NI/PI Coils

Transient Electro-Magnetic and Thermal Simulation of HTS NI/PI Coils

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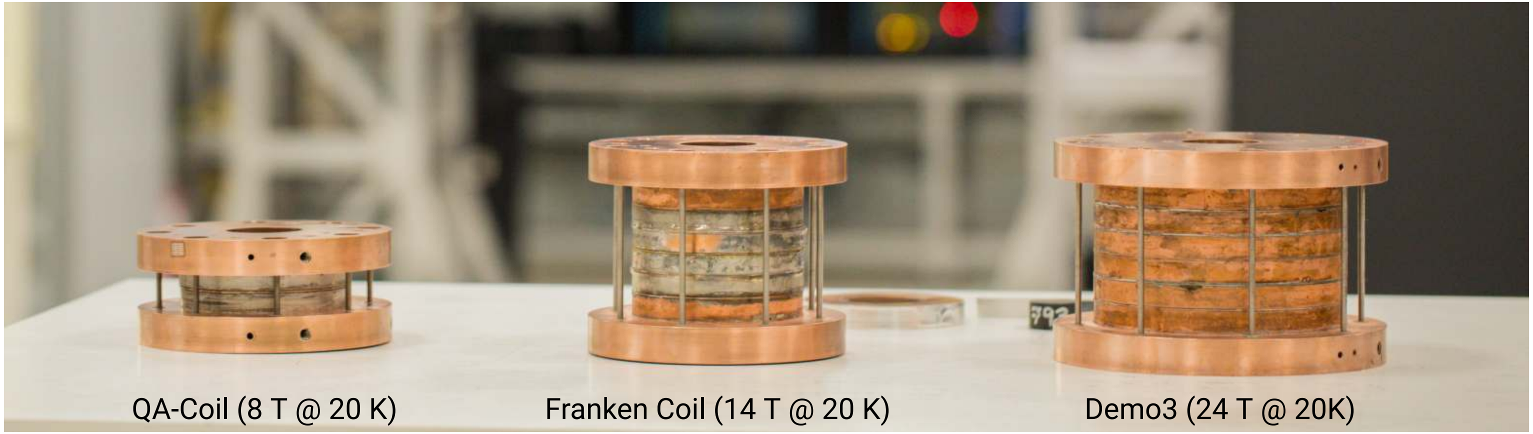
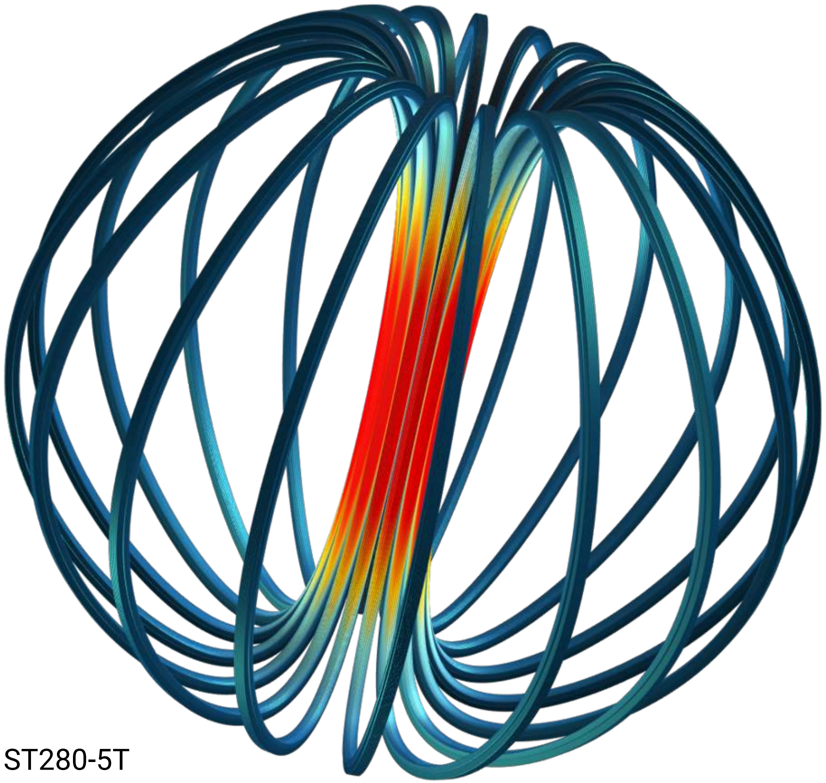
Tokamak Energy NI Coils



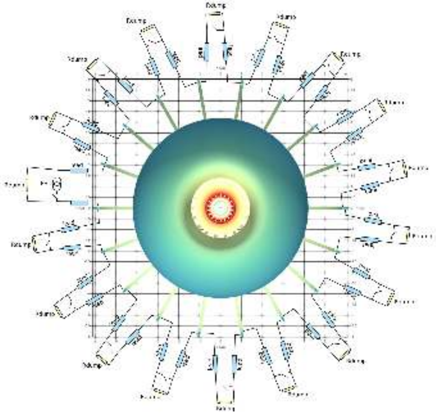
- No Insulation (NI) coils have no insulation between the turns.
- To learn about HTS manufacturing and test different tapes many of these coils were manufactured and tested at Tokamak Energy.
- NI-Coils have shown remarkable resilience against quenching.

Protecting Fusion Scale Magnets



ST280-5T

- Can we scale something like this to protect large HTS fusion sized coils?
- Fusion scaled Toroidal Field (TF) coils have stored magnetic energy of tens of GJ.
- Classical external extraction would require 60 kV voltage distributed along the circuit.



Wall power for Current Supply	Conventional Protection	Conventional Protection (Cold Switches)	RAPID Protection
Liquid nitrogen cooling only	0.49 MW	0.38 MW	0.027 MW
Nitrogen vapour cooling	0.16 MW	0.11 MW	0.008 MW
Helium gas cooling	0.36 MW	0.28 MW	0.020 MW

Talk Outline

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1. A brief introduction to NI coils.
2. Electrical Network Modeling NI coils.
3. Scaling up to large Magnets using NI like approach.

Demo2 (first step towards partially insulated coil)

Brief Introduction to NI Coils

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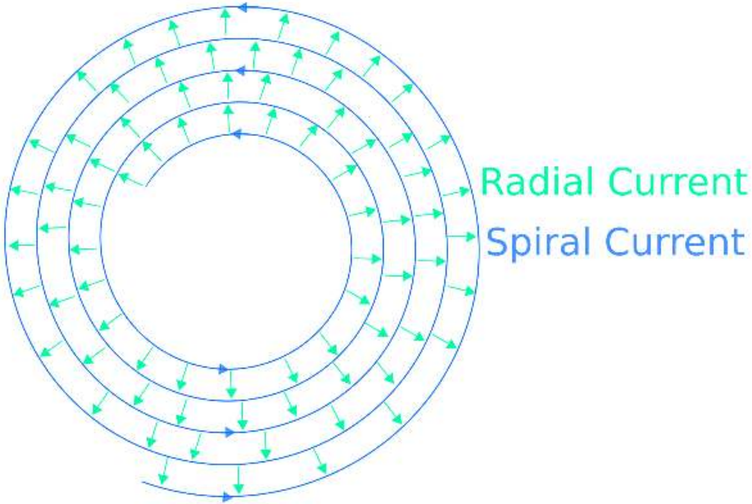
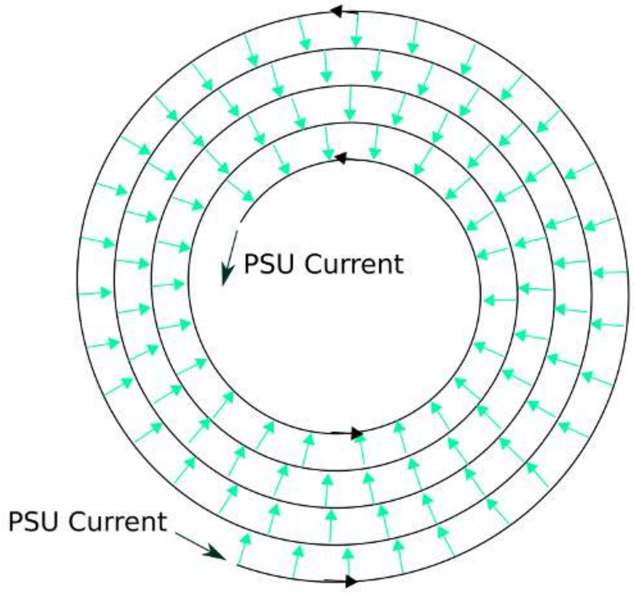
QA-Coil Solder Potted Pancake

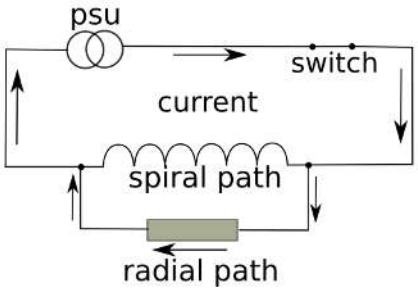
- Current can flow both in the radial and spiral paths.
- Only the spiral path will produce magnetic field.

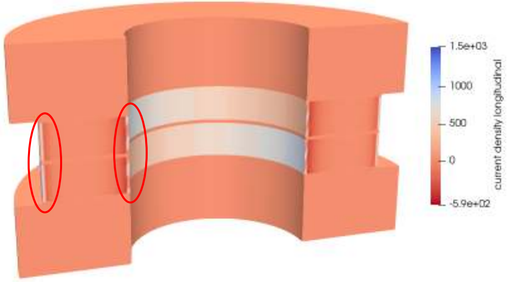


Powering an NI-Coil I

- When changing the current in an NI coil it will initially take the path with lowest inductance, i.e. the radial path.
- The first and last turn are used to spread the current around the coil.
- Due to the resistance there is a voltage over the coil.

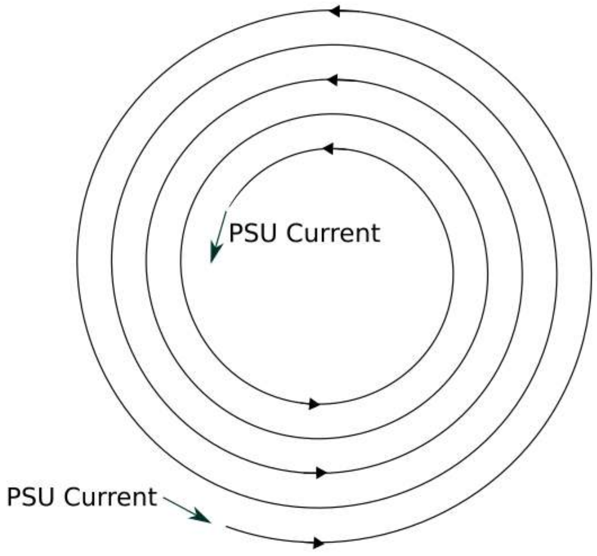


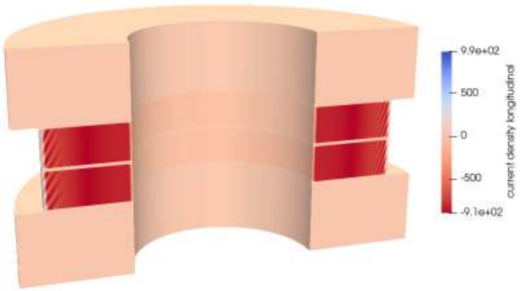


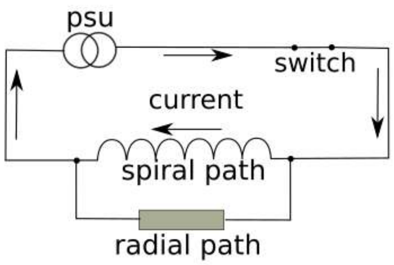


Powering an NI Coil II

- An eternity later the coil is finally powered ...
- The current is now in the path with least resistance, i.e. the superconducting spiral path.

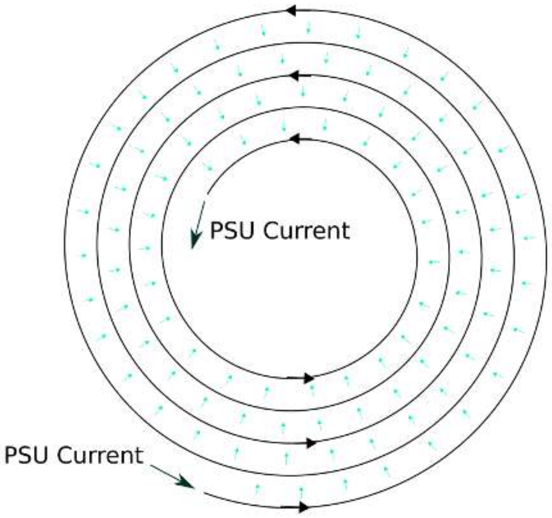


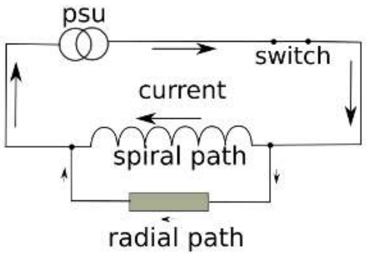


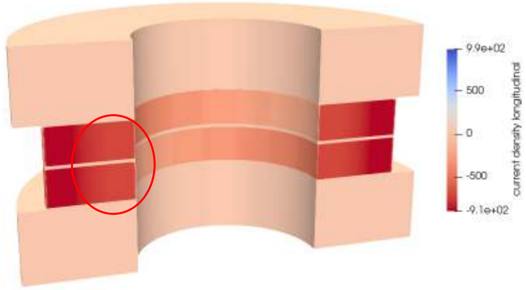


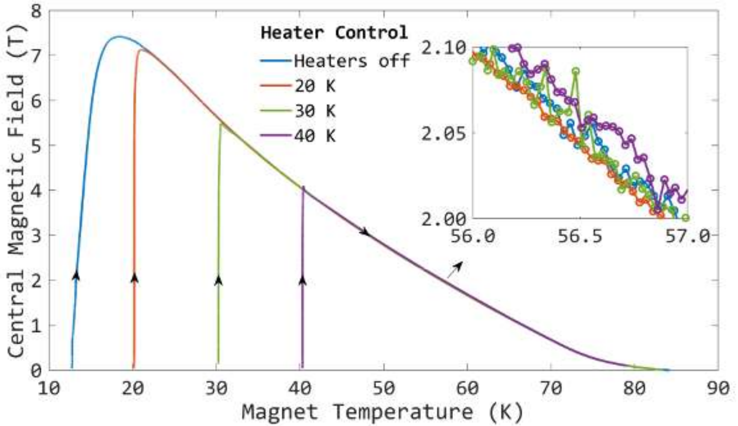
Saturated Mode

- When powered beyond the superconductor Ic the excess current flows radially.
- This way the coil can be saturated with current at the penalty of additional losses.

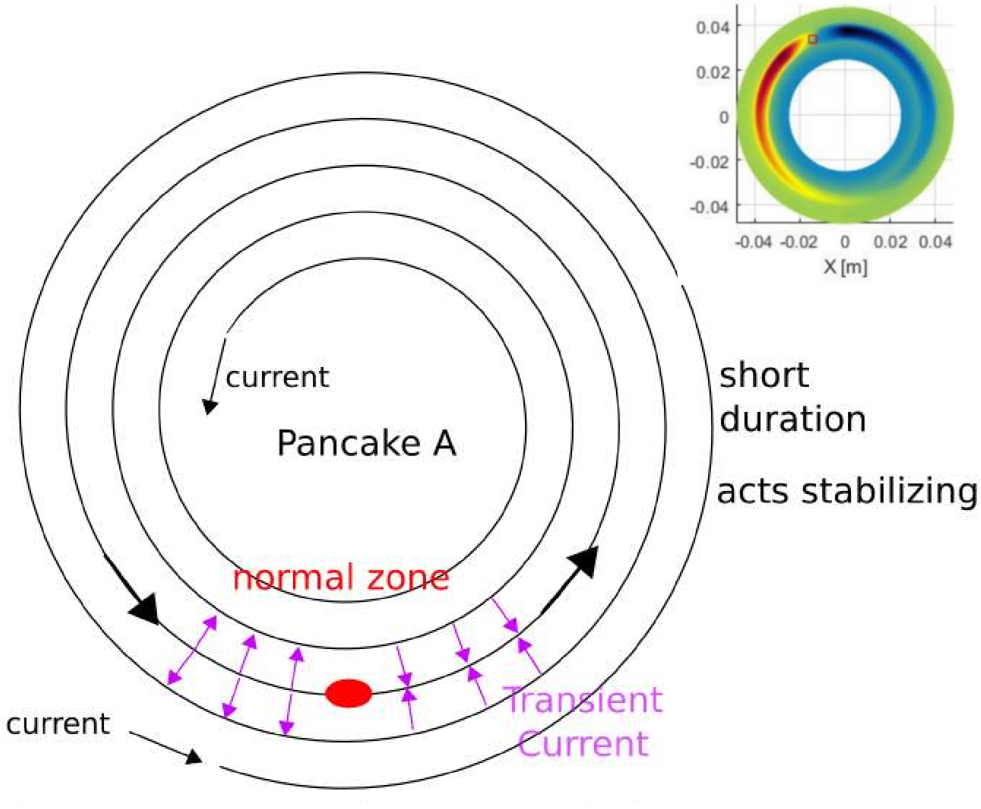








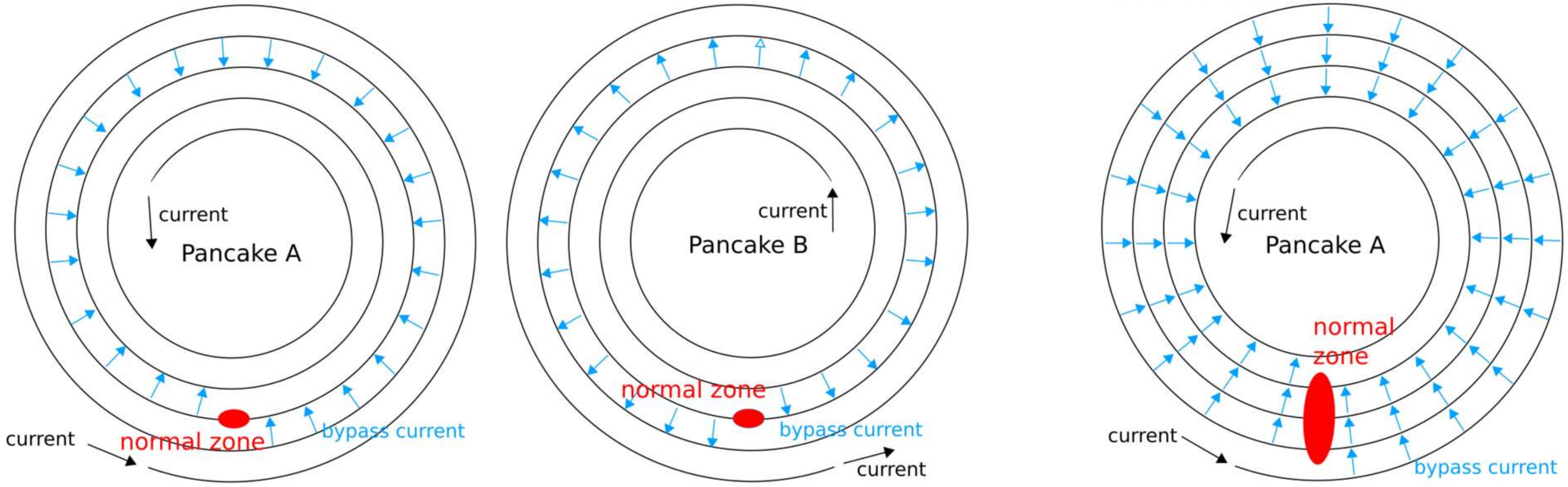
Transient Current



- The electrical current can almost freely bypass a hotspot.
- This significantly reduces heating in the hotspot itself.
- And therefore HTS coils the minimal quench energy is significantly higher than in a insulated coil.
- Initially the current redistribution occurs close to the hotspot (transient effect) ...

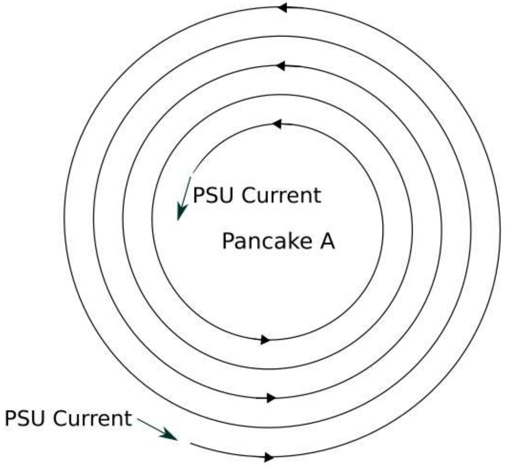
Normal Zone Bypass Current

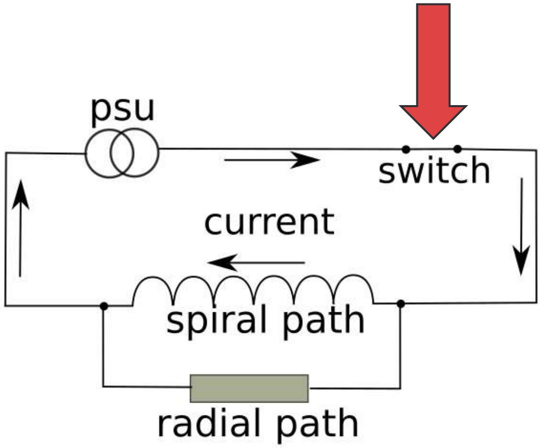
- After a while the current distribution occurs in the entire turn effectively bypassing it.
- When the hotspot grows in size multiple turns can be bypassed.
- Also improves stability.

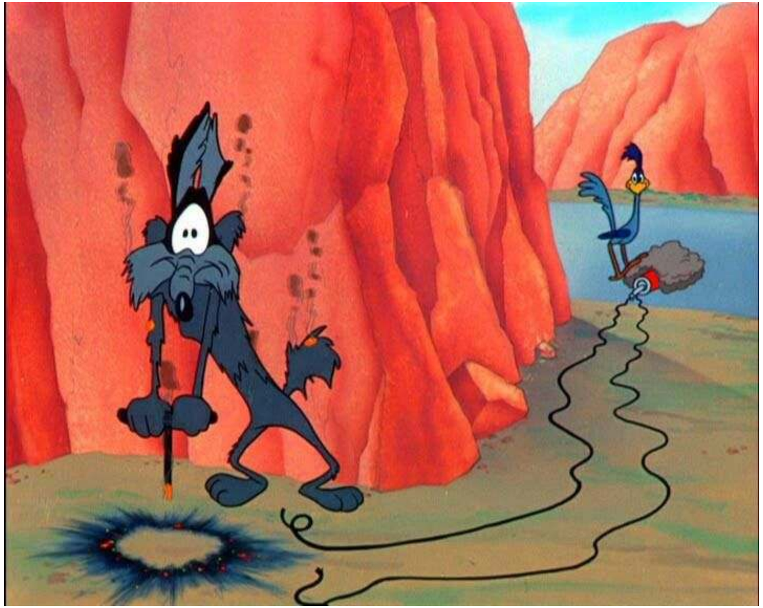


Open Circuit Current I

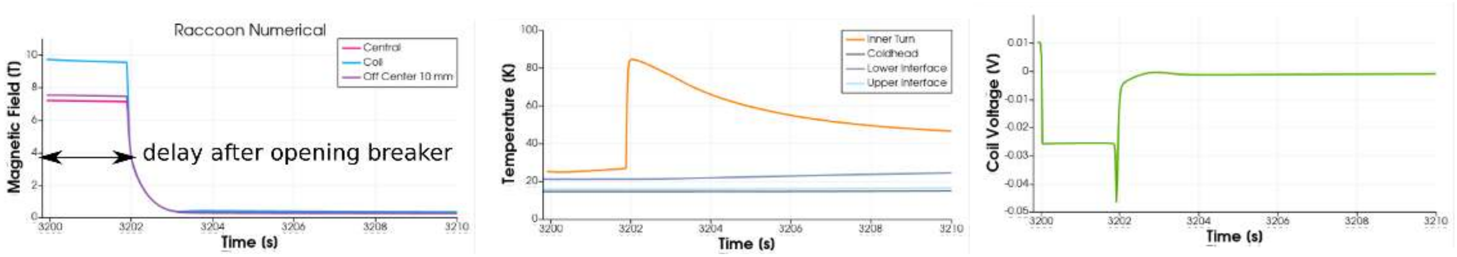
- Now lets do something that will drive our safety people mad. 😈
- Lets open the circuit breaker with the coil fully energized!

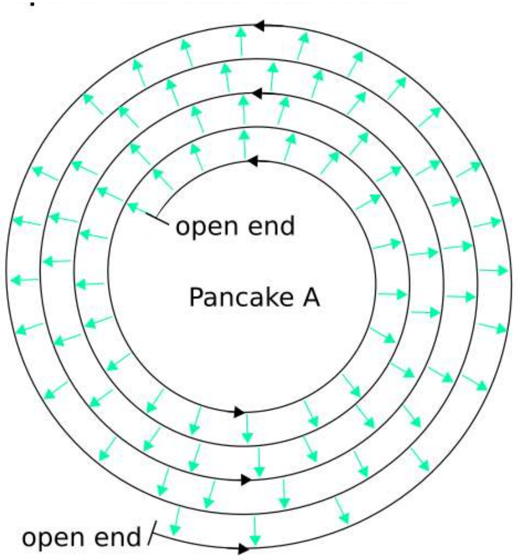


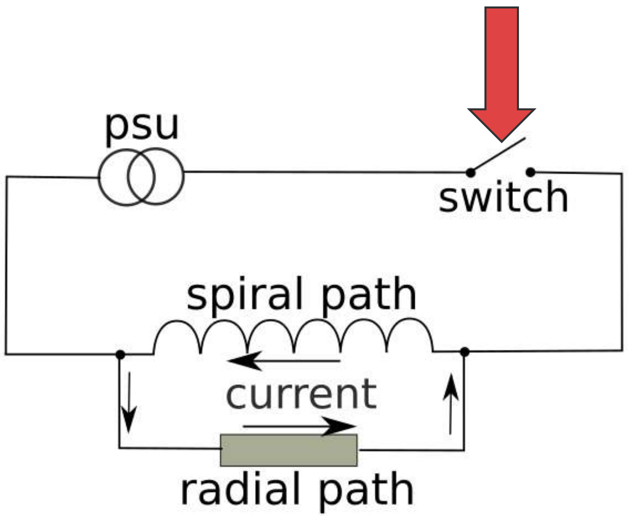




Open Circuit Current II

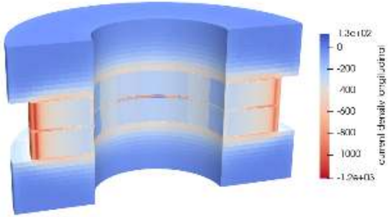




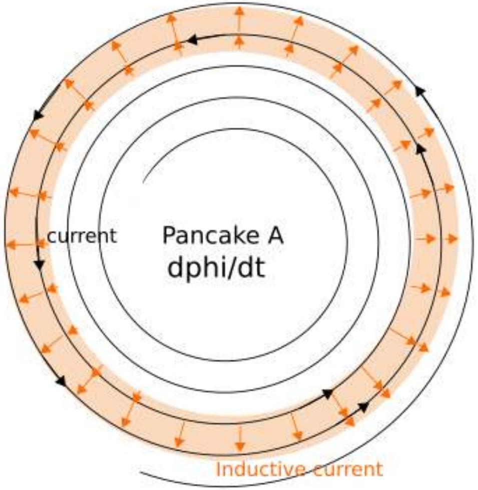


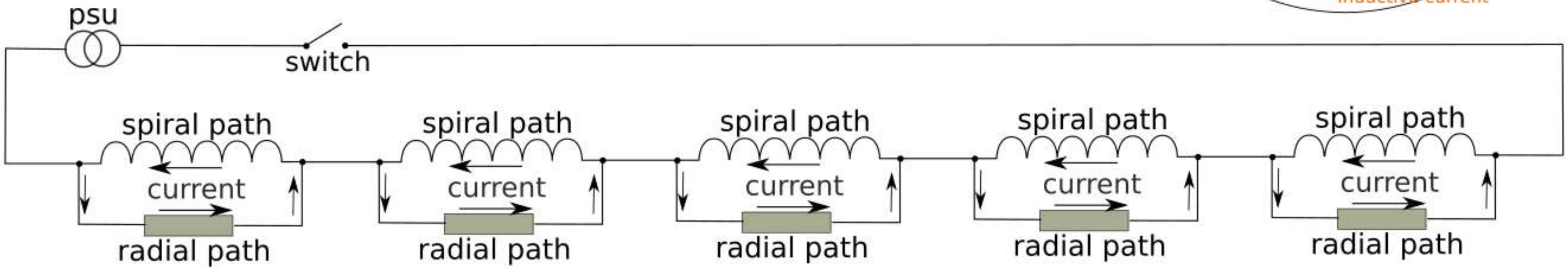
- In fact (initially) nothing happens ...
- The current uses the radial path to bypass the switch and power supply.
- The coil will heat up due to Ohmic heating in radial path and ultimately quench at the point with least margin.

Induced Current



- The radial path and spiral path are connected continuously.
- This means that each turn can be considered a separate current loop connected through inductance.
- When the circuit breaker is opened all transport current is converted into induced current.
- Driven by resistance, current can inductively transfer from loop-to-loop and even from coil-to-coil.

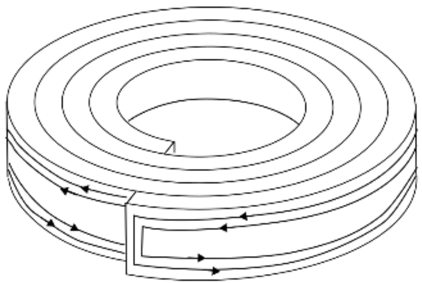




AC Currents

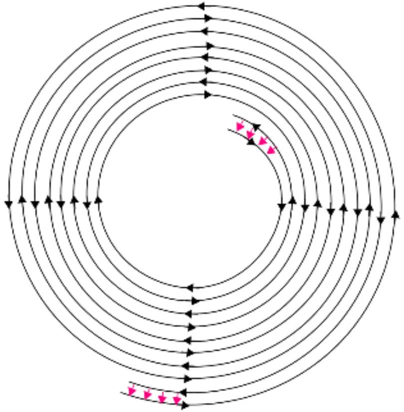
- There is more current paths to consider for example screening and coupling current (see my poster WED-PO2-204-09).
- However, all current use the same critical current budget within the tapes, therefore superposition is not really possible.

Screening Current

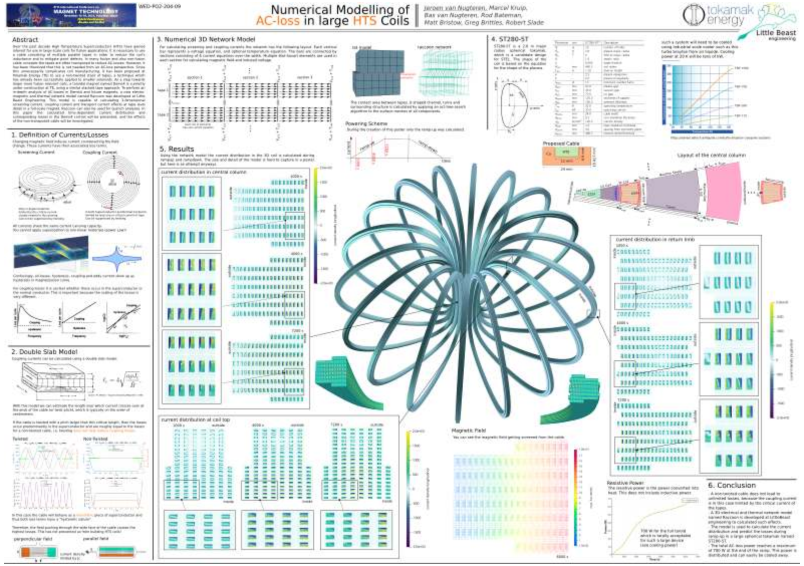


Tries to screen radial magnetic field
limited by the critical current of the tapes
therefore closely related to flux pinning

Coupling Current



Tries to screen axial field
Only in multi strand cables
Beware: also limited by critical current of tape!



Modeling NI-Coils

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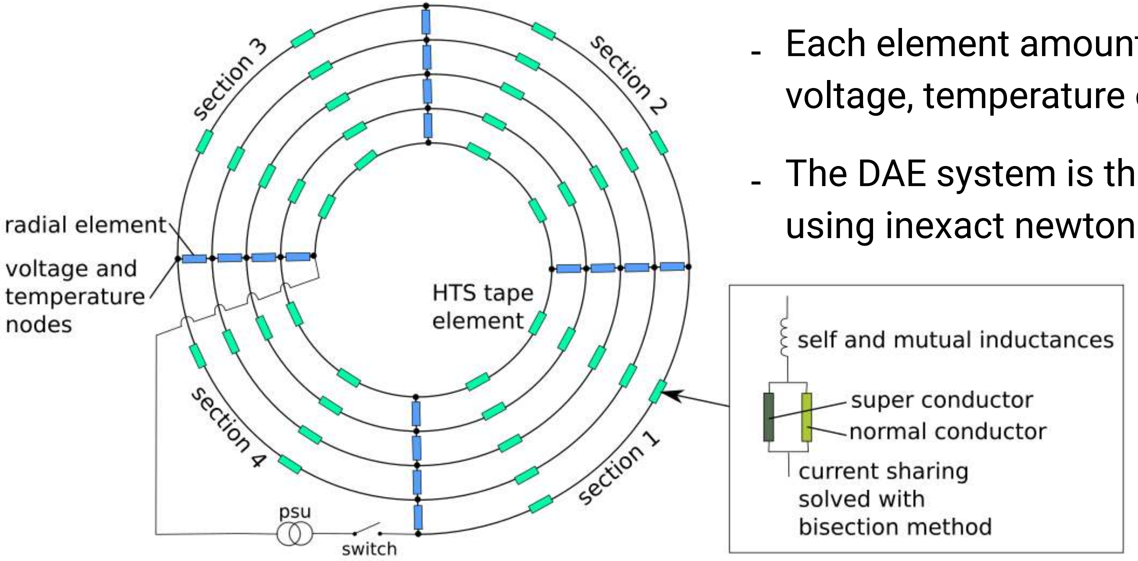
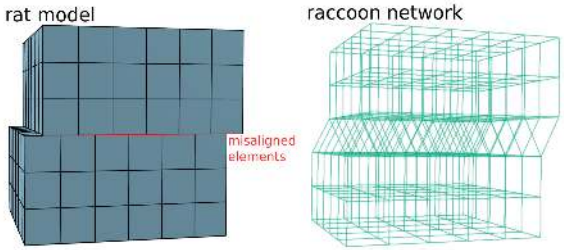
Raccoon Network Model

- The physics of NI coils can be captured well using an electrical network.
- The network is automatically constructed from a Rat model by meshing the coils and mapping the contact areas of all surface elements.



- Each element amounts to an equation for current, voltage, temperature or heat flux.
- The DAE system is then solved using Sundials IDA using inexact newton method from LLNL.



https://computing.llnl.gov/projects/sundials/ida

Model Validation Wang et al.

Y Wang et al 2015 Supercond. Sci. Technol. 28 045017

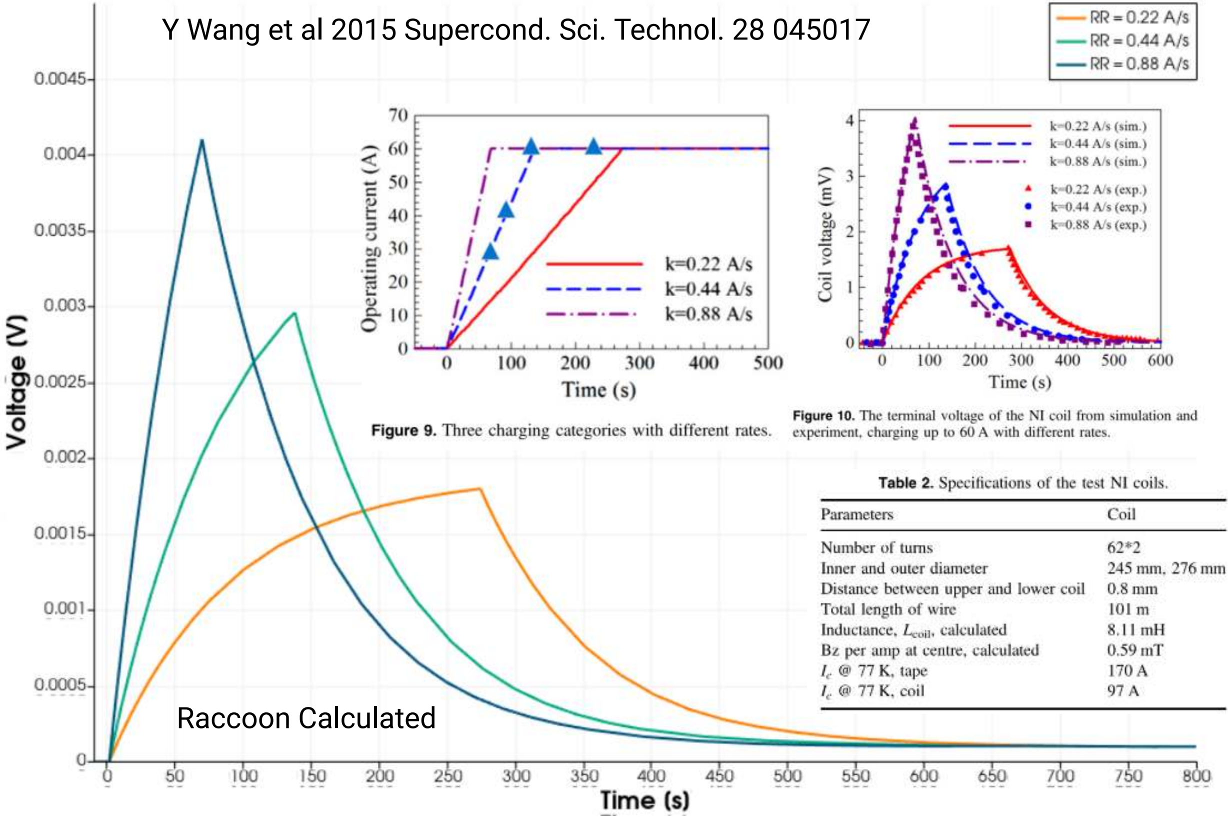


Figure 9. Three charging categories with different rates.

Figure 10. The terminal voltage of the NI coil from simulation and experiment, charging up to 60 A with different rates.

Table 2. Specifications of the test NI coils.

Parameters	Coil
Number of turns	62*2
Inner and outer diameter	245 mm, 276 mm
Distance between upper and lower coil	0.8 mm
Total length of wire	101 m
Inductance, L_{coil}, calculated	8.11 mH
Bz per amp at centre, calculated	0.59 mT
I_c @ 77 K, tape	170 A
I_c @ 77 K, coil	97 A

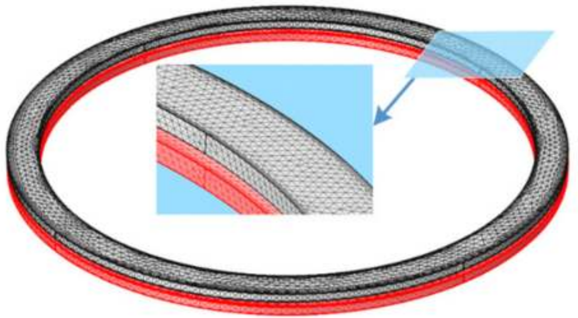


Figure 4. The FEM model of the DP coil to calculate the induced magnetic field.

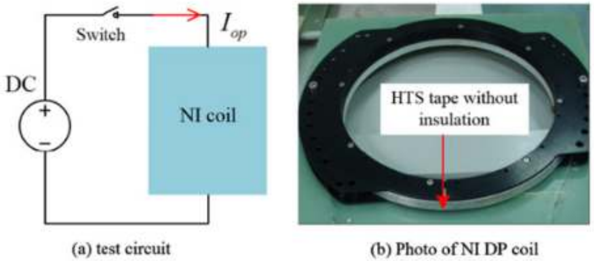
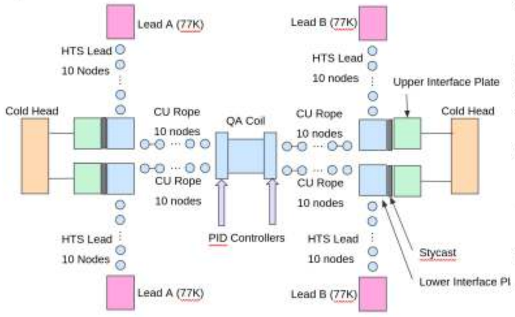


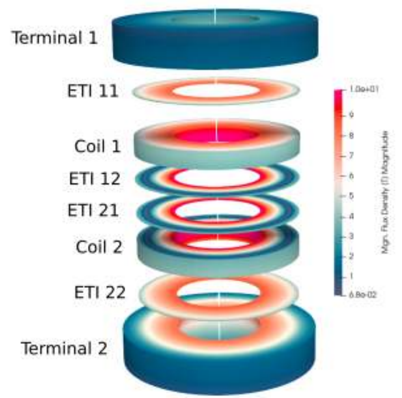
Figure 5. (a) Schematic drawing of the test circuit; (b) photo of the test NI coil.

Model Validation QA Coil

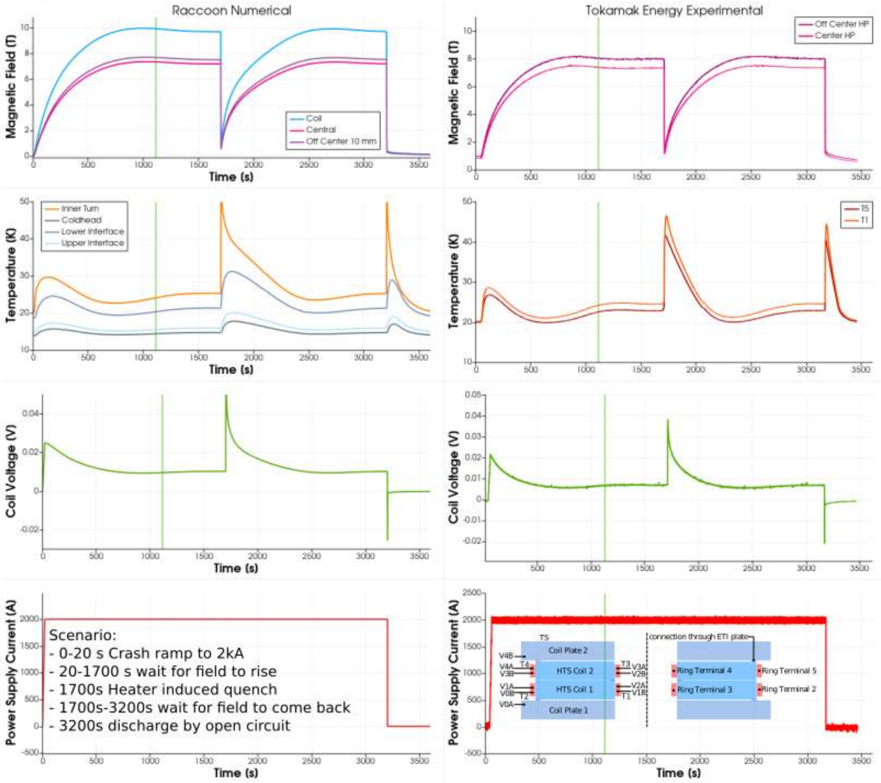
Cryo test rig thermal model



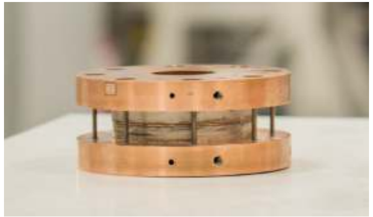
Coil Model



Compare Raccoon with Experimental Data

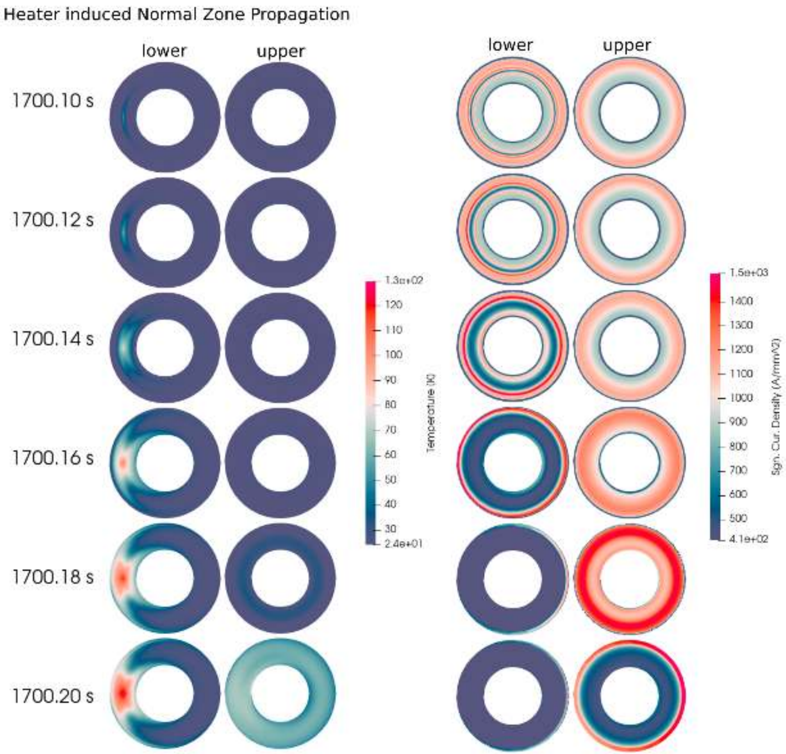


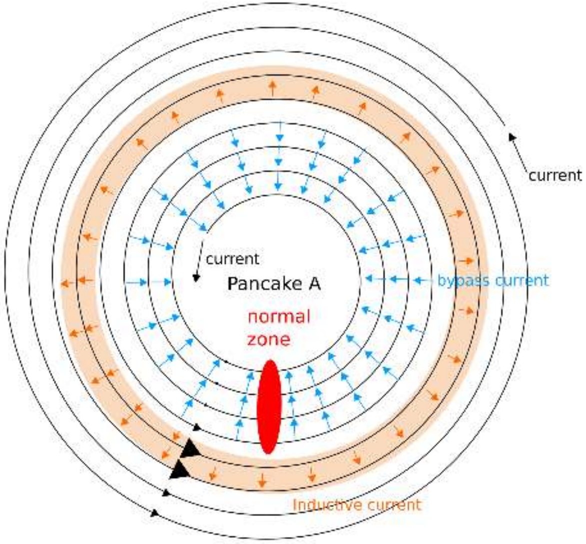
- With Raccoon we simulated in detail
  - Ramp-Up
  - Heater induced quench
  - Recovery
  - Discharge
- Excellent agreement



Shock-Wave Effect I

- One notable detail are the high current waves traveling through the coil during a heater induced a quench.
- These might cause high local stress concentrations.



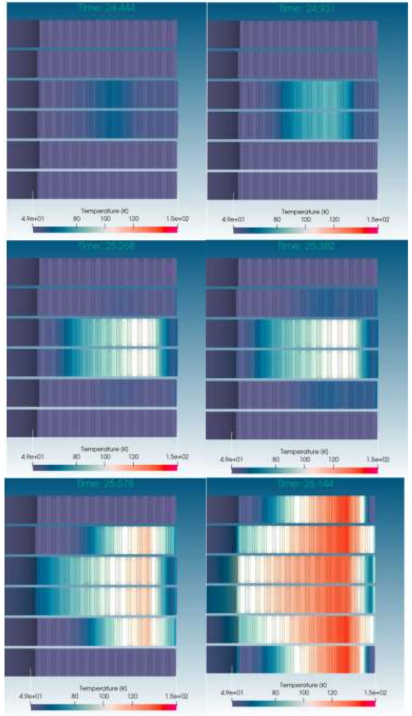


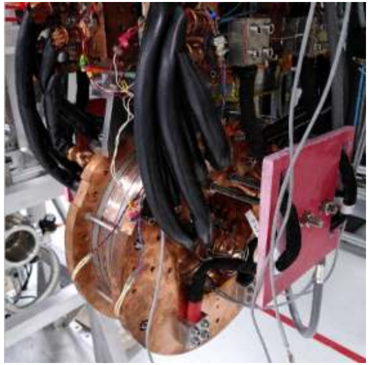
natural propagation direction
is alongside the spiral direction

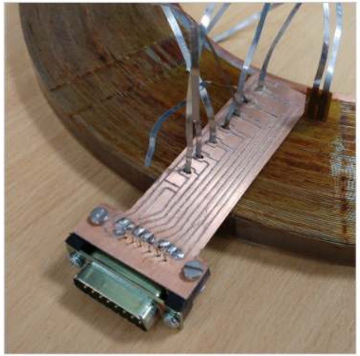
Model Validation Demo2

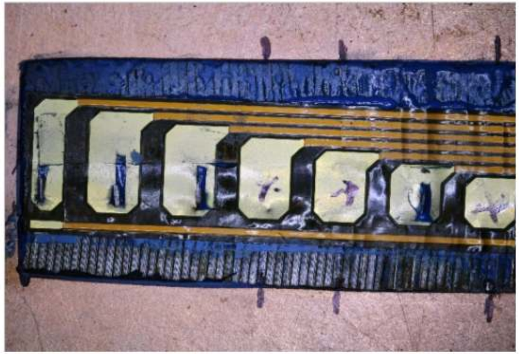
- Many features are similar, but quantitatively is a bit different.

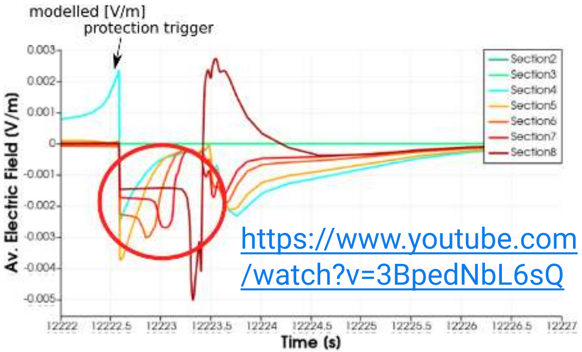
Temperature



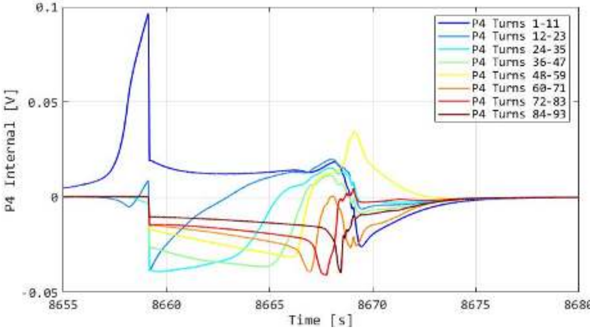








https://www.youtube.com/watch?v=3BpedNbL6sQ



Scaling Up

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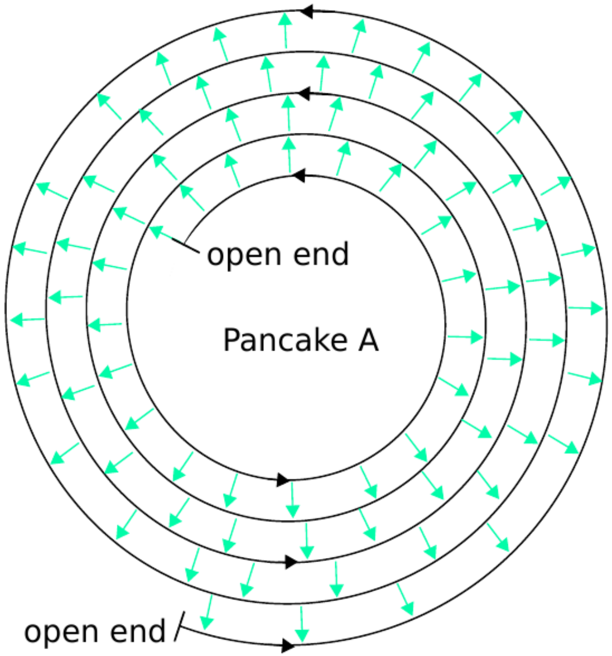
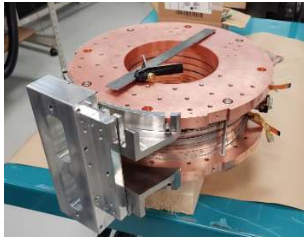
Partial Insulation Protection

- The idea is to use a Partially Insulated (PI) coil with high radial resistance.
  - Low ramp time constant (L/R).
  - When the circuit breaker is opened the open circuit current is forced through this high resistance path causing high heating.
  - When the coil is normal conducting the resistance of the spiral path converts the stored energy into heat.
- Essentially a fully distributed quench heater that uses the coil's stored energy to drive it.

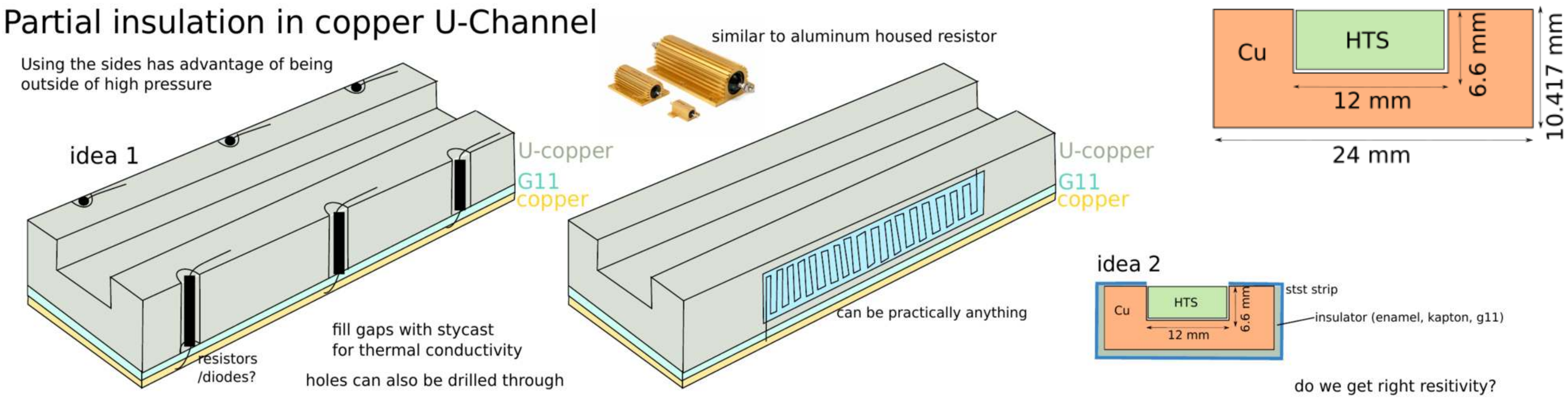
Open Circuit Current





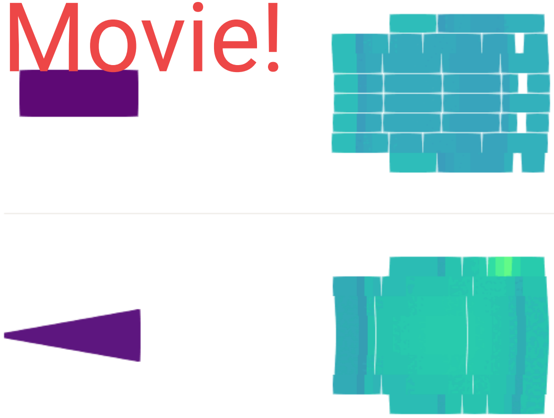
Integrating Partial Insulation

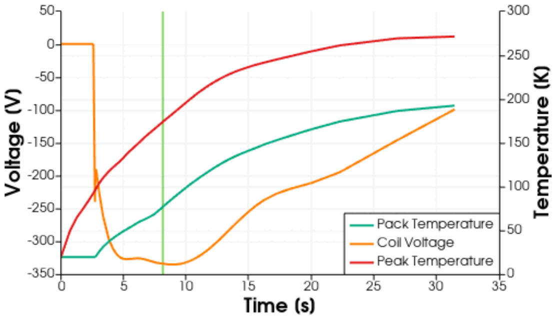
- We are proposing a copper U-shaped channel with HTS soldered into it.
- PI-insulation can be integrated into the channel. Options are limitless here:
    - Resistors, Diodes, Varistors (metrosil), Thyristors, Capacitors, MOSFETS, Hydraulic/Pressure switches, Superconductor, Special compounds, Circuits
- But beware, the stored energy of coil must be absorbed somewhere ...

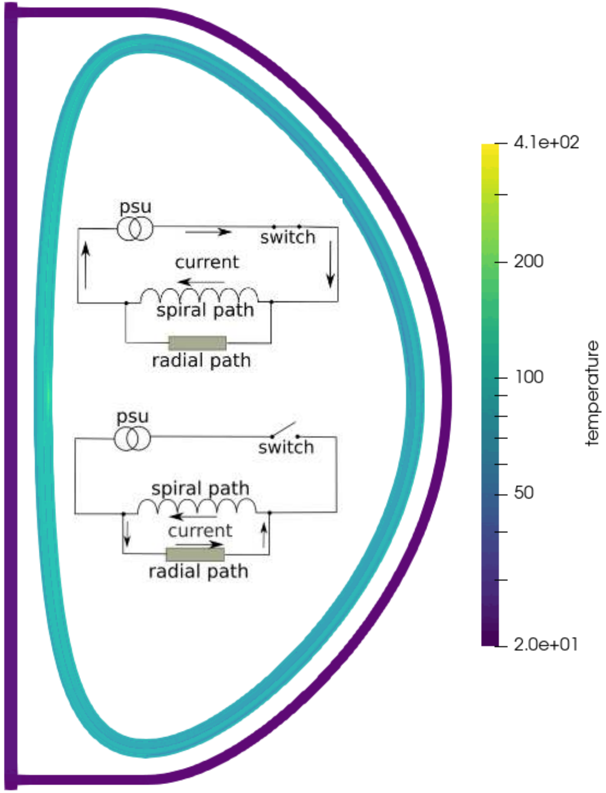


Energy Extraction with PI

Movie!



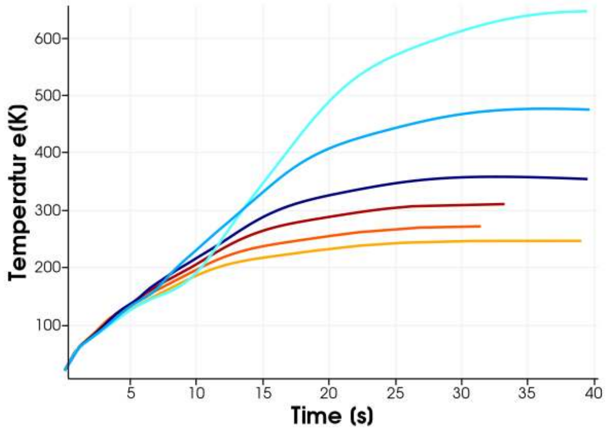


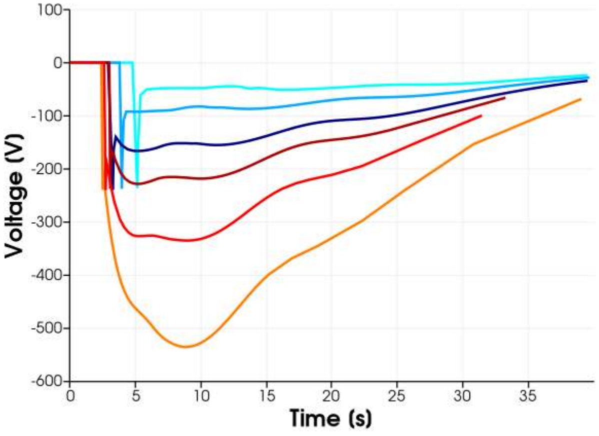


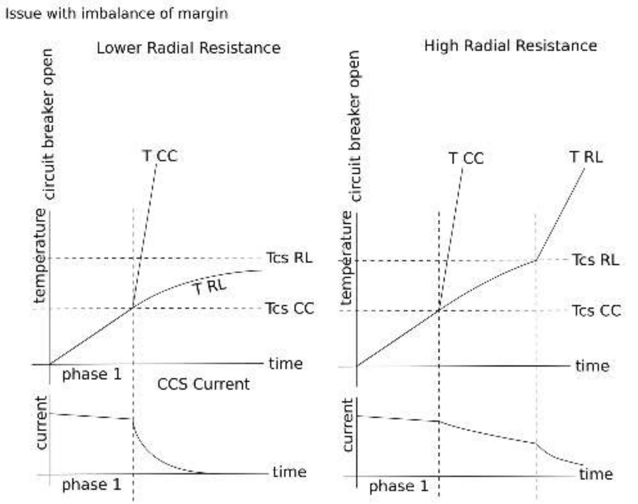
1. A normal zone is initiated using a 600 J (!) heat pulse.
2. The quench propagates until it is detected at 100 mV.
3. The circuit breaker opens forcing radial current.
4. The coil heats up over current sharing temperature.
5. The coil becomes resistive and heats up faster.
6. Final coil temperature 220K.

Effect of Voltage

- Thermal margin difference within the coil must be overcome with heating power.
- The radial resistance of the coil can be freely chosen. The open circuit voltage can therefore be controlled.
- For ST280-5T a voltage of 300 V per limb or 5.4 kV for full toroid seems reasonable.
- This is order of magnitude less than classical protection!







Conclusion

- Partial Insulation uses order of magnitude lower total protection voltage (allowing for) much less current leads.
- Less current leads:
  a. cooling wall-power reduction from several 100 kW to several 10 kW.
  b. More space for other components such as RF feeders etc.
- Far fewer components in protection circuit that can fail, such as switches etc.
- Self-protecting and reduced voltage in case of open circuit failure such as broken current leads.
- Cold mass must have sufficient heat capacity to take the stored energy of the coil (current density limit).

Thanks

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