Superconductor Stability

CERN Accelerator School
Superconductivity for Accelerators

Erice, April 25th – May 4th, 2013

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Plan of the lecture

- Training and degradation
- Perturbation spectrum overview
- Heat balance
- Stabilization strategies and criteria
- A summary and more complex topics

focus on LTS magnets
adiabatic, or helium cooled

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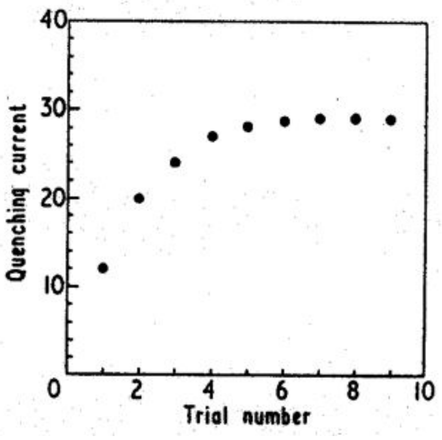
Training…

- 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***

NbZr solenoid
Chester, 1967



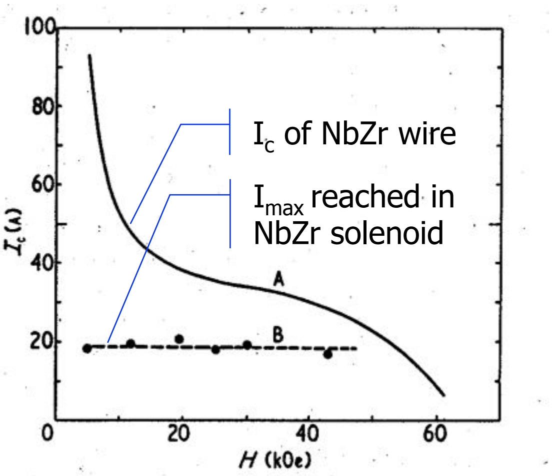
M.A.R. LeBlanc, Phys. Rev., **124**, 1423, 1961.

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



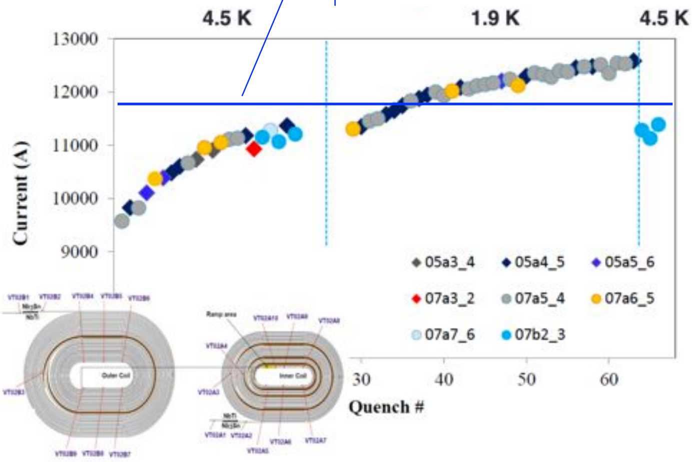
I_c of NbZr wire

I_{max} reached in NbZr solenoid

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

Training today

11 T field in the dipole bore



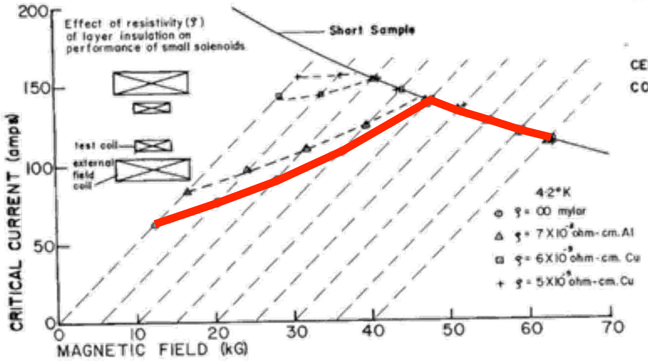
Courtesy of G. Chlachidze, Fermilab, April 2013, unpublished

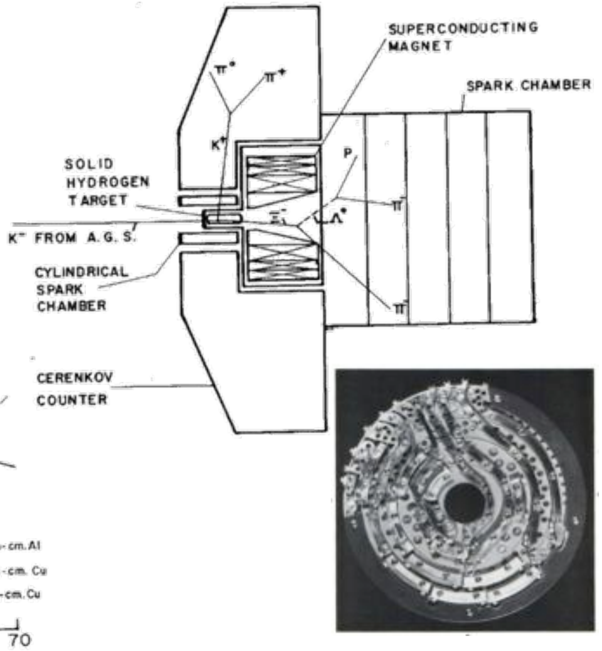
- Training of an model Nb_3Sn 11 T dipole for the LHC upgrade in liquid and superfluid helium
  - Still, training may be necessary to reach nominal operating current
  - Short sample limit is not reached, even after a long training sequence

stability is (still) important !

Dealing with early instabilities

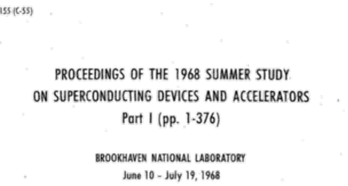
- *"Those tiny, primitive magnets were, of course, terribly unstable […] One had to have faith to believe that these erratic toys of the low temperature physicist would ever be of any consequence as large engineered devices"* (J. Hulm, ASC 1982)





W.B. Sampson, Proc. Int. Symp. Mag. Tech., SLAC, 530-535, 1965

A *Woodstock* for SC accelerator magnets



BNL 50155 (C-55)

PROCEEDINGS OF THE 1968 SUMMER STUDY
ON SUPERCONDUCTING DEVICES AND ACCELERATORS
Part I (pp. 1-376)

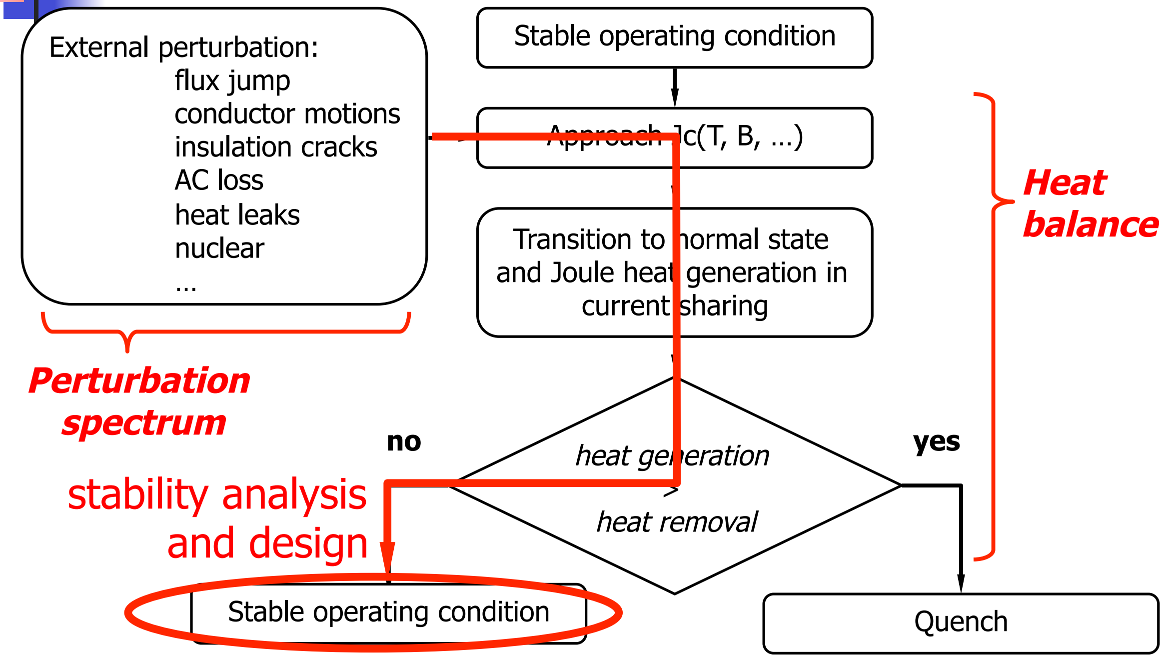
BROOKHAVEN NATIONAL LABORATORY
June 10 – July 19, 1968

M. Morpurgo B. Montgomery W. Sampson P. Smith P. Lazeyras R. Wittgenstein

J. Hale Y. Iwasa

- A six weeks summer study organized and hosted by BNL in 1968
- The ***crème de la crème*** addressed material and engineering issues of superconducting accelerators, among them:
  - **Stability**, training and degradation
  - **Flux-jumps** in composite superconductors
  - Twisting of multi-filamentary wires and cables

An event tree for stability (and quench)



External perturbation:
- flux jump
- conductor motions
- insulation cracks
- AC loss
- heat leaks
- nuclear
- …

Perturbation spectrum

Stable operating condition

Approach Jc(T, B, …)

Transition to normal state and Joule heat generation in current sharing

heat generation > heat removal

no

yes

Heat balance

stability analysis and design

Stable operating condition

Quench

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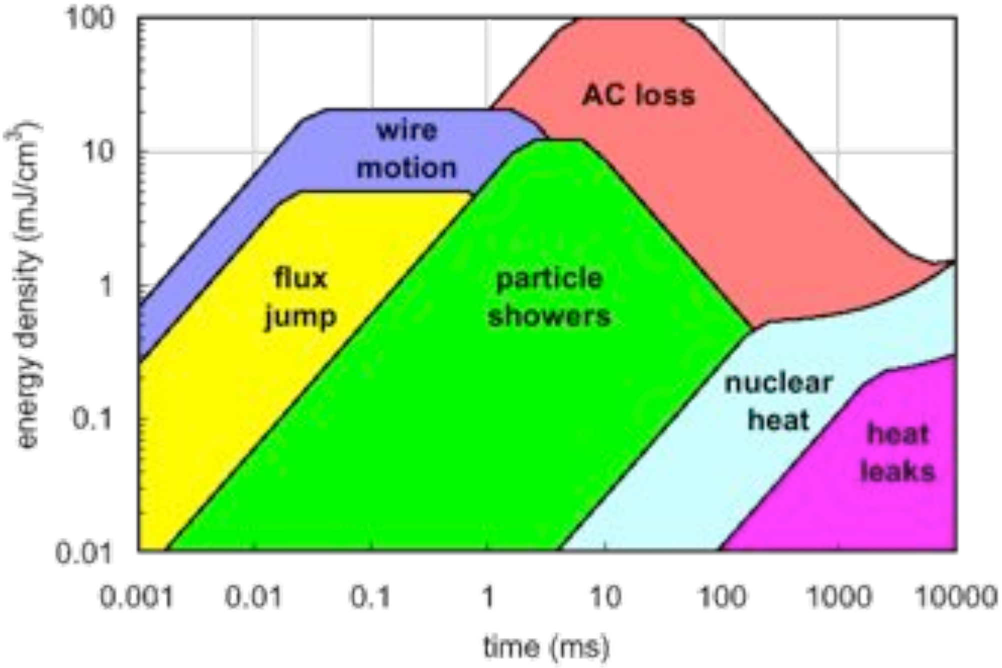
Perturbation spectrum

- 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

Perturbation scales

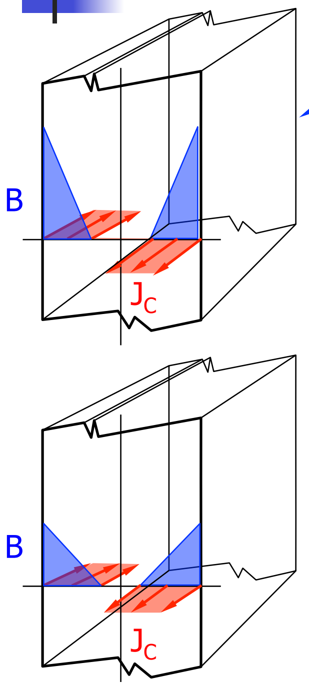
- Transient (stability concern)
    - point Q [Joules]
    - distributed Q''' [Joules/m^3] → [mJ/cm^3]
- Continuous (sizing of cooling system)
    - point q [Watts]
    - distributed q''' [Watts/m^3]

Perturbation overview



After the work of M.N. Wilson, *Superconducting Magnets*, Plenum Press, 1983

Flux jump mechanism



- External field change induces screening *persistent* currents (J_C) in the superconductor
- A small perturbation induces a temperature increase
- Critical current density decreases at increasing temperature
- A drop in screening current causes the field profile to enter in the superconductor
- Energy is dissipated (flux motion)
- Thermal diffusivity and heat capacity is small in the superconductor and the temperature increases

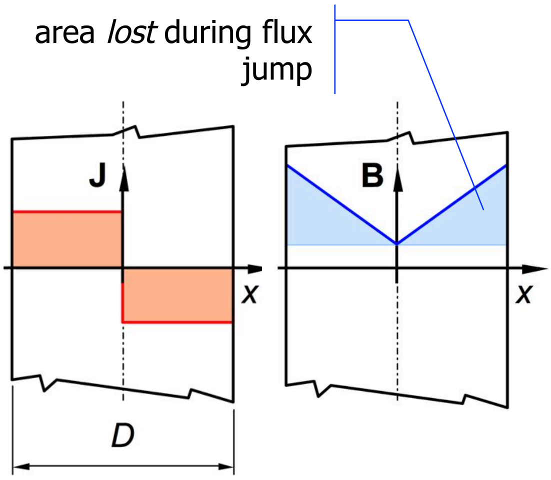
Flux-jumps energy

- During a complete flux-jump the field profile in a superconducting filament becomes flat:
  - e.g.: field profile in a fully penetrated superconducting slab

$$\delta B = \mu_0 J_c x$$

  - energy stored in the magnetic field profile:

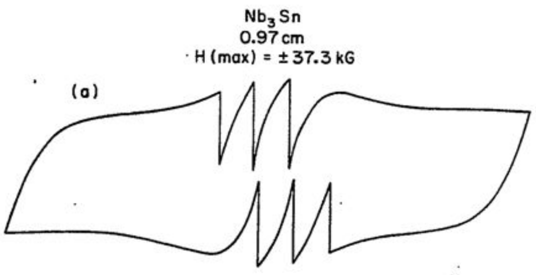
$$Q''' = \frac{2}{D}\int_0^{D/2} \frac{\delta B^2}{2\mu_0}\,dx = \frac{\mu_0 J_c^2 D^2}{24}$$



D = 50 μm, J_c = 10000 A/mm² → $Q''' \approx 6$ mJ/cm³

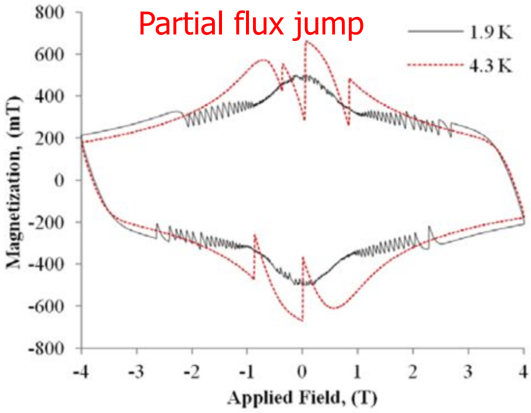
NOTE: to decrease Q''', one can decrease D

Flux jumps then and now



Complete flux jump

A.D. McInturrf, *Composite Materials*, Proceedings of the **1968** Summer School on Superconducting Devices and Accelerators, BNL 50155 (C-55)



Partial flux jump

B. Bordini, et al., *Magnetization Measurements of High-J_C Nb_3Sn Strands*, CERN-ATS-**2013**-029

Flux jumps is **not** an old story, we still suffer from magnetic instabilities when pushing for high conductor J_C

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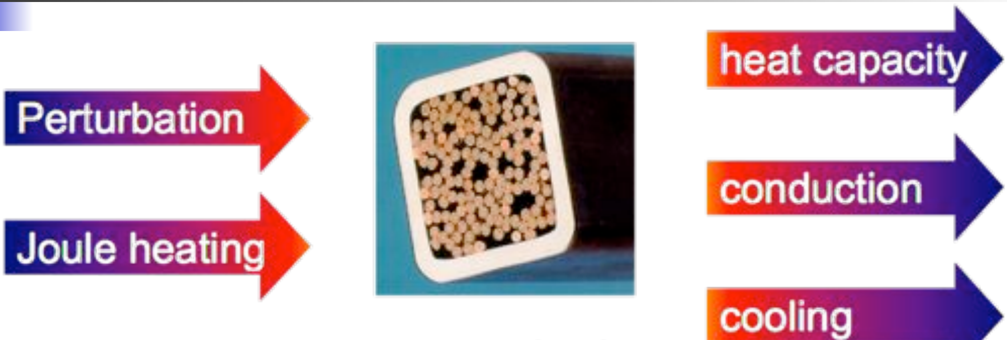
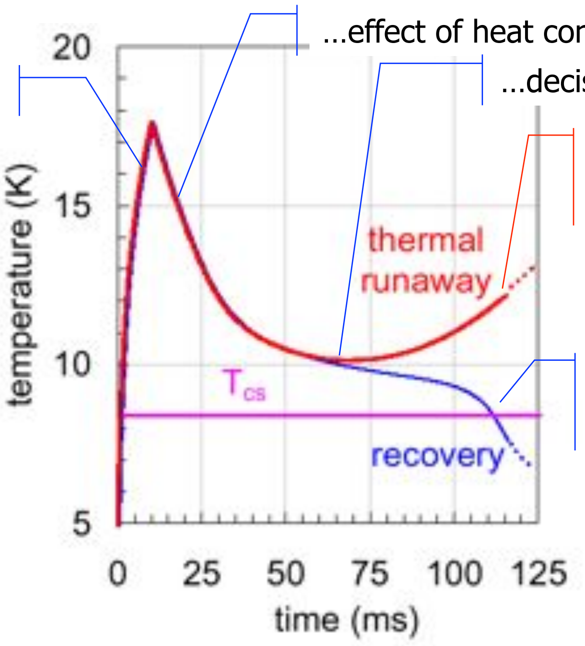
Prototype heat balance



superconducting cable

$$\underbrace{C\frac{\partial T}{\partial t}}_{\text{Heat capacity}} = \underbrace{\overbrace{q'''_{ext}}^{\text{Heat source}} + \overbrace{q'''_{J}}^{\text{Joule heat}}}_{\text{generation}} + \overbrace{\overbrace{\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)}^{\text{Conduction}} - \underbrace{\frac{wh}{A}\left(T - T_{he}\right)}_{\text{Heat transfer}}}^{\text{cooling}}$$

Temperature transient



heat pulse Q'''_{ext}…

…effect of heat conduction and cooling…

…decision time…

$Q'''_{ext} = \mathbf{Q'''}+\varepsilon$
generation > cooling

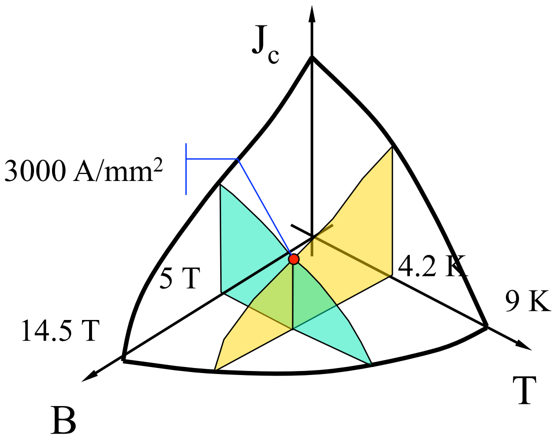
$Q'''_{ext} = \mathbf{Q'''}-\varepsilon$
generation < cooling

Energy margin…

- Q''', energy margin
  - Minimum energy density that leads to a quench
  - Maximum energy density that can be tolerated by a superconductor, still resulting in recovery
    - Simple and experimentally measurable quantity (…)
    - Measured in [mJ/cm^3] for convenience (values ≈ 1…1000)
    - Also called *stability margin*
    - Compared to the energy spectrum to achieve stable design
- Q, quench energy
    - Better adapted for disturbances of limited space extension
    - Measured in [μJ] to [mJ]

… and other useful margins

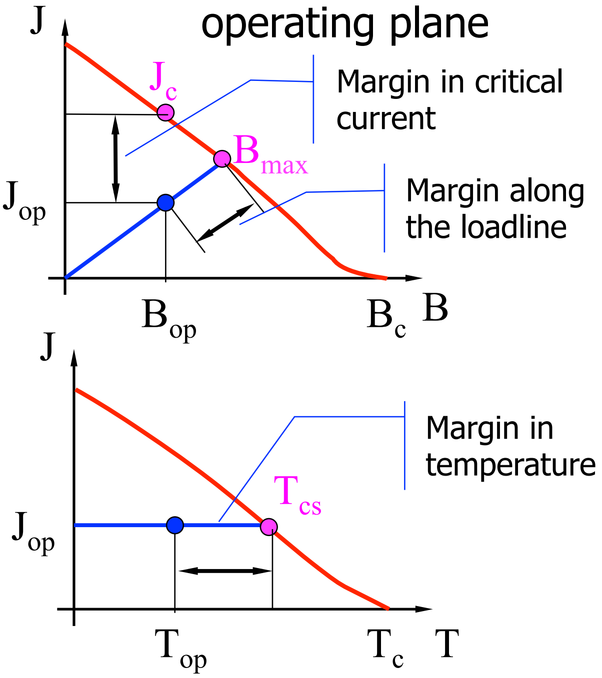
typical NbTi



$J_{op}/J_C \approx 0.5$

$B_{op}/B_{max} \approx 0.8$ (Todesco's 80 %)

$T_{cs}-T_{op} \approx 1…2$ K



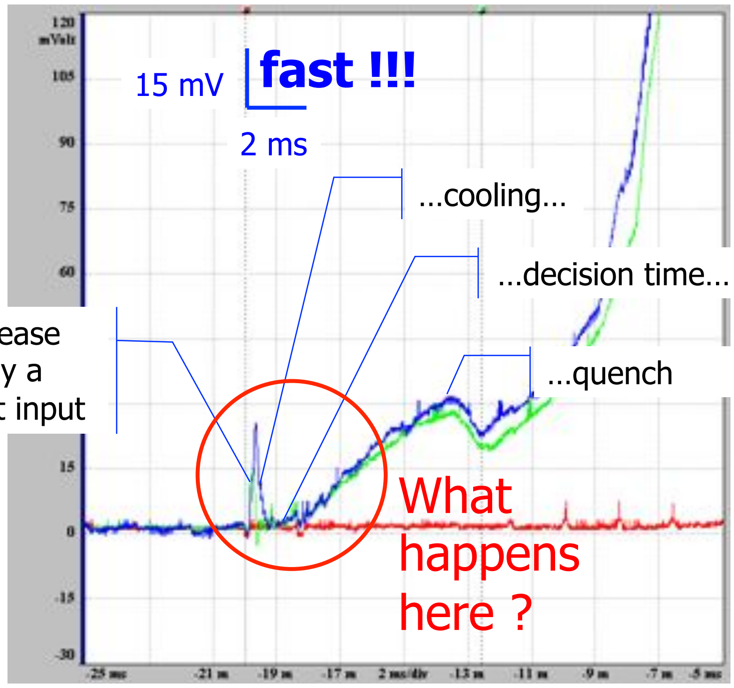
Margin in critical current

Margin along the loadline

Margin in temperature

A measured *stability transient*

(LHC dipole magnet training)



fast !!!

…cooling…

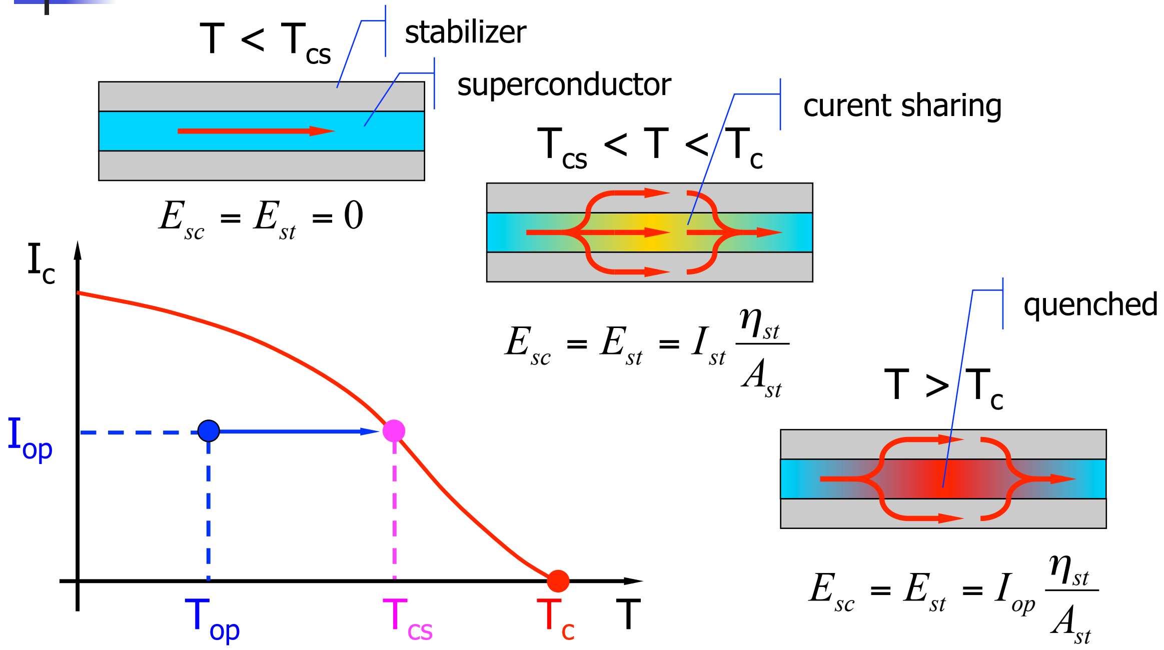
…decision time…

…quench

Voltage increase generated by a sudden heat input

What happens here ?

Current sharing

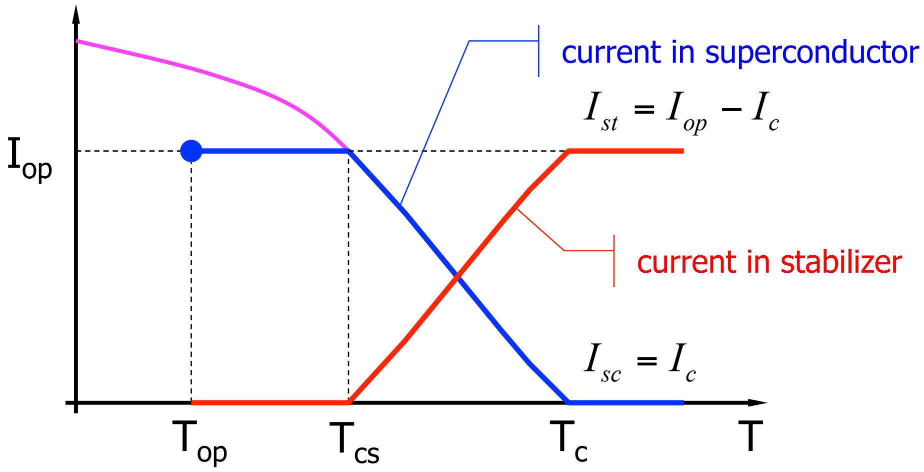


$$E_{sc}=E_{st}=0$$

$$E_{sc}=E_{st}=I_{st}\frac{\eta_{st}}{A_{st}}$$

$$E_{sc}=E_{st}=I_{op}\frac{\eta_{st}}{A_{st}}$$

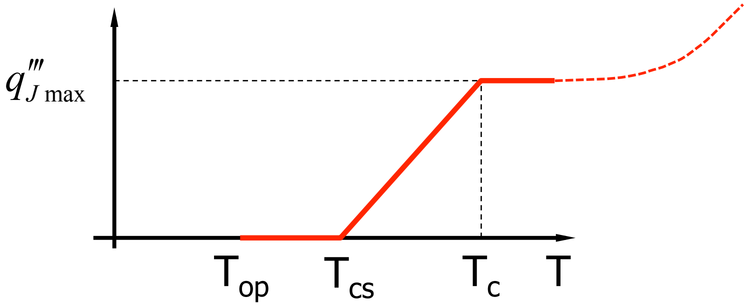
Joule heating



$$q'''_J=\frac{EI_{st}+EI_{sc}}{A}=\frac{EI_{op}}{A}=\frac{\eta_{st}}{A_{st}}\frac{I_{op}\left(I_{op}-I_c\right)}{A} \qquad q'''_{J\,\max}=\frac{\eta_{st}}{A_{st}}\frac{I_{op}^2}{A}$$

Joule heating (cont’d)

- Linear approximation for $I_c(T)$: $I_c \approx I_{op} \frac{T_c - T}{T_c - T_{cs}}$
- Joule heating



$$q'''_J = \begin{cases} 0 & \text{for} \quad T < T_{cs} \\ q'''_{J\,\max} \frac{T - T_{cs}}{T_c - T_{op}} & \text{for} \quad T_{cs} < T < T_c \\ q'''_{J\,\max} & \text{for} \quad T > T_c \end{cases}$$

$$q'''_{J\,\max} = \frac{\eta_{st}}{A_{st}} \frac{I_{op}^2}{A}$$

Cooling: many options

- Indirect: (adiabatic, no cooling)
  - Contact to a heat sink through conduction (e.g. to a cryo-cooler)
  - In practice, no cooling on the time scale of interest for stability
- Direct: (cooling by heat transfer at the surface)
  - Bath cooling, to a pool of liquid helium at atmospheric pressure and saturation temperature (4.2 K)
  - Force-flow cooling to a supercritical or two-phase flow
  - Superfluid cooling to a stagnant bath of He-II

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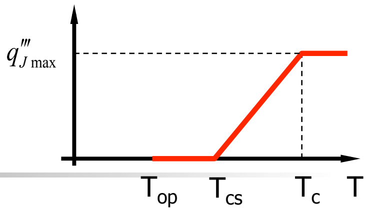
Adiabatic stability



- Adiabatic conditions:
  - No cooling (dry or impregnated windings)
  - Energy perturbation over large volume (no conduction)

$$C\frac{\partial T}{\partial t} = q'''_{ext} + \cancel{q'''_J} + \frac{\partial}{\partial x}\cancel{\left(k\frac{\partial T}{\partial x}\right)} - \frac{wh}{A}\cancel{\left(T - T_{he}\right)}$$

- Stable only if q'''$_{Joule}$=0 ($T \le T_{cs}$) !

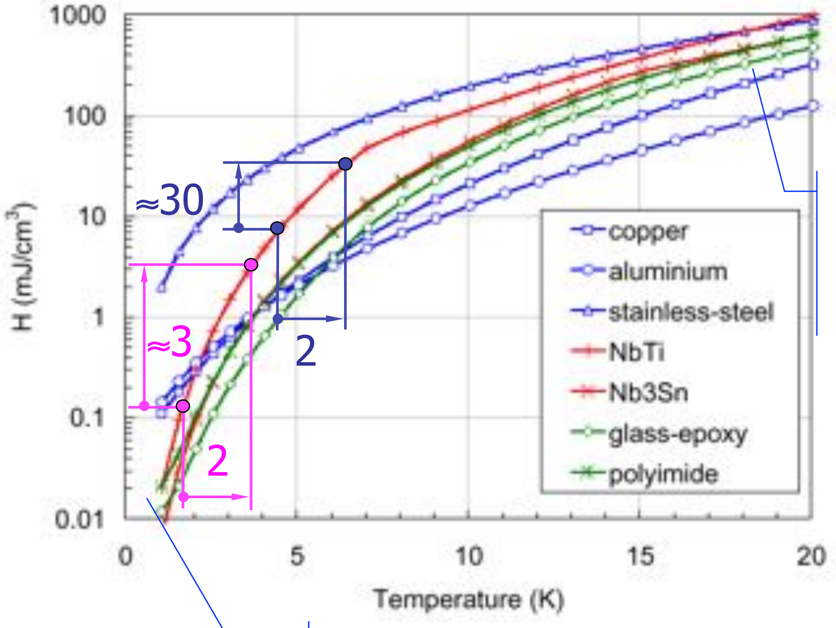
energy margin

$$\int_0^\infty q'''_{ext}\,dt = \int_{T_{op}}^{T_{cs}} C\,dT \Longrightarrow \boxed{Q''' = H\left(T_{cs}\right) - H\left(T_{op}\right)}$$

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

Specific enthalpy

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



enthalpy reserve increases at increasing T (Note: HTS !)

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

Adiabatic stability re-cap

- Applies to:
  - Adiabatic, compact, high current density windings (*dry* or indirectly cooled)
  - Very fast heat perturbations (flux-jumps)
- The heat capacity of the conductor absorbs the external heat perturbation
- Stability (at equal temperature margin) improves as the temperature increases (HTS !)
- Choose materials with high heat capacity (e.g. loading of epoxy)
- Relatively small energy margin: 1…10 mJ/cm^3

A.R. Krantowitz, Z.J.J. Stekly, Appl. Phys. Lett., **6**, 3, 56-57, 1965.
Z.J.J. Stekly, J.L. Zar, IEEE Trans. Nucl. Sci., **12**, 367-372, 1965.

Cryostability

- Cooling in a bath of pool boiling helium
  - Ignore conduction for large energy perturbations volumes
  - Request steady state stability in all conditions

$$\cancel{C\frac{\partial T}{\partial t}} = \cancel{q'''_{ext}} + q'''_J + \frac{\partial}{\partial x}\cancel{\left(k\frac{\partial T}{\partial x}\right)} - \frac{wh}{A}\left(T - T_{he}\right)$$

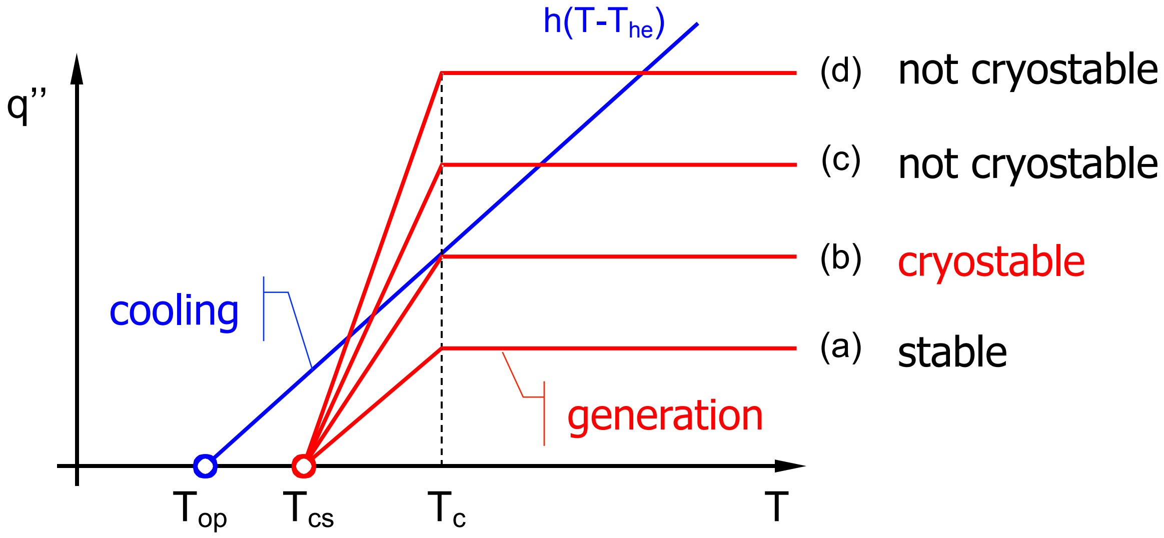
cooling

$$q'''_J \le \frac{wh}{A}\left(T - T_{op}\right) \xrightarrow{\text{worst possible case}} \boxed{\frac{\eta_{st}}{wA_{st}} I_{op}^2 \le h\left(T_c - T_{op}\right)}$$

generation

Heat balance (*ideal* case)

constant heat transfer to the helium

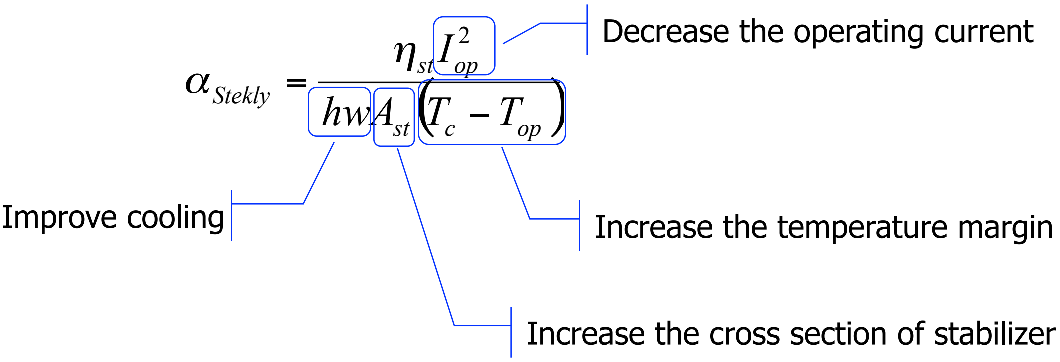


Stekly-α

- Stekly cryostability condition:

$$\frac{\eta_{st}}{wA_{st}} I_{op}^2 \le h\left(T_c - T_{op}\right)$$

- can be formulated as $\alpha_{Stekly} \le 1$:



$$\alpha_{Stekly} = \frac{\eta_{st} \boxed{I_{op}^2}}{\boxed{hw}\boxed{A_{st}}\boxed{\left(T_c - T_{op}\right)}}$$

Decrease the operating current

Improve cooling

Increase the temperature margin

Increase the cross section of stabilizer

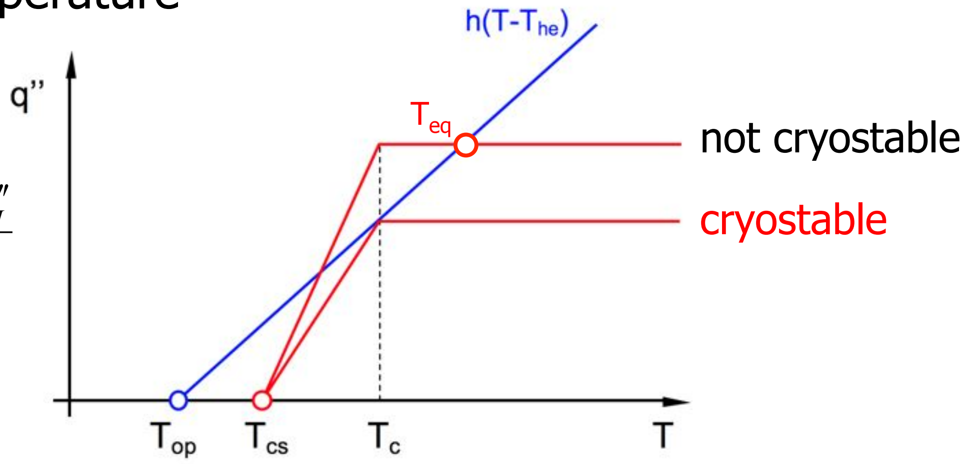
Cryo-stability recap

- Applies to:
  - Well-cooled, low current density windings (pool-boiling)
  - Any type of heat perturbations, all time and space scales
- The coolant can take the Joule heating under all possible conditions
- Ideally infinite energy margin

Cold-end effects – 1

- Assume that the normal zone is *long* and above cryostable operating conditions
- The temperature will reach an *equilibrium* temperature

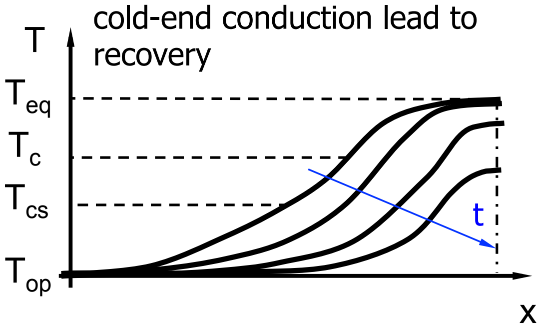
$$T_{eq} = T_{op} + \frac{Aq'''_J}{wh}$$



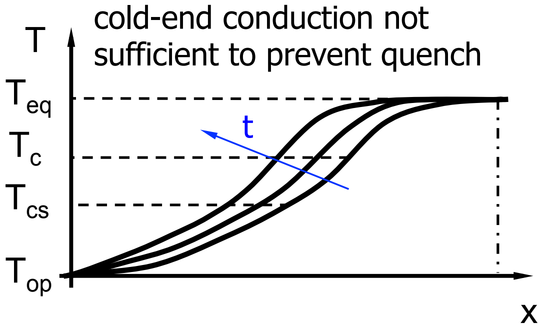
Cold-end effects – 2

- What happens if the ends are *cold* ?

cold-end conduction lead to recovery



cold-end conduction not sufficient to prevent quench



- Request steady state stability in all conditions

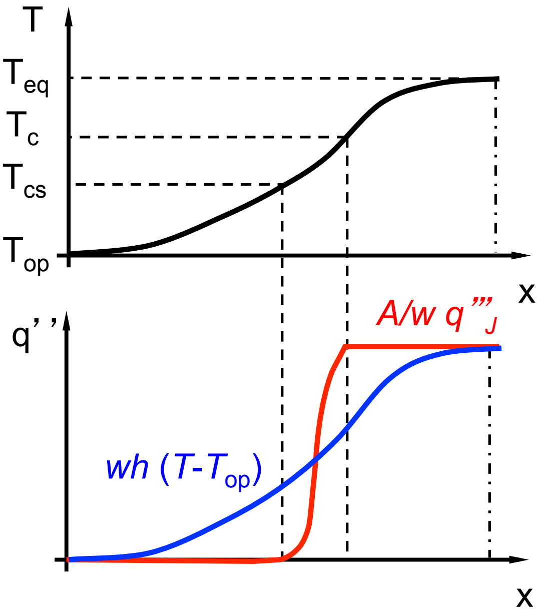
$$\cancel{C\frac{\partial T}{\partial t}} = \cancel{q'''_{ext}} + q'''_J + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

B.J. Maddock, G.B. James, W.T. Norris, Cryogenics, **9**, 261-273, 1969.

Cold-end effects – 3

$$C\cancel{\frac{\partial T}{\partial t}} = \cancel{q'''_{ext}} + q'''_J + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

- introduce a new variable *S*: $S = k\frac{\partial T}{\partial x}$



$$k\left[\frac{wh}{A}\left(T - T_{he}\right) - q'''_J\right] = S\frac{\partial S}{\partial T}$$

$$\int_{T_{op}}^{T_{eq}} k\left[\frac{wh}{A}\left(T - T_{he}\right) - q'''_J\right]dT = \int_{S_{op}}^{S_{eq}} S\,dS$$

$S_{op} = 0$ ↓ $S_{eq} = 0$

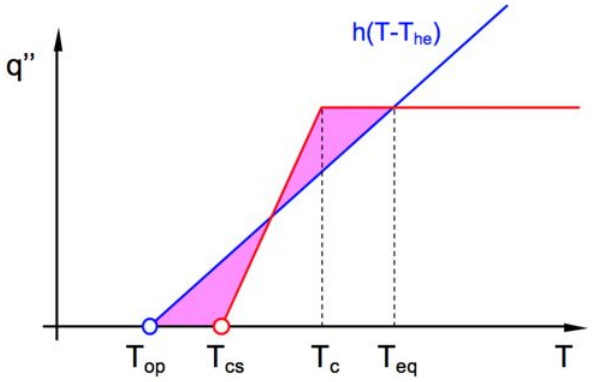
$$\boxed{\int_{T_{op}}^{T_{eq}} \left[h\left(T - T_{he}\right) - \frac{A}{w}q'''_J\right]dT = 0}$$

B.J. Maddock, G.B. James, W.T. Norris, Cryogenics, **9**, 261-273, 1969.

An equal area theorem

$$\boxed{\int_{T_{op}}^{T_{eq}} \left[h\left(T - T_{he}\right) - \frac{A}{w}q'''_J\right]dT = 0}$$

Stable conditions are obtained when the net area between generation and cooling curves is zero



$$\alpha \leq 1 + \frac{\left(T_{cs} - T_{op}\right)}{\left(T_c - T_{op}\right)} \approx 2 - f_{op}$$

Values of α nearly twice as large as from the Stekly criterion are possible !

Stekly: $\alpha \leq 1$

Maddock: $\alpha \leq 2\text{-}f_{op}$

Cold-end effects recap

- Applies to:
  - Well-cooled, low current density windings (pool-boiling)
  - Any type of heat perturbations, all time and space scales
- The coolant and the cold ends take the Joule heating under all possible conditions
- Ideally infinite energy margin
- Improved stability with respect to the cryostability condition, allow operation at higher current

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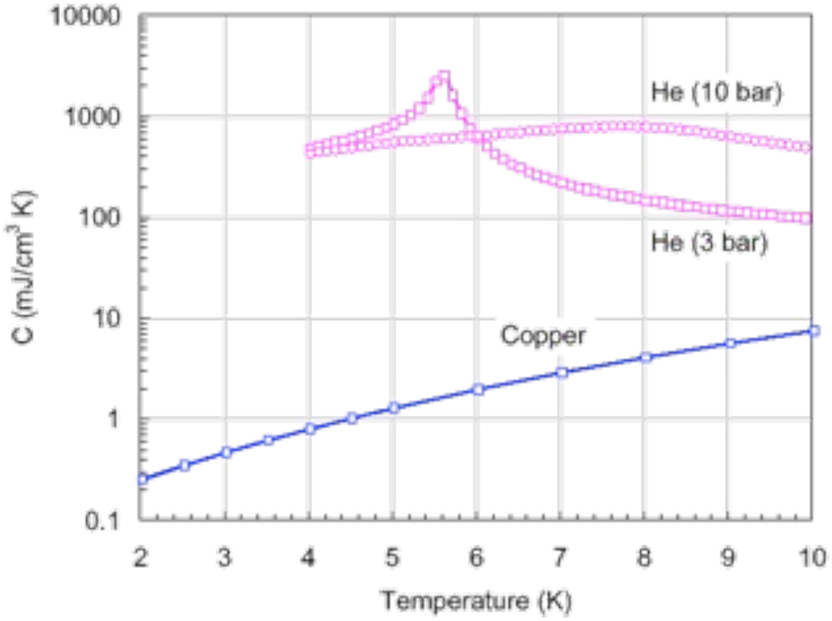
Meta-stable conductors

- Adiabatically stabilized conductors:
  - High J_{op} (good for cost)
  - Small Q''' (bad for large magnets)
- Cryo-stabilized conductors (including cold-ends):
  - Large Q''', ideally infinite (good for large magnets)
  - Low J_{op} (bad for cost)

Is there a compromise ?

Idea-1: helium !

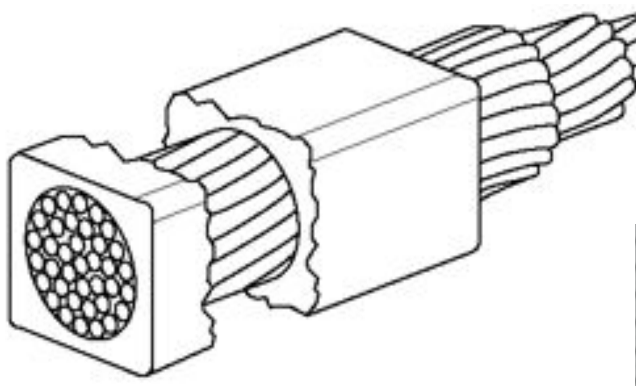


The helium heat capacity is orders of magnitude larger than for metals at low temperature

Add helium in intimate contact with the cable

M.O. Hoenig, Y. Iwasa, D.B. Montgomery,
Proc. 5th Magn. Tech. Conf., Frascati, 519, (1975)

ICS’ s and CICC’ s



ROUND BUNDLE WITH 37 STRANDS ENCLOSED IN RECT
CONDUIT - SHOWING TRANSPOSITION OF STRAN

Heat balance for CICC's

- Conductor temperature:

$$C\frac{\partial T}{\partial t} = q'''_{ext} + q'''_{J} + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\left(T - T_{he}\right)$$

- But the helium temperature evolves as well:

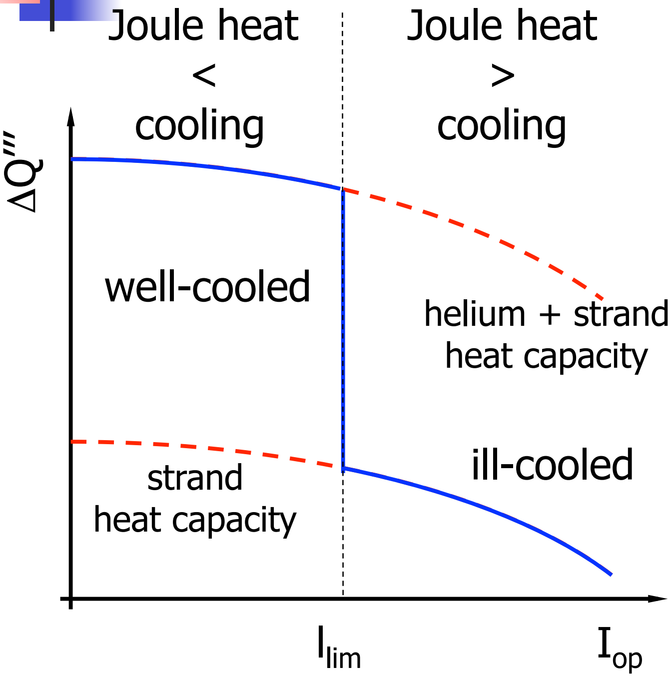
$$C_{he}\frac{\partial T_{he}}{\partial t} = \frac{wh}{A_{he}}\left(T - T_{he}\right)$$

- Under which conditions the heat capacity is effectively used ?

NOTE: at large enough *h*, $T \approx T_{he}$

J.W. Lue, J.R. Miller, L. Dresner, J. Appl. Phys., 51, 1, 772, (1980)
J.H. Schultz, J.V. Minervini, Proc. 9th Magn. Tech. Conf., Zurich , 643, (1985)

Stability of CICC's



balance of Joule heat and cooling at:

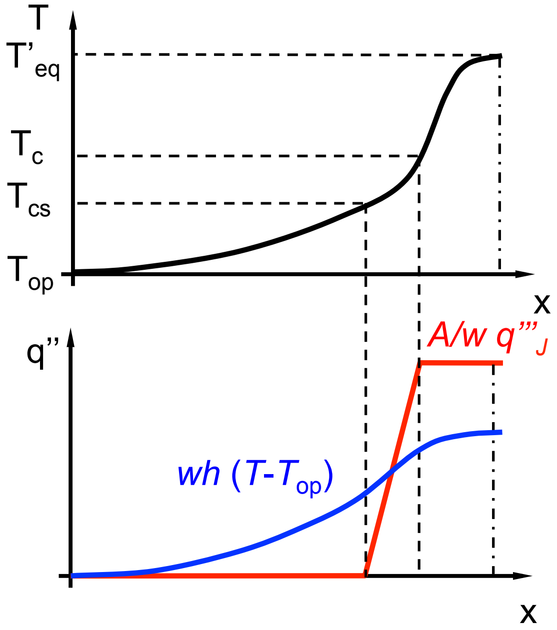
$$I_{\lim} = \sqrt{\frac{A_{st}wh\left(T_c - T_{op}\right)}{\eta_{st}}}$$

equivalent to $\alpha_{Stekly} = 1$

In this case however the CICC is meta-stable as a large enough energy input will cause a quench !

Idea-2: heat conduction !

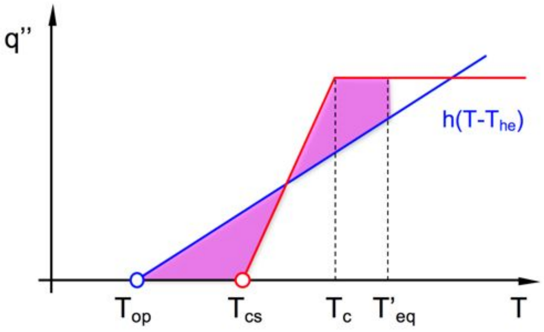
Short normal zone



S=0 at the boundaries

$$\int_{T_{op}}^{T_{eq}} \left[h\left(T - T_{he}\right) - \frac{A}{w} q'''_J \right] dT = 0$$

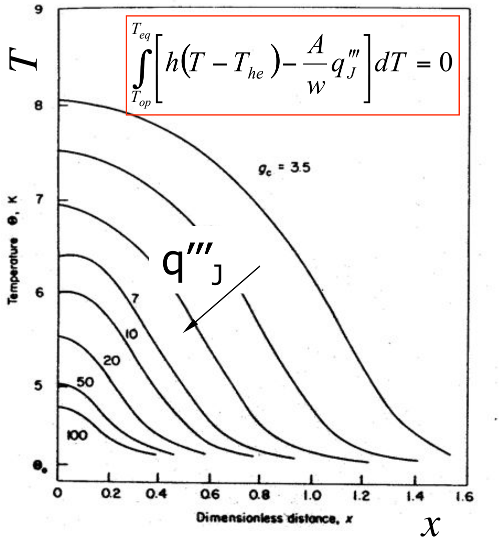
equal area still possible
but implies lower T'$_{eq}$ < T$_{eq}$



Normal zone temperature

- The temperature profile can be traced by numerical integration of the *equal area* balance
- This is an unstable equilibrium temperature profile, and defines the minimum length of superconductor that could grow and develop into a quench: Minimum Propagating Zone **(MPZ)**
- The energy required to form the MPZ is the Minimum Quench Energy **(MQE)**

M.N. Wilson, Y. Iwasa, Cryogenics, 18, 17-25, 1978



$$\int_{T_{op}}^{T_{eq}} \left[h\left(T - T_{he}\right) - \frac{A}{w} q'''_J \right] dT = 0$$

After the work of M.N. Wilson, Superconducting MagnetsPlenum Press, 1983

MPZ estimates

- To estimate the size of the MPZ we can solve the heat balance approximately
  - Steady state conditions and no cooling

$$\cancel{C\frac{\partial T}{\partial t}} = \cancel{q'''_{ext}} + q'''_J + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \frac{wh}{A}\cancel{\left(T - T_{he}\right)}$$

$$0 = \bar{\eta}_{st} J_{op}^2 + \frac{d}{dx}\left(\bar{k}\frac{dT}{dx}\right)$$

$$0 \approx \bar{\eta}_{st} J_{op}^2 L_{MPZ} - \bar{k}\frac{\left(T_C - T_{op}\right)}{L_{MPZ}/2}$$

$$\boxed{L_{MPZ} \approx \sqrt{\frac{2\bar{k}\left(T_C - T_{op}\right)}{\bar{\eta}_{st} J_{op}^2}}}$$

J_{op} = 400 A/mm2
k = 500 W/m K
η = 1 nΩ m
T_C-T_{op} = 2 K

MPZ ≈ 3.5 mm
MQE ≈ 10 μJ

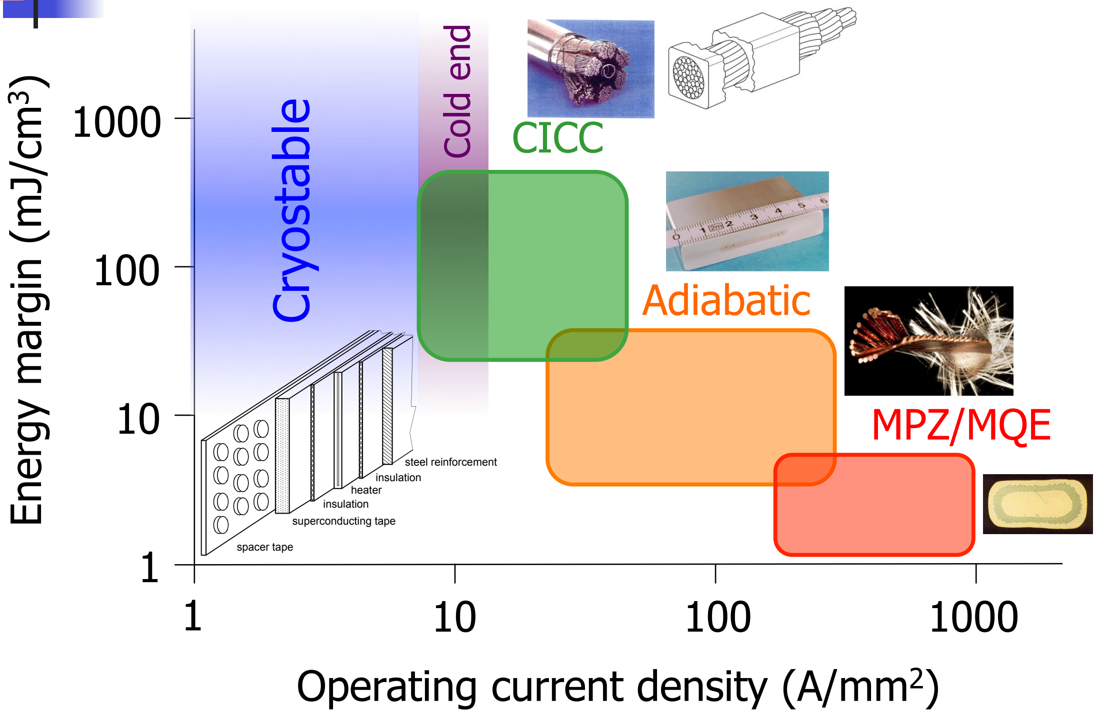
Plan of the lecture

- Training and degradation
- Perturbation spectrum overview
- Heat balance
- Stabilization strategies and criteria
- A summary and more complex topics

Summary

- Superconductor stability is the art of balancing large stored energies (and potential for energy release) with a little capital (aka: "leveraging" for our US colleagues)
  - Extremely important in LTS-based magnet to reach the desired performance (10 MJ vs 10 mJ)
  - Generally not an issue for HTS-based magnets
- Stability is not *absolute*, it implies comparing the perturbation spectrum to the available margin
- Several strategies can be applied to achieve stable operating conditions under the envelope of foreseeable perturbation spectrum

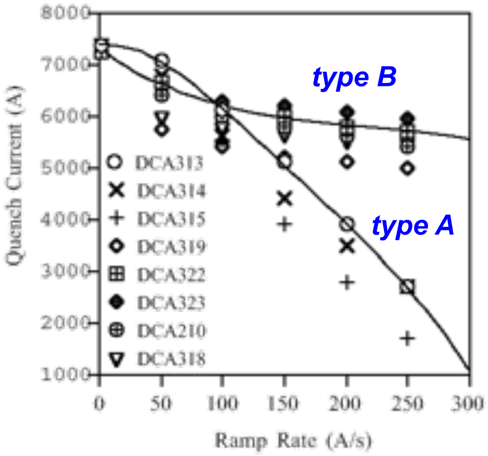
A summary of strategies



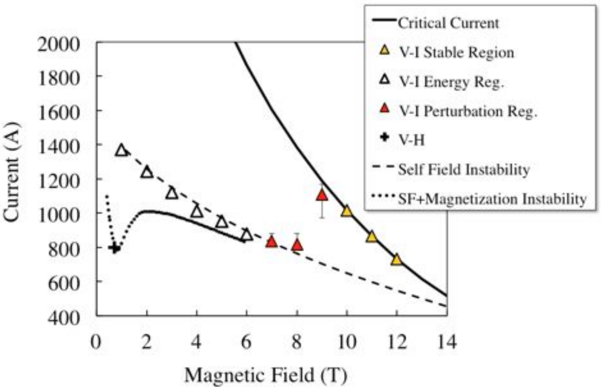
There are more things in heaven and earth, Horatio,
Than are dreamt of in your philosophy.

Advanced topics

- Current distribution and RRL
  - Ramp-rate quenches
  - Holding quenches
- Magneto-thermal instabilities
  - Dynamic stability
  - Self-field instability



A. Devred, T. Ogitsu, *Frontiers of Accelerator Magnet Technology*, World Scientific, 184, 1996



B. Bordini and L. Rossi, IEEE TAS, 19, 2470 (2009).

Ah, and… what if it falls ???

Then, you need to **protect !**

Where to find out more

- Papers, reviews and proceedings:
    - A.R. Krantowitz, Z.J.J. Stekly, *A New Principle for the Construction of Stabilized Superconducting Coils*, Applied Physics Letters, 6, 3, 56-57, 1965.
    - P.F. Chester, *Superconducting Magnets*, Rep. Prog. Phys., **XXX**, Part II, 561-614, 1967.
    - B.J. Maddock, G.B. James, W.T. Norris, *Superconductive Composites: Heat Transfer and Steady State Stabilization*, Cryogenics, 9, 261-273, 1969.
    - M.N. Wilson, Y. Iwasa, *Stability of Superconductors against Localized Disturbances of Limited Magnitude*, Cryogenics, 18, 17-25, 1978.
    - L. Dresner, *Superconductor Stability 1983: a Review*, Cryogenics, 24, 283, 1984.
- Books:
    - M.N. Wilson, *Superconducting Magnets*, Plenum Press, 1983.
    - L. Dresner, *Stability of Superconductors*, Plenum Press, 1995.
    - P.J. Lee ed., *Engineering Superconductivity*, J. Wiley & Sons, 2001.
    - B. Seeber ed., *Handbook of Applied Superconductivity*, IoP, 1998.
    - Y. Iwasa, *Case Studies in Superconducting Magnets*, Plenum Press, 1994.