Magnets (SC)

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CAS - Introduction to Accelerator Physics

Grand Hotel Varna, Varna, Bulgaria

19 September - 1 October, 2010
Overview

- Magnets NC vs. SC - a motivation
- A superconductor physics primer
- From material physics to magnet engineering
- Superconducting magnet design
  - Magnetic design
  - Operating margins
  - Stability, quench and protection
  - Magnetization and AC loss
  - Cooling of superconducting magnets
  - Low-temperature mechanics
- The making of a superconducting magnet
- Other examples of superconducting magnet systems
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NC vs. SC Magnets - 1/2

- **Normal conducting** accelerator magnets
  - *Magnetization* ampere-turns are *cheap*
  - Field is generated by the iron yoke (but limited by saturation to $\approx 2$ T for iron)
  - Low current density in the coils to limit electric power and cooling needs
  - Bulky and heavy, large mass of iron (cost driver)

One of the dipole magnets of the PS, in operation at CERN since 51 years
Superconducting accelerator magnets

- *Superconducting* ampere-turns are *cheap*
- Field generated by the coil current (but limited by critical current to $\approx 10$ T for Nb-Ti)
- High current density, compact, low mass of high-tech SC material (cost driver)
- Requires efficient and reliable cryogenics cooling for operation (availability driver)
Why superconductivity?

- **Abolish Ohm’s law!**
  - No power consumption (but needs refrigeration power)
  - High current density
  - Large ampere turns in small volume, so don’t need iron (although often used for shielding)

- **Consequences**
  - lower running cost $\Rightarrow$ new commercial possibilities
  - energy savings
  - high current density $\Rightarrow$ smaller, lighter, cheaper magnets $\Rightarrow$ reduced capital cost
  - higher magnetic fields economically feasible $\Rightarrow$ new research possibilities
The advantage of high current density

The field produced by an ideal dipole is:

\[ B \approx \frac{1}{\pi} \mu_0 J_E t \]

\[ J_E = 375 \text{ Amm}^{-2} \]

9.5x10^5 Amp turns
=1.9x10^6 A.m per m

660mm

Graphics by courtesy of M.N. Wilson
High current density: solenoids

- The field produced by an infinitely long solenoid is:
  \[ B = \mu_0 J_e t \]

- In solenoids of finite length the central field is:
  \[ B = \mu_0 f J_e t \]
  where \( f \) is a factor less than 1, typically \( \sim 0.8 \)

- The thickness (volume, cost) of a solenoid for a given field is inversely proportional to the engineering current density \( J_e \)
As usual, there are exceptions to the established rules

- Normal conducting magnets for *very high field* applications
- Superconducting magnets for *low field* applications

*Florida-Bitter* plate producing 30 T in a 15 T insert at *NHMFL*

We forget exceptions for the rest of the talk!
Abolish Ohm’s law -
The (f)lower-power dipole

Super-conducting dipole

Normal-conducting dipole

<table>
<thead>
<tr>
<th></th>
<th>Super-conducting dipole</th>
<th>Normal-conducting dipole</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron weight [tons]</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Peak voltage [V]</td>
<td>34</td>
<td>41</td>
</tr>
<tr>
<td>Average AC loss power [W]</td>
<td>1.3</td>
<td>Resistive power [W]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>27000</td>
</tr>
</tbody>
</table>

Potential for saving 7 MW of the 15 MW estimated total power consumption of an accelerator complex
How large is the market volume?

Worldwide Markets for Superconductivity

Conectus, December 2001

* CONsortium of European Companies (determined) To Use Superconductivity
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*
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A great physics problem in 1900

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

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

X-rays are an hoax

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

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

W. Thomson (Lord Kelvin)
Superconductors Pre-history

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

H. Kamerlingh-Onnes (1911)
Cooper Pairs

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

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

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

Bardeen, Cooper and Schrieffer
Pairing mechanism

Lattice displacement
\[ \downarrow \]
phonons (sound)
\[ \downarrow \]
coupling of charge carriers

Only works at low temperature

Bardeen, Cooper, Schrieffer (BCS) - 1957

Proper physics: the binding energy is small, of the order of $10^{-3}$ eV. Pairs can be broken easily by thermal energy. The interaction is long range, and Cooper pairs overlap and can exchange electrons.
First (not last) superconducting magnet project cancelled

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

Third International Congress of Refrigeration, Chicago (1913)

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

Solvay conference (1914)

Superconductivity languished for 40 years...
Low-Tc timeline - depressing...

Theoretical limit around 30 K
1986 - A Big Surprise

Bednorz and Mueller
IBM Zuerich, 1986

Graphics by courtesy of P. Grant
1987 - The prize!

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

2 Get Nobel for Unlocking Superconductor Secret
High-Tc timeline - impressive !!!

It’s not over yet
Hey, what about field?

$\kappa = \frac{\lambda_L}{\xi}$

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

Complete field exclusion

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

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

Partial field exclusion

Lattice of fluxons

Dirty materials: alloys, intermetallic, ceramic
$B_C \approx 10 \ldots 10^2$ T

Meissner & Ochsenfeld, 1933

Ginsburg, Landau, Abrikosov, Gor’kov, 1950...1957
Free energy and critical field

- The Gibbs free energy of a material in a magnetic field is given by:

\[ G = U - TS - \mu_0 M \cdot H \]

Thermal energy    Magnetic energy

- The superconducting phase, by excluding the magnetic field \((M=-H)\), has lower free energy: \( G_{\text{sup}}(H=0) < G_{\text{normal}} \)

- The material will reach critical conditions when the energy of the field will equal the jump in free energy:

\[ \frac{\mu_0}{2} H_c^2 = G_{\text{normal}} - G_{\text{sup}}(H=0) \]
London penetration length $\lambda_L$

- Field profile

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

- *London* penetration length

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

$\lambda_L$ is of the order of 20 to 100 nm in typical superconducting materials.

H. and F. London, 1935
Coherence length $\xi$

- The density of paired electron $n_S$ cannot change quickly at an interface, but rises smoothly from zero (at the surface) to the asymptotic value.
- The characteristic length of this transition is the coherence length $\xi$.

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

$\xi$ is of the order of 1 to 1000 nm in typical superconducting elements and alloys.

Ginzburg–Landau, 1950
Different behaviors are found as a function of the Ginzburg-Landau parameter \( \kappa = \frac{\lambda_L}{\xi} \)

\[ \lambda_L \ll \xi \Rightarrow \kappa \ll 1 \]

\[ \lambda_L \gg \xi \Rightarrow \kappa \gg 1 \]

Ginzburg–Landau, 1950
### Values of $\lambda_L$, $\xi$ and $\kappa$

<table>
<thead>
<tr>
<th>Material</th>
<th>$\lambda_L$ (nm)</th>
<th>$\xi$(B=0) (nm)</th>
<th>$\kappa$ (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>16</td>
<td>1600</td>
<td>0.01</td>
</tr>
<tr>
<td>Pb</td>
<td>32</td>
<td>510</td>
<td>0.06</td>
</tr>
<tr>
<td>In</td>
<td>24</td>
<td>360</td>
<td>0.07</td>
</tr>
<tr>
<td>Cd</td>
<td>110</td>
<td>760</td>
<td>0.15</td>
</tr>
<tr>
<td>Sn</td>
<td>30</td>
<td>170</td>
<td>0.18</td>
</tr>
<tr>
<td>Nb</td>
<td>32</td>
<td>39</td>
<td>0.82</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td></td>
<td>$\approx$ 30</td>
<td></td>
</tr>
</tbody>
</table>

Type I

Type II
Lattice of quantum flux lines

\[ \Phi_0 = \frac{h}{2e} = 2.07 \times 10^{-15} \text{ Wb} \]

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

Essmann & Träuble, 1967
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 intermetallic compounds.
Hey, what about current?

- A current flowing in a magnetic field is subject to the Lorentz force that deviates the charge carriers:
  \[ \mathbf{F} = \mathbf{J} \times \mathbf{B} \]

- This translates into a *motion of the fluxoids* across the superconductor \( \Rightarrow \) energy dissipation \( \Rightarrow \) loss of superconductivity.

- To carry a significant current we need to *lock the fluxoids* so to resist the Lorentz force. For this we mess-up the material and create *pinning centers* that exert a pinning force \( F_p \).
Pinning mechanisms

Precipitates in alloys

Microstructure of Nb-Ti

Grain boundaries in inter-metallic compounds

Microstructure of Nb₃Sn

Graphics by courtesy of Applied Superconductivity Center at NHMFL
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**:

$$J_C(B,T,\ldots) = \frac{F_P}{B}$$

**Jc (5 T, 4.2 K) \approx 3000 \text{ A/mm}^2**
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 $J_C(B,T,...)$

- The maximum current that can be carried is the $I_C = A_{SC} \times J_C$
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From materials to magnets

- Materials must be made in high-current wires, tapes and cables\(^{(1)}\) 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).

\(^{(1)}\) See: Stability, quench and protection
Nb-Ti manufacturing route

NbTi billet

I_c(5 T, 4.2 K) ≈ 1 kA

extrusion

cold drawing

heat treatments

LHC wire

NbTi is a ductile alloy that can sustain large deformations

L ≈ 1 mm

Graphics by courtesy of Applied Superconductivity Center at NHMFL
\( \text{Nb}_3\text{Sn} \) manufacturing routes

\( \text{Nb}_3\text{Sn} \) is brittle and cannot be drawn in final form. The precursors are drawn and the wire is heat-treated at about 650\(^\circ\)C for several hours, to form the \( \text{Nb}_3\text{Sn} \) phase.

\[ I_c(12 \text{ T, } 4.2 \text{ K}) \approx 1.5 \text{ kA} \]
Oxide powder in tube OPIT

1) Draw down BSCCO powder in a silver tube

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

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

BSCCO is also brittle: a special sequence of rolling and sintering heat treatments must be used. Silver has the important feature that it is transparent to Oxygen at high temperature, but does not react with it.

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

YBCO has better critical properties than BSCCO but, unlike BSCCO, grains do not align during processing. If grains are not aligned the super-current cannot jump between the grains. The manufacturing processes are all forcing a certain degree of alignment in the microstructure.

1) produce a tape with an aligned texture
2) coat the tape with a buffer layer
3) coat the buffer with a layer \( \text{YBa}_2\text{Cu}_3\text{O}_7 \) such that the texture of the YBCO follows that of the buffer and substrate

![Diagram of YBCO tape with layers](image-url)
Engineering current density

- All wires, tapes and cables consist of an array of fine filaments\(^{(1)}\), and contain additional components:
  - Left-overs from the precursors of the SC formation
  - Barriers, texturing and buffering layers
  - Low resistance matrices\(^{(2)}\)

- The SC material fraction \(\lambda = \frac{A_{SC}}{A_{total}}\) is hence always < 1. To compare materials on the same basis, we use an engineering current density:

\[
J_E = J_C \times \lambda
\]

\(^{(1)}\) See: Magnetization and AC loss
\(^{(2)}\) See: Stability, quench and protection
Best of Superconductors J_E

Graphics by courtesy of Applied Superconductivity Center at NHMFL
Practical conductors: high $J_E$

- Multifilamentary wires have current carrying capability of 100... 1000 A and can be used to make all kind of small size magnets.

- Large size magnets (e.g. LHC dipoles) need large operating currents (10 to 100 kA) to:
  - Decrease inductance,
  - Lower the operating voltage,
  - Ease magnet protection\(^{(1)}\)

- Rutherford cables are ideally suited for this task.

\[^{(1)}\] See: Stability, quench and protection
Rutherford cable machine @ CERN

Strands fed through a cabling tongue to shaping rollers

Strand spools on rotating tables
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

$J_E \approx 50 \text{ A/mm}^2$
Superconducting wires and tapes for all taste...

- NbTi
- Nb₃Sn, Nb₃Al
- YBCO
- MgB₂
... and superconducting cables

Rutherford

Braids for power transmission

CICC

Super-stabilized

Internally cooled
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Magnetic design

- NC: magneto motive force, reluctance and pole shapes
  \[ R = \frac{F}{\Phi} \]  
  Hopkinson's law

- SC: Biot-Savart law and coil shapes
  \[ B \approx \mu_0 \frac{NI}{g} \]
  \[ B \approx \mu_0 \frac{NI}{\pi r} \]

\[
\begin{align*}
  B & \approx \mu_0 \frac{NI}{g} \\
  g &= 100 \text{ mm} \\
  NI &= 100 \text{ kAtturn} \\
  B &= 1.25 \text{ T}
\end{align*}
\]

\[
\begin{align*}
  B & \approx \mu_0 \frac{NI}{\pi r} \\
  r &= 45 \text{ mm} \\
  NI &= 1 \text{ MAturn} \\
  B &= 8.84 \text{ T}
\end{align*}
\]
Design of an ideal dipole magnet

\[ I = I_0 \cos(\theta) \Rightarrow B_1 = -\mu_0 \frac{I_0}{2} r \]

Intersecting circles \( \Rightarrow B_1 = -\mu_0 \frac{J d}{2} \)

Intersecting ellipses \( \Rightarrow B_1 = -\mu_0 \frac{J d b}{a+b} \)

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

None of them is practical!
Magnetic design - sector coils

- Dipole coil
- Quadrupole coil

\[
B_1 = -2\mu_0/\pi J (r_2 - r_1) \sin(\phi)
\]

\[
B_2 = -2\mu_0/\pi J \ln(r_2/r_1) \sin(2\phi)
\]

This is getting much more practical for the construction of superconducting coils!
Harmonics of the field

A technical current distribution can be considered as a series approximation:

\[ J(x, y) = J_1 \cos(\theta) + J_3 \cos(3\theta) + \ldots \]

Technical windings contain field errors that can be minimized by proper placing of the conductors.
Technical coil windings

LHC Arc Dipole (6 Blocks-2009)

Magnet bore

Coil blocks

Spacers

Superconducting cable

LHC Arc Quadrupole
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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\(^{(1)}\), i.e. a temperature margin:
  \[ \Delta T = T_{CS} - T_{op} \]

(1) See: Stability, quench and protection
Operating margins

- Practical operation always requires margins:
  - Critical current margin: $I_{\text{op}}/I_Q \approx 50\%$
  - Critical field margin: $B_{\text{op}}/B_Q \approx 75\%$
  - Margin along the loadline: $I_{\text{op}}/I_{\text{max}} \approx 85\%$
  - Temperature margin: $T_{CS} - T_{\text{op}} \approx 1...2\ K$

- The margin needed depends on the design and operating conditions
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Training...

Superconducting solenoids built from NbZr and Nb$_3$Sn in the early 60’s quenched much below the rated current ...

... the quench current increased gradually quench after quench: training


... 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!

---

Training today

- 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!

10 T field in the dipole bore

8.3 field in the dipole bore

quench current (A)

quench number (-)

Courtesy of A. Siemko, CERN, 2002
Stability and quench: a heat balance

perturbation
Joule heating

Heating < Cooling

recovery

Heating > Cooling

Heating capacity
conduction
cooling

superconducting cable

quench
Perturbation overview

Typical range is from a few to a few tens of mJ/cm³
Current sharing

\[ T < T_{cs} \]

\[ E_{sc} = E_{st} = 0 \]

\[ T_{cs} < T < T_c \]

\[ E_{sc} = E_{st} = I_{st} \frac{\eta_{st}}{A_{st}} \]

\[ T > T_c \]

\[ E_{sc} = E_{st} = I_{op} \frac{\eta_{st}}{A_{st}} \]
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!
Helium is a great heat sink!

3 orders of magnitude
Stability recipes

- A sound design is such that the expected energy spectrum is smaller than the expected stability margin.

To increase stability:
- Increase temperature margin
- Increase heat removal (e.g. conduction or heat transfer)
- Decrease Joule heating by using a stabilizer with low electrical conductance
- Make best use of heat capacity
  - Avoid sub-cooling (heat capacity increases with T, this is why stability is not an issue for HTS materials)
  - Access to helium for low operating temperatures
What if it *quenches*?

- the magnetic energy stored in the field:
  \[ E_m = \int \frac{B^2}{2\mu_0} dv = \frac{1}{2} LI^2 \]

  is converted to heat through Joule heating \( RI^2 \).

  If this process happened uniformly in the winding pack:
  - Cu melting temperature 1356 K
  - corresponding \( E_m = 5.2 \times 10^9 \, \text{J/m}^3 \)

  limit would be \( B_{max} \leq 115 \, \text{T} \): NO PROBLEM!

**BUT**

*the process does not happen uniformly* (as little as 1% of mass can absorb total energy)
Lots of energy!

Courtesy of A. Siemko, CERN
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.

Typical quench sequence:

1. Quench initiation
2. Local heating (hot spot)
3. Normal zone propagation
4. Voltage development
5. Quench detection
6. Safety discharge
Hot-spot limits

- 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)

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

$T_{max} < 100$ K for negligible effect
Adiabatic hot spot temperature

- adiabatic conditions at the hot spot:

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

where:

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

- can be integrated:

\[ \int_{T_{op}}^{T_{max}} \frac{C}{\eta_{st}} dT = \int_{0}^{\infty} J^{2} dt \approx \int_{0}^{\infty} J^{2} dt \approx J_{op}^{2} \tau_{\text{decay}} \]

The function \( Z(T_{\text{max}}) \) is a cable property
How to limit $T_{\text{max}}$

- stabilizer material property
- implicit relation between $T_{\text{max}}$, $f_{\text{st}}$, $J_{\text{op}}$, $\tau_{\text{decay}}$

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

electrical operation of the coil (energy, voltage)

cable fractions design

implicit relation between $T_{\text{max}}$, $f_{\text{st}}$, $J_{\text{op}}$, $\tau_{\text{decay}}$

- to decrease $T_{\text{max}}$
  - reduce operating current density ($J_{\text{op}} \downarrow$)
  - discharge quickly ($\tau_{\text{decay}} \downarrow$)
  - add stabilizer ($f_{\text{st}} \uparrow$)
  - choose a material with large $Z(T_{\text{max}}) \uparrow$
$$Z(T_{\text{max}}) \approx \frac{1}{f_{\text{st}}^2 J_{\text{op}}^2 \tau_{\text{decay}}}$$

$Z(T_{\text{max}})$ for typical stabilizers

![Graph showing temperature dependence of $Z$ for different materials with RRR values.]
Quench protection

- The magnet stores a magnetic energy $\frac{1}{2} LI^2$
- During a quench it dissipates a power $RI^2$ for a duration $\tau_{\text{decay}}$ characteristic of the powering circuit

The initial magnetic energy is given by:

$$\tau_{\text{decay}} \int_0^{\tau_{\text{decay}}} R(t)I_{op}^2 dt \geq \frac{1}{2} LI_{op}^2$$

**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.

\[ V_{\text{measured}} = V_{\text{quench}} + L \frac{dI}{dt} \]

\[ R_2 L_1 = R_1 L_2 \]

\[ V_{\text{measured}} = V_{\text{quench}} \]
Strategy 1: energy dump

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

\[ I = I_{op} e^{-\frac{t - \tau_{\text{detection}}}{\tau_{\text{dump}}}} \]

\[ \tau_{\text{dump}} = \frac{L}{R_{\text{dump}}} \]

- the integral of the current:

\[ \int_{0}^{\infty} J^2 \, dt \approx J_{op}^2 \left( \tau_{\text{detection}} + \frac{\tau_{\text{dump}}}{2} \right) \]

- can be made small by:
  - fast detection
  - fast dump (large \( R_{\text{dump}} \))
Dump time constant

- Magnetic energy:
  \[ E_m = \frac{1}{2} LI_{op}^2 \]

- Maximum terminal voltage:
  \[ V_{\text{max}} = R_{\text{dump}} I_{\text{op}} \]

- Dump time constant:
  \[ \tau_{\text{dump}} = \frac{L}{R_{\text{dump}}} = \frac{2E_m}{V_{\text{max}} I_{\text{op}}} \]

Increase \( V_{\text{max}} \) and \( I_{\text{op}} \) 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 $T_{\text{max}}$)
  - 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

![Diagram of coupled secondary system]
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 $T_{\text{max}}$)
  - transient current and dissipation can be used to speed-up quench propagation (quench-back)

- disadvantages:
  - induced currents (and dissipation) during ramps
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 bypassed 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 recipes

- A **good conducting material** (Ag, Al, Cu) 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

- Magnets NC vs. SC - a motivation
- A superconductor physics primer
- From material physics to magnet engineering
- **Superconducting magnet design**
  - Magnetic design
  - Operating margins
  - Stability, quench and protection
  - Magnetization and AC loss
  - Cooling of superconducting magnets
  - Low-temperature mechanics
- The making of a superconducting magnet
- Other examples of superconducting magnet systems
A superconductor in varying field

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

Quiz: how much is $J$? $J_C$, $B$, and shielding currents are depicted in the diagram.
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 $E \Rightarrow 0$.
- 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 *(filament diameter !)*
**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
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, leading to a flux jump!
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 $\Delta Q$. 

(Graphics by courtesy of M.N. Wilson)
All superconducting wires and are twisted to decouple the filaments and reduce the magnitude of eddy currents and associated loss.
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.
- The magnetic moment associated to DC (persistent) and AC (coupling) currents perturbs the field quality of the magnet.
- To reduce loss:
  - Use fine superconducting filaments, and in any case < 50 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.
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Basic thermodynamics

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

\[
\frac{W}{Q} = \frac{T_{\text{hot}} - T_{\text{cold}}}{T_{\text{cold}}}
\]

Coefficient Of Performance

\[
\text{COP} = \frac{P_{\text{warm}}}{P_{\text{cold}}}
\]

\( \approx 250 \)
Helium as a low-temperature coolant

- Forced-flow
- Pool-boiling
- Sub-cooled superfluid
- Superfluid
Fridge’s

Cryocoolers: \( \approx 1.5 \text{ W @ 4.2 K} \)

LHC refrigerators: \( \approx 140 \text{ kW @ 4.2 K} \)
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Mechanical issues in accelerator magnets (e.g. a dipole)

- Electromagnetic forces are exerted in all directions, radially, azimuthally, and axially, and need to be contained to guarantee mechanical integrity

- Remember:
  - Material properties are (sometimes strong) function of temperature
  - Thermal contraction is very different among the various components of a magnet (e.g. metals vs. insulators)
  - Field quality and stability depends on reliable coil dimension to the $\mu$m
Orders of magnitude of the force

- Dipole magnet with field $B$ in a bore radius $R$
  - Approximation of the force on a quadrant per unit length:

$$F_x = -F_y = \frac{4}{3} R \frac{B^2}{2\mu_0}$$

![Graph showing $F_x (MN)$ vs $B (T)$]

$LHC \approx 2$ MN/m
Design principle

- Stick-slip or frictional motions (at the μm level) are undesirable and can lead to quench or affect the field quality
- In accelerator magnets the coils are (generally) blocked inside a rigid support structure:

  locked-in collar pack

**Roman arch principle**

promulgated by R. Perin (CERN)
Towards higher fields (HE-LHC)

- Several R&D programs are underway to demonstrate the feasibility of magnets with Lorentz force levels far exceeding those of LHC.

![Graph showing stored energy vs resulting force per quadrant](Image)

by courtesy of A. Devred
New force containment principles

Example: the bladder and key concept from LBNL

Coil wound in *blocks* to manage the distribution of stress in the cross section
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$B_{\text{nominal}}$ current

stored energy cold mass Cost

\[
\begin{align*}
8.3 & \quad (T) \\
11850 & \quad (A) \\
\approx 10 & \quad (MJ) \\
\approx 35 & \quad (\text{tonnes}) \\
\approx 1 & \quad (\text{MCHF})
\end{align*}
\]
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

10 μm precision!

Stored coils

Coil winding machine

Cable insulation
Ends, transitions, and any deviation from the regular structure are the most delicate part of the magnet.
Collaring and yoking

- Collaring
- Yoking

85 tons/m
175 tons/m
Cold mass
Cryostat

Vacuum enclosure

Low conduction foot

Thermal screens
Current leads

Warm end (300K)

Intermediate temperature (50K)

HTS

Cold end (4K)
Finally, in the tunnel!
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Magnetic Resonance Imaging (MRI)
NMR spectroscopy

First 1 GHz (23.5 T) commercial NMR system
Motors & generators

Motor with HTS rotor
American Superconductor and Reliance

700 MW generator
NbTi rotor
Hitachi, Toshiba, Mitsubishi
Transformers & energy storage

HTS Transformer
630 kVA, 18.7kV to 0.42 kV

KfZ Karlsruhe

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

superconducting solenoid, enclosed within iron shield

stainless steel canister containing ferromagnetic mesh

pipes feeding the kaolin slurry for separation

photo courtesy of Carpco
Thermonuclear fusion

ITER
International Thermonuclear Experimental Reactor
HEP detectors of the past...

Omega

BEBC
... and HEP of the present (CMS and ATLAS)
Other uses of superconductivity

The Church of the Latter Day Snakes
founded 1905, revived 1950

We have a big interest in this machine...

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

Does it make much noise...

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

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

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

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

I put in five pounds for you... This is only the start.
A word of closing

- Superconducting magnet design is **a lot about superconductors** (materials, wires, cables, and their electric and thermal properties)...

- ... but not only!
  - High field & forces bear **mechanical problems** that are tough to solve ($B=10$ T $\Rightarrow p_{mag} = 1600$ bar !)
  - **Materials at low temperature** are not what we are used to (mechanical and magnetic properties, thermal expansion, electrical insulation)
  - **Cooling** is an applied science by itself

Thank you for your attention
Where to find out more - 1/3

Superconducting magnets:

- Proc European Conference on Applied Superconductivity EUCAS, pub UK Institute of Physics
Where to find out more - 2/3

**Cryogenics**
- Cryogenics: published monthly by Elsevier

**Materials - Superconducting properties**
- Superconductor Science and Technology, published monthly by Institute of Physics (UK).
- IEEE Trans Applied Superconductivity, published quarterly
Where to find out more - 3/3

- Materials - Mechanical properties
  - Nonmetallic materials and composites at low temperatures: Ed AF Clark, RP Reed, G Hartwig pub Plenum
  - Nonmetallic materials and composites at low temperatures 2, Ed G Hartwig, D Evans, pub Plenum 1982