Unit 16
Degradation and Training I

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Outline

- Introduction
- Quench of a superconductor
- Classification of quenches
- Conductor limited quenches
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- Cryogenic stabilization
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- Summary

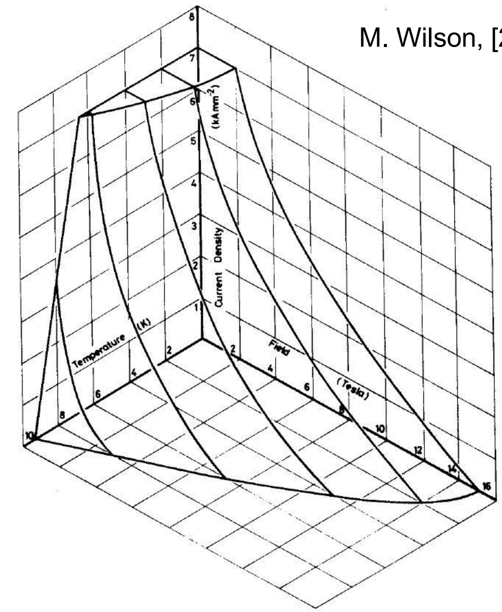
Introduction

- In this unit we will address the following questions
  - What is a quench?
  - How can we classify a quench according to the different causes?
  - What is the maximum current that a wire can carry and how can we measure it?
  - Which are the volumes and the energies involved in the quench phenomenon?
  - What is the role of the stabilizer and of the liquid helium?

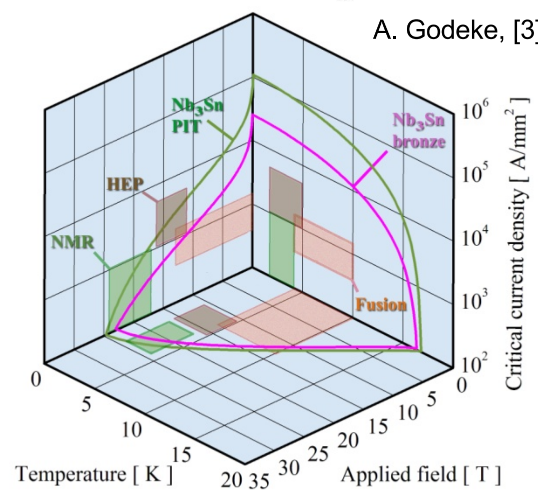
Quench of a superconductor

- The superconducting state is defined by the critical surface
  - B (T), J (A/mm^2), T (K)
- A superconducting magnet operates in conditions corresponding to a point located beneath the critical surface, and defined by $T=T_{op}$, $J=J_{op}$, and $B=B_{op}$.
- Let's assume (A. Devred, [1]) that, starting from the operational conditions, we increase the current in the magnet, and, as a result, the magnetic field.
- At a certain point, the critical surface is crossed, and a small volume V of superconductor becomes normal.
- Therefore, the volume V starts dissipating energy in the form of Joule heating, and the temperature increases.

M. Wilson, [2]

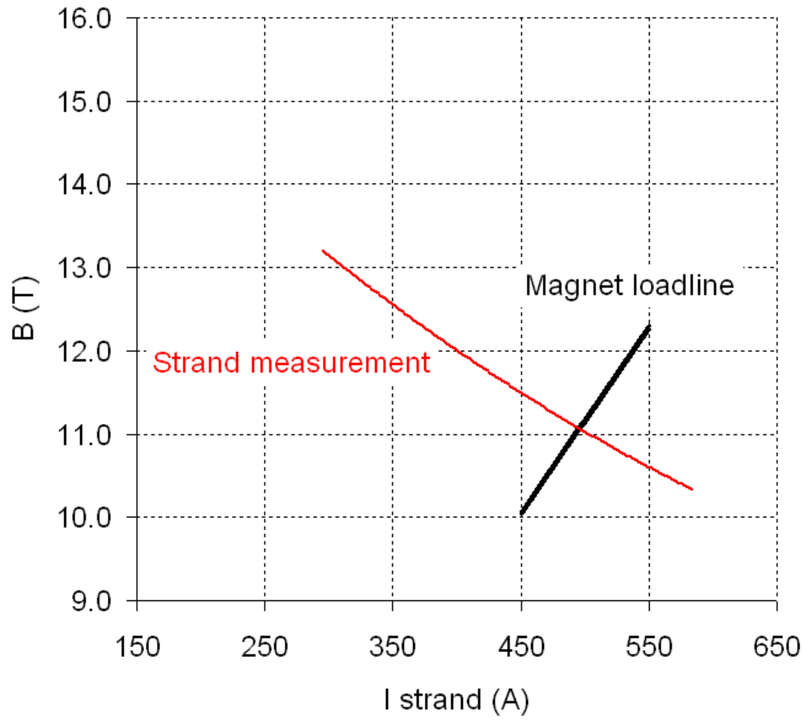


A. Godeke, [3]



Quench of a superconductor

- Due to thermal diffusion, the surrounding volume dV undergoes an increase in temperature as well.
- If the heat dissipated by V is **enough,** dV reaches the critical temperature, becomes normal conducting, and dissipates heat.
- In certain conditions, the normal zone propagates through the coil: this phenomenon is called a **quench.**
- Depending on its causes, a quench can be classified and defined in different ways.



Classification of quenches

- A first classification (A. Devred, [1])
  - The maximum field seen by the conductor in the coil is referred to as the **peak field** (B_{peak}).
  - At a given temperature T_0, the maximum current that the conductor can reach will be $I_{max}=I_c\ (B_{peak},\ T_0)$, where I_c is the critical current at B_{peak} and T_0.
  - When the magnet quenches, we can have either $I_{quench} = I_{max}$ or $I_{quench} < I_{max}$.
  - If $I_{quench} = I_{max}$ we have a *conductor-limited quench* (or *exhausted margin quench*).
    - If the maximum current is consistent with measurements performed on wire short samples, we have a *short-sample quench* (success!!)

But if $\mathbf{I_{quench} < I_{max}}$

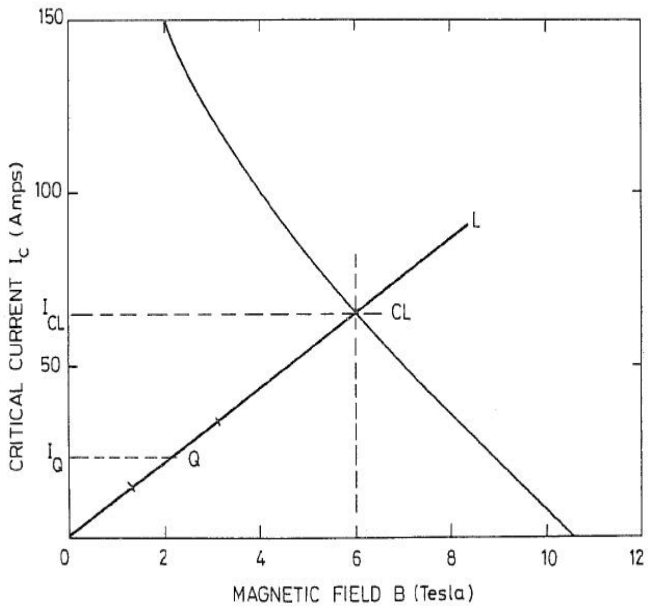
Classification of quenches

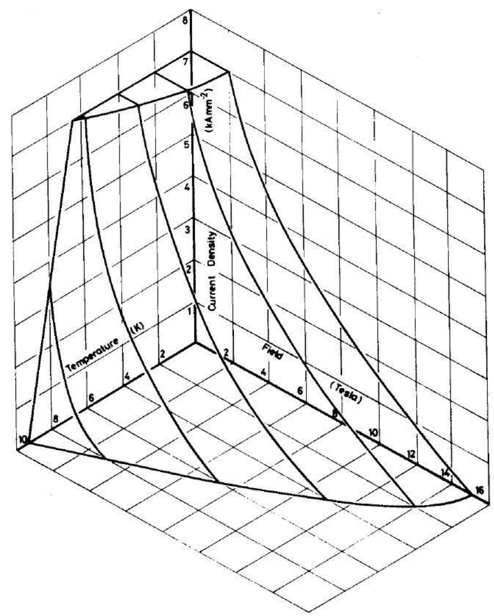
We have a problem . . .

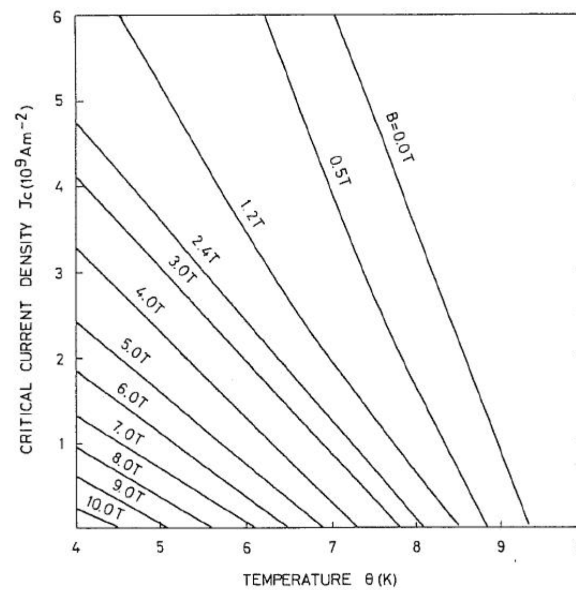
- More often than not, this is the case.
- Accelerator magnets, in contrast to most other types are aggressively designed.
  - Compact
  - High current density
  - Geometry (dipoles, quads, . . . Are mechanically more complex
- In this case we say that the magnet performance is *degraded,* either due to a mechanical instability, damage to the conductor, AC losses or some other flaw (like a bad splice joint).
- In either case, a quench occurs because of a release of energy that increases the temperature of the conductor beyond the critical temperature. These are called *energy-deposited quenches* or, also, *premature quenches.*

Classification of quenches

- In the first case the critical surface is crossed because of an increase of I (and B); in the second case the critical surface is crossed because of an increase of temperature.







M. Wilson, [2]

Classification of quenches

A second, more detailed classification (M. Wilson, [2])

- We can define a **spectrum of disturbances**, which classifies the energy disturbances along two dimensions: time and space.

		Space	
		Point	Distributed
Time	Transient	J	J/m^3
	Continuous	W	W/m^3

- **Continuous disturbances** are due to a steady power dissipation in the coil
  - Point: ramp splice with high resistance joint
  - Distributed: a.c. losses in the conductor, thermal leak of the cryogenic system.

- These causes are relatively easy to diagnose and remedy or at least understand.

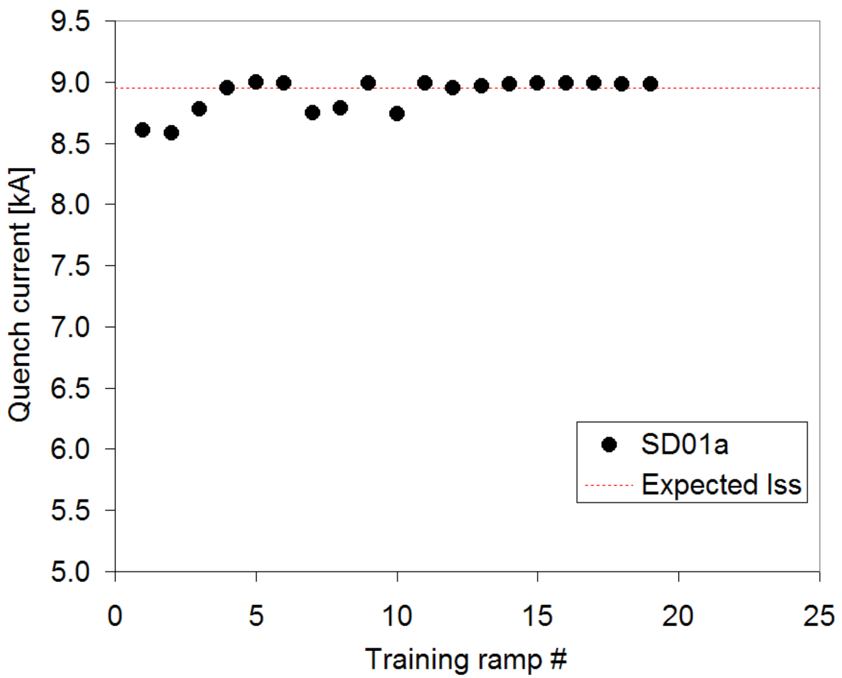
Classification of quenches

		Space	
		Point	Distributed
Time	Transient	J	J/m^3
	Continuous	W	W/m^3

- Transient quenches are due to a sudden release of energy, either over a small volume (J) or over a large volume (J/m^3)
  - Flux jumps: dissipative redistribution of magnetic field within the superconductor. It can be eliminated with small filaments.
  - Mechanical disturbances: wire frictional motion, epoxy cracking. They are less predictable and difficult to avoid, since they are related to mechanical design, material properties, fabrication processes, etc.

Conductor limited quenches

- Conductor limited quenches are usually very stable.
- A series of conductor limited quenches in a “quench current vs. quench number” graph (or **training curve**) appears as a stable plateau. For these reasons they are also called *plateau quenches*.
- After having reached the maximum current of the magnet, we have to compare it with the critical current measured on a short sample of the conductor (I_{ss}).



Conductor limited quenches
Measurements of the conductor critical current

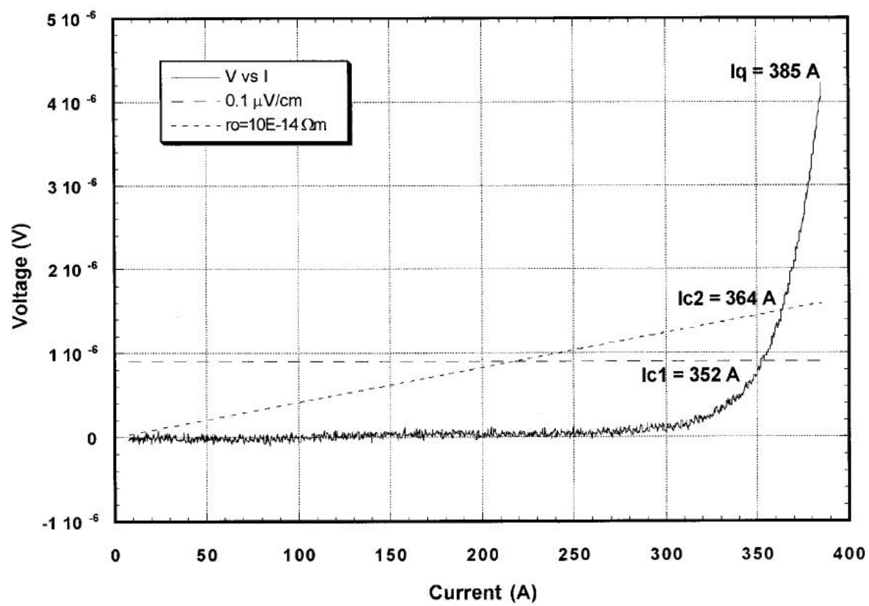
- The critical current of a conductor is measured by winding a sample of the wire around a sample holder.
- To avoid premature quenching induced by Lorentz forces during ramping, the wire must be well supported
  - Stycast epoxy may be used to constrain the wire around the holder
- In the case of Nb_3Sn wires, a sample holder made of titanium is used. (Better thermal-mechanical match to the wire)
- Once the wire is cooled-down and placed in a given magnetic field, the current is increased until the transition occurs.

A. Devred, [4]

Conductor limited quenches
Measurements of the conductor critical current

- The transition from the superconducting to the normal state is observed through an increase of voltage.
- The increase is initially slow and reversible. By further increasing the current, the voltage rise becomes more steep, until it takes off and becomes irreversible: we refer in this case to the short sample quench current I_{ss}.
- In different conditions (wire as a part of a cable in a magnet, in different cooling conditions) the quench may occur at a different current.

A. Devred, [4]



- The conventions to determine the quench current are the following [4].
  - Let's assume that we have a wire of length L and cross-sectional area S *and* λ as the copper to superconductor or copper to non-copper ratio.
  - The resistivity of the superconductor and the electrical field are

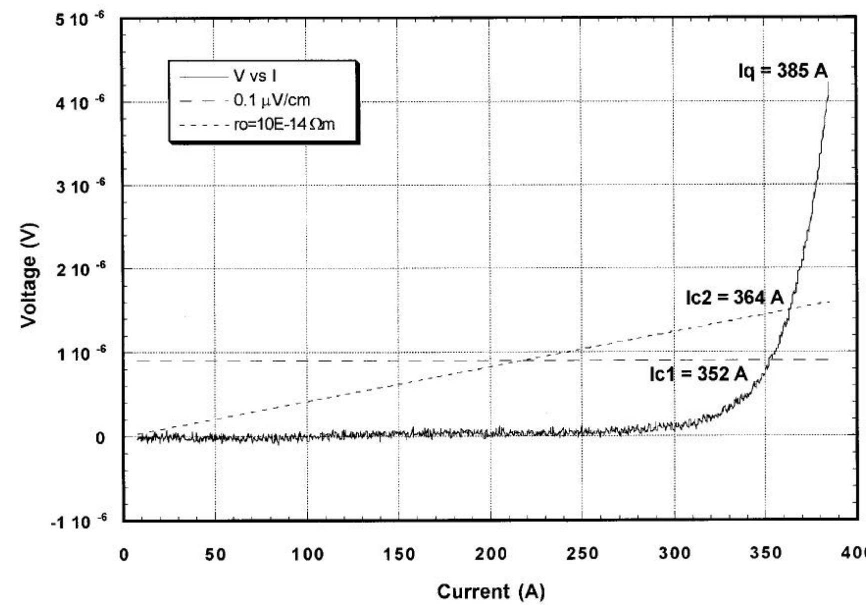
$$\rho_{sc} = \frac{1}{1+\lambda} \frac{V}{L} \frac{S}{I} \qquad E = \frac{V}{L}$$

and V is the measured voltage across the wire.

  - The critical current I_c is defined as the current where $\rho_{sc} = 10^{-14}$ Ωm or $E = 0.1$ μV/cm.

This is standard practice for LTS strands

A. Devred, [4]



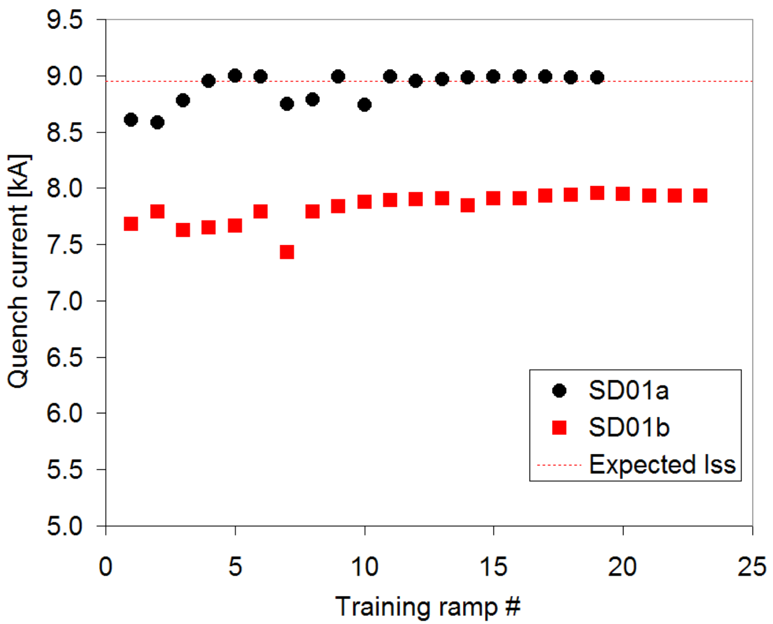
"It has been verified, in particular for accelerator magnets, that the critical currents defined above can be used to make fairly accurate estimations of the maximum quench current of a superconducting magnet" [4].

Conductor limited quenches
Degradation

- The critical current is measured in a few different conditions of temperature and field. By fitting the data with known parameterizations, the entire critical surface can be reconstructed. (In the case of Nb-Ti there is a large data base of measurements that have been parametrized, giving very reliable predictions of expected magnet behavior)
- If the magnet reaches the maximum current computed through the intersection of the measured critical surface and the load line, i.e. $I_{max} = I_{ss}$, one can declare victory (at least from the quench performance point of view).
- If the magnet maximum current I_{max} is lower that I_{ss} , the quench performance is expressed in terms of fraction of short sample (I_{max}/ I_{ss}).
- A conductor-limited quench or a plateau at a level lower than the expected short sample is an indication of *conductor degradation*

Conductor limited quenches
Degradation

- Degradation in a superconductor can be due to
  - Conductor damage or error in cable manufacturing
  - Depressed I_c due to stress (strain)
- ….but, sometimes, magnet performance can be interpreted as degraded in the case of
  - An error in the evaluation of maximum current
    - Computation of peak field
    - Measurements of temperature
    - Difference between coil and witness sample reaction temperature and time.
      - During the reaction of Nb_3Sn coils, the temperature in the oven is not uniform.
- In general, there is about a 5% uncertainty in the short sample current estimate for Nb_3Sn. Less for Nb-Ti.



Energy deposited quenches

- Let's imagine that, in a coil operating in the superconducting state, a certain amount of energy E is released. This energy will bring a volume V of the superconductor to a temperature $T \geq T_c$.
- One can imagine that if E or V are not large enough, the temperature of the superconductor will decrease to below the critical temperature, because of cooling and or thermal conductivity.
- If, on the other hand, E or V are large enough, the normal zone will increase and a quench will propagate.

Energy deposited quenches MQE and MPZ

- The minimum energy necessary to initiate a quench is defined as the

minimum quench energy MQE

- The minimum volume of superconductor that must be brought beyond the critical temperature in order to initiate a quench is defined as the

minimum propagation zone MPZ

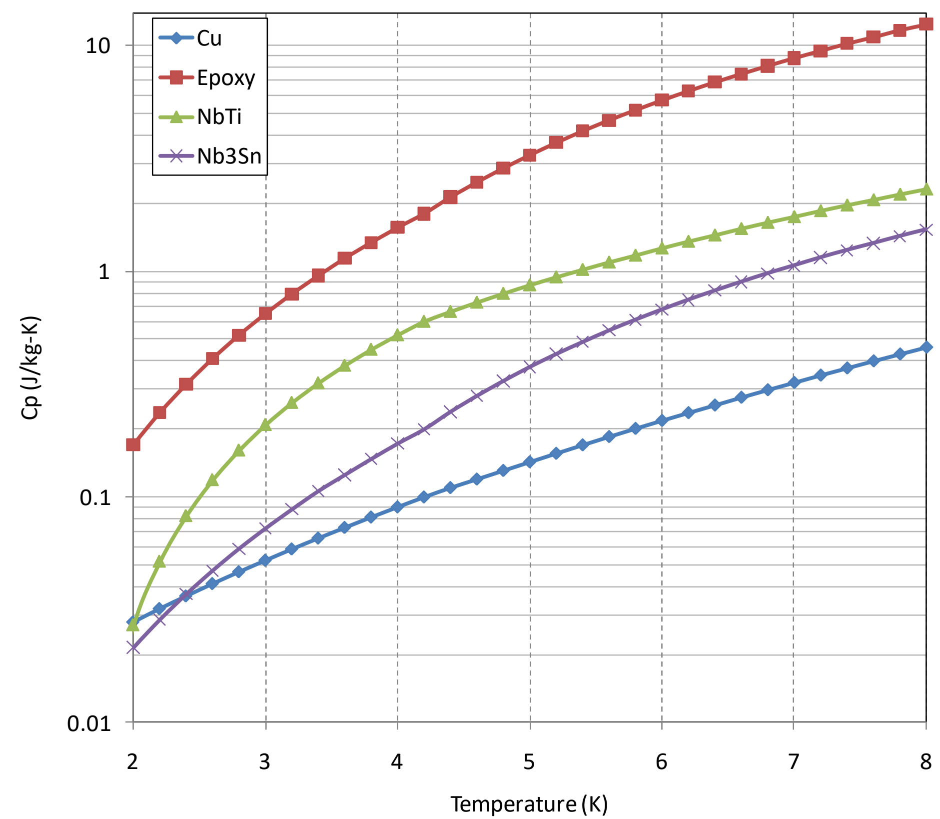
- The two parameters are connected: *MQE* is the energy necessary to create a *MPZ*, i.e [5]

$$E_{MQE} = V_{MPV} \int_{\theta_0}^{\theta_C} \gamma C(\theta) d\theta$$

where C is the specific heat [J kg^{-3} K^{-1}] and γ is the density [kg m^{-3}].

Energy deposited quenches
Distributed disturbances

- Consider a disturbance where the release of energy is uniformly distributed. This situation corresponds to an adiabatic condition.
  - The temperature increase is uniform and no heat is conducted along the coil.
- In this condition, the temperature rise depends only on the specific heat *Cp* (J/kg-K)
- Very little energy is required for a significant temperature rise since *Cp's* are about 10^{-3} of the room temperature values.
  - For copper, Cp from 28e-3 J/kg-K at 1.8 K to 380 J/kg-K at 300 K



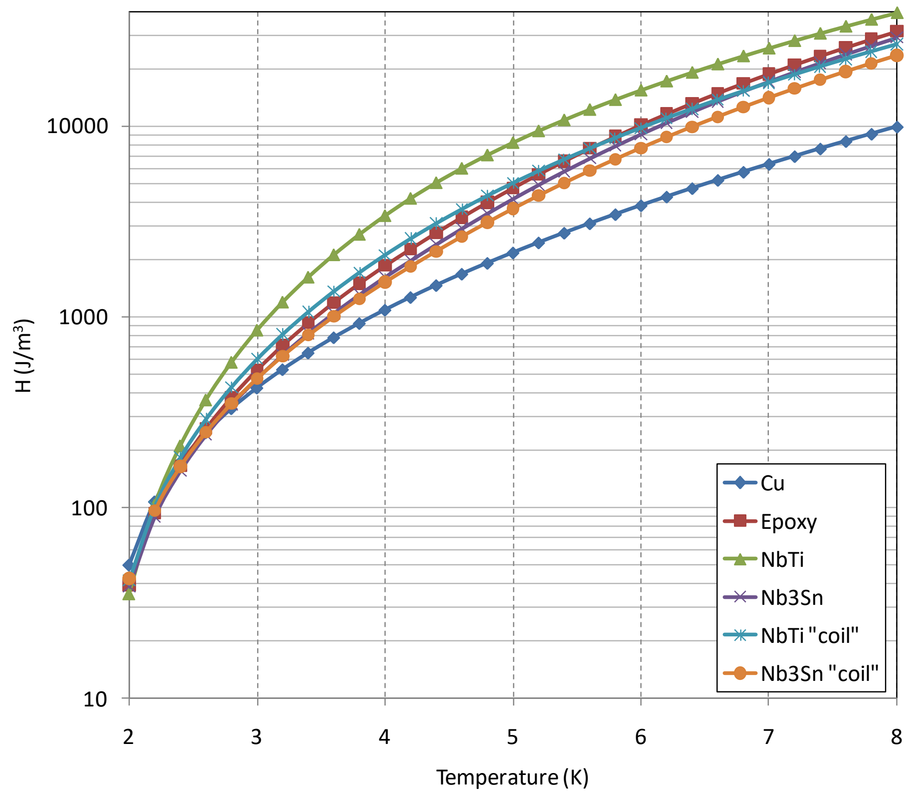
Energy deposited quenches
Distributed disturbances

- Because of the change in *Cp* with temperature, for the computation of the energy density required to quench a coil, it is convenient to use the volumetric specific enthalpy *H* (J/m^3)

$$H(\theta) = \gamma \int_{1.8}^{\theta} C(\theta) d\theta$$

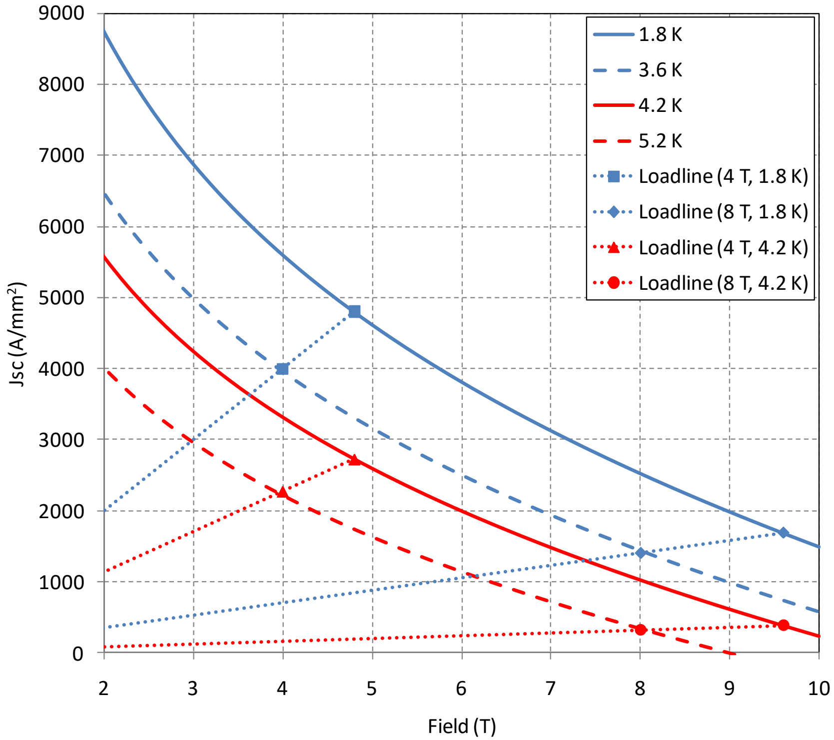
where γ (kg/m^3) is the density of the material.

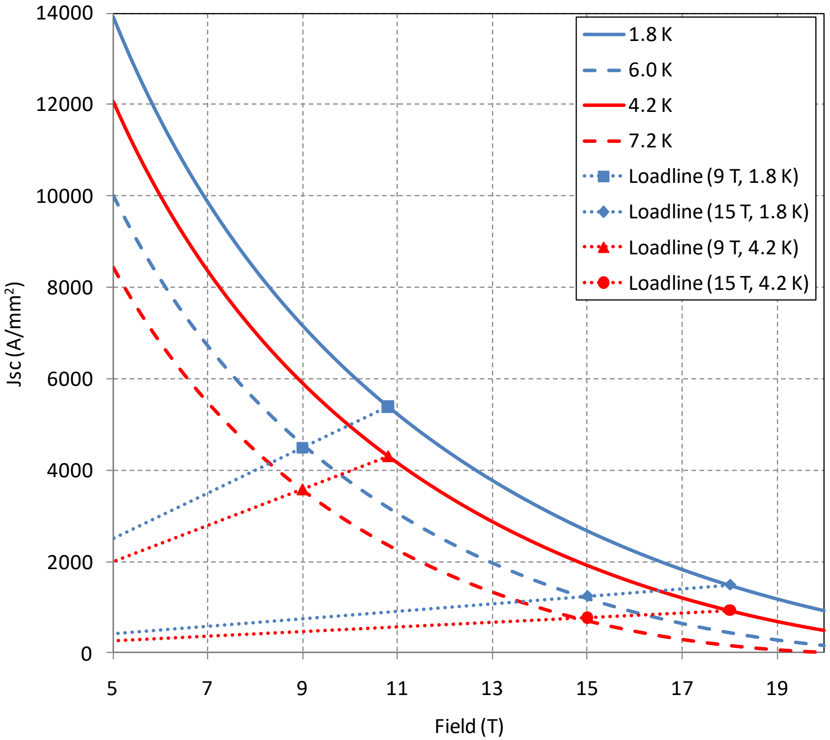
- Assuming a volume fraction of 1/3 superconductor , 1/3 copper, and 1/3 epoxy, we can estimate a Nb-Ti and Nb_3Sn coil volumetric specific enthalpy.
- Then, it is possible to compute the energy density to quench, but we need the temperature margins.



Temperature margins at 80% of I_{ss}

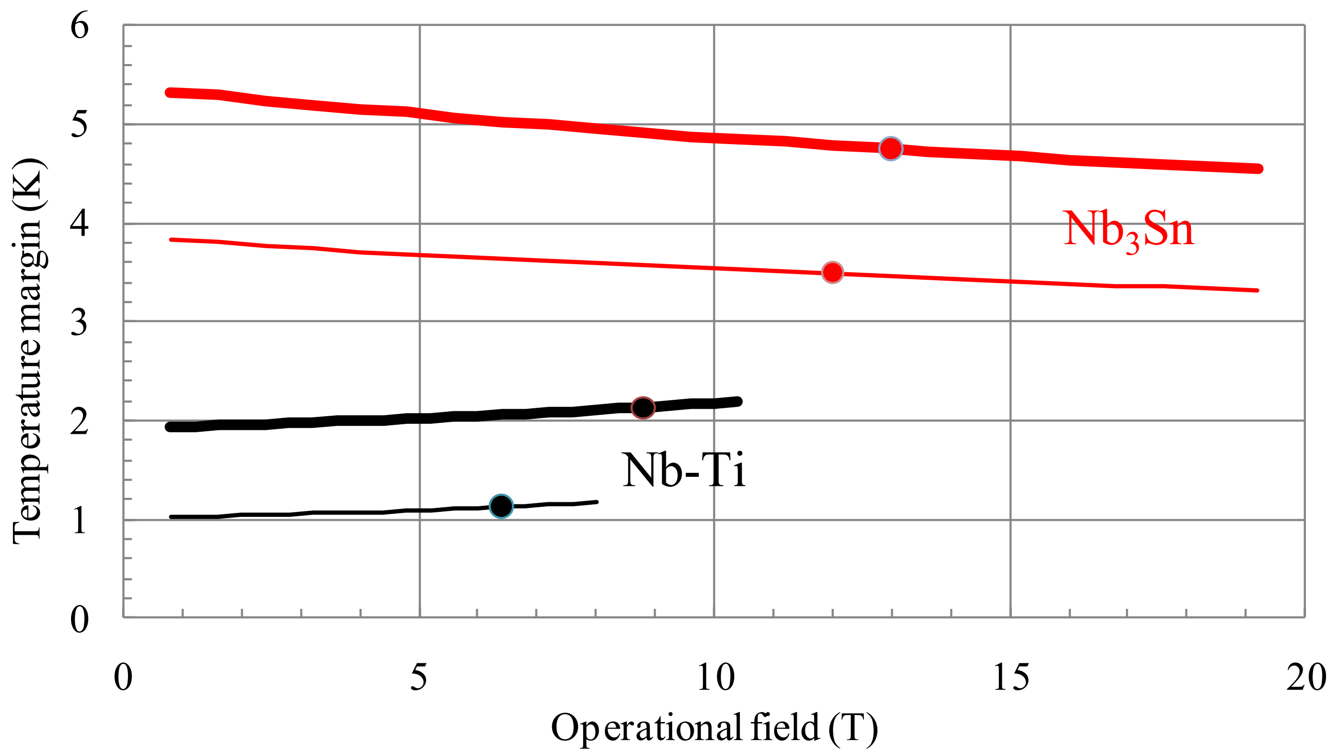
- Nb-Ti
  - At 1.8 K
    - 1.8 K of margin
  - At 4.2 K
    - 1.0 K of margin
- Nb_3Sn
  - At 1.8 K
    - 4.2 K of margin
  - At 4.2 K
    - 3.0 K of margin





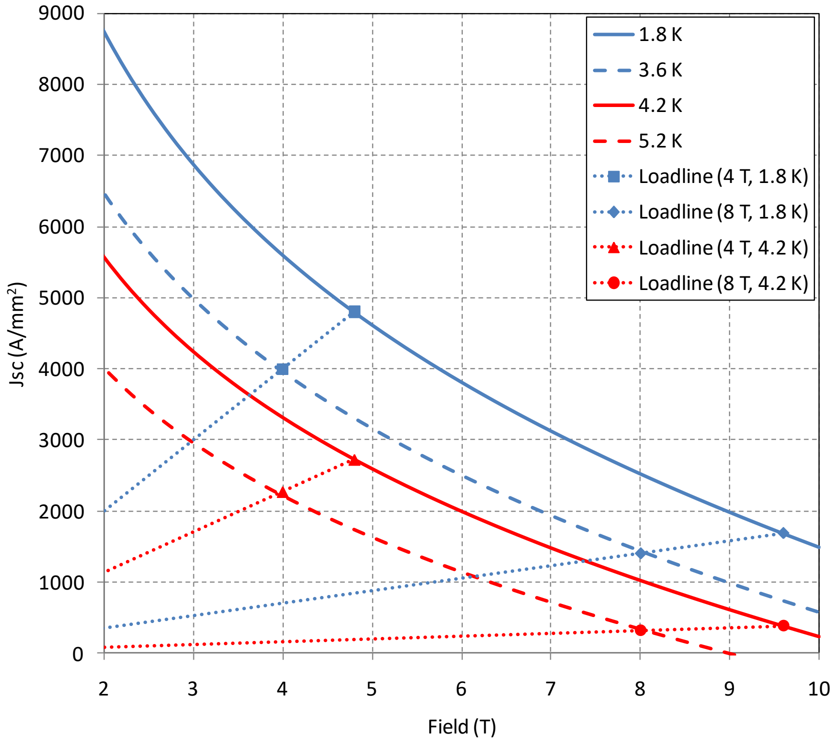
Temperature margins at 80% of I_{ss}

- Margin roughly independent of operational field

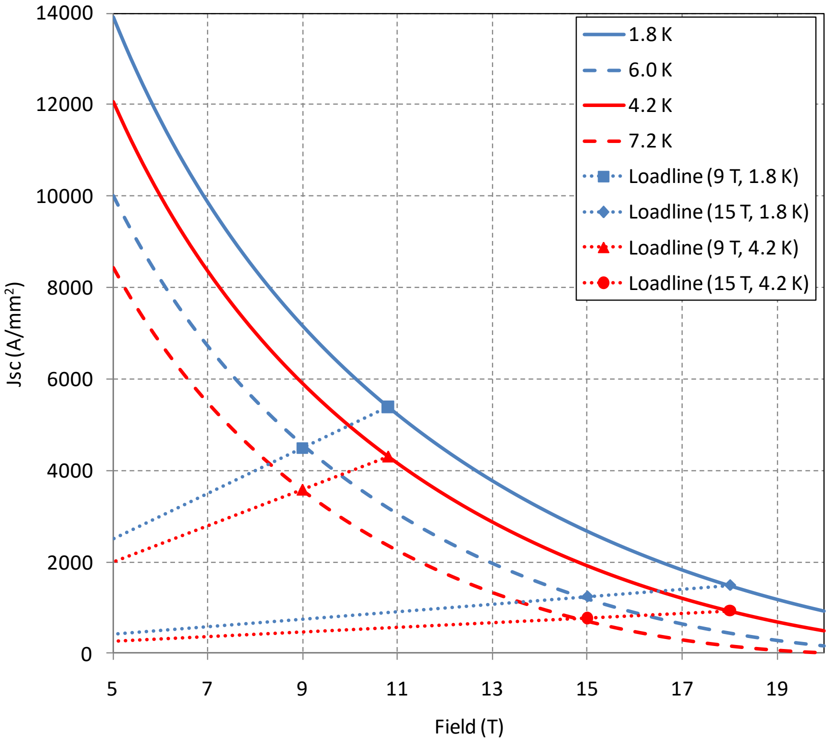


Quench energy densities (Impregnated Nb-Ti and Nb_3Sn coils)

- Nb-Ti
  - At 1.8 K
    - 1.8 K of margin: $1.4 \cdot 10^3$ J/m^3
  - At 4.2 K
    - 1.0 K of margin: $3.3 \cdot 10^3$ J/m^3



- Nb_3Sn
  - At 1.8 K
    - 4.2 K of margin: $7.7 \cdot 10^3$ J/m^3
  - At 4.2 K
    - 3.0 K of margin: $13.9 \cdot 10^3$ J/m^3



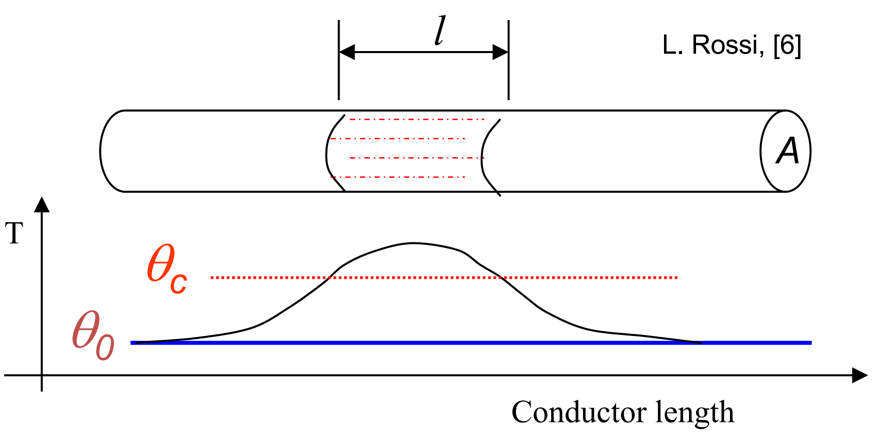
Energy deposited quenches
Point disturbances

- We start considering a wire made purely of superconductor.
- Let's assume that a certain amount of energy E increased the temperature of the superconductor beyond θ_c over a length l. The segment l of superconductor is dissipating power given by $J_c^2 \rho A l$ [W].
- Part (or all) of the heat is conducted out of the segment because of the thermal gradient, which can be approximated as $(\theta_c - \theta_0)/l$. With k the thermal conductivity [W m^{-1} K^{-1}] we set the dissipated power equal to the power conducted away, and obtain

$$\frac{2kA(\theta_c - \theta_0)}{l} = J_c^2 \rho A l$$

which results in

$$l = \sqrt{\frac{2k(\theta_c - \theta_0)}{J_c^2 \rho}}$$



Energy deposited quenches
Point disturbances

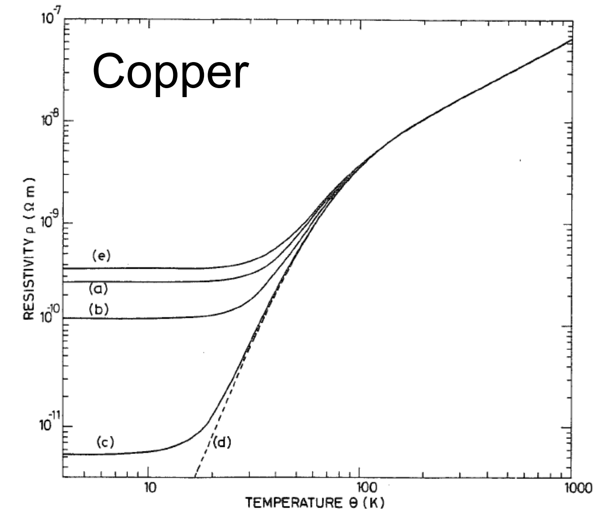
- The length l defines the MPZ (and MQE).
  - A normal zone longer that l will keep growing (quench). A normal zone shorter than l will collapse.
- An example [2]
  - A typical Nb-Ti 6 T magnet has the following properties
    - $J_c = 2 \times 10^9$ A m^{-2}
    - $\rho = 6.5 \times 10^{-7}$ Ω m
    - $k = 0.1$ W m^{-1} K^{-1}
    - $\theta_c = 6.5$ K
    - $\theta_o = 4.2$ K

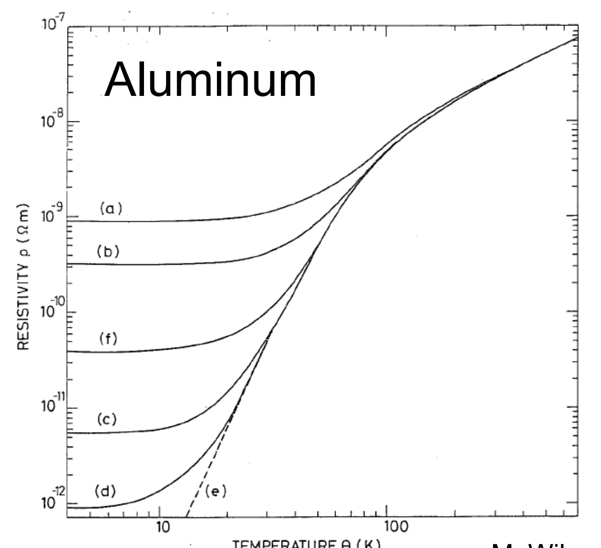
$$l = \sqrt{\frac{2k(\theta_c - \theta_0)}{J_c^2 \rho}}$$

  - In this case, l = 0.5 μm and, assuming a 0.3 mm diameter, the required energy to bring to θ_c is 10^{-9} J.
- A wire made purely of superconductor, without any stabilizer (like copper) around, would quench with nJ of energy.
  - In order to increase l, since we do not want to reduce J_c, we have to increase k/ρ: we need a composite conductor!

Energy deposited quenches
Point disturbances

- We now consider the situation where the superconductor is surrounded by material with low resistivity and high conductivity.
- At 4.2 K copper can have
  - resistivity $\rho = 3 \times 10^{-10}\ \Omega$ m (instead of $6.5 \times 10^{-7}\ \Omega$ m for Nb-Ti)
  - $k = 350$ W m^{-1} K^{-1} (instead of 0.1 W m^{-1} K^{-1} for Nb-Ti).
- We can therefore increase k/ρ by almost a factor of 10^7.
- A significant improvement was achieved in the early years of superconducting magnet development after the introduction of composite conductor.
  - Both for flux jumps and stability

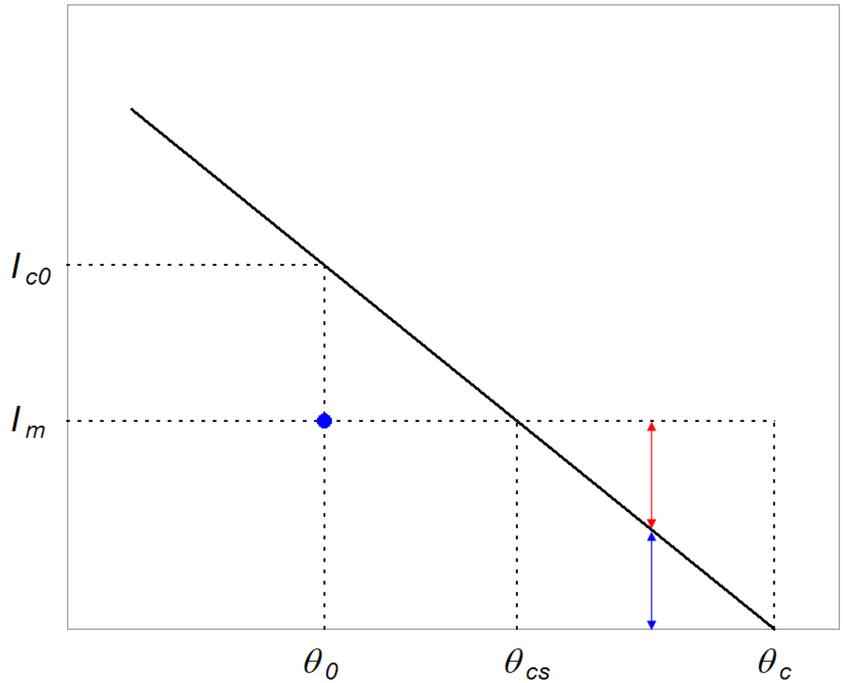




M. Wilson, [2]

Energy deposited quenches
Point disturbances

- In a composite superconductor, when a transition from the normal to superconducting state occurs, the heat dissipated per unit volume of the entire wire (stabilizer and superconductor) G [W m^{-3}], can be subdivided into three parts
  - All the current flows in the superconductor
  - The current is shared by the superconductor and the stabilizer (current sharing temperature)
  - All the current flows in the stabilizer.



- The heat dissipated per unit volume of the entire wire (stabilizer and superconductor) G [W m^{-3}] has a linear increase from θ_{cs} to θ_c .

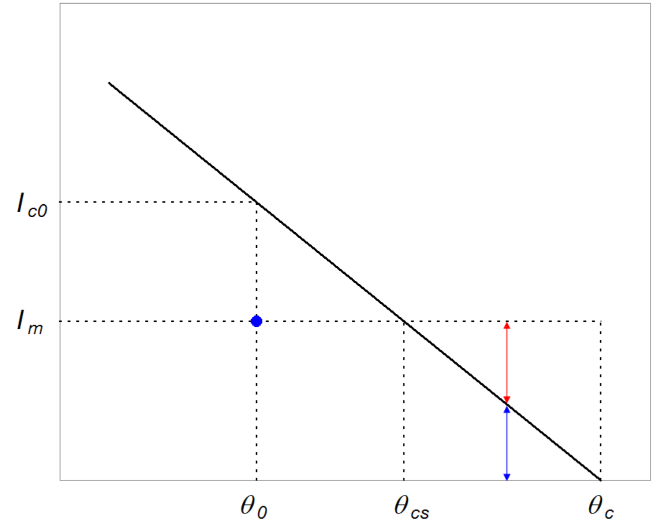
$$\theta < \theta_{cs} \longrightarrow G = 0$$

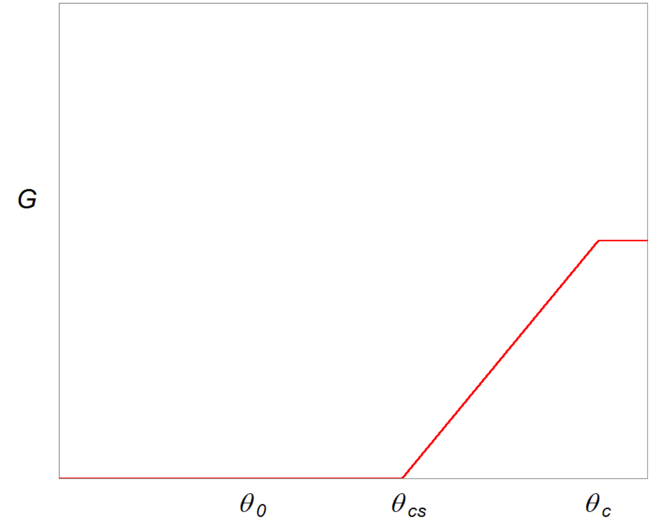
$$\theta > \theta_c \longrightarrow G = G_c = \rho_{stab} \frac{\lambda^2 J_m^2}{1-\lambda}$$

$$\theta_{cs} < \theta < \theta_c \longrightarrow G = G_c \frac{(\theta - \theta_{cs})}{(\theta_c - \theta_{cs})} = \rho_{stab} \frac{\lambda^2 J_m^2}{1-\lambda} \frac{(\theta - \theta_{cs})}{(\theta_c - \theta_{cs})}$$

$$\lambda = \frac{A_{sc}}{A_{tot}}$$

$$J_m = \frac{I_m}{A_{sc}}$$





Energy deposited quenches
Point disturbances

- Now that we have an expression for *G(θ)*, we can modify the one-dimensional equation considered for the pure superconductor case, to a three-dimensional equation which includes the transverse conductivity.
- Assuming the coil as an isotropic continuum with two-direction conduction, the steady state equation of heat conduction becomes

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk_r\frac{\partial\theta}{\partial r}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial\theta}{\partial z}\right)+\lambda_w G(\theta)=0$$

where

- k_r is the conductivity along the wire
- k_z is the conductivity transverse to the wire
- λ_w is the fraction in volume of the composite conductor (both superconductor and stabilizer) over the coil.

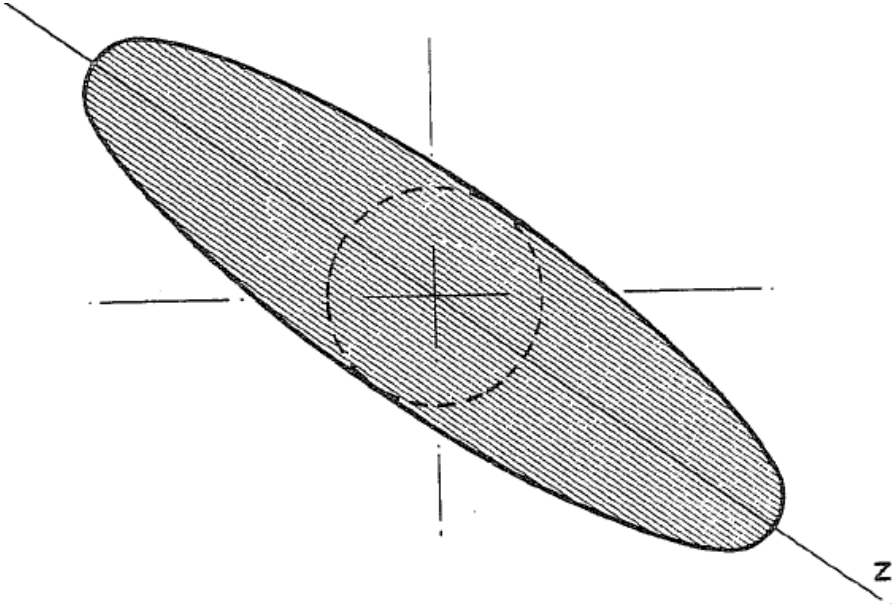
Energy deposited quenches
Point disturbances

- The solution provides an MPZ that is an ellipsoid elongated in the z direction (along the cable), with a semi-axis R_g in z

$$R_g = \pi\sqrt{\frac{k_z(\theta_c - \theta_{cs})}{\lambda_w G_c}}$$

and a circular cross-section in the transverse plane with radius r_g

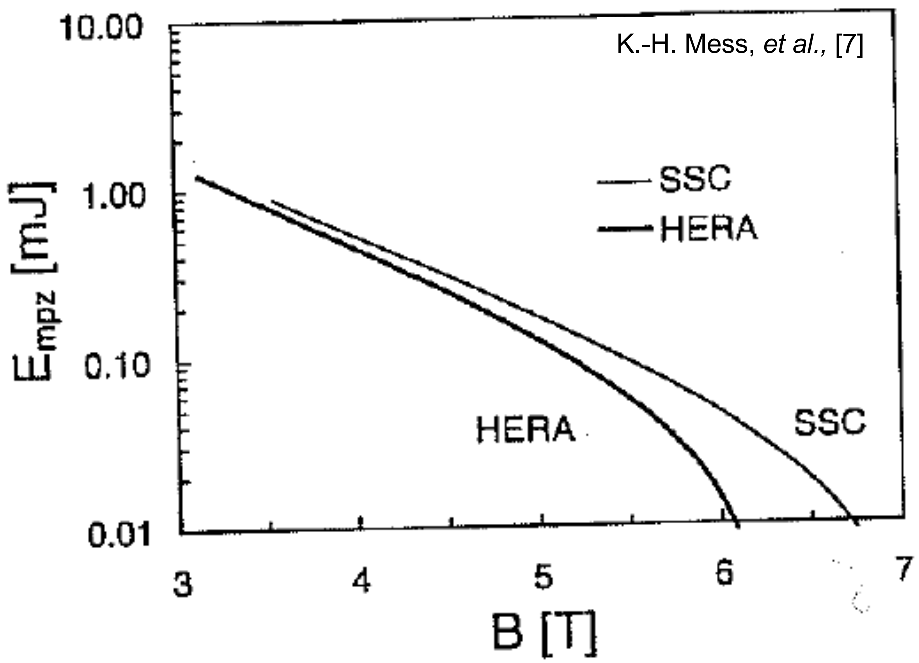
$$r_g = R_g\sqrt{\frac{k_r}{k_z}}$$



M. Wilson, [2]

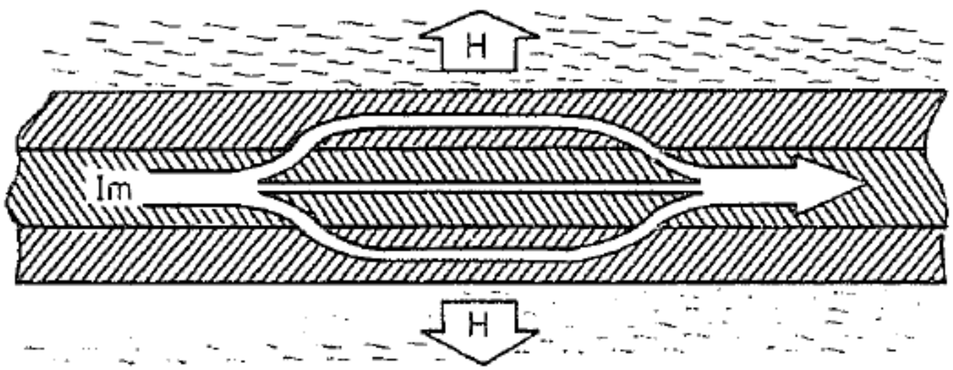
- The MQE necessary to generate the MPZ is significantly increased, from the nJ level to the 10-100 μJ level.

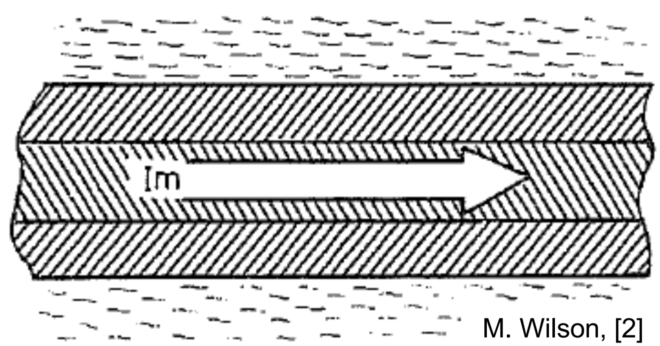
- SSC
  - The design field (> 6.6 T) is close to the short sample field
  - MQE = 10 μJ
  - MPZ is less than a strand diameter
    - "Adiabatic" condition (no heat exchanged with liquid helium) is a conservative estimate.
- HERA
  - The design field (5 T) is not as close to the short sample field
  - MQE = 150 μJ
  - MPZ is several mm
    - Helium cooling will increase the energy threshold.



Cryogenic stabilization

- When a *distributed disturbance* (large volume) produces a transition in the superconductor to a normal zone, or when the MPZ is significantly larger than the strand diameter, we abandon the adiabatic conditions described previously.
- In this case, we have to take into account the cryogenic liquid (liquid Helium) in contact with the wire.





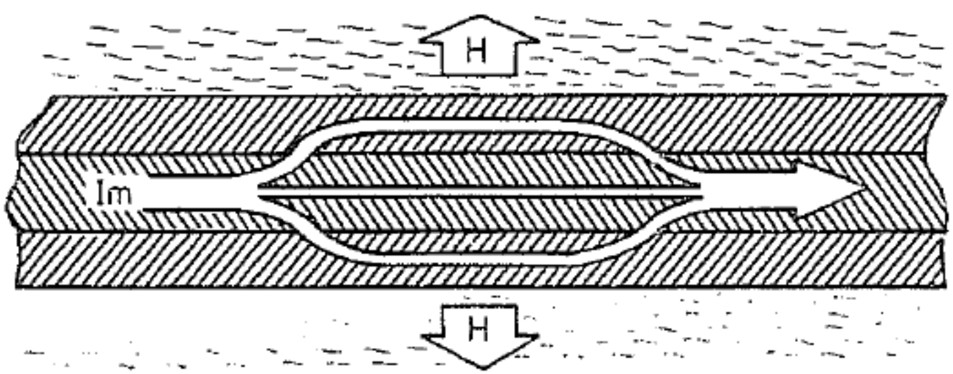
M. Wilson, [2]

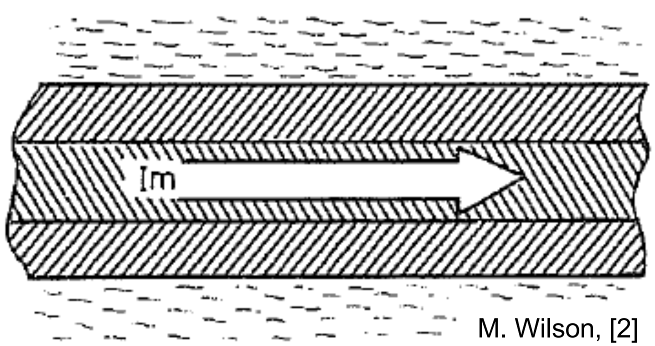
Cryogenic stabilization

- The heat generation per unit of cooled area is given by

$$G(\theta) = \frac{\lambda^2 J_c \rho}{(1-\lambda)} \frac{(\theta - \theta_0)}{(\theta_c - \theta_0)} \frac{A}{P} = G_c \frac{(\theta - \theta_0)}{(\theta_c - \theta_0)} \frac{A}{P}$$

where we assumed that $\theta_0 = \theta_{cs}$ (i.e. $J_m = J_c$), and A is the cross-sectional area of the conductor and P is the cooled perimeter.





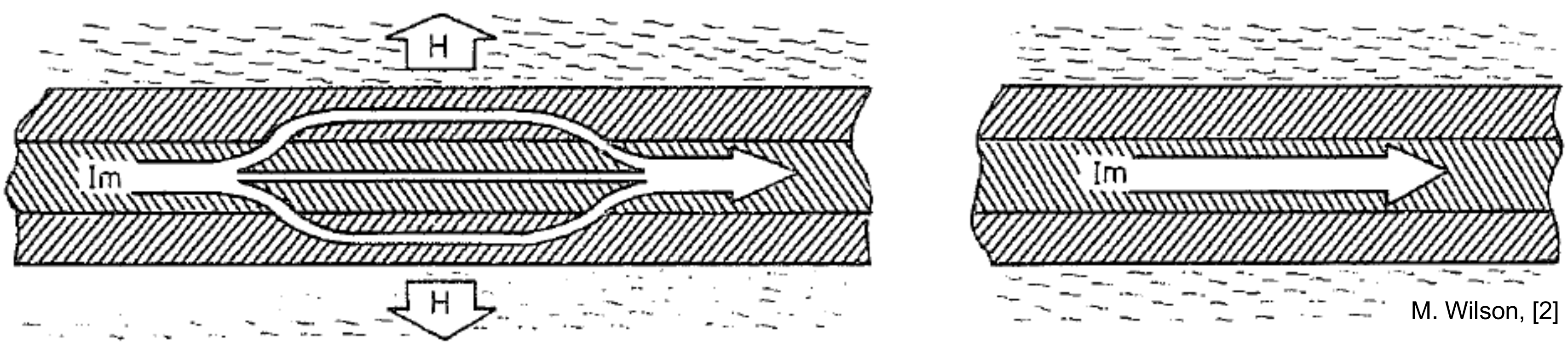
M. Wilson, [2]

Cryogenic stabilization

- The cooling per unit of cooled area is given by

$$h(\theta - \theta_0)$$

where h [W m^{-1} K^{-1}] is the heat transfer coefficient (we assume it is a constant) and θ_0 the temperature of the bath.



M. Wilson, [2]

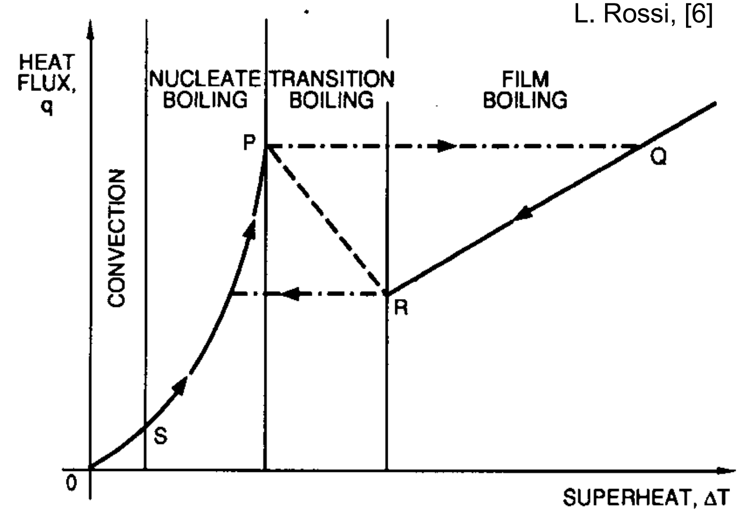
Cryogenic stabilization
Stekly criteria

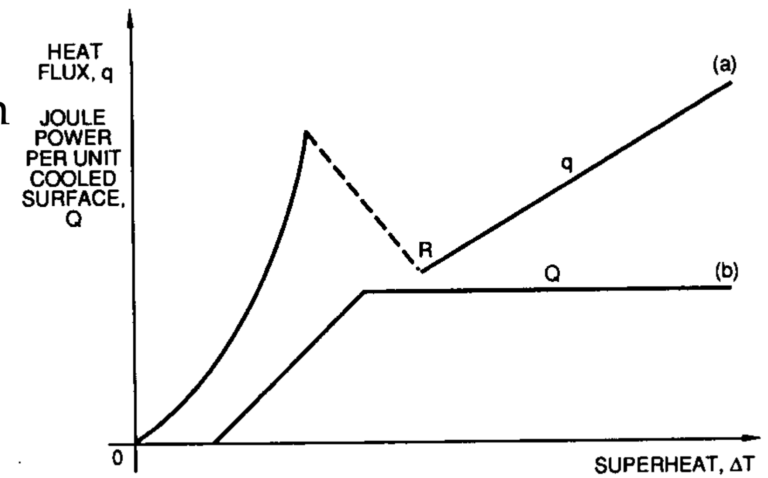
- The criterion for cryogenic stability (Stekly and Zar) is therefore

$$\alpha = \frac{\lambda^2 J_c^2 \rho A}{(1-\lambda) Ph(\theta_c - \theta_0)} = \frac{G_c A}{Ph(\theta_c - \theta_0)} < 1$$

- In reality h is characterized by three zones
  - Nucleate boiling
  - Transition boiling
  - Film boiling
- In general, we have cryogenic stability when the curve of the dissipated power $G(\theta)$ stays below the curve of the power removed by helium.
- The Stekly criteria requires an ohmic heat per unit area of cooled surface < 1.5-2.0 kW/m^2

L. Rossi, [6]

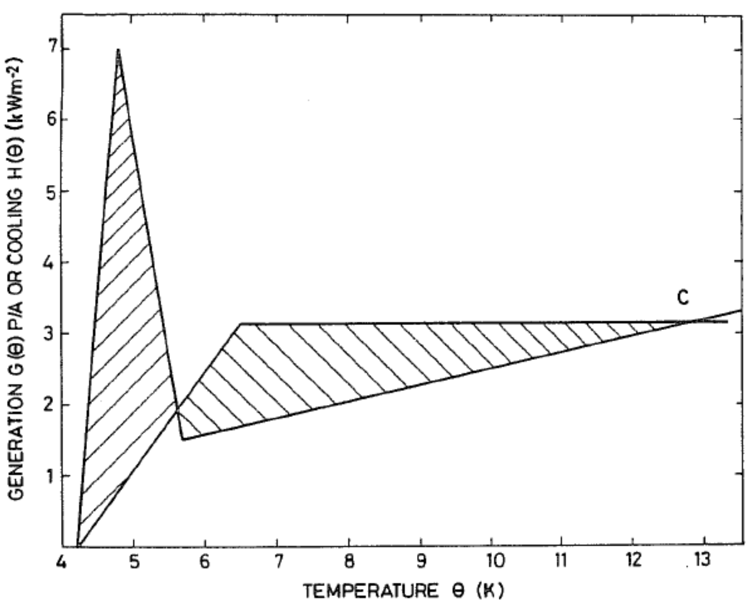




- The Stekly criteria neglects heat conduction.
- But, if the hot zone has finite dimensions and is surrounded by a cold zone, the heat conduction at the boundaries can improve the stability
  - Conductor can also be stable if $G > H$
- Maddock, *et al.*, [10] proposed an equal area theorem
  - The surplus of heat generation must be balanced by a surplus of cooling.
- Maddock criteria requires an ohmic heat per unit area of cooled surface < 3 kW/m^2

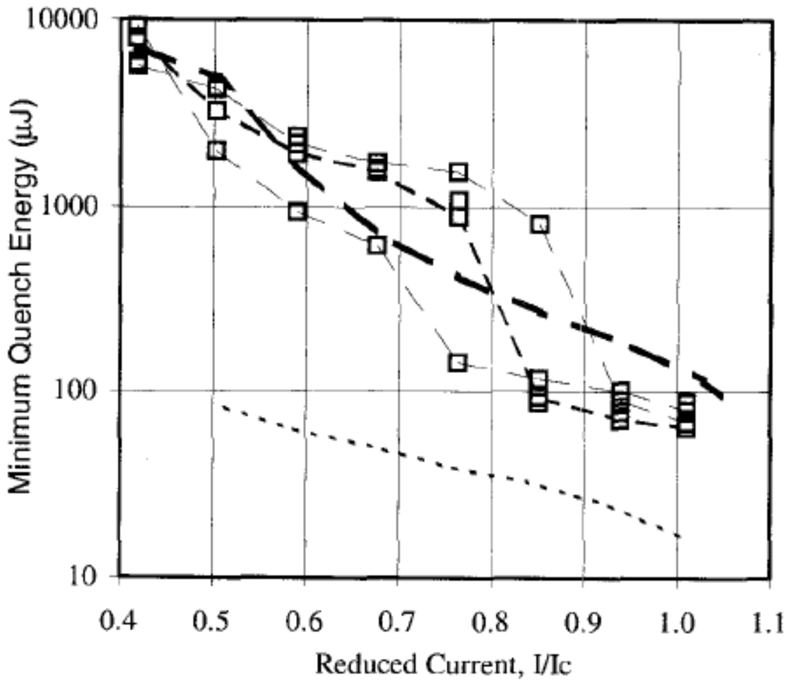
$$\int_{\theta_0}^{\theta_1} \left\{ H(\theta) - \frac{A}{P} G(\theta) \right\} k(\theta) d\theta = 0$$

M. Wilson, [2]



- Wire
  - Measurements showed that the most important parameter is the amount of helium in contact with the strand.
  - The MQE at 0.8 I_c is
    - 10 μJ in adiabatic conditions
    - 1000 μJ in an open bath
- Cable
  - A "kink" is observed
    - Zone where the strands behave collectively
    - Zone where the strands behave individually
  - Above the kink
    - MQE is around 100 μJ
  - Below the kink
    - MQE is > 1000 μJ

A.K. Ghosh, *et al.*, [9]



Summary

- Classification of quenches in superconducting magnets
  - Conductor limited quenches
  - Energy deposited quenches

- We introduced the concept of MPZ and MQE
  - Depending on the assumptions, the energy required to quench a magnet is
    - 10^{-9} J in the case of a "pure superconductor"
    - 10-100 μJ in the case of a composite wire
    - More than 1000 μJ in an open bath

- In the case of a distributed disturbance, the minimum quench energy density can be on the order of 10^3 J m^{-3} (Nb-Ti magnets).

- Considering the effect of liquid He, a conductor can be stable up to an ohmic heat per unit area of cooled surface of about 3 kW/m^2.

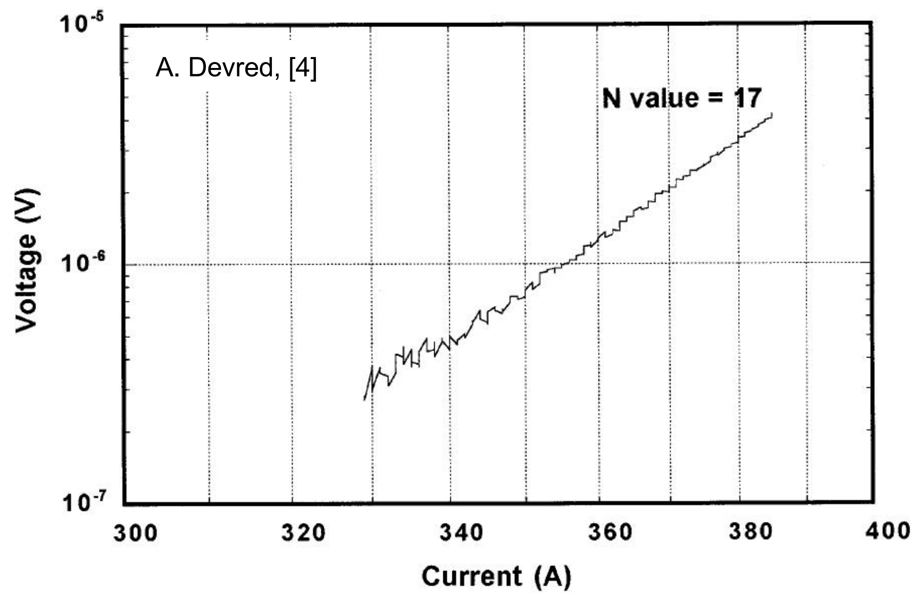
Appendix I

Conductor limited quenches
Measurements of the conductor critical current

- Both the increase in ρ_{sc} and V can be fit by a scaling law like

$$\frac{\rho_{sc}}{\rho_c} = \left(\frac{I}{I_C}\right)^{N-1} \qquad \frac{V}{V_c} = \left(\frac{I}{I_C}\right)^{N}$$

- N is called the resistivity transition index, or N-value, and it is an indication of the sharpness of the transition from the superconducting to the normal state.
- Usually, the better quality the conductor, the higher (≥ 30) is the N-value.



Acknowledgement

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References

[1] A. Devred, "*Quench Origins*", AIP Conference Proceedings 249, edited by M. Month and M. Dienes, 1992, p. 1309-1372.

[2] M. Wilson, "*Superconducting magnets*", Oxford UK: Clarendon Press, 1983.

[3] A. Godeke, "*Performance boundaries in Nb_3Sn superconductors*", PhD thesis, 2005.

[4] A. Devred, "*Practical low-temperature superconductors for electromagnets*", CERN-2004-006, 2006.

[5] Y. Iwasa, "*Mechanical disturbances in superconducting magnets – A review*", IEEE Trans. Magn., Vol. 28, No. 1, January 1992, p. 113-120.

[6] L. Rossi, "*Superconducting Magnets*", CERN Academic Training, 15-18 May 2000.

[7] K.-H. Mess, P. Schmuser, S. Wolff, "*Superconducting accelerator magnets*", Singapore: World Scientific, 1996.

[8] D. Leroy, "*Review of the R&D and supply of the LHC superconducting cables*", IEEE Trans. Appl. Supercond. , Vol. 16, No. 2, June 2006, p. 1152- 1159.

[9] A.K. Ghosh, et al., "*Minimum quench energies of rutherford cables and single wires*", IEEE Trans. Appl. Supercond. , Vol. 7, No. 2, June 1997, p. 954-957.

[10] B.J. Maddok, et al., "*Superconductive composites: heat transfer and steady state stabilization*", Cryogenics 9, 1969, p. 261-273.