Aspects of quench detection and protection for HTS

T. Mulder

Lectures on Superconducting Magnet Test Stands, Magnet Protections and Diagnostics

“HTS magnets are super stable, the magnet will not quench. No need for quench protection.”

“Non-insulated magnets are self-protected, current will just bypass the resistive area.”

~~“HTS magnets are super stable, the magnet will not quench. No need for quench protection.”~~

~~“Non-insulated magnets are self-protected, current will just bypass the resistive area.”~~

Introduction

Before quench protection:

(ReBCO) HTS conductor,

Insulated HTS magnets,

Non-insulated HTS magnets,

Magnet operation and behavior.

Protection starts with proper design and operation.

Quench protection:

Detection techniques.

Protection techniques.

Quench protection recipes for I and NI HTS coils.

Thanks to M. Wozniak from whom I copied some slides.

HTS Performance

1G HTS: BSCCO 2212 (round) & 2223 (tape)

2G HTS: ReBCO (tape)

→ Ceramic, but bendable, solderable & no heat treatment required.

(Picture courtesy of ACT)

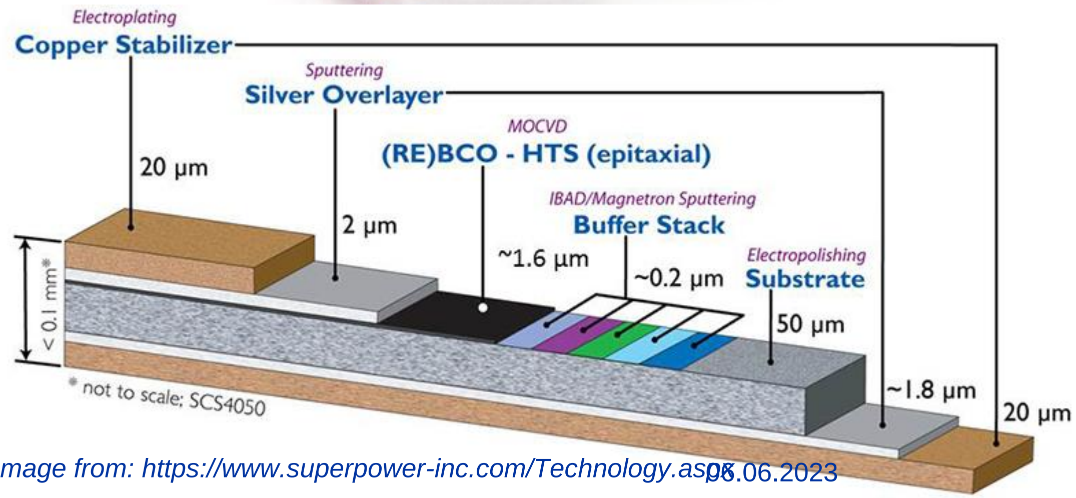
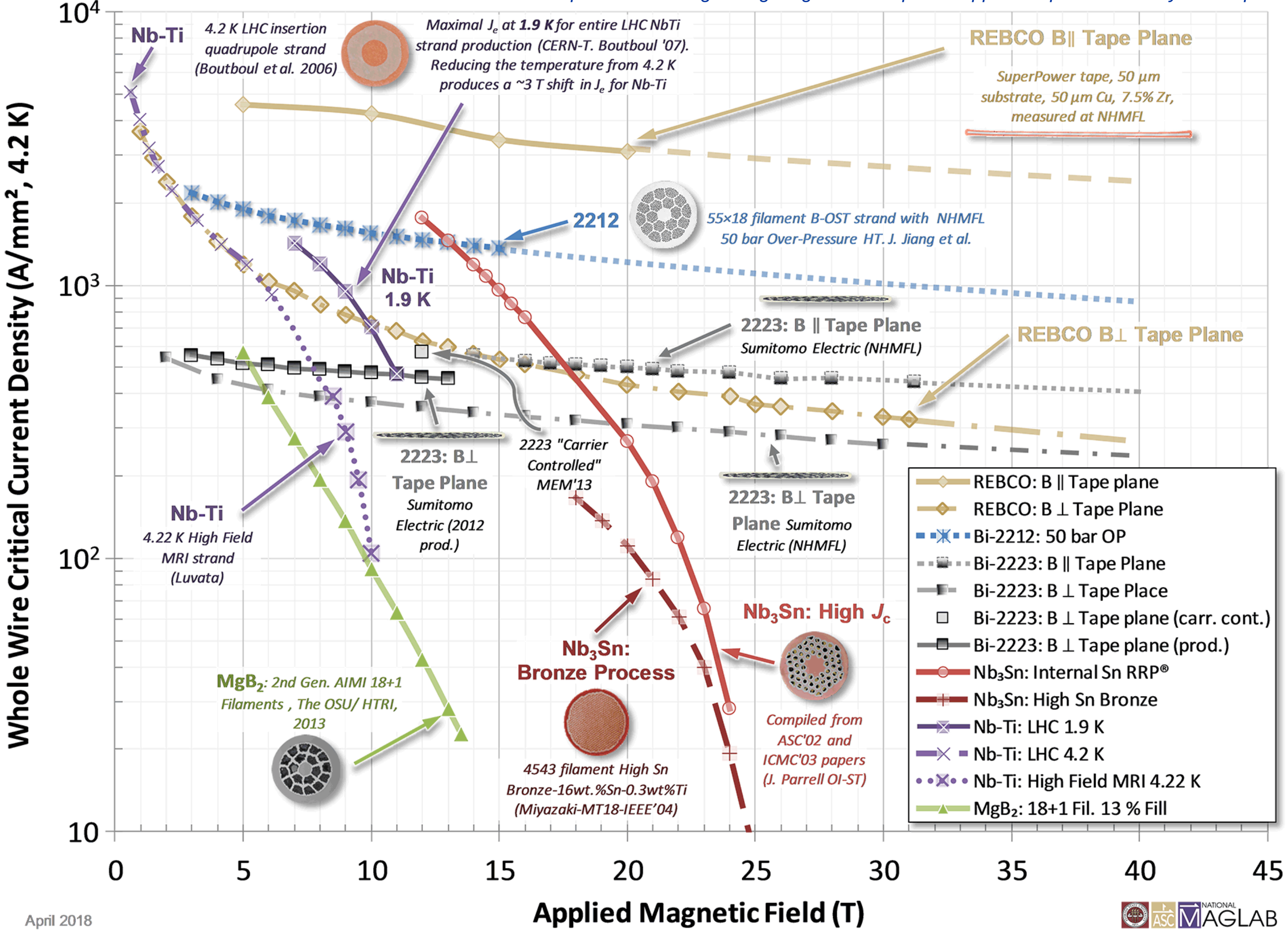
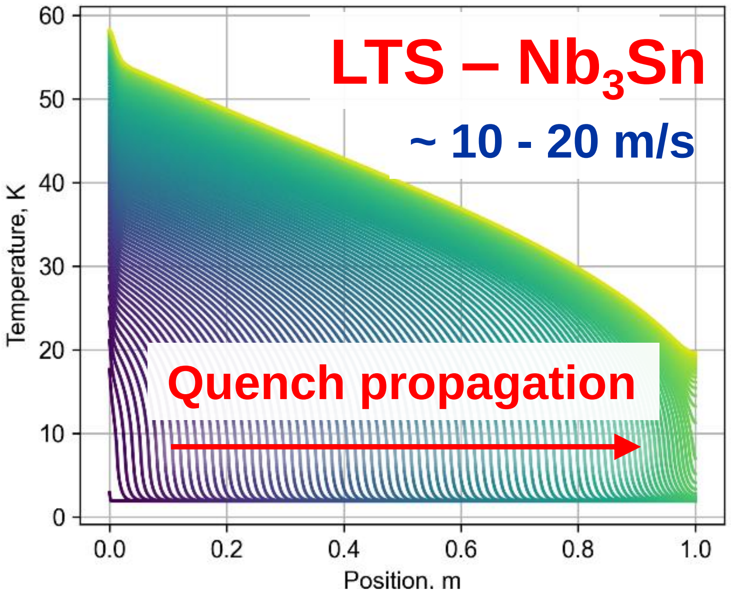


Image from: https://www.superpower-inc.com/Technology.aspx

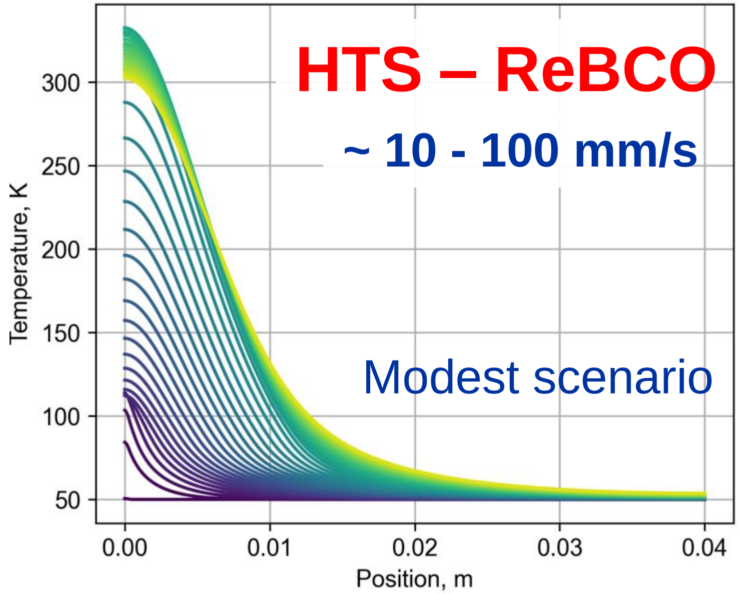
https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

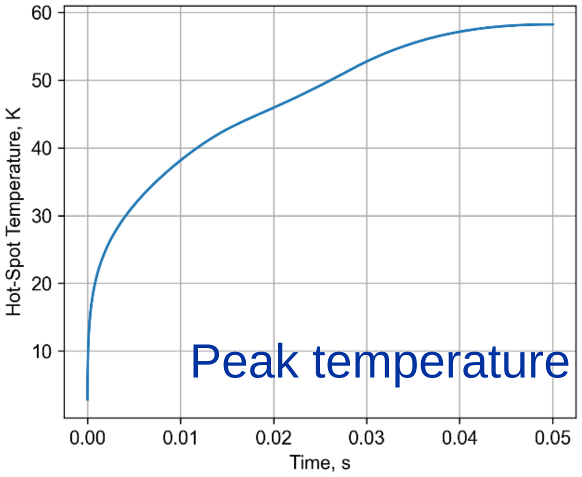


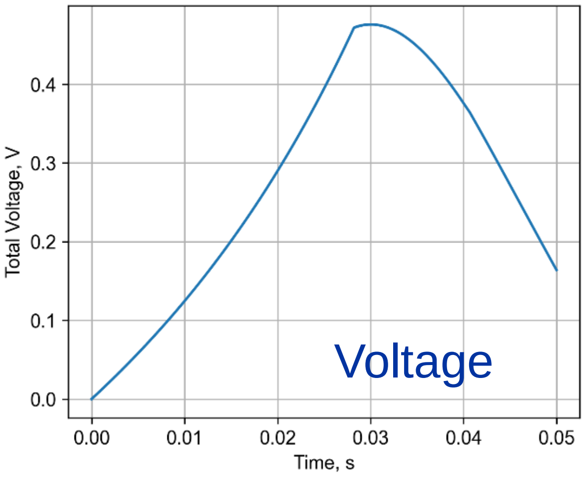
Normal-Zone Propagation: LTS vs. HTS

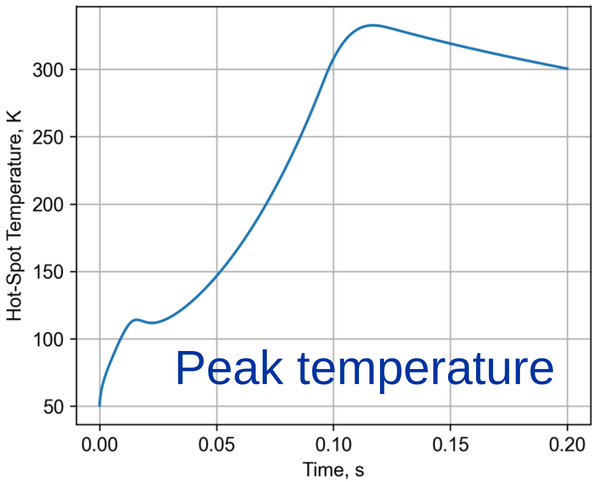


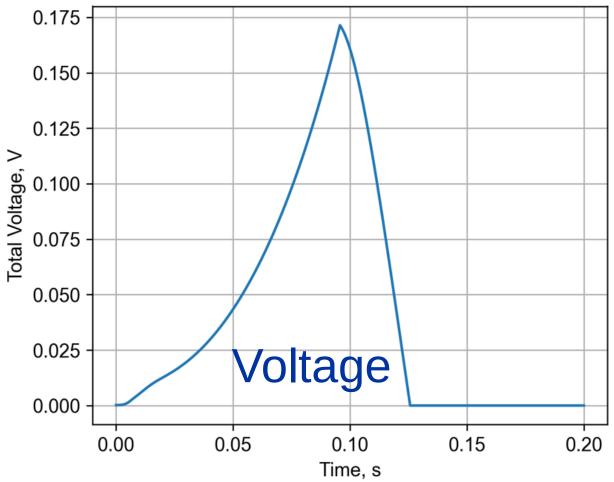
$V_{detection}$ = 0.1 V
t_{delay} = 20 ms











*should be avoided in a real magnet

Dissipation of the Stored Energy

Magnet stored energy: $E = \frac{1}{2} L I^2$ (Often in the kJ to many MJ range,
energy density of a few kJ/kg to some tens of kJ/kg)

When a magnet quenches -> energy dissipated in the resistive region.

→ Larger resistive region, better distribution of dissipated energy + higher resistive voltage.

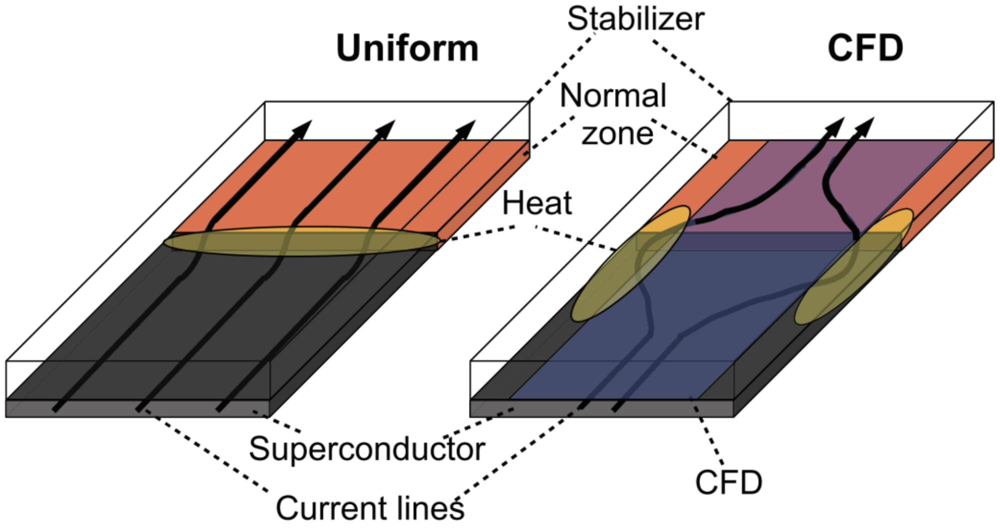
Large NZPV in LTS magnets.
Possibility of a self-protected magnet.

Low NZPV in HTS magnets.
No possibility of a self-protected insulated magnet.

HTS resistive region doesn’t grow fast enough!

Are there ways to speed up the NZPV?

Normal-Zone Propagation: LTS vs. HTS



- ✓ **The current flow diverters** also belong to this category [1, 2]
- ✓ They are very effective at speeding up the NZPV and reducing the time constant τ and reducing T_{max}

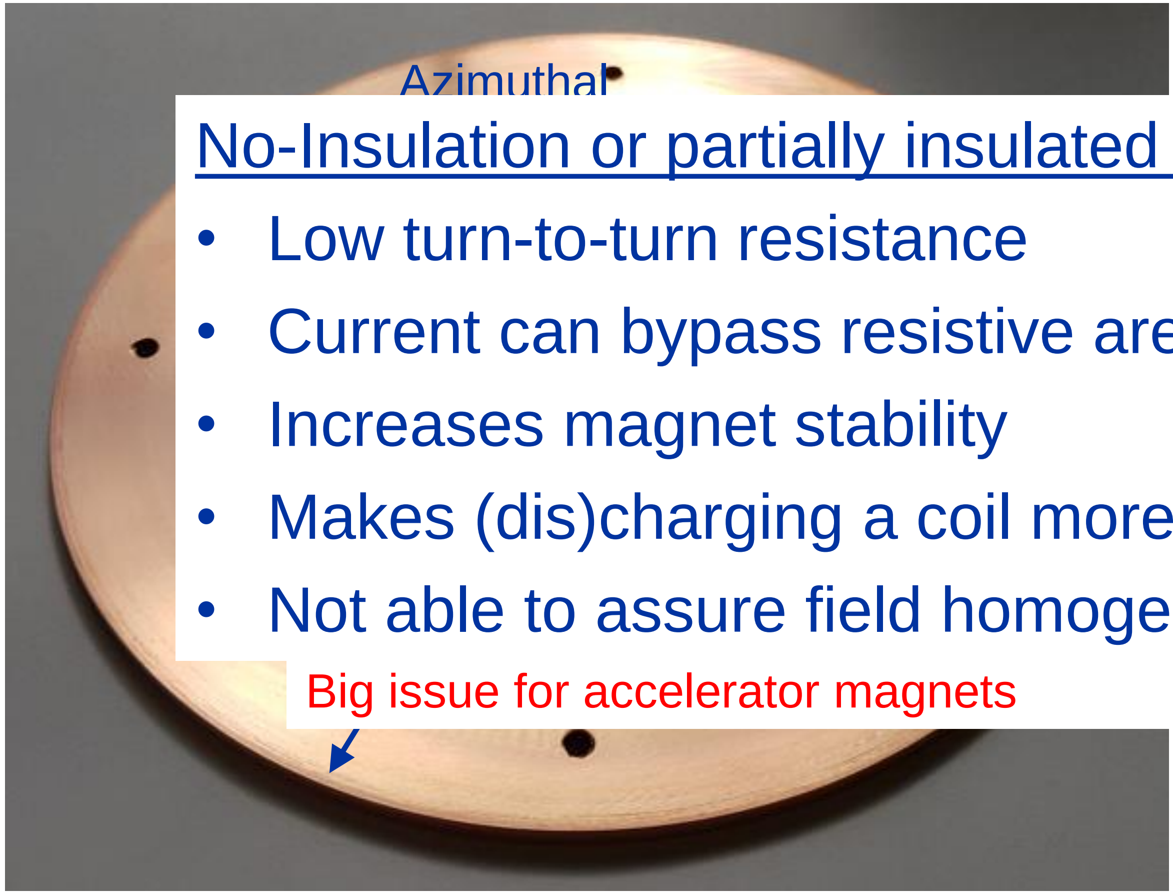
$$\int_0^\infty J^2(t)dt = \int_{T_{op}}^{T_{max}} c_v\,(T)/\rho(T)dT \;= F(T_{max})$$

- ✓ This helps with distributing the stored energy in the coil structure.
- ✓ This is completely passive system, very attractive indeed!
- ✓ But, it requires tape modification or a dedicated manufacturing process ($$$).

[1] Christian Lacroix, et al. Supercond. Sci. Technol. 27 (2014) 055013 (6pp)
[2] Frederic Sirois, presentation at HiTAT, CERN, 2023.

No-Insulation (NI) HTS Coils

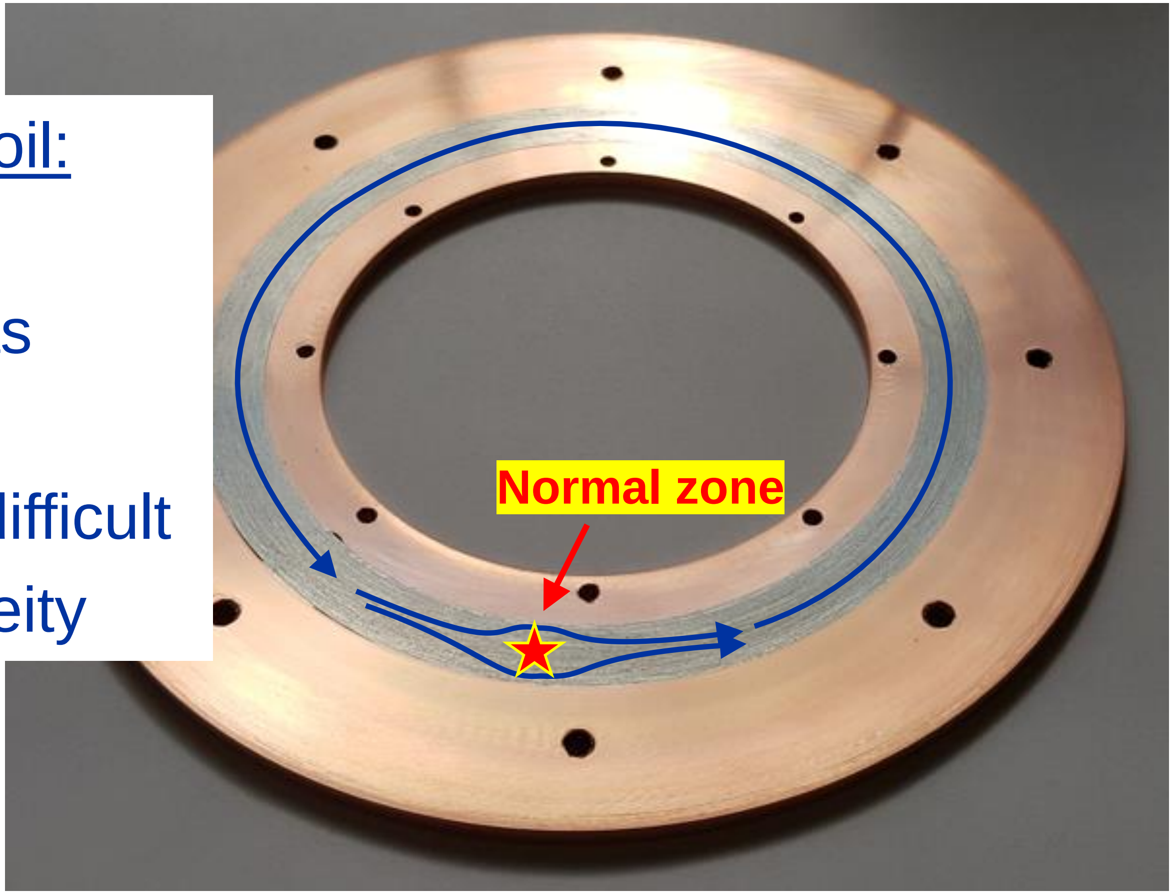
Parallel path for the current around a normal zone.



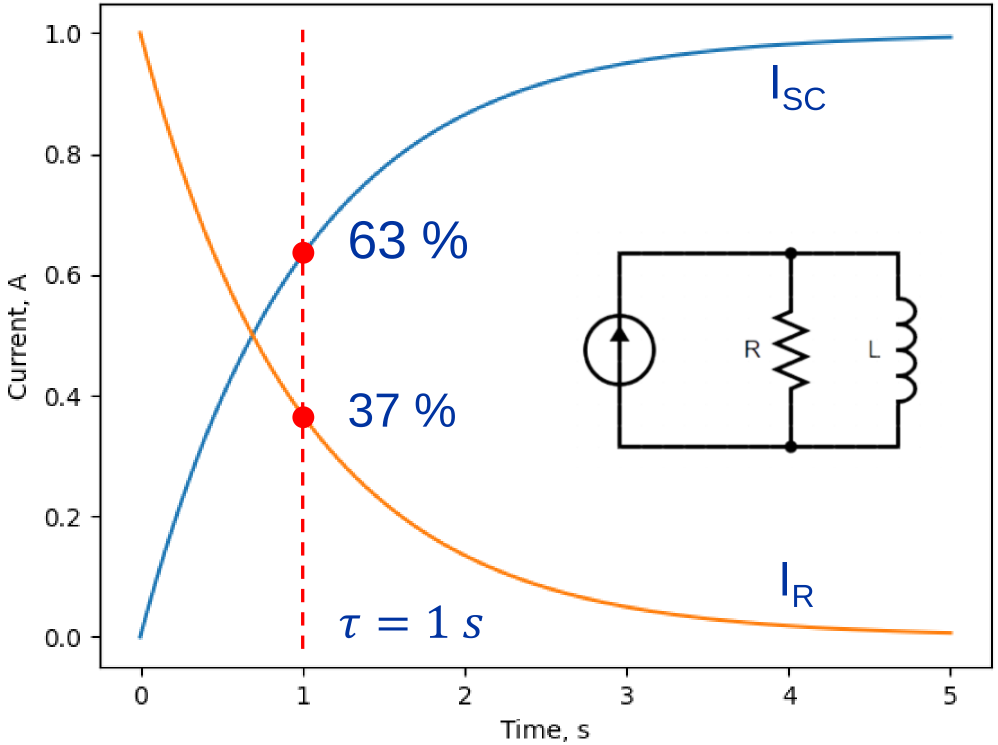
No-Insulation or partially insulated coil:

- Low turn-to-turn resistance
- Current can bypass resistive areas
- Increases magnet stability
- Makes (dis)charging a coil more difficult
- Not able to assure field homogeneity

Big issue for accelerator magnets



NI Coil operation



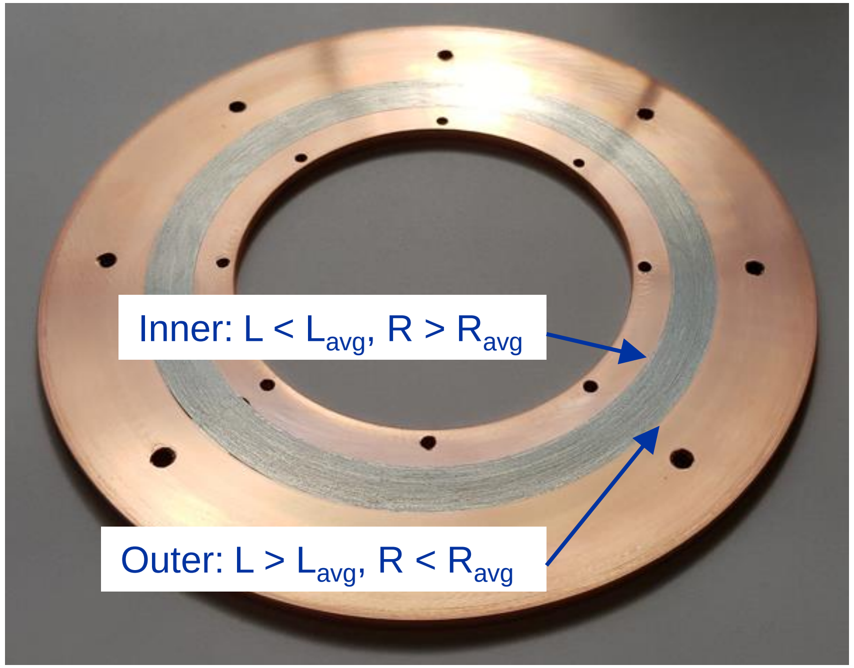
~5 times τ to get current in a NI coil!

$$V = I_r * R = I_{sc}R_{sc} + L\frac{dI_{sc}}{dt}$$

Time constant: $\tau = \frac{L}{R}$ (To fit τ, use the magnetic field data)

Discharge: $I = I_0 e^{-\frac{t}{\tau}} \longrightarrow I = \sum I_n e^{-\frac{t}{\tau_n}}$

Charge: $I = I_0(1 - e^{-\frac{t}{\tau}}) \rightarrow I = \sum I_n(1 - e^{-\frac{t}{\tau_n}})$

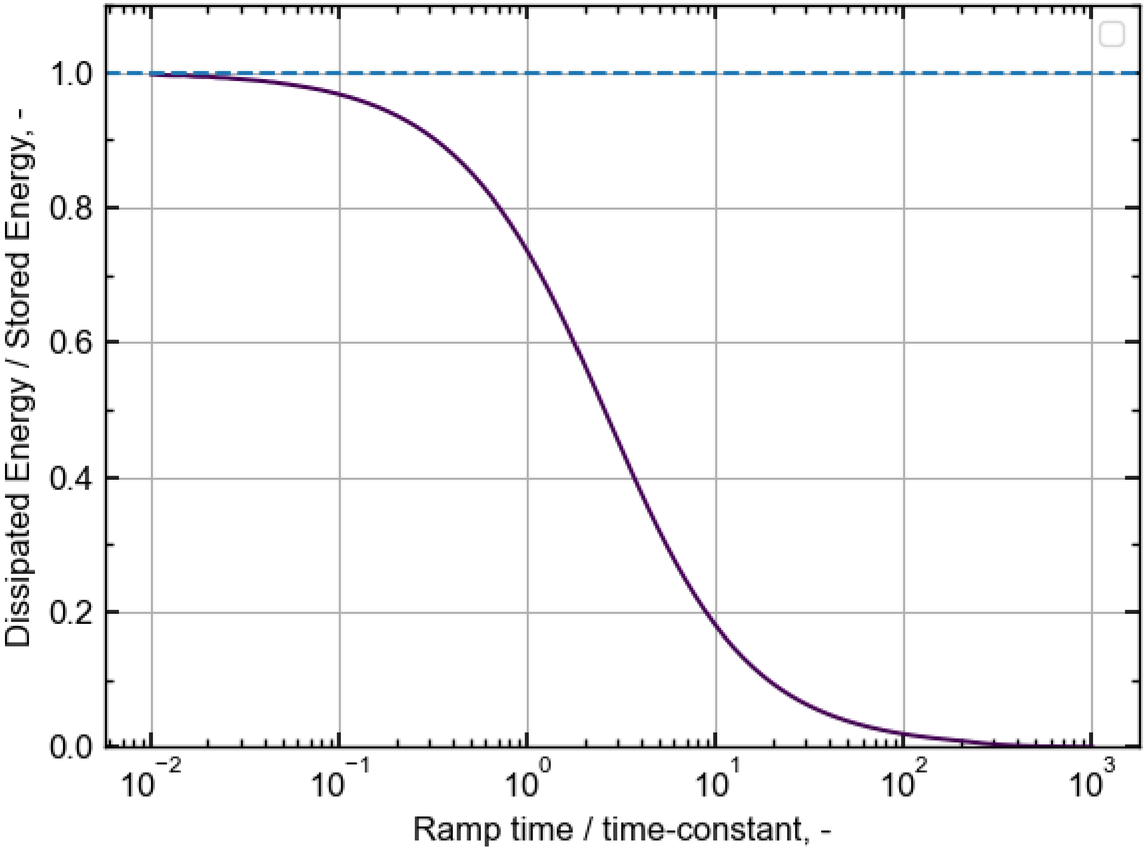


Inner: $L < L_{avg}$, $R > R_{avg}$

Outer: $L > L_{avg}$, $R < R_{avg}$

Stability during ramp & operation

$$V = \underbrace{I_r * R}_{\text{Dissipates heat}} = I_{sc}R_{sc} + L\frac{dI_{sc}}{dt}$$



Amount of heat dissipated during ramp:

t_{ramp} = 0.1 τ = 0.97 * E_{stored} at I_{op}
t_{ramp} = 1.0 τ = 0.74 * E_{stored} at I_{op}
t_{ramp} = 10 τ = 0.18 * E_{stored} at I_{op}
t_{ramp} = 100 τ = 0.02 * E_{stored} at I_{op}

During ramp (important when cooled by cryocooler):

Higher R -> lower τ -> allows you to ramp faster
Lower R -> larger τ -> ramp slower

However, during operation:

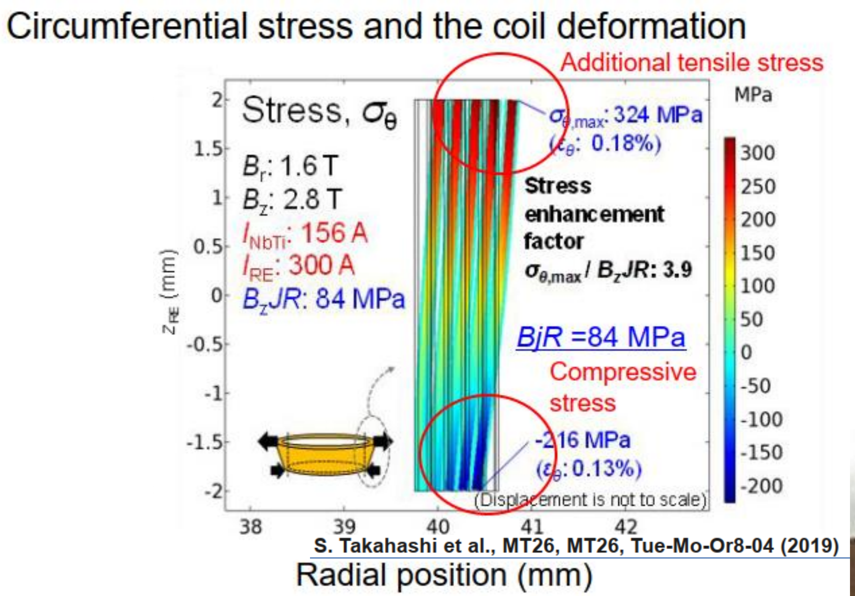
Lower R -> less heat dissipation in case of a defect
Thus, improved stability, slower runaway, more time to react.

What τ is better in case of a quench??

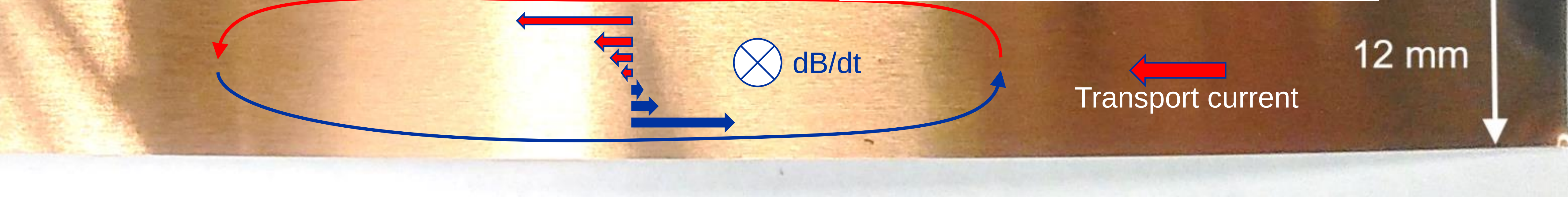
Screening currents

- LTS twisted filament: screening currents, AC-loss & time-constants well known.
- HTS (wide) tapes: no twisting, not transposed, large aspect ration results in large screening currents, effects:
- Affects magnetic field.
- Lorentz forces -> stress.
- AC loss -> heat.

Circumferential stress and the coil deformation

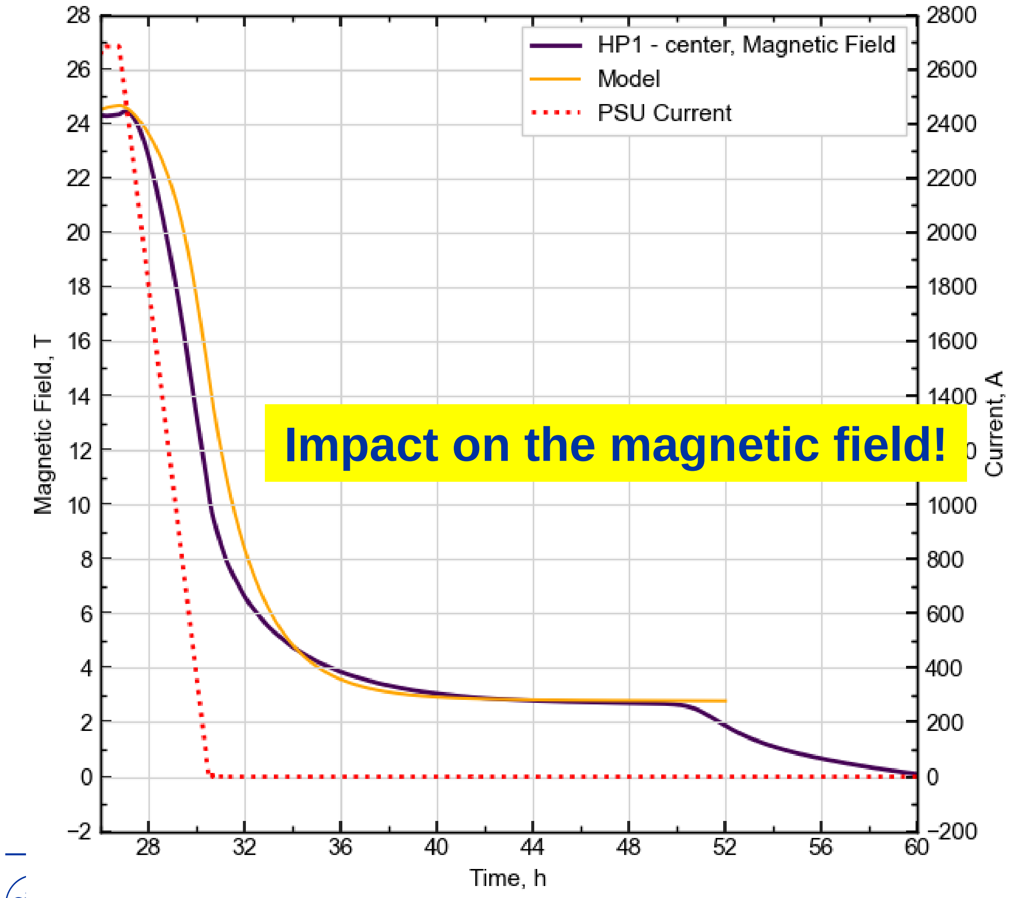


S. Takahashi et al., MT26, MT26, Tue-Mo-Or8-04 (2019)

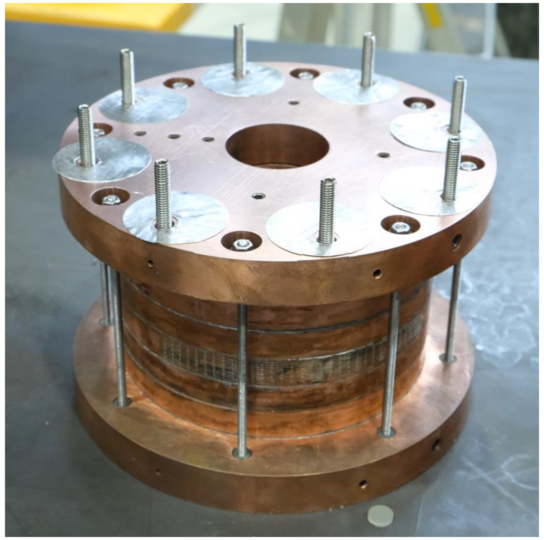


Screening currents

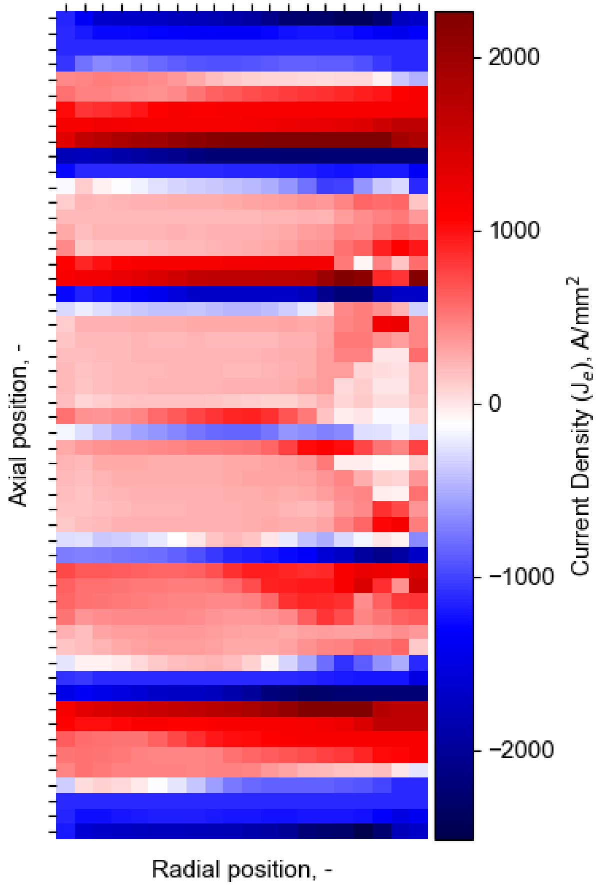
Practical example: LHe test of a NI coil comprising 6 pancakes.



Impact on the magnetic field!



More info: https://www.tokamakenergy.co.uk/



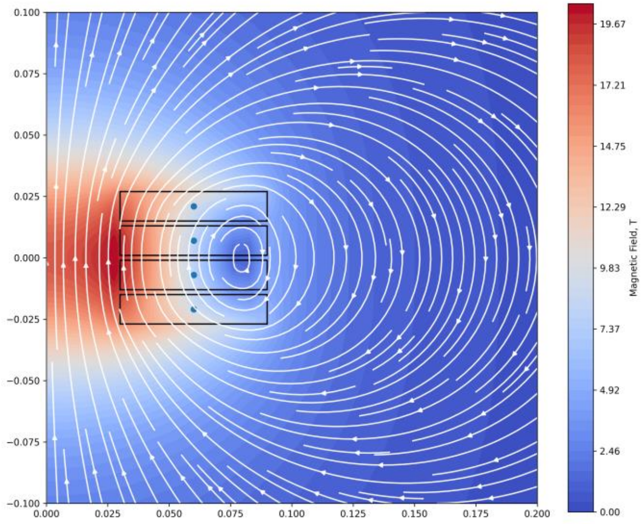
Free 3 T ! Just from screening currents, but…
it reduces the peak field after ramp-up.

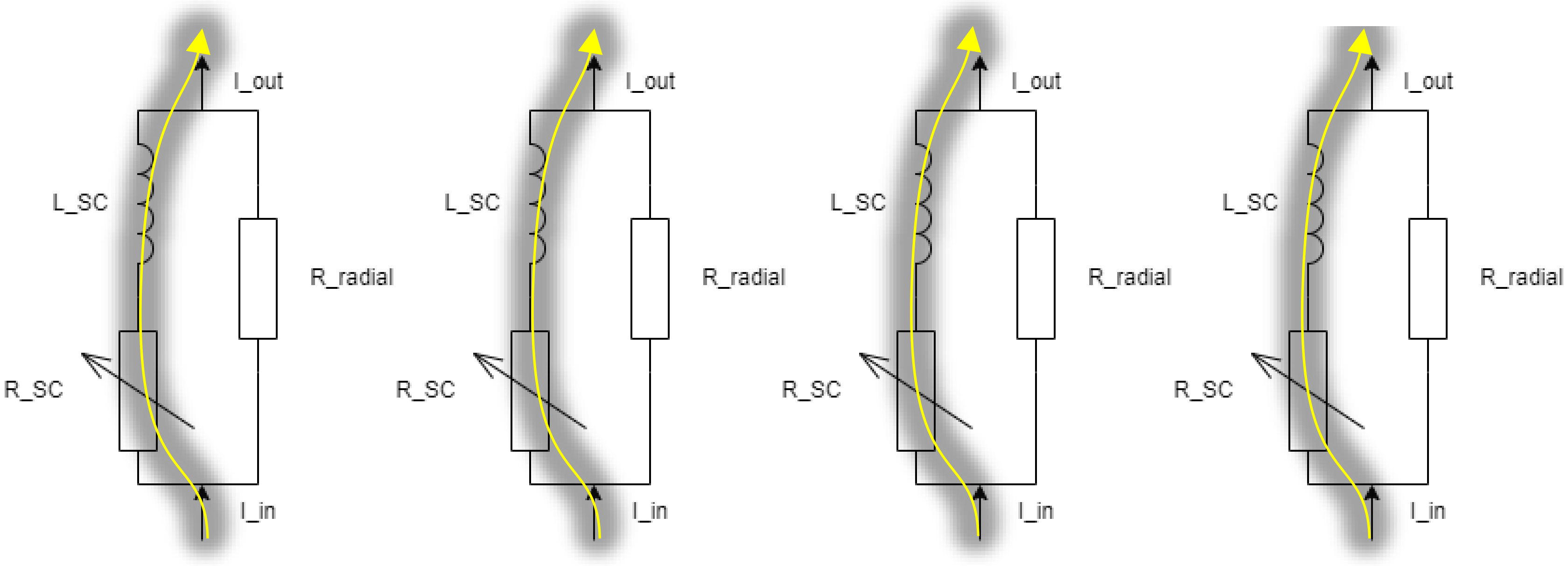
Quench propagation in NI coils

1) Classic thermal quench propagation:

- Slow thermal runaway.
- Happens when $I \ll I_c$ & stored energy is low.
- Stored energy dissipated in the coil.
- Current in the turn-to-turn resistance keeps on heating.

What happens during a thermal quench?





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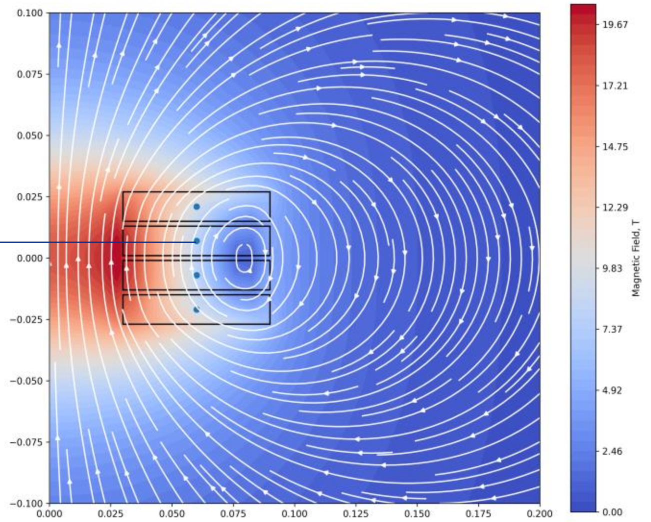

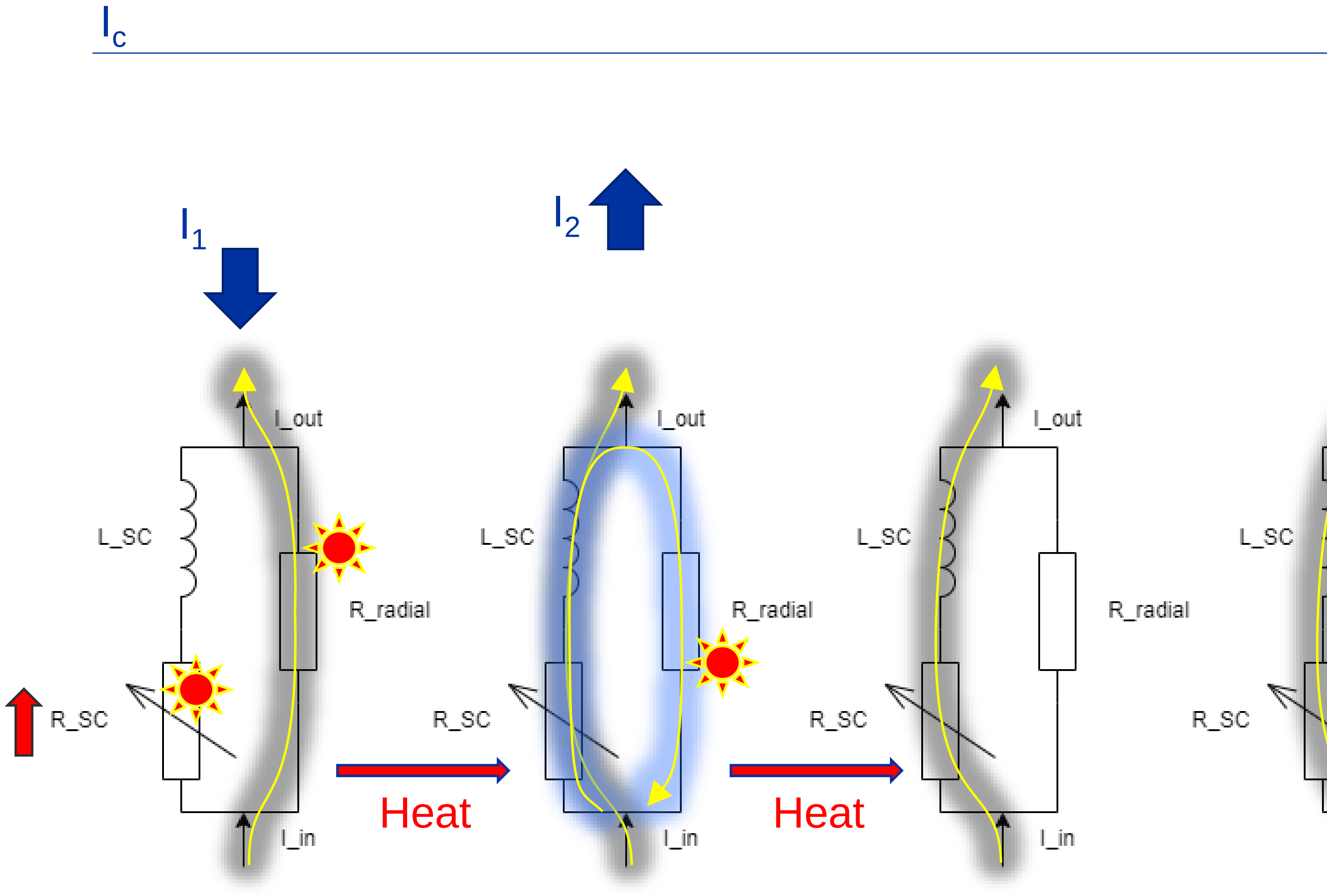

Quench propagation in NI coils

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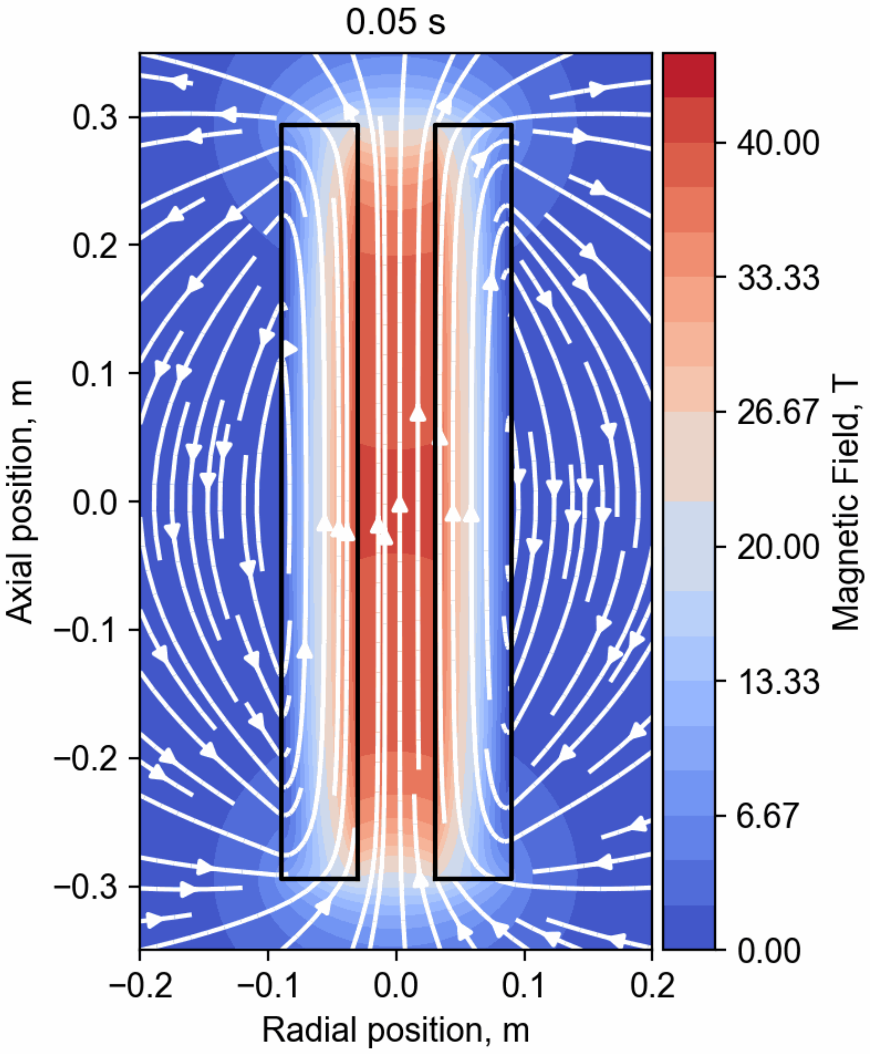
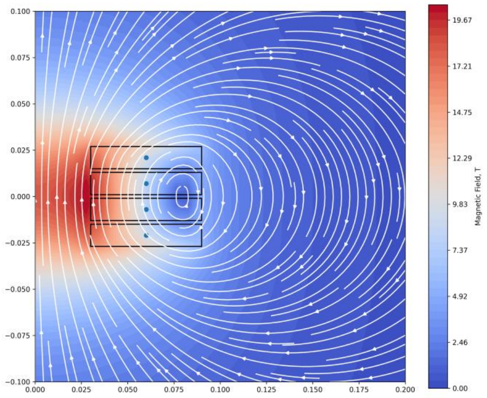
2) Inductive quench propagation: (magnetic pumping)

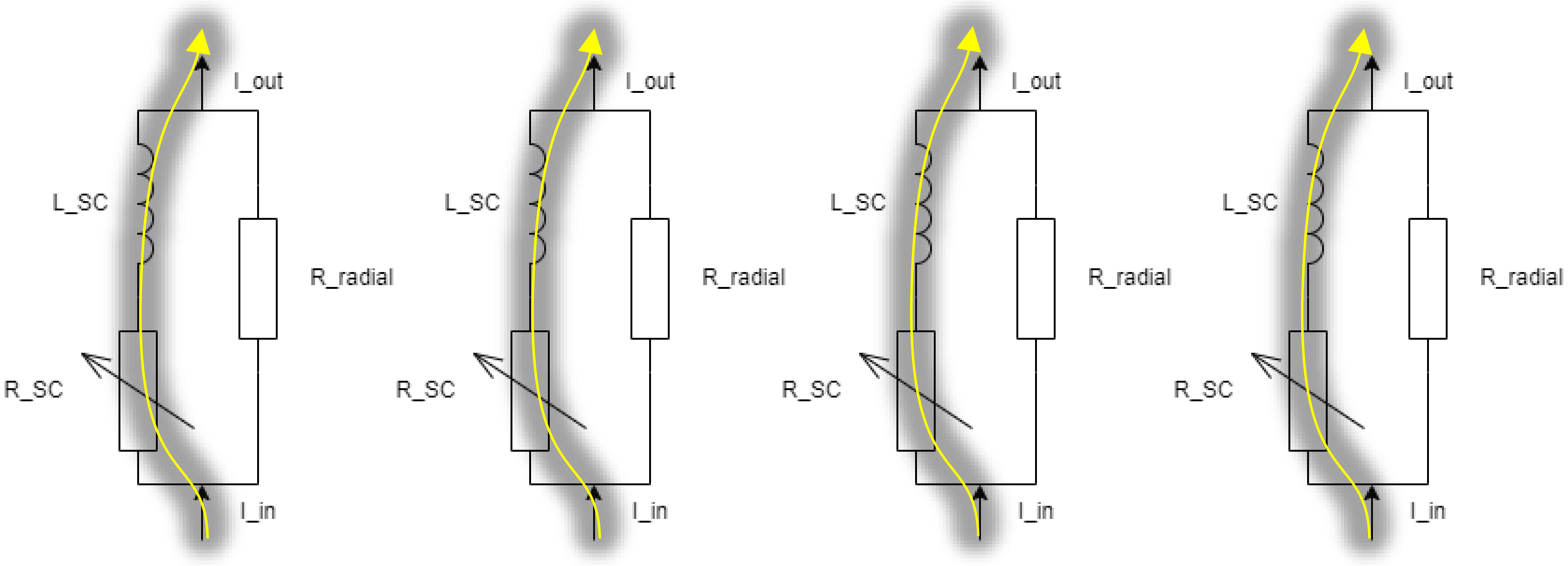
- Happens when I < I_c, commonly when the energy density is large.
- Slow thermal runaway.
- Stored energy dissipated, part of the current/energy is displaced.
- Adjacent turns reach I_c due to the displaced current and quench.

Example: 40 T NI coil quench:



So what happens during an inductive quench?





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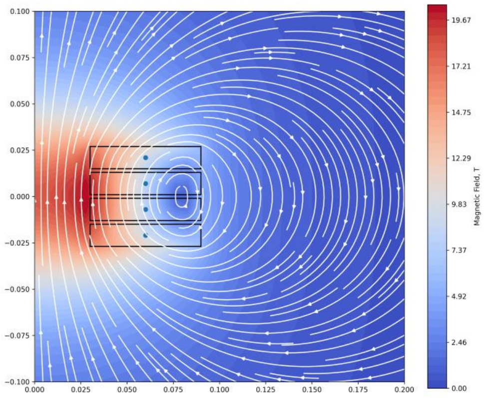

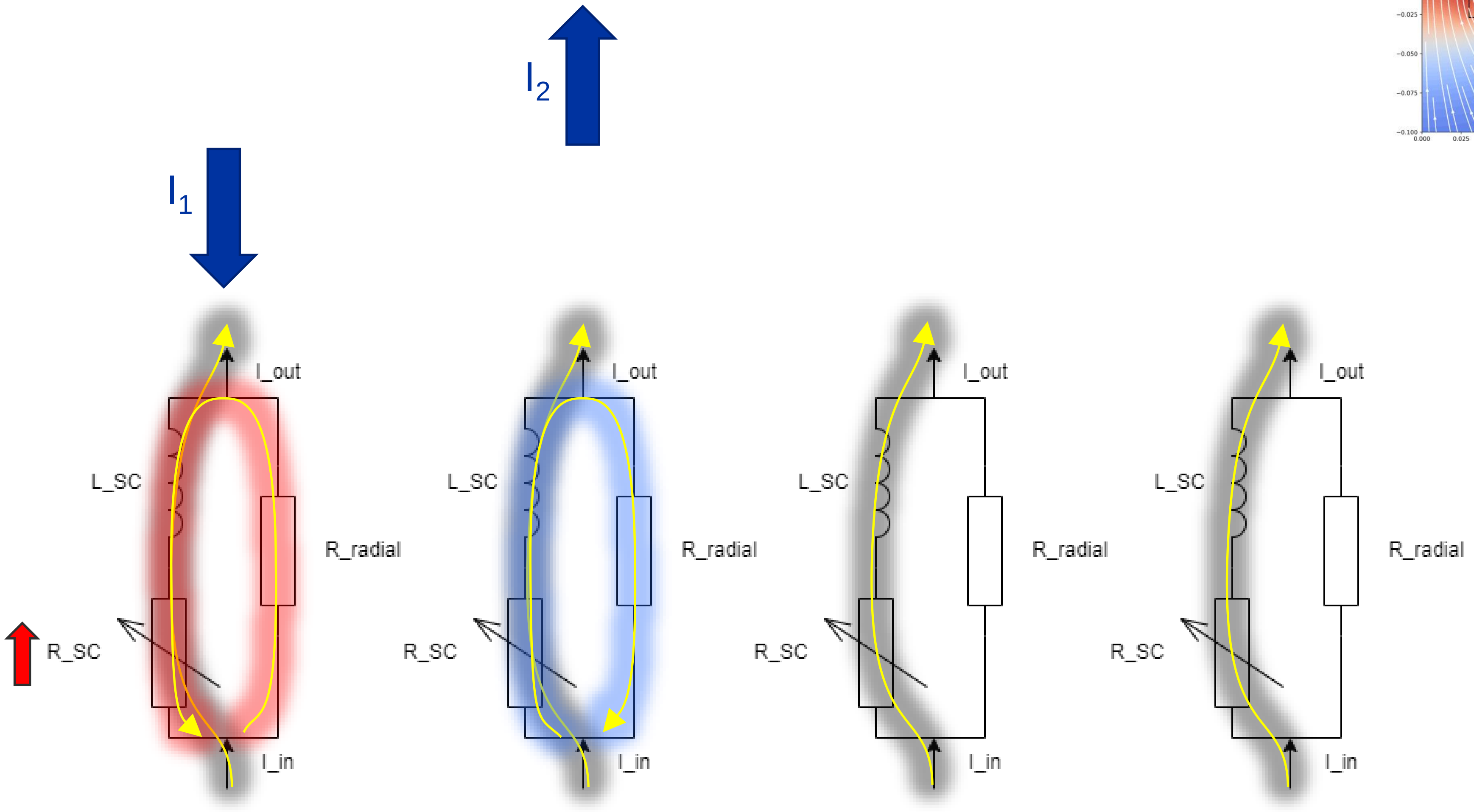

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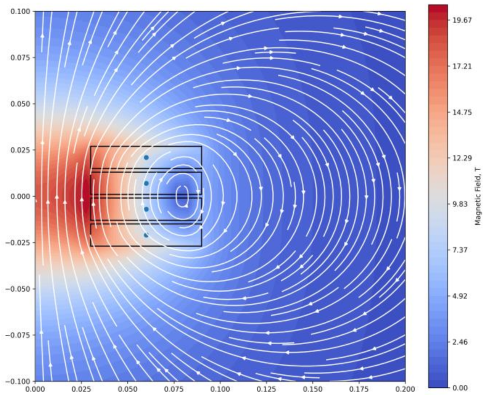

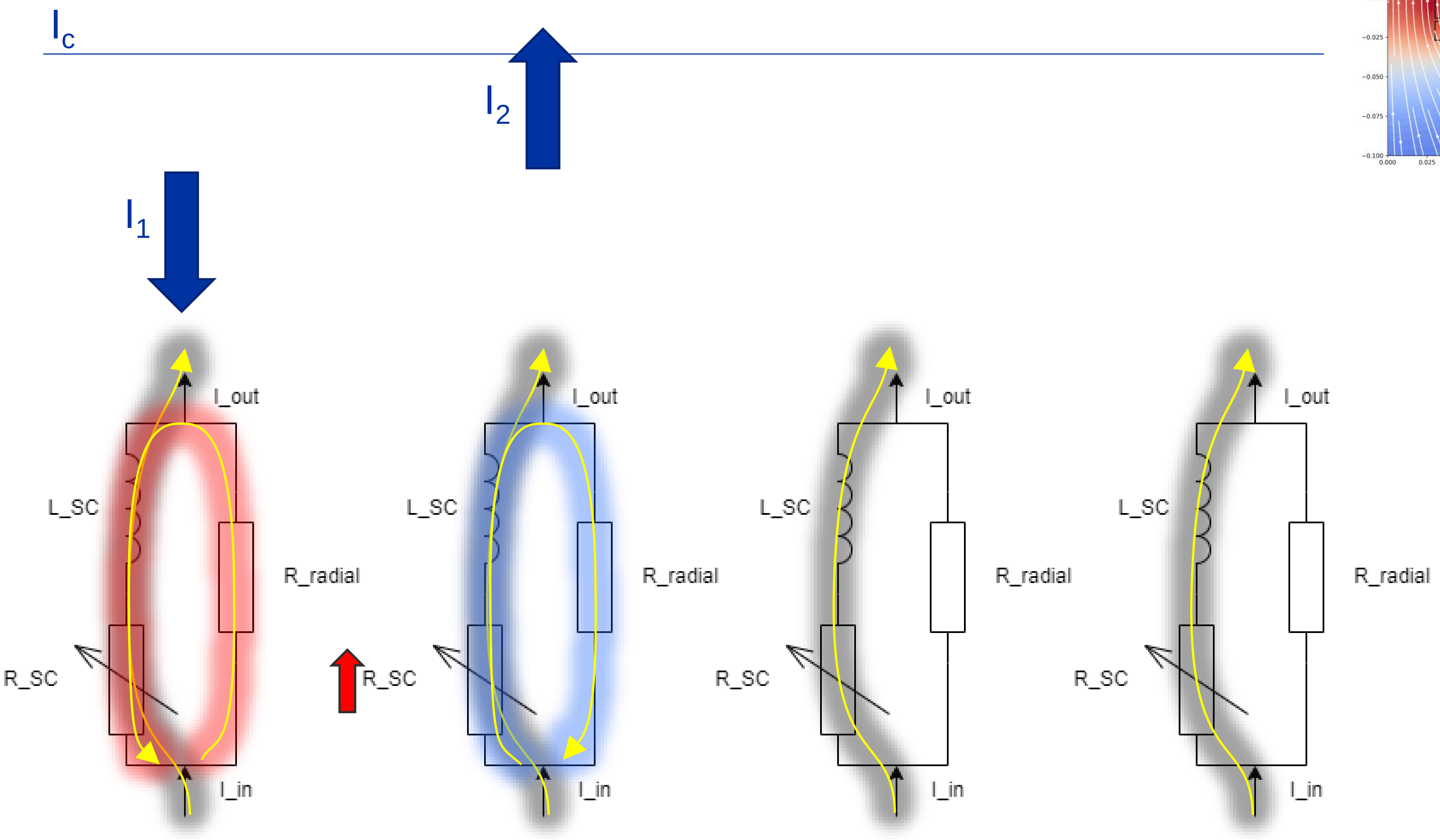

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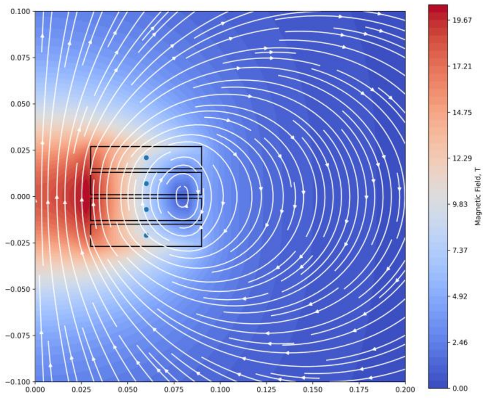

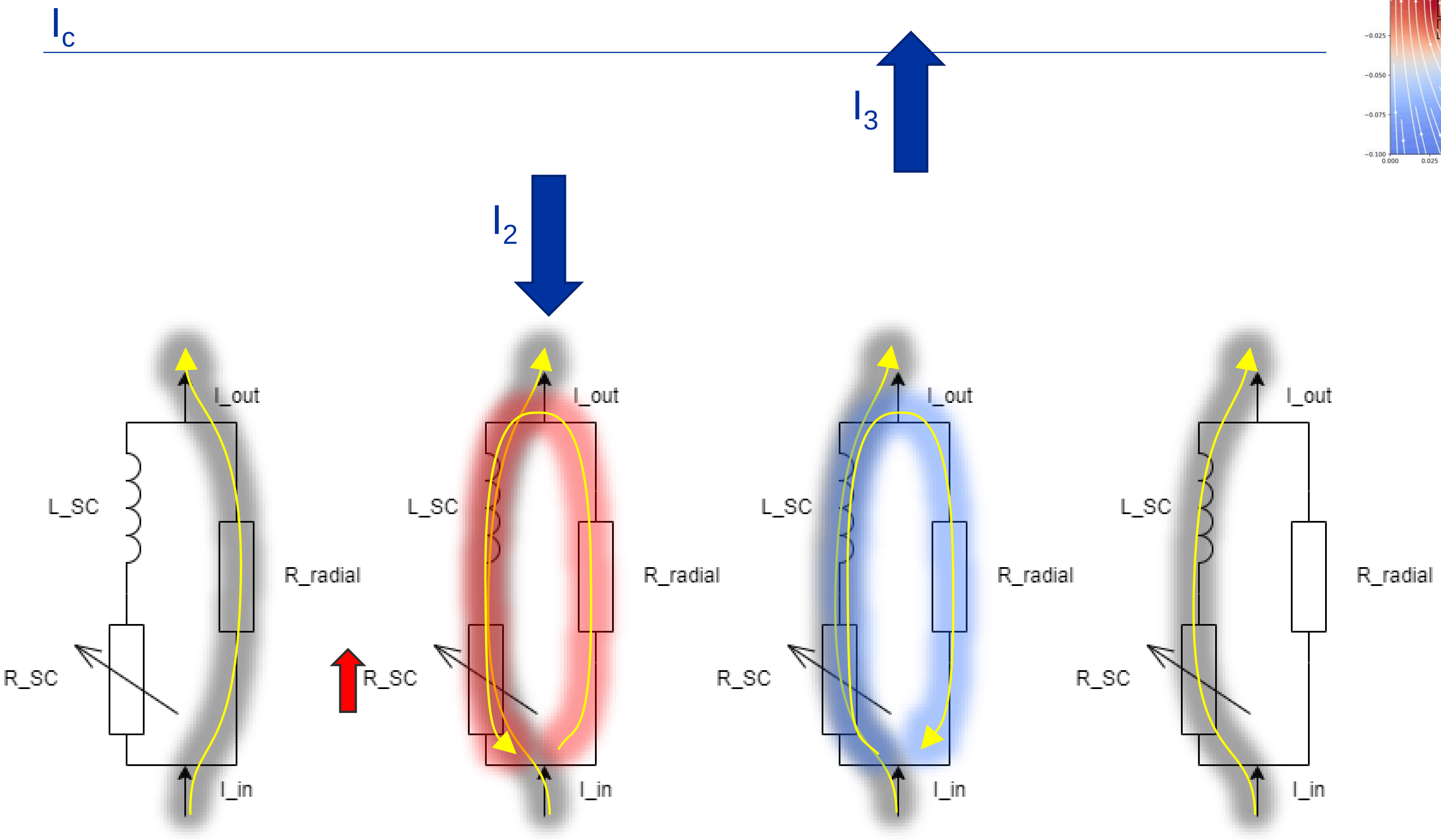

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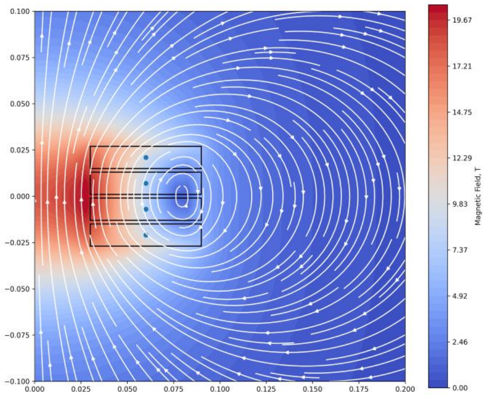
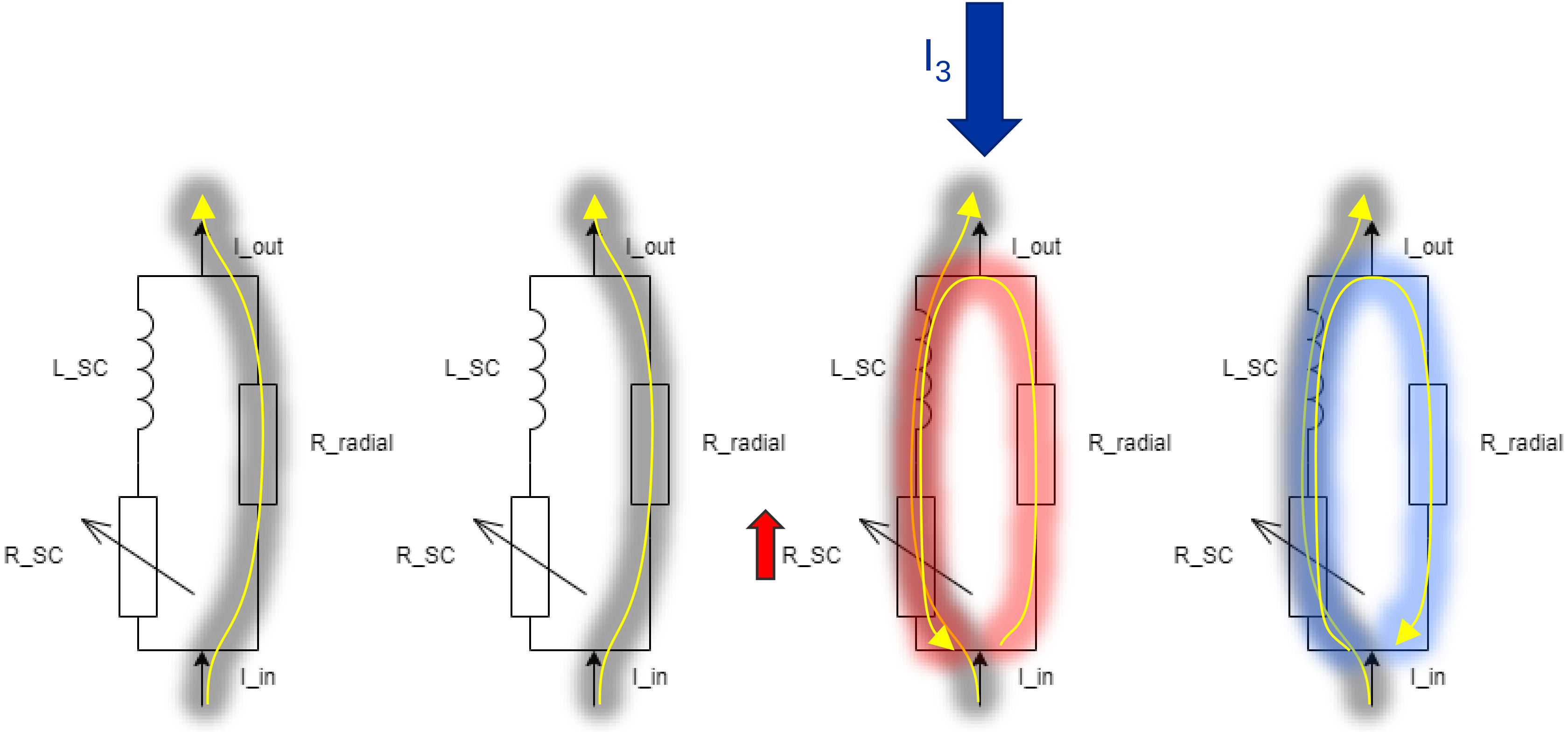


I_c

I_4



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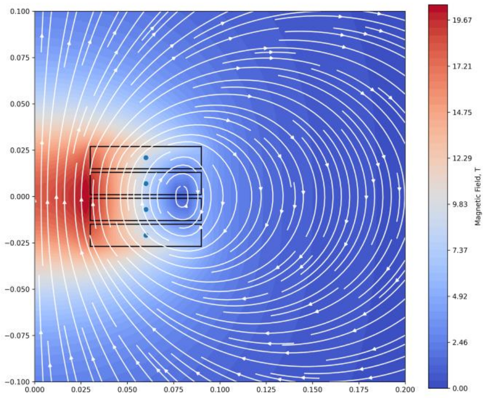

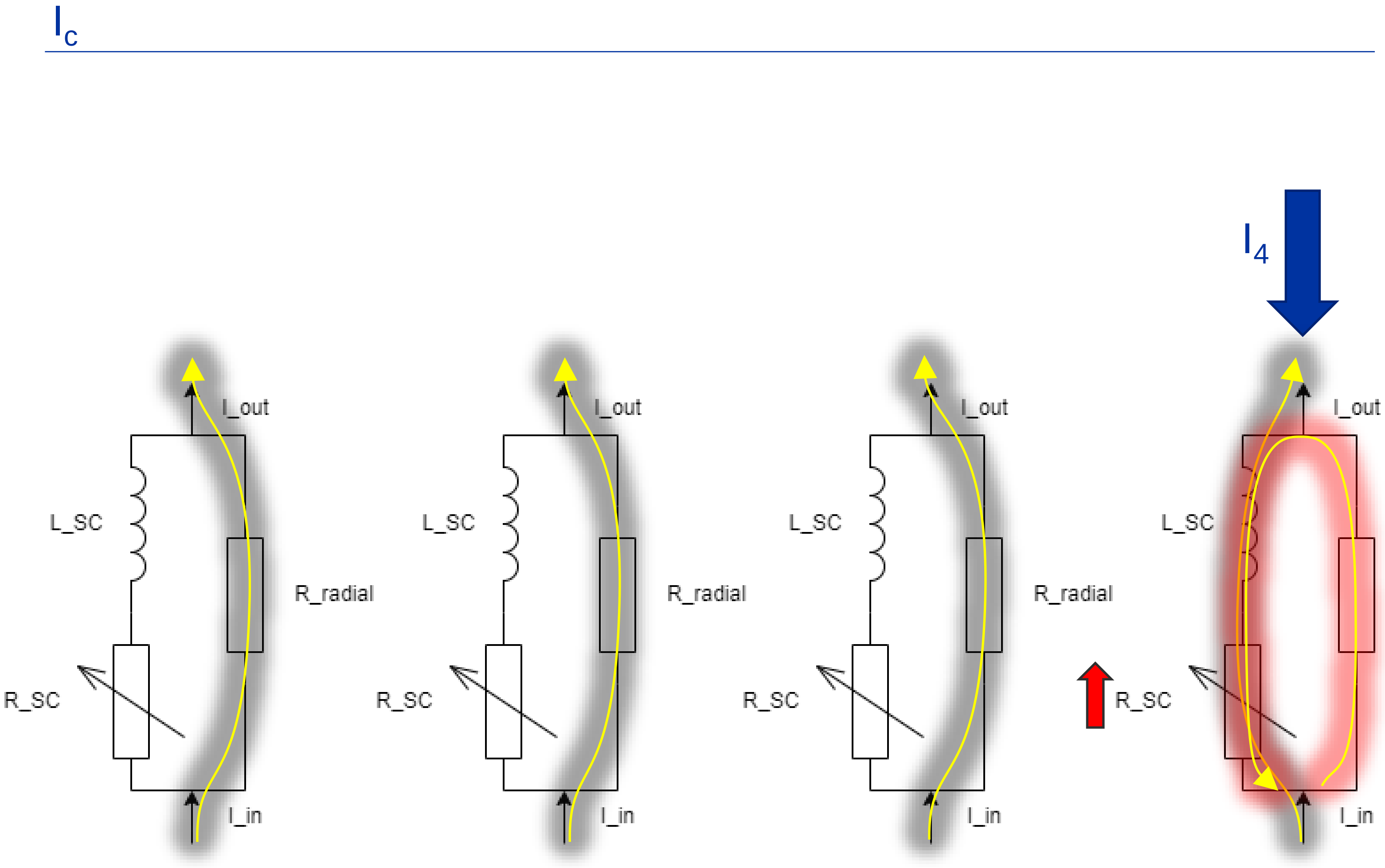

Energy cannot be displaced further.

Most energy dissipated in the extremities.

Quench propagation in NI coils

1) Classic thermal quench propagation:

- Slow thermal runaway.
- Happens when $I << I_c$ & stored energy is low.
- Stored energy dissipated in the coil.
- Current in the turn-to-turn resistance keeps on heating.

2) Inductive quench propagation: (magnetic pumping)

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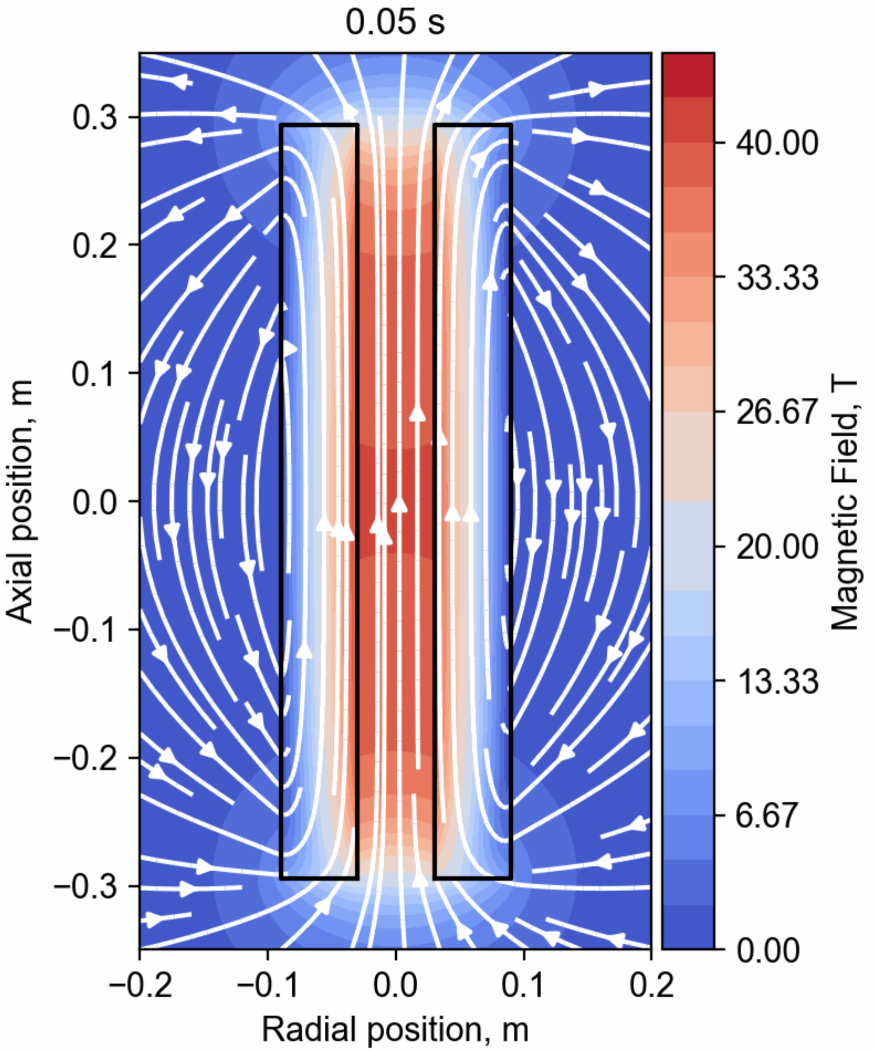
- Happens when $I < I_c$, commonly when the energy density is large.
- Stored energy dissipated, part of the current/energy is displaced.
- Adjacent turns reach I_c due to the displaced current and quench.

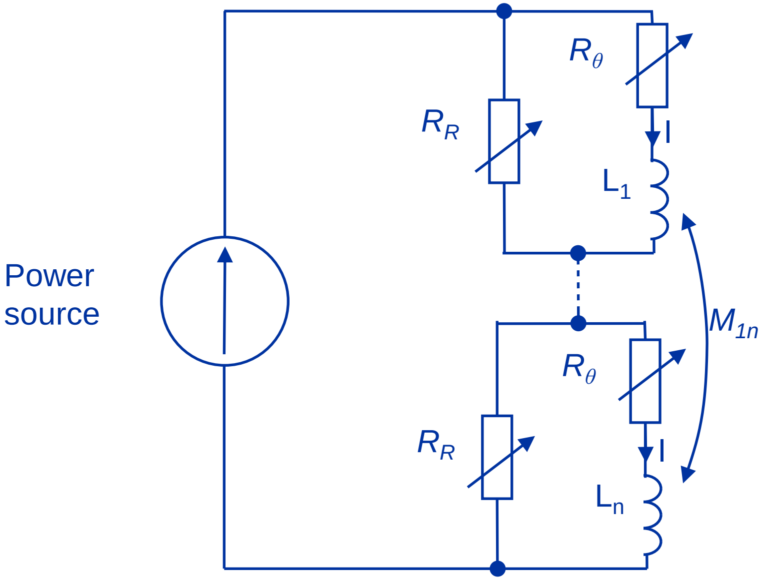
Fast NZP, magnet quenches completely! Good?

Issues: Mechanical forces and displaced energy.

Example: 40 T NI coil quench:



Energy Displacement in NI Coils



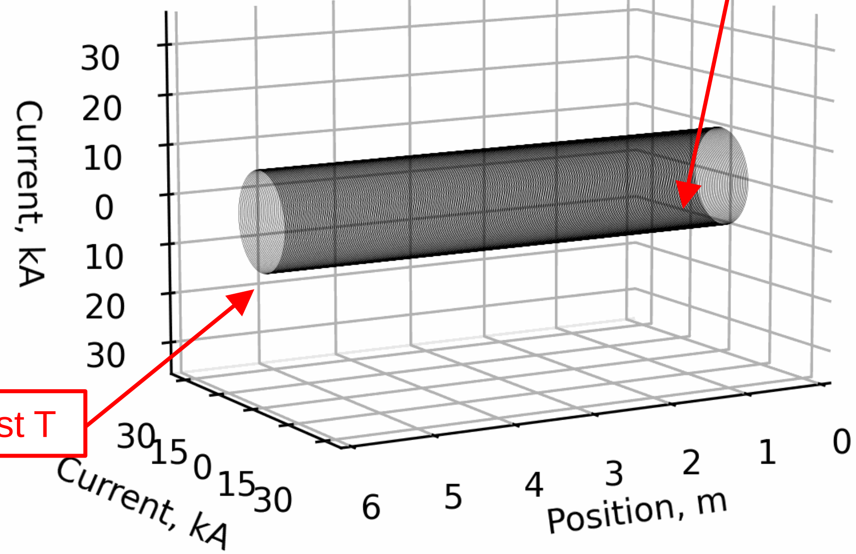
- ✓ Coils in the stack are mutually coupled, turns are mutually coupled.
- ✓ A decrease of current in one coil causes increase of current in the others.
- ✓ This leads to magnetic pumping and **redistribution of energy density and force density.**
- ✓ One needs to be careful in limiting the deposited magnet energy or over-stress in the pancake that **quenches last**.

Non-insulated

Example: AMS-100

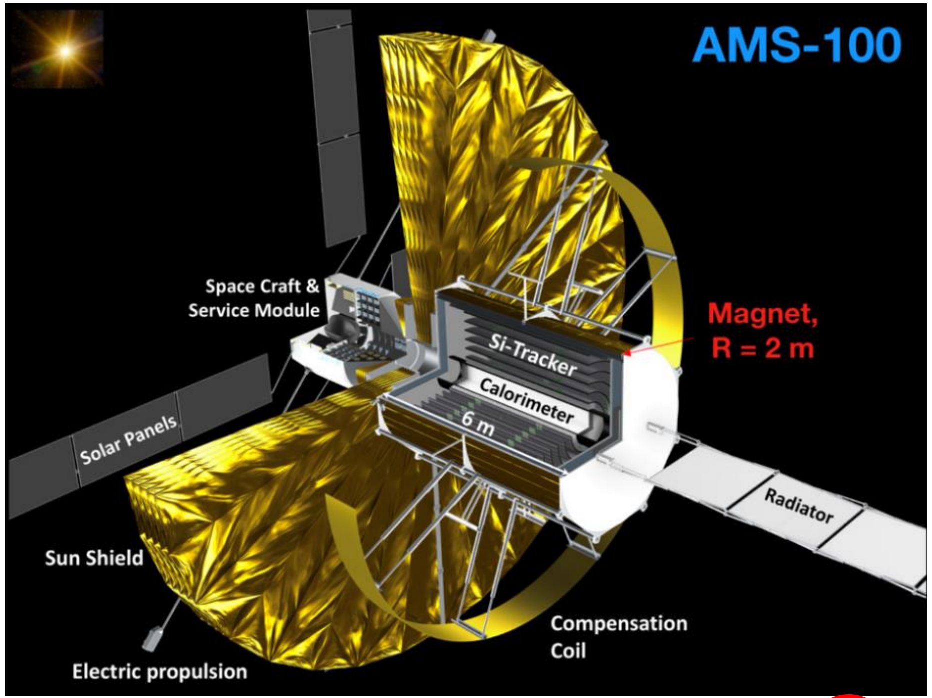
t = 0.06 s

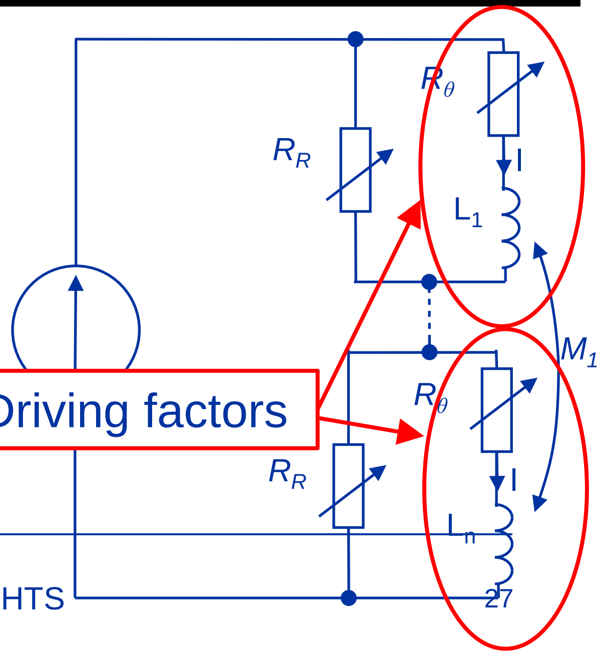
Simulated current during a quench:



Quench position

Highest T





Driving factors

- ✓ Large thin-walled solenoid of 6 m long and a diameter of 4 m.
- ✓ Main solenoid: 14.3 MJ of stored energy and an energy density of 14 kJ/kg.

Time constant minimal influence on the quench behavior, when τ >> quench time.
Larger time constant helps with magnet stability.

Non-insulated

Insulated magnets

Mechanical limits of HTS Coils

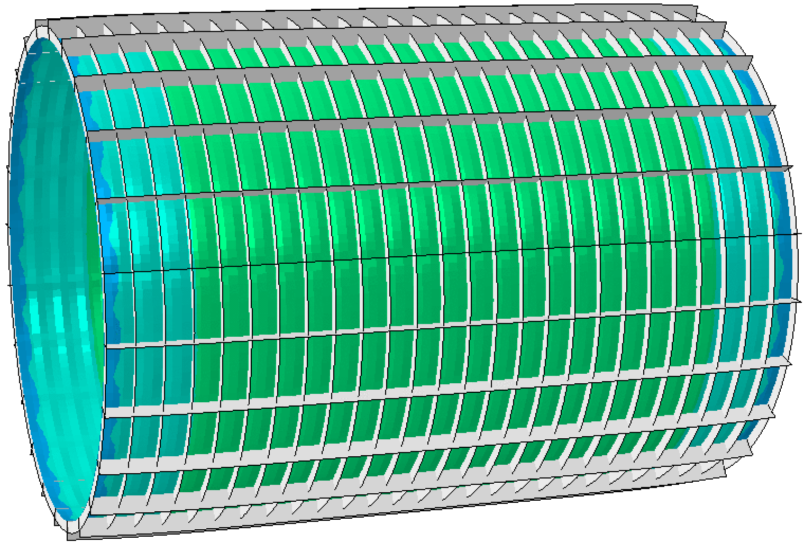
Lorentz force is given by: $F = IL \, x \, B$

Insulated magnets: $F_{max} = I_{nom} L \, x \, B_{nom}$

Non-insulated magnets: $F_{max} = I_{max} L \, x \, B_{max}$

Induced currents >> I_{nom} -> local force increases

May locally be several times higher during a quench due to magnetic pumping.



AMS-100, J. Zimmermann & D. Pridöhl, RWTH Aachen

- For magnet survivability, this possible higher force (thus larger stress) must be considered during design.
- Smaller margin to I_c reduces the amount of current that can be induced.

✓ Basics

Quench Protection – Goals and increasing complexity

Quench protection is a technique used to prevent any potential damage to a magnet, its circuitry, and surrounding components, when a portion of the magnet undergoes an irreversible transition to a normal state.
This is achieved by **managing the stored magnetic energy** in a way that mitigates any potential damage.

The scope of “any potential damage” predominantly means:

- **voltages** and **temperature** (in most cases) -> **Nb-Ti**
- **voltages**, **temperatures,** and **conductor level stresses** -> **Nb_3Sn**
- **voltages, temperatures, conductor level stress** and often **superconductor level stress** and for **NI coils,** a potential for a **force density redistribution** -> **YBCO**

✓ Each measure above needs its safe operational range. These are extremely resource intensive to establish, if can be fully established at all.

✓ A proper quench protection analysis of an HTS often exceeds the expertise of a single person and the capabilities of a single software tool. Quench protection of HTS is a multidisciplinary team effort!

Quench Detection

Voltage measurements →
- Soldered wires
- Spring-loaded pins
- Trace

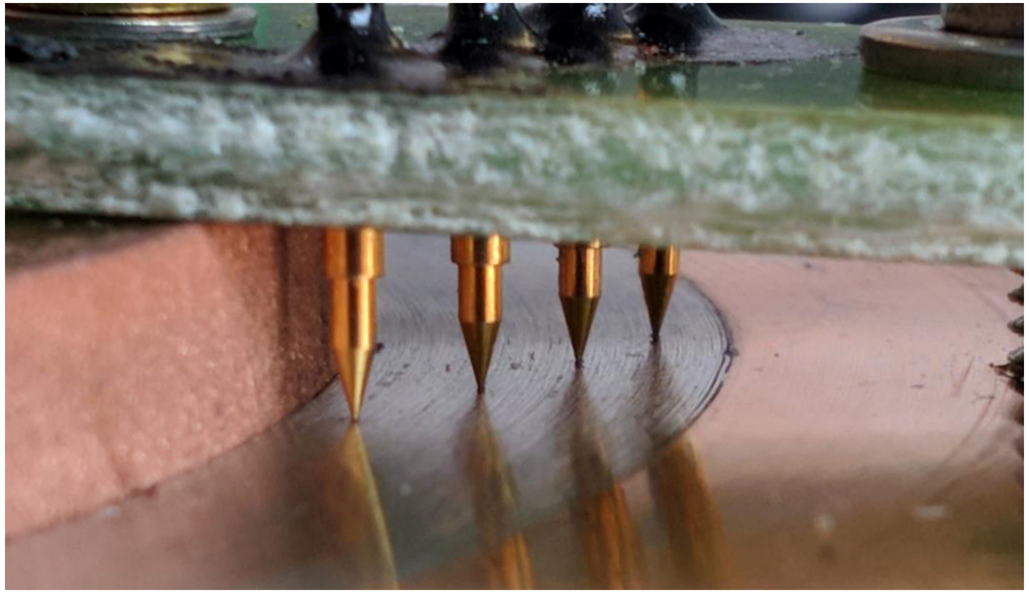
Co-wound wire

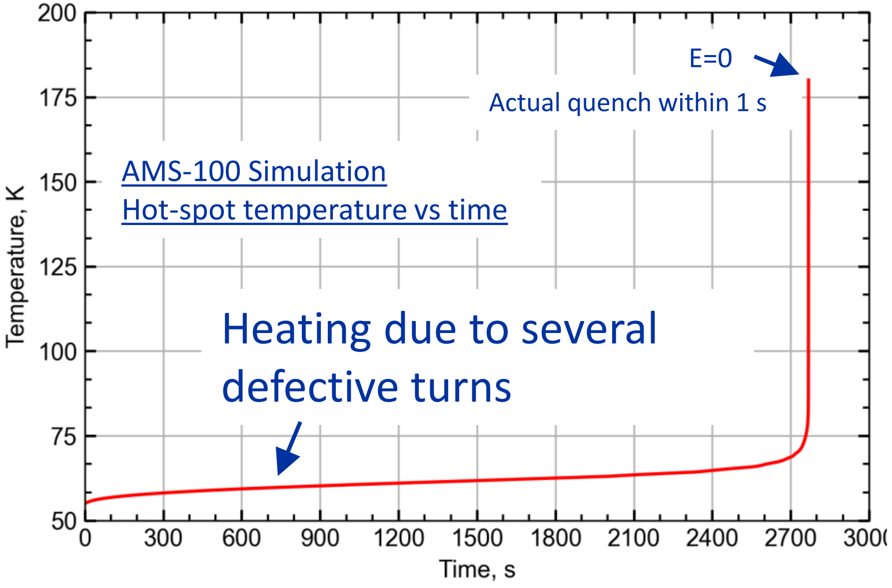
Pickup coils / Quench antenna

Direct magnetic measurements (hall probes)

Temperature sensors / Fiberoptics (Presentation tomorrow by H. Bajas)

Many other methods.





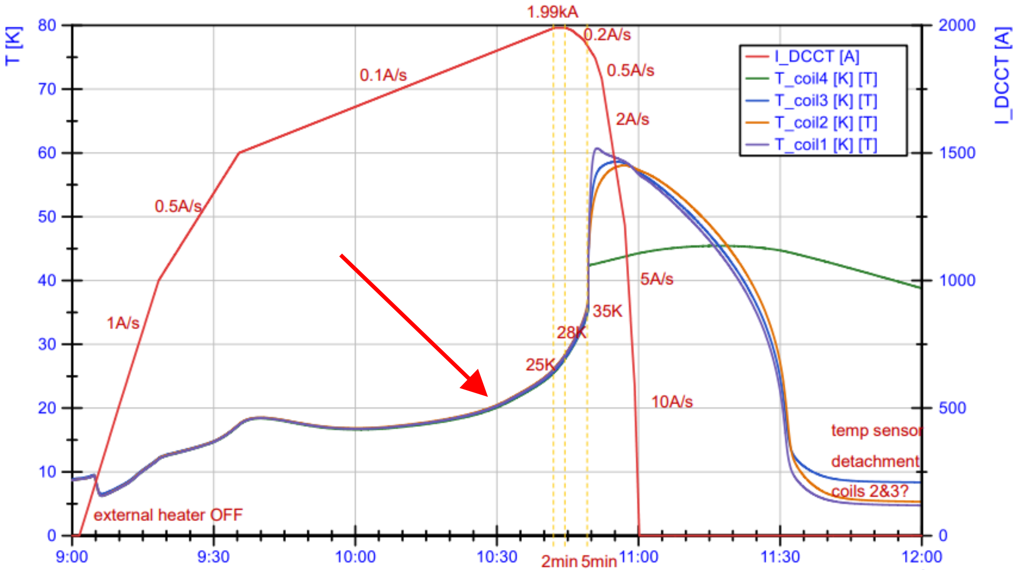
E=0

Actual quench within 1 s

AMS-100 Simulation

Hot-spot temperature vs time

Heating due to several defective turns



B. Auchmann, HTS Program at PSI, HiTAT 2023, slide 13

Courtesy M. Duda

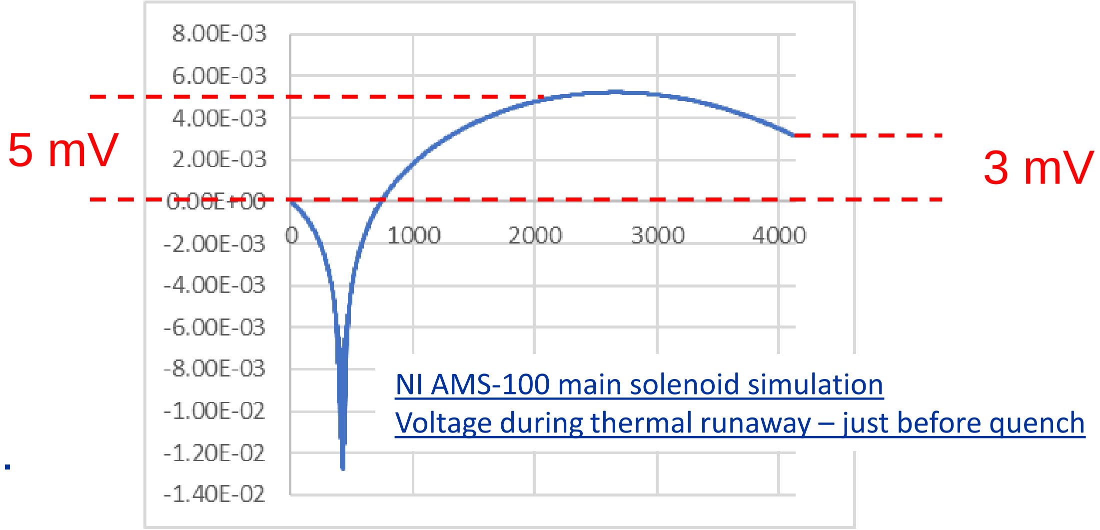
Quench Detection – Voltage measurements

Insulated magnets

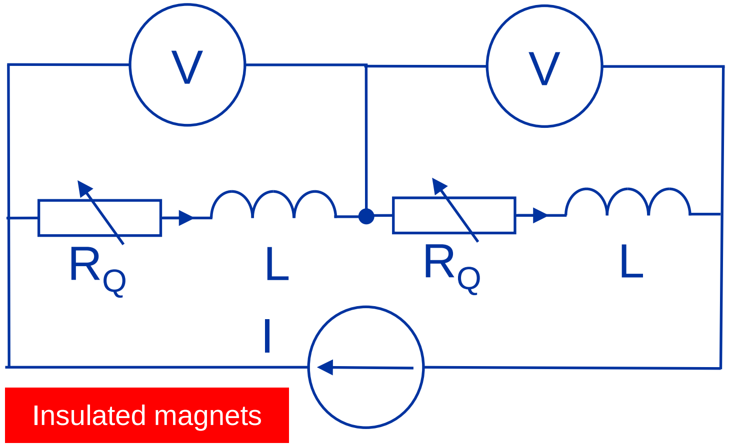
- Similar voltage balancing possible as with LTS magnets.
- Slow NZPV limits the resistive region size, thus voltage.

Non-insulated magnets

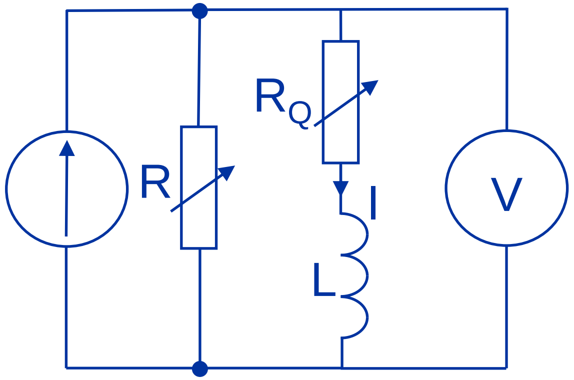
- Inductive voltage + resistive voltage combined.
- Low turn-to-turn bypass resistance doesn't allow high voltages.
- Voltage balanced quench detection possible, but not trivial.



NI AMS-100 main solenoid simulation
Voltage during thermal runaway – just before quench



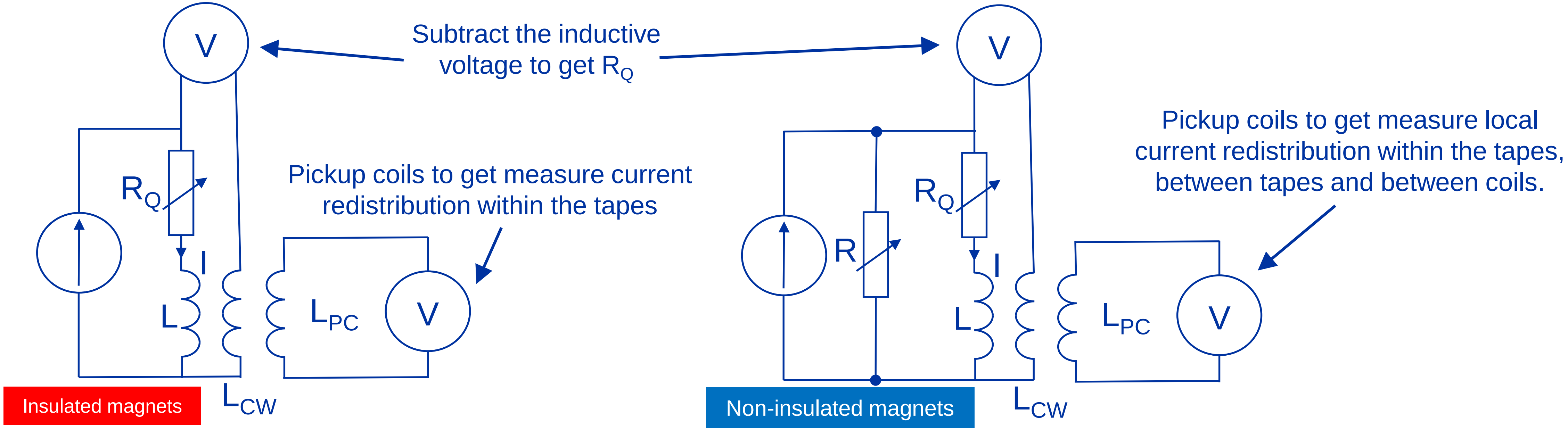
Insulated magnets



Non-insulated magnets

Quench Detection – Inductive + Magnetic

- Pickup coils or co-wound voltage taps can be used to extract coil resistance.
- Positioning of them is crucial as rapid change in B is shielded in NI coils.
- Significant voltages can be picked up when 1-to-1 co-wound in NI coils.
- Local magnetic field can be measured to detect current redistribution.



Subtract the inductive voltage to get R_Q

Pickup coils to get measure current redistribution within the tapes

Pickup coils to get measure local current redistribution within the tapes, between tapes and between coils.

Insulated magnets

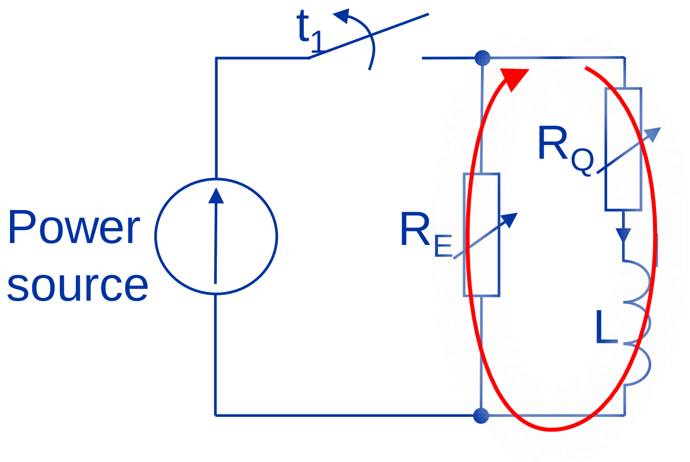
Non-insulated magnets

What to do when a quench or thermal runaway is detected?

1. **Energy extraction**
2. **Coupled circuits**
3. **Opening of the breaker**
4. **Quench heaters**
5. **Coupled loss**
6. **Capacitor discharge**

Energy extraction – Insulated magnets

- The same concept as used with many LTS magnets (see yesterdays presentation).
- Active quench protection, extracts stored energy and dissipates it outside of the magnet.
- Max voltage dictates R_E and the current decay curve.
- Normal zone hardly propagates, so magnet R_Q does not increase over time.
- May not be sufficient is E_{stored} is large, can be combined with other protection methods.

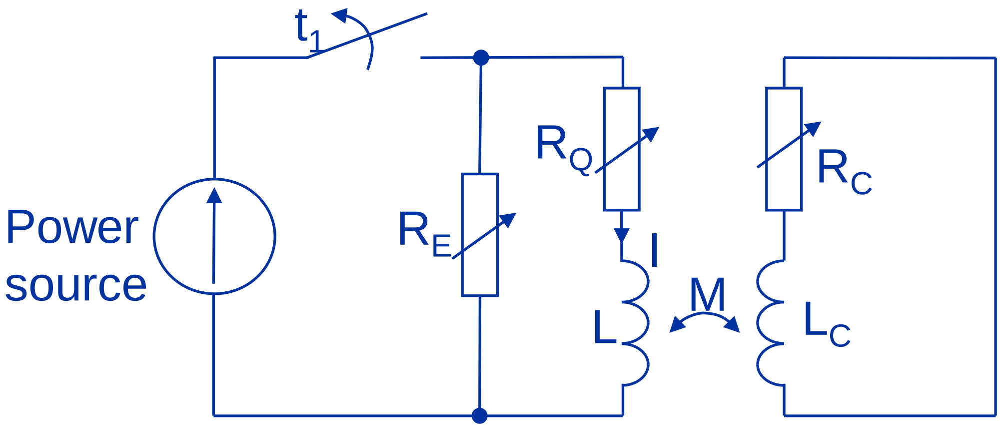


Time constant: $\tau = \frac{L}{R}$

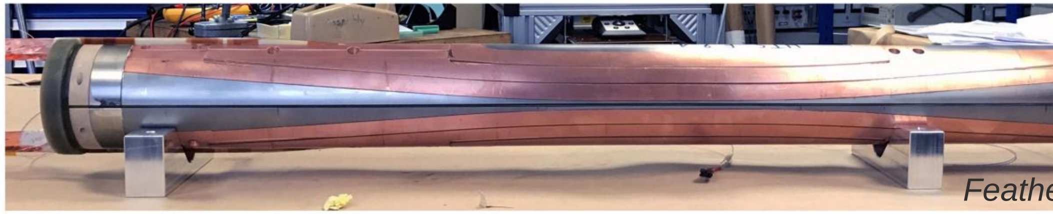
Discharge: $I = I_0 e^{-\frac{t}{\tau}}$

$$\int_0^\infty J^2(t)dt = \int_{T_{op}}^{T_{max}} c_v(T)/\rho(T)dT = F(T_{max})$$

Energy Extraction + Coupled Circuit



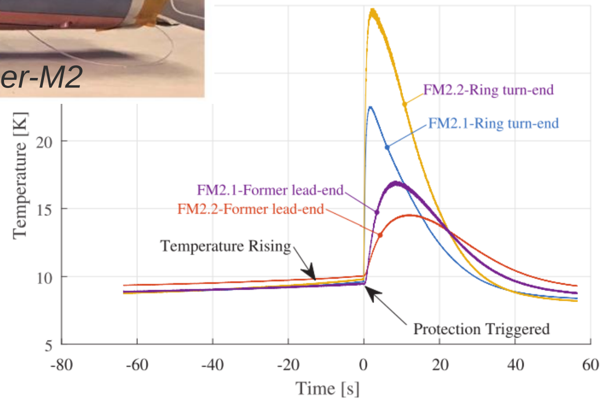
- ✓ A relatively high dB/dt is needed to remove energy by the magnetic coupling. Electric Energy Extraction can be used to create the high dB/dt.
- ✓ The effectives of magnetic coupling is higher for varistors than resistors [1]

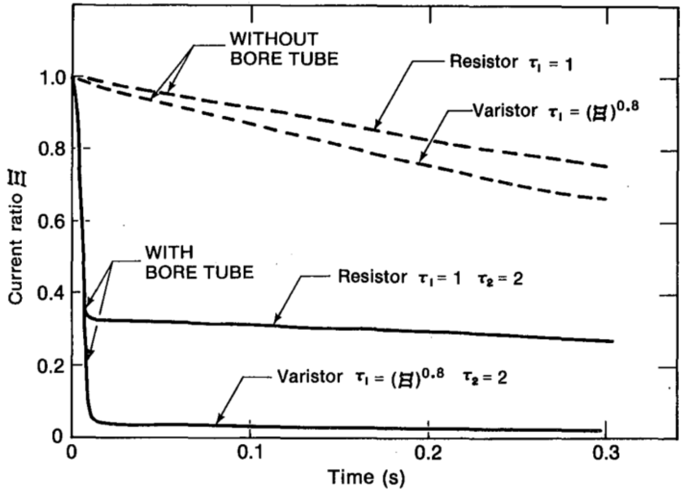


Feather-M2

J van Nugteren et al 2018 Supercond. Sci. Technol. 31 065002

- 50 mΩ dump resistor
- Copper rings around the coil
- Detection possible tens of seconds before protection was triggered.





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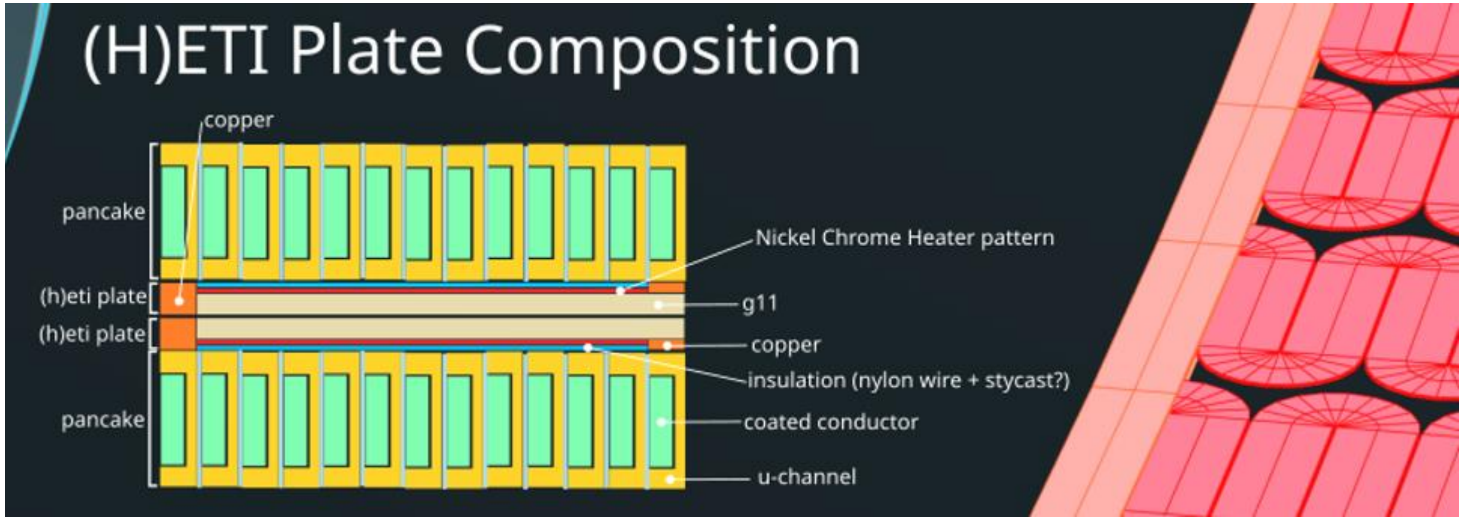
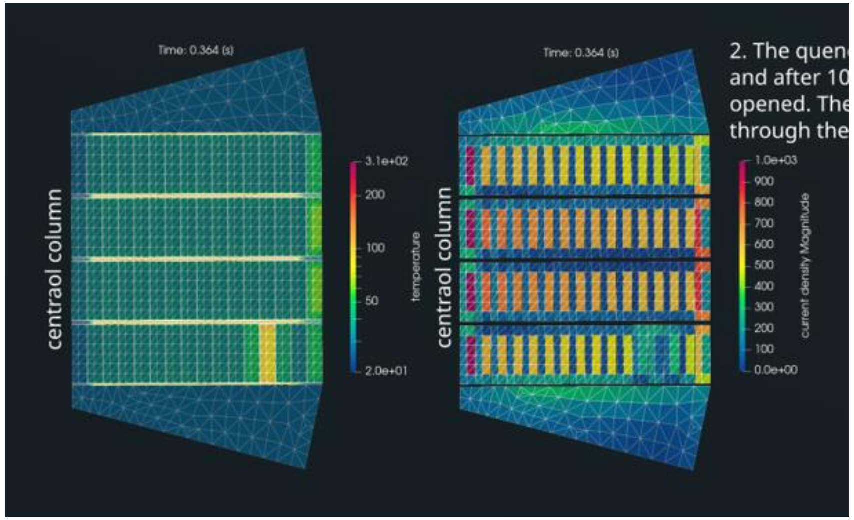
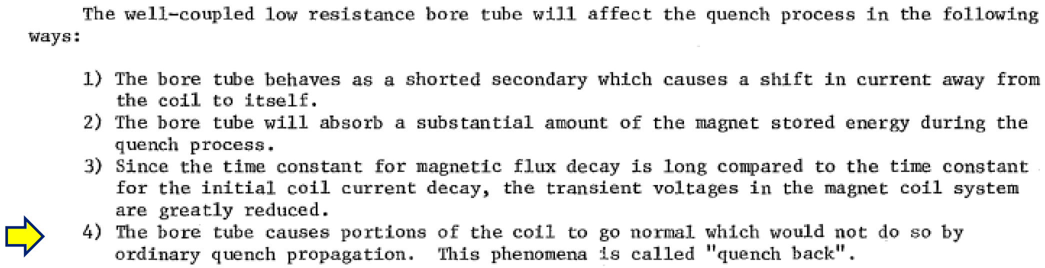
[1] Eberhard P H et al (1977), "Quenches in large superconducting magnets," Proceedings of the Sixth International Conference on Magnet Technology MT-6, Bratislava, pp 654-661.

Energy Extraction + Coupled Circuit + Heater





R. Bateman, Overview of the HTS program for the fusion programs, HiTAT 2023, slide 12

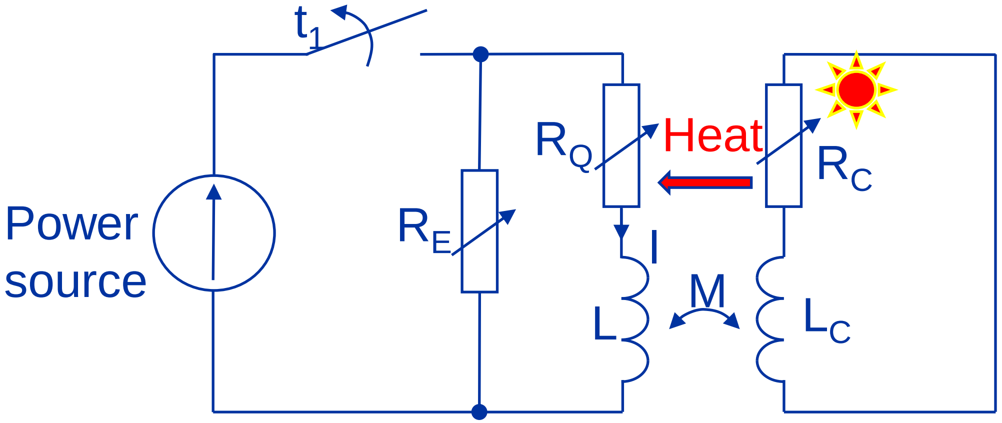


The well-coupled low resistance bore tube will affect the quench process in the following ways:

1) The bore tube behaves as a shorted secondary which causes a shift in current away from the coil to itself.
2) The bore tube will absorb a substantial amount of the magnet stored energy during the quench process.
3) Since the time constant for magnetic flux decay is long compared to the time constant for the initial coil current decay, the transient voltages in the magnet coil system are greatly reduced.
4) The bore tube causes portions of the coil to go normal which would not do so by ordinary quench propagation. This phenomena is called "quench back".

Eberhard P H et al (1977), "Quenches in large superconducting magnets," Proceedings of the Sixth International Conference on Magnet Technology MT-6, Bratislava, pp 654-661.

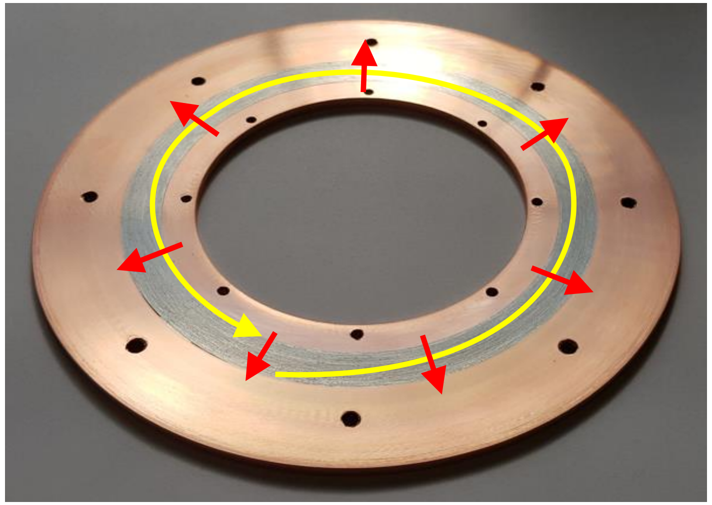
Old concepts are still very relevant today!

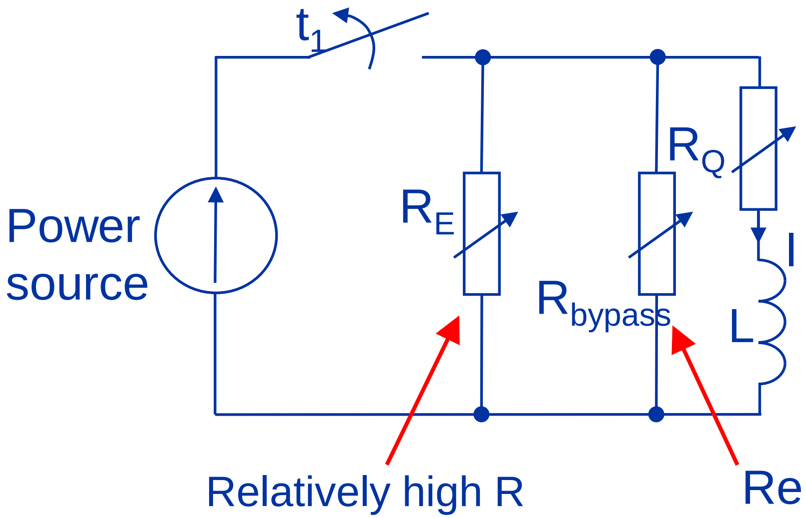


Opening the breaker – NI Coils

No-Insulation or partially insulated coil:

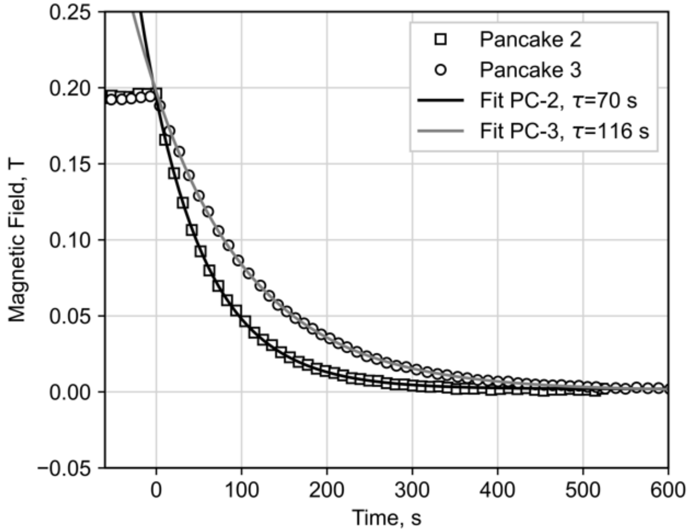
- All current flows back via the turn-to-turn resistance.
- Stored energy is dissipated in the turn-to-turn resistance.
- Larger R_{bypass} means more heating power.
- Energy extraction resistors have almost no effect for most NI coils.



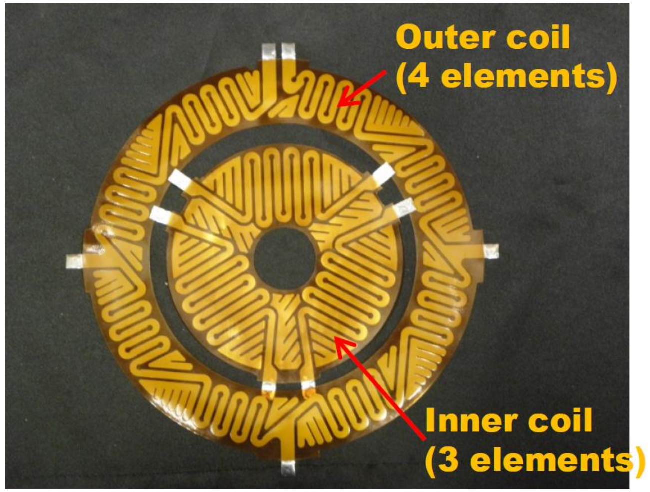


Time constant: $\tau = \frac{L}{R}$

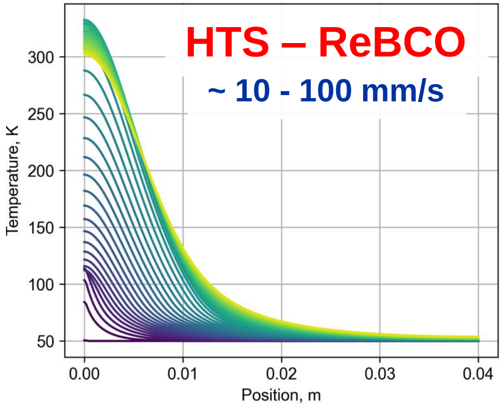
Discharge: $I = I_0 e^{-\frac{t}{\tau}}$



Quench heaters



HTS quench heater [1]

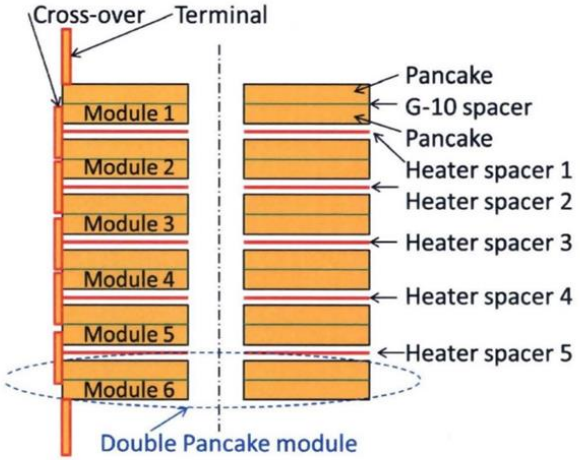


LTS Magnets:

- Well established and proven.
- Relies on heater stations and NZPV between stations.

Insulated HTS magnets

- NZPV is low, in general heaters are not very efficient.
- Heaters only effective when large section heated, large energy requirement.



Heater layout example [1]

Non-insulated HTS magnets

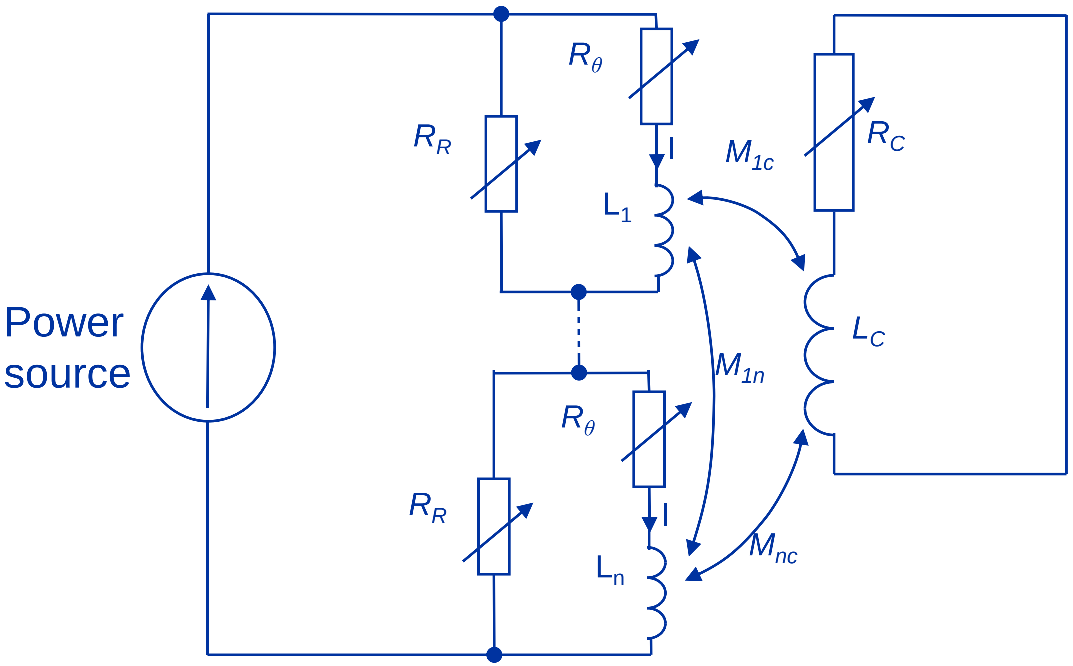
- Used to initiate a hot-spot, followed by inductive quench propagation.
- Magnet can be quenched in most favorable position.
- May cause issues due to mechanical stress concentrations & electrical integrity.

---

[1] A. Gavrilin et al. Comprehensive quench analysis of the NHMFL 32T all-superconducting magnet, CHATS 2015, Bologna, Italy

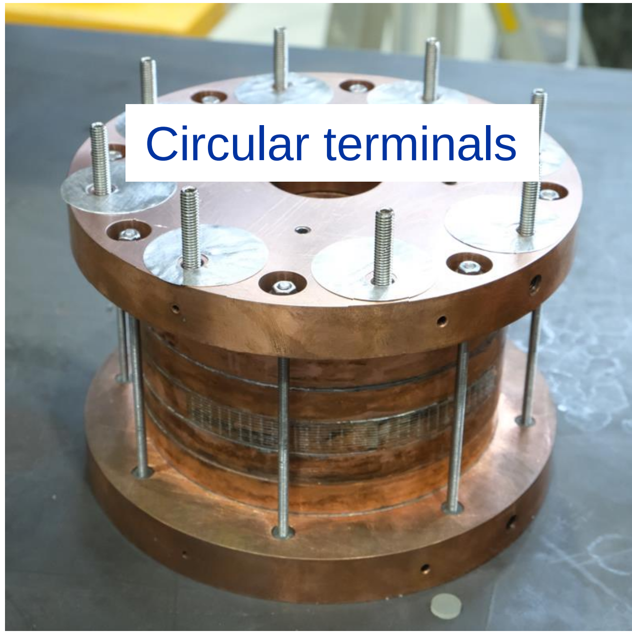
Coupled circuits

- Coil mutually coupled with terminals other cylindrical parts.
- Allows faster current extraction, reduces dB/dt.
- Part of the magnet’s energy is dissipated in the coupled circuit.
- Current induced during ramp -> loss, affect field.

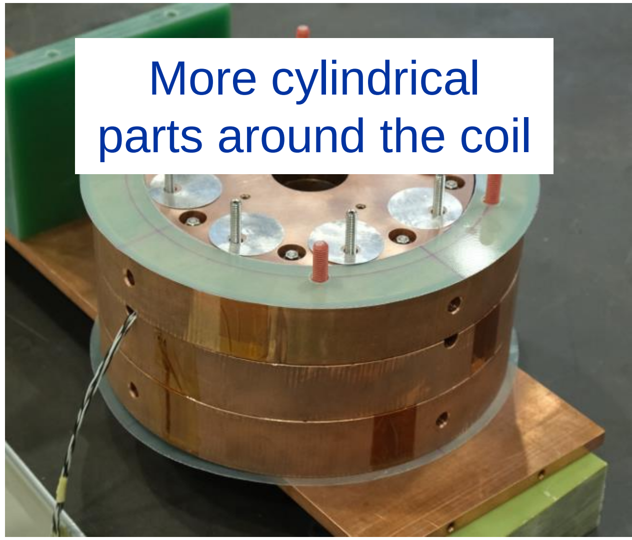


Structural elements /
Other coils

Not only to protect the coil, but also elements around it.



Circular terminals



More cylindrical parts around the coil

Coupled circuit + Quench heaters

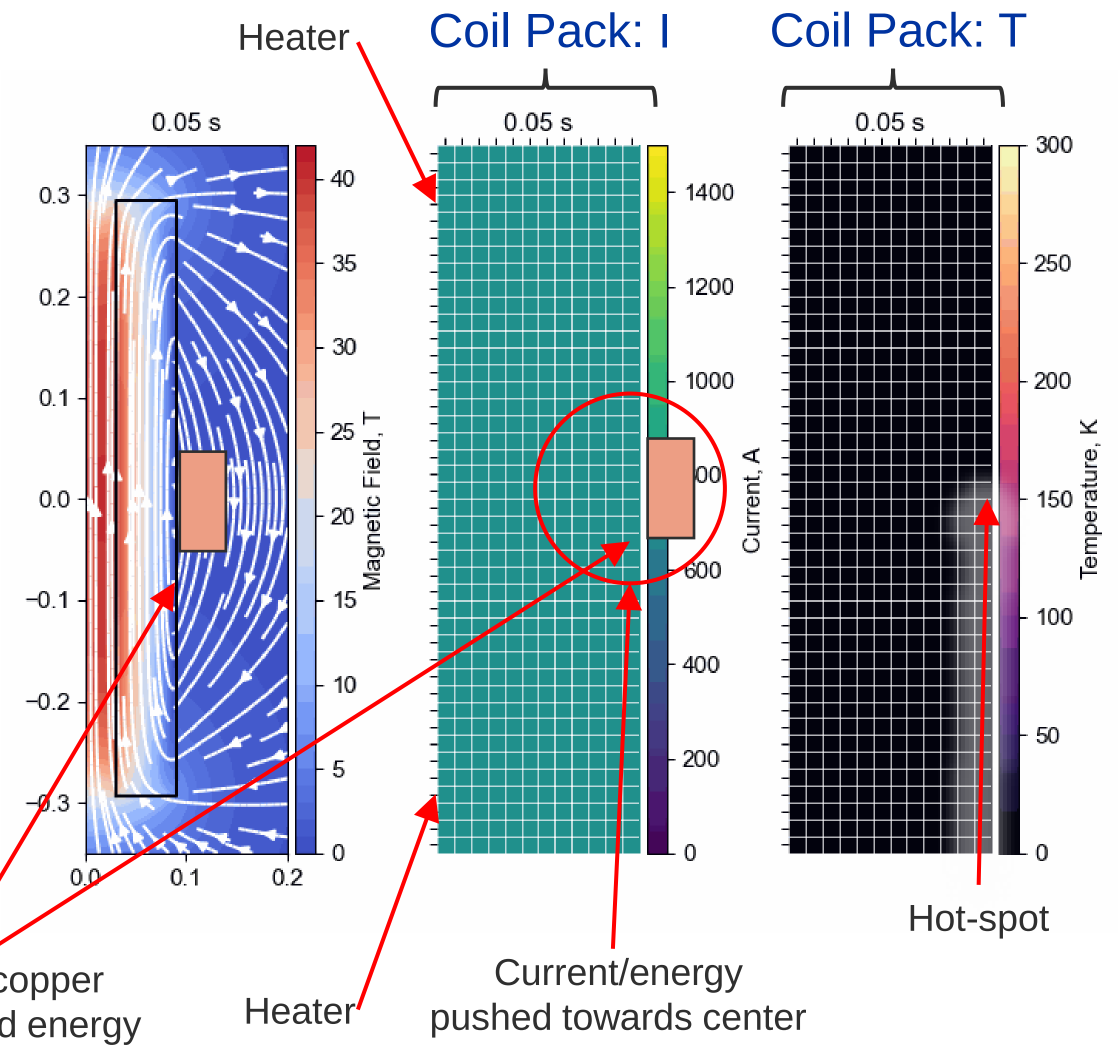
Heaters:

- **Deliberately quenching** parts of the magnet at strategically chosen **locations** and **time.**
- Followed by inductive quench propagation.

Coupled Circuit:

- Placed at strategically chosen locations.
- Adsorbs part of the stored energy during quench.
- Reduced hot-spot temperature of the coil.
- May help with mechanical stress management.
- Only local -> minimal during ramp.

Combining technologies is important!



Add local copper adsorb stored energy

Heater

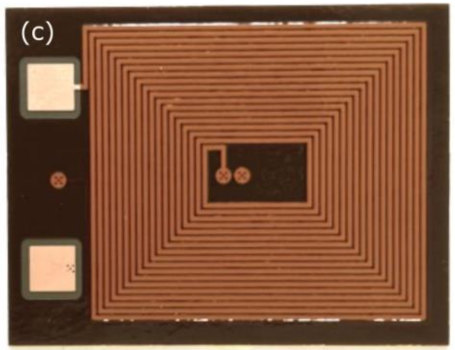
Current/energy pushed towards center

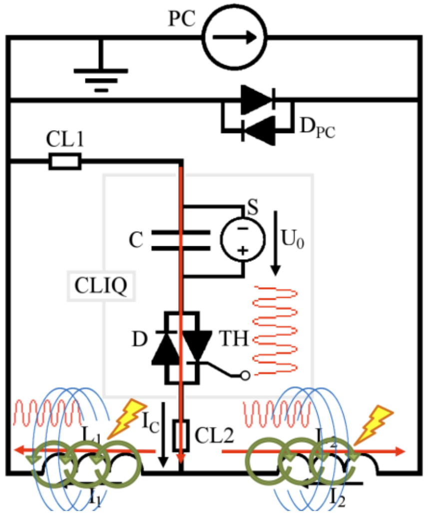
Hot-spot

Coupled Loss & Capacitor Discharge

E. Ravaioli. Optimisation of CLIQ for HTS, WAMHTS-2, 2015, https://indico.cern.ch/event/396905/contributions/1837520

CLIQ? E-CLIQ? Will it work on HTS coils?



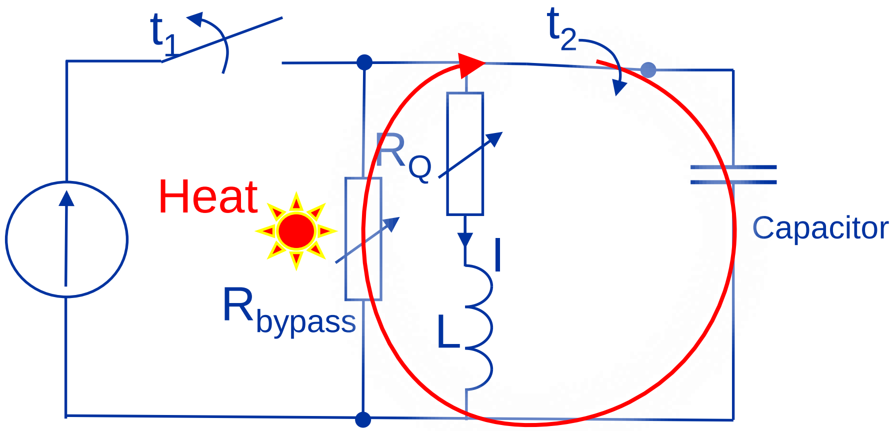


Insulated:

- CLIQ: Yes, but a large stored energy is needed.
- E-CLIQ: Works as a quench heater, therefore not super effective.

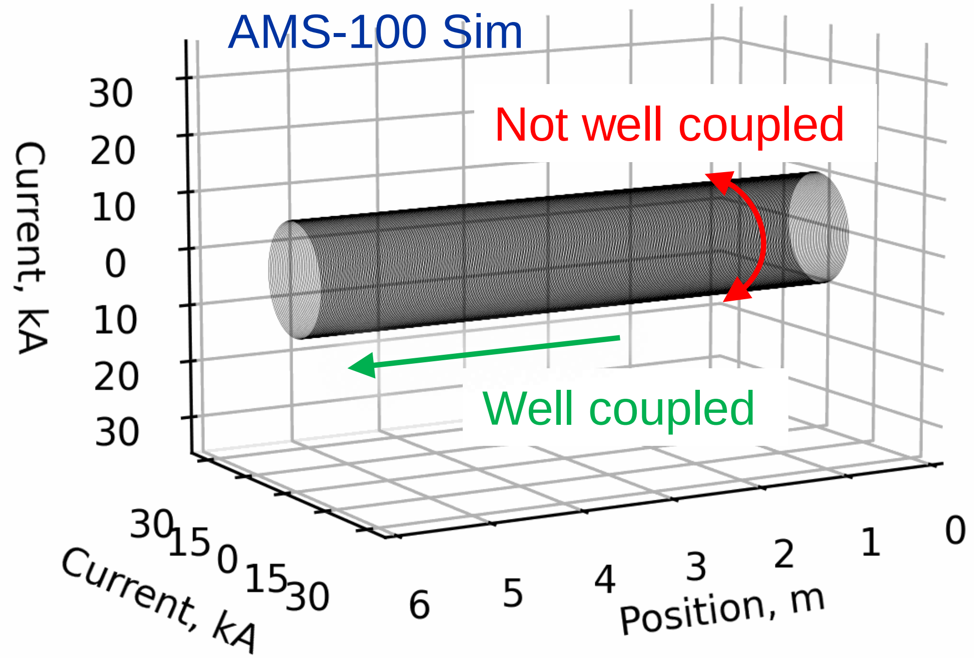
Non-Insulated:

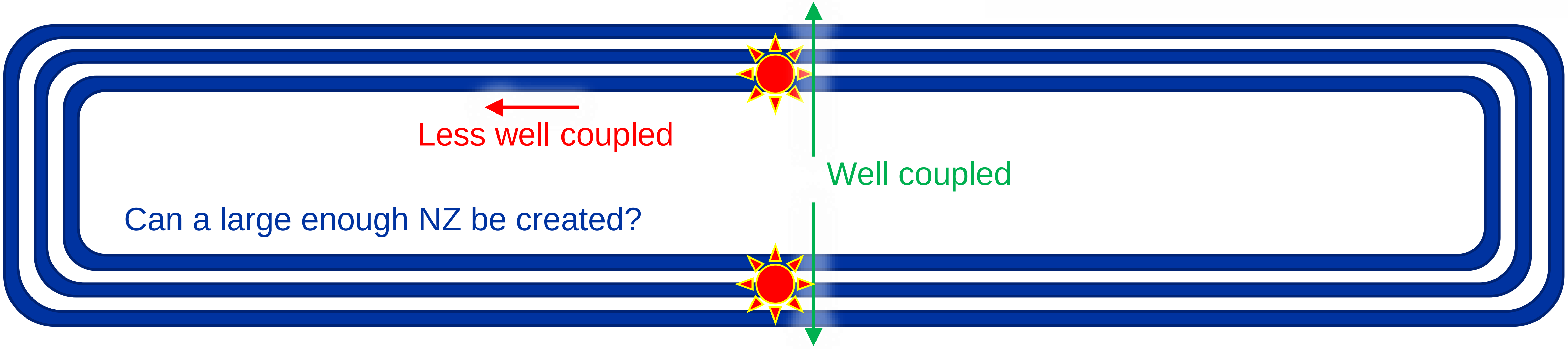
- CLIQ: inductance of resistive bypass is small, will not work.
- E-CLIQ: works as a quench heater, may initiate a quench at a preferential position.
- DIQ (Discharge Induced Quench):
  - Injects a high current pulse in (part of) the magnet.
  - Generates heat in the bypass resistance, quench preferential position.
  - Currently being investigated.



Large NI-Racetrack coils

- Protection of NI solenoids relies on coupling between pancakes.
- Coupling in longitudinal direction is much less in racetracks.
- Sufficiently fast NZP for protection?
- Quench protection of such coil is a big question mark.





Can a large enough NZ be created?

Semiconductor Epoxy / Varistor Paste

- Best scenario is to have an insulated magnet that becomes non-insulated in case of a hot-spot.
- Allows good field quality + protection of NI-coils.
- Solutions comes in the shape of oxide-powders mixed with epoxy.
- At certain T_c switch from insulation to metallic.
- Some small demonstrators, no large-scale demonstration yet.
- Very interesting, technology not ready.

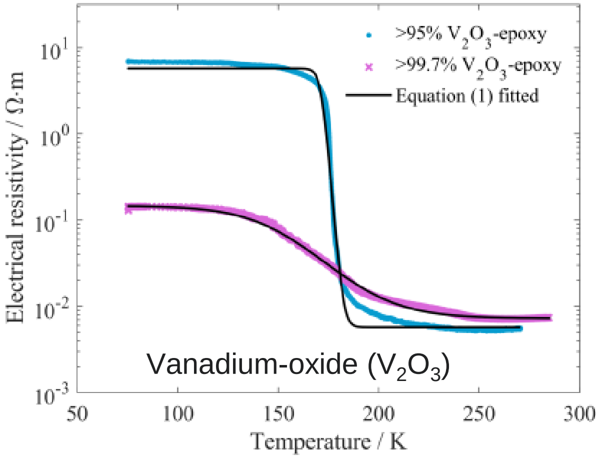


Fig. 2. Temperature dependent resistivity.

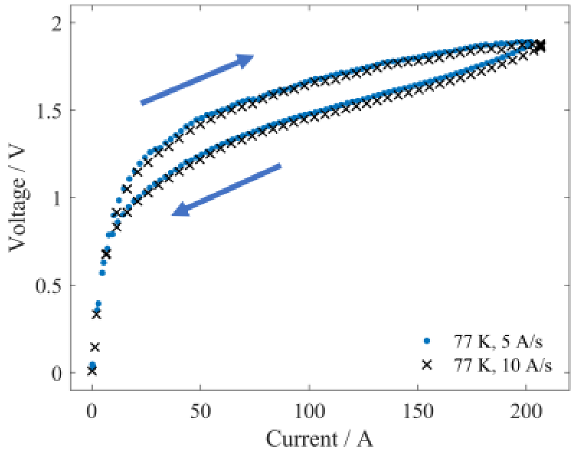
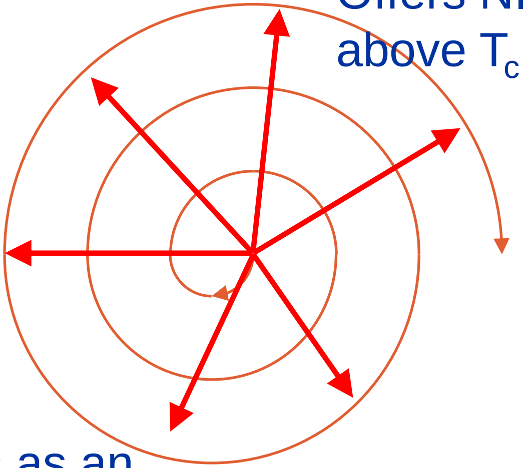


Fig. 3. Current-to-voltage characteristics of >99.7% V_2O_3-epoxy.

A. Vaskuri, Towards Ultra-Thin Detector Magnet Designs by Insulating Coil Windings with V2O3-Epoxy Composite, ASC 22, 2022

G. Kirby et al 2022 IEEE TAS 9751387



Offers NI protection above T_c

Behaves as an insulated coil below Tc

What is the best quench protection recipe?

Large toolbox, solution still very magnet dependent, but in general:

Insulated HTS

Key ingredients:
- Fast quench detection
- Energy extraction

Optional flavors:
- Magnetic coupling with secondary circuit

Non-insulated HTS

Key ingredients (for a solenoid with a large energy density):
- Magnetic coupling with secondary circuit
- Mechanical stress management

Optional flavors:
- Heaters, to force a quench to start in a specific position.

Conclusions

- ✓ There are many approaches that can be followed to protect an HTS magnet.
- ✓ Broadly, the approaches can be divided into distributing the energy inside the magnet or removing it.
- ✓ These approaches are often not mutually exclusive and, if needed or required, can be used in conjunction.
- ✓ This logic can be followed for NI magnets, for which it might be necessary due to the possibility of energy and force density redistribution during a quench.
- ✓ Limits for protection for HTS are becoming increasingly complex and not well understood or defined.
- ✓ Collaboration, teamwork, experimental data and simulations are needed to maximize progress in HTS protection development.