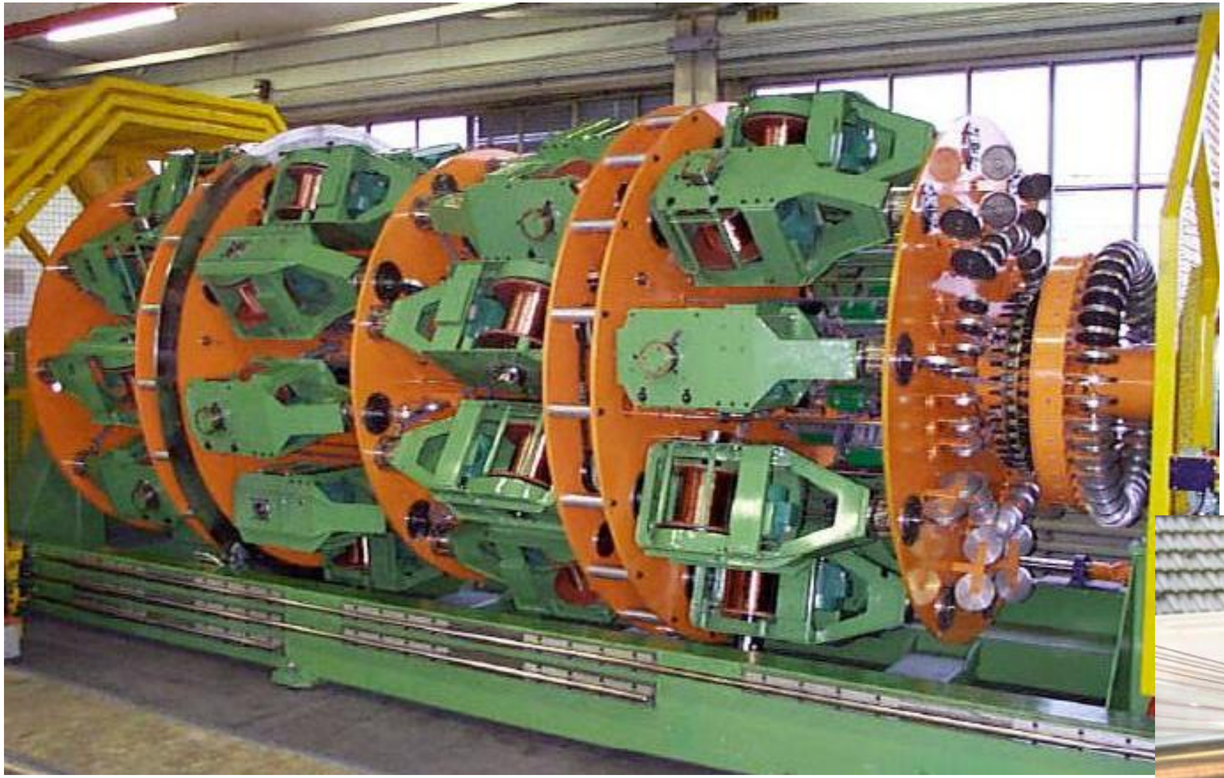
Motivation - Re-cap

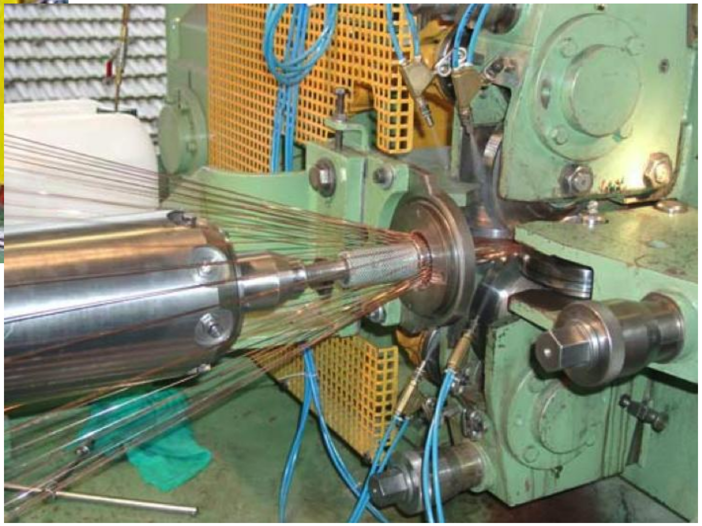
- The main motivation to design magnets using superconductors is to abolish Ohm's law
- This is used either to:
    - Decrease power consumption, and thus improve the performance and operation balance (cost + efficiency) replacing existing technology ⇒ *technology displacer*
    - Allow to reach higher magnetic field, over larger bore and for longer time, allowing new physics or technological opportunities ⇒ *technology enabler*
- *Both these effects are important for accelerators*

Rutherford cable machine @ CERN



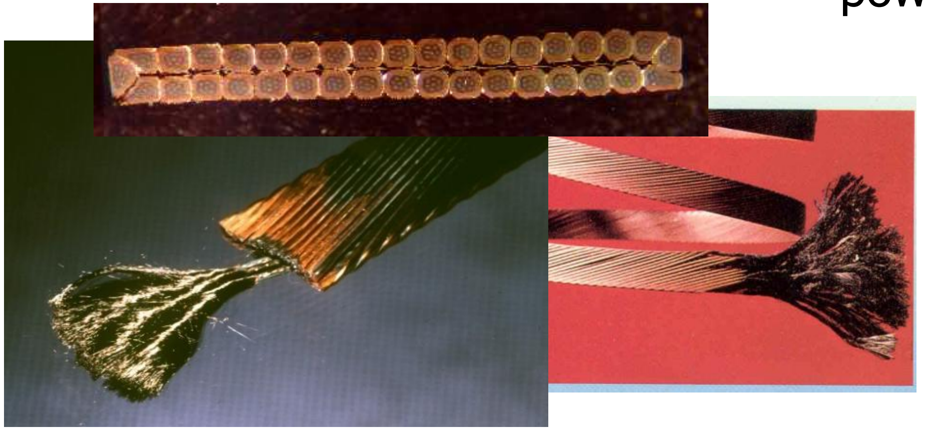
Strand spools on rotating tables

Strands fed through a cabling tongue to shaping rollers

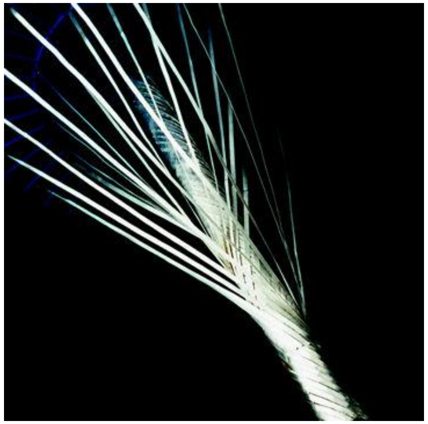


Superconducting cables

Rutherford

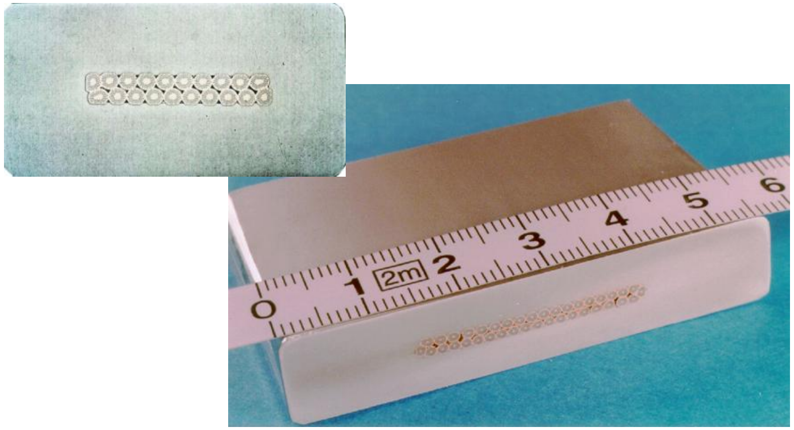


Braids for
power transmission



CICC

Super-stabilized



Internally cooled

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)

Operating margins - Re-cap

- To maximize design and operating margin:
  - Choose a material with high J_C for the desired field
- Logically, we would tend to:
  - Cool-down to the lowest practical temperature ($J_C \Uparrow$)
  - Use a lot of superconductor ($J_E \Uparrow$)
- However ! Superconductor is expensive, and cooling to low temperature is not always optimal. We shall find out:
  - How much margin is really necessary ? (energy spectrum vs. stability)
  - What is the best way to get it ? (AC loss, cooling)
  - What if all goes wrong ? (quench and protection)

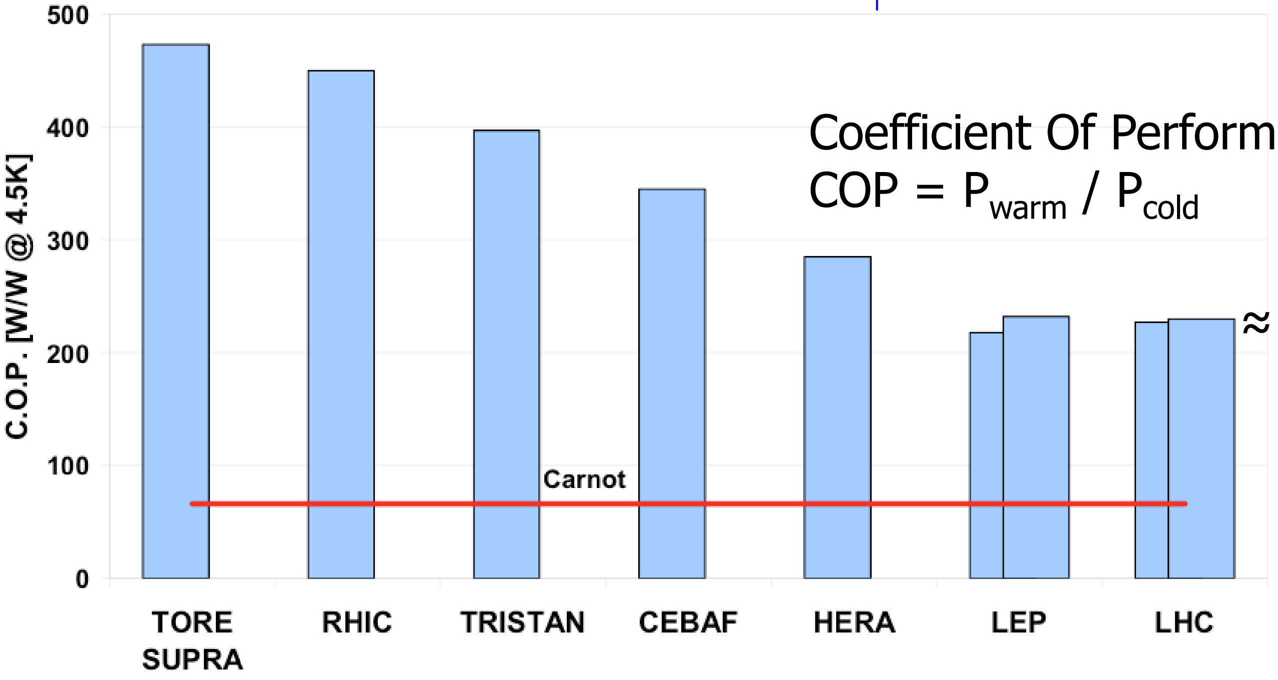
Basic thermodynamics

- The maximum efficiency that can be achieved by a heat machine is that of the Carnot cycle:

Work at the warm end

Heat at the cold end

$$W/Q = (T_{hot} - T_{cold}) / T_{cold}$$



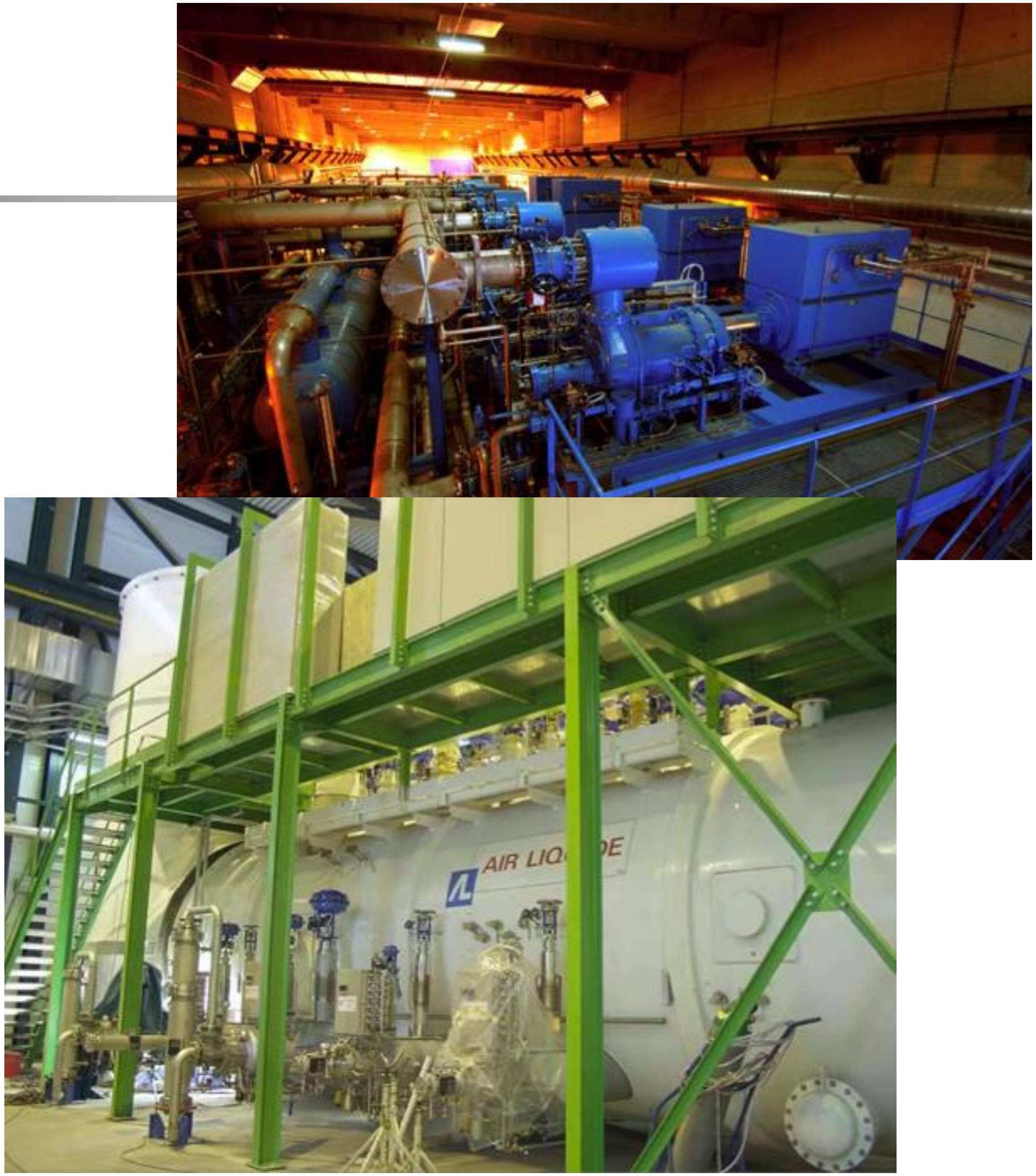
Coefficient Of Performance

$COP = P_{warm} / P_{cold}$

≈ 250

Fridge's

Cryocooler: 0.1 W @ 4 K



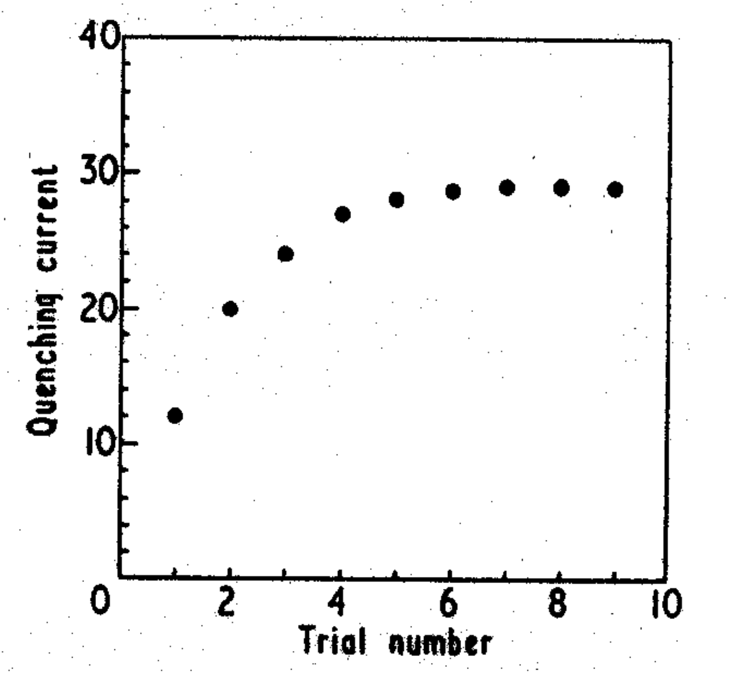
LHC refrigerators: 140 kW @ 4.5 K

Training…

- Superconducting solenoids built from NbZr and Nb_3Sn in the early 60’s quenched much below the rated current …
- … the quench current increased gradually quench after quench: training

M.A.R. LeBlanc, Phys. Rev., **124**, 1423, 1961.

NbZr solenoid
Chester, 1967

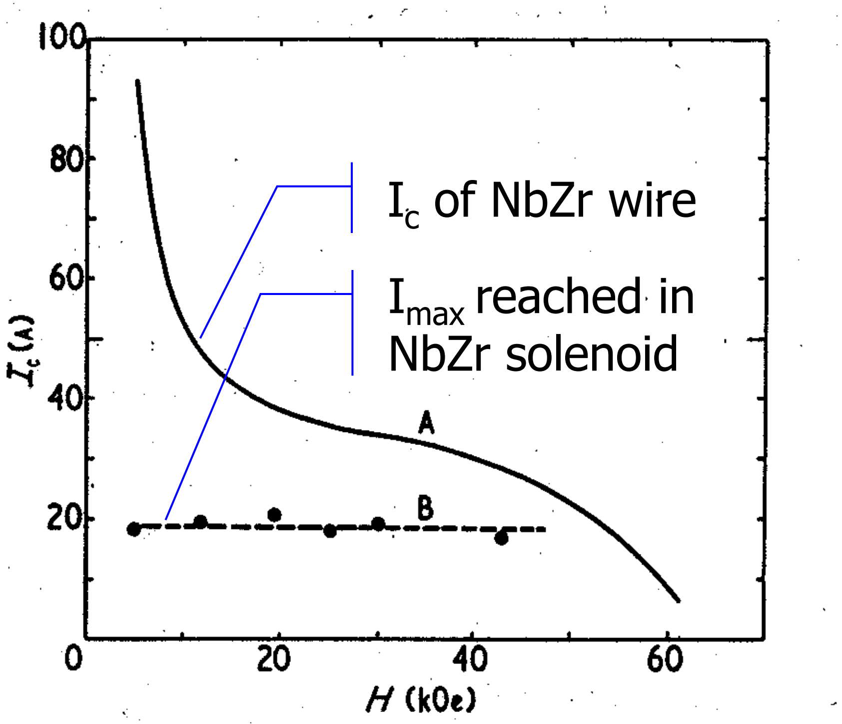


P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

… and degradation

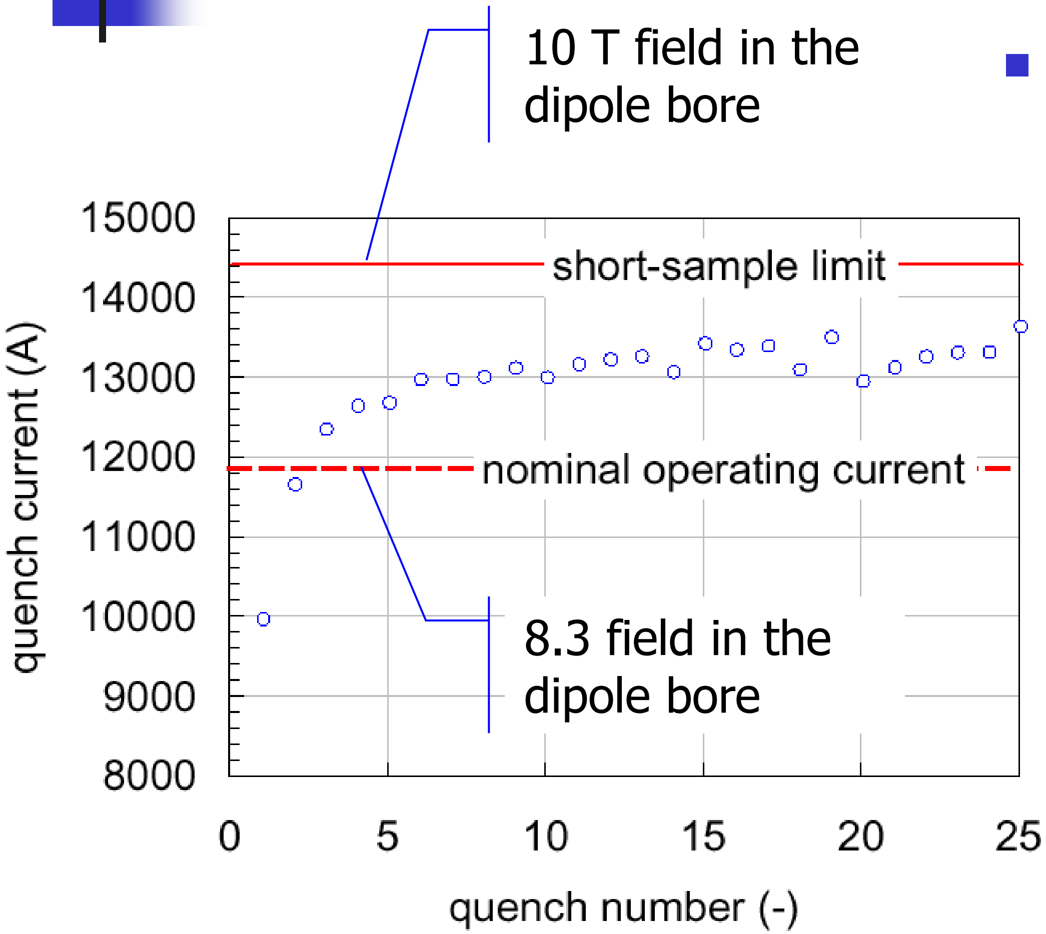
- … but did not quite reach the expected maximum current for the superconducting wire !
- This was initially explained as a local damage of the wire: *degradation*, a very misleading name.
- All this had to do with stability !

NbZr solenoid vs. wire
Chester, 1967



P.F. Chester, Rep. Prog. Phys., **XXX**, II, 561, 1967.

Training today

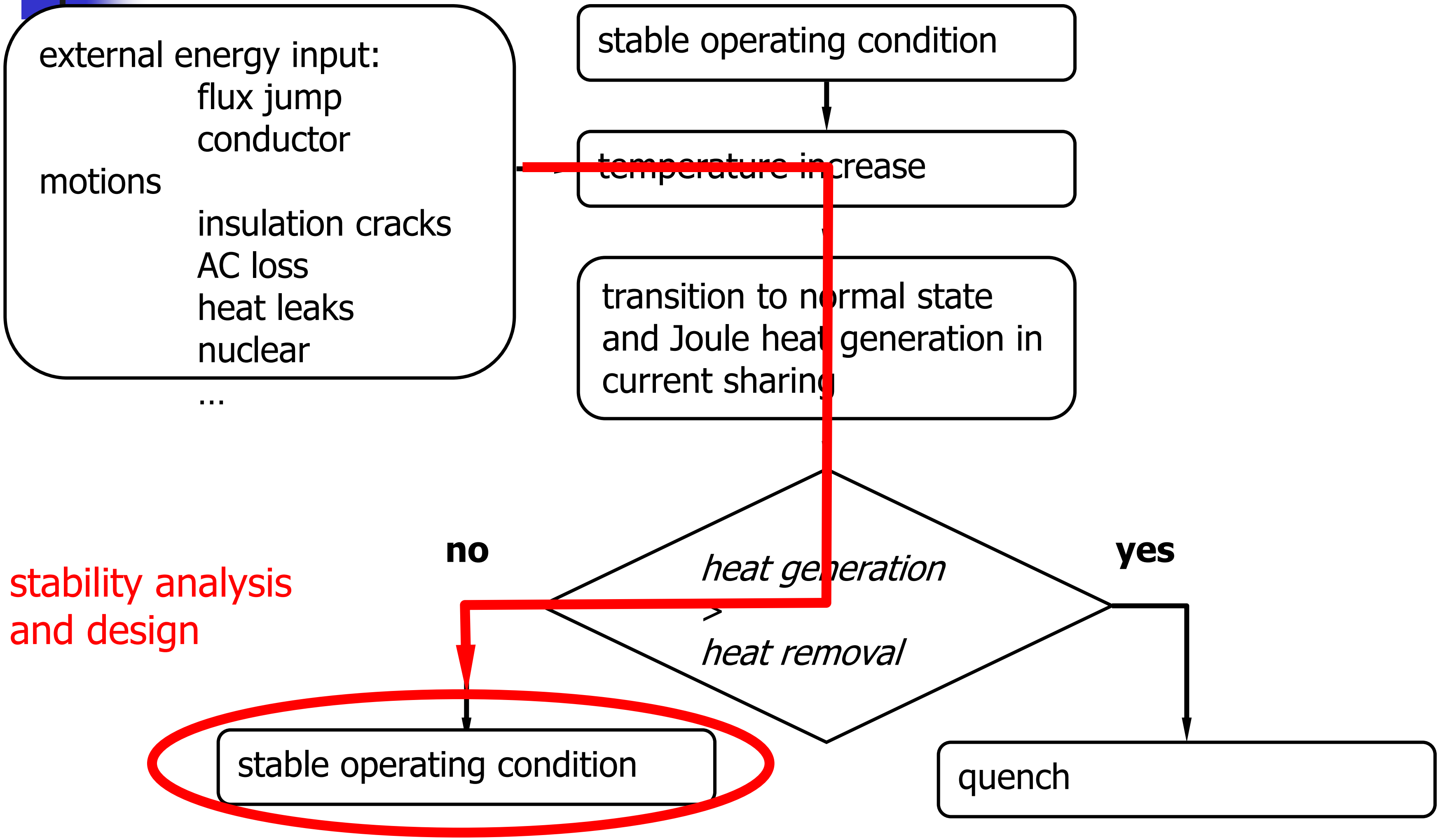


Courtesy of A. Siemko, CERN, 2002

- training of an LHC short dipole model at superfluid helium
  - still (limited) training may be necessary to reach nominal operating current
  - short sample limit is not reached, even after a long training sequence

stability is (still) important !

Why training ?



external energy input:
flux jump
conductor motions
insulation cracks
AC loss
heat leaks
nuclear
…

stable operating condition

temperature increase

transition to normal state and Joule heat generation in current sharing

heat generation > heat removal

no

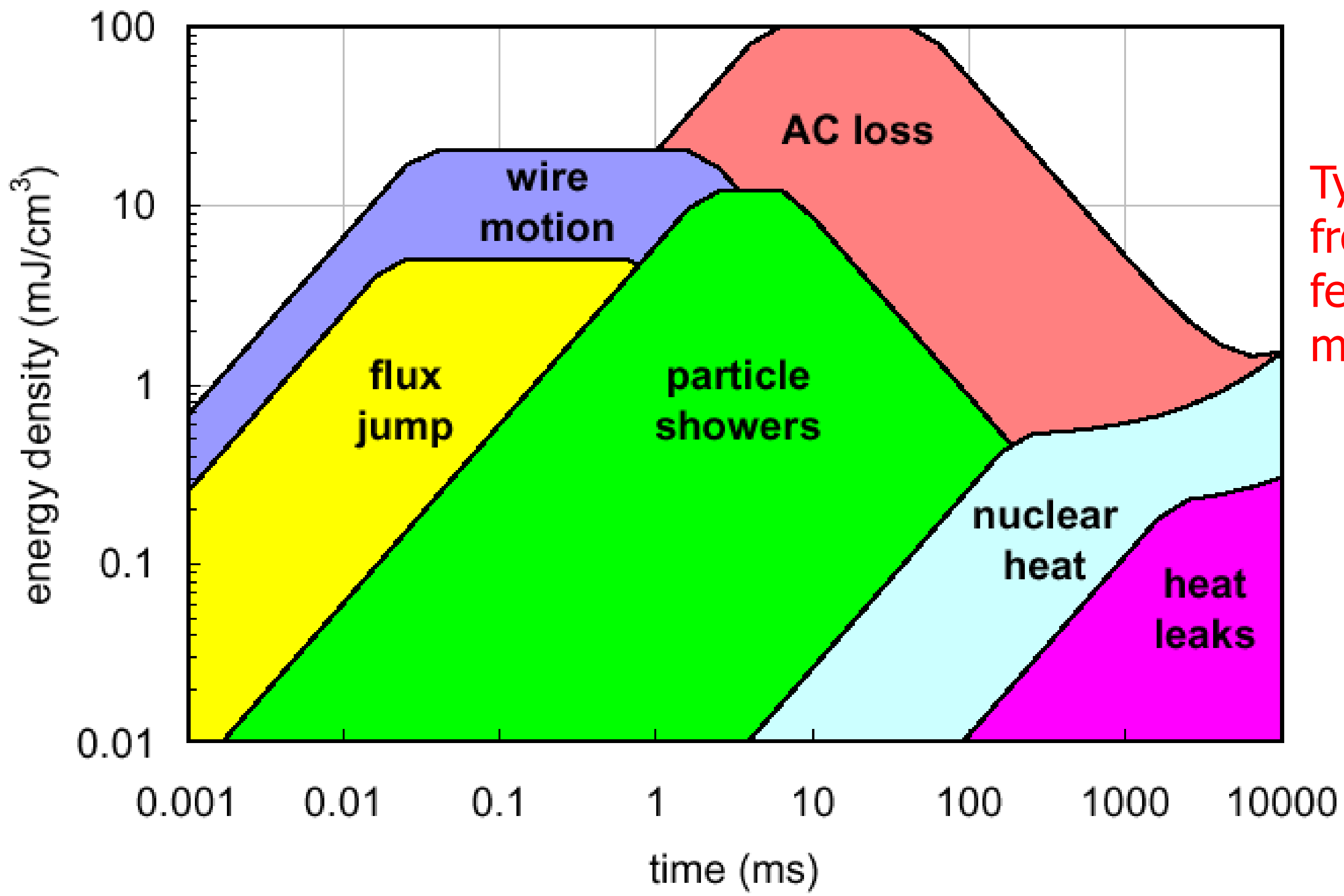
stable operating condition

yes

quench

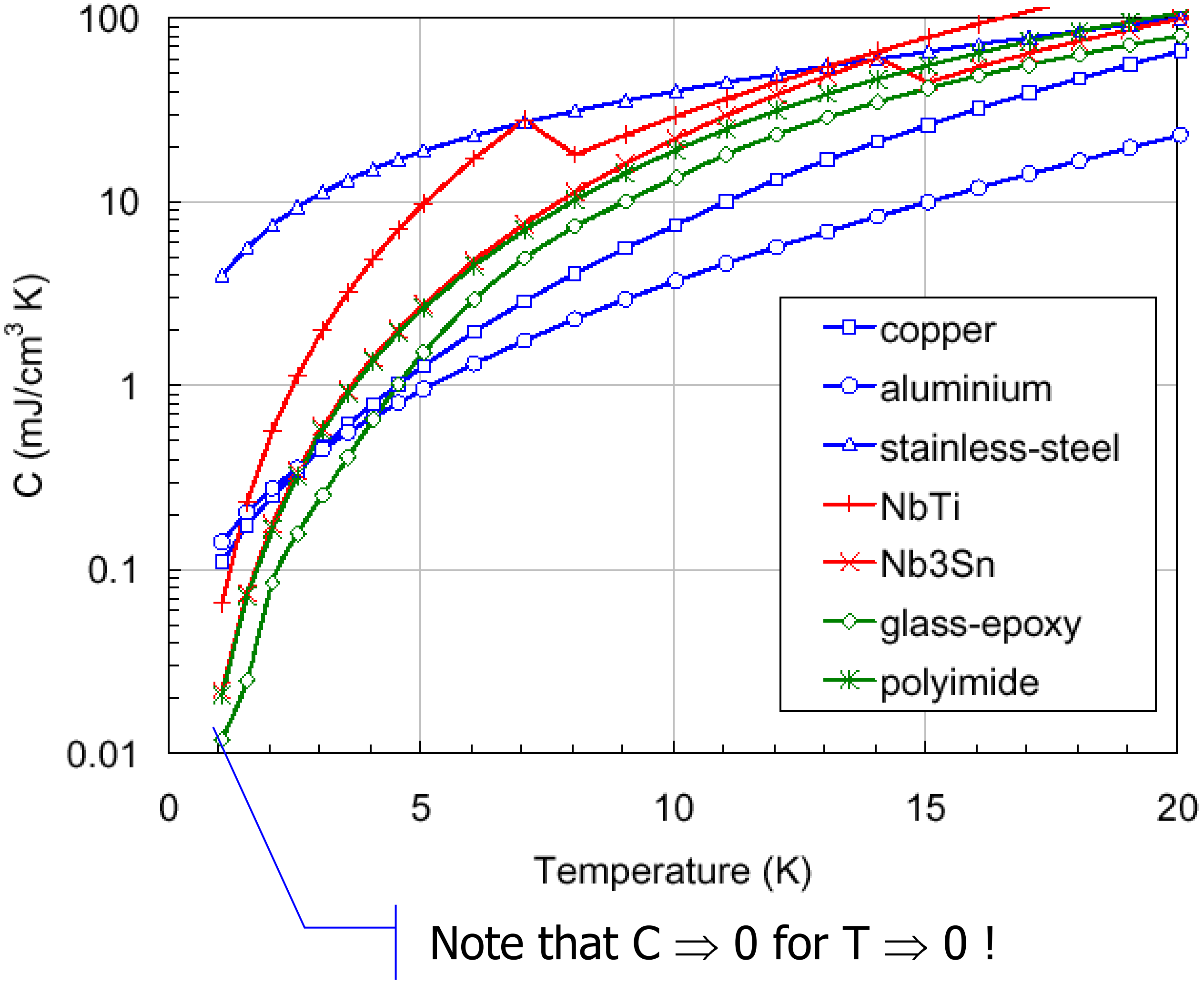
stability analysis and design

Perturbation overview



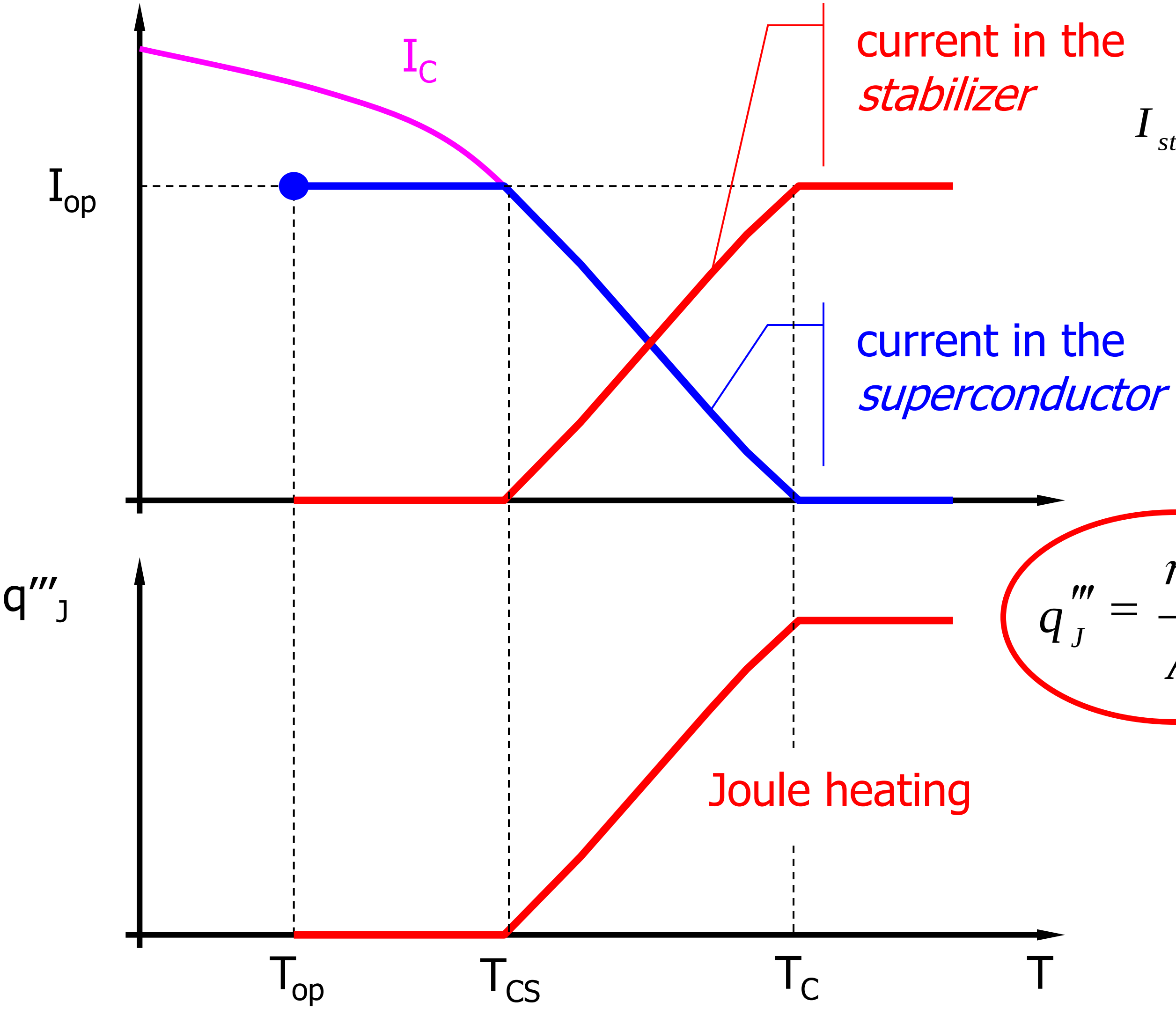
Typical range is from a few to a few tens of mJ/cm^3

Low temperature heat capacity



Note that C ⇒ 0 for T ⇒ 0 !

Joule heating



$$I_{st} = I_{op} - I_c$$

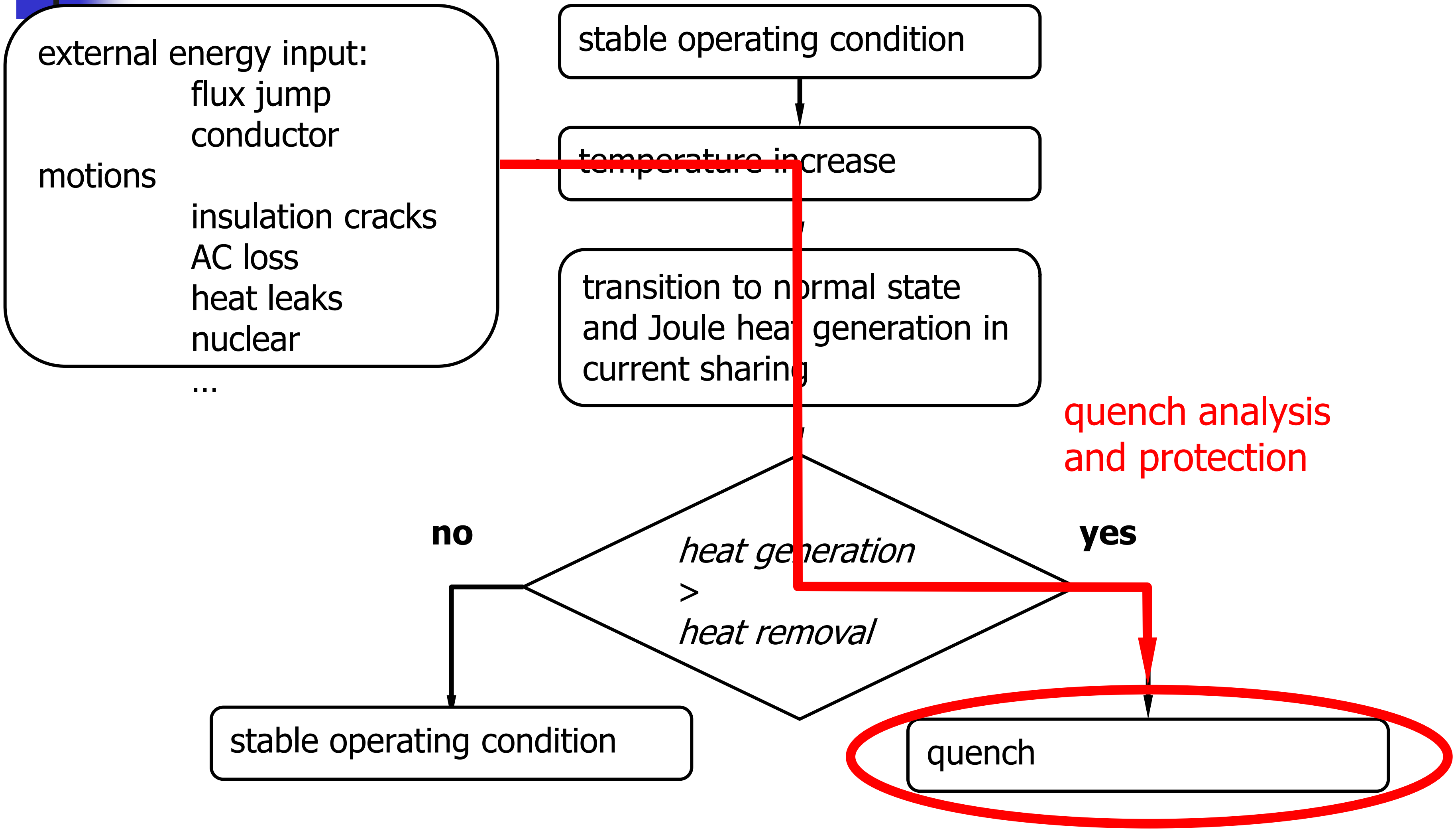
$$I_{sc} = I_c$$

$$q'''_J = \frac{\eta_{st}}{A_{st}} \frac{I^2}{A}$$

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 is a quench ?



external energy input:
flux jump
conductor motions
insulation cracks
AC loss
heat leaks
nuclear
…

stable operating condition

temperature increase

transition to normal state and Joule heat generation in current sharing

heat generation
\>
heat removal

no

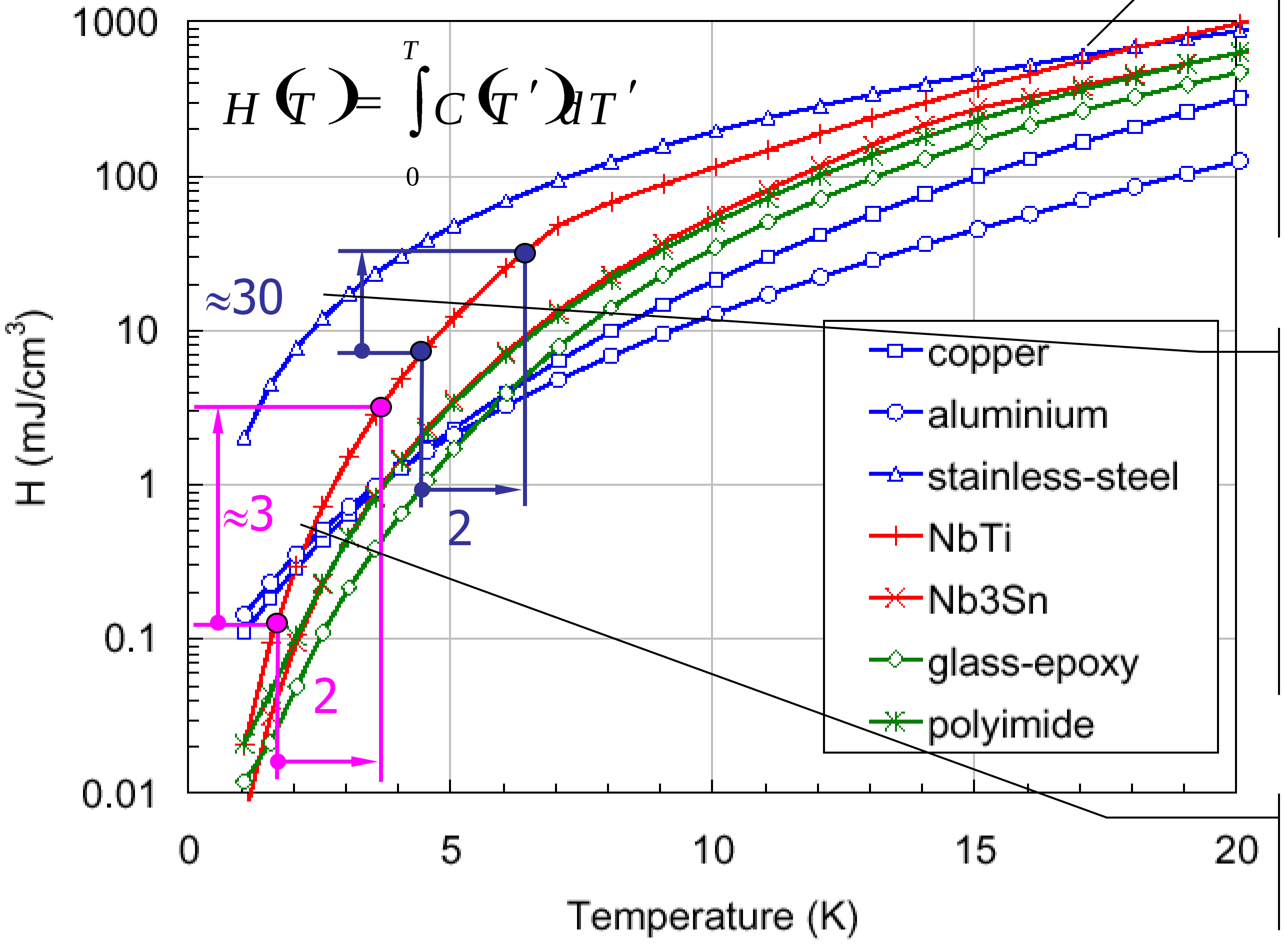
stable operating condition

yes

quench

quench analysis and protection

Enthalpy reserve



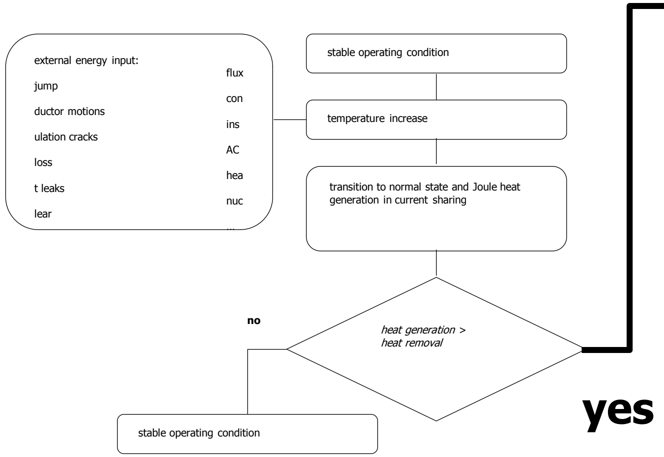
$$H(T) = \int_0^T C(T')\,dT'$$

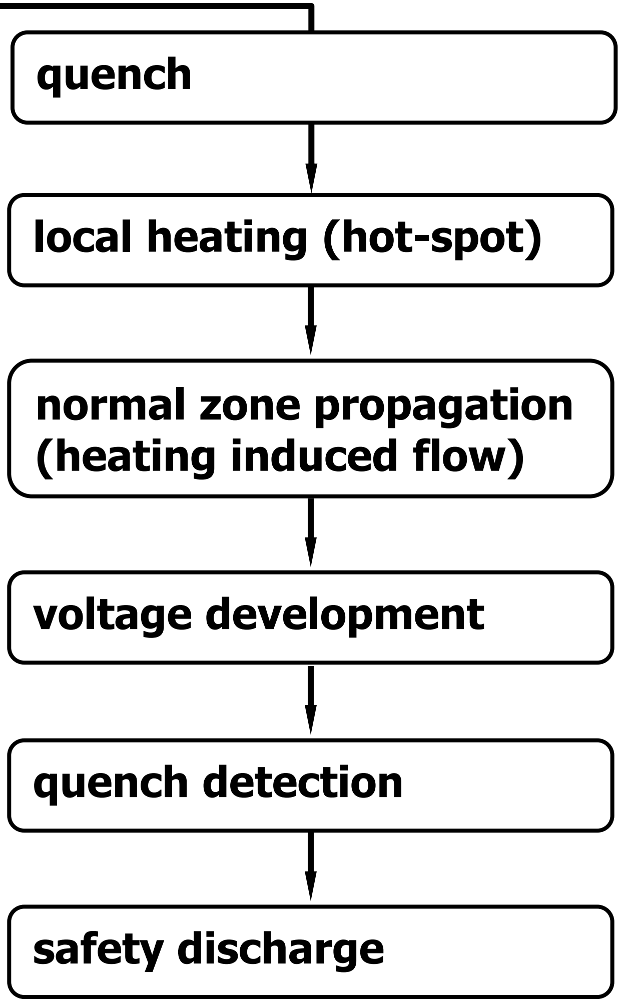
Enthalpy reserve increases massively at increasing T: stability is not an issue for HTS materials

Enthalpy reserve is of the order of the expected perturbation spectrum: stability is an issue for LTS magnets

do not sub-cool if you can only avoid it !

Quench sequence





quench

local heating (hot-spot)

normal zone propagation (heating induced flow)

voltage development

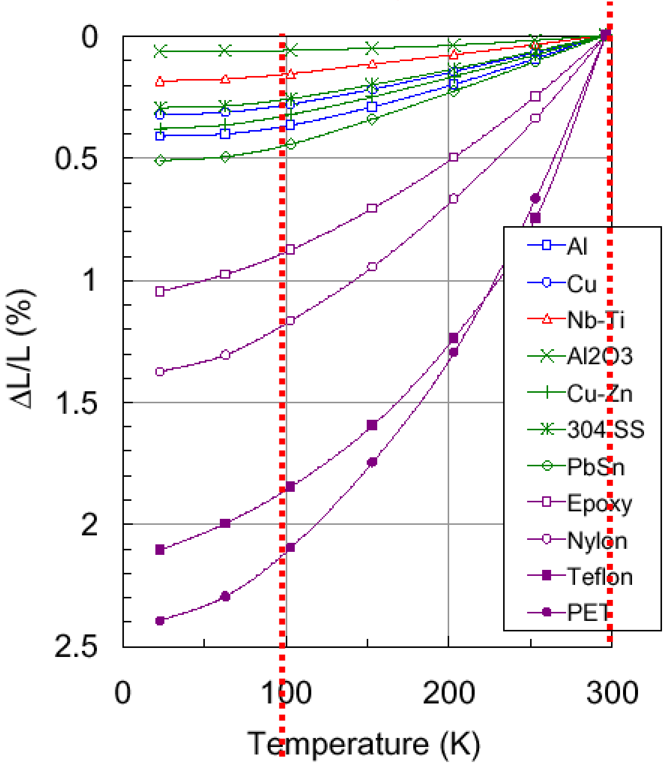
quench detection

safety discharge

A quench is a part of the normal life of a superconducting magnet. Appropriate detection and protection strategies should be built in the design from the start

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)

B.J. Maddock, G.B. James, Proc. IEE, **115** (4), 543, 1968

Adiabatic hot spot temperature

- adiabatic conditions at the hot spot :

$$C\frac{\partial T}{\partial t} = q'''_{J}$$

where:

$$q'''_{J} = \frac{\eta_{st}}{A_{st}}\frac{I^{2}}{A}$$

- can be integrated:

total volumetric heat capacity

stabilizer resistivity

stabilizer fraction

cable operating current density

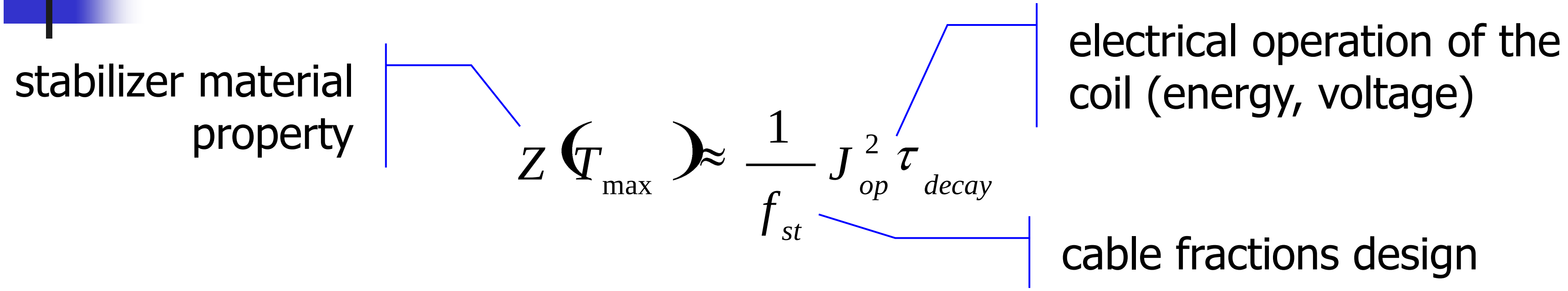
$$\int_{T_{op}}^{T_{\max}} \frac{C}{\eta_{st}}\, dT = \frac{1}{f_{st}}\int_{0}^{\infty} J^{2}\, dt$$

$$\boxed{Z(T_{\max}) = \int_{T_{op}}^{T_{\max}} \frac{C}{\eta_{st}}\, dT}$$

$$\boxed{\int_{0}^{\infty} J^{2}\, dt \approx J_{op}^{2}\,\tau_{decay}}$$

The function $Z(T_{max})$ is a *cable property*

How to limit T_{max}



stabilizer material property

electrical operation of the coil (energy, voltage)

$$Z\left(T_{\max}\right) \approx \frac{1}{f_{st}} J_{op}^{2} \tau_{decay}$$

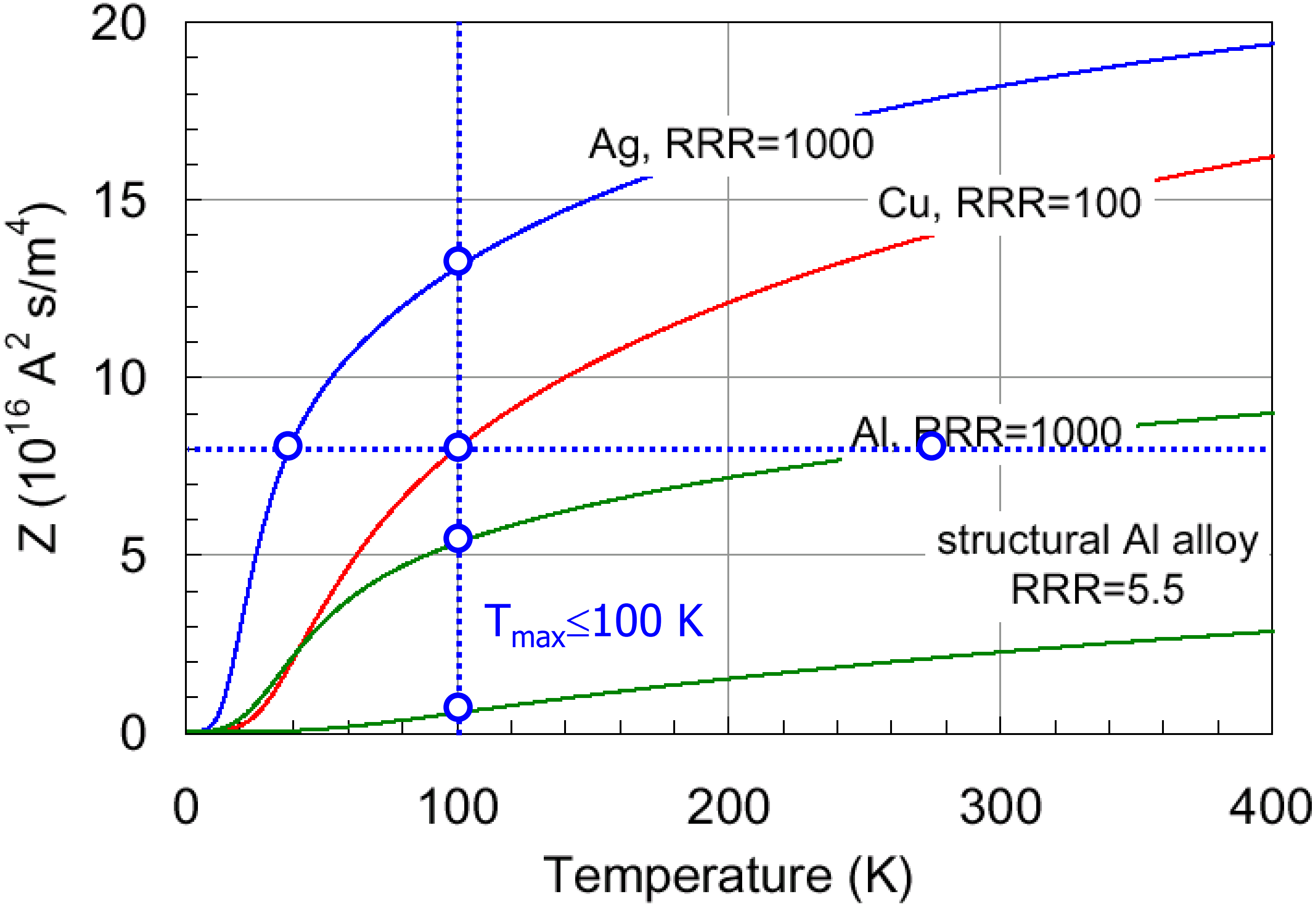
cable fractions design

implicit relation between T_{max} , f_{st} , J_{op} , τ_{decay}

- to decrease T_{max}
  - reduce operating current density (J_{op}⇓)
  - discharge quickly (τ_{decay}⇓)
  - add stabilizer (f_{st}⇑)
  - choose a material with large $Z(T_{max})$ ⇑

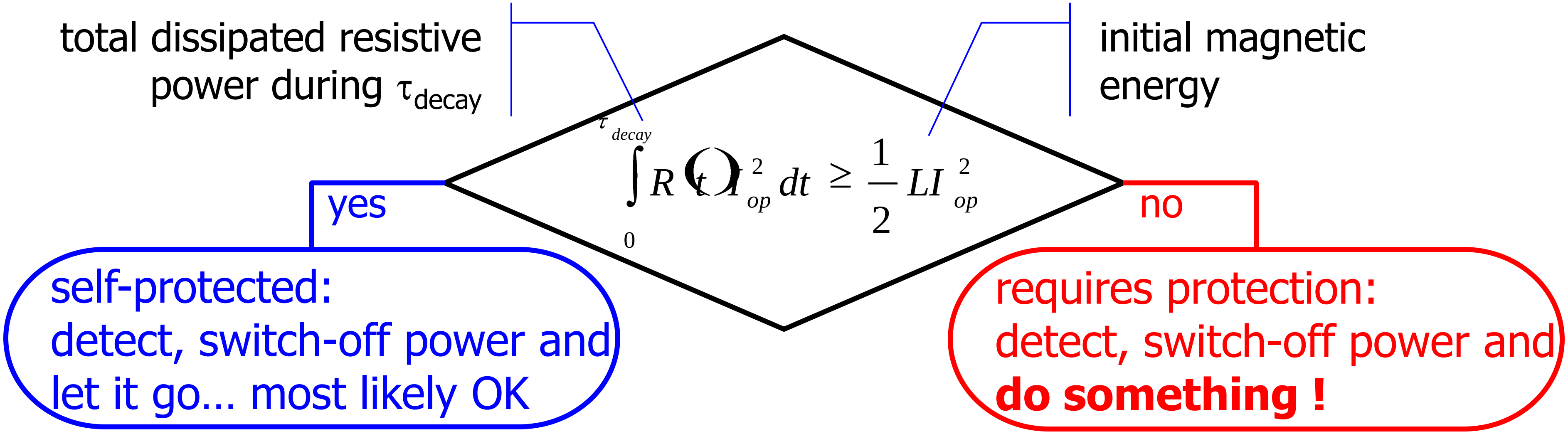
$$Z\left(T_{\max}\right) \approx \frac{1}{f_{st}} J_{op}^{2} \tau_{decay}$$

Z(T_{max}) for typical stabilizers



Quench protection

- The magnet stores a magnetic energy 1/2 L I²
- During a quench it dissipates a power R I² 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

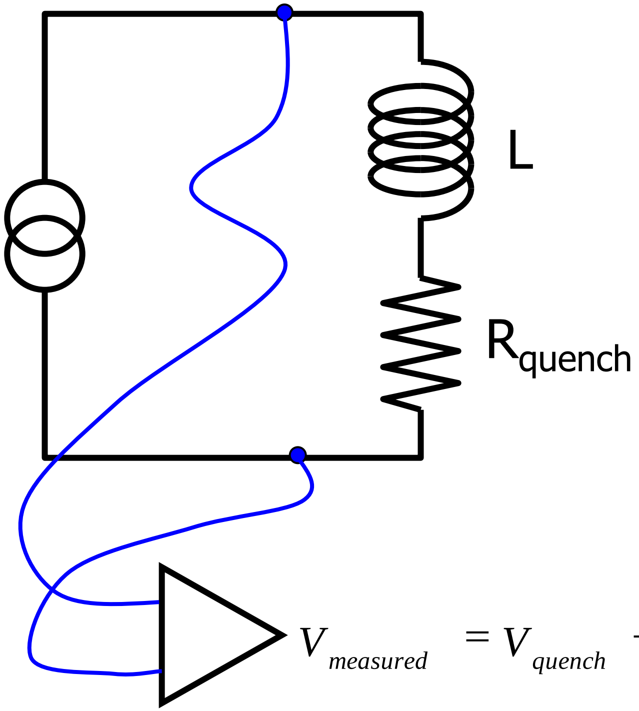
requires protection:
detect, switch-off power and **do something !**

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

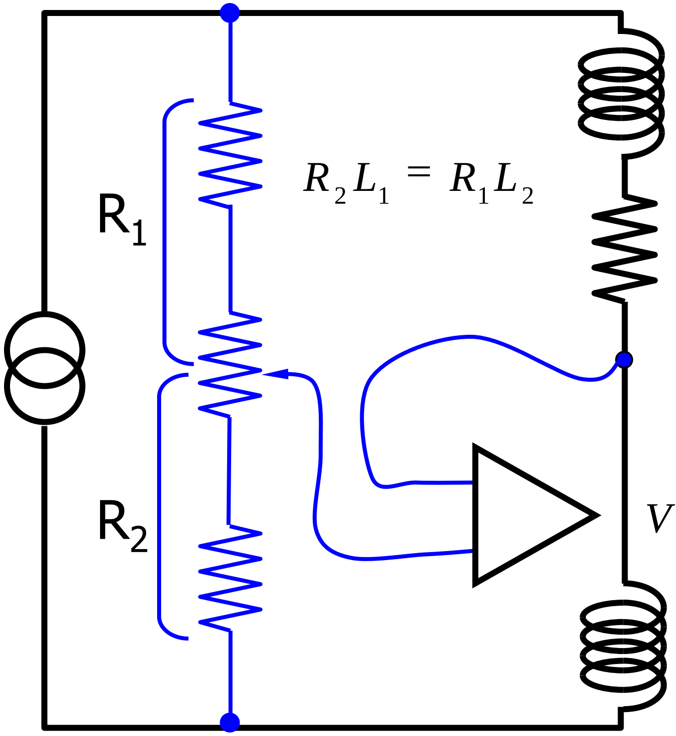
Quench detection: voltage

- a direct quench voltage measurement is subject to inductive pick-up (ripple, ramps)

- immunity to inductive voltages (and noise rejection) is achieved by *compensation*



$$V_{measured} = V_{quench} + \boxed{L\frac{dI}{dt}}$$

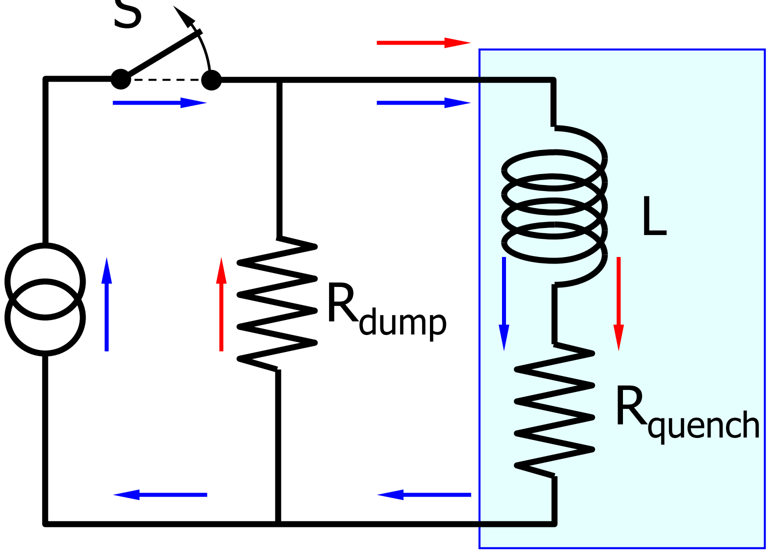


$$R_2 L_1 = R_1 L_2$$

$$V_{measured} = V_{quench}$$

B.J. Maddock, G.B. James, Proc. Inst. Electr. Eng., **115**, 543, 1968

Strategy 1: 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})

Dump time constant

- magnetic energy:

$$E_m = \frac{1}{2} L I_{op}^2$$

- maximum terminal voltage:

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

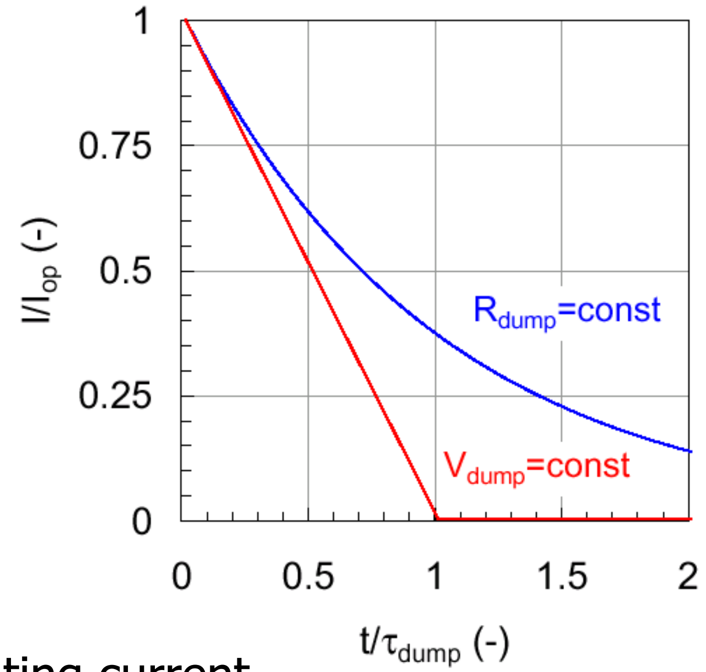
- dump time constant:

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

maximum terminal voltage

operating current

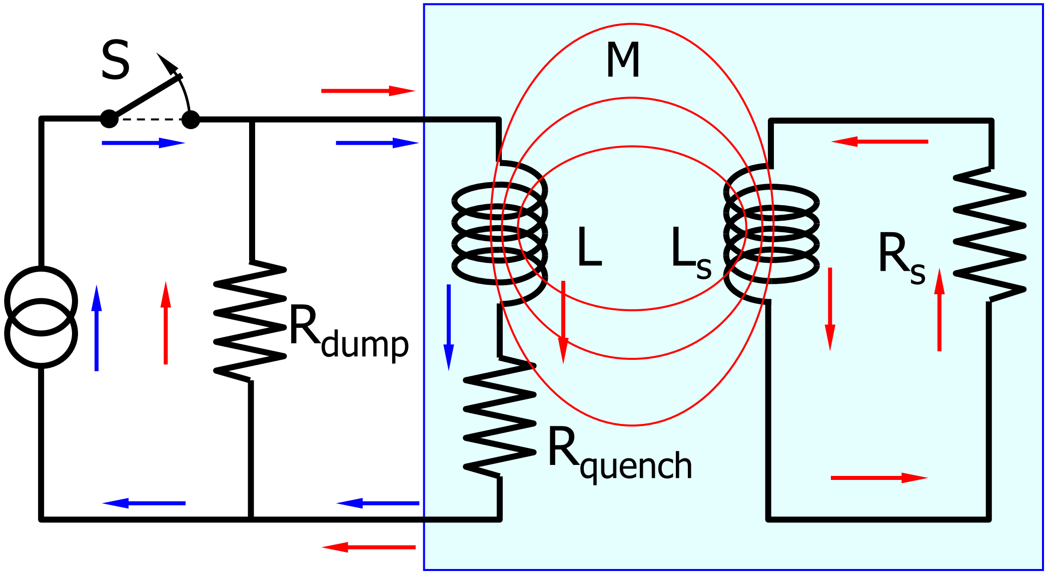
interesting alternative:
non-linear R_{dump} or voltage source



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

Strategy 2: coupled secondary

- the magnet is coupled inductively to a secondary that absorbs and dissipates a part of the magnetic energy



- advantages:
  - magnetic energy partially dissipated in R_s (lower T_{max})
  - lower effective magnet inductance (lower voltage)
  - heating of R_s can be used to speed-up quench propagation (quench-back)
- disadvantages:
  - induced currents (and dissipation) during ramps

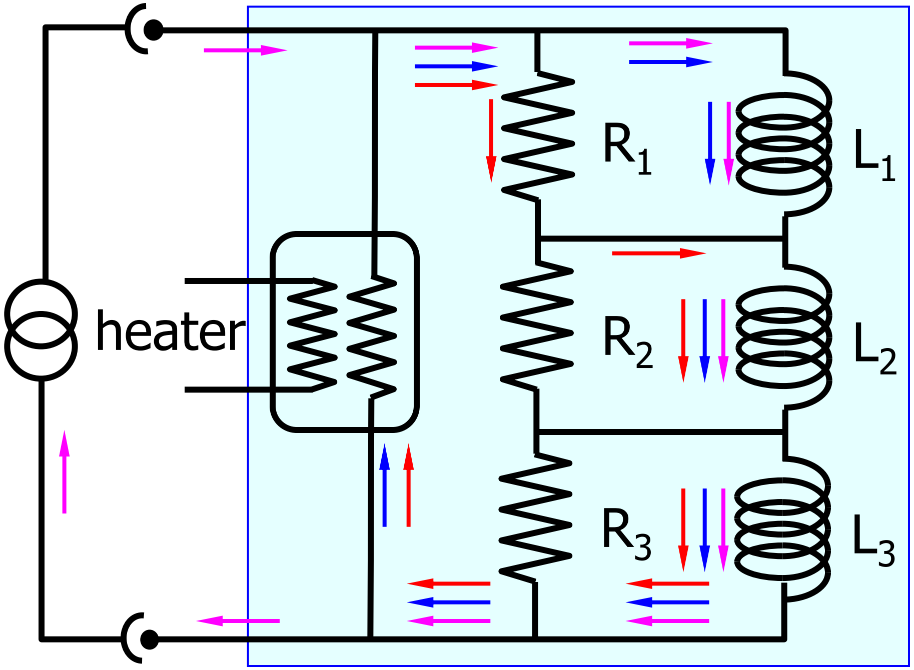
← normal operation

← quench

P.F. Smith, Rev. Sci. Instrum., **34** (4), 368, 1963.

Strategy 3: subdivision

- the magnet is divided in sections, with each section shunted by an alternative path (resistance) for the current in case of quench



- advantages:
  - passive
  - only a fraction of the magnetic energy is dissipated in a module (lower T_{max})
  - transient current and dissipation can be used to speed-up quench propagation (quench-back)
- disadvantages:
  - induced currents (and dissipation) during ramps

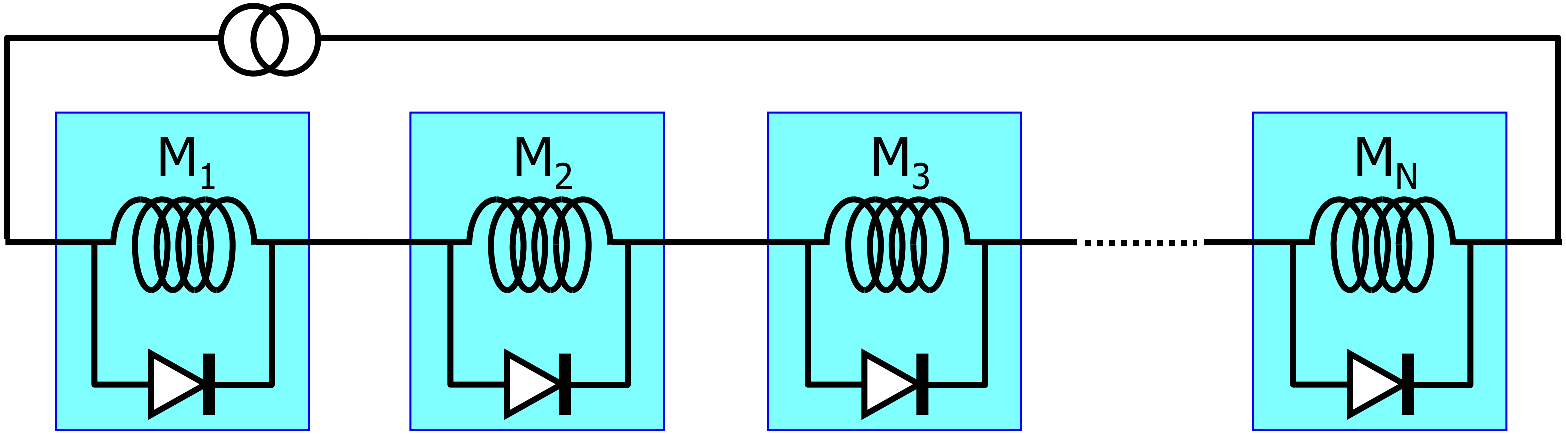
← charge

← normal operation

← quench

Magnet strings

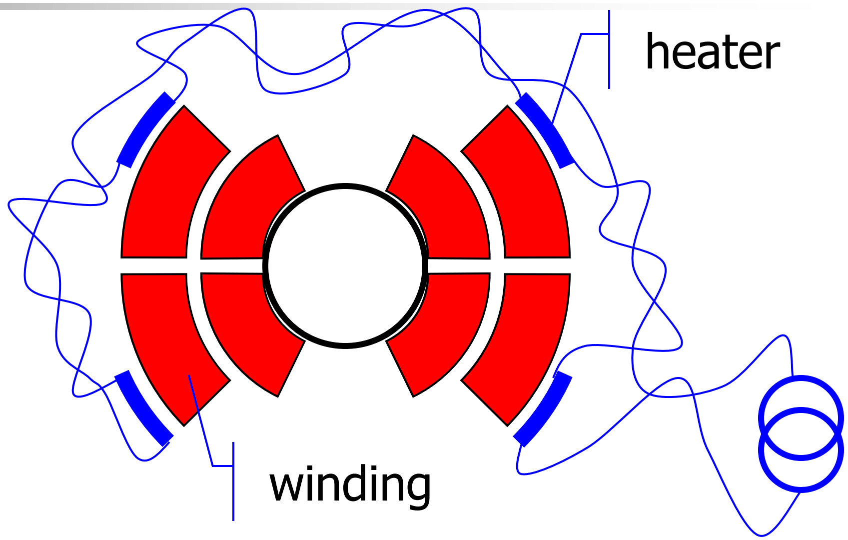
- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
    - energy dump takes very long time (10…100 s)
    - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
    - the diode acts as a shunt during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



Strategy 4: heaters

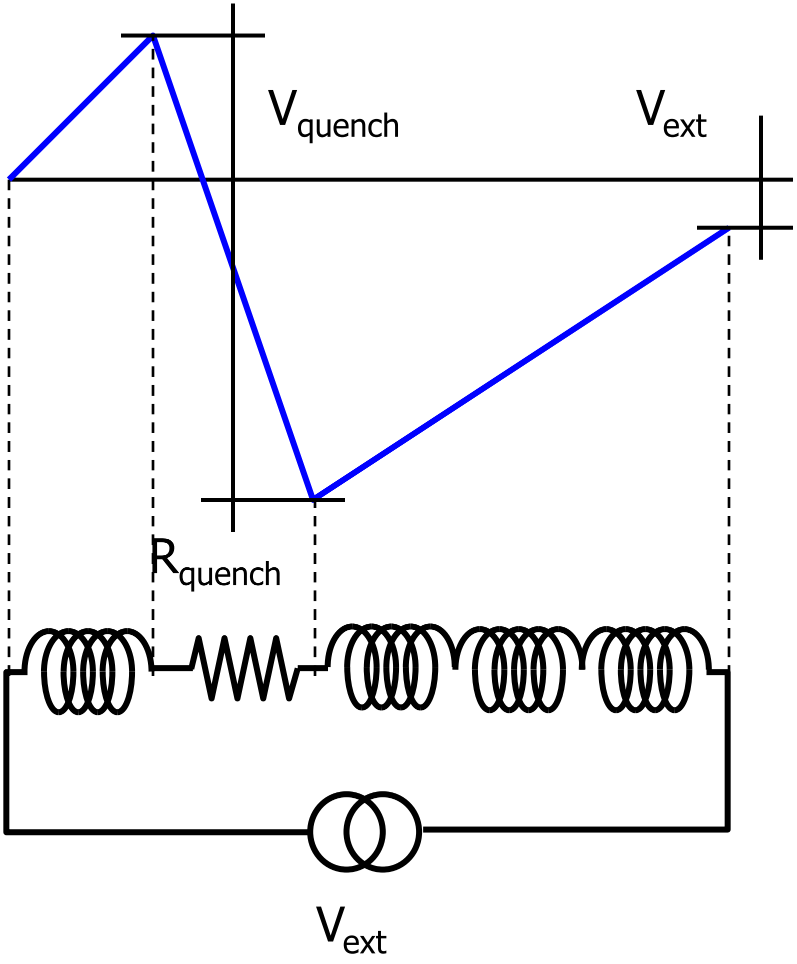
- the quench is spread actively by firing heaters embedded in the winding pack, in close vicinity to the conductor

- 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

Quench voltage



- electrical stress can cause serious damage (arcing) to be avoided by proper design:
  - insulation material
  - insulation thickness
  - electric field concentration
- REMEMBER: in a quenching coil the maximum voltage is not necessarily at the terminals
- the situation in subdivided and inductively coupled systems is complex, may require extensive simulation

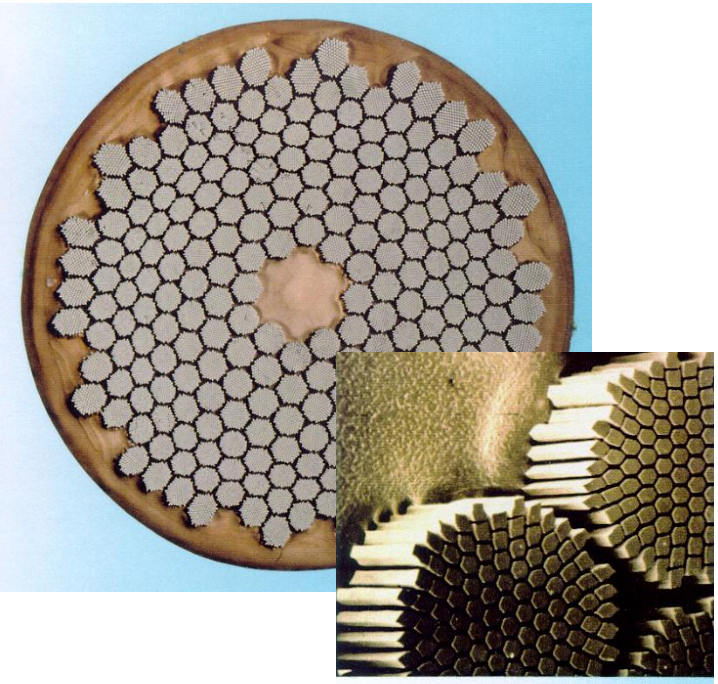
Quench and protection - Re-cap

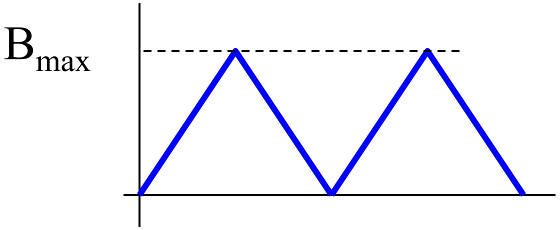
- A good conducting material (Ag, Al, Cu: large $Z(T_{max})$) must be added in parallel to the superconductor to limit the maximum temperature during a quench
- The effect of a quench can be mitigated by
  - Adding stabilizer (⇔ operating margin, stability)
  - Reducing operating current density (⇔ economics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

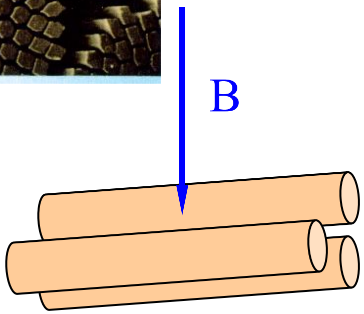
Overview

- Why superconductors ? A motivation
- A superconductor physics primer
- Superconducting magnet design
  - Wires, tapes and cables
  - Operating margins
  - Cooling of superconducting magnets
  - Stability, quench and protection
  - AC loss
- The making of a superconducting magnet
- Examples of superconducting magnet systems

A superconductor in varying field

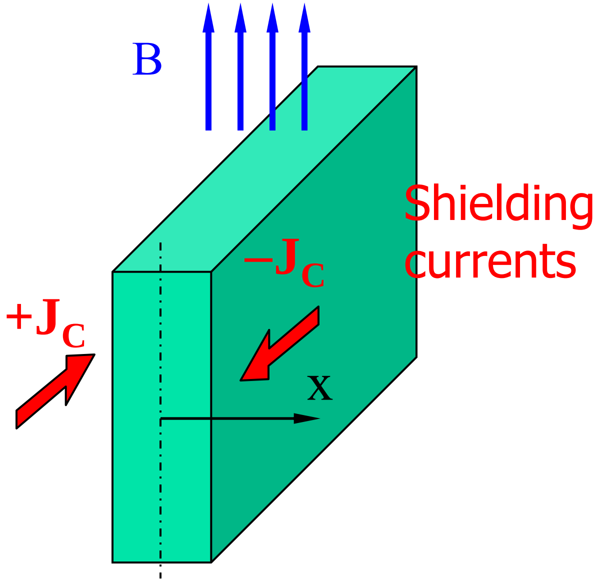






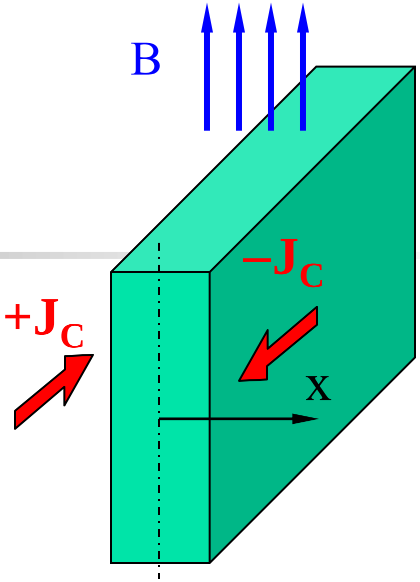
A filament in a time-variable field

A simpler case: an infinite slab in a uniform, time-variable field



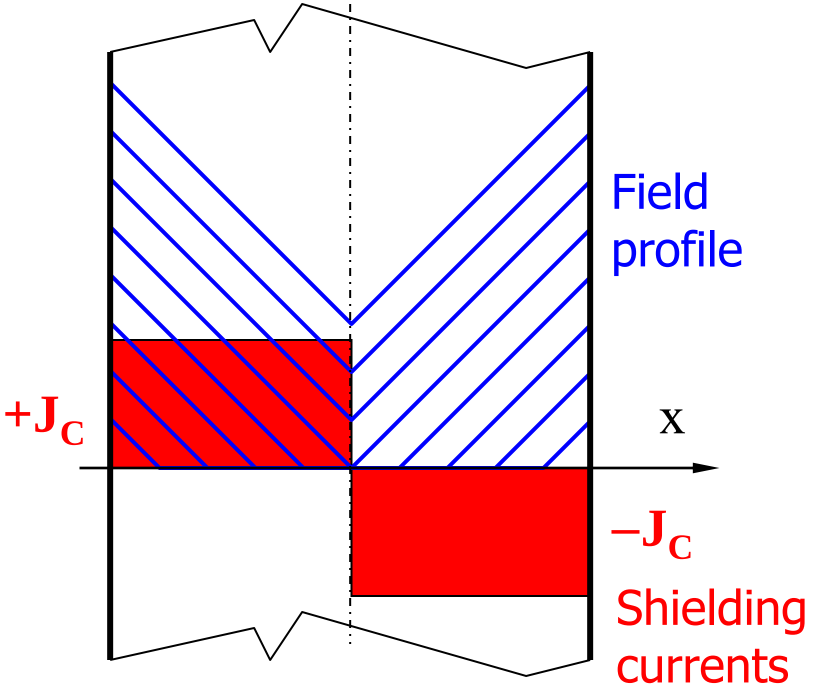
Quiz: how much is J ?

Persistent currents

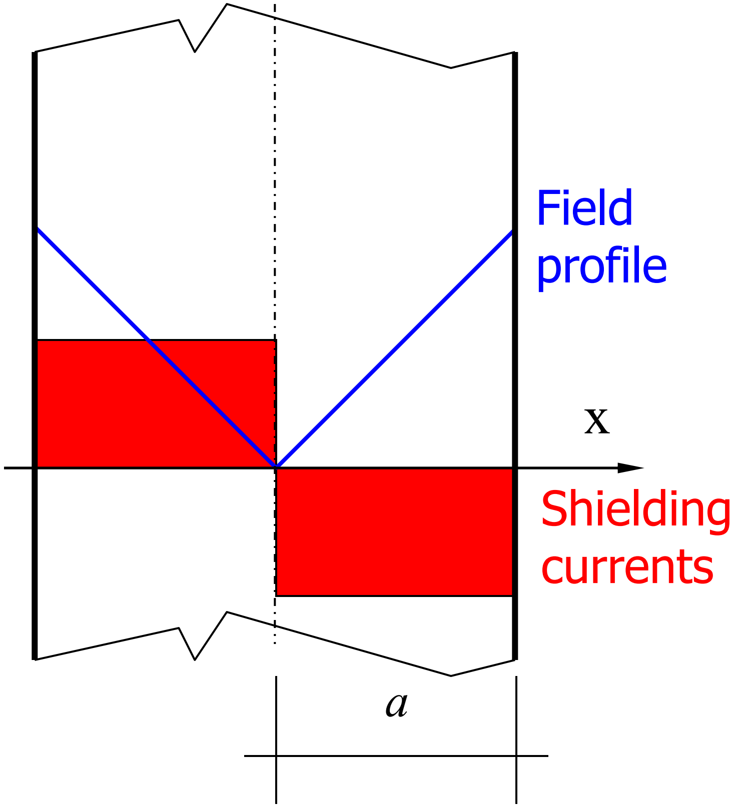


- dB/dt produces an electric field E in the superconductor which drives it into the resistive state
- When the field sweep stops the electric field vanishes E ⇒ 0
- The superconductor goes back to J_C and then stays there
- This is the critical state (Bean) model: *within a superconductor, the current density is either* $+J_C$, $-J_C$ *or zero, there's nothing in between!*

$$J = \pm J_C$$



Magnetization



- Seen from outside the sample, the persistent currents produce a magnetic moment. We can define a *magnetization*:

$$M = \frac{1}{a}\int_0^a J_c \, x \, dx = \frac{J_c a}{2}$$

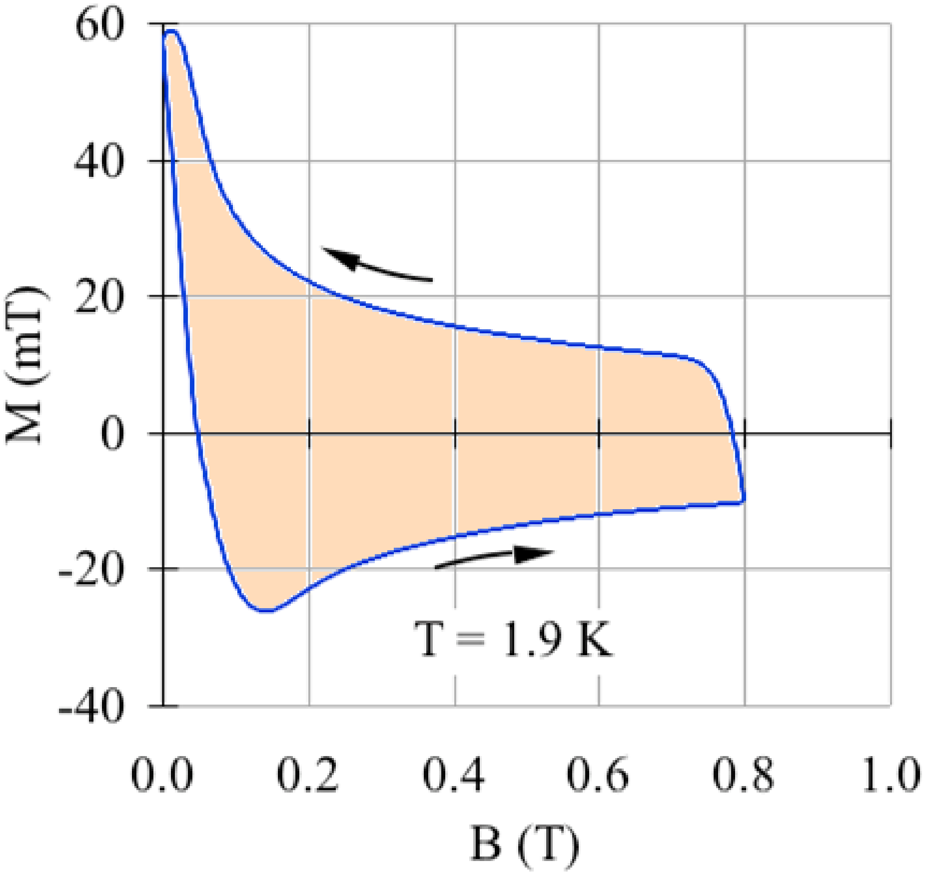
- The magnetization is proportional to the critical current density and to the size of the superconducting slab

Hysteresis loss

- The response of a superconducting wire in a changing field is a field-dependent magnetization (remember M $\propto$ $J_C(B)$)
- The work done by the external field is:

$$Q = \oint \mu_o M dH = \oint \mu_o H dM$$

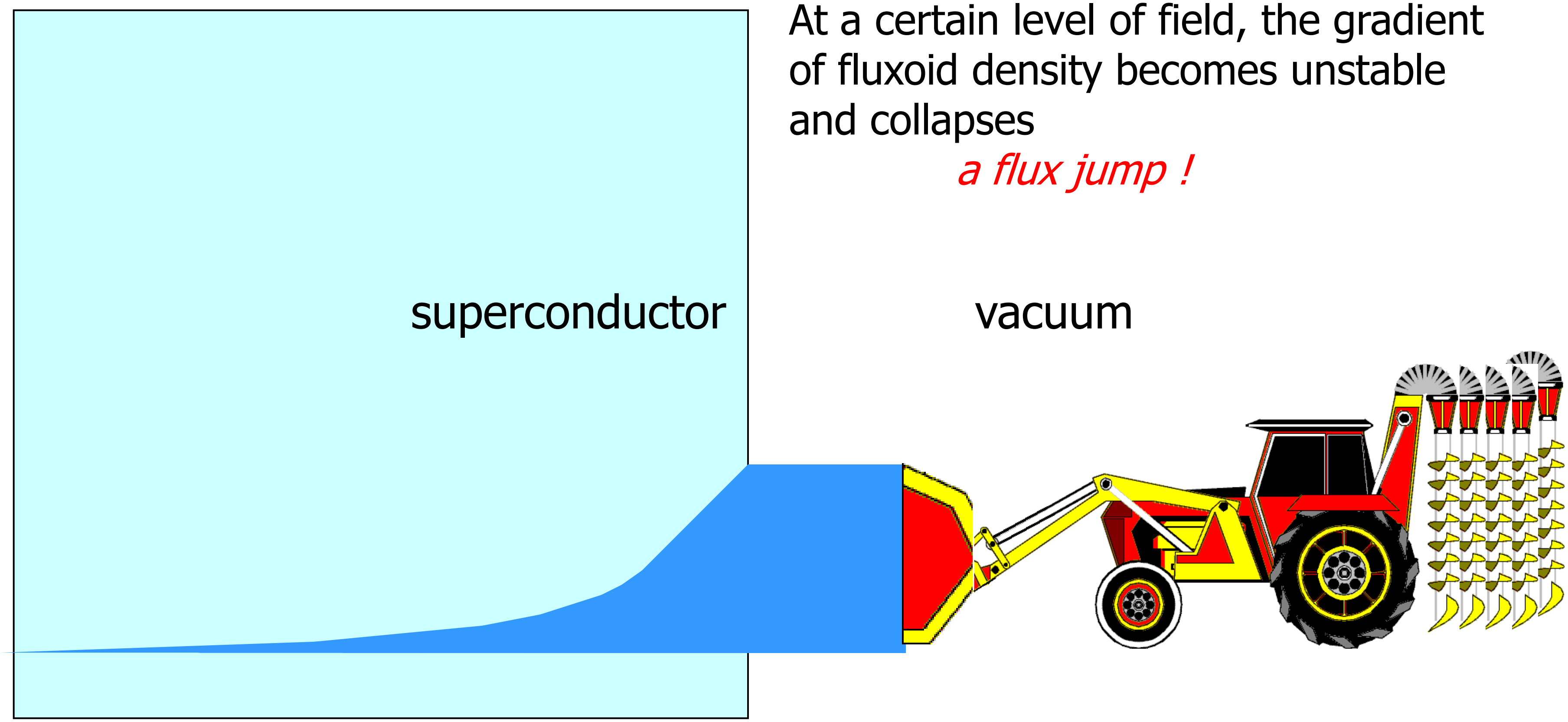
i.e. the area of the magnetization loop



Graphics by courtesy of M.N. Wilson

A different view of flux penetration

The screening currents are a gradient in fluxoid density. The increasing external field exerts pressure on the fluxoids against the pinning force, and causes them to penetrate, with a characteristic gradient in fluxoid density (J_C)



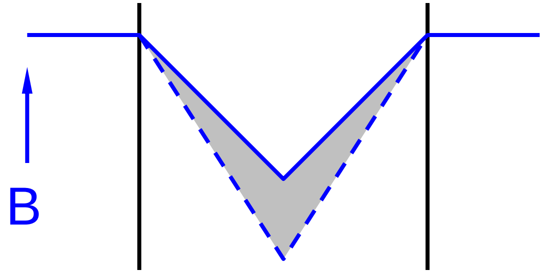
At a certain level of field, the gradient of fluxoid density becomes unstable and collapses

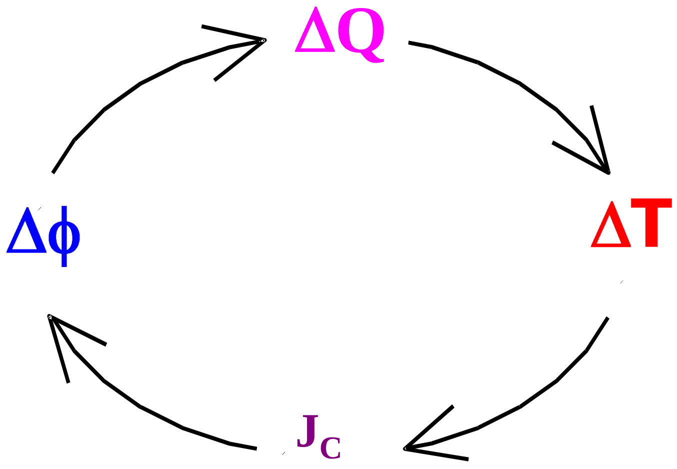
a flux jump !

Graphics by courtesy of M.N. Wilson

Flux jumps

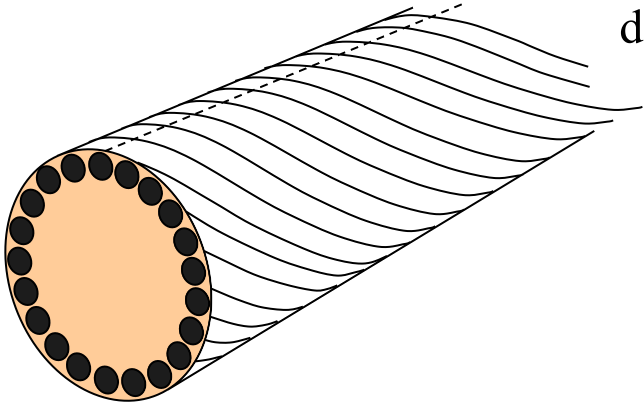
- Unstable behaviour is shown by all superconductors when subjected to a magnetic field:
    - B induces screening currents, flowing at critical density J_C
    - A change in screening currents allows flux to move into the superconductor
    - The flux motion dissipates energy
    - The energy dissipation causes local temperature rise
    - J_C density falls with increasing temperature

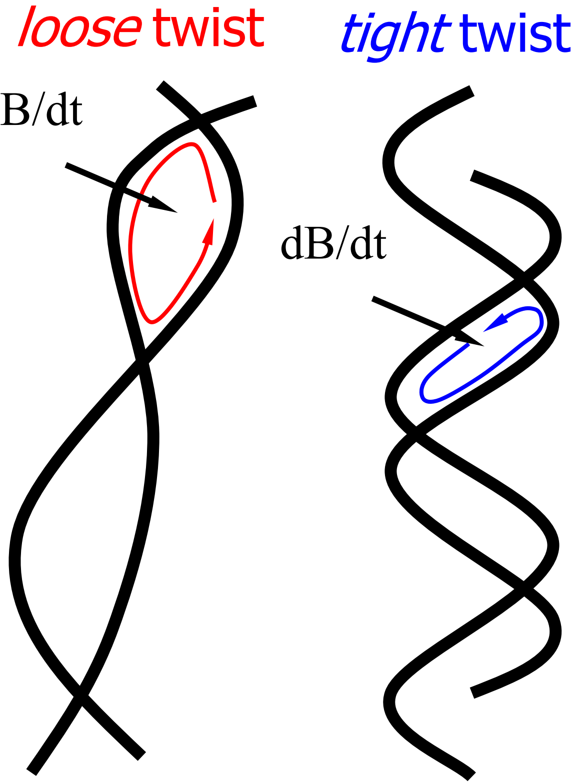




Flux jumping is cured by making superconductor in the form of fine filaments. This weakens the effect of $\Delta\phi$ on ΔQ

Filaments coupling





All superconducting wires and are twisted to decouple the filaments and reduce the magnitude of eddy currents and associated loss

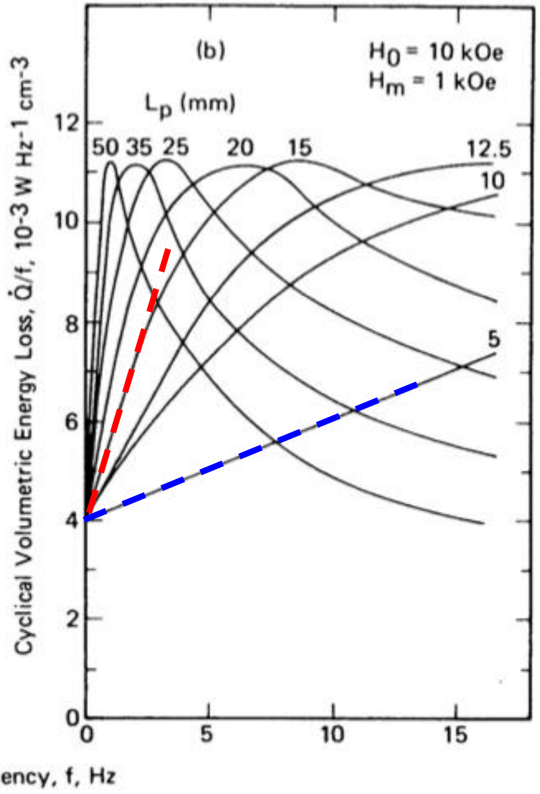
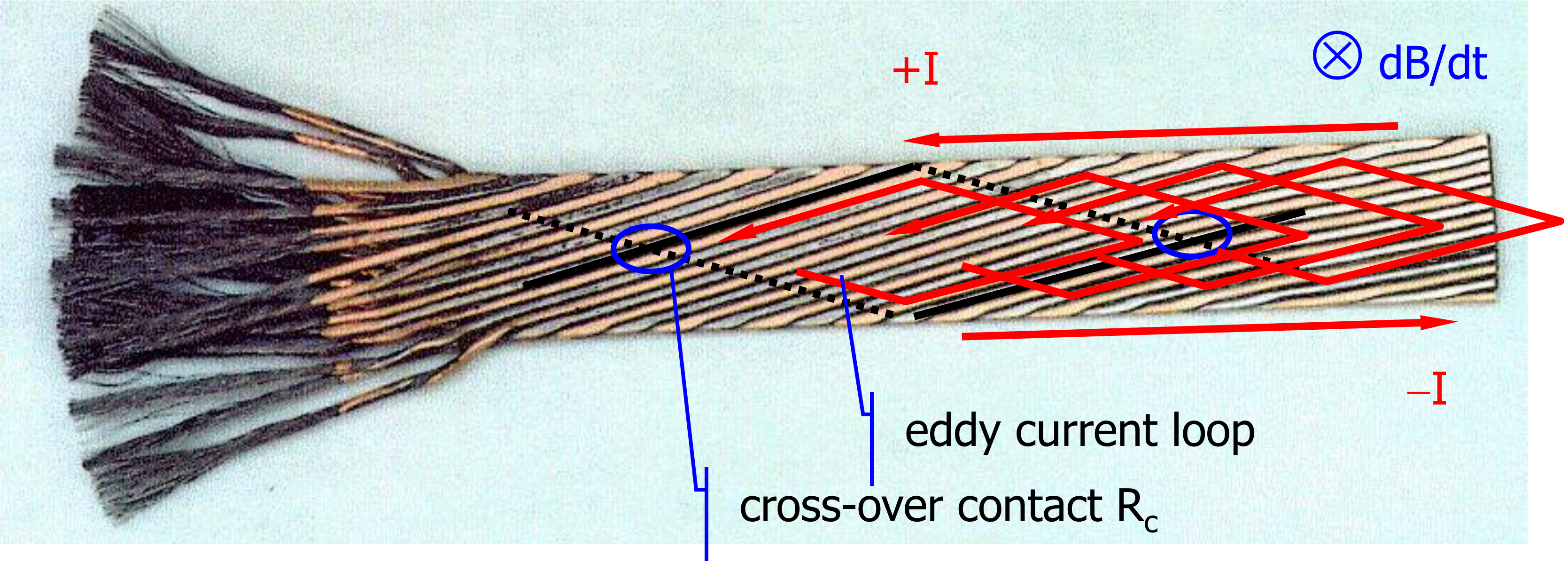


Figure 26-8. Energy loss per cycle ($\equiv \dot{Q}/f$) plotted *versus* frequency of the alternating component of an applied field $H_a(\omega) = H_0 + H_m \sin \omega t$. (a) The per-cycle *coil* loss is plotted for six values of H_m between 0.25 and 1.25 kOe at $H_0 = 10$ kOe; (b) the per-cycle *volumetric* loss of the composite is plotted for eight values of the twist pitch, L_p, at $H_0 = 10$ kOe, $H_m = 1$ kOe—after KWASNITZA and HORVATH [KWA74, KWA76].

Coupling in cables

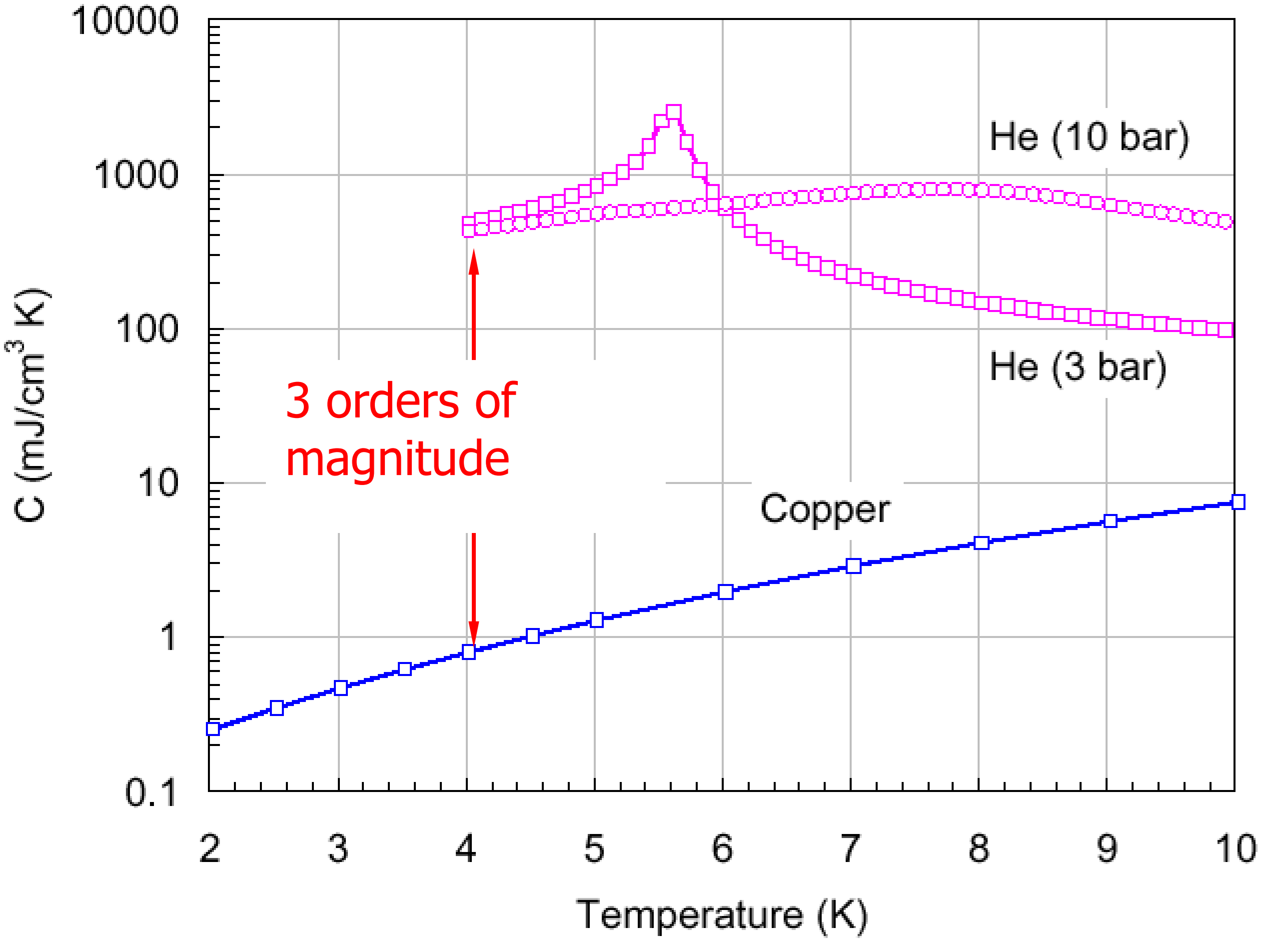


The strands in a cable are coupled (as the filaments in a strand). To decouple them we require to twist (transpose) the cable and to control the contact resistances

AC loss - Re-cap

- AC loss is usually the major source of internal heat in pulsed and cycled superconducting magnets
- To reduce loss
  - Use fine superconducting filaments, and in any case < 50…10 μm to avoid flux-jump instability
  - Use tight twist pitch, and small cable dimensions
  - Include resistive barriers in the wires and cables
- The theory and calculation of AC loss is a **complicated matter !** Rely heavily on measurements

Helium is a great heat sink !



Pairing mechanism

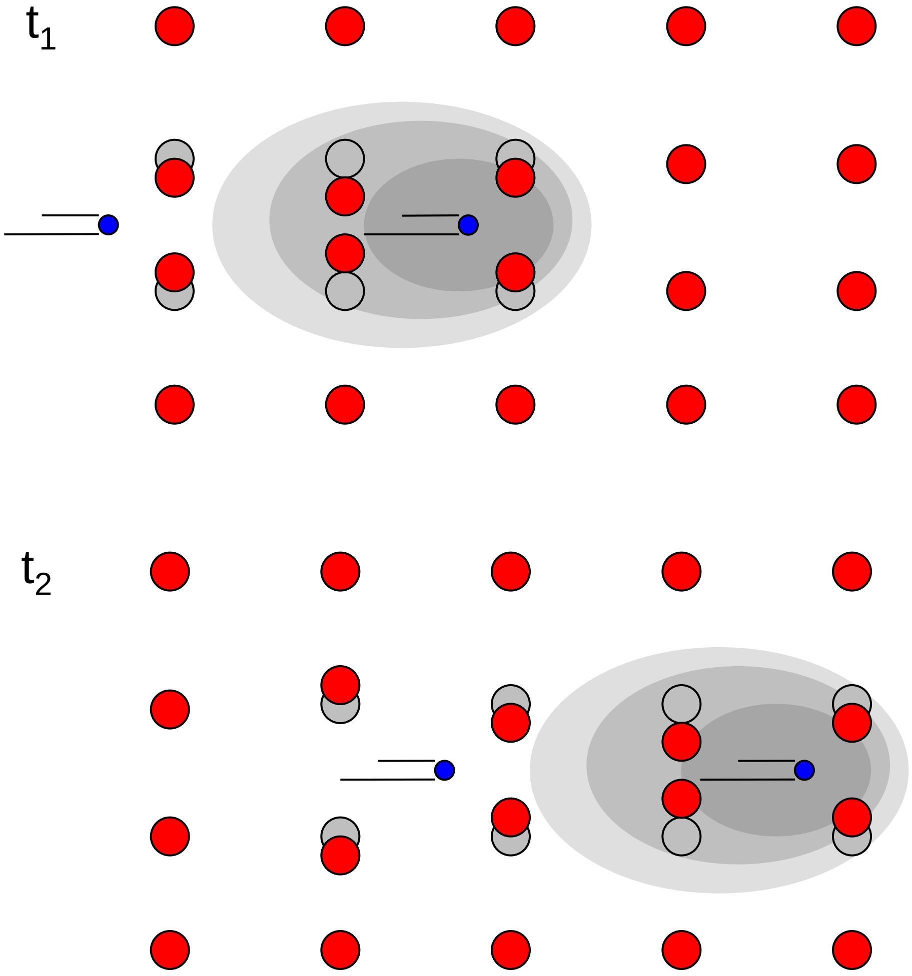
Lattice displacement

⇓

phonons (sound)

⇓

coupling of charge carriers



Bardeen, Cooper, Schrieffer (BCS) - 1950

Superconductors physics - Re-cap

- 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 $J_C(B,T,\dots)$
- The maximum current that can be carried is the $I_C = A_{SC} \times J_C$

Graphics by courtesy of M.N. Wilson

Flux jumps

- Unstable behaviour is shown by all superconductors when subjected to a magnetic field:
  - B induces screening currents, flowing at critical density J_C
  - A change in screening currents allows flux to move into the superconductor
  - The flux motion dissipates energy
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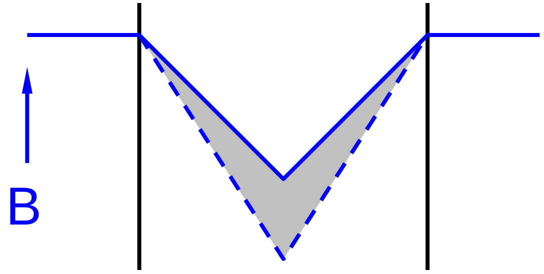

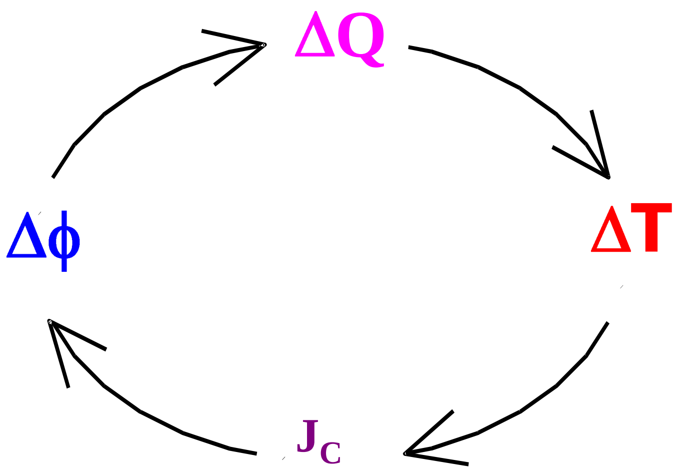

Flux jumping is cured by making superconductor in the form of fine filaments and twisting the conductor. This weakens the effect of $\Delta\phi$ on ΔQ