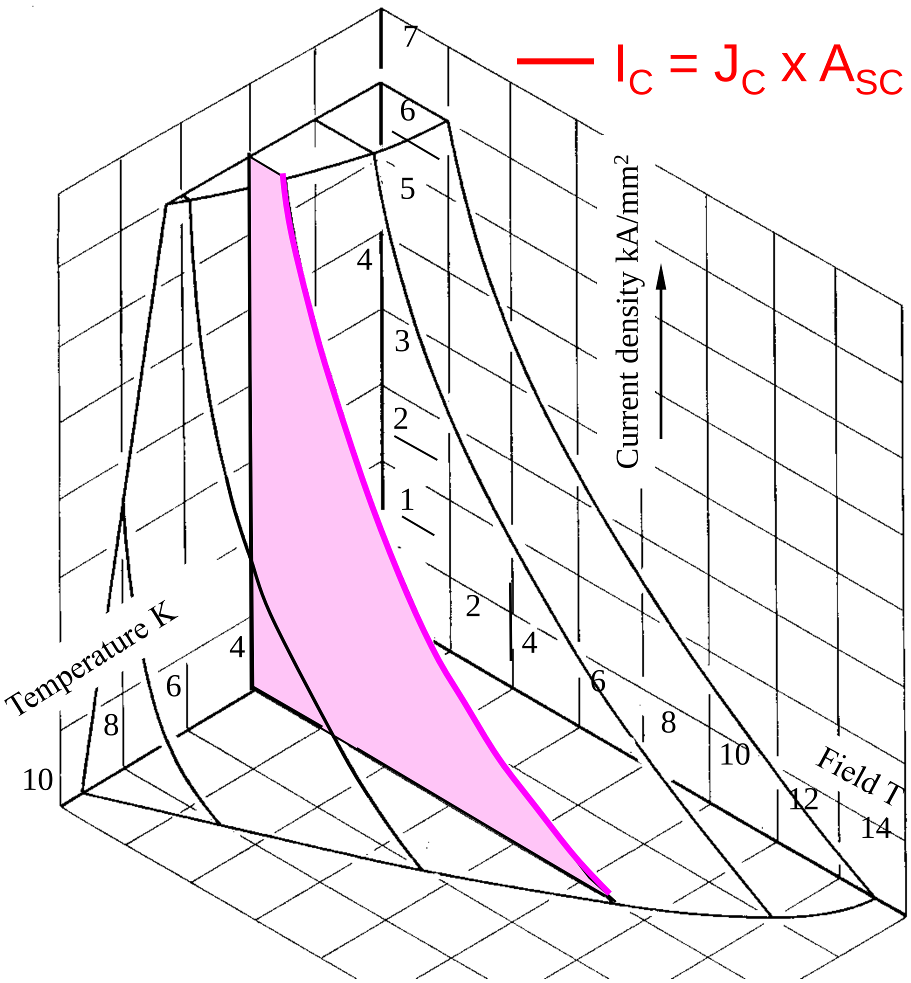






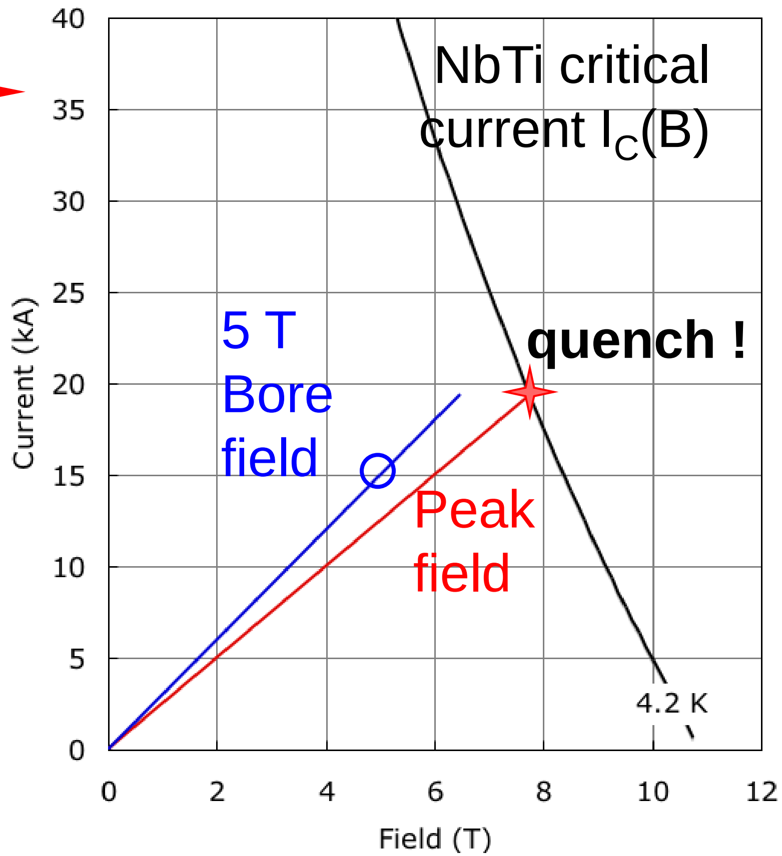
Critical line and magnet load lines

NbTi critical surface



$I_C = J_C \times A_{SC}$

e.g. a 5 T magnet design

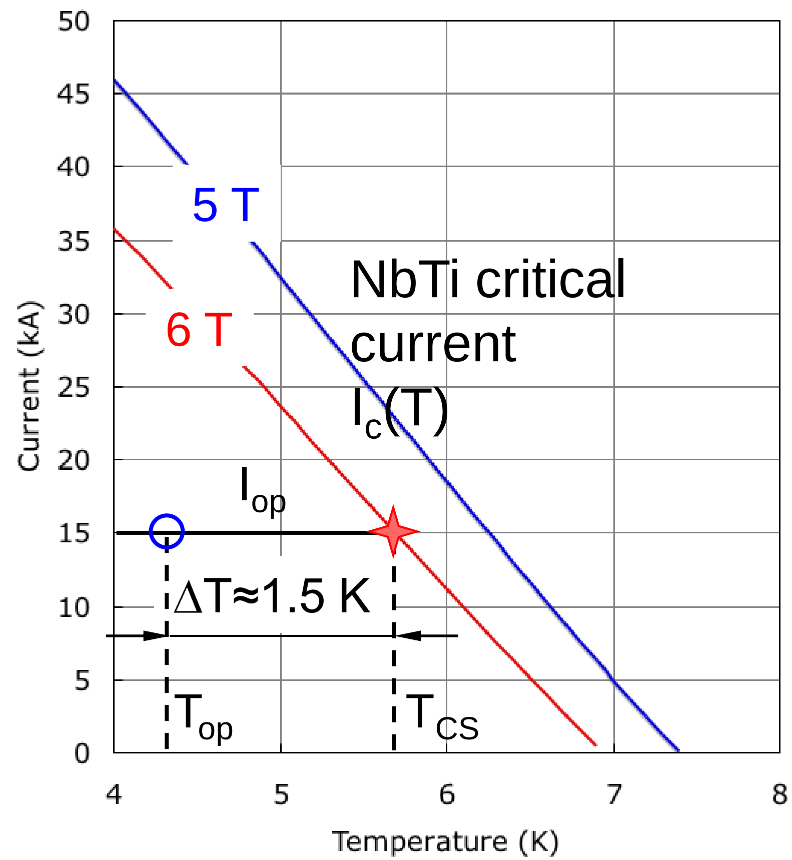


we expect the magnet to go resistive i.e. to **'quench',** where the peak field load line crosses the critical current line

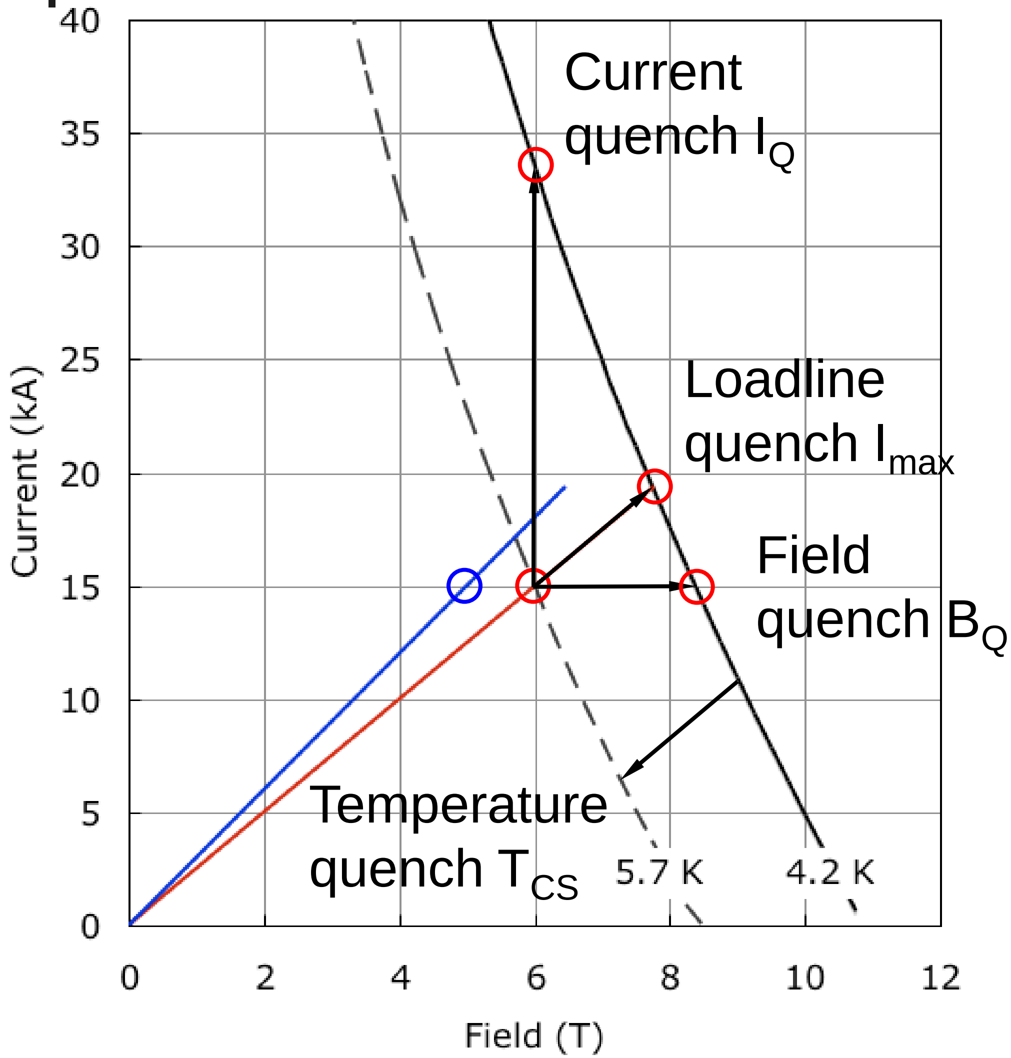
Temperature margin

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

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



Operating margins

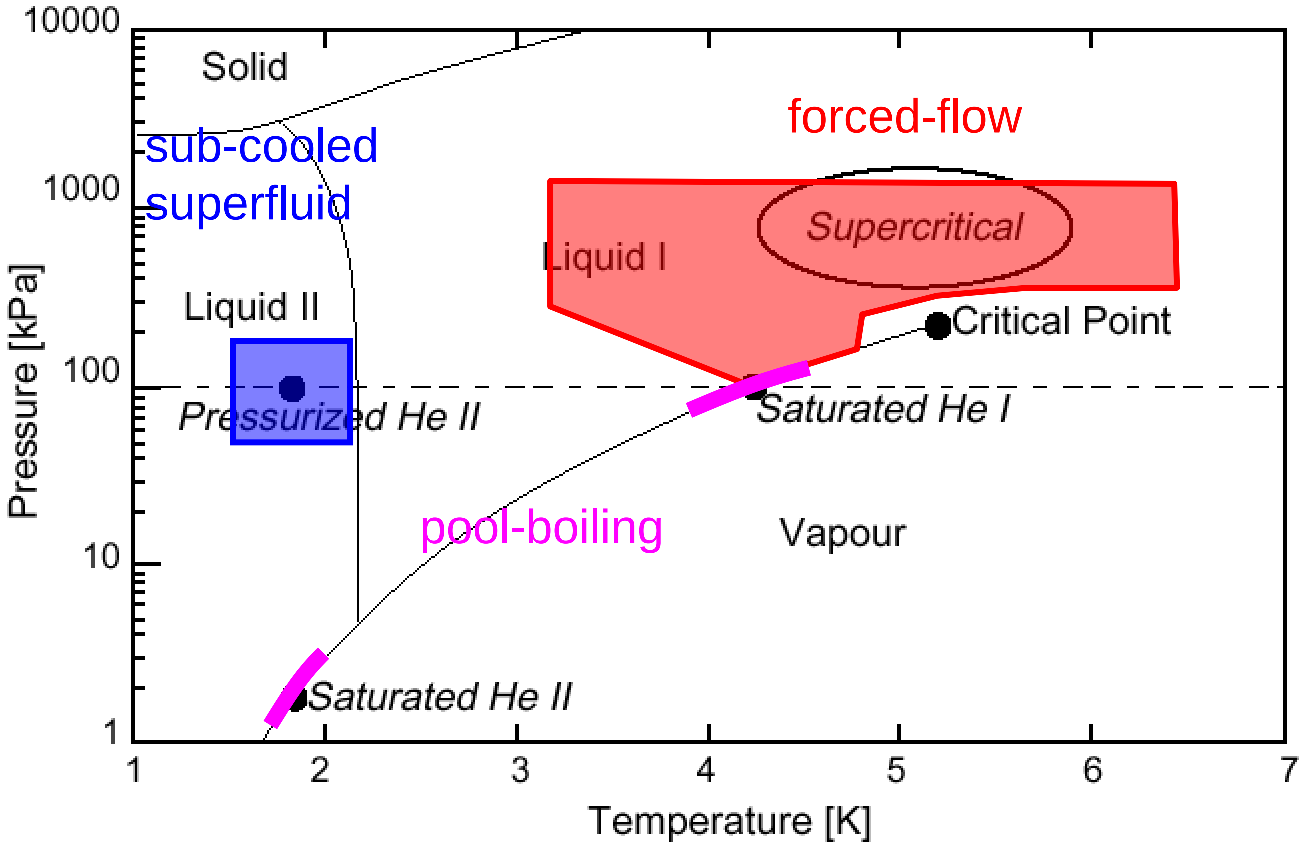


- Practical operation always requires margins:
  - Critical current margin: $I_{op}/I_Q \approx 50$ %
  - Critical field margin: $B_{op}/B_Q \approx 75$ %
  - Margin along the loadline: $I_{op}/I_{max} \approx 85$ %
  - Temperature margin: $T_{CS} - T_{op} \approx 1 \ldots 2$ K
- The margin needed depends on the design and operating conditions (see later)

Cooling of Superconductors Various Possibilities Exist

- Indirect (*adiabatic* magnets)
  - contact to a heat sink through conduction (cryoplant, cryocooler)
  - in practice ≡ no cooling on the time scale of interest for stability and quench
- bath cooling (*pool boiling* magnets)
  - pool of liquid cryogen at atmospheric pressure and saturation temperature (e.g. helium at 4.2 K)
  - boiling heat transfer
- force-flow cooling
  - supercritical or two-phase flow, warm or cold circulation
- superfluid cooling
  - stagnant bath, heat removal through counter-flow heat exchange

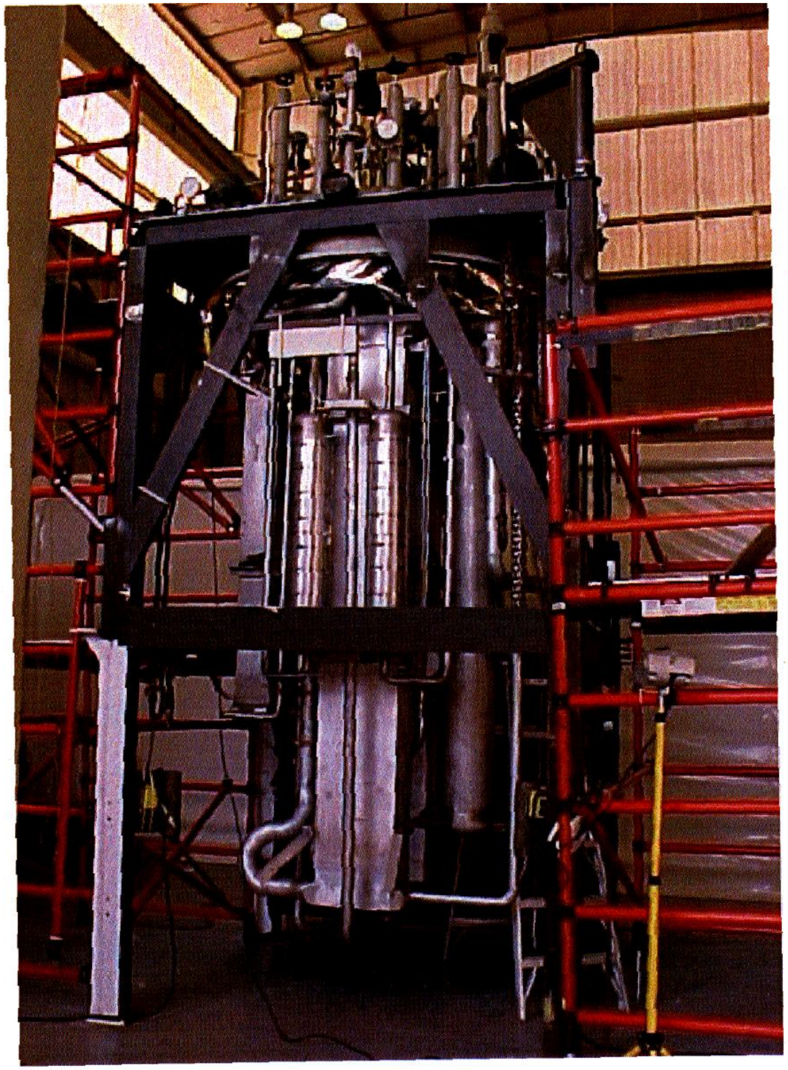
Helium as a coolant



Cryogenic Refrigeration

- Cooling for superconducting magnets is well within the state of the art
- Many commercial options exist (either off the shelf or custom)
- The cryogenic system is best designed along with the magnet system as opposed to added on later

Cryogenic Refrigeration Examples



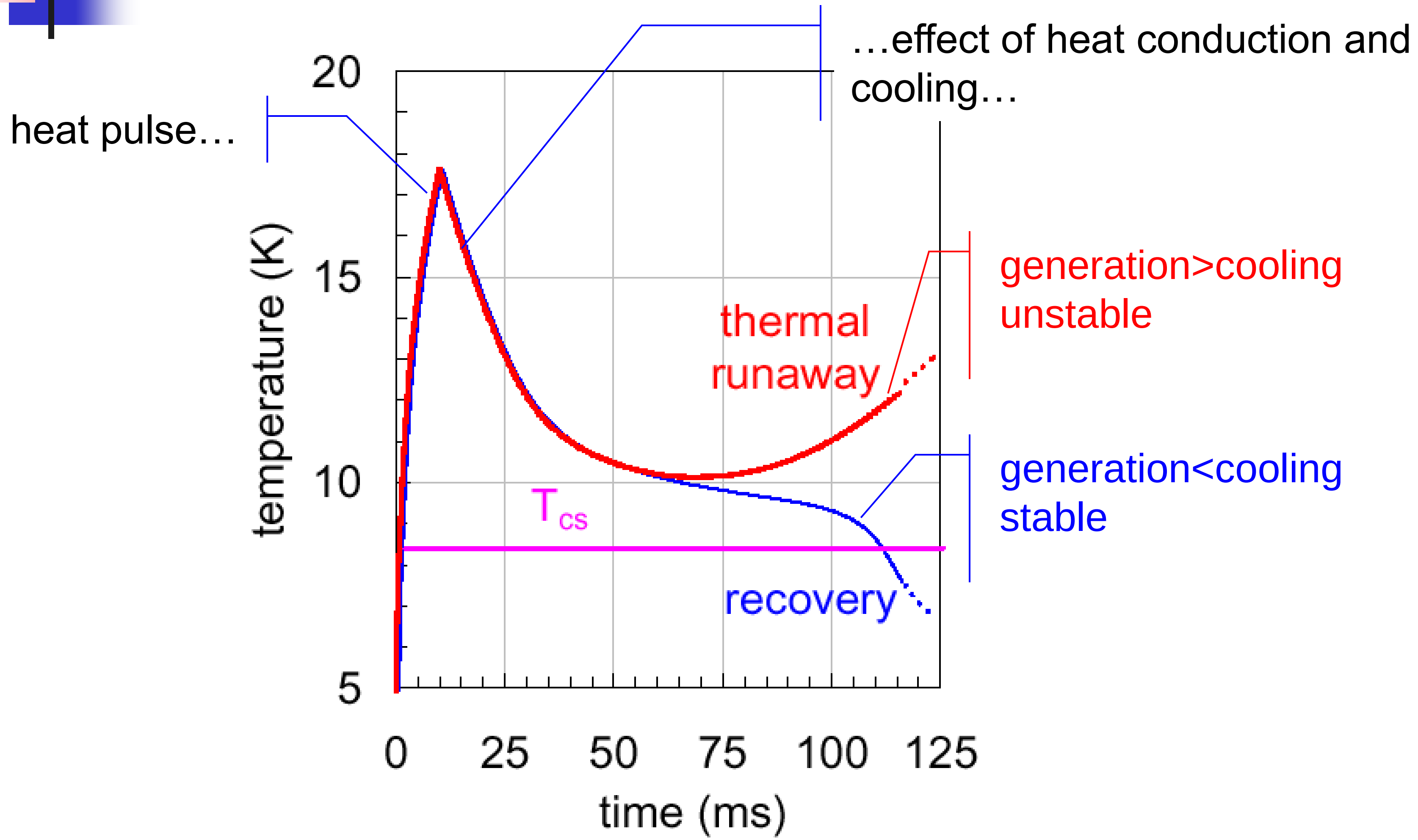
Helium Refrigerator Coldbox
(CTI400)
1200 W at 4.5 K

Cryocooler:
0.1 W @ 4 K

Stability of Superconducting Magnets

- When 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)
- Which occurs depends on the amount of heat generation and cooling

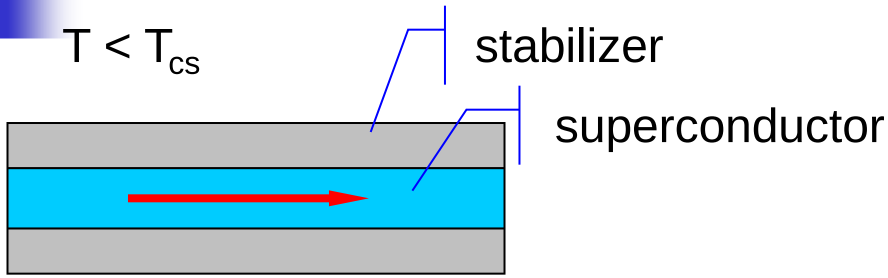
A prototype temperature transient

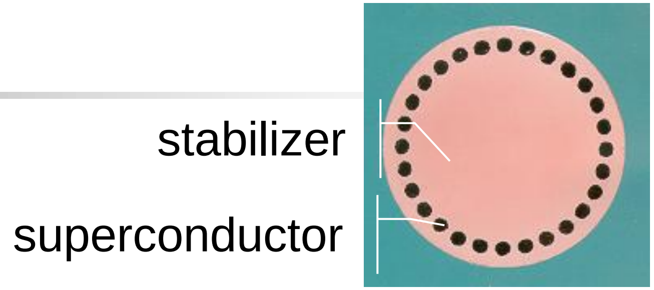


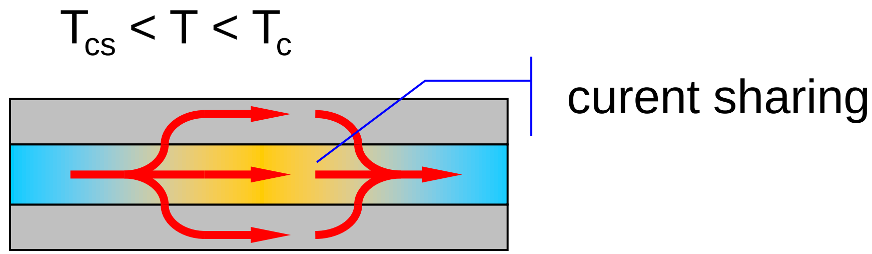
Perturbation spectrum

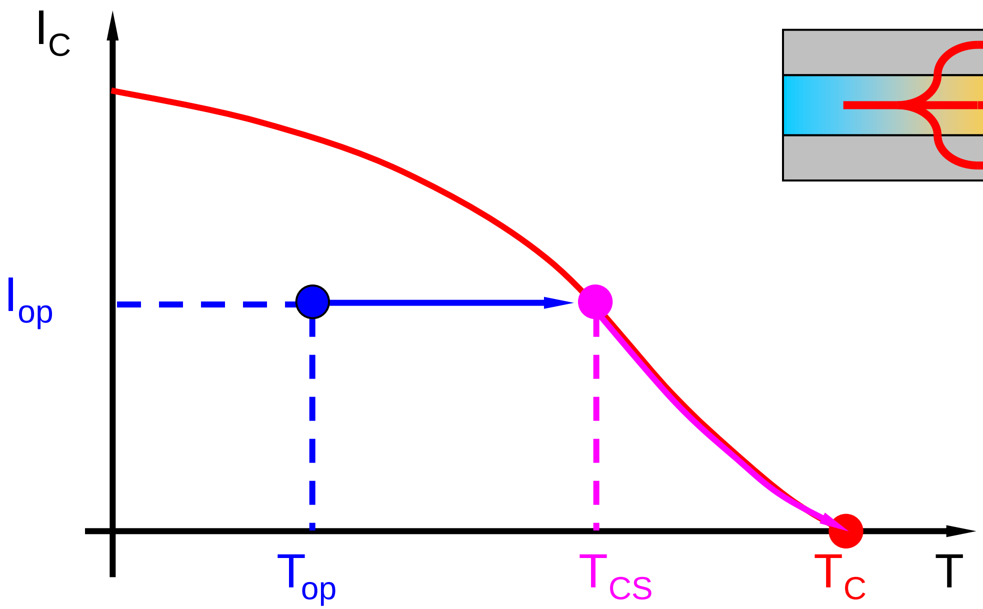
- mechanical *events*
  - wire motion under Lorentz force, micro-slips
  - winding deformations
  - failures (at insulation bonding, material yeld)
- electromagnetic *events*
  - flux-jumps (important for large filaments, old story !)
  - AC loss (most magnet types)
  - current sharing in cables through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

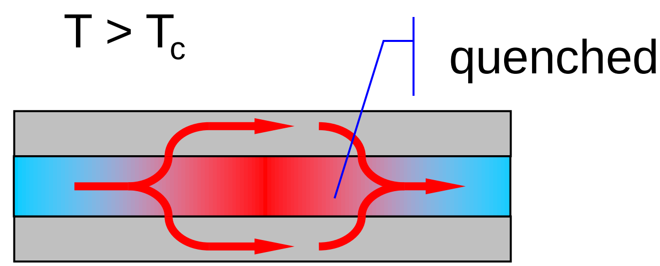
Current sharing











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
- Partially cryostable: magnet will recover if normal is not too big – more typical of accelerator magnets

Criteria for Fully Cryostable Magnets

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

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

α < 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)

Quench Detection & Protection

- 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!

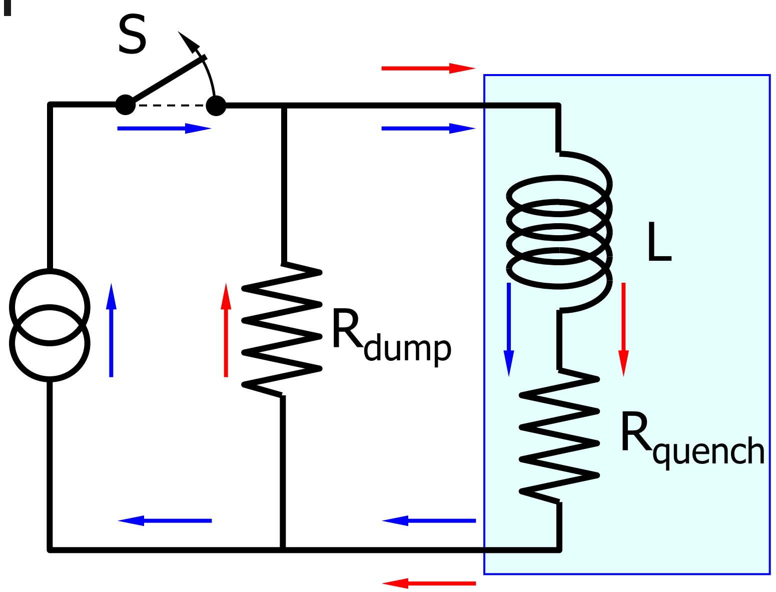
Quench Detection & Protection

- The goal is to rapidly and accurately detect the quench and safely dispose of the energy
  - Evenly 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

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”

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:

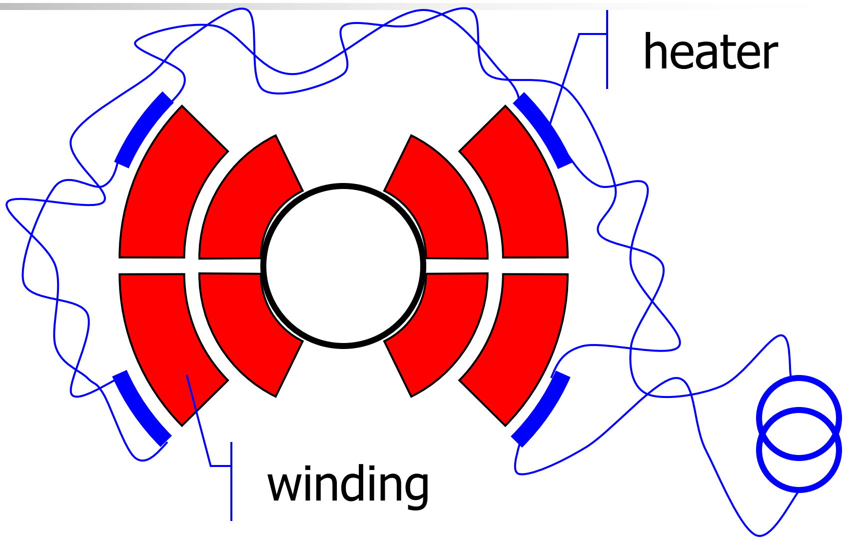
$$\int_0^\infty J^2 dt \approx J_{op}^2 \left(\tau_{detection} + \frac{\tau_{dump}}{2} \right)$$

- 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, in close vicinity to the conductor

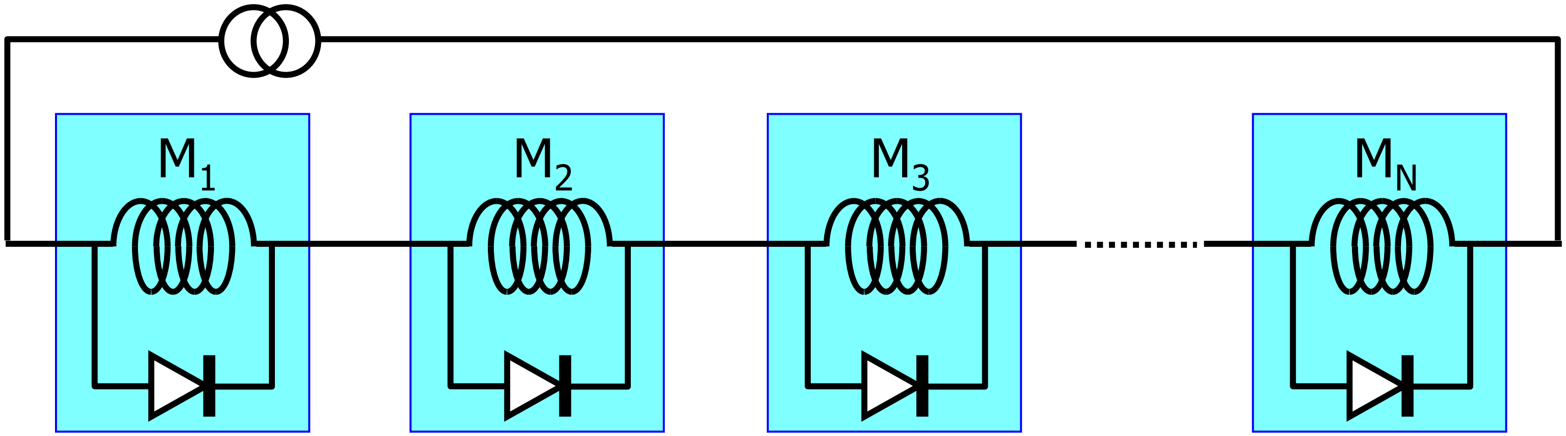
- heaters are mandatory in:
  - high performance, aggressive, cost-effective and highly optimized magnet designs…
  - …when you are really desperate



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

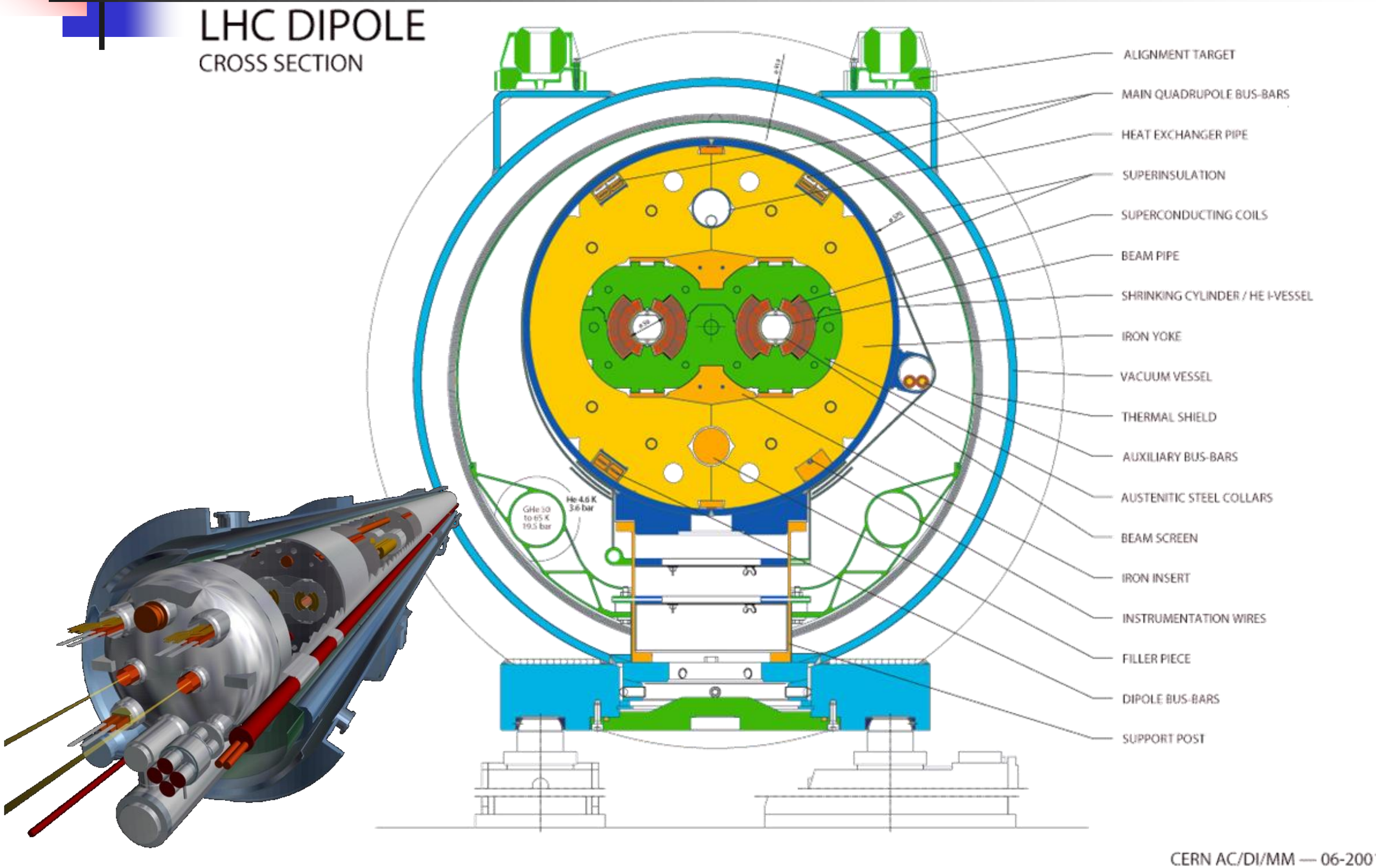
Magnet strings

- 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

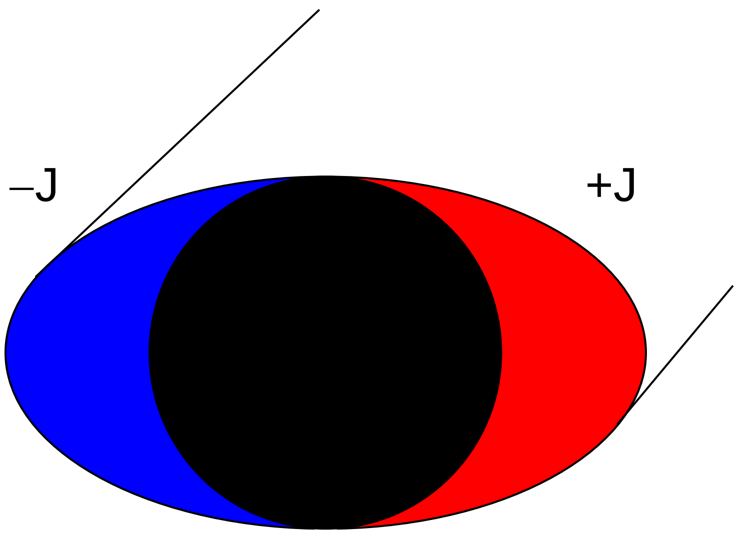


LHC dipole

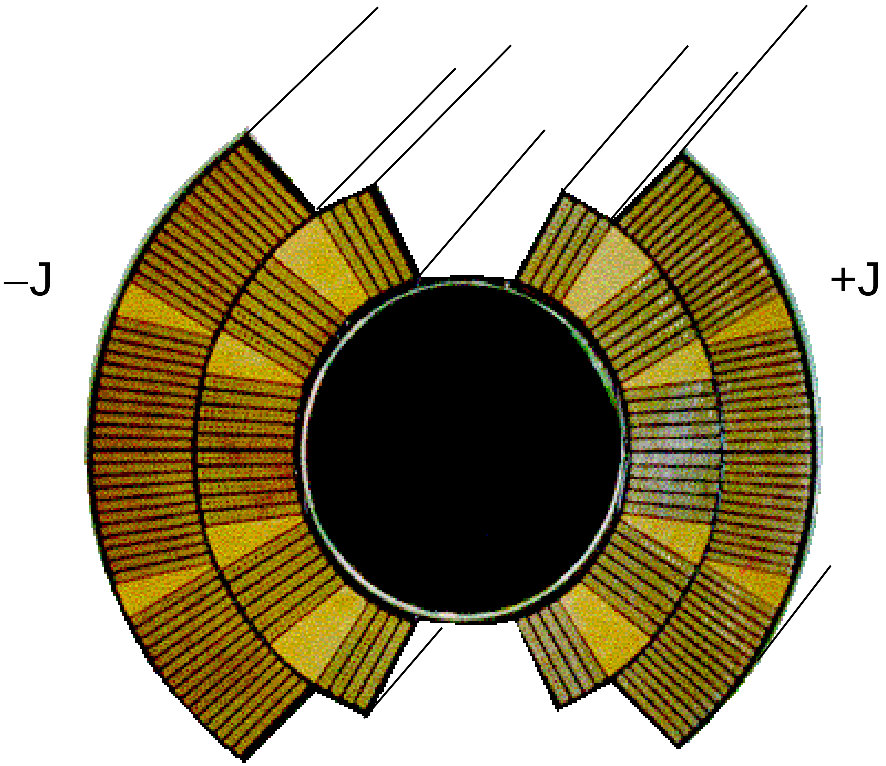
$B_{nominal}$	8.3	(T)
current	11850	(A)
stored energy	≈ 1	(MJ)
cold mass	≈ 35	(tonnes)



Superconducting dipole magnet coil

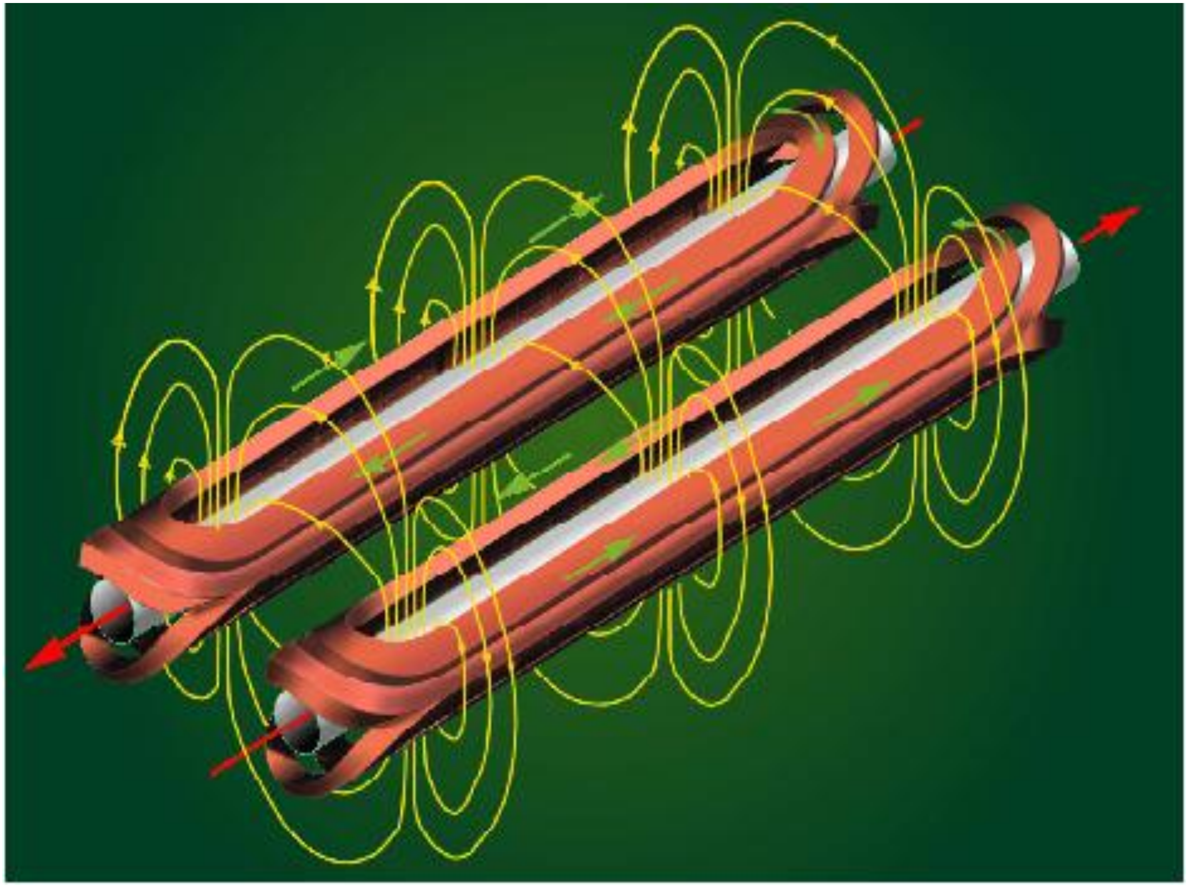


Ideal current distribution that generates a perfect dipole



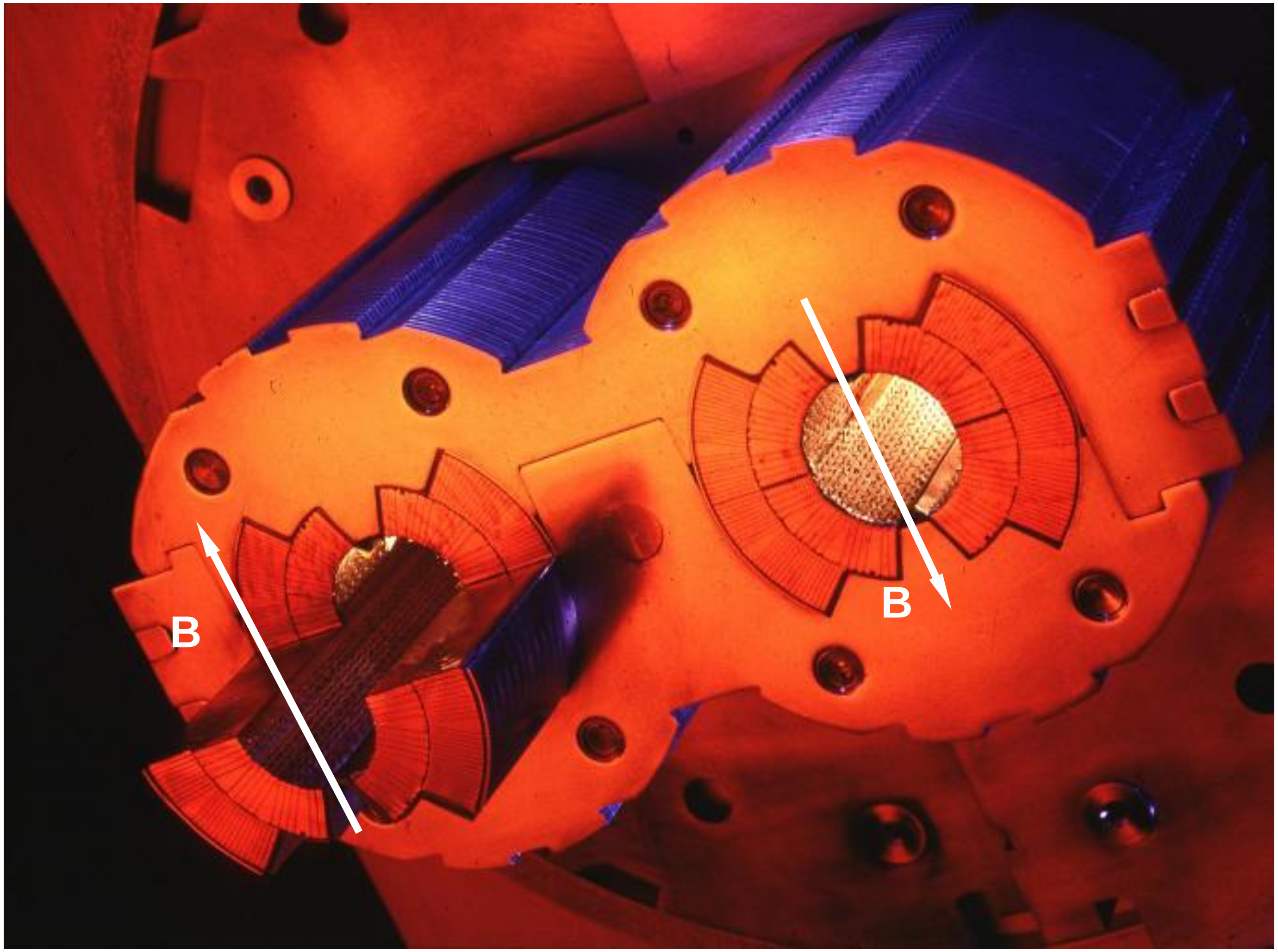
Practical approximation of the ideal distribution using Rutherford cables

Twin coil principle



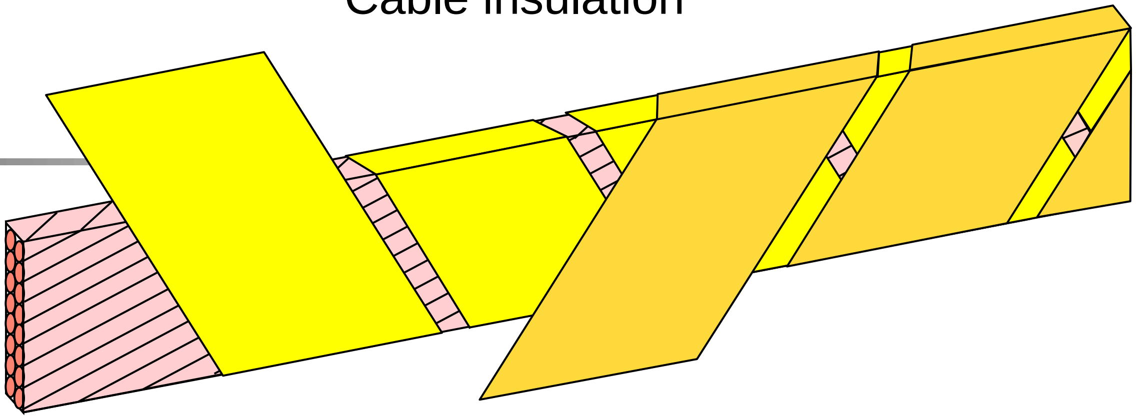
Combine two magnets in one
Save volume, material, cost

LHC dipole coils

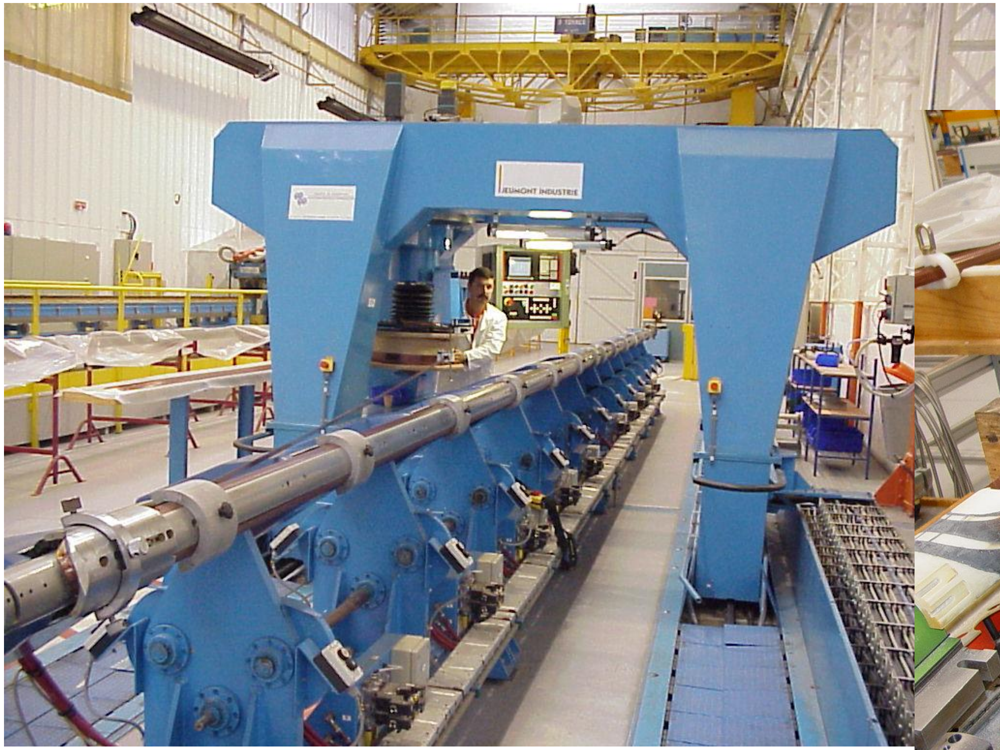


Coil winding

Cable insulation



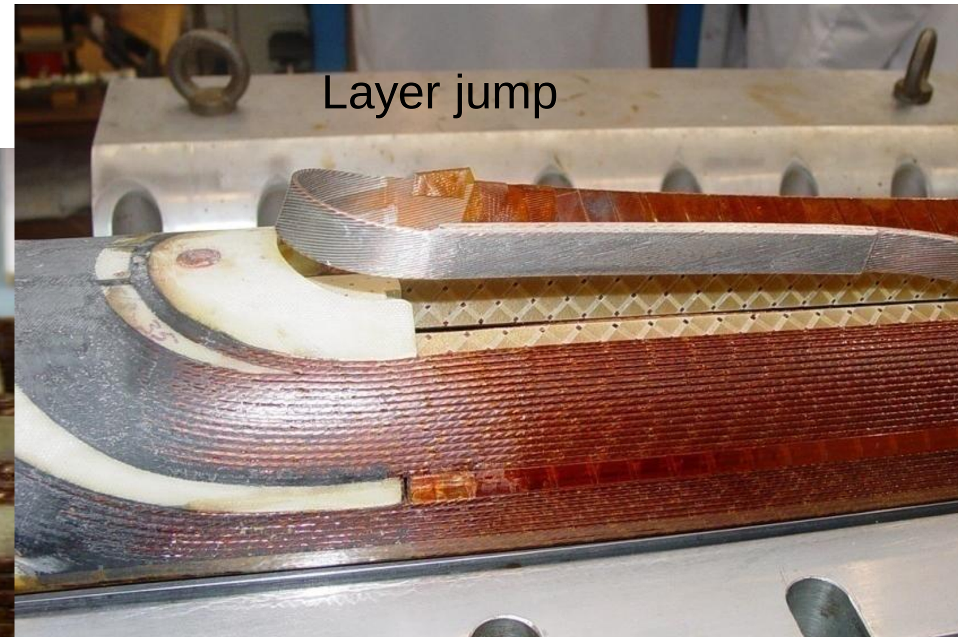
10 μm precision !

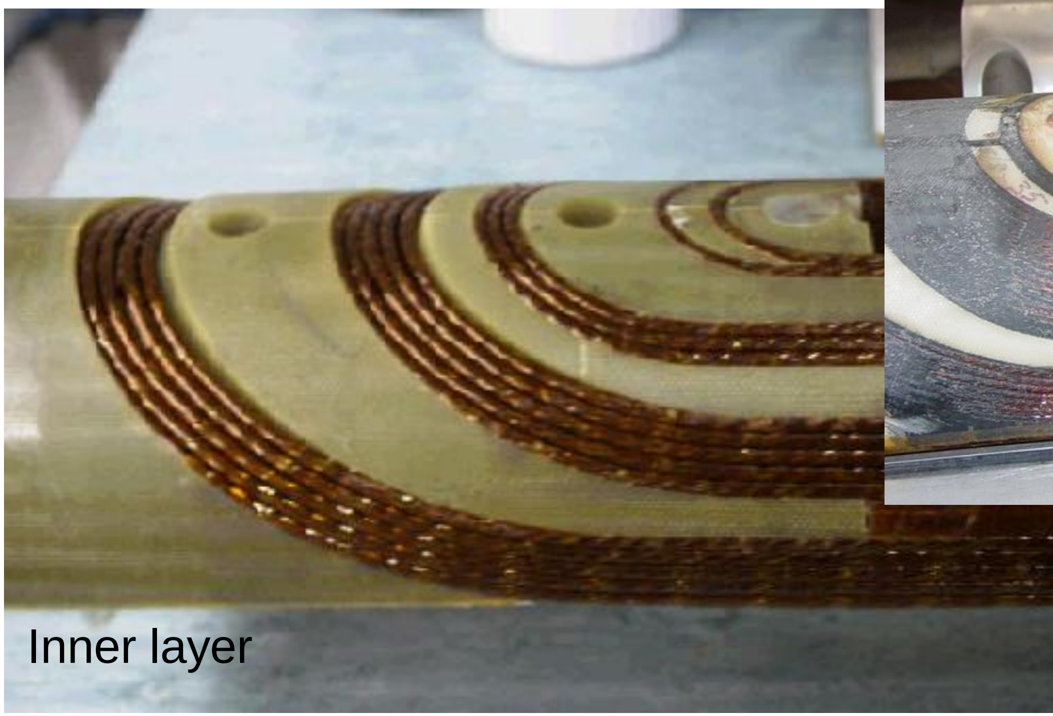


Coil winding machine

Stored coils

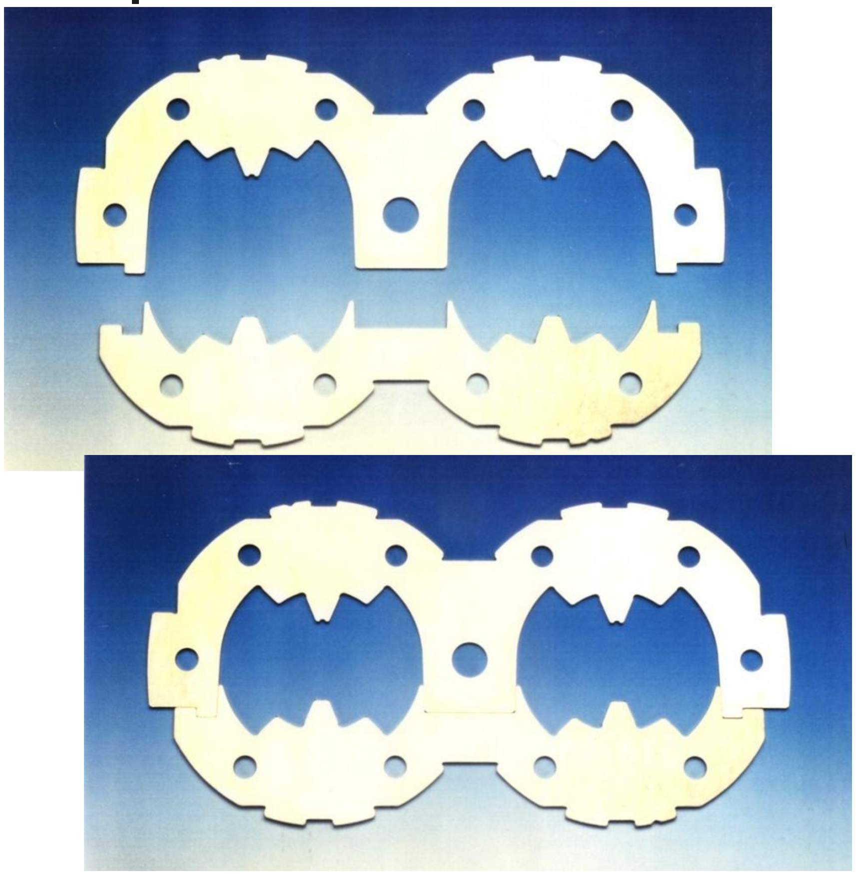
Ends



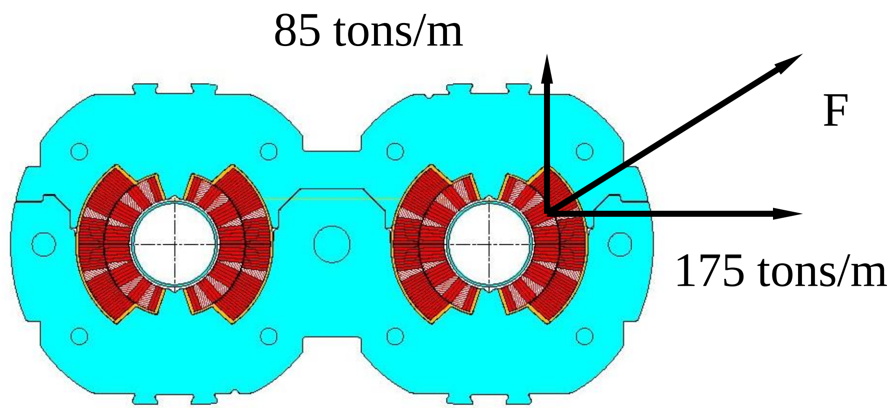


Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet

Collaring and yoking

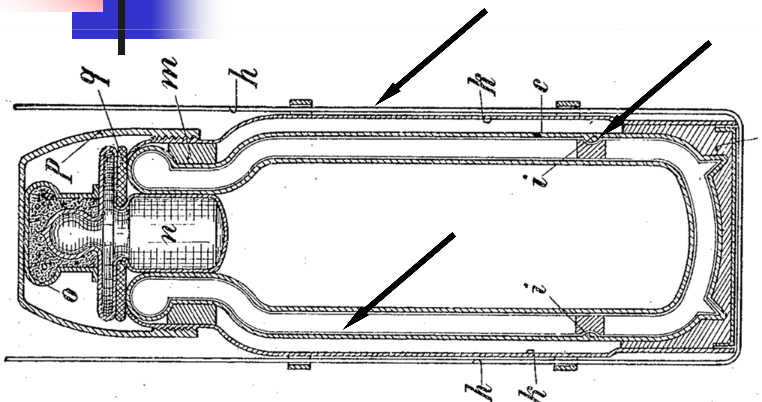


collaring



Cold mass

Cryostat



Thermal screens

Low conduction foot

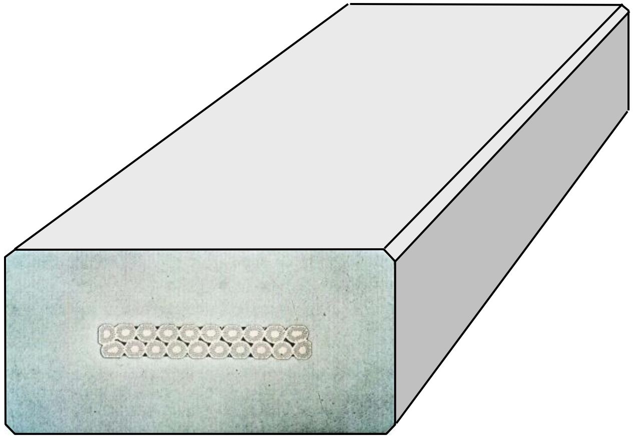
Finally, in the tunnel !

Example 2
BaBar Detector S/C Solenoid

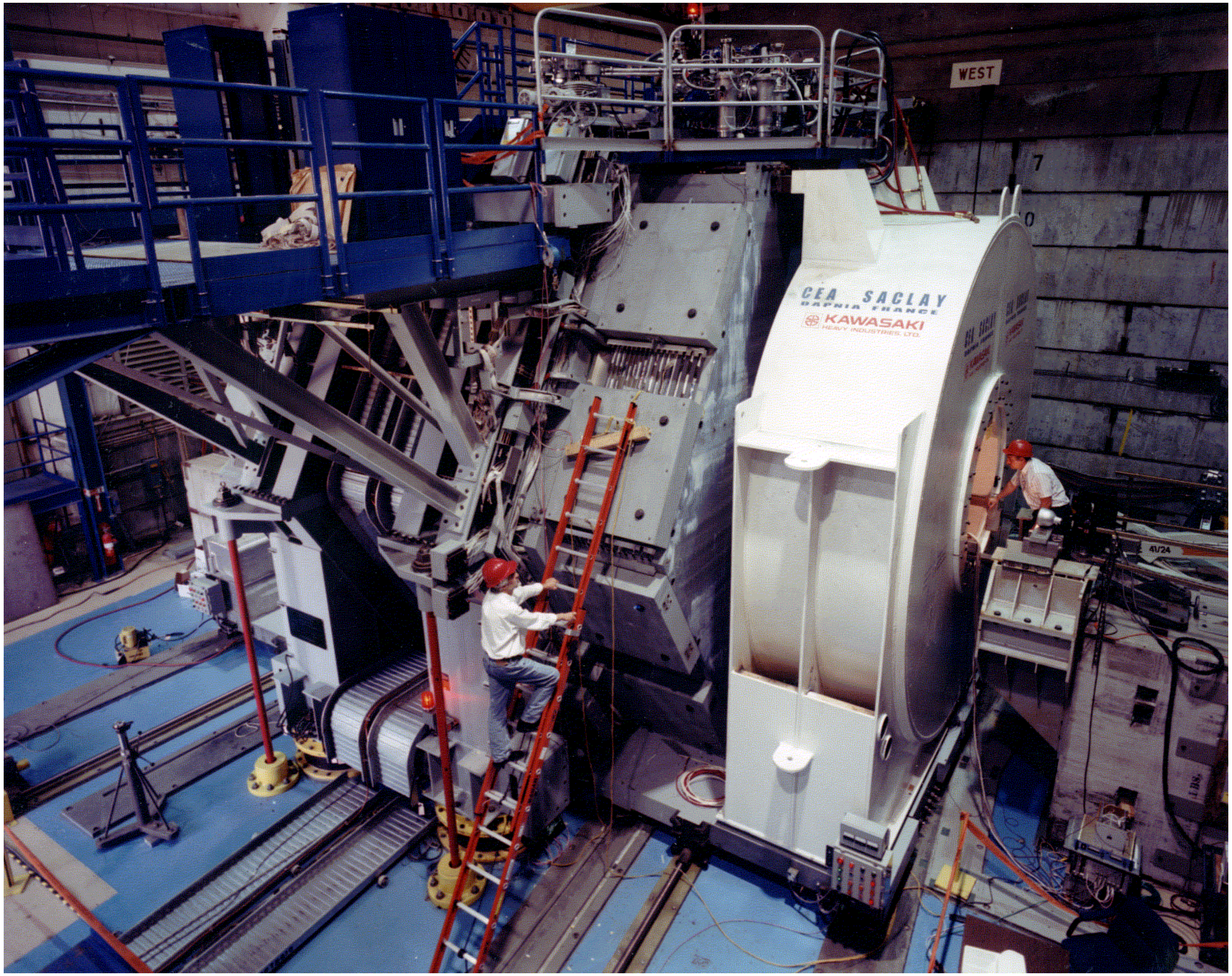
- Provided background field for particle identification for the BaBar detector at SLAC
- Physics requirements dictated a relatively thin solenoid

Properties of BaBar Solenoid

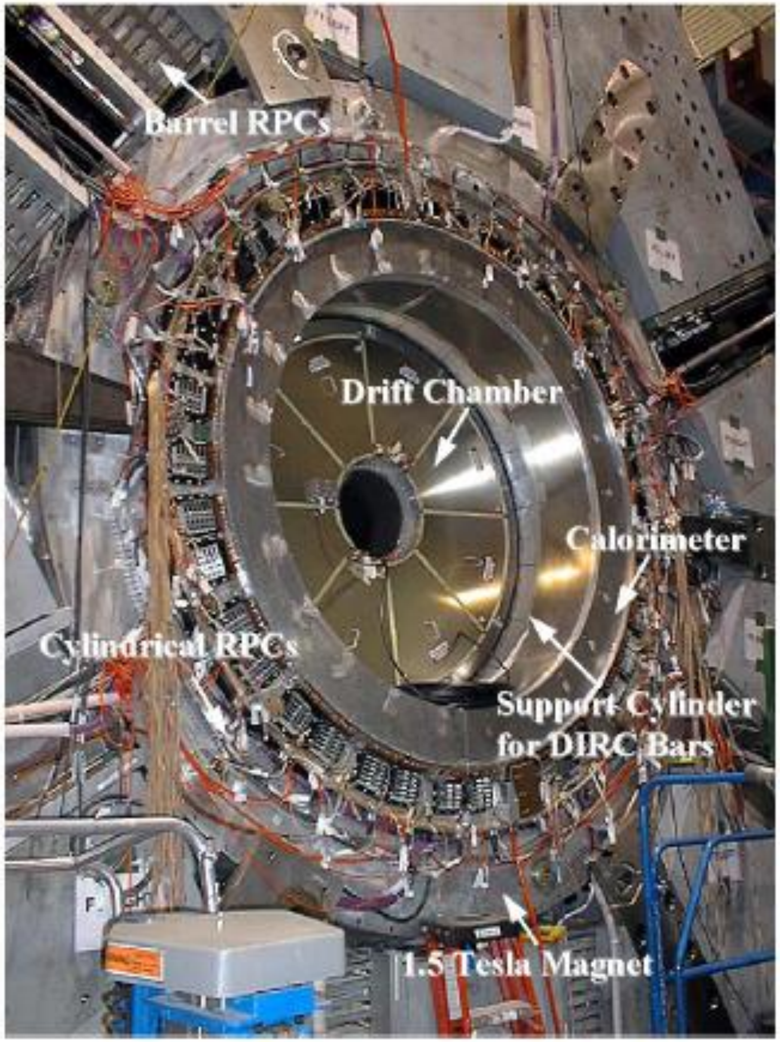
- Field: 1.5 Tesla
- Stored Energy: 27 MJ
- Operating Current: 4596A
- Tc= 8.3K
- Operating Temp: 4.5K
- Total Heat Load at 4.5K: 225liquid-liters/hr
- Cryogenics: indirectly cooled using the force flow technique where the liquid He is circulated in cooling pipes welded to the outside diameter of the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



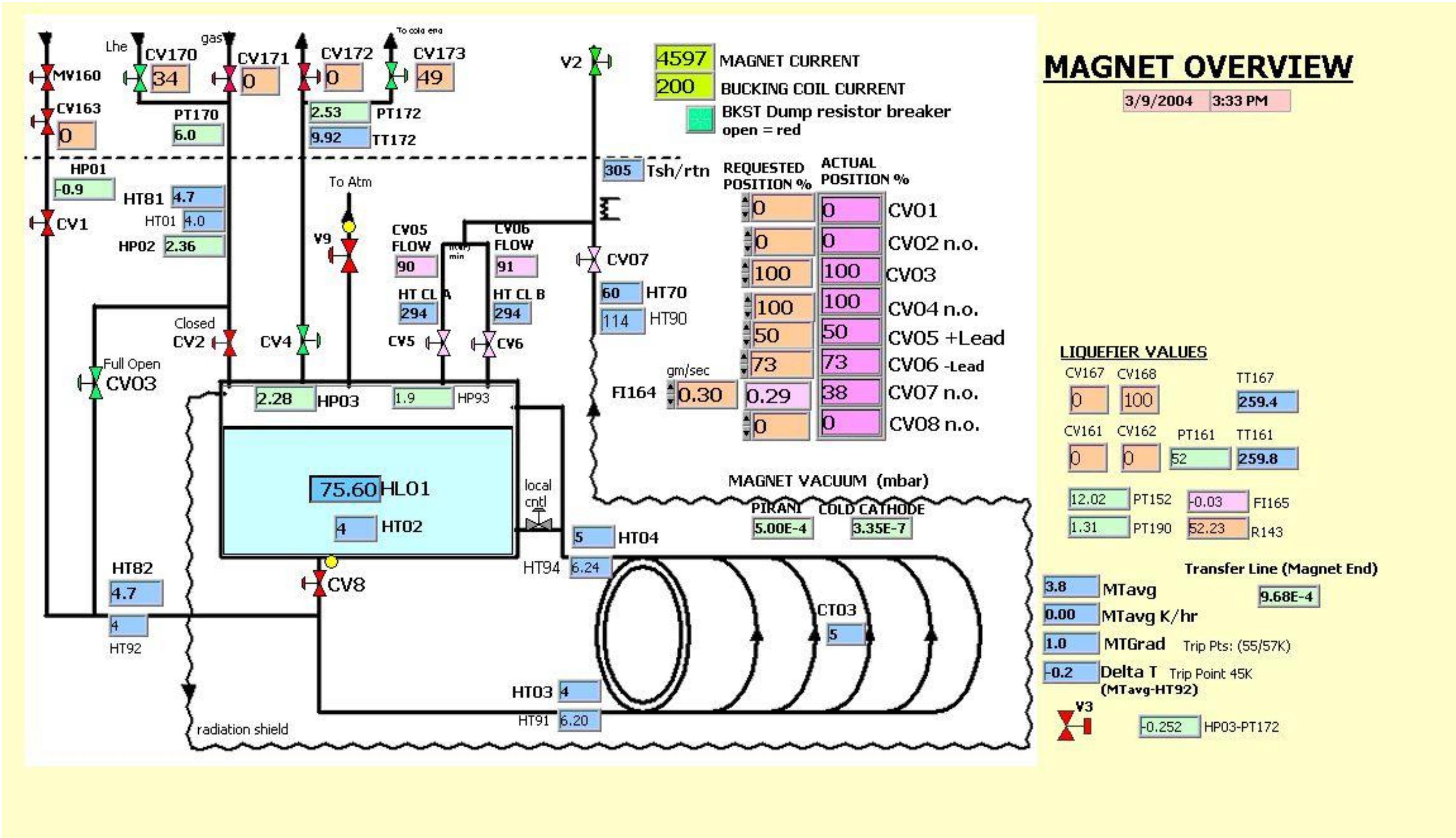
BaBar Detector Under Construction



BaBar Detector



Cryogenic Flow Schematic for BaBar Solenoid



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 HEP accelerators
  - They are also key for MRI systems and heavy ion machines such as FRIB, NSCL 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.
- HEP superconducting magnet requirements have driven and enabled many advances in s/c materials, wire and ancillary systems