Quench Protection of Stacks of No-Insulation HTS Pancake Coils by Capacitor Discharge

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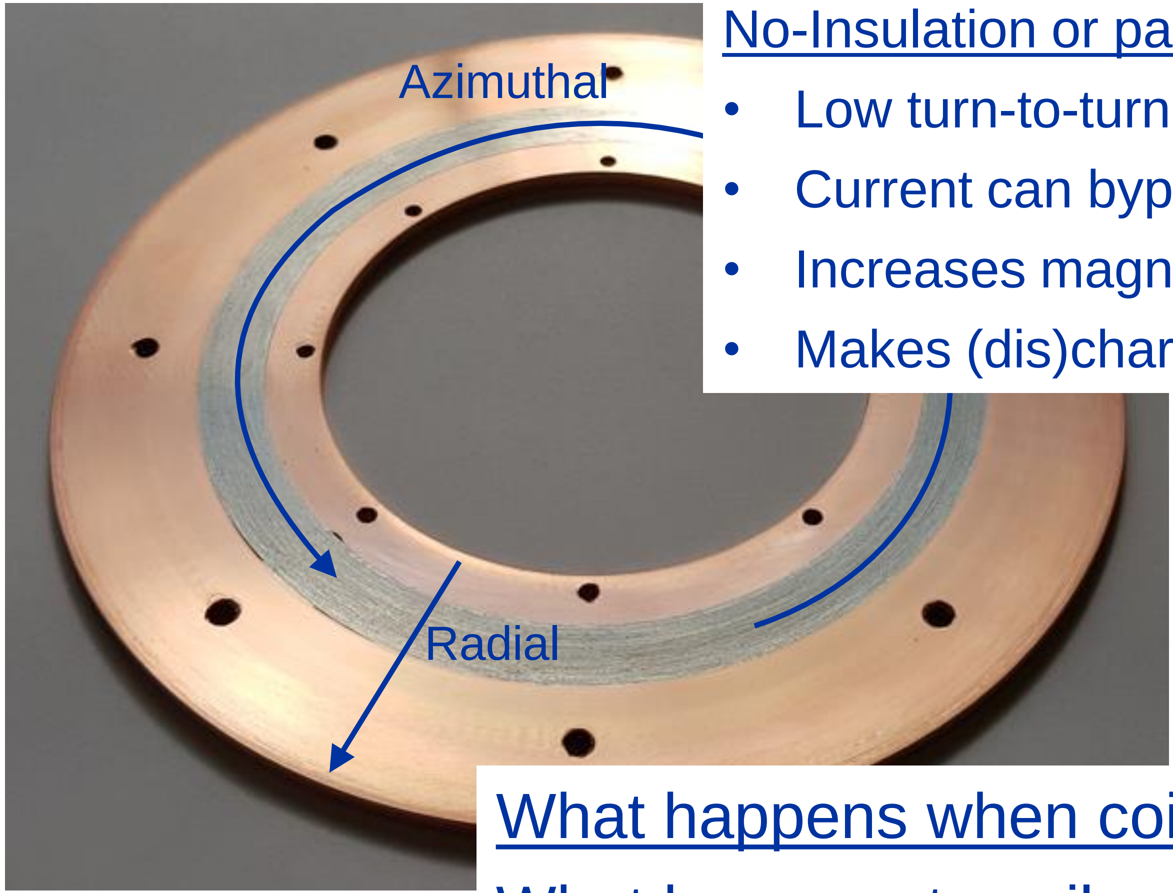
16/11/2023

Presented during the MMWG, 16/11/2023

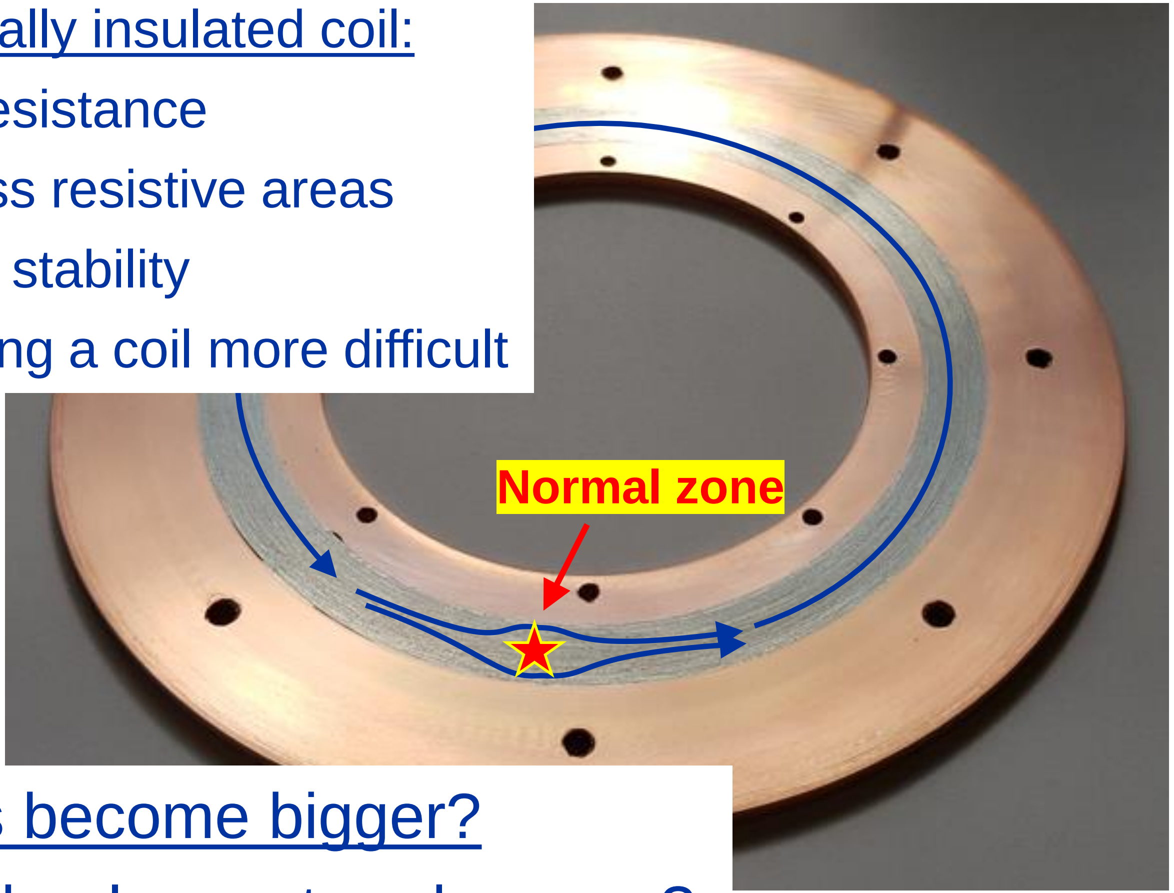
Quench behavior of NI HTS coils

Parallel path for the current around a normal zone.



No-Insulation or partially insulated coil:

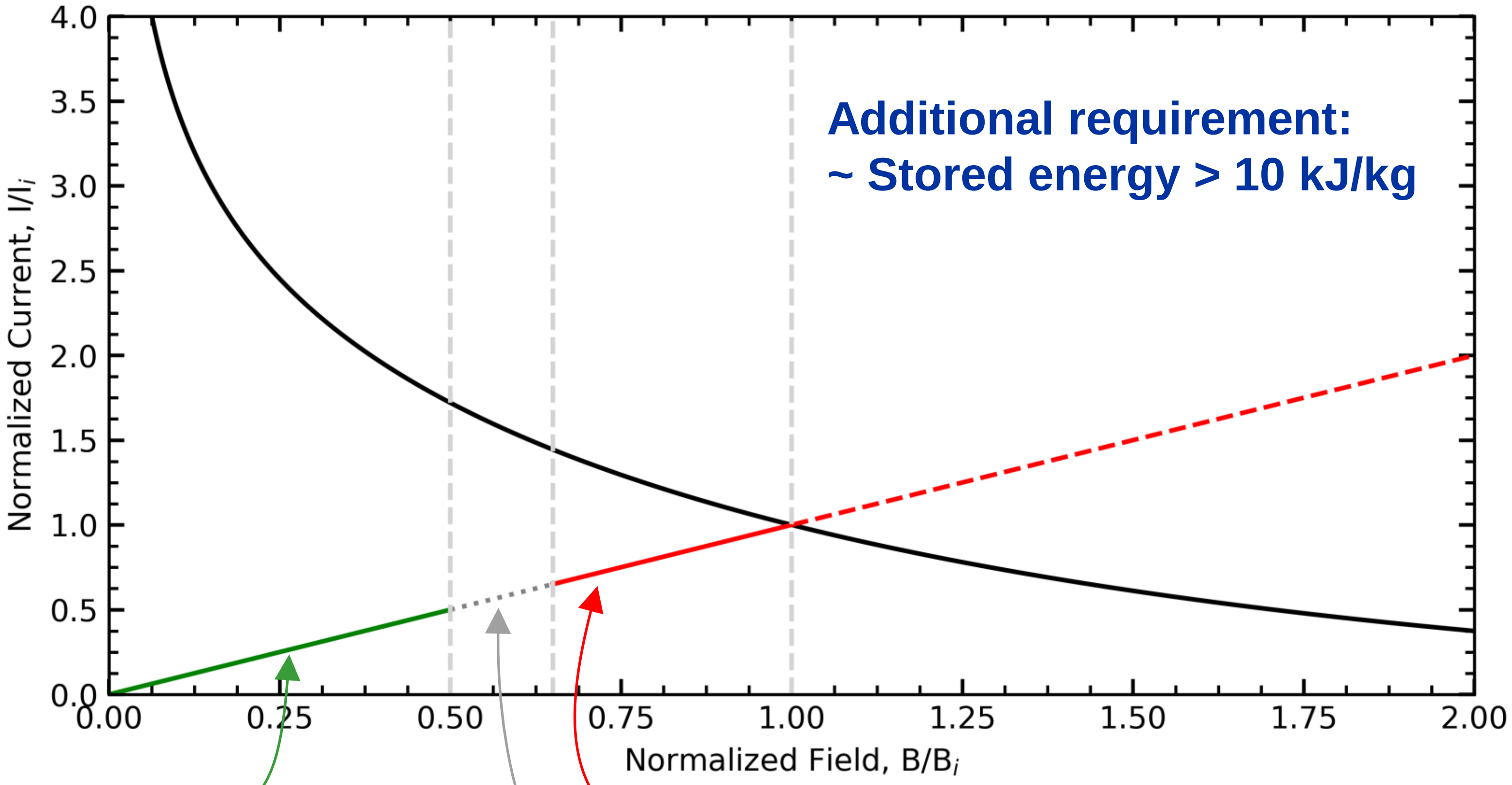
- Low turn-to-turn resistance
- Current can bypass resistive areas
- Increases magnet stability
- Makes (dis)charging a coil more difficult



What happens when coils become bigger?

What happens to coils with a large stored energy?

Quench behavior of Large NI HTS coils



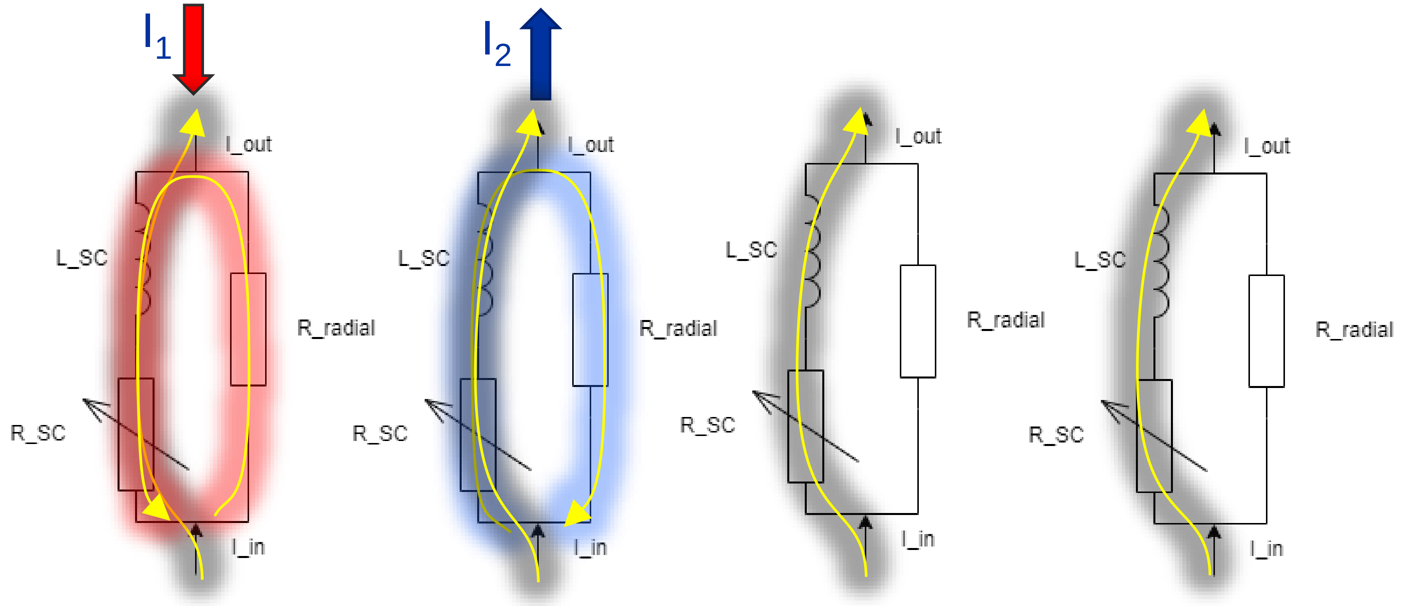
Classical behavior
Slow thermal diffusion

Fast inductive quench propagation

Unique to well coupled NI coils with high energy density

Grey area

Inductive Quench Propagation



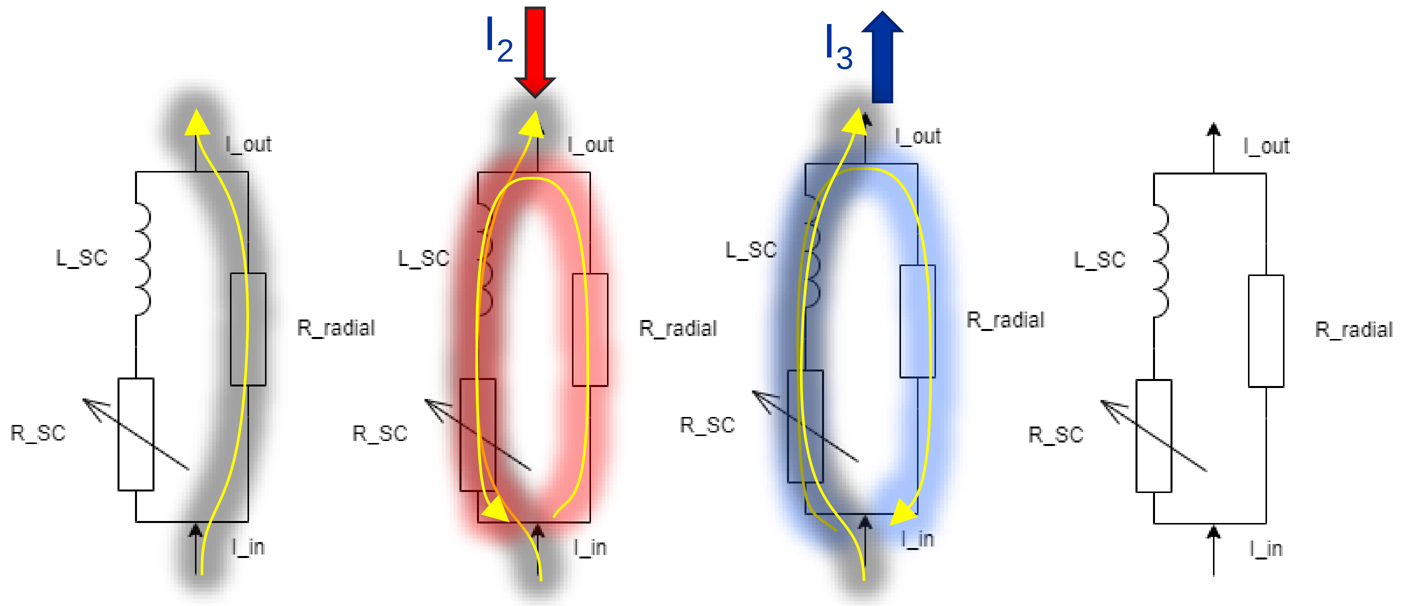
Part of the energy is dissipated inside each turn/pancake.

Part of the energy is push forward towards adjacent turns/pancakes.

Two main disadvantages:

1) Local Lorentz force may increase significantly due to induced current
2) Local energy density may increase significantly, dissipated most likely in the extremities.

Inductive Quench Propagation



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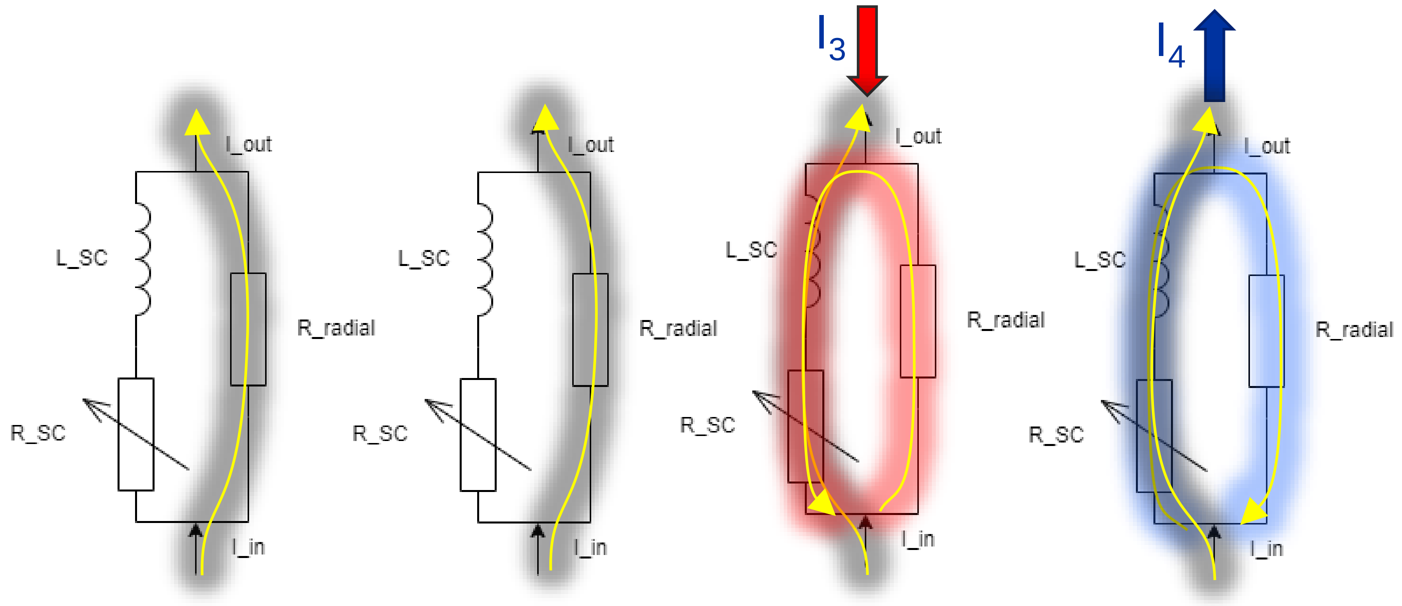

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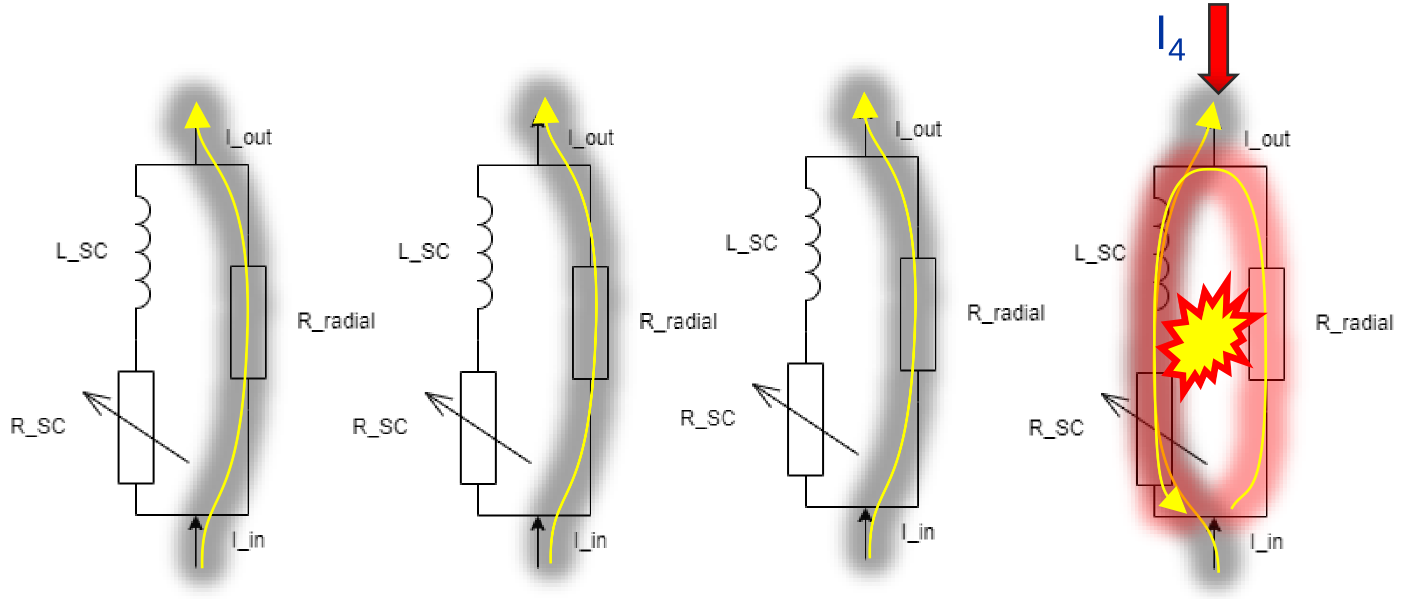

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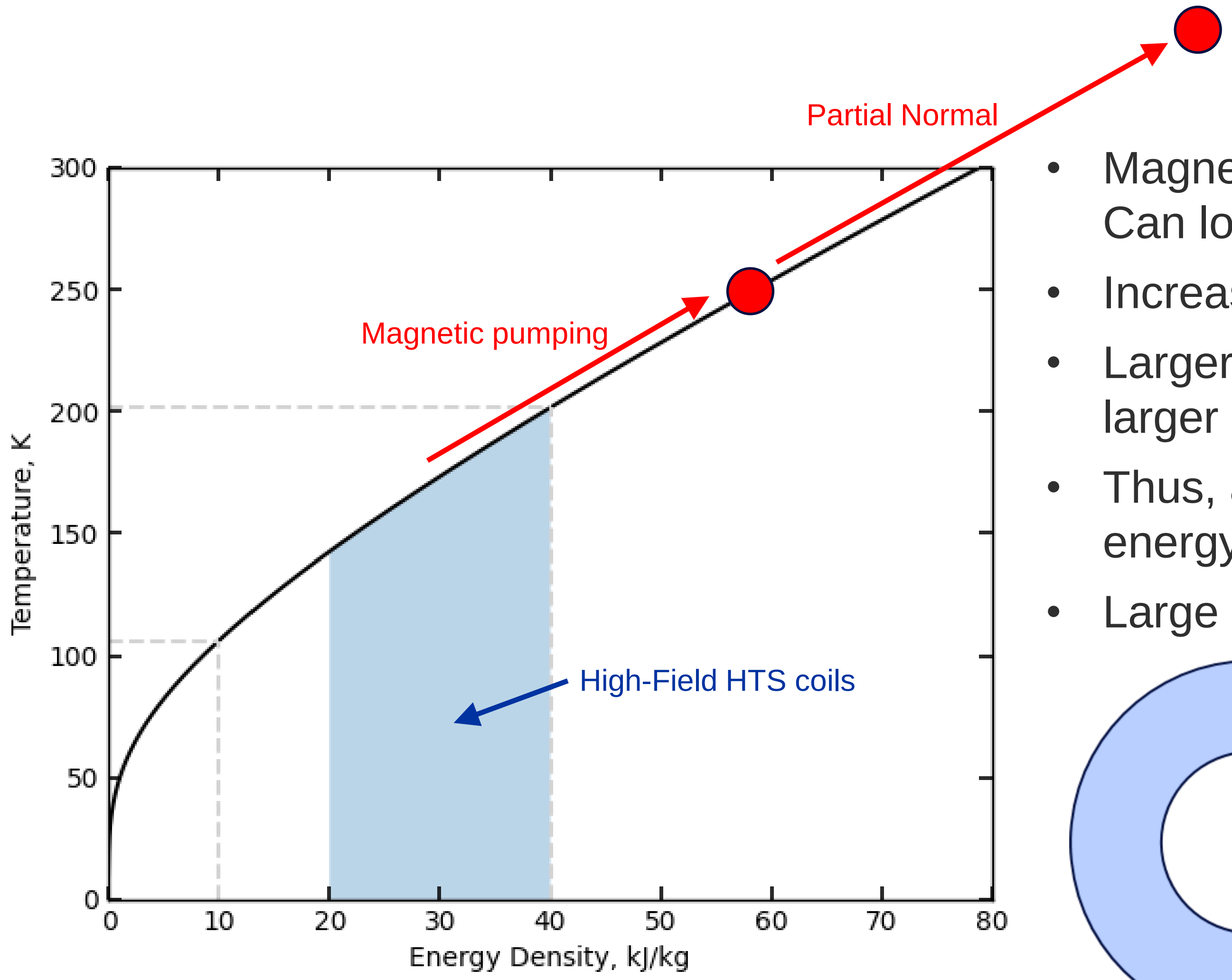
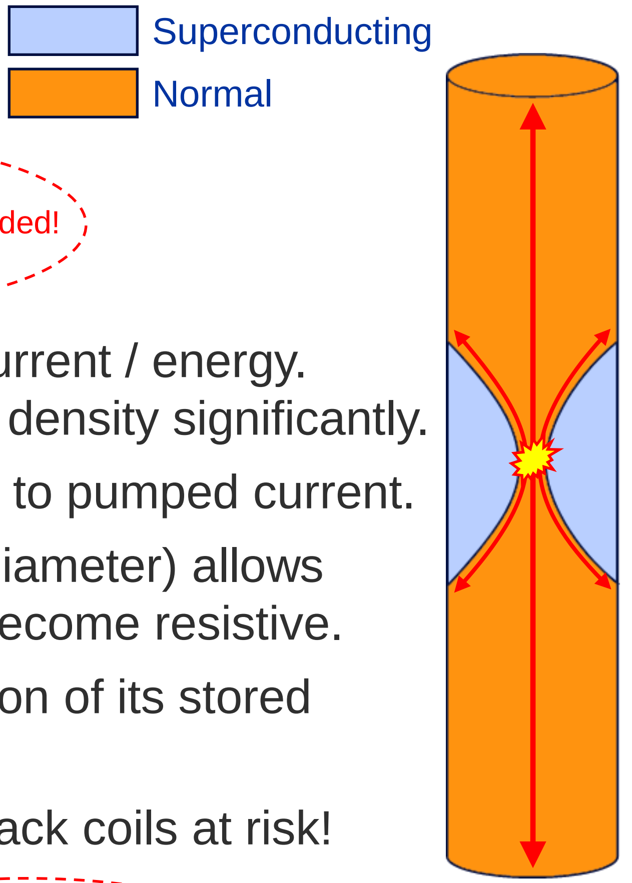
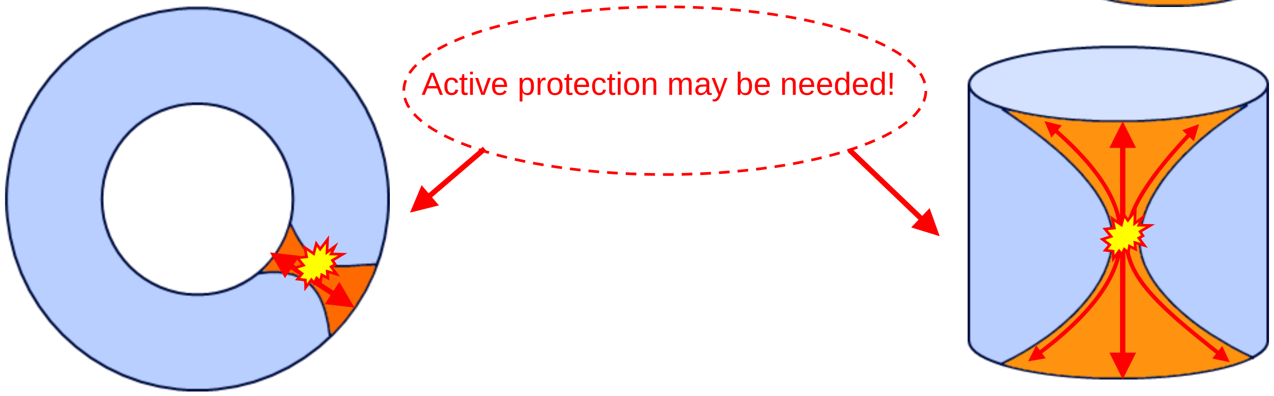
Quench Challenges of NI Coils



- Magnetic pumping moves current / energy. Can locally increase current density significantly.
- Increased Lorentz force due to pumped current.
- Larger aspect ratio (length/diameter) allows larger portion of the coil to become resistive.
- Thus, allows better distribution of its stored energy.
- Large flat NI pancake/racetrack coils at risk!





Protection of NI HTS magnets

Passive - Reduce energy density by increasing the mass of the magnet:

- Thicker conductor, additional turns, lower I_{op} and thus higher conductor price-tag.
- Surround copper for inductive coupling.
- Mechanical impact and possible additional loss during ramp.

Active - Applying heat, traditionally done with heaters:

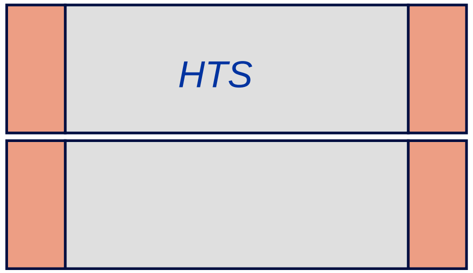
- Transition large section of the coil to normal state, <u>preferably over entire circumference</u>.
- Due to high TEM stability, large energy required to transition entire magnet to normal state.
- Able to quench the coil in the most favourable position.
- Heaters: separate electrical circuit, trade-off between electrical and thermal insulation.
- Heaters: integration of heaters may impact coil’s mechanical integrity.

Capacitive Discharge into the NI Pancakes

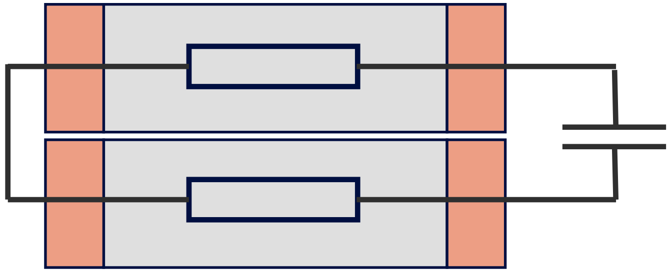
- Capacitor discharge often affiliated with CLIQ (coupling loss), proven for LTS magnets.
- Similar solution proposed/investigated for insulated HTS coils, results not optimistic.
- Does not work for NI/MI/PI coils due to the low inductive path via turn-to-turn shorts.

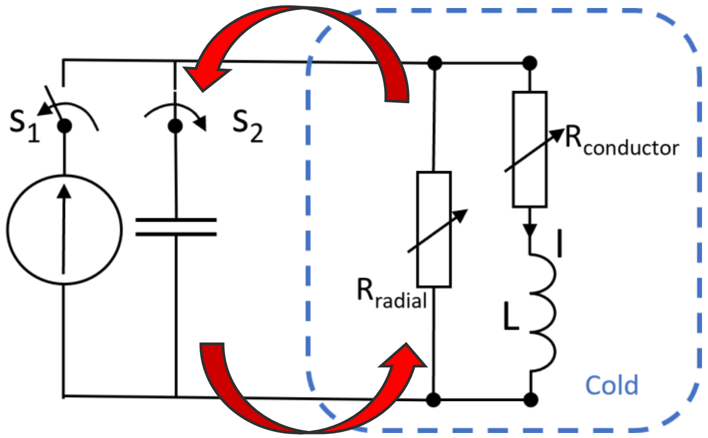
However, instead R(L)C discharge → Large current pulse.

Generate heat in the turn-to-turn resistance. Alternative to Quench Heaters.



Double Pancake

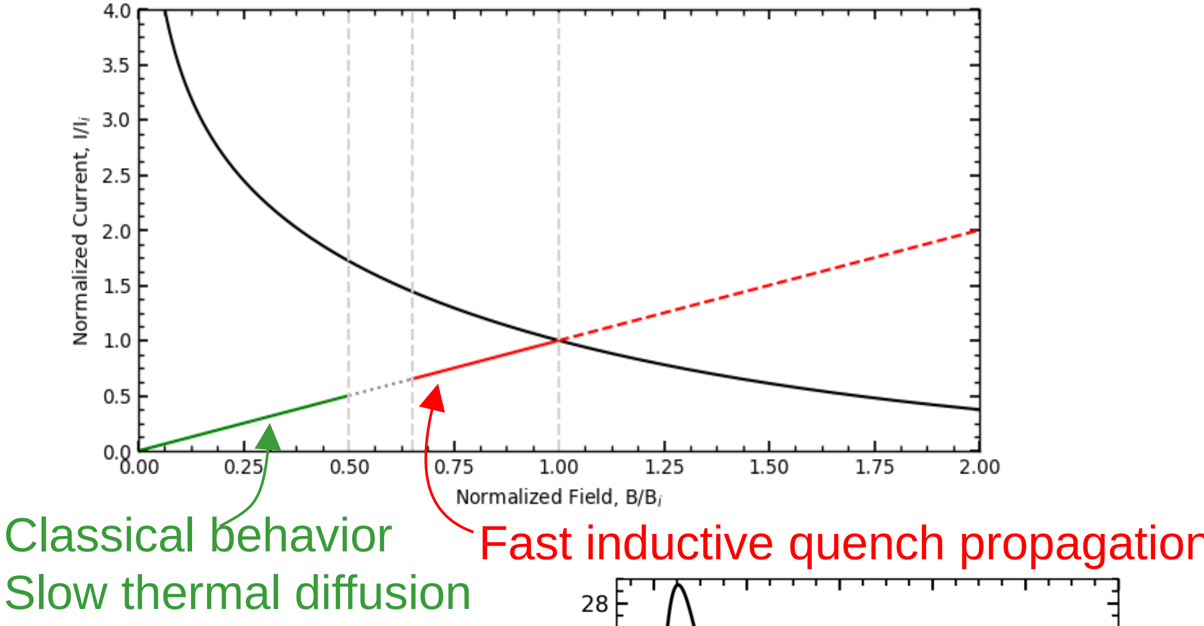




Capacitive Discharge (CD)

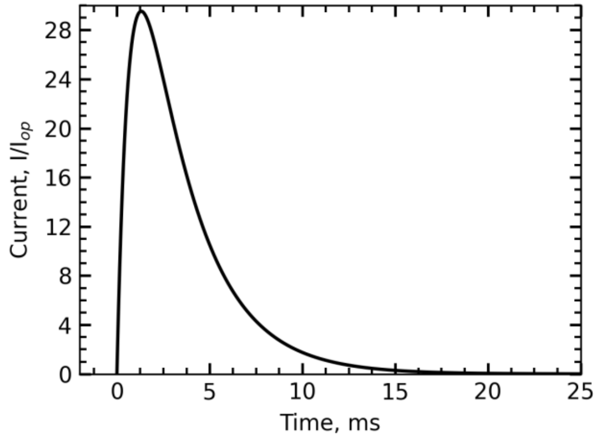
Advantages:

- No additional internal components required.
- Heat directly deposited inside the coil.
- Quench initiation within a few milliseconds.



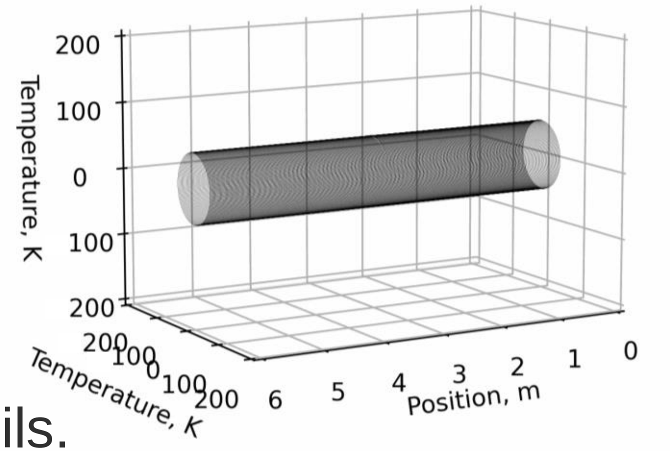
Requirements:

- Tuned turn-to-turn resistance (time-constant) of the pancake coils.
- Operation near T_{cs} or deposit a very large amount of energy.
- Sufficiently large energy density to transition entirely to normal state.
- Current connections that can withstand current of a few kA for several milliseconds.



Simulation Tool: NICQS

AMS-100 ~ 30% normal state without protection,
> 75% normal state with protection.

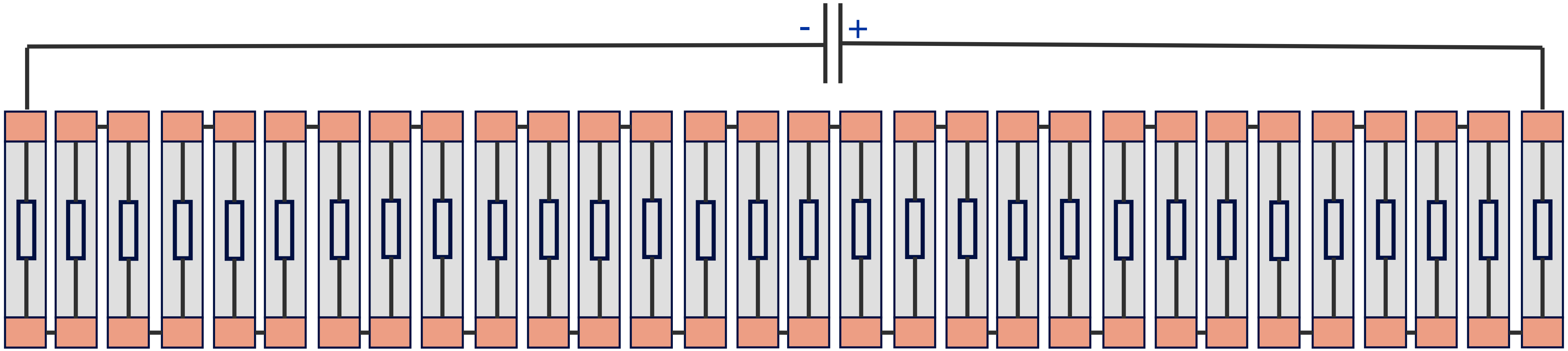


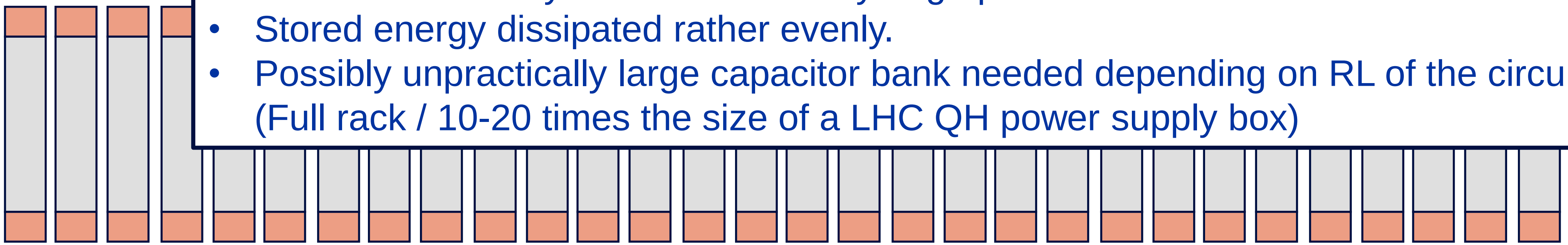
2D Model:

- Model to simulate normal operation and quench events in NI HTS coils.
- Allows any number of cylindrically shaped coil elements.
- Includes screening currents by dividing the tapes into multiple sections.
- Includes quench-back cylinders.
- Written in python, additional functionality can be added relatively easily.
- Since it is 2D, no 3D effects are included. Assumed is that a 'natural quench' transitions approx. 50% of the 40 T coil to normal state, based on AMS-100 3D simulations.

Multi-pancake HTS Solenoids

Example: 42 HTS NI pancakes,
40 T & Energy density of ~ 30 kJ/kg





- Ideal case where you transition a very large part of the coil to normal state.
- Stored energy dissipated rather evenly.
- Possibly unpractically large capacitor bank needed depending on RL of the circuit. (Full rack / 10-20 times the size of a LHC QH power supply box)

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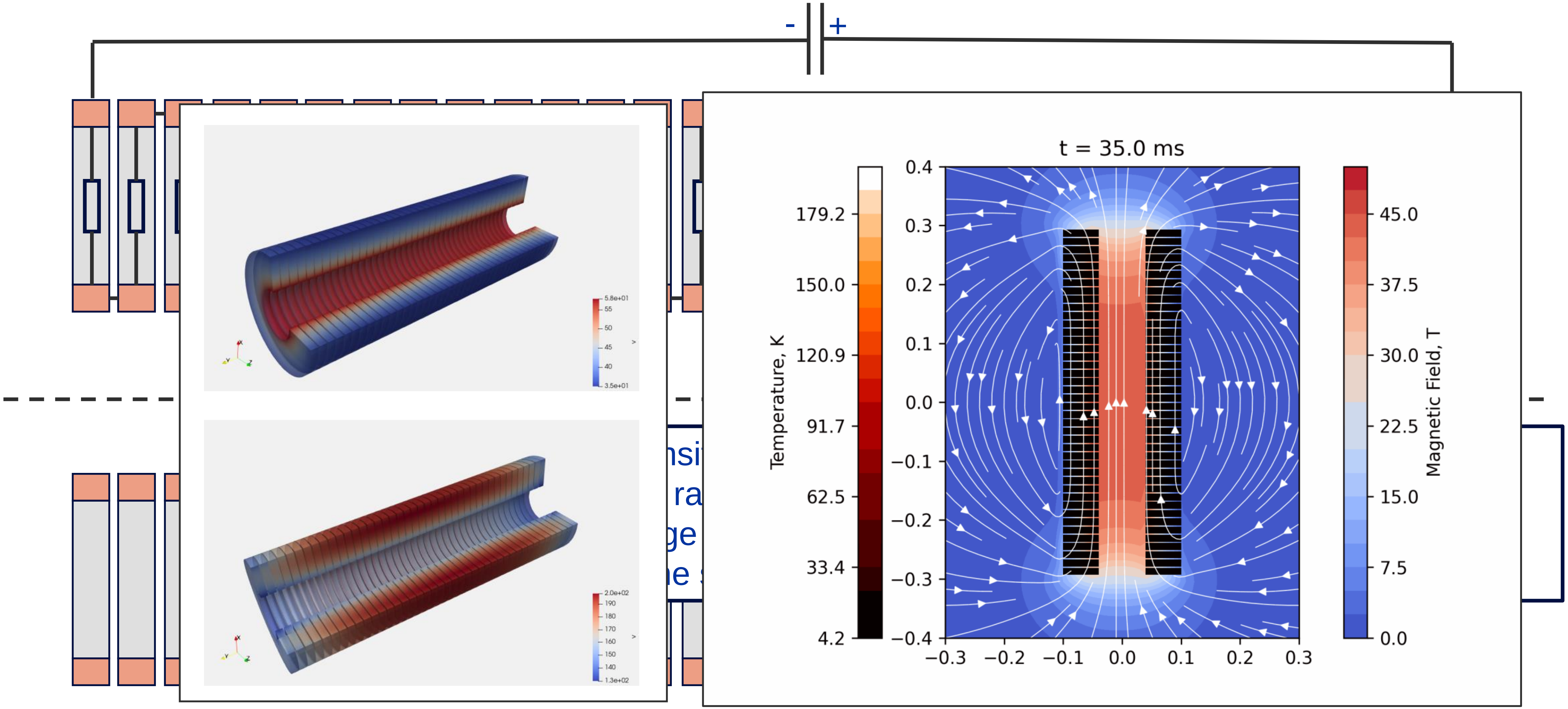

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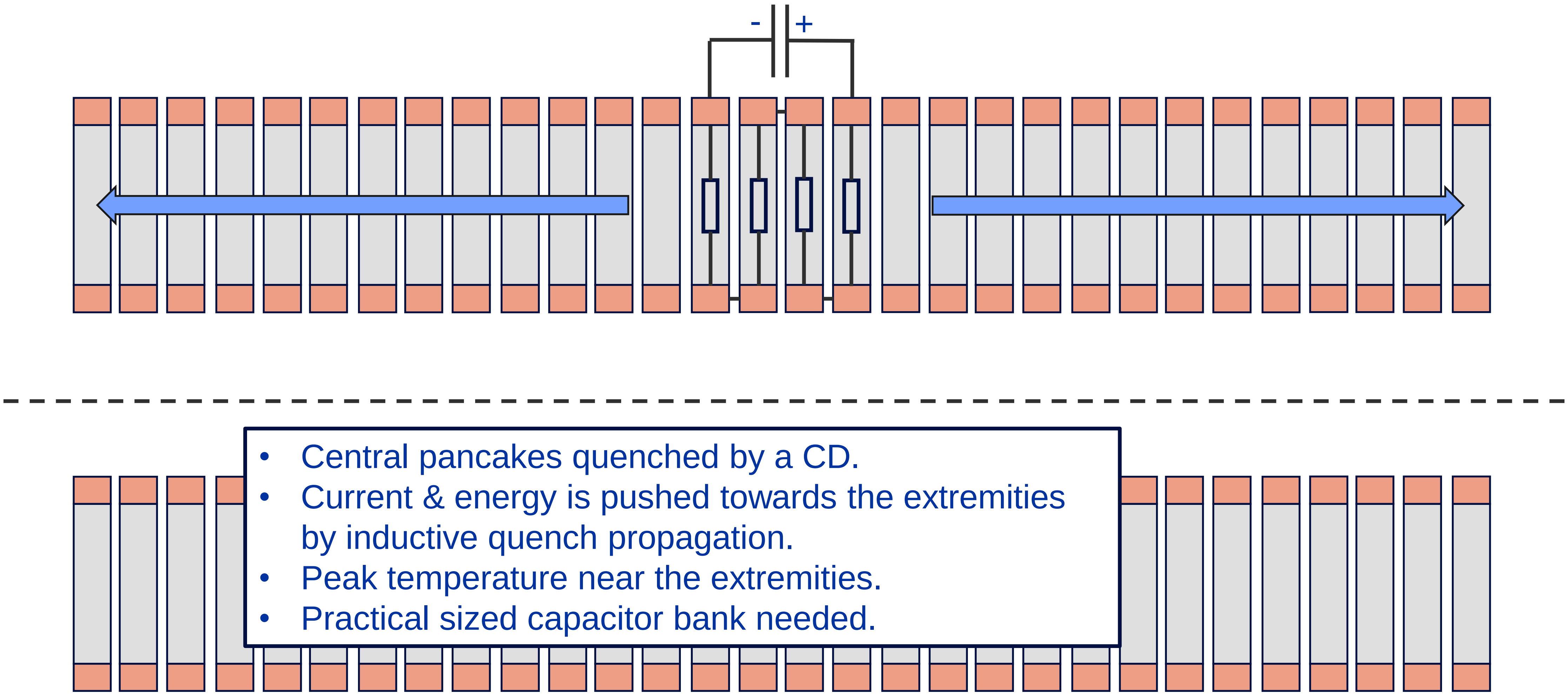

- Central pancakes quenched by a CD.
- Current & energy is pushed towards the extremities by inductive quench propagation.
- Peak temperature near the extremities.
- Practical sized capacitor bank needed.

Multi-pa enoids

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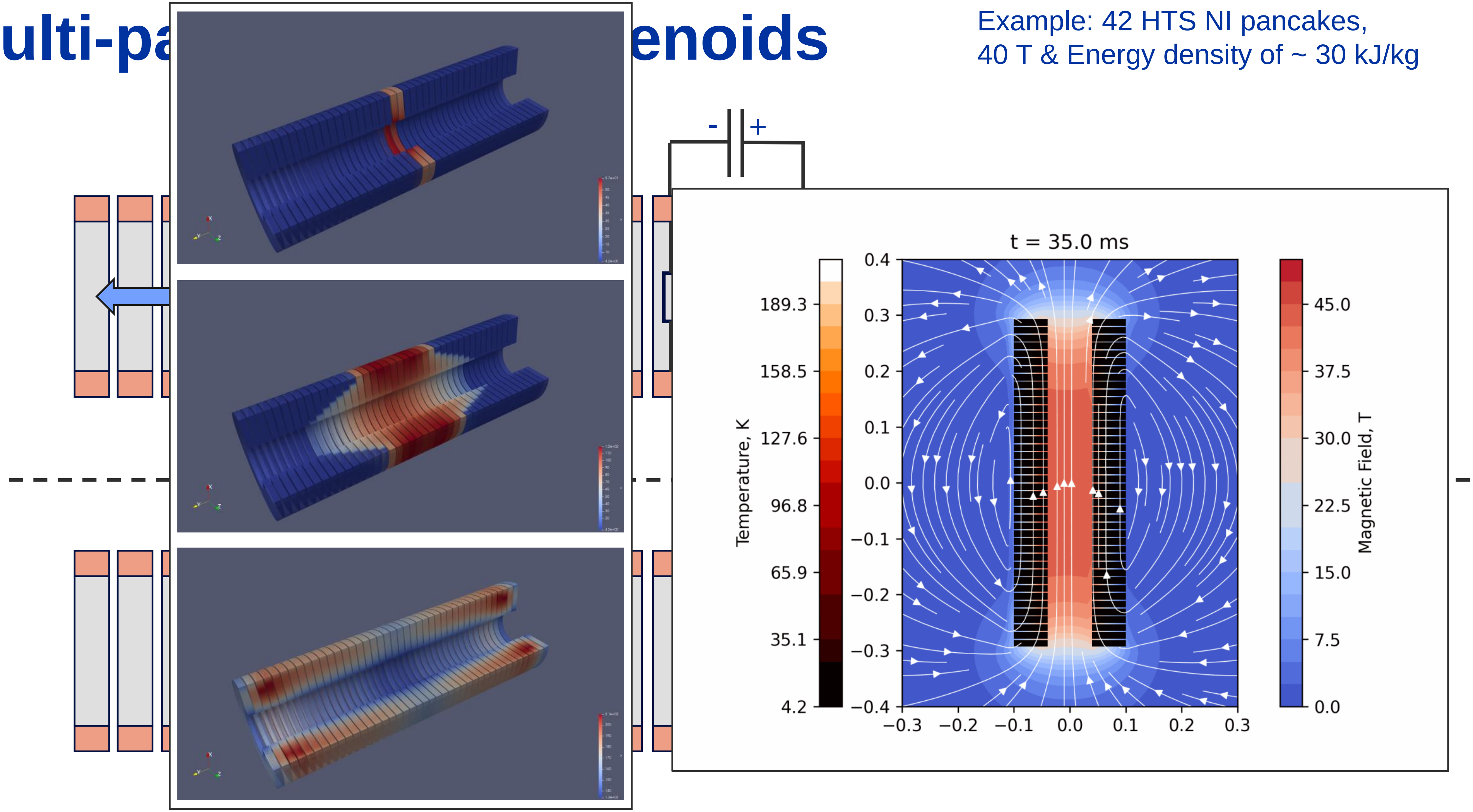

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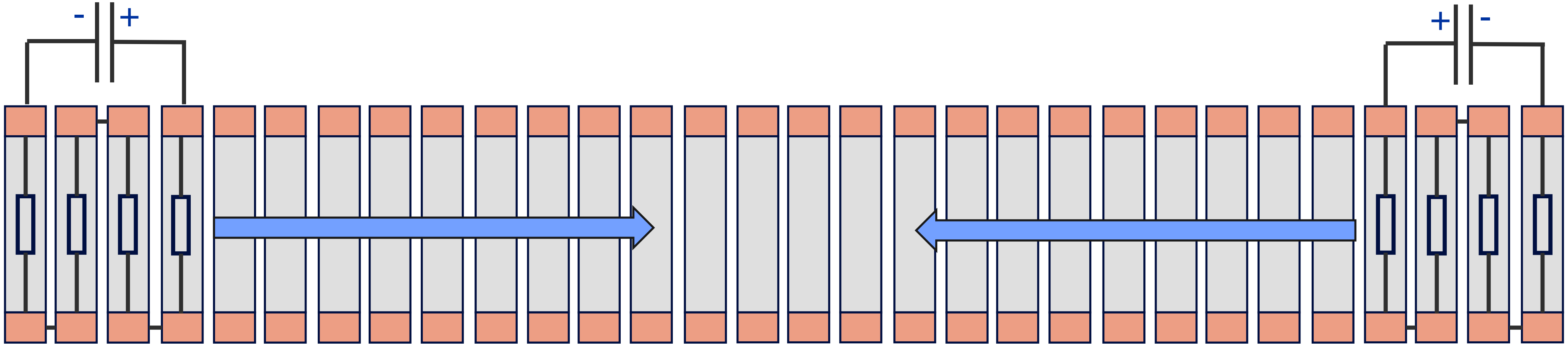

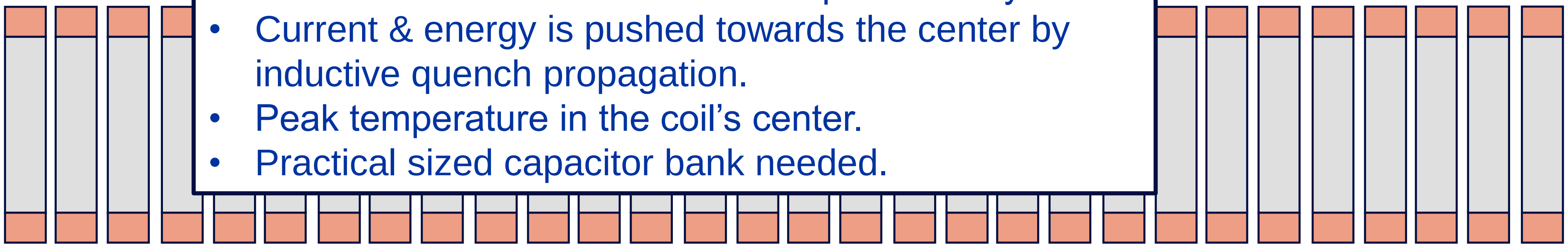

- Pancakes in the coil’s extremities quenched by a CD.
- Current & energy is pushed towards the center by inductive quench propagation.
- Peak temperature in the coil’s center.
- Practical sized capacitor bank needed.

Multi-pa... enoids

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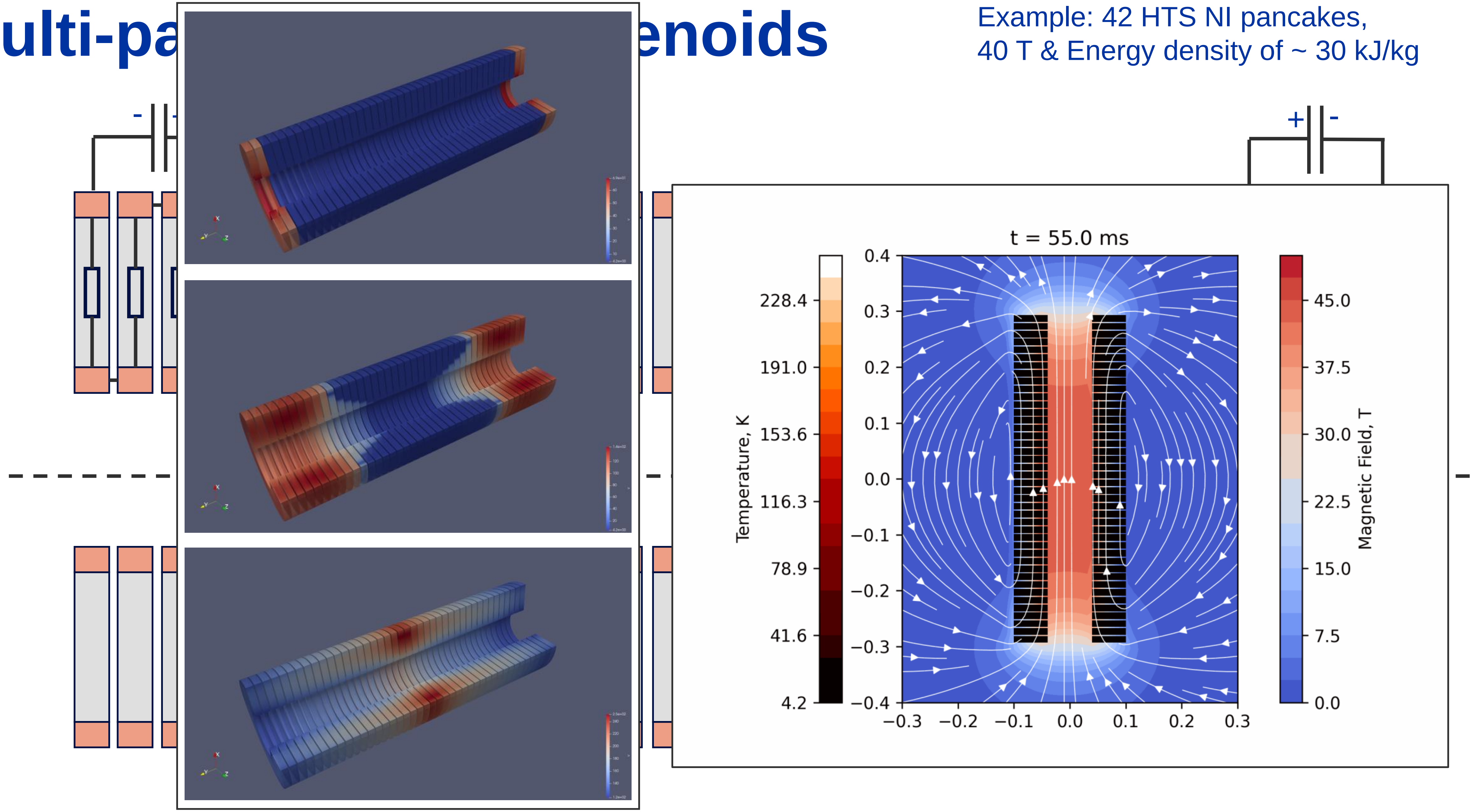
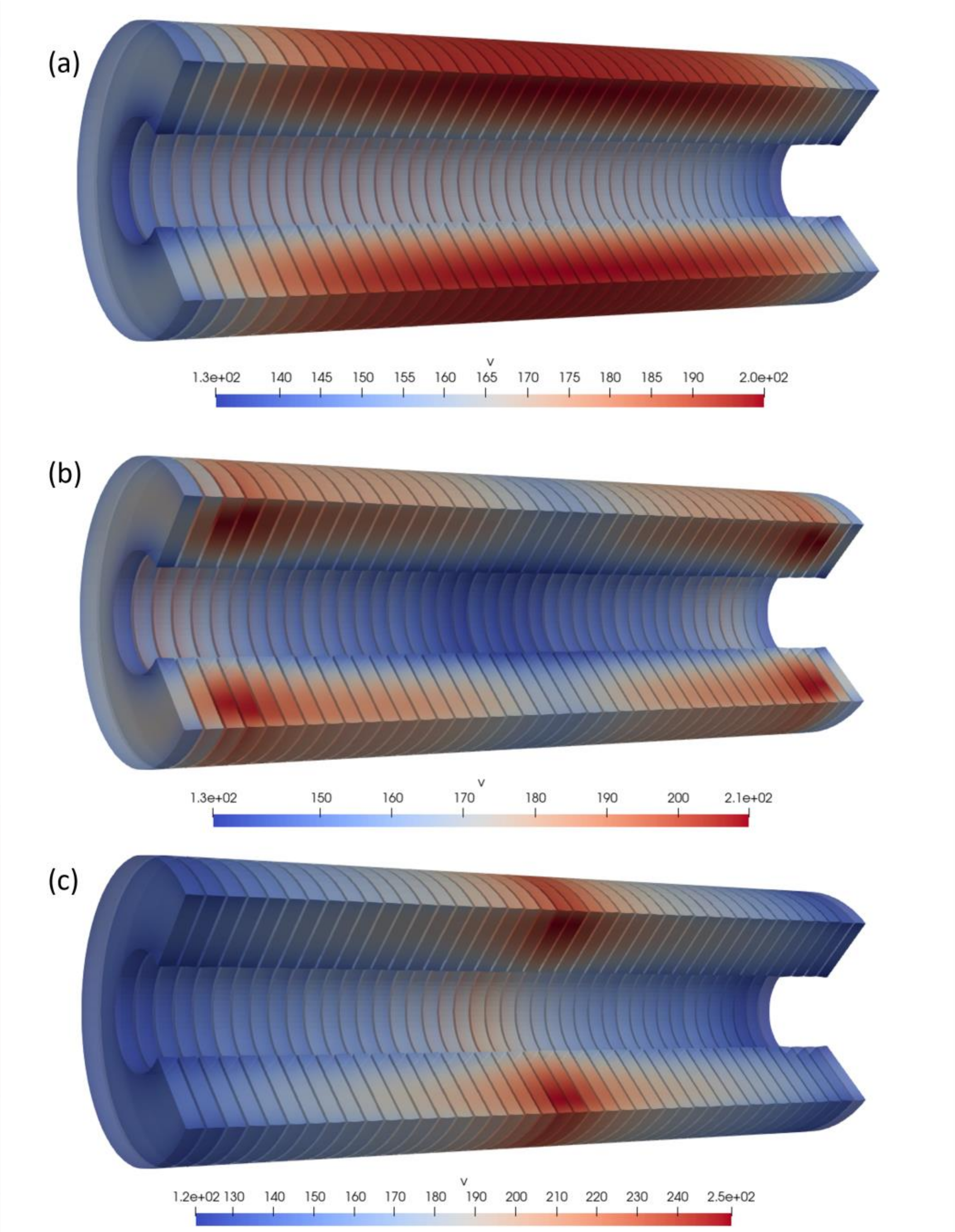
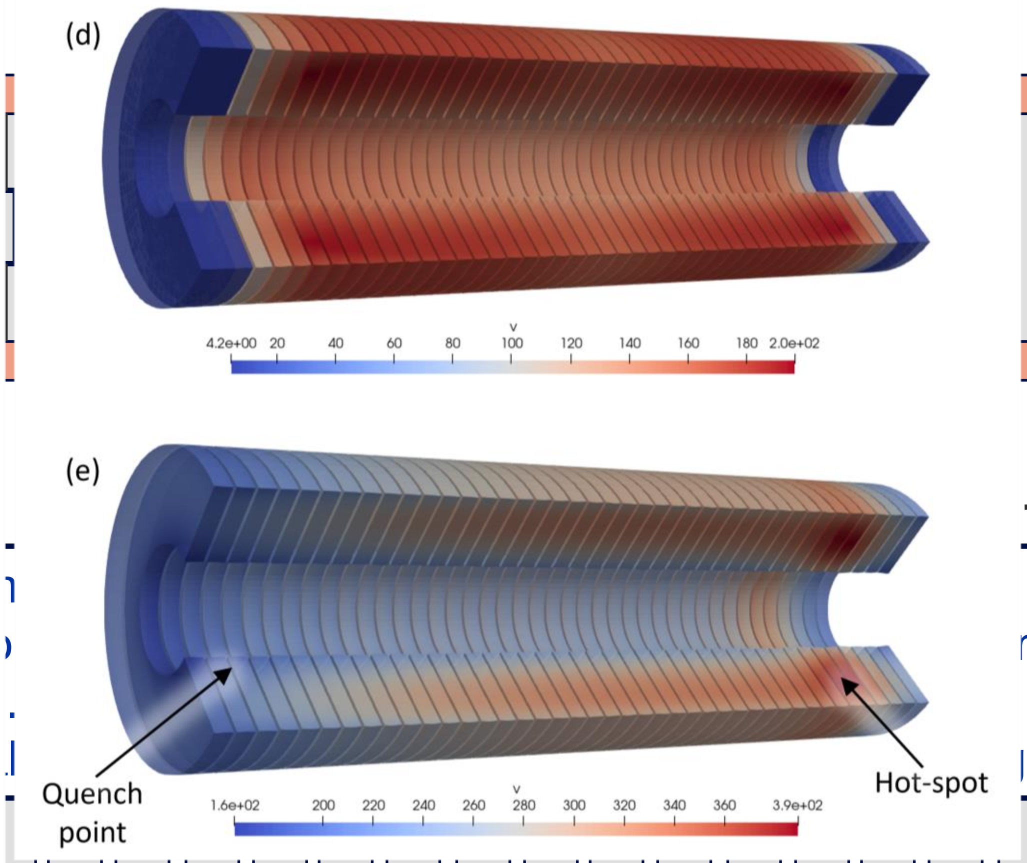


Cap ductive Quench Back





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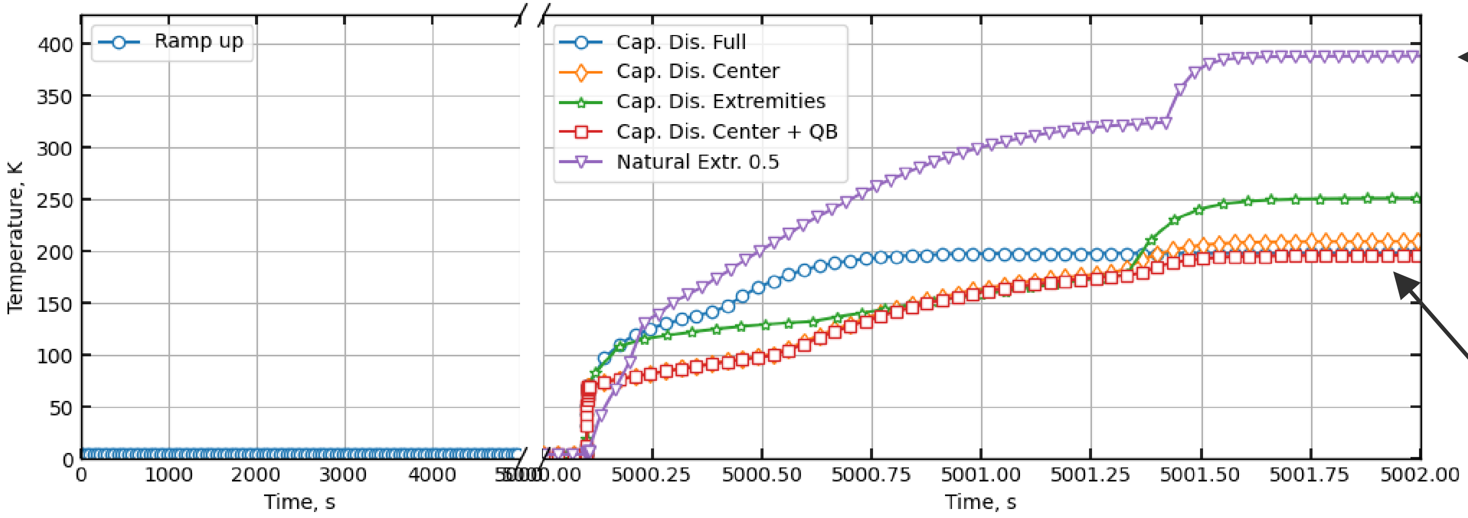
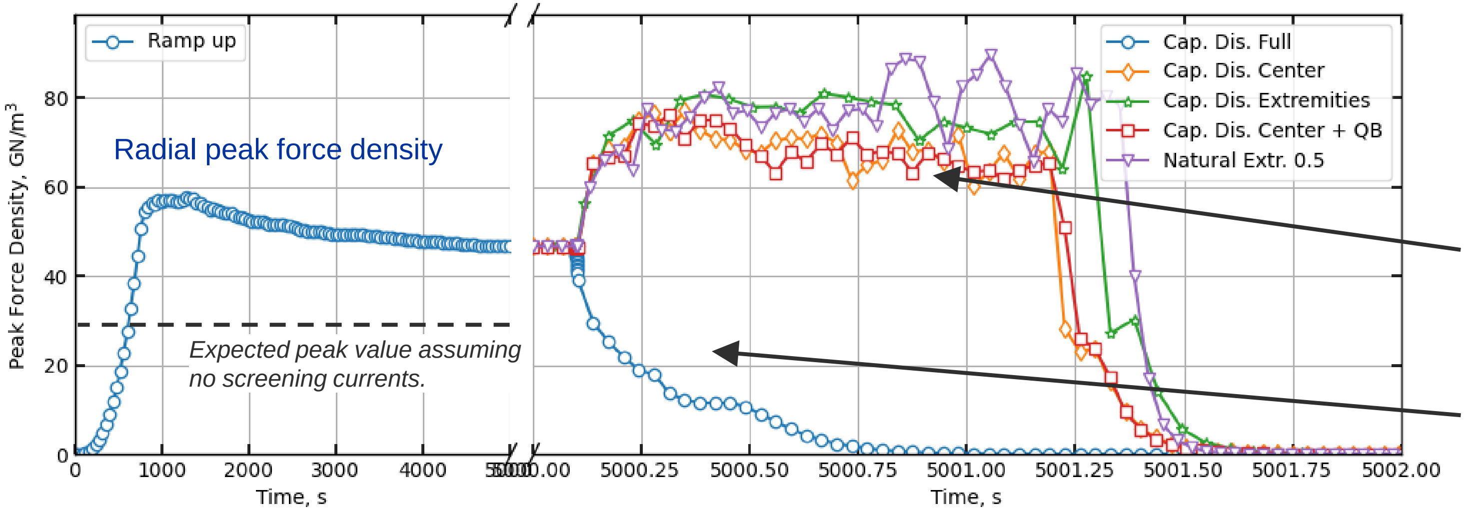
Potential improvements – Numerical Results



Natural quench, assuming the stored energy is dissipated in 50% of the coils mass.

Capacitor discharge, assuming the stored energy is dissipated in 80% of the coils mass. Can reduce the hot-spot temperature!

Similar peak temperature – CD full magnet and CD in the coils center + quench back cylinders.



Large increase in radial force density during partial quench, best result with a CD in the coil's center.

<u>Quenching the full coil at once prevents high induced currents and increased force density.</u>

Conclusion

- Novel Quench protection method by capacitor discharge (alternative to QH).
- May be interesting for HTS solenoids comprising many NI pancake coils.
- Allows fast quench initiation on the pancake's inner turns.
- Able to completely transition full coil circumference from SC to normal state.
- Subsequently increase normal fraction of the magnet to dissipate stored energy.
- Potential to reduce the peak temperature and peak conductor stress significantly.
- Zero additional components needed between coil packs.

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