Quench 101

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WAMSDO 2013 – January 15th-16th, 2013

Workshop on Accelerator Magnets, Superconductors, Design and Optimization

Outline

- What is a quench ? Process and issues
- The transition from SC to NC state
- The event tree
- Physics of a quench
- Hot-spot temperature limits
  - External-dump and self-dump limits
  - Quench propagation and time scales
- Quench voltages
- Pressure and expulsion
- Conclusions and open questions

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What is a quench ?

Coke being pushed into a *quenching car*

quench (kwĕnch)

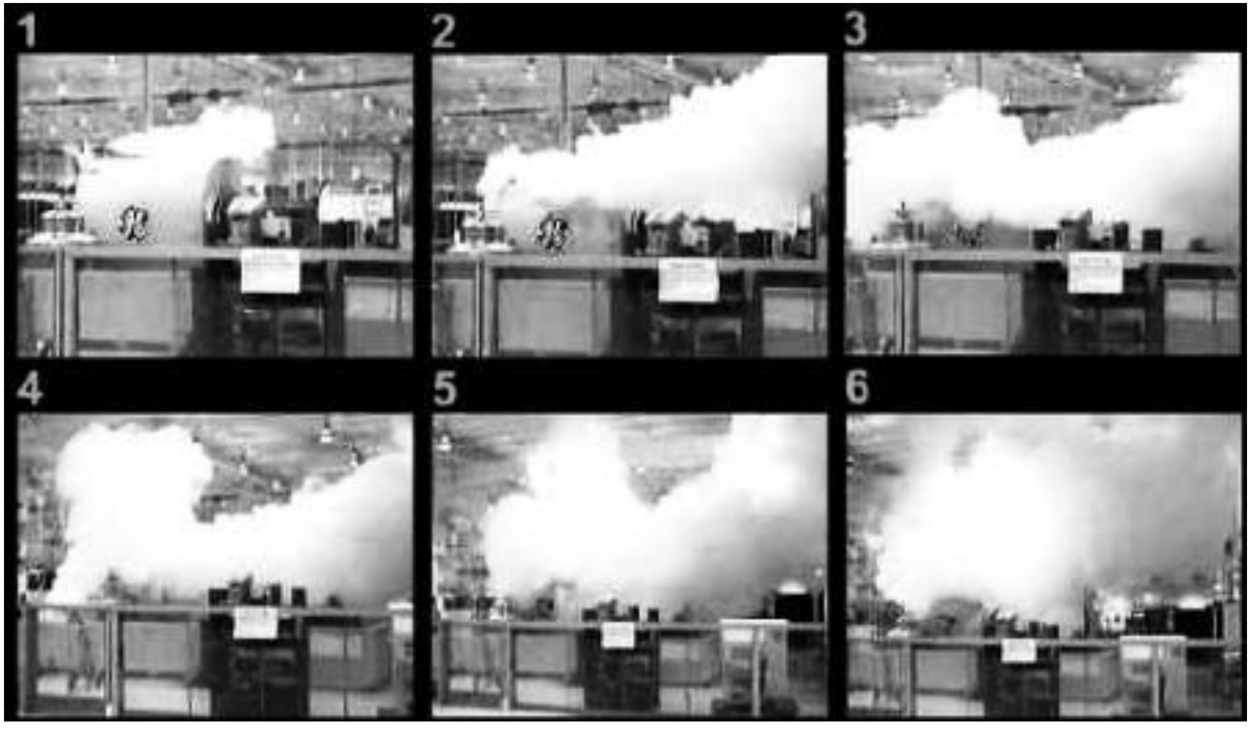
tr.v. **quenched**, **quench·ing**, **quench·es**

1. To put out (a fire, for example); **extinguish**.
2. To suppress; squelch: The **disapproval of my colleagues** quenched my enthusiasm for the plan.
3. To put an end to; **destroy**.
4. To slake; satisfy: Mineral water quenched our thirst.
5. To cool (**hot metal**) by thrusting into water or **other liquid**.

A potentially destructive phenomenon involving hot metals and cold liquids that requires shutting down and causes much consternation in the office

Really, what is a quench ?

- Quench is the result of a resistive transition in a superconducting magnet, leading to appearance of voltage, temperature increase, thermal and electro-magnetic forces, and cryogen expulsion.



This is a quench of a GE MRI magnet during tests at the plant

This is the result of a chain of events triggered by a quench in an LHC bus-bar

Why is it a problem ?

- the magnetic energy stored in the field:

$$E_m = \int_V \frac{B^2}{2\mu_0} dv = \frac{1}{2} L I^2$$

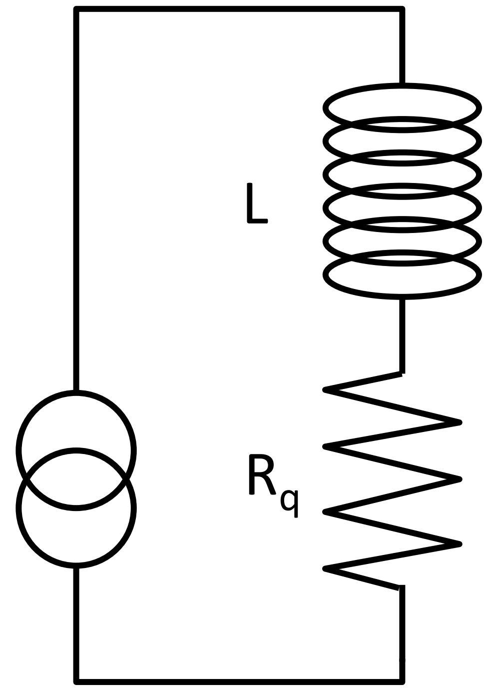
  is converted to heat through Joule heating $R_q I^2$

- If this process happened uniformly in the winding pack:
  - Cu melting temperature 1356 K
  - corresponding E_m=5.2 109 J/m^3

  limit would be Bmax ≤ 115 T: NO PROBLEM !

BUT

- the process does not happen uniformly, and as little as 1 % of the total magnet mass can absorb total energy – **large damage potential !**



Issues to be considered

- Temperature increase and temperature gradients (thermal stresses)
- Voltages within the magnet, and from the magnet to ground (whole circuit)
- Forces caused by thermal and electromagnetic loads during the magnet discharge transient
- Cryogen pressure increase and expulsion

A quench invariably requires **detection** and may need **actions** to safely turn-off the power supply (possibly more)

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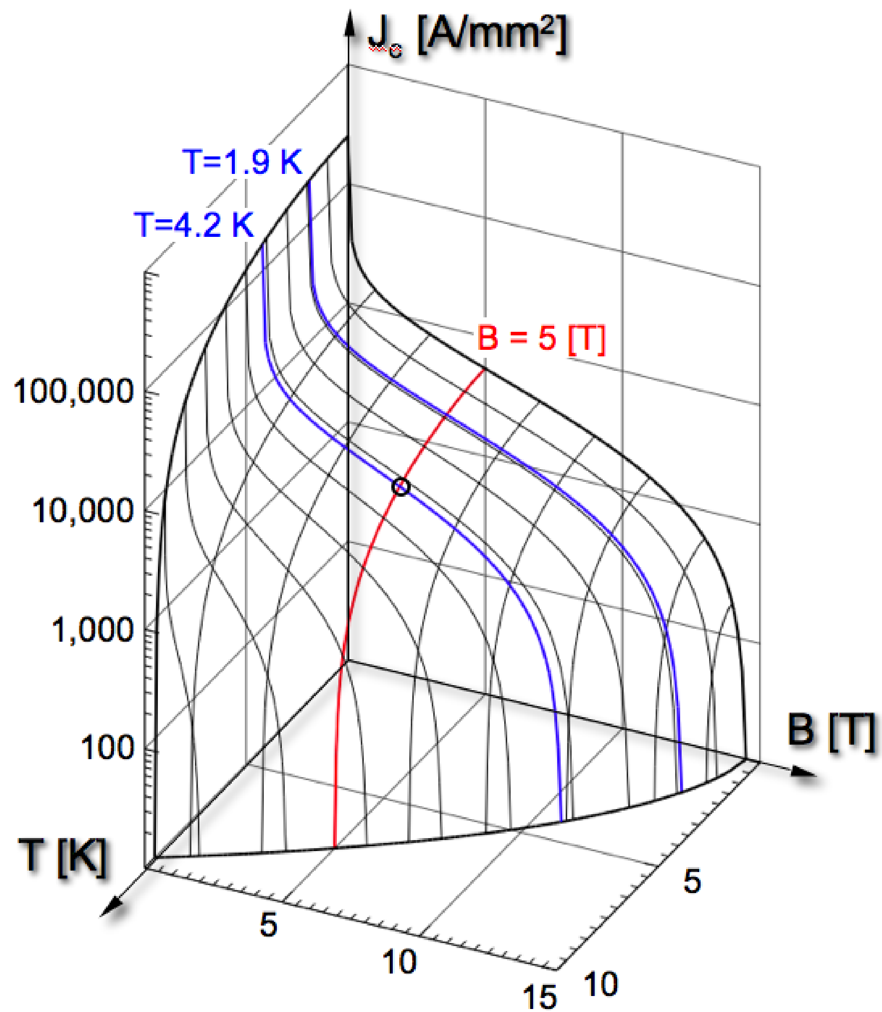
Superconductor limits

- A superconductor is such only within a limited space of field B, temperature T, and current density J
- This defines a critical surface $J_C(B,T,\varepsilon,\Phi)$ beyond which the superconducting material becomes normal conducting
- The maximum current that a superconductor can carry is the **critical current**:

$$I_C = J_C A_{SC}$$

LHC Nb-Ti critical surface



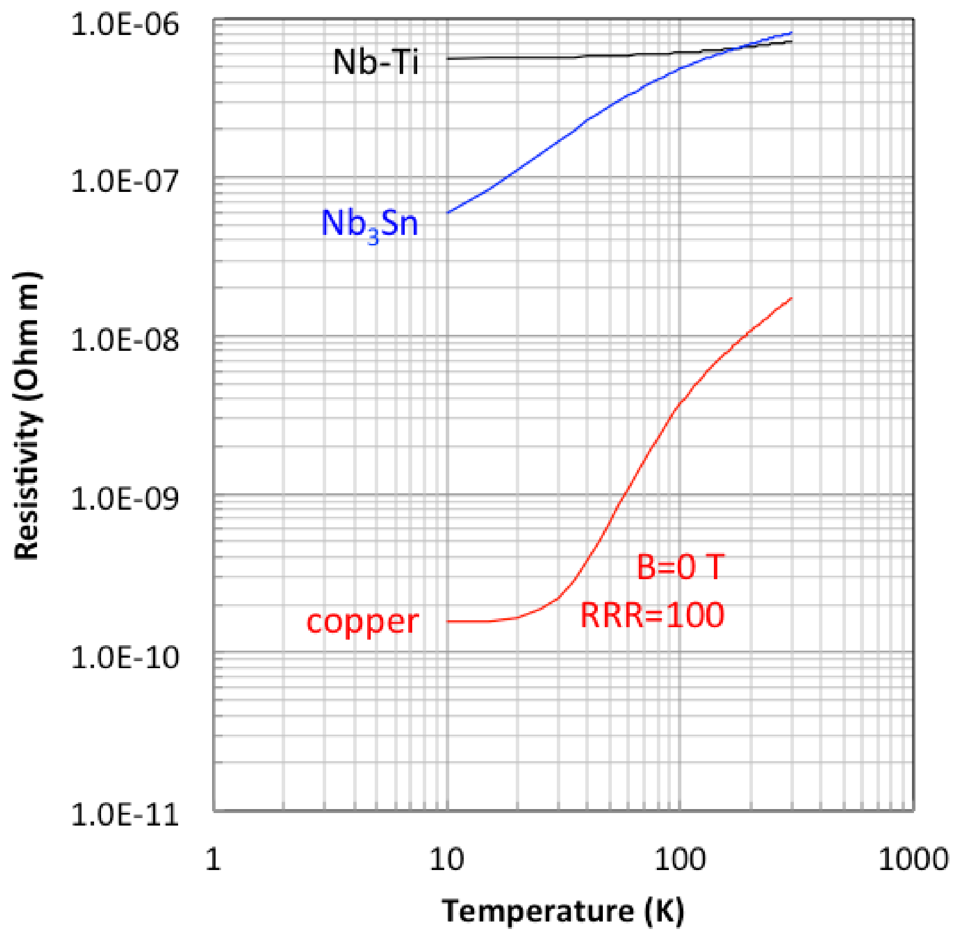
Normal state resistivity

- The critical field of a superconductor is proportional to its normal state resistivity (GLAG):

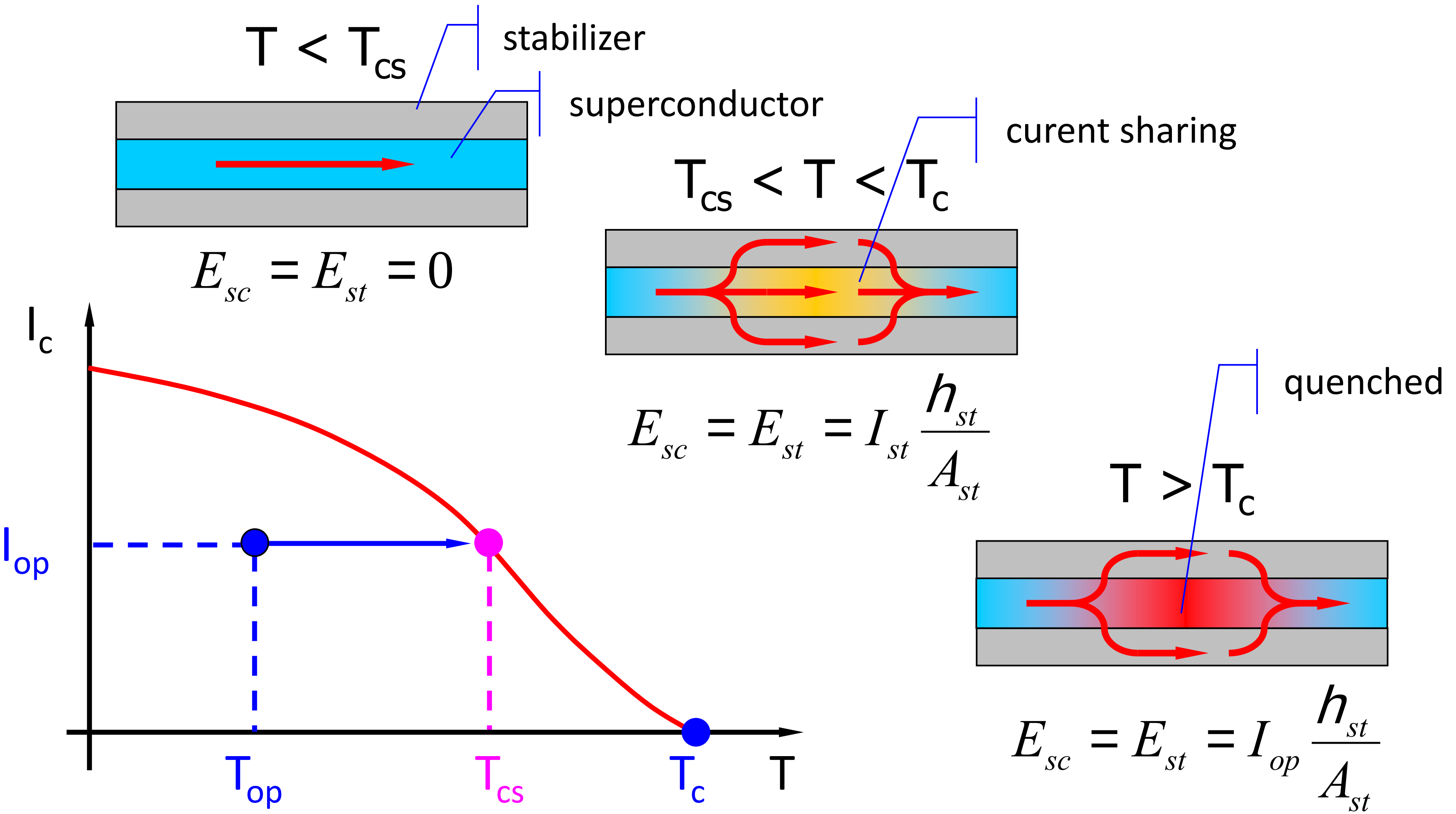
$$B_C \propto \gamma T_C \rho_n$$

good superconductors (high B_C) are *bad* normal conductors (high ρ_n)

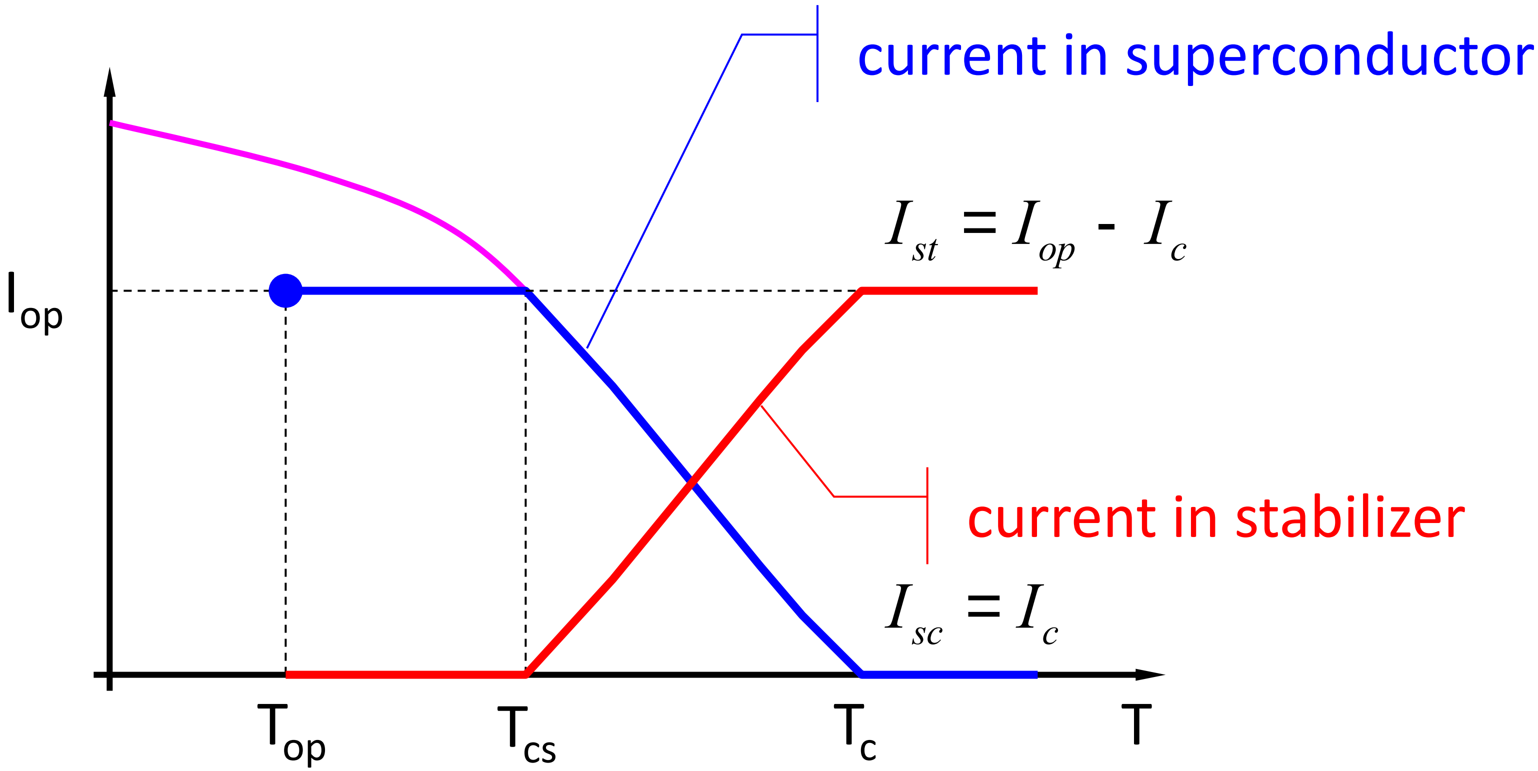
- Typically, the normal state resistivity of LTS materials is two to four orders of magnitude higher than the typical resistivity of good stabilizer materials



The *current sharing* process



Current sharing and Joule heating



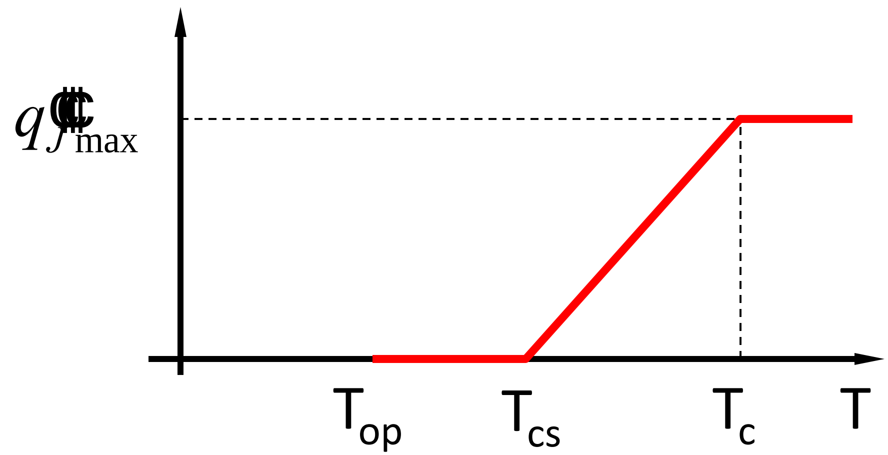
$$q'''_J = \frac{EI_{st} + EI_{sc}}{A} = \frac{EI_{op}}{A} = \frac{\eta_{st}}{A_{st}} \frac{I_{op}\left(I_{op} - I_c\right)}{A}$$

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

Joule heating approximation

- linear approximation for Jc(T): $I_c \approx I_{op} \dfrac{T_c - T}{T_c - T_{cs}}$

- Joule heating



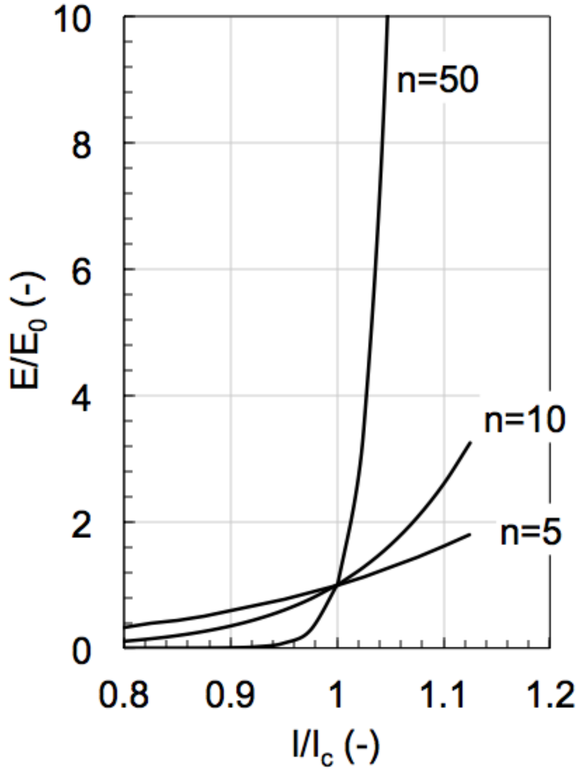
$$q'''_f = \begin{cases} 0 & \text{for} \quad T < T_{cs} \\ q'''_{f\,max} \dfrac{T - T_{cs}}{T_c - T_{op}} & \text{for} \quad T_{cs} < T < T_c \\ q'''_{f\,max} & \text{for} \quad T > T_c \end{cases}$$

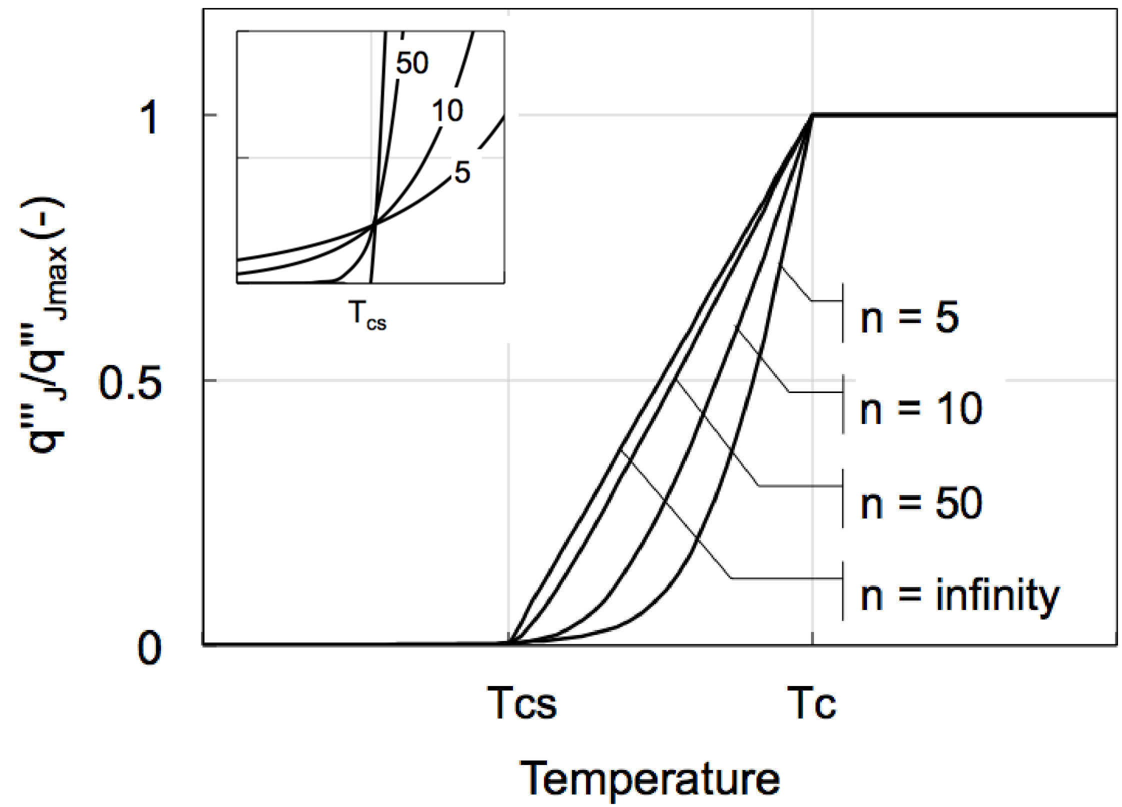
$$q'''_{f\,max} = \frac{h_{st}}{A_{st}} \frac{I_{op}^2}{A}$$

Joule heating for finite *n*-index

$$E = E_0 \left(\frac{I_{sc}}{I_c} \right)^n$$

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





A finite *n*-index *mollifies* the transition

Q: quantitative effect of finite, low n-index ?

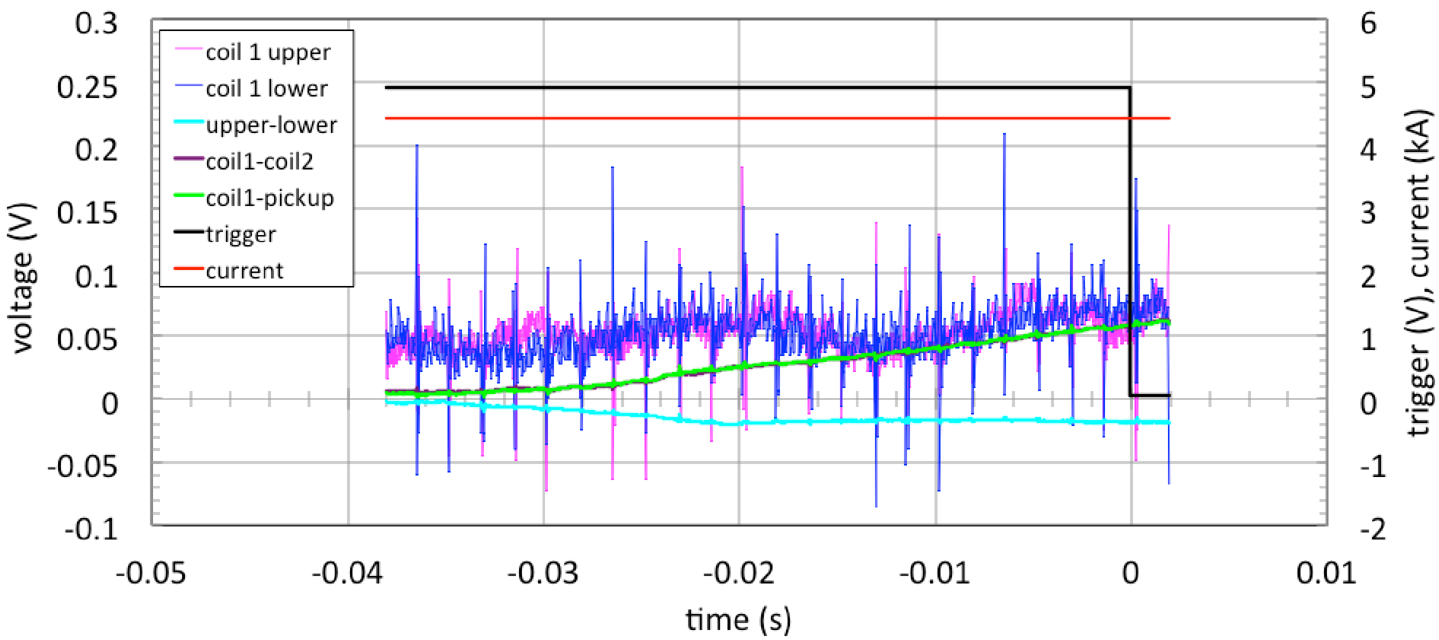
Normal zone voltage

- The normal zone generates a voltage

$$V_{NZ} = RI = \frac{\eta_{st}}{f_{st}} J_{op} L_{NZ}$$

- This voltage is visible at the magnet terminals, but is generally *muddled* by noise

Compensation techniques reduce noise. Example of FCM magnet, coil differences, as well as a co-wound wire are used



Q: what is the intrinsic detection level of a given method ?

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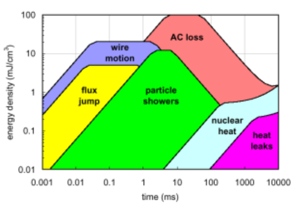
Quench sequence

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

Operating margin and stability analysis

yes

quench

local heating (hot-spot)

normal zone propagation (heating induced flow)

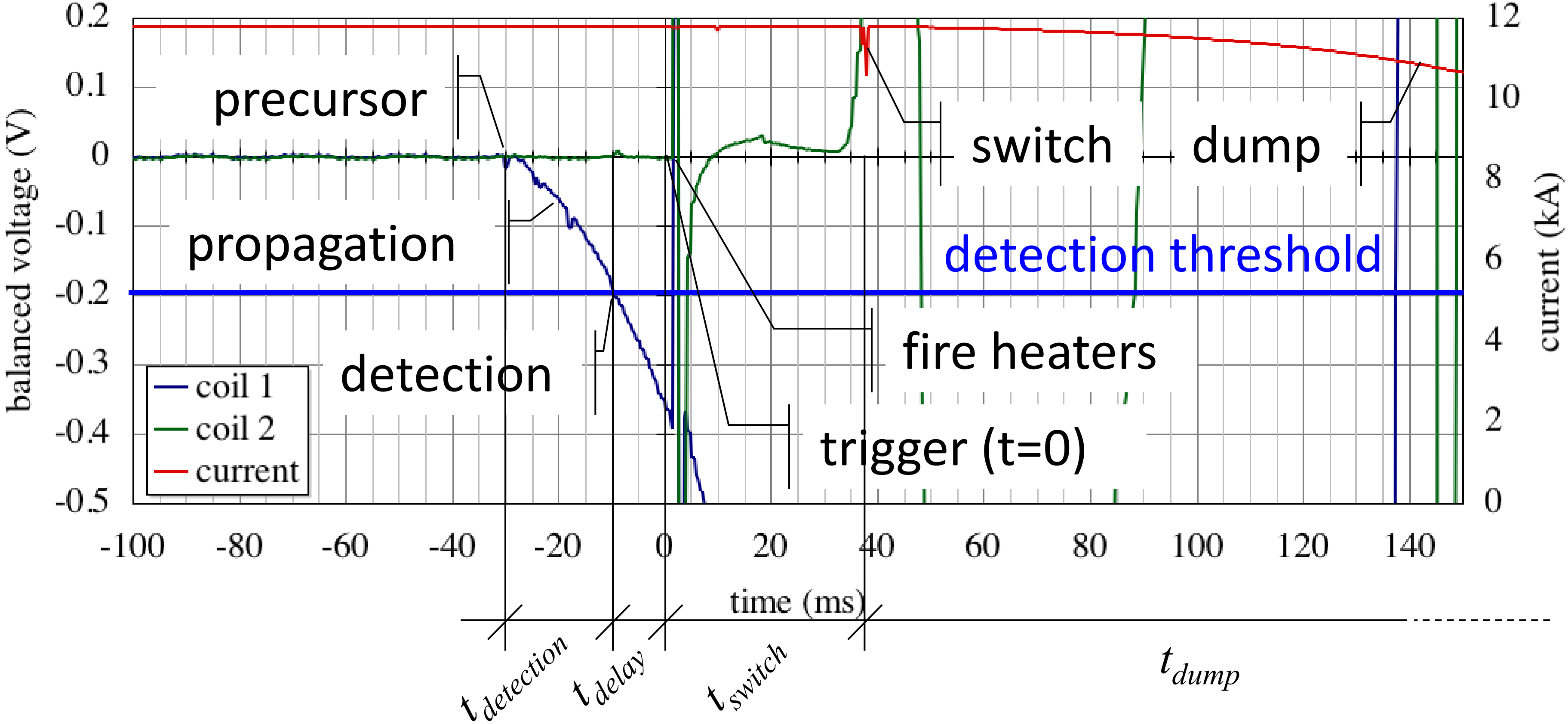
voltage development

quench detection

safety discharge

Detection, switch and dump

Example of an LHC dipole magnet training quench



$$t_{quench} \approx \underbrace{t_{detection} + t_{delay} + t_{switch}}_{t_{discharge}} + f\, t_{dump}$$

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A multi-physics playground !

- Heat conduction in solids

Temperature, quench propagation

$$A\bar{C}\frac{\partial T_{co}}{\partial t} - \frac{\partial}{\partial x}\left(A\bar{k}\frac{\partial T_{co}}{\partial x}\right) = A\dot{q}'''_{Joule} + p_w h\left(T_{he} - T_{co}\right)$$

- Coolant mass, momentum and energy

Pressure, flow, propagation

$$A_{he}\rho_{he}\frac{\partial v_{he}}{\partial t} + A_{he}\rho_{he}v_{he}\frac{\partial v_{he}}{\partial x} + A_{he}\frac{\partial p_{he}}{\partial x} = -A_{he}F_{he}$$

$$A_{he}\frac{\partial p_{he}}{\partial t} + A_{he}v_{he}\frac{\partial p_{he}}{\partial x} + A_{he}\rho_{he}c_{he}^2\frac{\partial v_{he}}{\partial x} = A_{he}\phi_{he}v_{he}F_{he} + \phi_h p_w h\left(T_{co} - T_{he}\right)$$

$$A_{he}\rho_{he}c_{he}\frac{\partial T_{he}}{\partial t} + A_{he}\rho_{he}v_{he}c_{he}\frac{\partial T_{he}}{\partial x} + A_{he}\rho_{he}\phi_{he}c_{he}T_{he}\frac{\partial v_{he}}{\partial x} = A_{he}v_{he}F_{he} + p_w h\left(T_{co} - T_{he}\right)$$

- Operating current

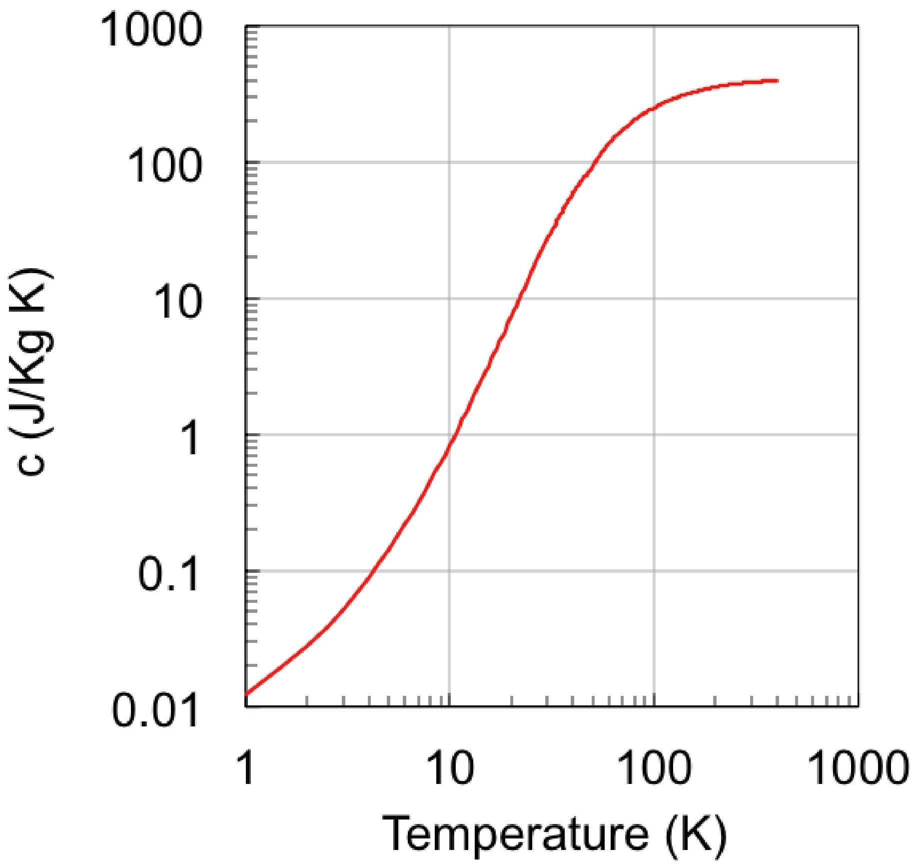
Joule heat (temperature), voltages

$$\mathbf{L}\frac{d\mathbf{I}}{dt} + \mathbf{RI} = \mathbf{V}$$

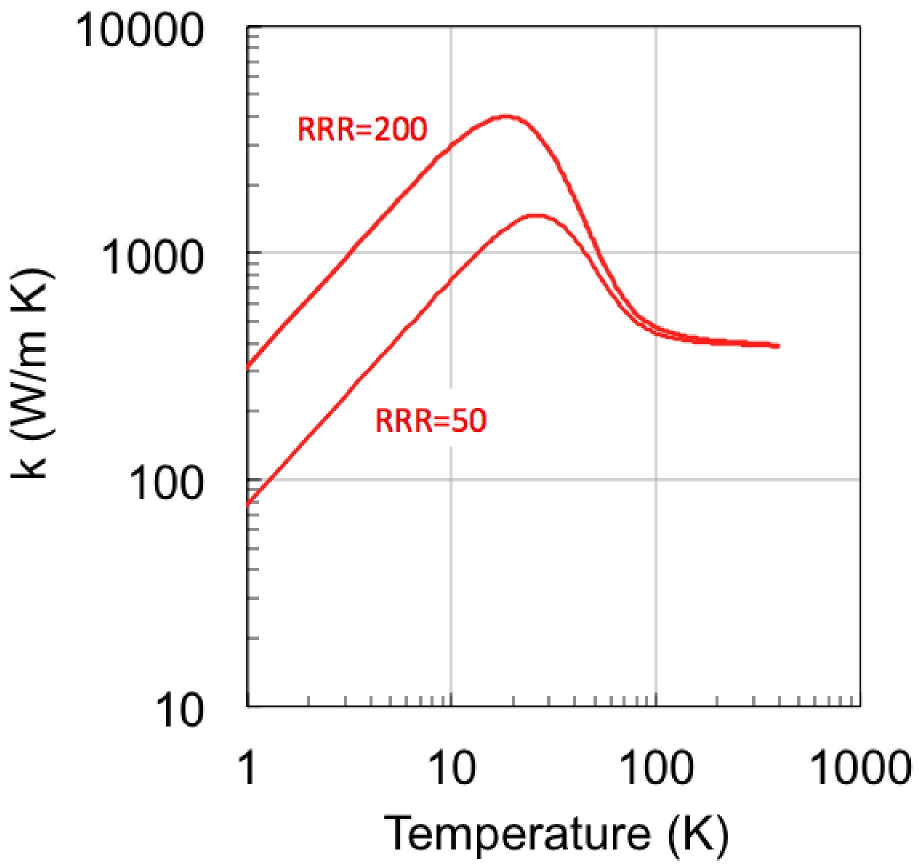
Q: which tools ?

Transport properties

Copper specific heat



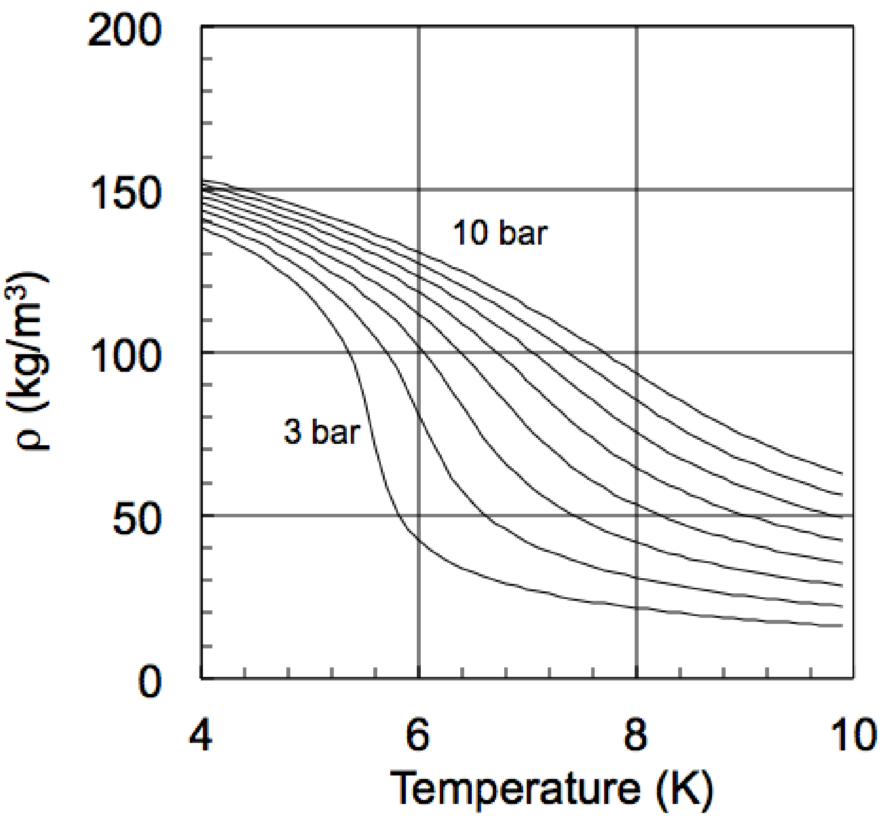
Copper thermal conductivity



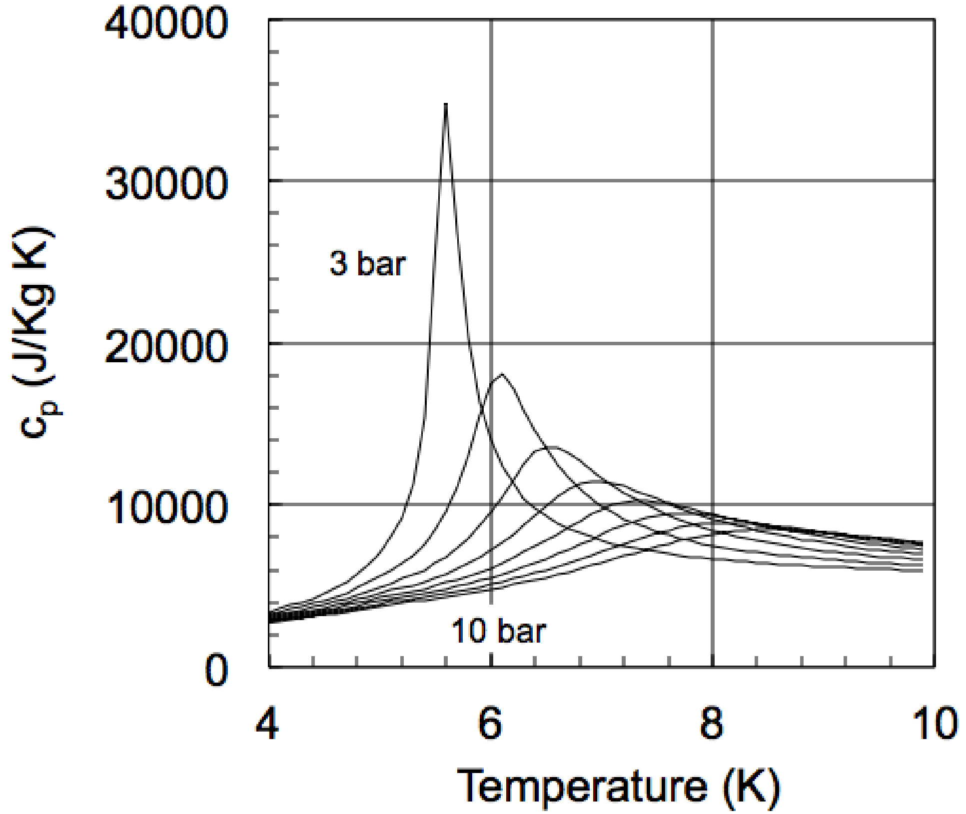
Orders of magnitude variation in the range of interest

Fluid properties

Helium density



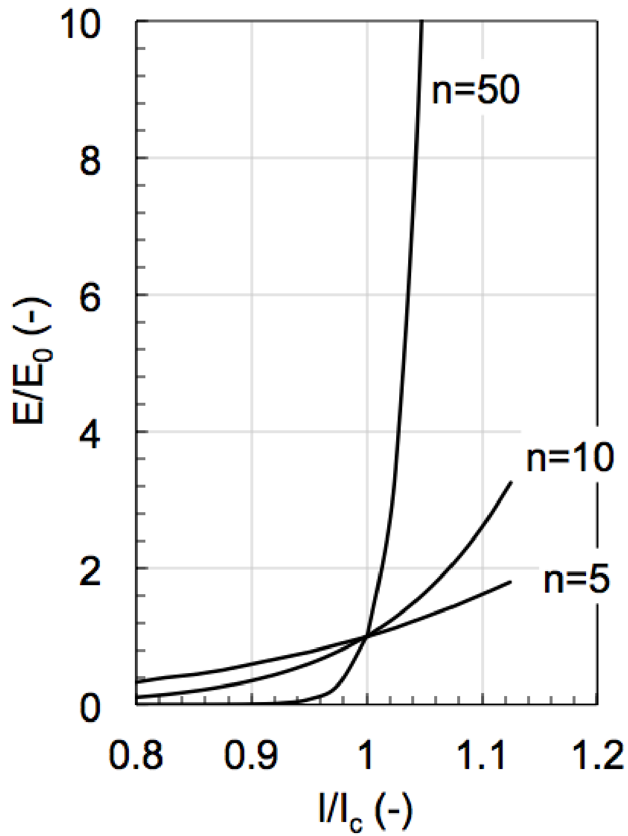
Helium specific heat



Factors of variation in the range of interest

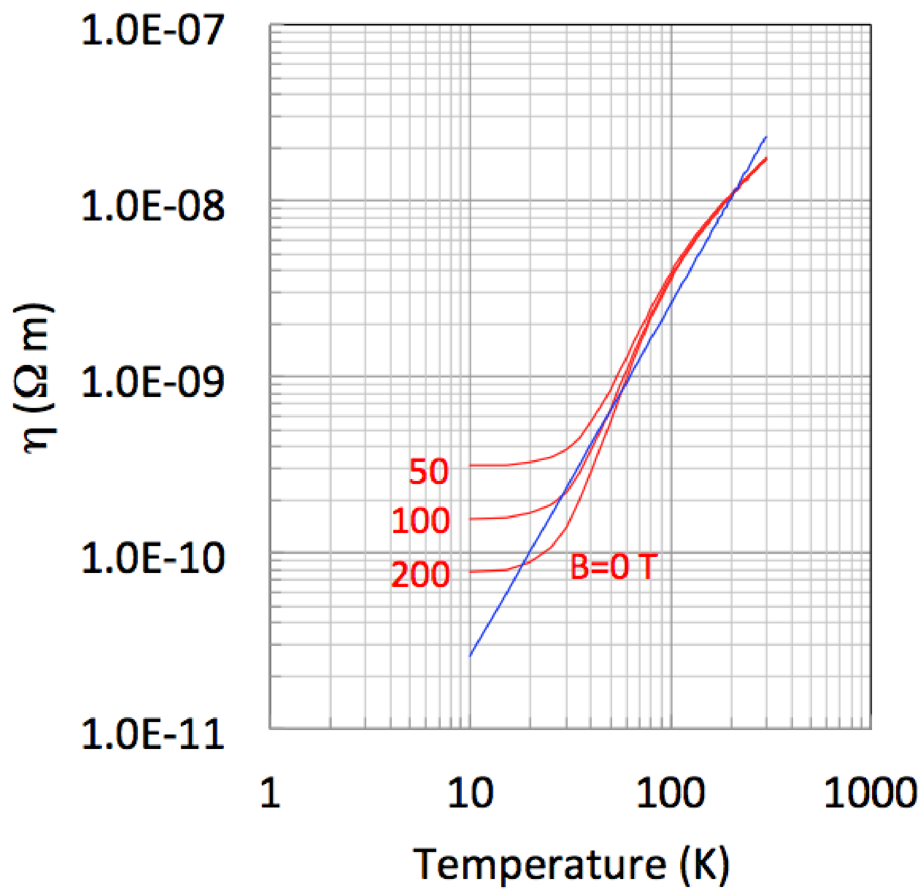
Electrical properties

SC resistivity



Highly non-linear

copper resistivity



Useful power approximation

$$\eta(T) = \eta_0 \left(\frac{T}{T_\eta} \right)^n$$

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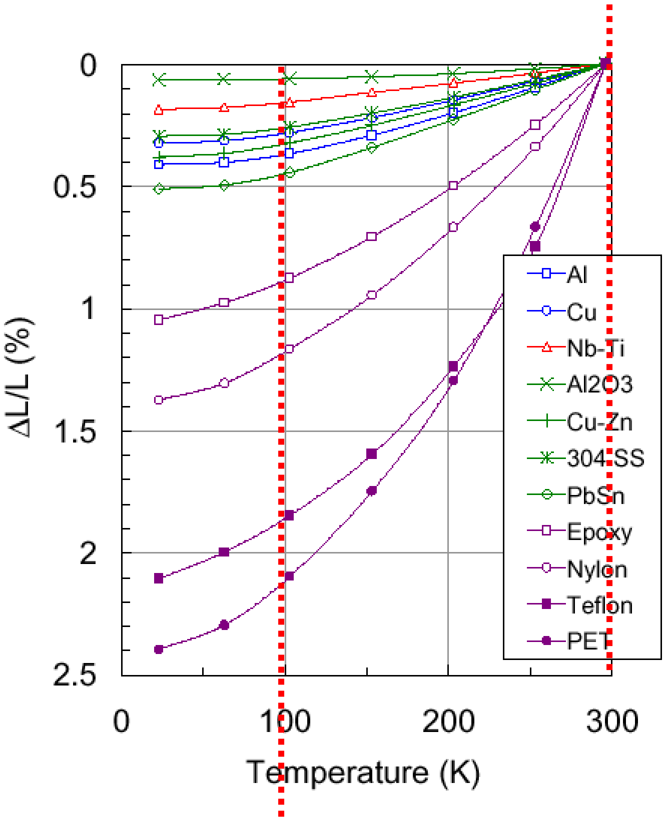
Hot-spot limits

T_{max} < 300 K for well-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)

Q: What are the real limits for the hot-spot temperature ?

Adiabatic heat balance

- The simplest (and conservative) approximation for the evolution of the maximum temperature during a quench is to assume adiabatic behavior at the location of the hot-spot:

$$A\bar{C}\frac{\partial T_{co}}{\partial t} - \frac{\partial}{\partial x}\left(A\bar{k}\frac{\partial T_{co}}{\partial x}\right) = A\dot{q}'''_{Joule} + p_w h\left(T_{he} - T_{co}\right) \rightarrow \boxed{\bar{C}\frac{dT_{co}}{dt} = \bar{\eta}J^2}$$

- Average heat capacity: $\bar{C} = \sum_i f_i \rho_i c_i$

- Average resistivity: $\frac{1}{\bar{\eta}} = \sum_i \frac{f_i}{\eta_i}$

Hot spot temperature

- adiabatic conditions at the hot spot :

$$\bar{C}\frac{dT_{co}}{dt} = \bar{\eta} J_{op}^2$$

- can be integrated:

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

total volumetric heat capacity

stabilizer resistivity

cable operating current density

$$\int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}} dT = \int_0^{\infty} J^2 dt$$

$$\Gamma(T_{max}) = \int_{T_{op}}^{T_{max}} \frac{\bar{C}}{\bar{\eta}} dT$$

$$\int_0^{\infty} J_{op}^2 dt = J_{op}^2 t_{quench}$$

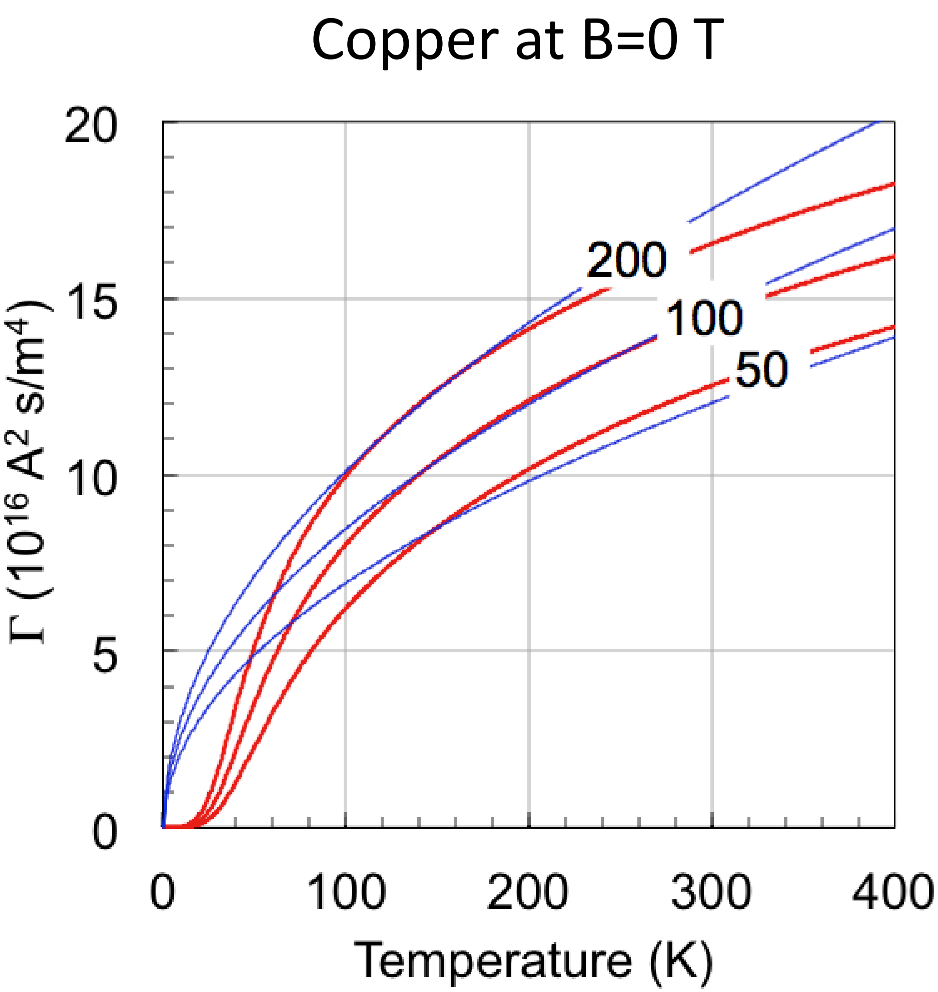
The function $\Gamma(T_{max})$ is a cable property

quench capital

The integral of J depends on the circuit

quench tax

$\Gamma(T_{max})$ for pure materials



- Assume that the cable is made of stabilizer only (good first guess):

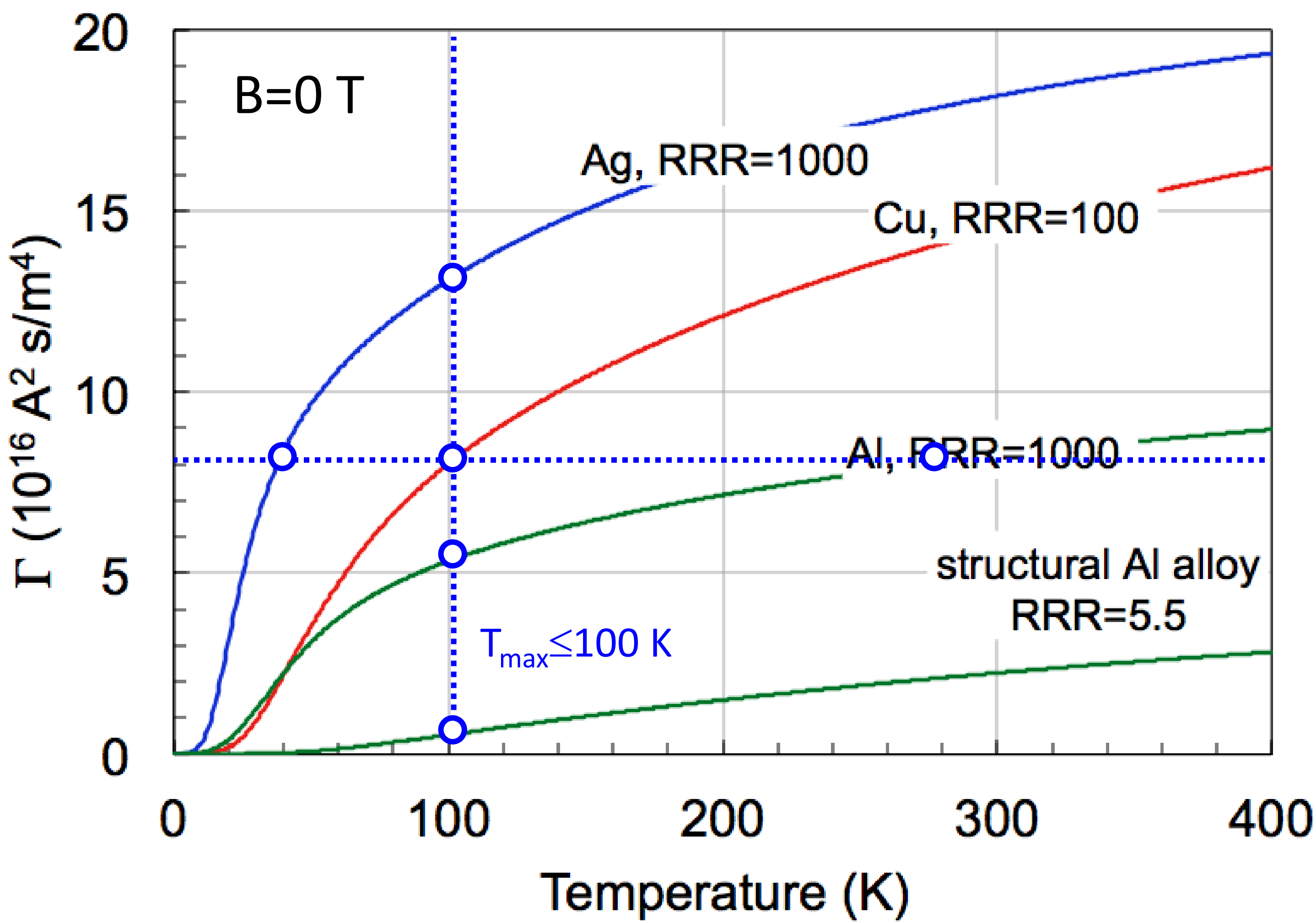
$$\bar{C} = \rho_{st} c_{st} \qquad \bar{\eta} = \eta_{st}$$

- $\Gamma(T_{max})$ is a *material property* and can be tabulated
- A useful approximation is:

$$\Gamma(T) \approx \Gamma_0 \left(\frac{T}{T_\Gamma} \right)^{\frac{1}{2}}$$

Wilson's Gamma

$\Gamma(T_{max})$ for typical stabilizers



Larger value of Γ corresponds to lower T_{max} for a given *quench tax*, or higher *quench capital* for a given T_{max}

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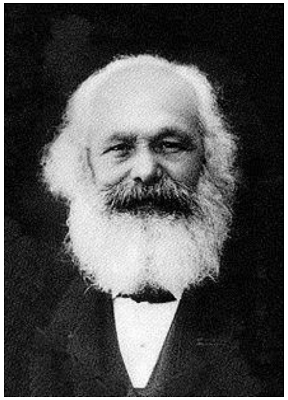


Quench Capital vs. Tax

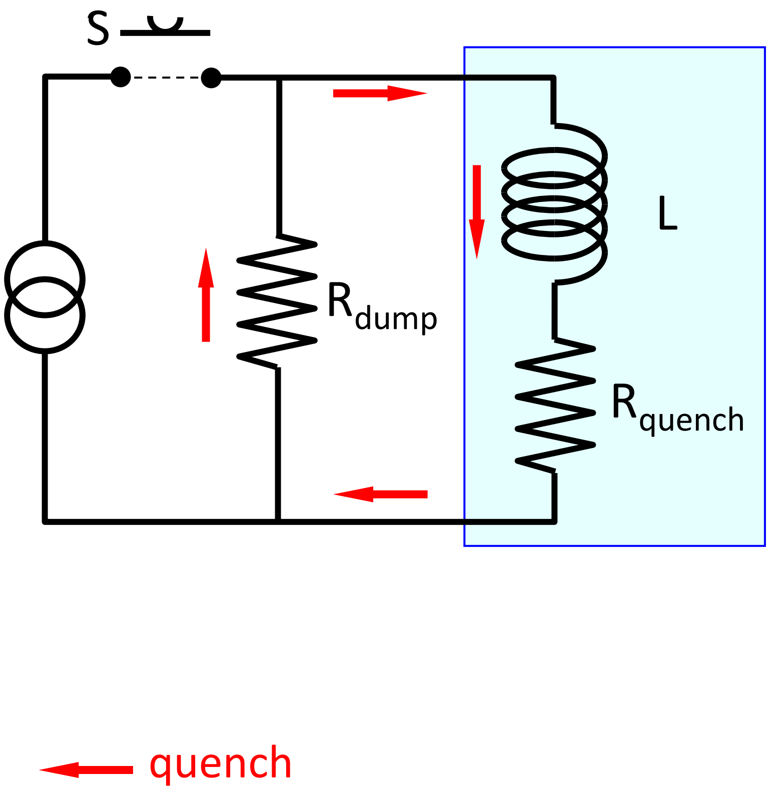
$$\Gamma(T_{\max}) = \int_{T_{op}}^{T_{\max}} \frac{\bar{C}}{\bar{\eta}} dT = \int_0^{\infty} J^2 \, dt = J_{op}^2 t_{quench}$$

- The real problem is to determine the integral of the current waveform: how much is the quench time t_{quench} ?
- Consider two limiting cases:
  - **External-dump:** The magnet is dumped externally on a large resistance (R_{dump} >> R_{quench}) as soon as the quench is detected
  - **Self-dump:** The circuit is on a short circuit and is dumped on its internal resistance (R_{dump} = 0)

External dump

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

$$R_{dump} >> R_{quench}$$



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

$$I = I_{op} e^{-\frac{t - t_{discharge}}{t_{dump}}} \qquad t_{dump} = \frac{L}{R_{dump}}$$

- The *quench tax* integral is:

$$\int_0^\infty J^2\, dt = J_{op}^2 \left(t_{discharge} + \frac{t_{dump}}{2} \right)$$

- and the quench time is:

$$t_{quench} = \left(t_{discharge} + \frac{t_{dump}}{2} \right)$$

Dump time constant

- Magnetic energy:

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

- Maximum terminal voltage:

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

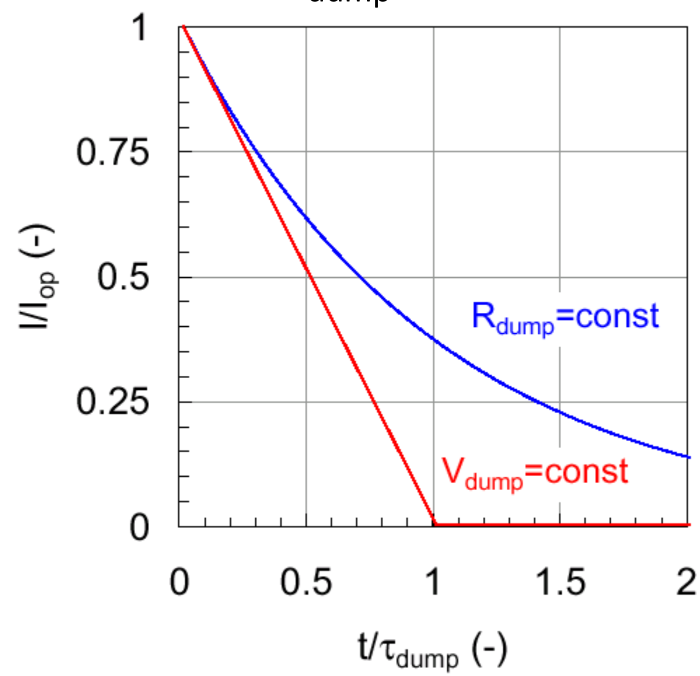
- Dump time constant:

$$t_{dump} = \frac{2E_m}{V_{\max} I_{op}}$$

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

Scaling for external dump

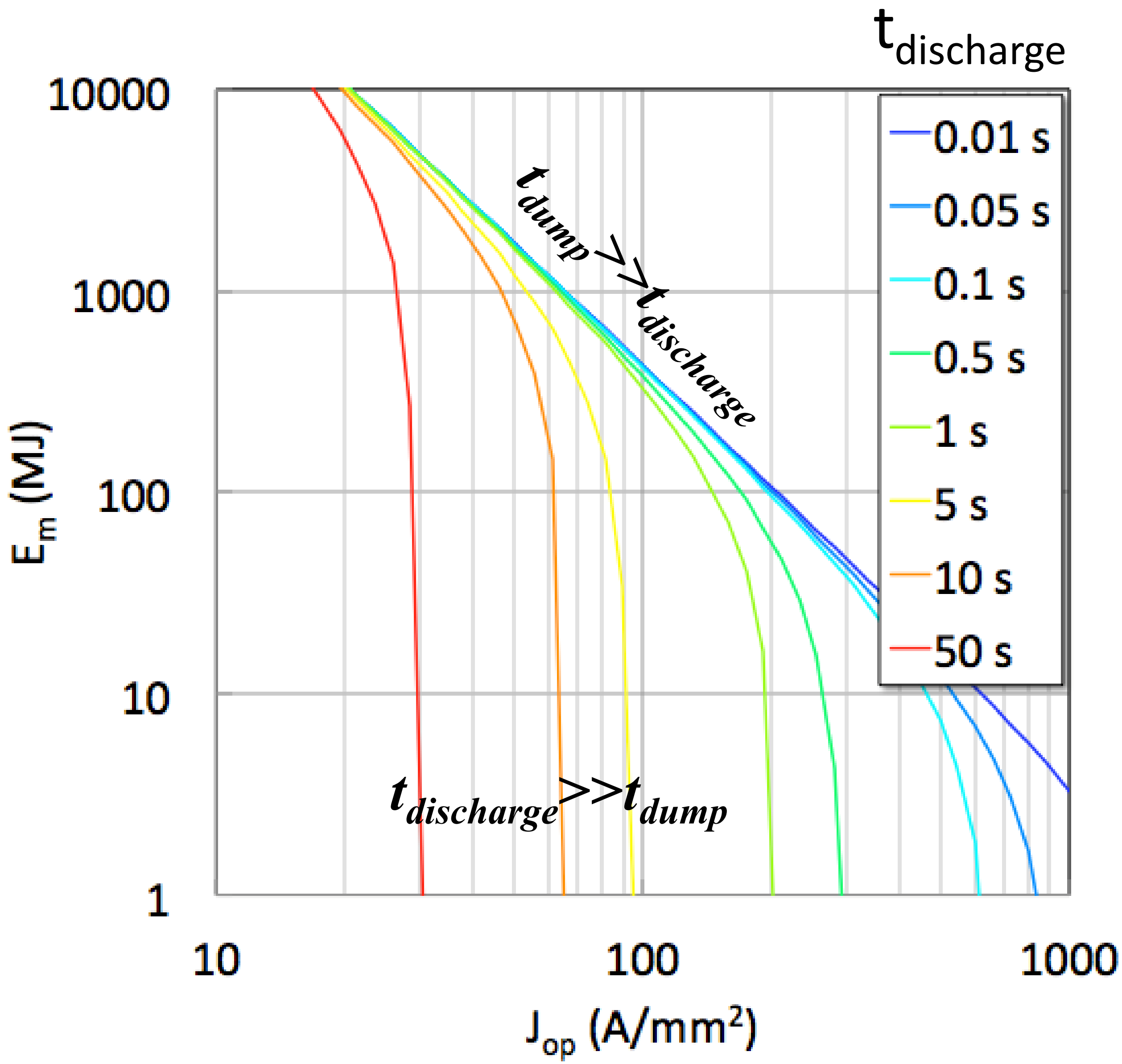
- Use *Wilson's Gamma*

$$T_{\max} = \frac{T_{\Gamma}}{\Gamma_0^2} J_{op}^4 \left(t_{discharge} + \frac{E_m}{V_{\max} I_{op}} \right)^2$$

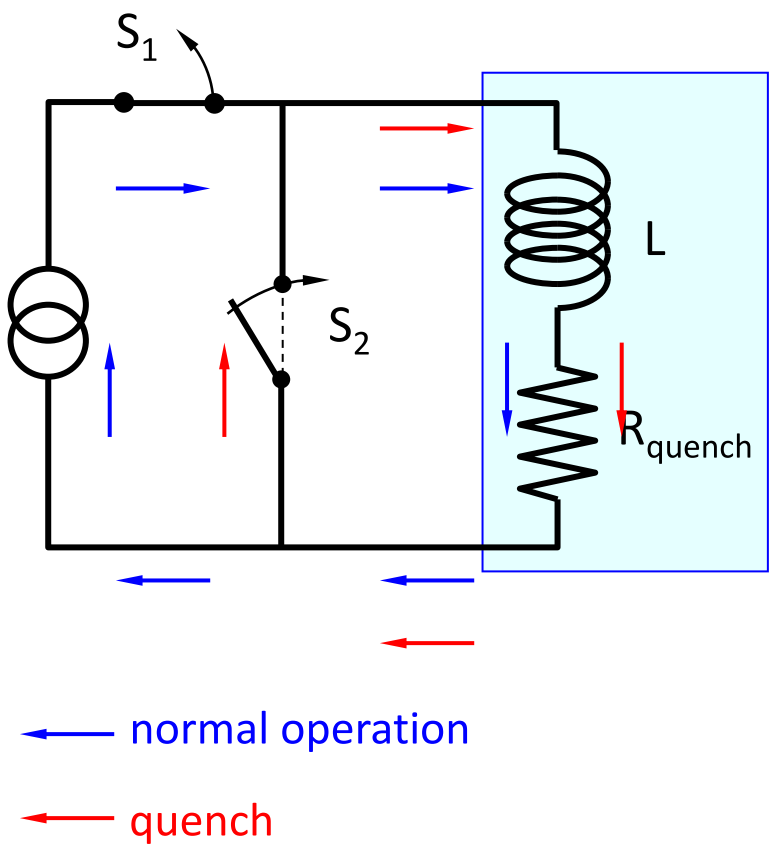
- To limit the hot-spot temperature:
  - Detect rapidly (quench propagation)
  - Use a large terminal voltage (voltage rating)
  - Make the cable large (reduce inductance)

Sample scaling study – external dump

- Cu/Nb_3Sn
- $f_{Cu} = 0.55$
- $f_{SC} = 0.45$
- $I_{op} = 10$ kA
- $V_{max} = 10$ kV
- $T_{max} = 300$ K



Self dump



- The magnetic energy is completely dissipated in the internal resistance, which depends on the temperature and volume of the normal zone
- In this case it is not possible to separate the problem in quench capital and quench tax, but we can make approximations
- Assume that:
  – The whole magnet is normal at $t_{discharge}$ (perfect heaters)
  – The current is constant until t_{quench} then drops to zero
  – Wilson's Gamma and the power resistivity

Scaling for self dump

- Temperature

magnet bulk

$$T_{bulk} = \frac{T_\Gamma}{\Gamma_0^2}(2n+1)^{\frac{2}{2n+1}}\left(\frac{e_m}{\alpha}\right)^{\frac{2}{2n+1}}$$

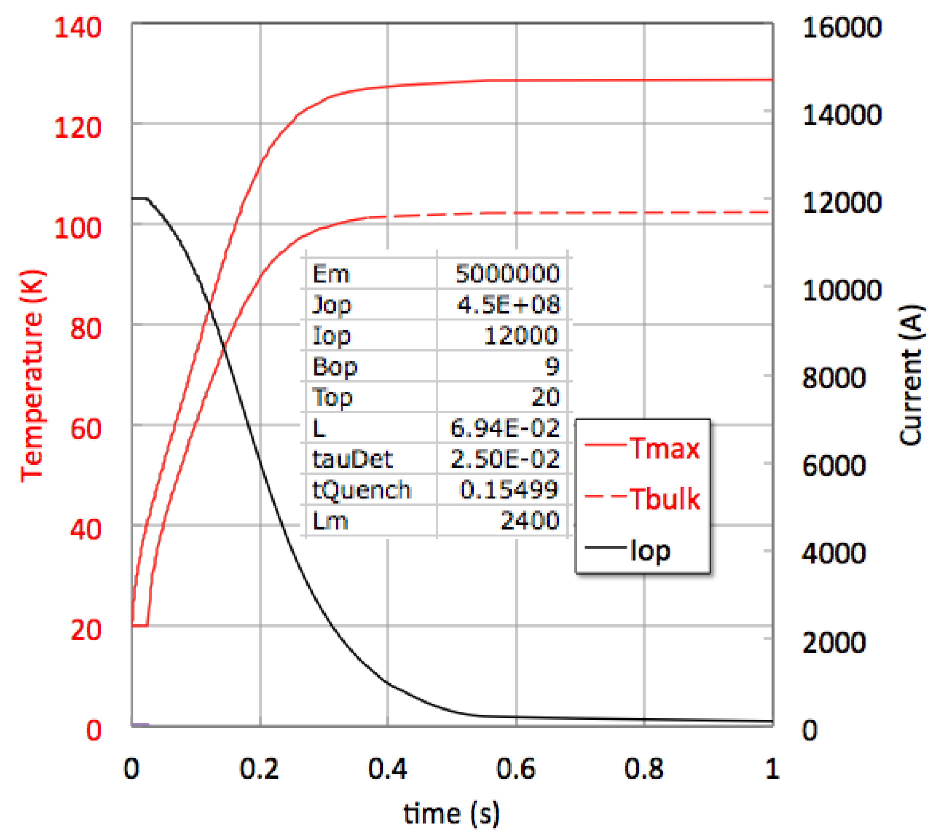
hot-spot

$$T_{\max} = \frac{T_\Gamma}{\Gamma_0^2} J_{op}^4 \left(t_{discharge} + t_{quench}\right)^2$$

- Quench time

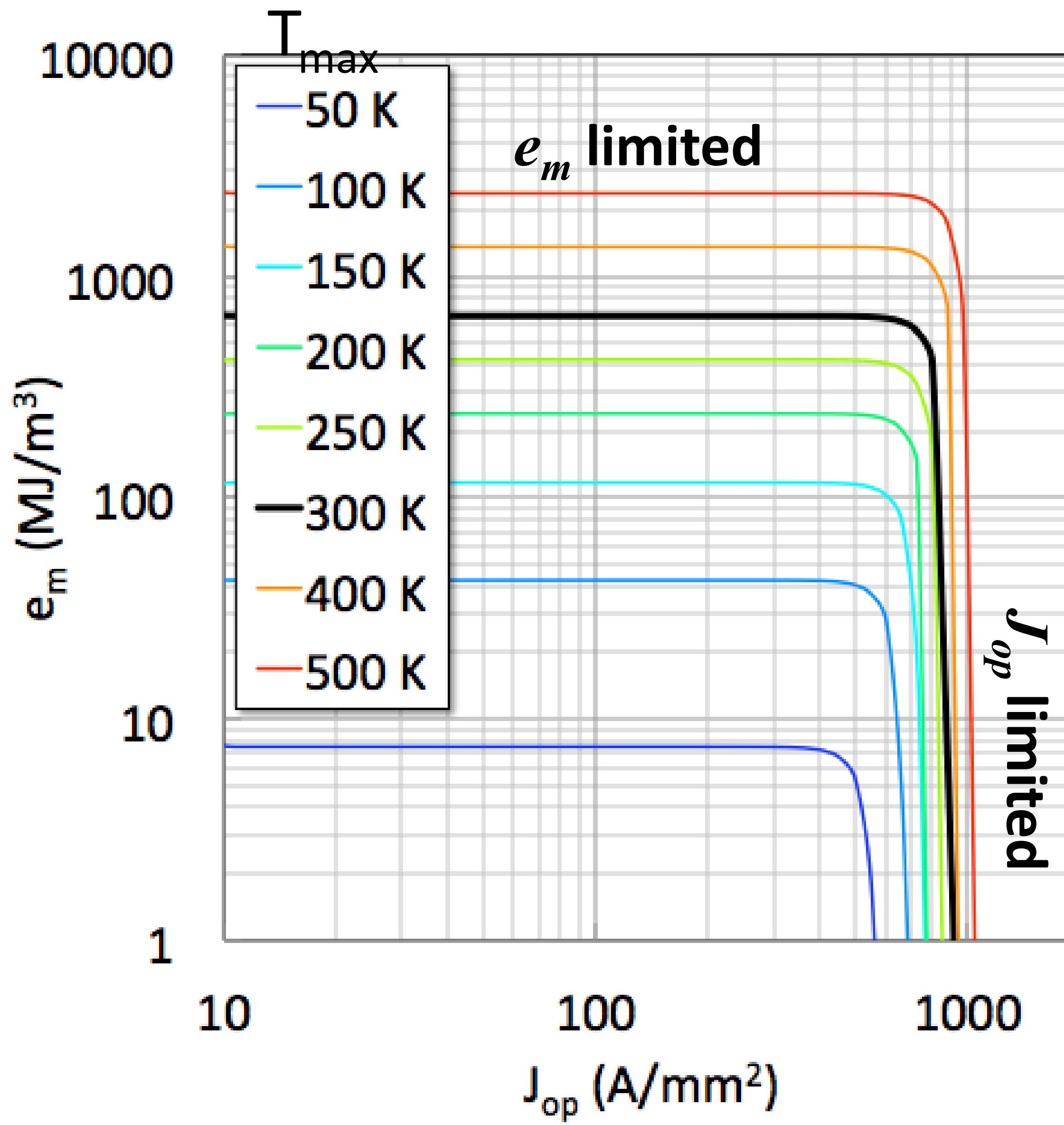
$$t_{quench} = (2n+1)^{\frac{1}{2n+1}}\left(\frac{e_m}{\alpha}\right)^{\frac{1}{2n+1}}\frac{1}{J_{op}^2}$$

$$\alpha = \eta_0\left(\frac{T_\Gamma}{T_\eta \Gamma_0^2}\right)^n$$



Sample scaling study – self dump

- Cu/Nb_3Sn
- $f_{Cu} = 0.55$
- $f_{SC} = 0.45$
- $I_{op} = 10$ kA
- $t_{discharge} = 0.1$ s



Ezio will dwell more on these results

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How long is $t_{discharge}$?

- It depends on
  - Quench initiation and propagation velocity (3-D)
  - Detection thresholds, methods, lags
  - Quench heater method, firing delay, efficiency
  - Quench-back mechanisms
- An accurate knowledge and control of $t_{discharge}$ is of paramount importance for the protection of magnets running at high J_{op}

Q: What is the most efficient method to detect a quench ?

Q: What is the most efficient method to induce a quench ?

Propagation velocity

- Adiabatic conductor (e.g. fully impregnated)

$$v_{adiabatic} = \frac{J_{op}}{C}\sqrt{\frac{\eta_{st} k_{st}}{\left(T_J - T_{op}\right)}}$$

- Bath cooled conductor (e.g. porous insulation)

$$v_{quench} = \frac{1 - 2y}{\sqrt{1 - y}} v_{adiabatic} \qquad y = \frac{hwA_{st}\left(T_J - T_{op}\right)}{\eta_{st} I_{op}^2} \approx \frac{1}{\alpha_{Stekly}}$$

- Force-flow cooled conductor (e.g. ITER CICC)

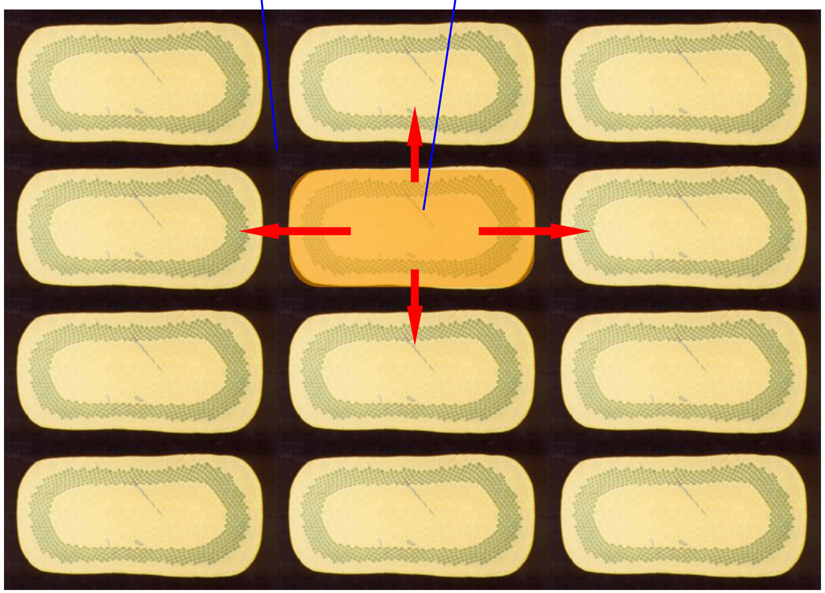
$$v_{quench} = \frac{R r_0 L_q}{2 p_0} \frac{1}{f_{st}} \frac{\eta_{st} J_{op}^2}{C}$$ Low pressure rise regime

The quench propagation velocity is a constant that scales with a power (1…2) of J_{op} and B (1…2)

Q: do we know the propagation velocity in our magnets ?

M. Wilson, *Superconducting Magnets*, Plenum Press, 1983.

Turn-to-turn propagation



- Heat conduction spreads the quench from turn to turn as it plods happily along a conductor at speed $v_{longitudinal}$. The $v_{transverse}$ is approximated as:

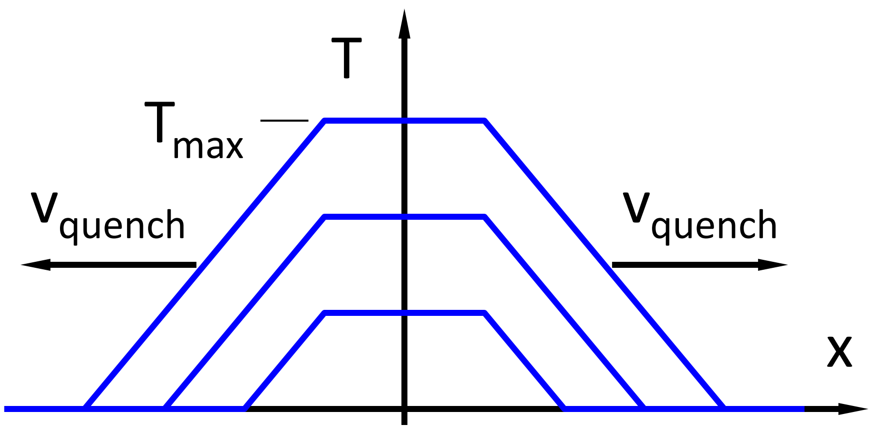
insulation conductivity

$$\frac{v_{transverse}}{v_{longitudinal}} = \sqrt{\frac{k_{transverse}}{k_{longitudinal}}} = \kappa$$

(large) correction factors for geometry, heat capacity, non-linear material properties apply to the scaling !

Quench voltage: 1-D

- take: M. Wilson, *Superconducting Magnets*, Plenum Press, 1983.
  - short initial normal zone, initially at constant current
  - Wilson's Gamma and power resistivity (n≈2)
  - 1-D quench propagation with v_{quench} = constant
- then:



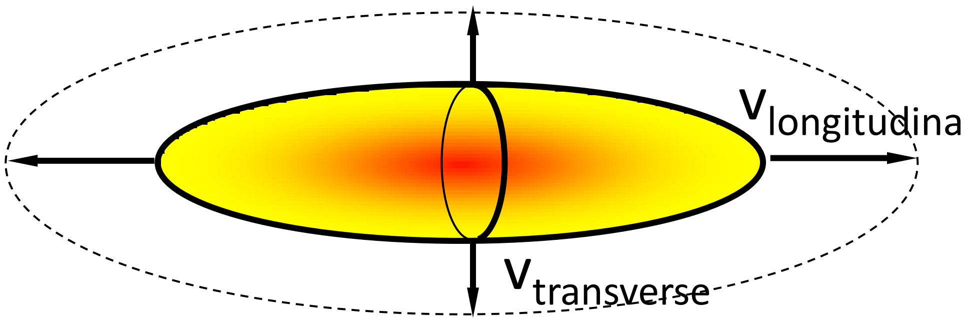
$$V \approx \frac{2}{5} \alpha J_{op}^{9} v_q t^5$$

$$\alpha = \eta_0 \left(\frac{T_\Gamma}{T_\eta \Gamma_0^2} \right)^n$$

Quench voltage : 3-D

- In reality the quench propagates in 3-D

M. Wilson, *Superconducting Magnets*, Plenum Press, 1983.



- The voltage can be computed solving a volume integral:

3-D vs. 1-D

$$V \approx \frac{4\pi}{105}\alpha\kappa^2\frac{J_{op}^9 v_q^3}{A}t^7$$

$$V \approx \frac{2}{5}\alpha J_{op}^9 v_q t^5$$

Scaling study – detection time

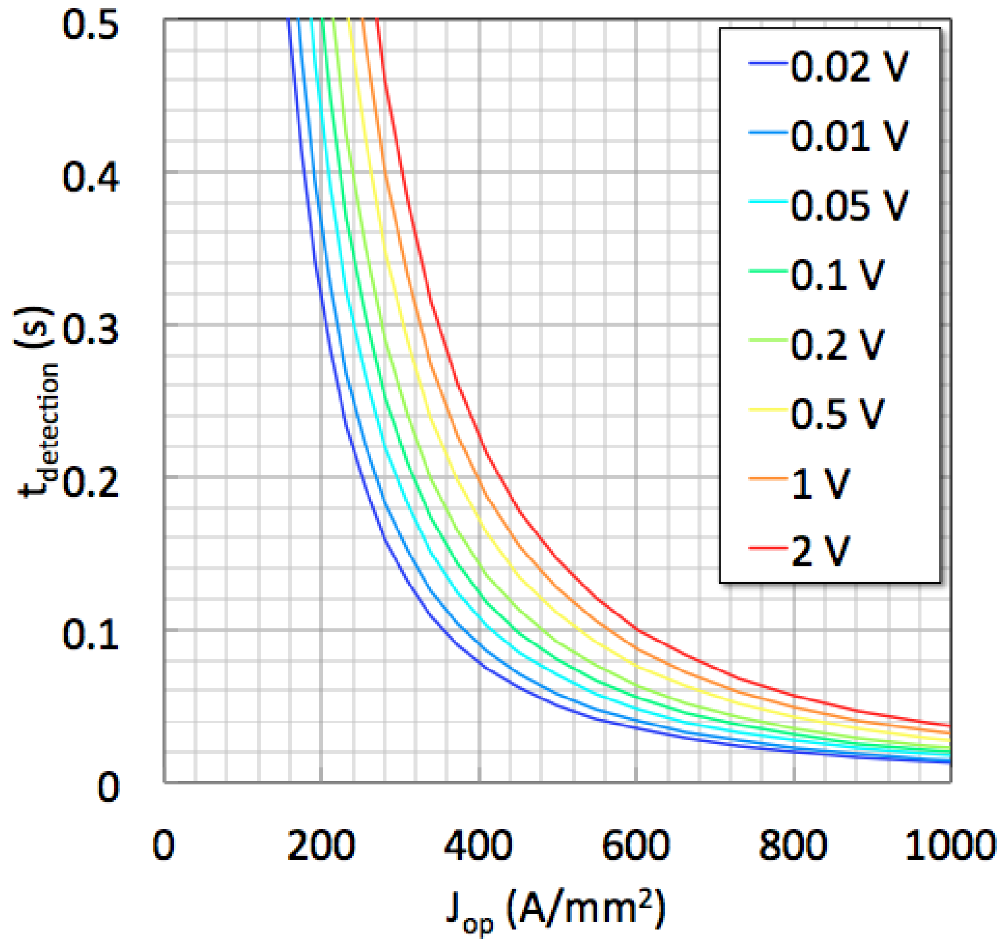
- Take for simplicity the 1-D case, with:

$$v_q = \frac{J_{op}}{C}\sqrt{\frac{\bar{\eta}\bar{k}}{(T_s - T_{op})}} = \beta J_{op}$$

- The detection time scales as:

$$t_{detection} = \left(\frac{V_{detection}}{\frac{2}{5}\alpha\beta}\right)^{\frac{1}{5}} \frac{1}{J_{op}^2}$$

Cable and field dependent

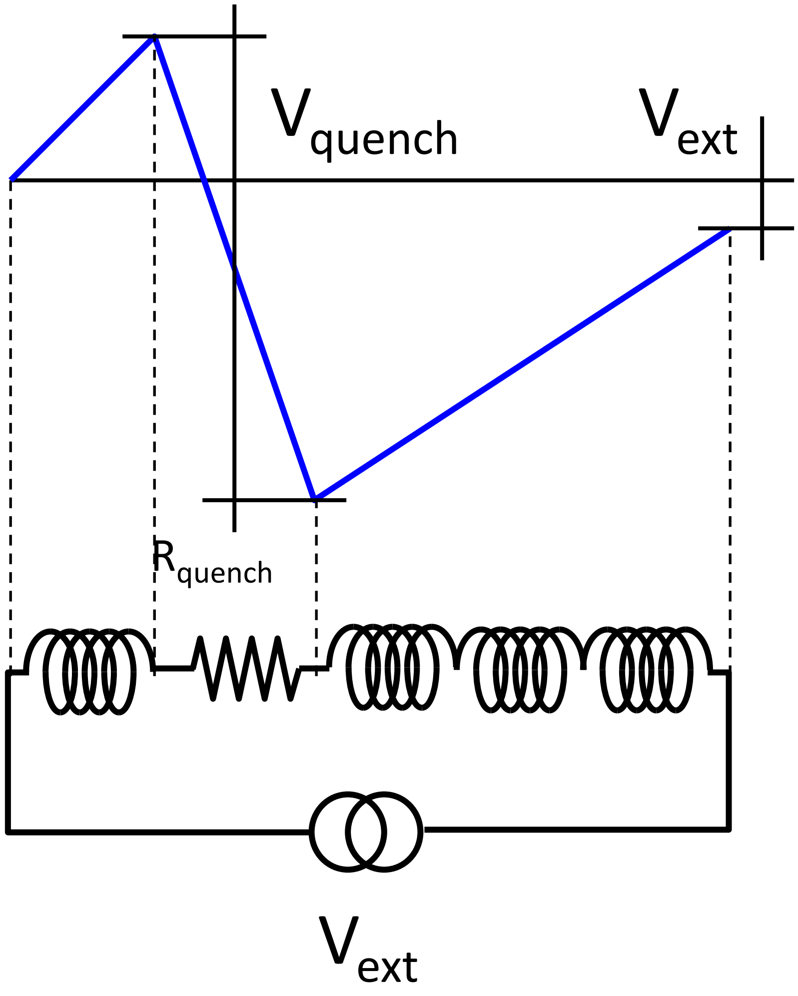


Ezio will dwell more on these results

Outline

- What is a quench ? Process and issues
- The transition from SC to NC state
- The event tree
- Physics of a quench
- Hot-spot temperature limits
  - External-dump and self-dump limits
  - Quench propagation and time scales
- Quench voltages
- Pressure and expulsion
- Conclusions and open questions

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

Q: what is an appropriate voltage criterion for our magnets ?

Voltage peak (self-dump)

Whole magnet

$$R_{quench} I + L \frac{dI}{dt} \approx 0$$

Normal zone

$$V_{quench} = R_{quench} I - M_{NZ} \frac{dI}{dt}$$

$$V_{quench}(t) = I(t) R_{quench}(t) \left(1 - \frac{M_{NZ}(t)}{L} \right)$$

- $R_{quench}(t)$ increases with time (see earlier)
- $I(t)$ decreases with time as the energy is dissipated
- $1 - M_{NZ}(t)/L$ decreases with time as the normal zone propagates
- $V_{quench}(t)$ reaches a maximum during the dump

Outline

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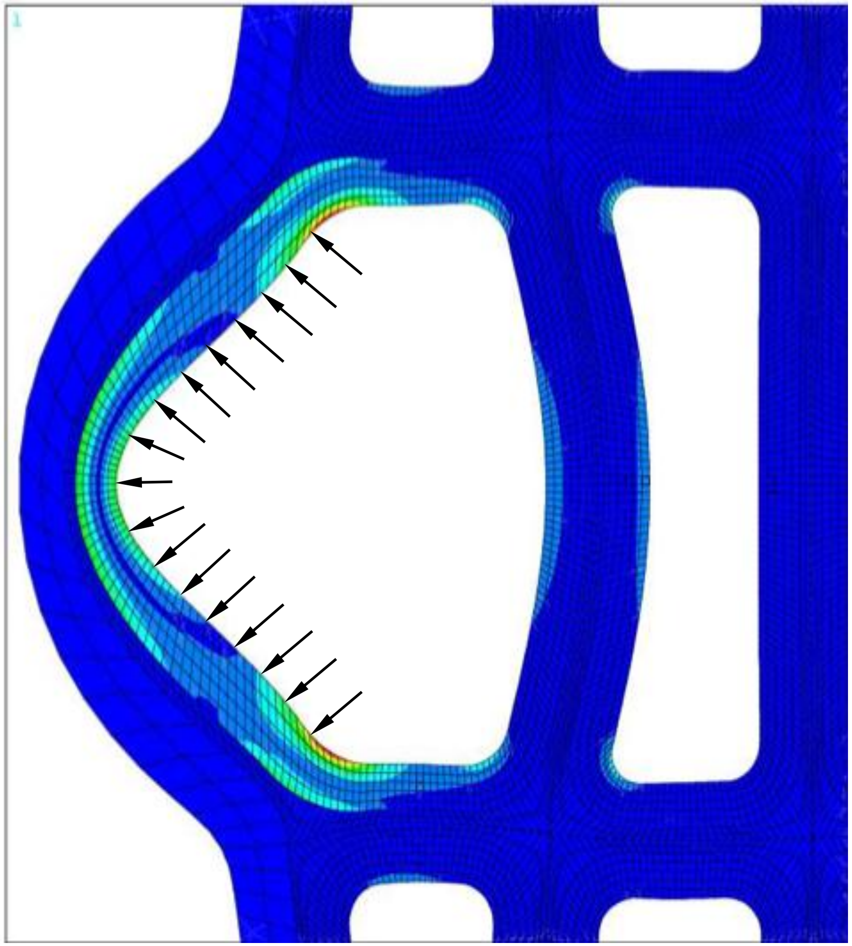
Helium expulsion

- The helium in the normal zone is heated:
  - The pressure increaseses: by how much ? (stresses in the conduits/pipes !)
  - Helium is blown out of the normal zone: at which rate ? (venting and sizing of buffers !)



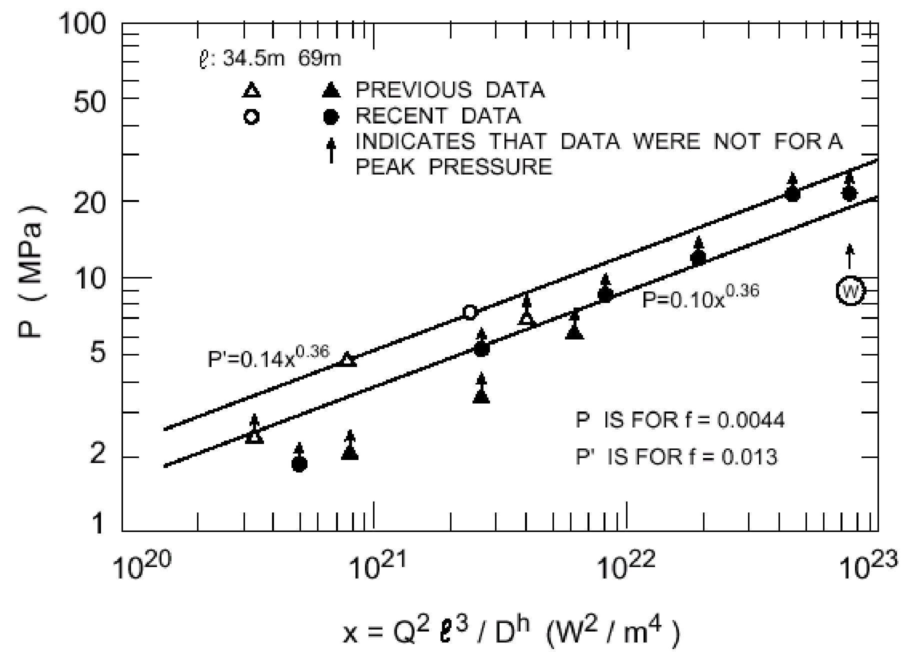
Analysis of deformation of the CICC jacket in EDIPO, by courtesy of A. Portone, F4E, Barcelona

Pressure rise

J.R. Miller, L. Dresner, J.W. Lue, S.S. Shen, H.T. Yeh, Proc. ICEC-8, 321, 1980.

- Maximum pressure during quench for:
  - full length normal
  - constant heating rate

$$p_{\max} = 0.65\left[\frac{f}{D_h}\left(\frac{L}{2}\right)^3\left(\frac{h_{st} J_{op}^2}{f_{he} f_{st}}\right)^2\right]^{0.36}$$



- Wall thickness and diameter of venting lines must be sized accordingly !
- Use numerical codes to get proper estimates

Outline

- What is a quench ? Process and issues
- The transition from SC to NC state
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- Hot-spot temperature limits
  - External-dump and self-dump limits
  - Quench propagation and time scales
- Quench voltages
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- Conclusions and open questions

Conclusions – 1/2

- Physics:
  - Do we know the propagation velocity in our magnets ?
  - Quantitative effect of finite, low n-index ?
- Limits:
  - What are the *real* limits for the hot-spot temperature ?
  - What is an appropriate voltage criterion for our magnets ?
- Detection:
  - What is the most efficient method to detect a quench ?
  - What is the intrinsic detection level of a given method ?
- Dump:
  - What is the most efficient method to induce a quench ?
- Tools:
  - What is the optimal design method ?

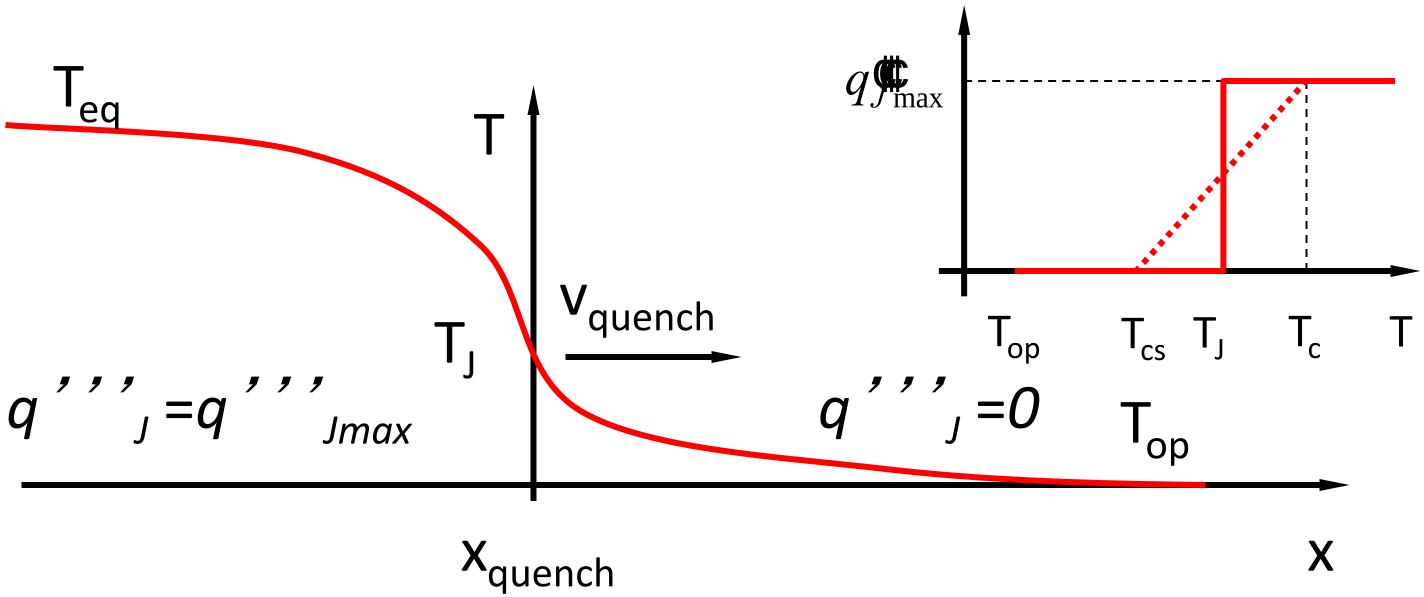
Conclusions – 2/2

- There is obviously much more, for the rest of the workshop !

Backup slides

- Propagation velocities
- Shaji’s universe of quench
- Quench detection methods
- Protection strategies

Adiabatic propagation



$$C\frac{\partial T}{\partial t} = q'''_J + \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)$$

fixed reference frame

$$\xi = x - x_{quench} = x - v_{quench}t$$

moving reference frame

$$k\frac{\partial^2 T}{\partial \xi^2} + v_{quench}C\frac{\partial T}{\partial \xi} + q'''_J = 0$$

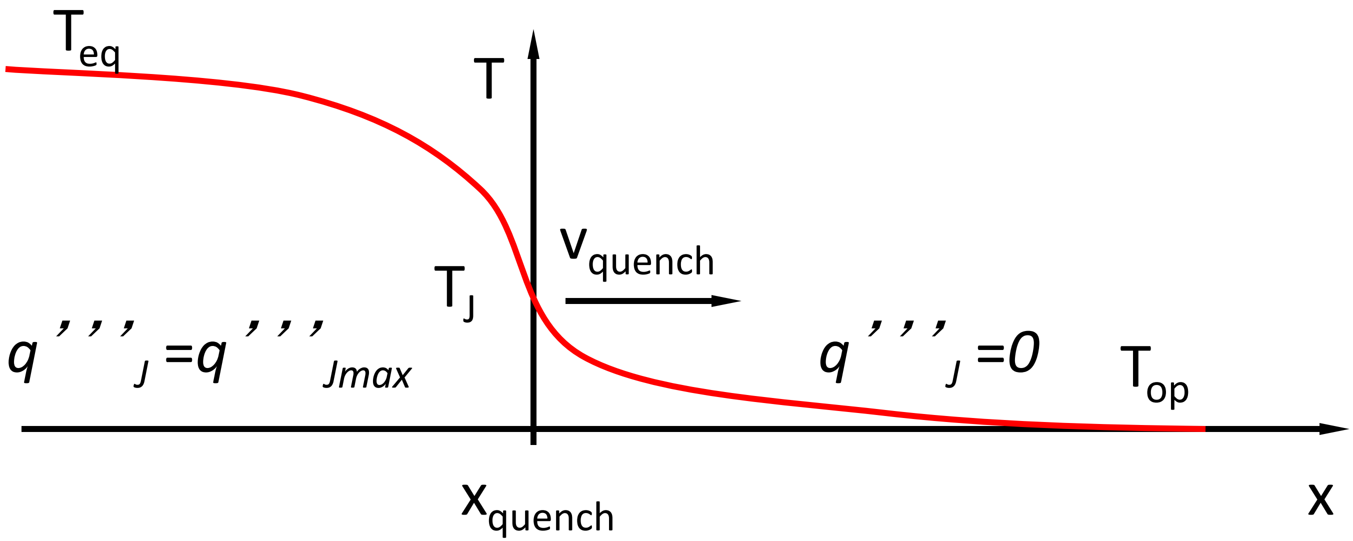
Adiabatic propagation

for *constant* properties (η, k, C)

$$v_{adiabatic} = \frac{J_{op}}{C}\sqrt{\frac{\eta_{st} k_{st}}{(T_J - T_{op})}}$$

- Constant quench propagation speed
- Scales linearly with the current density (and current)
- Practical estimate. HOWEVER, it can give largely inaccurate (over-estimated) values

Bath-cooled propagation



$$C \frac{\partial T}{\partial t} = q_J''' + \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x} \right) - \frac{wh}{A}\left(T - T_{he} \right)$$ fixed reference frame

$$\xi = x - x_{quench} = x - v_{quench} t$$

moving reference frame $$k \frac{\partial^2 T}{\partial \xi^2} + v_{quench} C \frac{\partial T}{\partial \xi} + q_J''' - \frac{wh}{A}\left(T - T_{he} \right) = 0$$

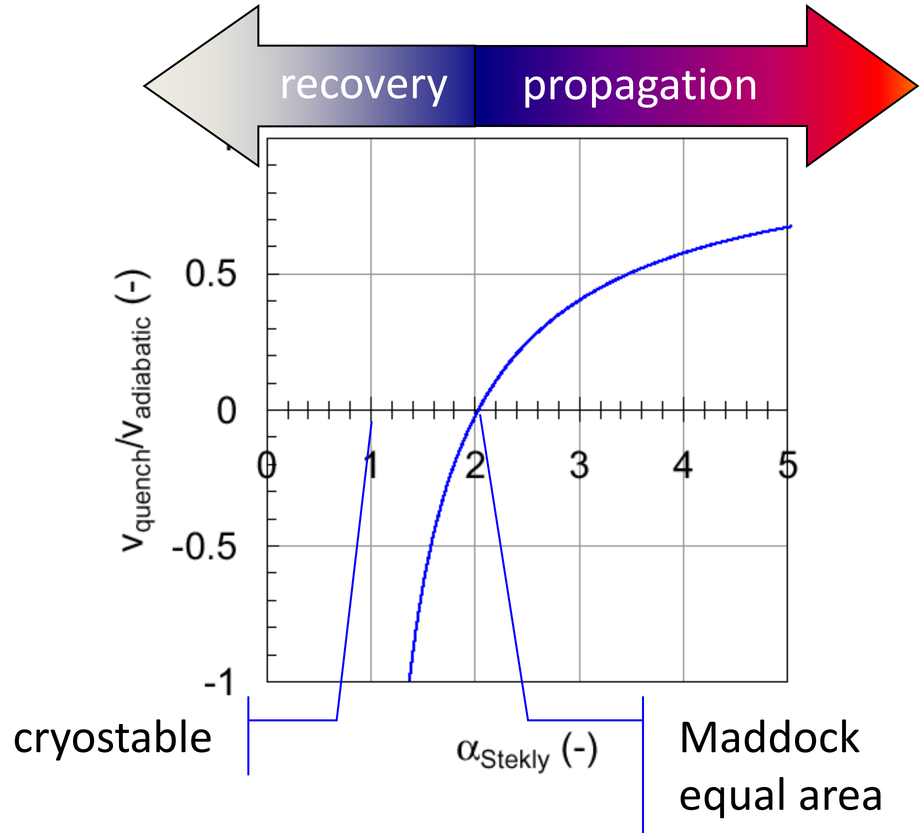
Bath-cooled propagation

for *constant* properties (η, k, C)

$$v_{quench} = \frac{1-2y}{\sqrt{1-y}} v_{adiabatic}$$

$$v_{adiabatic} = \frac{J_{op}}{C} \sqrt{\frac{\eta_{st} k_{st}}{\left(T_J - T_{op}\right)}}$$

$$y = \frac{hwA_{st}\left(T_J - T_{op}\right)}{\eta_{st} I_{op}^2} \approx \frac{1}{\alpha_{Stekly}}$$

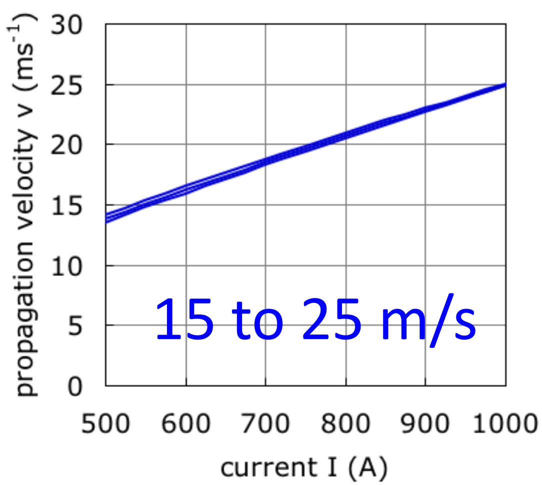


M. Wilson, *Superconducting Magnets*, Plenum Press, 1983.

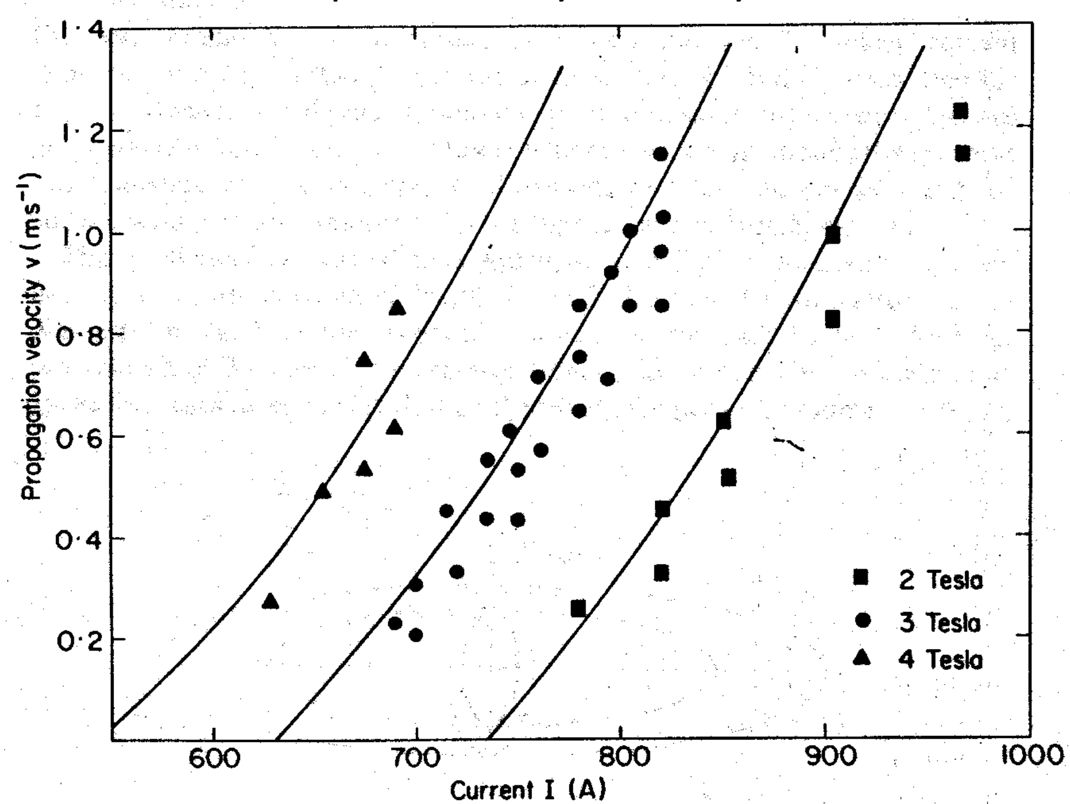
Data for bath-cooled quench

J.R. Miller, J.W. Lue, L. Dresner, IEEE Trans. Mag., **13** (1), 24-27, 1977.

- NbTi conductor
  - $A_{NbTi} = 0.5\ mm^2$
  - $A_{Cu} = 5.1\ mm^2$
- Adiabatic propagation velocities:

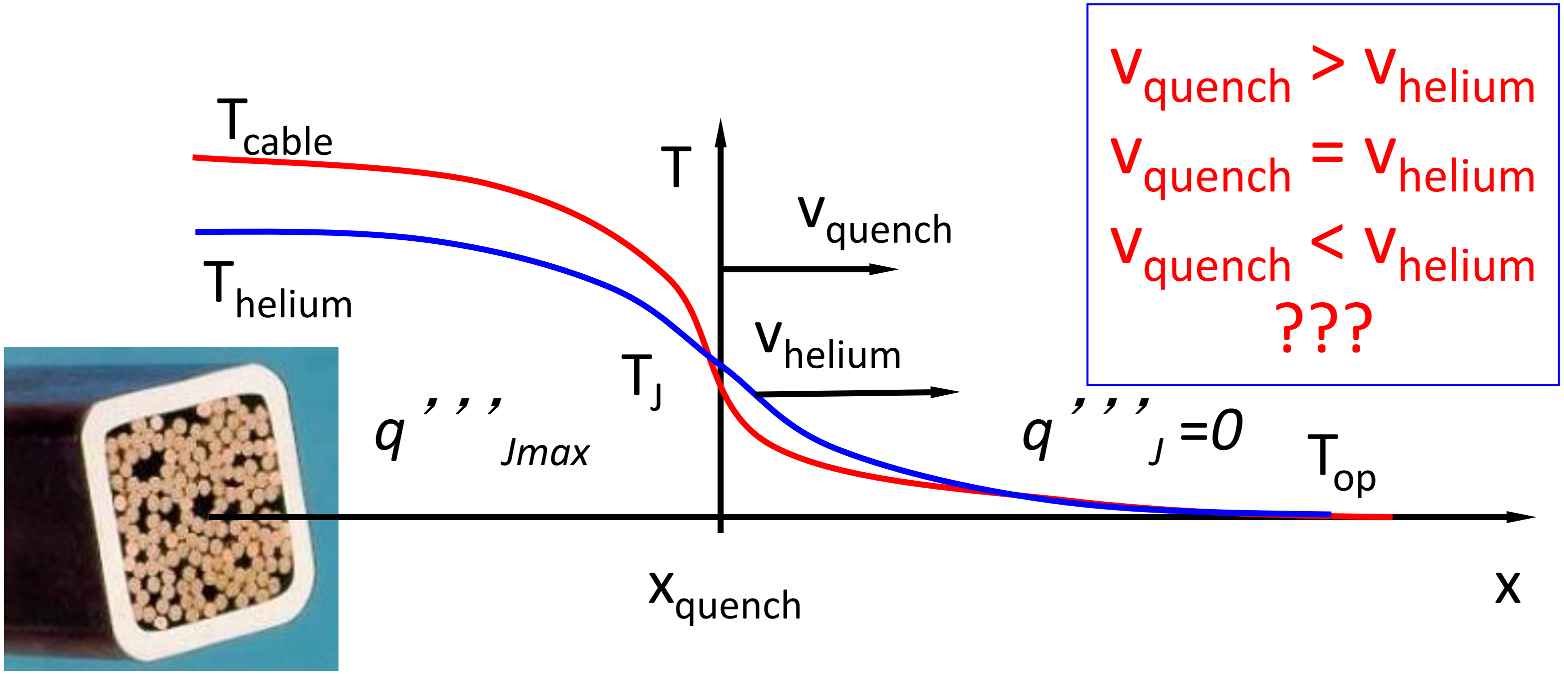


Reproduced by courtesy of M. Wilson

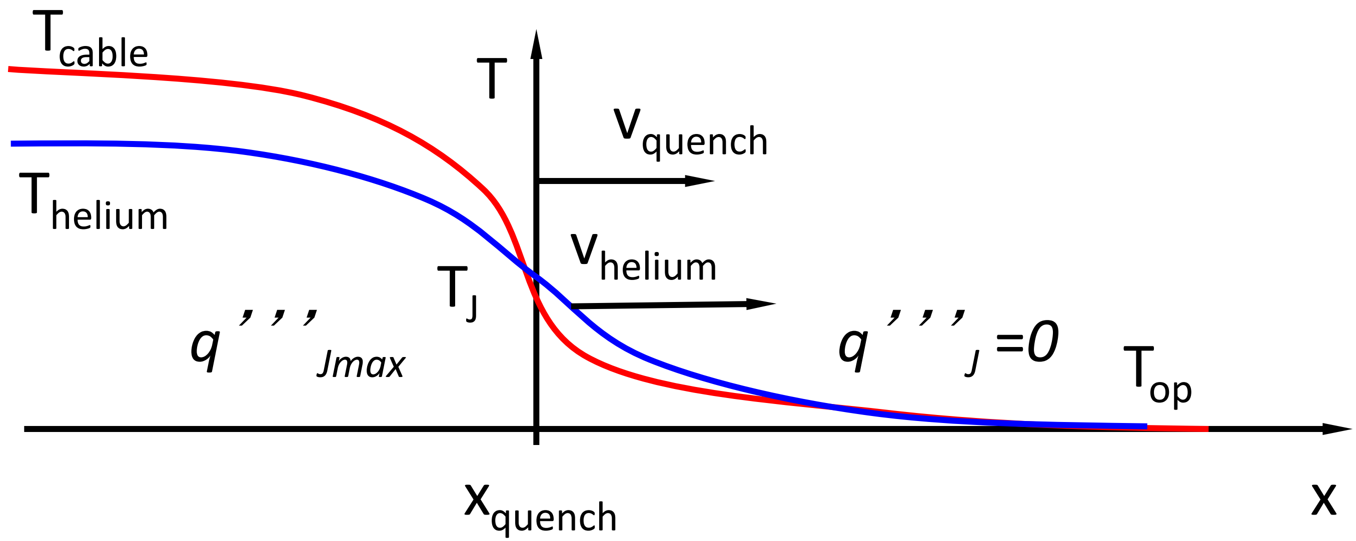


Force-flow-cooled propagation

- the helium is heated in the normal zone and expands ($d\rho/dT < 0$)
    - pressure increase
    - heating induced massflow of *hot* helium



Force-flow-cooled propagation



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

conductor

helium

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho v}{\partial x} = 0$$

$$\frac{\partial p}{\partial x} \approx - \frac{2f}{D_h} \rho v |v|$$

coupling

$$C_{he} \frac{\partial T_{he}}{\partial t} + v_{he} C_{he} \frac{\partial T_{he}}{\partial x} + \varphi C_{he} T_{he} \frac{\partial v_{he}}{\partial x} = \frac{2 f \rho |v_{he}| v_{he}^2}{D_h} + \frac{wh}{A_{he}}\left(T - T_{he}\right)$$

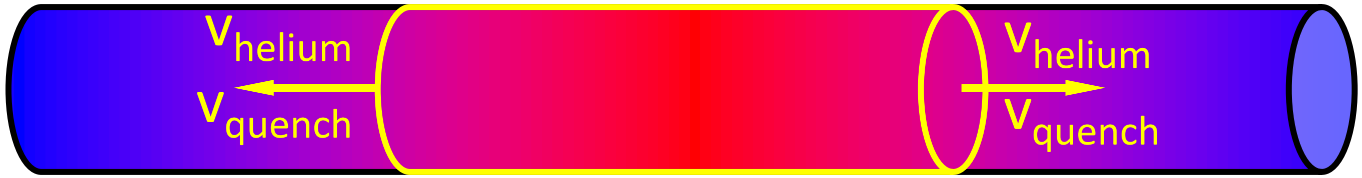
Dresner' s helium bubble

- Dresner' s postulate: L. Dresner, Proc. 10th Symp. Fus. Eng.ng, 2040, 1983

  …the velocity of the normal zone propagation equals the local velocity of expansion of helium.

- consequence: L. Dresner, Proc. 11th Symp. Fus. Eng.ng, 1218, 1985

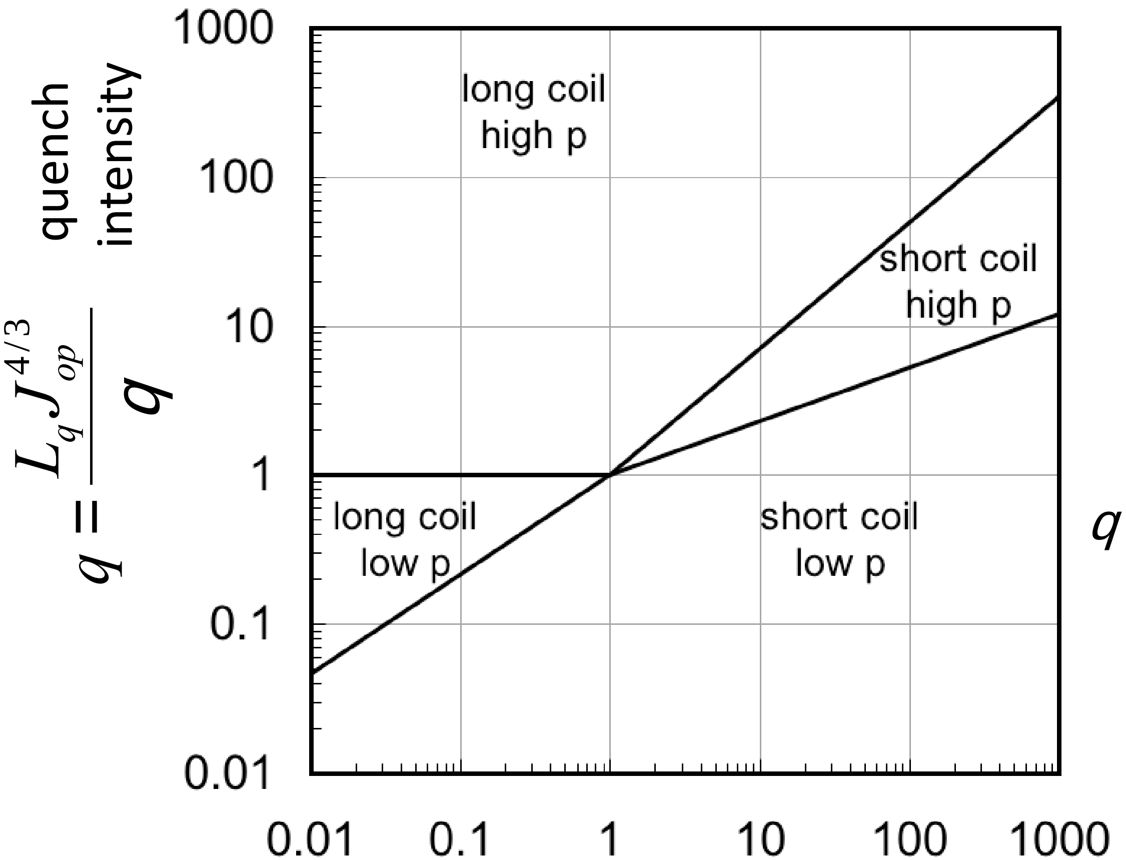
  …the normal zone engulfs no new helium, or in other words […] the heated helium comprises only the atoms originally present in the initial normal zone. We are thus led to the picture of a bubble of hot helium expanding against confinement by the cold helium on either side of it.



- OK if h is large and cable conduction is small

Shajii's Universe of Quench

A. Shajii, J. Freidberg, J. Appl. Phys., **76** (5), 477-482, 1994.



$$l = \frac{\lambda L_q}{L}$$

quenched length

normalization

$$\lambda = 1.7\left(\frac{\rho_0 R T_{\max}}{p_0}\right)\left(\frac{c_0^2 \rho_0}{p_0}\right)$$

$$\theta = \frac{2.6}{R}\left(\frac{p_0^5}{c_0^2 \rho_0^5 T_{\max}} \frac{D_h}{4f} f_{st}^2 \frac{C^2}{h_{st}^2}\right)^{1/3}$$

Propagation speed

A. Shajii, J. Freidberg, J. Appl. Phys., **76** (5), 477-482, 1994.

long coil
high pressure rise

$$v_{quench} = 0.766\left(\frac{D_h}{2 f t_M}\right)^{1/5}\left(\frac{R L_q}{c_0}\frac{1}{f_{st}}\frac{\eta_{st} J_{op}^2}{C}\right)^{2/5}$$

short coil
high pressure rise

$$v_{quench} = \left(\frac{D_h}{f}\frac{R L_q}{2L}\frac{1}{f_{st}}\frac{\eta_{st} J_{op}^2}{C}\right)^{1/3}$$

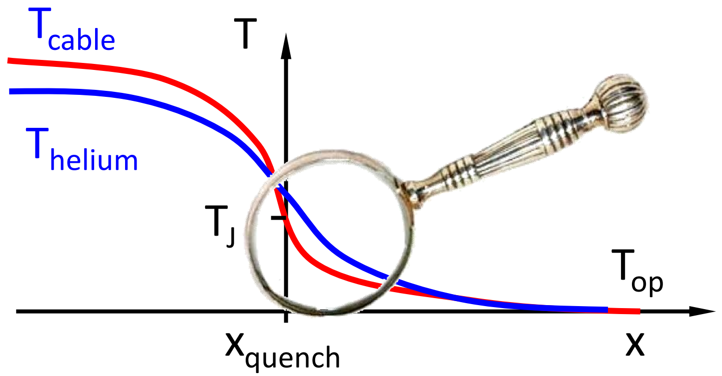
long coil
low pressure rise

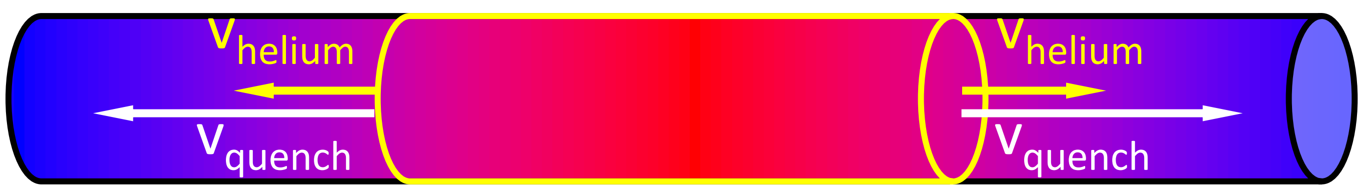
short coil
low pressure rise

$$v_{quench} = \frac{R \rho_0 L_q}{2 p_0}\frac{1}{f_{st}}\frac{\eta_{st} J_{op}^2}{C}$$

Thermal-hydraulic quench-back

- The helium at the front:
  - is compressed adiabatically (Dresner)
  - performs work agains the frictional drag (Shajii and Freidberg)
- Both effects cause pre-heating of the helium **and** superconductor
- The normal front advances faster than the helium expulsion velocity

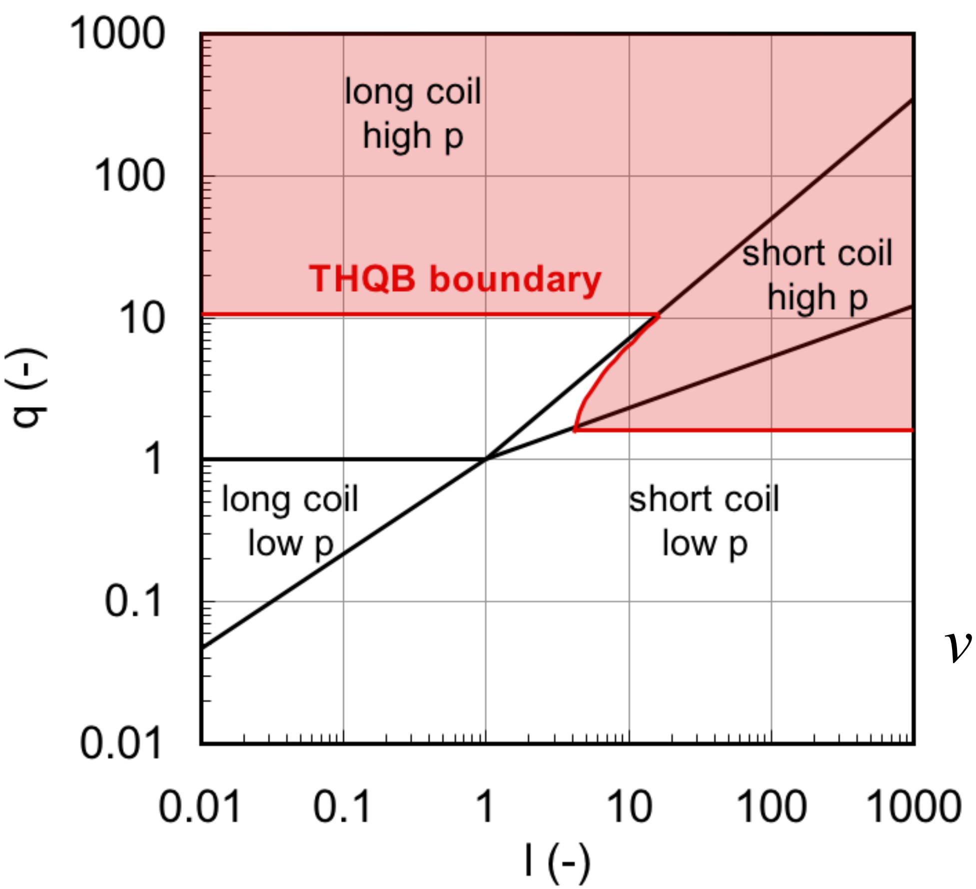




The normal zone engulfs an increasing mass and the quench accelerates: a Thermal-Hydraulic Quench-Back !

THQB in Shajii's UoQ

A. Shajii, J. Freidberg, Int J. Heat Mass Transfer, **39**(3), 491-501, 1996.

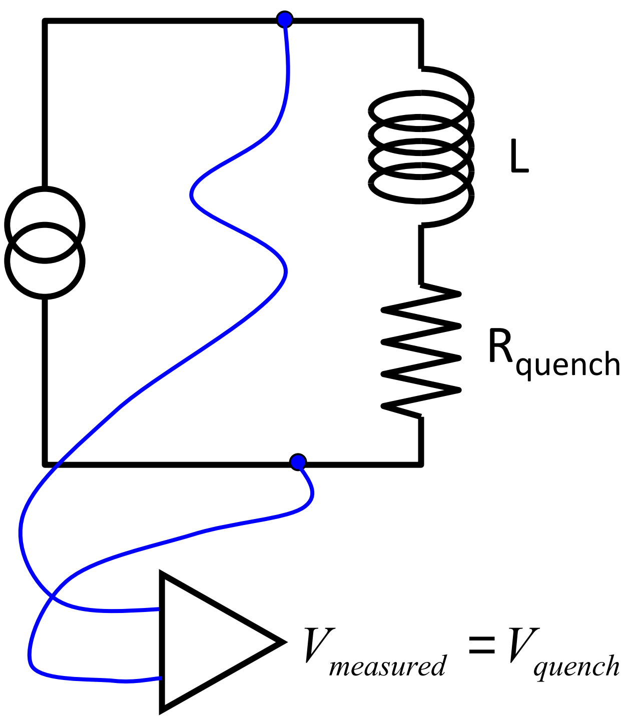


- THQB takes place when the quench has a sufficient intensity q, and length l
- The quench propagation speed in THQB is:

$$v_{qb} = \phi_0 \left(\frac{D_h}{2 f \rho_0} \right)^{\frac{1}{3}} \left(\frac{\eta_{st} J_{CS}^2}{f_{st} f_{he}} \right)^{\frac{1}{3}} \left(\frac{T_0}{T_{cs} - T_0} \right)^{\frac{2}{3}}$$

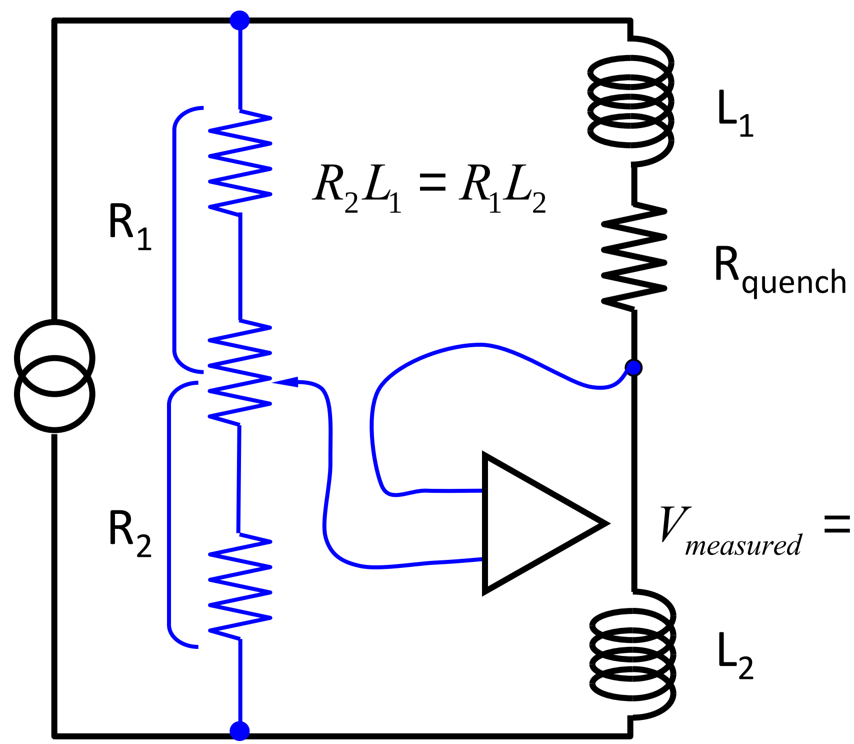
Quench detection: voltage

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



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

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

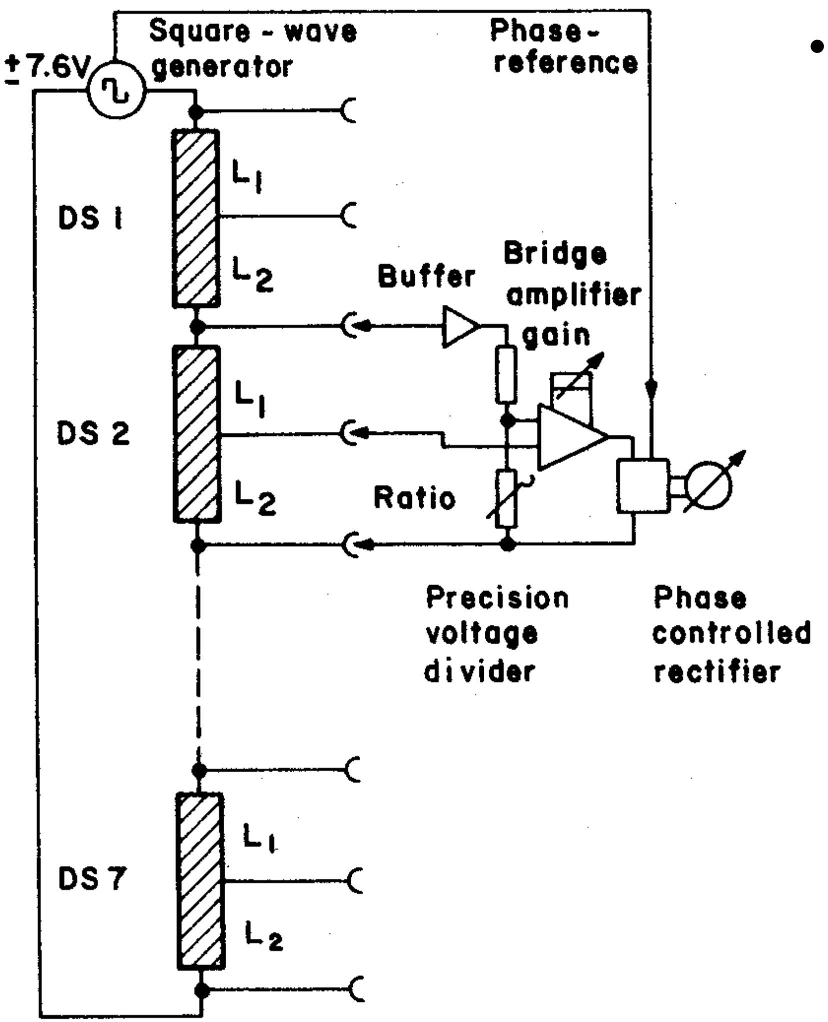


$$R_2 L_1 = R_1 L_2$$

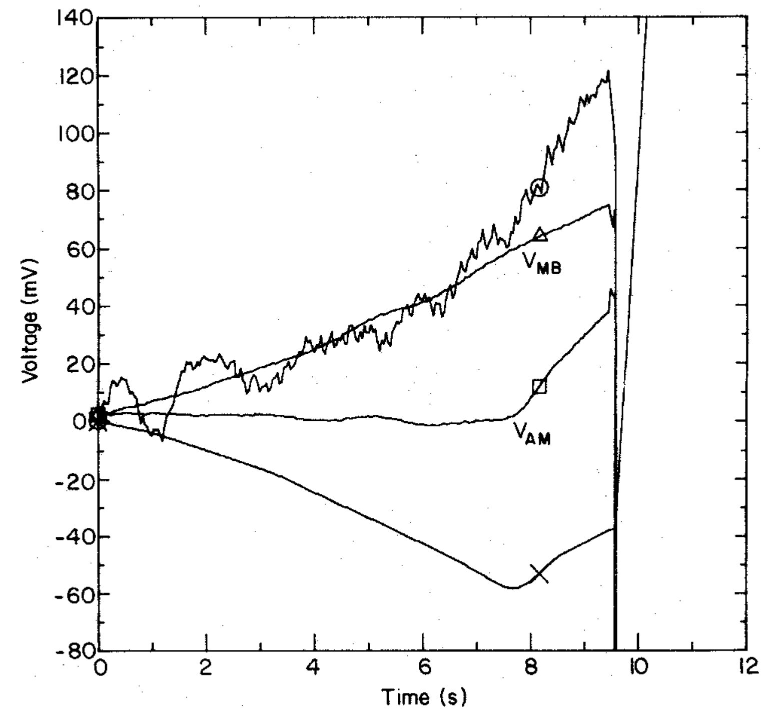
$$V_{measured} = V_{quench}$$

LCT quench detection scheme

G. Noether, et al., Cryogenics, **29**, 1148-1153,1989.

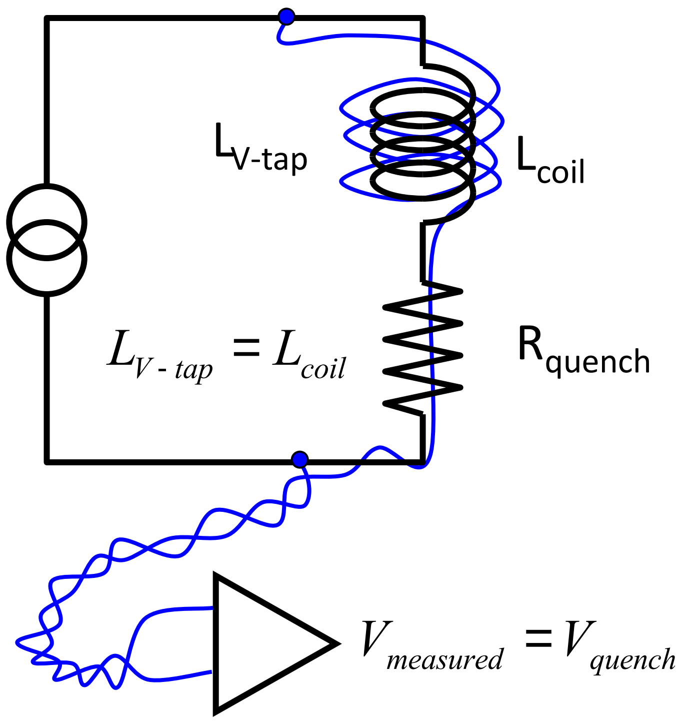


- A symmetric bridge does not see a symmetric quench ! **BEWARE of all possible conditions**

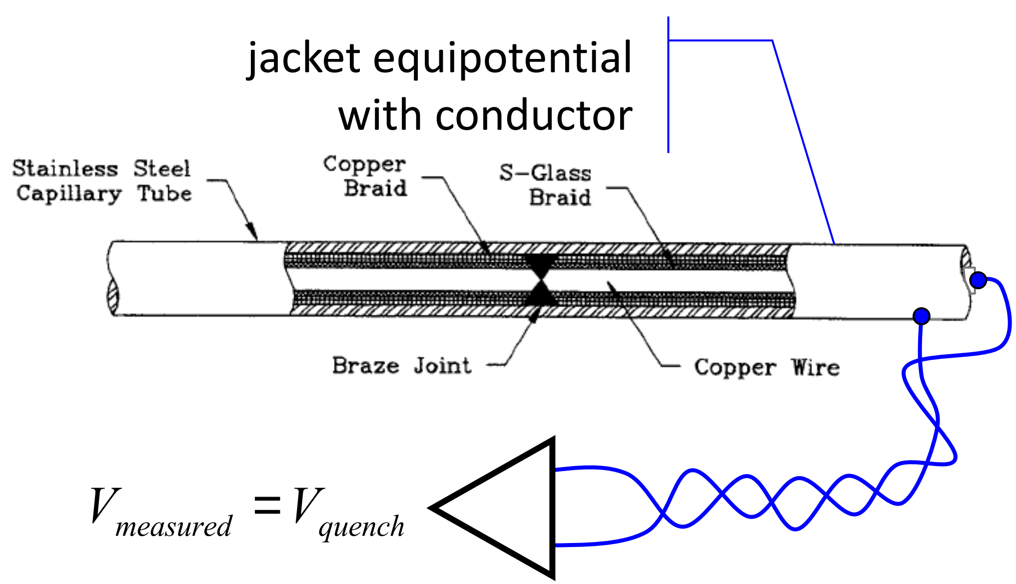


Co-wound voltage taps

- co-wound (non-inductive) voltage taps are an alternative to achieve compensation



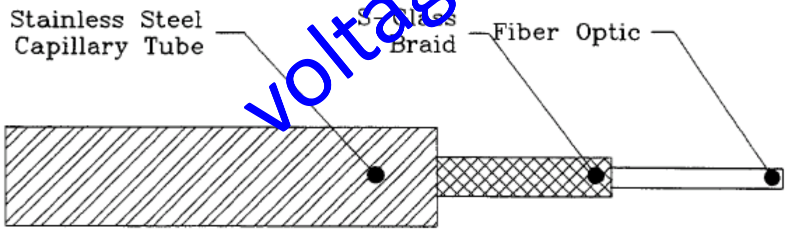
- sometimes the voltage tap can be directly inserted in the conductor, thus providing the best possible voltage compensation and noise rejection

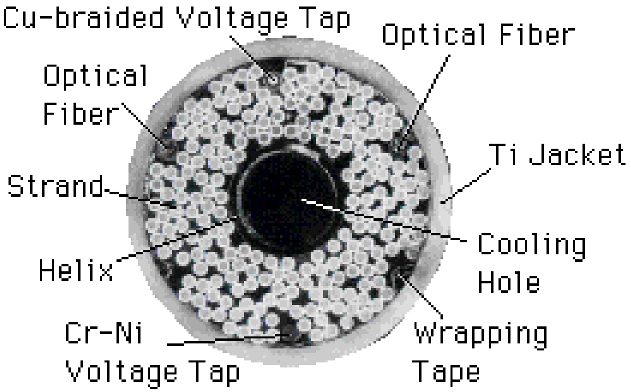


Quench detection: indirect

- quench antenna’s: variation of magnetization and current distribution in cables generates a voltage pick-up from a magnetic dipole change localised at the quenching cable
- optical fibers in cables/coils: variation of fiber refraction index with temperature is detected as a change of the interference pattern of a laser beam traveling along the fiber
- pressure gauges and flow-meters: heating induced flow in internally cooled cables is detected at the coil inlet/outlet
- co-wound superconducting wires: variation of resistance with temperature can be measured

voltage measurement is still best

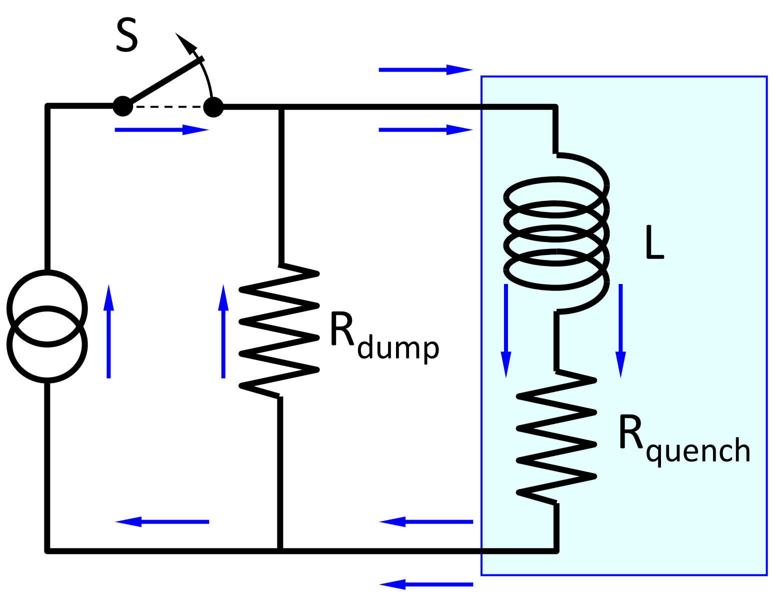




the QUELL experiment:
a quench detection nightmare

Strategy 1: energy dump

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



$$R_{dump} >> R_{quench}$$

normal operation

quench

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

$$I = I_{op} e^{-\frac{(t - t_{detection})}{\tau_{dump}}} \qquad \tau_{dump} = \frac{L}{R_{dump}}$$

- the integral of the current:

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

- 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:

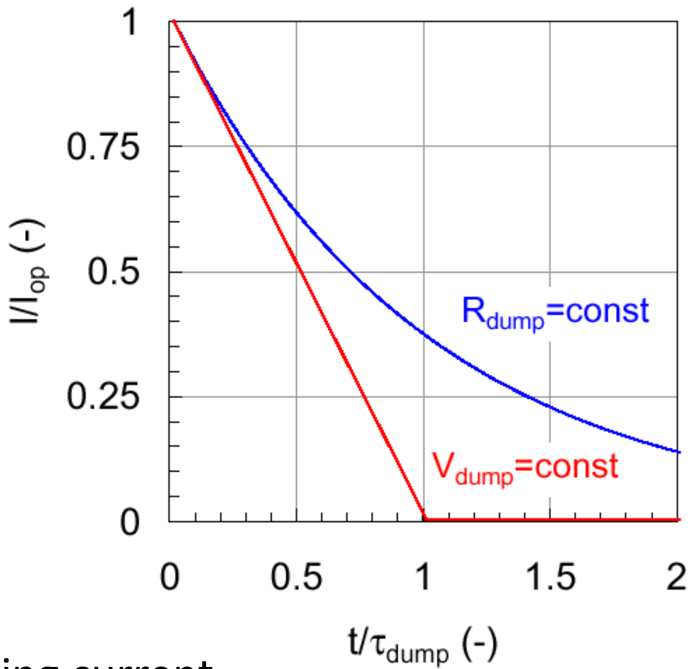
$$t_{dump} = \frac{L}{R_{dump}} = \frac{2E_m}{V_{\max} I_{op}}$$

maximum terminal voltage

operating current

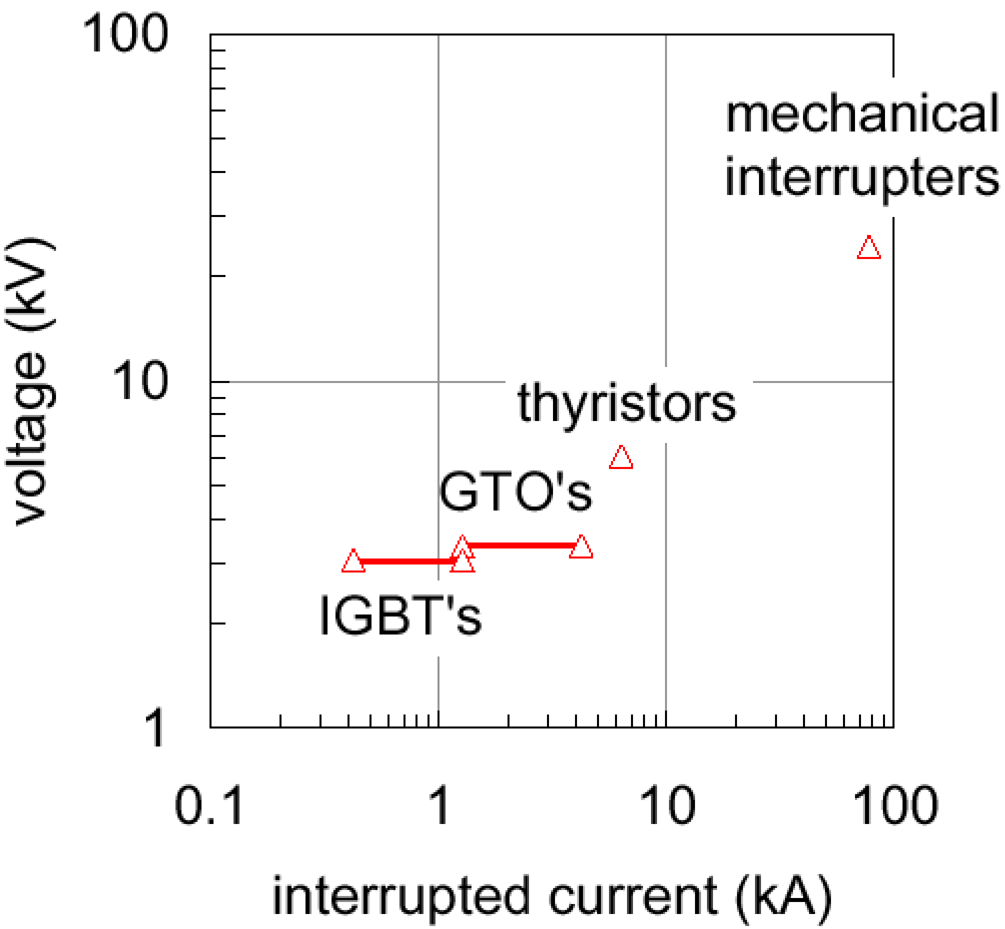
increase V_{max} and I_{op} to achieve fast dump time

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



Switches

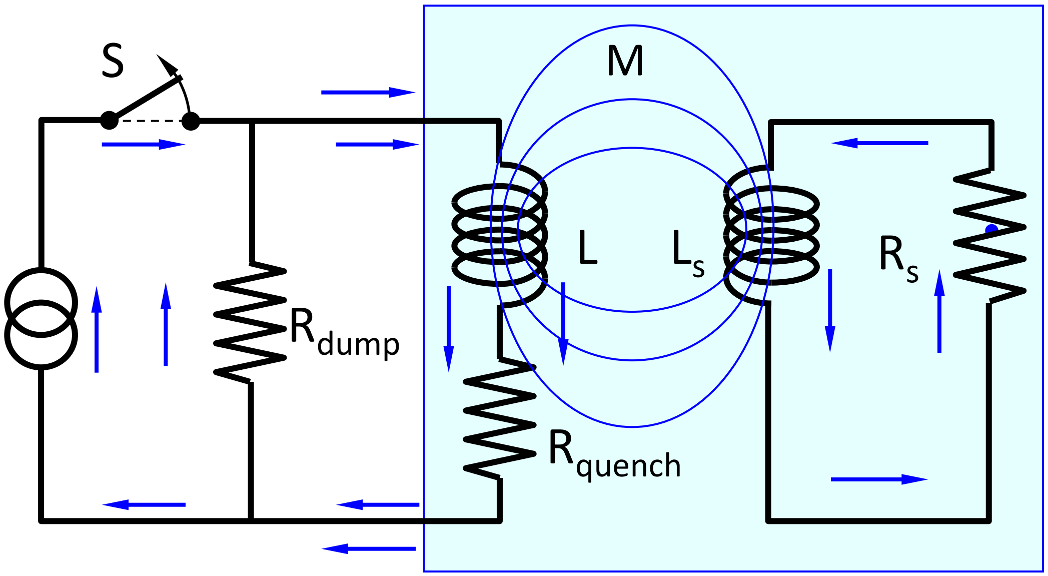
By courtesy of J.H. Schlutz, MIT-PSFC, 2002.



- switching kA's currents under kV's of voltage is not easy:
  - mechanical interrupters
  - thyristor's
  - Gate Turn-Off thyristor's
  - Insulated Gate Bipolar Transistor's
  - fuses (explosive, water cooled)
  - superconducting
- cost and reliability are most important !

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

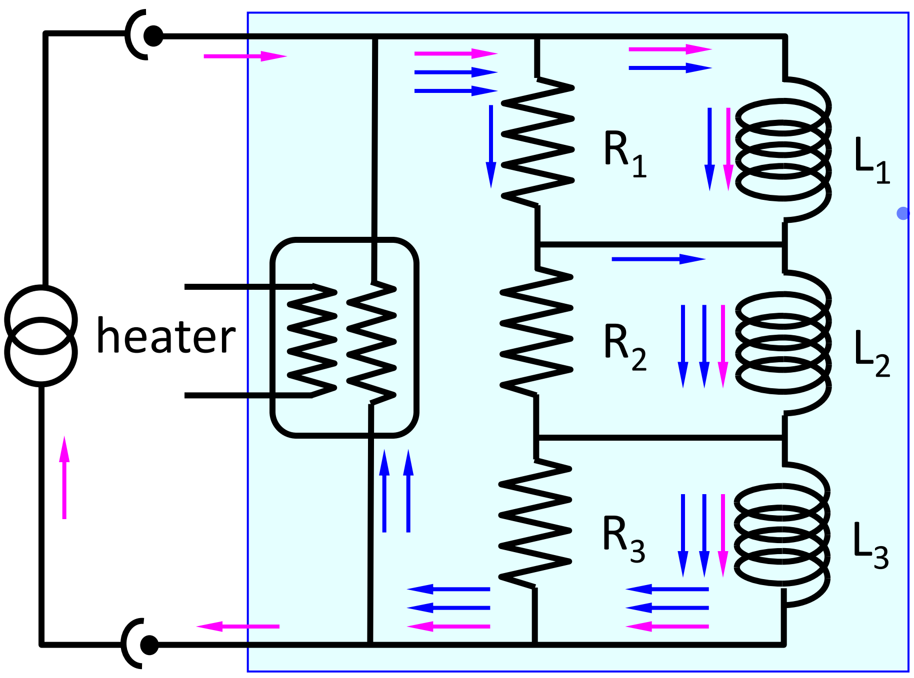
⟵ normal operation

⟵ quench

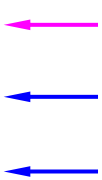
Strategy 3: subdivision

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

- 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



T_{max} in subdivided system

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

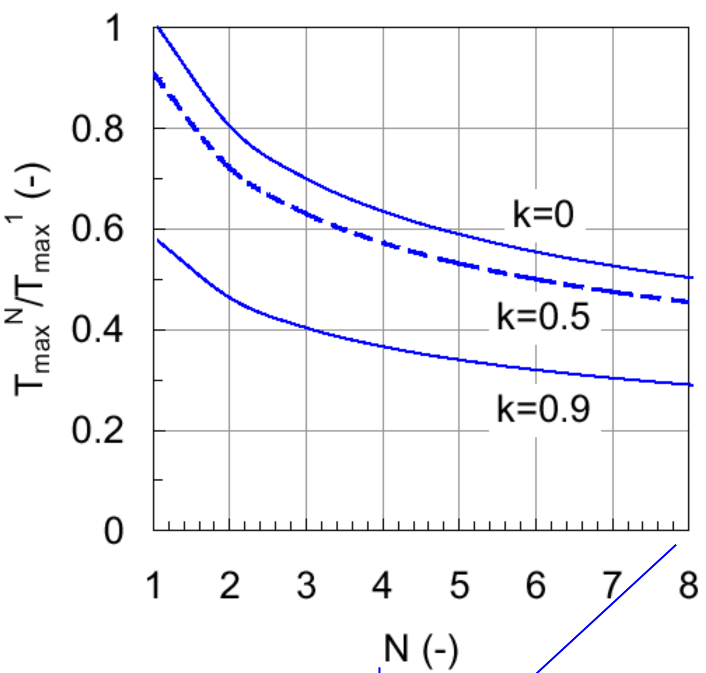
- in a subdivided system the energy dumped in each section is reduced because of
    - the resistive bypass
    - inductive coupling, reducing the effective inductance of each section:

$$L_{effective} \propto \left(1 - k^2\right) L_{section} \approx \left(1 - k^2\right) \frac{L_{system}}{N}$$

- the hot spot temperature scales as:

$$T_{\max} \propto \sqrt[3]{L_{effective}}$$

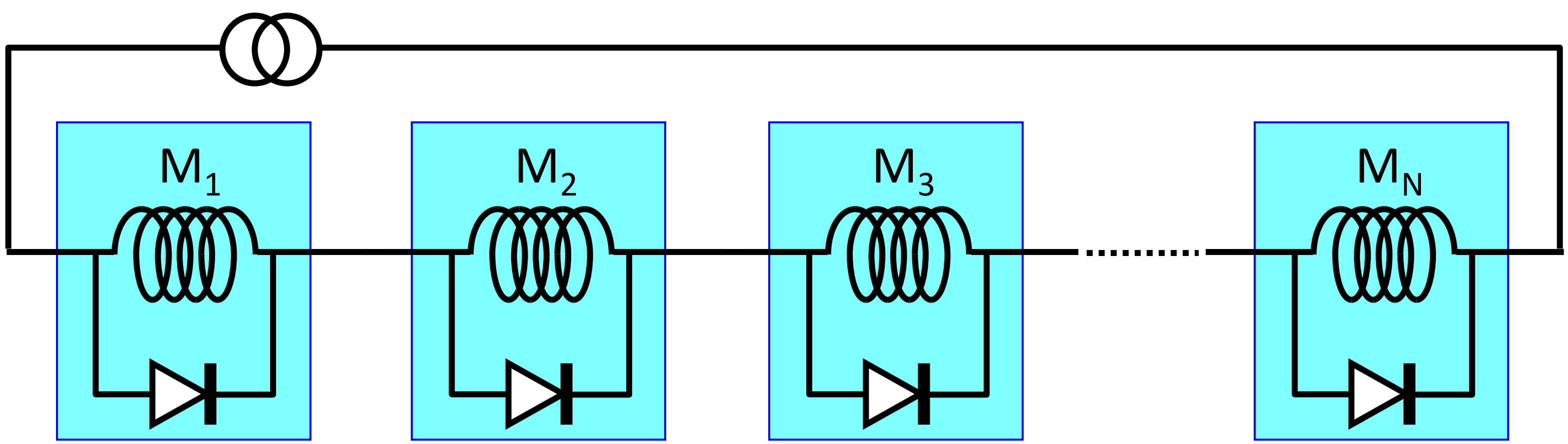
ratio of T_{max}^{N} in a system subdivided in N sections relative to the T_{max}^{1} in the same system with no subdivision



construction becomes complicated !

Magnet strings

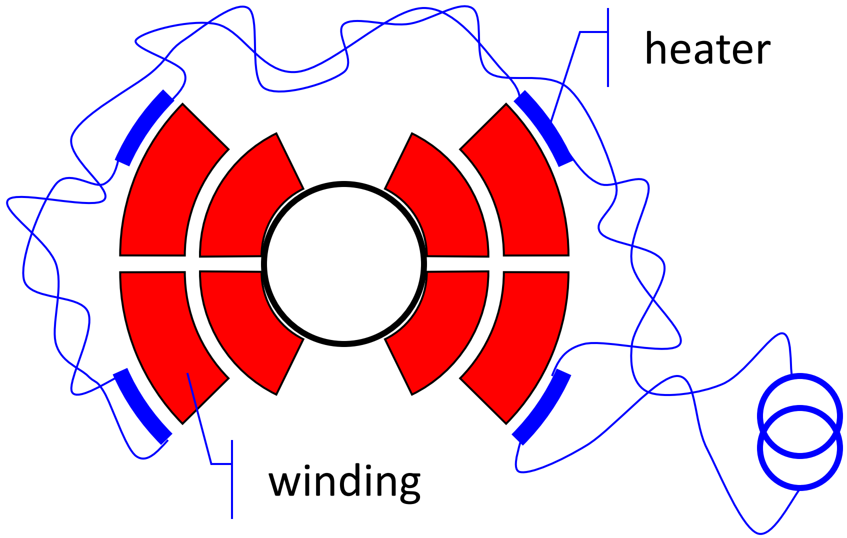
- magnet strings (e.g. accelerator magnets, fusion magnetic systems) have exceedingly large stored energy (10's of GJ):
    - energy dump takes very long time (10…100 s)
    - the magnet string is *subdivided* and each magnet is by-passed by a diode (or thyristor)
    - the diode acts as a shunt during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