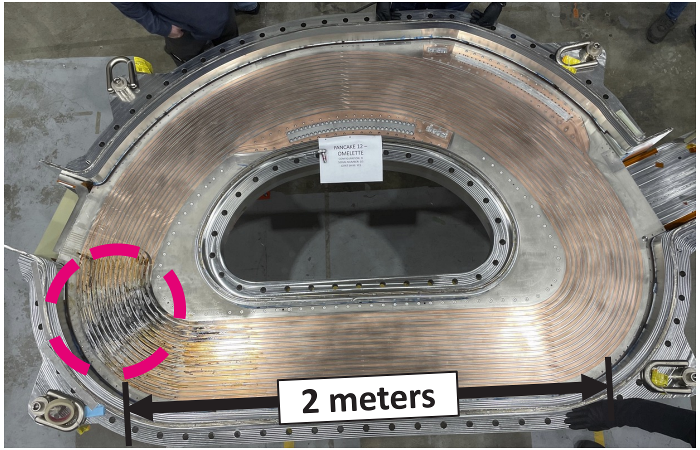
“Are REBCO NI Magnets Really Self-protected?”

Case in point:

Quench Response of the SPARC Toroidal Field Model Coil



Brian LaBombard

MIT PSFC

September 4, 2024

3J-ML-Or2A-05

Plasma Science and Fusion Center

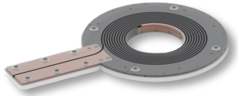
Commonwealth Fusion Systems

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

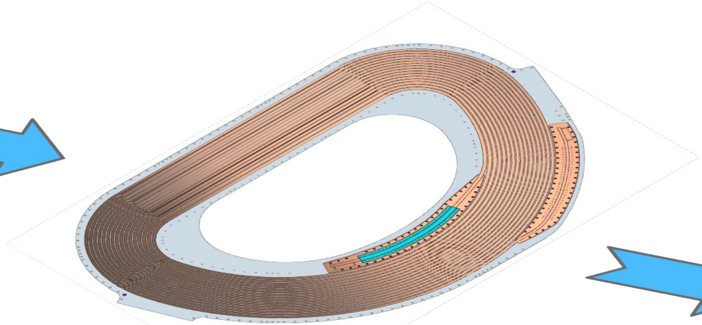
"Are REBCO NI Magnets Really Self-protected?"

SPARC

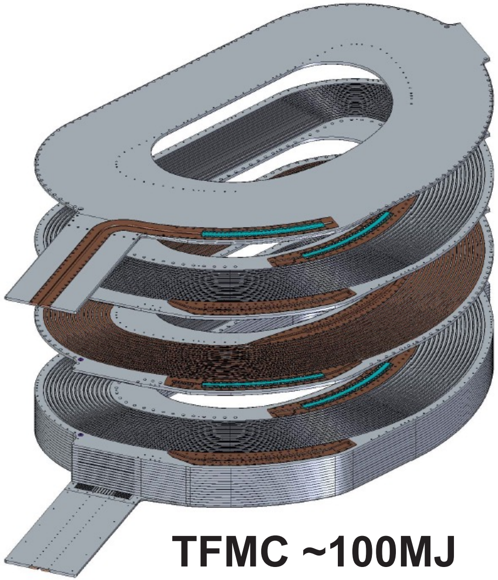
MIT Plasma Science and Fusion Center and **Commonwealth Fusion Systems** executed a REBCO no-insulation magnet development program – culminating in the construction, operation and quench-testing of the SPARC Toroidal Field Model Coil.*



Double Pancake Quench Test Coils ~3kJ
2018 – 2019



Single Pancake D Coils ~20kJ
2019 – 2020



TFMC ~100MJ
2021

A review of lessons learned serves to inform this question.

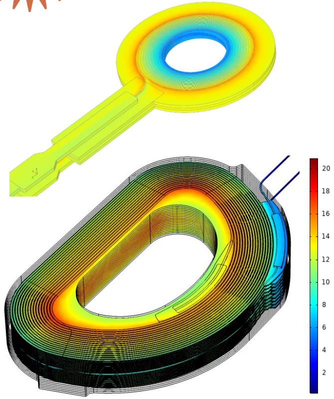
*Hartwig, Z.S., *et al.*, "The SPARC Toroidal Field Model Coil Program," IEEE Transactions on Applied Superconductivity 34 (2024) 1.

MIT Plasma Science and Fusion Center

Acknowledgements! SPARC NI magnet development made possible by an outstanding PSFC/CFS Team!

CFS Commonwealth Fusion Systems



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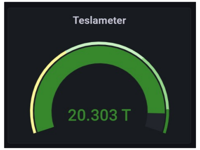
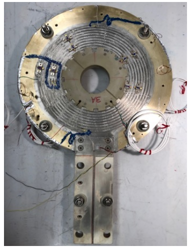
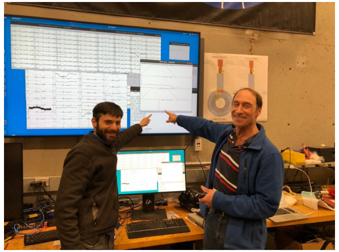
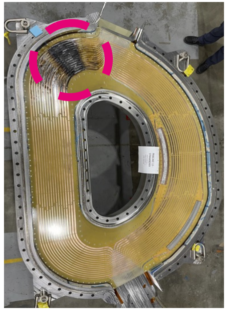


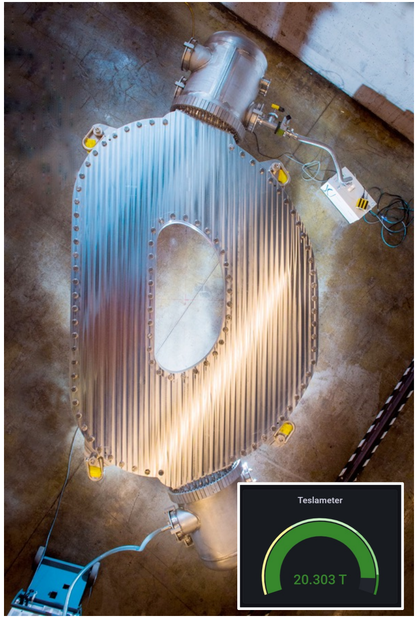




All work funded by Commonwealth Fusion Systems

TFMC achieved many programmatic goals* – one of them was to deliberately quench!

SPARC



- ✓ Design, build and operate a no-insulation HTS DC magnet at relevant scale for fusion power application – demonstrating 20T on conductor
- ✓ Employ a modular design that meets electrical, mechanical, thermal requirements for SPARC and facilitates rapid manufacturing
- ✓ De-risk magnet design and manufacturing for SPARC TF
- ✓ ***Determine quench response – by deliberately forcing quench via abrupt and sustained open circuit condition***

Key takeaway: NI coils are inherently stable and quench resistant!

*** TFMC Publications in IEEE Transactions on Applied Superconductivity 34 (2024) 1.**

Hartwig, Z.S., *et al.*, "The SPARC Toroidal Field Model Coil Program"

Vieira, R.F., *et al.*, "Design, Fabrication, and Assembly of the SPARC Toroidal Field Model Coil"

Golfinopoulos, T., *et al.*, "Building the Runway: A New Superconducting Magnet Test Facility Made for the SPARC Toroidal Field Model Coil"

Michael, P.C., *et al.*, "A 20-K, 600-W, Cryocooler-Based, Supercritical Helium Circulation System for the SPARC Toroidal Field Model Coil Program"

Fry, V. , *et al.*, "50-kA Capacity, Nitrogen-Cooled, Demountable Current Leads for the SPARC Toroidal Field Model Coil"

Whyte, D.G., *et al.*, "Experimental Assessment and Model Validation of the SPARC Toroidal Field Model Coil"

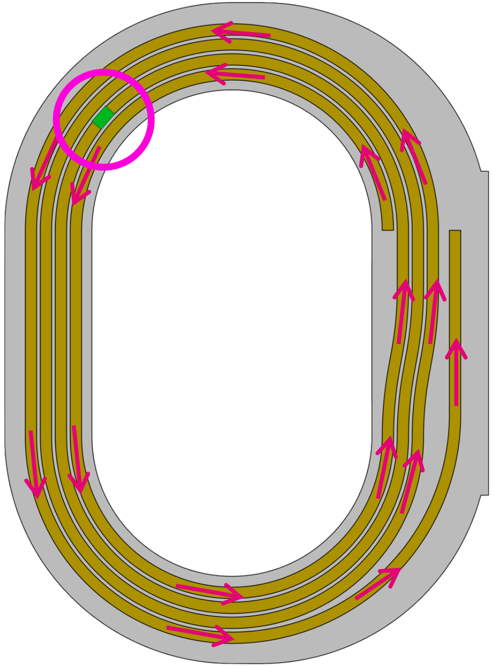
First –

How might NI coils be damaged?

First – How might NI coils be damaged?

Consider 'three phases of quench' for an NI-coil

A . **Normal zone formation**



Normal Zone Formation

First – How might NI coils be damaged?

SPARC

Consider 'three phases of quench' for an NI-coil

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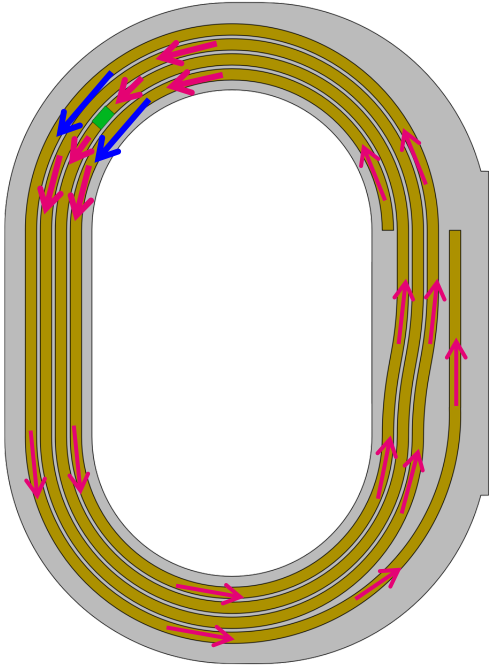
- Current bypasses normal zone
  - **This is a robust self-protection response.** Normal zone heating is minimized; thermal conduction away from normal zone promotes thermal stability.



Normal Zone Formation

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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SPARC

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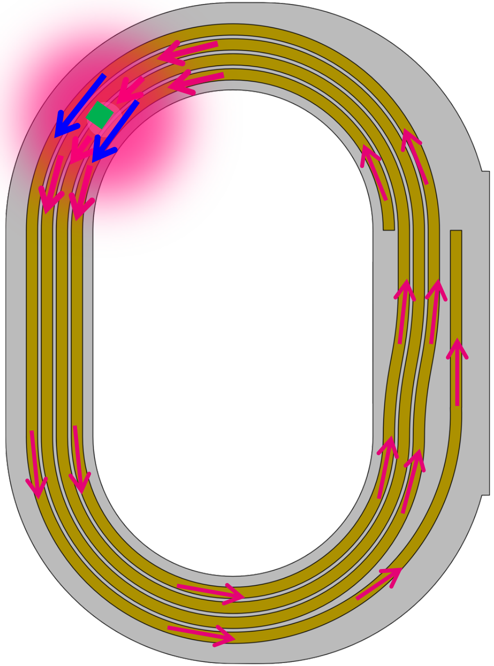
- But if coil inductance and sustained current densities are high enough, thermal instability grows.
- The result is a hot spot, potentially resulting in overheat and burn – depending on thermal diffusion lengths, L/R time, current density, … that determine the volume heated and stored magnetic energy deposited in that volume.



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Hot spot, burn

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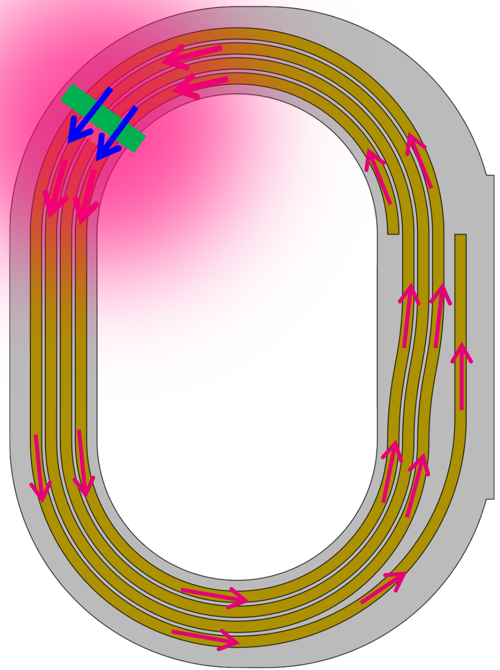


If normal zone extends across all turns before stored energy is dissipated, current bypass protection is eliminated.

Normal Zone Formation

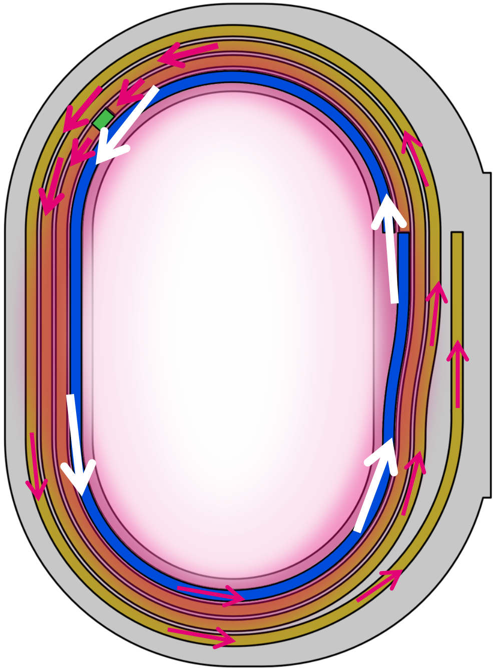
Hot spot, burn

First – How might NI coils be damaged?

SPARC

Consider 'three phases of quench' for an NI-coil

B. **Inductive quench cascade**



Normal Zone Formation → Inductive Quench Cascade

Hot spot, burn

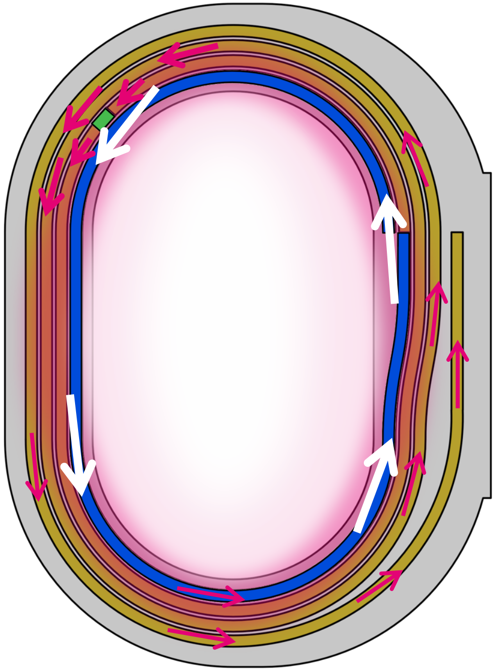
First – How might NI coils be damaged?

SPARC

Consider ‘three phases of quench’ for an NI-coil

B. **Inductive quench cascade**

- Current in adjacent turns increase to conserve flux – potentially causing a turn-by-turn inductively-driven quench cascade.
  - **This is potentially a self-protection response --** producing secondary normal zones with large azimuthal extent in adjacent turns and pancakes.
  - Azimuthal extent of secondary normal zones may provide sufficient volume to handle stored energy dump.



Normal Zone Formation → Inductive Quench Cascade

Hot spot, burn

First – How might NI coils be damaged?

Consider 'three phases of quench' for an NI-coil

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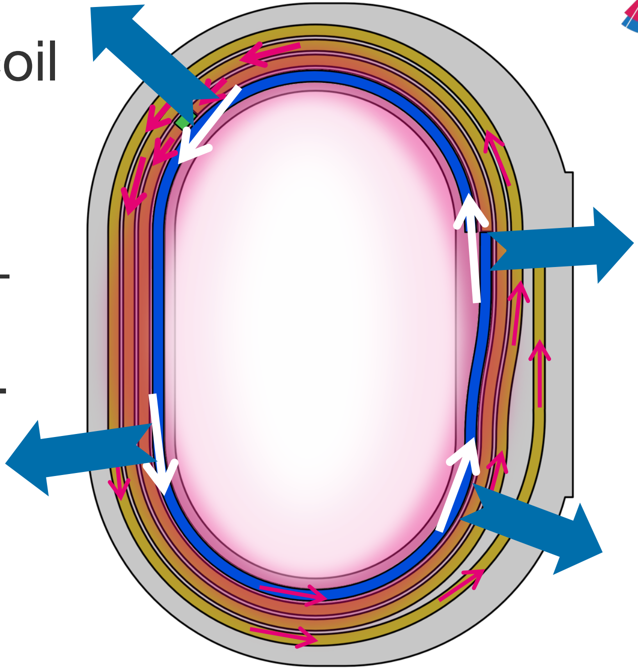
  - **This is potentially a self-protection response --** producing secondary normal zones with large azimuthal extent in adjacent turns and pancakes.
  - Azimuthal extent of secondary normal zones may provide sufficient volume to handle stored energy dump.
- But -- peak currents and resultant Lorentz loads on conductor can be quite large, potentially causing structural damage



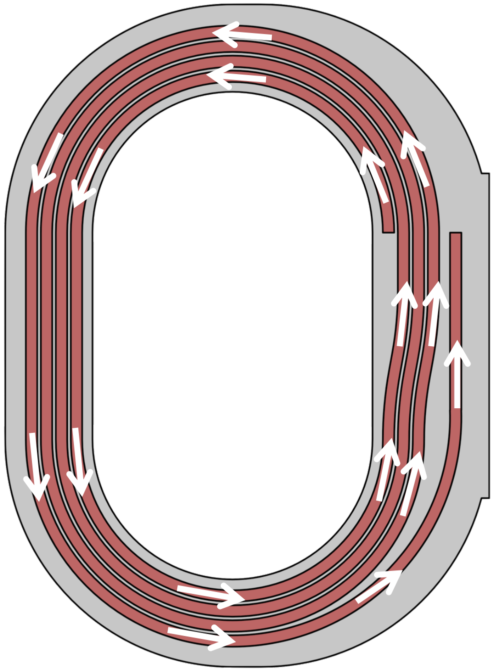
Normal Zone Formation → Inductive Quench Cascade

Hot spot, burn → **Damaging Lorentz Loads**

First – How might NI coils be damaged?

Consider 'three phases of quench' for an NI-coil

C. **"Copper coil" energy dump**



Normal Zone Formation → Inductive Quench Cascade → 'Copper Coil' Energy Dump

Hot spot, burn | Damaging Lorentz Loads

IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

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SPARC

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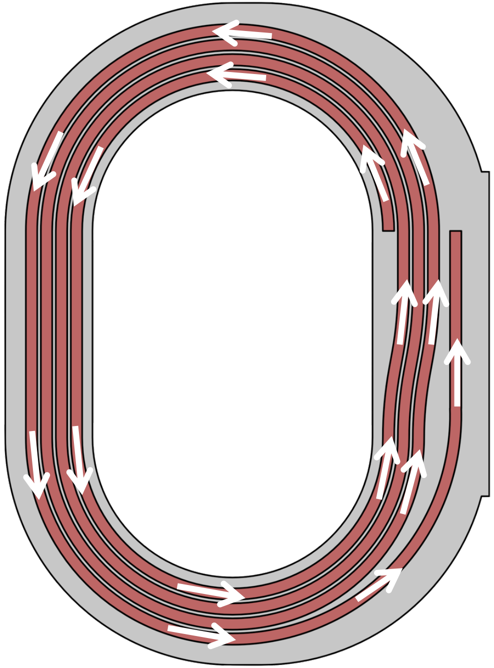
C. **"Copper coil" energy dump**

- With HTS normal everywhere, azimuthal current continues to flow until magnet stored energy is fully dissipated.
  - **This is a challenge for high stored energy NI coils -- *the coil functions as its own dump resistor.***



Normal Zone Formation → Inductive Quench Cascade → 'Copper Coil' Energy Dump

Hot spot, burn

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SPARC

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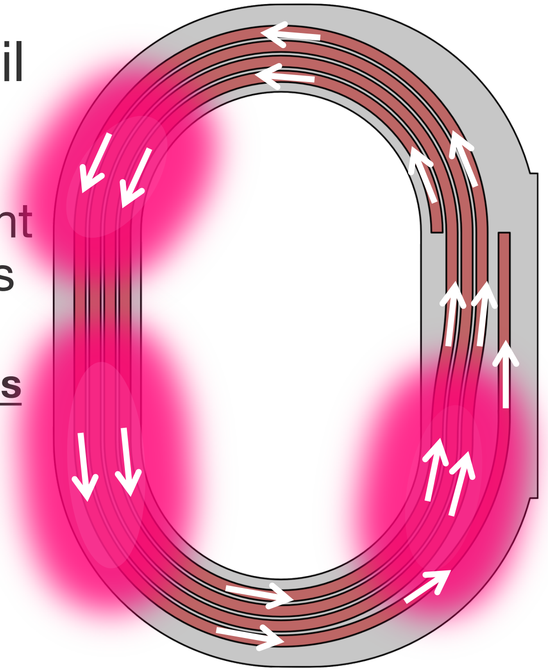
C. "Copper coil" energy dump

- With HTS normal everywhere, azimuthal current continues to flow until magnet stored energy is fully dissipated.
  - **This is a challenge for high stored energy NI coils -- *the coil functions as its own dump resistor.***
- Current takes the azimuthal path of least resistance -- and deposits heat in the most resistive portion of that path.
- Depending on stored energy and ability to azimuthally 'flatten' energy dissipation, excess temperature and/or temperature gradients can result, causing damage.



Normal Zone Formation → Inductive Quench Cascade → 'Copper Coil' Energy Dump

Hot spot, burn | Damaging Lorentz Loads | **Peak coil temperatures exceed allowable**

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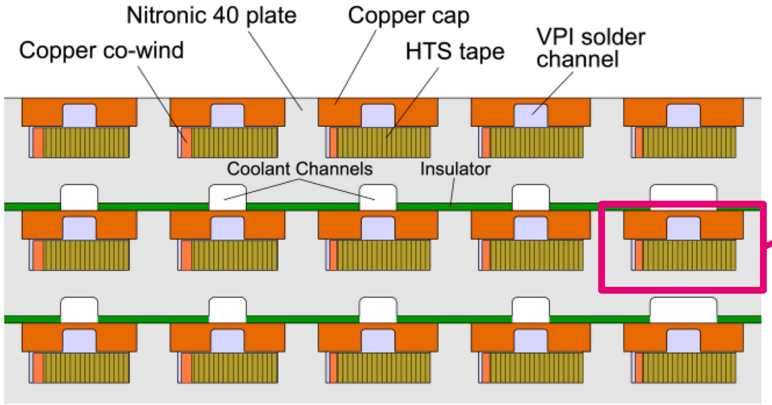
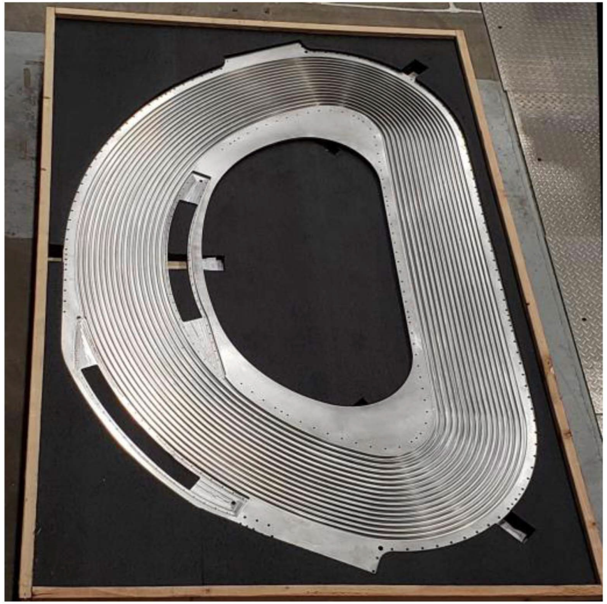
Lessons Learned from SPARC NI Coil Development

SPARC NI Coils Employ Unique No-Insulation Design*

- HTS tape stack and copper co-conductor is inserted and soldered into spiral groove cut into Nitronic® radial plates.



Conductor unit cell volume that thermally participates during quench



- **Provides for excellent thermal / electrical connection among all components in unit cell**
- **Accommodates high Lorentz loading**

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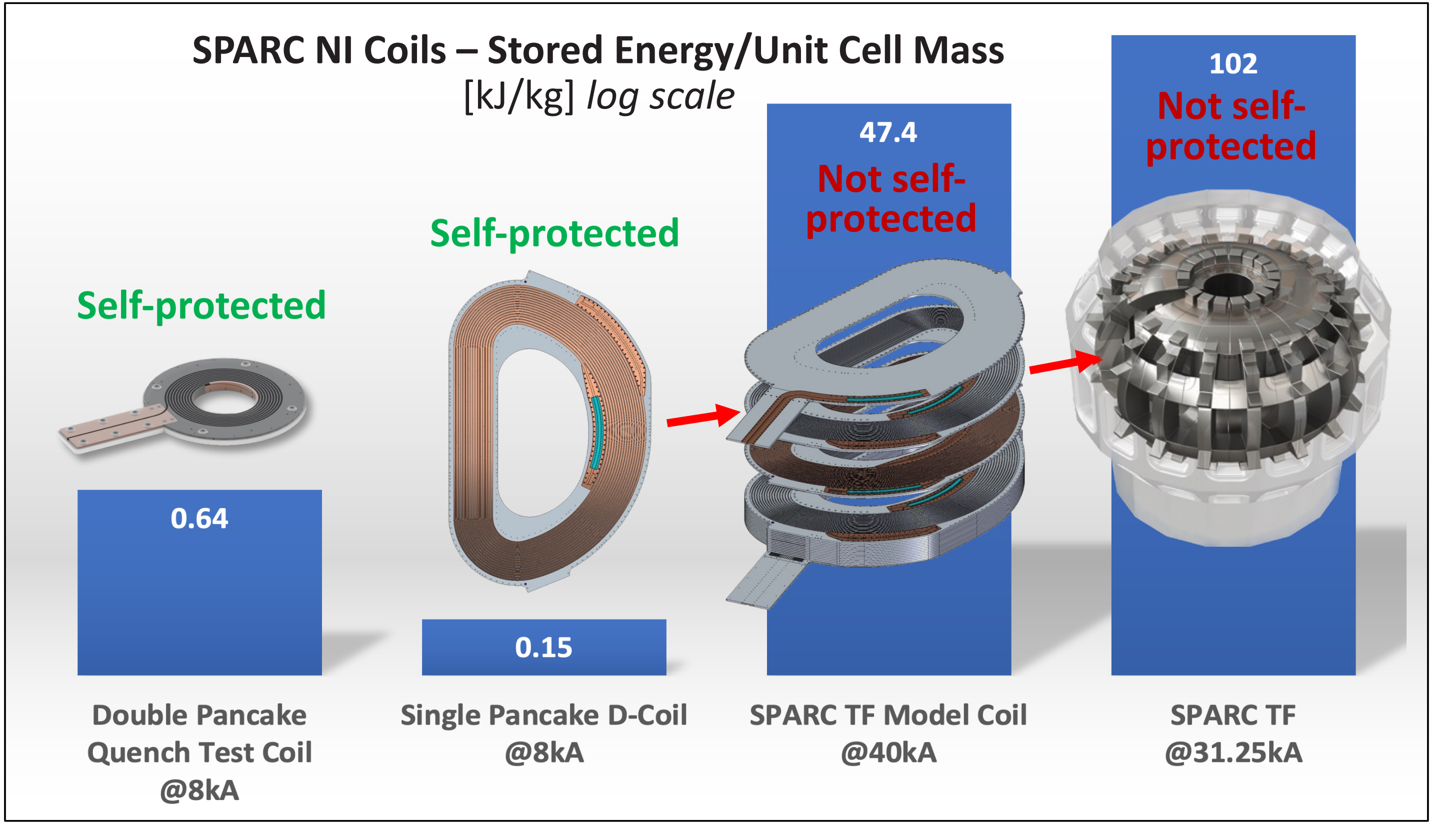
* Vieira, R.F., *et al.*, "Design, Fabrication, and Assembly of the SPARC Toroidal Field Model Coil," IEEE Transactions on Applied Superconductivity 34 (2024) 1.

Metric: NI Coil Stored Energy – Normalized to Conductor Unit Cell Mass (that thermally participates during quench)

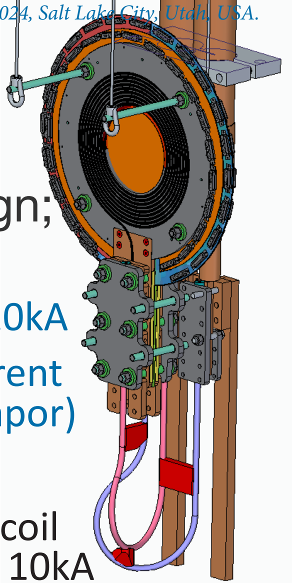
SPARC

While not the only metric that matters, it's is a good measure of the NI Self-Protection Challenge.

- Low stored energy NI coils exhibit similar quench dynamics as high stored energy, but with much less risk of runaway hot spots, burn and local overheating.
- *Based on that experience, there's a tendency to think that NI coils are in general self-protected -- but they're not.*
- Self-protection is lost in x100 increase from small Quench Test Coils to SPARC TFMC and TF

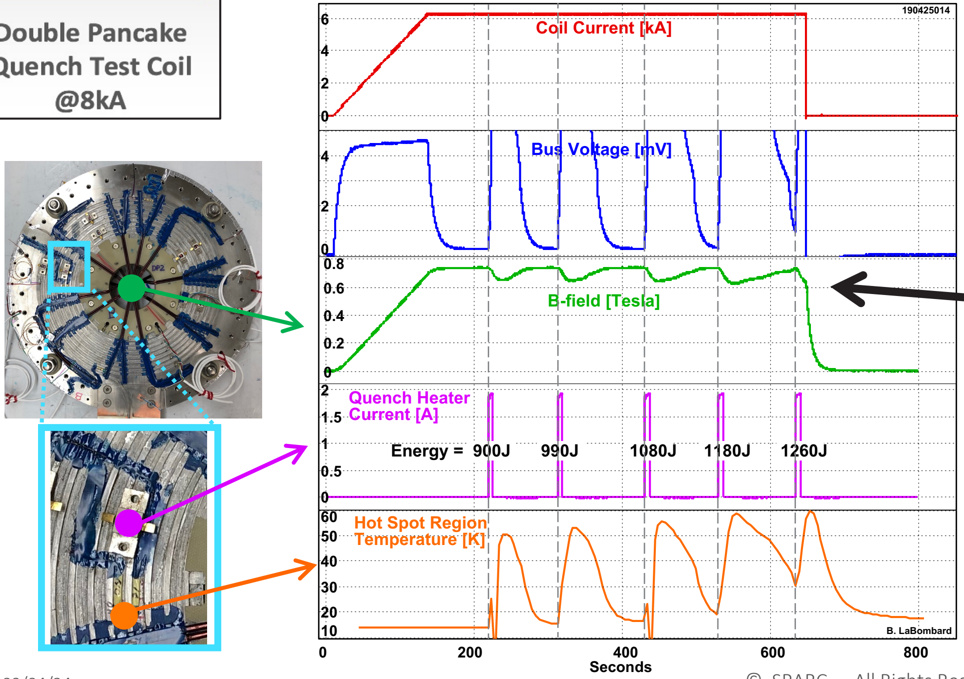


Double-Pancake Quench Test Coils
– found to be robustly stable and robustly self-protecting



Objectives: Test grooved, stacked plate concepts; refine design; develop manufacturing methods; explore quench response

- 18 turn double pancake, I_{op} < 10kA
- Heater-triggered and over-current quench tests at 12K (helium vapor)



Result:
- No damage from quench with coil current forced to remain on at 10kA
- Current bypasses normal zone – leading to quench recovery in response to heater-triggered normal zones
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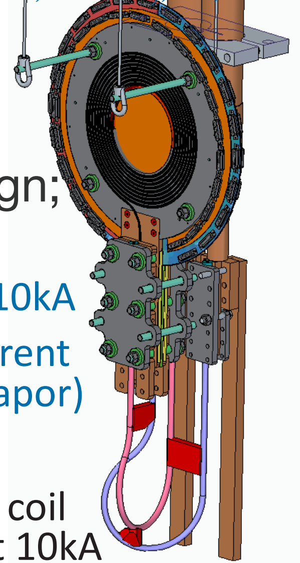

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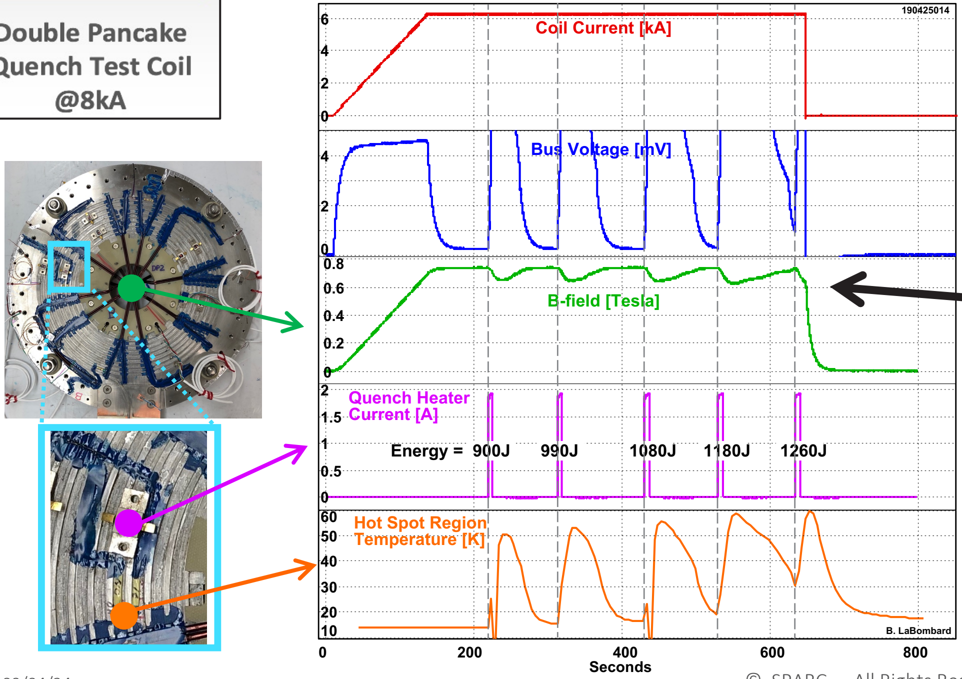
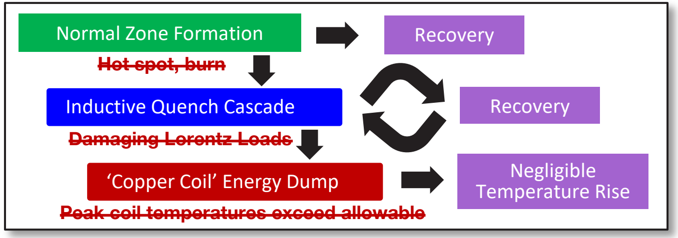
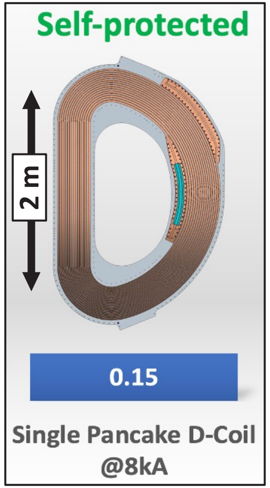




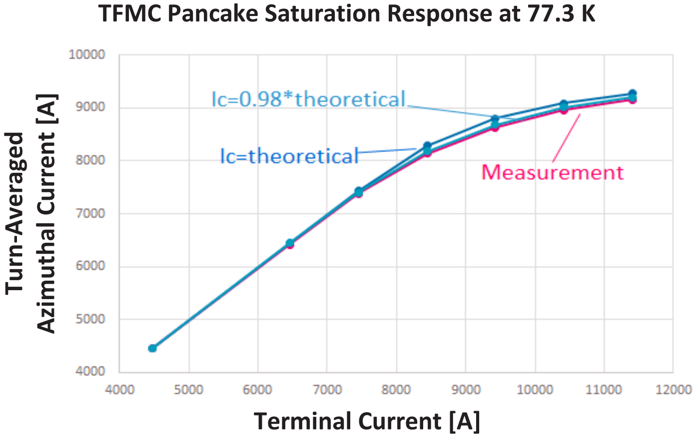
IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

Individual TFMC Pancakes Tested at 77K
– found to be robustly stable and robustly self-protecting



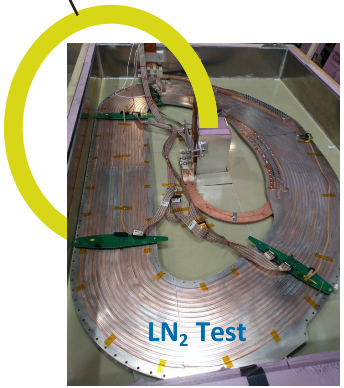
Objectives: Verify HTS performance by pushing TFMC pancakes into saturation at 77K, comparing azimuthal current with model projections

- 16 turn single pancakes, LN_2, $I_{op} < 12kA$
- Pushed well into saturation



All 16 TFMC pancakes were tested by comparing measured saturation response (current and voltages) against theoretical projections from HTS tape data.

Fiber optic measurement of azimuthal current



Result:
- No risk of quench damage
- Current bypasses low Ic zones
- Large pancake surface area in LN_2 immersion accommodates dissipation at the highest current levels
- Low stored energy/mass => TFMC pancake is quench damage safe even if it is warmed up at full test current, open circuited

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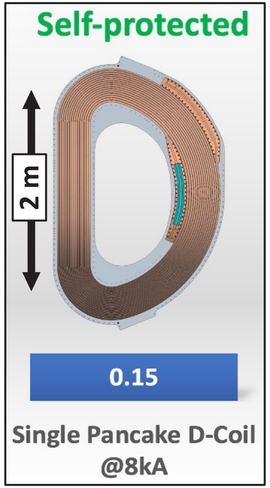

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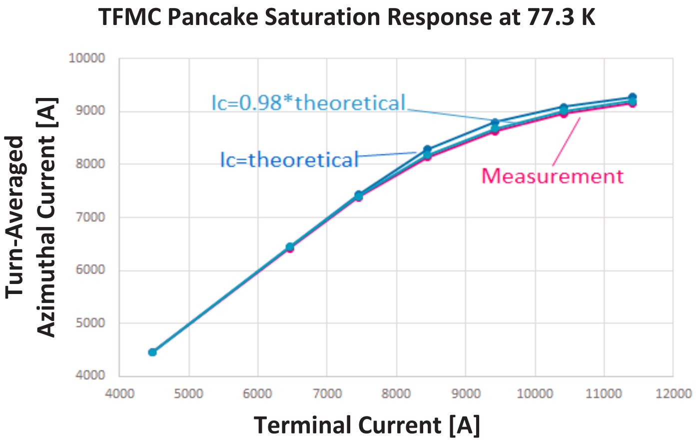

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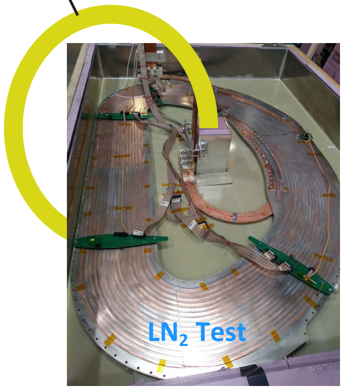

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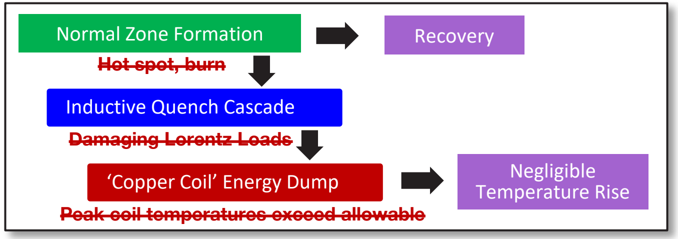
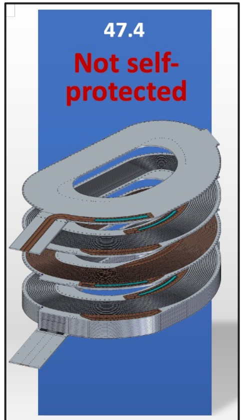


IEEE-CSC, ESAS and CSSJ SUPERCONDUCTIVITY NEWS FORUM (global edition), Issue No. 57, Oct 2024. Presentation given at ASC 2024, Sept 2024, Salt Lake City, Utah, USA.

SPARC TFMC Operating at 40 kA, 20T
– Validated HTS NI design for SPARC*



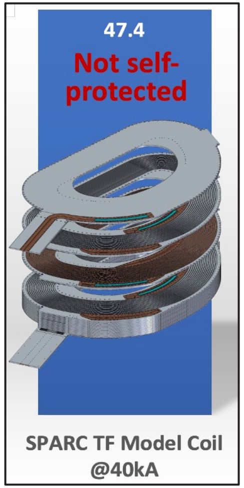
SPARC TF Model Coil @40kA

Objective 1: Demonstrate 20T on conductor in large-bore D-shaped coil using SPARC TF design*

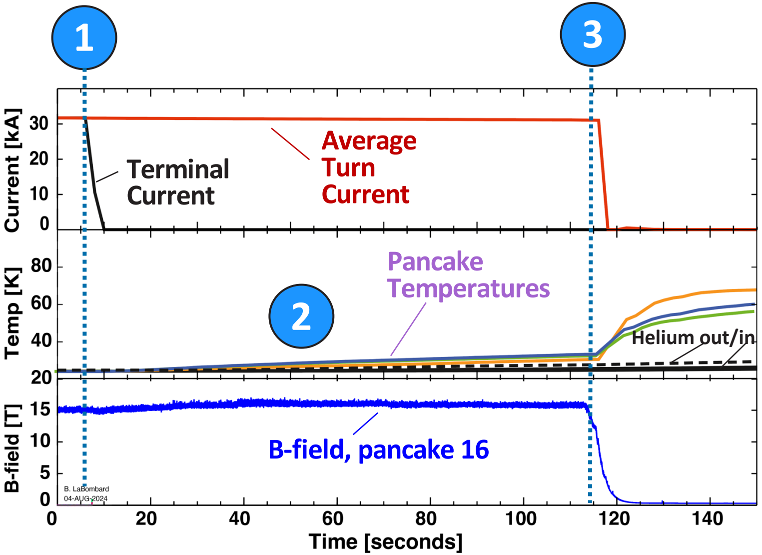
* Whyte, D.G., *et al.*, "Experimental Assessment and Model Validation of the SPARC Toroidal Field Model Coil," IEEE Trans on Applied Supercon 34 (2024) 1.

SPARC TFMC Operating at 32 kA, 16T

– found robustly stable, but not self-protected to sustained open circuit condition



Objective 2: Test self-protection response to open-circuit fault.



Sequence:

1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

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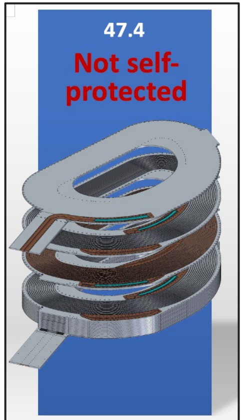
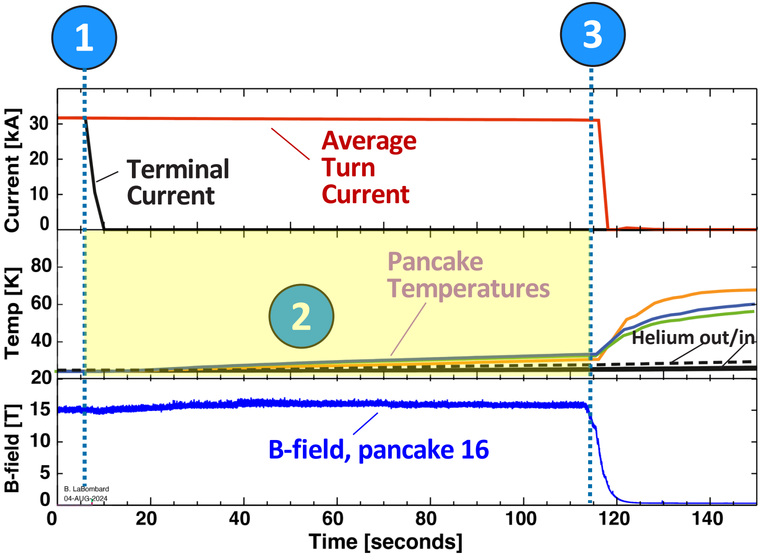


SPARC TF Model Coil @40kA

Objective 2: Test self-protection response to open-circuit fault.

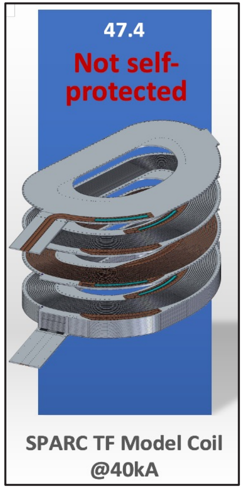


Sequence:
1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Robust stability against quench

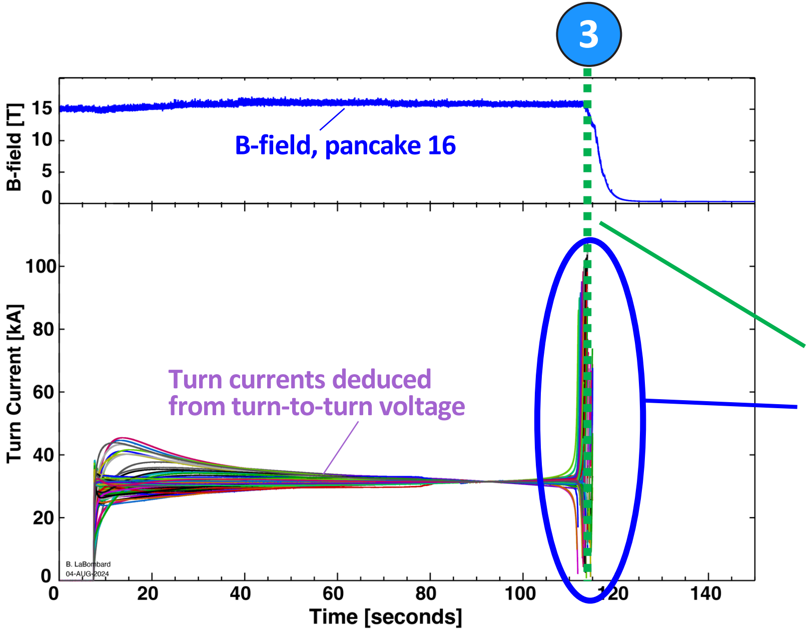
Quench occurs only after ~2.9 MJ is injected from sustained radial current flow with helium coolant turned off.

Key Point:
Quench is caused by a facility fault not by flaw in NI coil design/construction



SPARC TFMC Operating at 32 kA, 16T
– found robustly stable, but not self-protected to sustained open circuit condition

Objective 2: Test self-protection response to open-circuit fault.

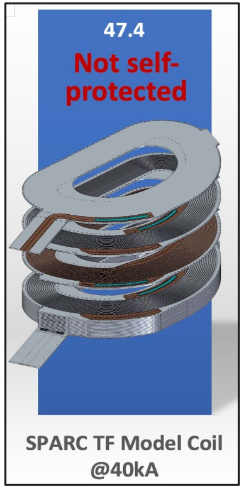


Sequence:

1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Result:

- Normal Zone Formation
- Inductive Quench Cascade



SPARC TF Model Coil @40kA

SPARC TFMC Operating at 32 kA, 16T
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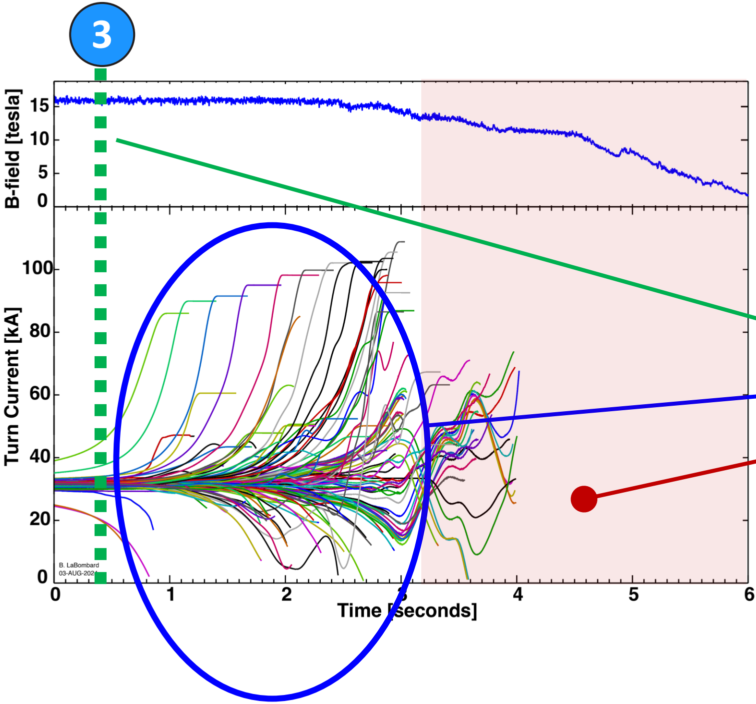
Objective 2: Test self-protection response to open-circuit fault.



Sequence:

1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Result:

- Normal Zone Formation
- Inductive Quench Cascade
- “Copper Coil” Energy Dump

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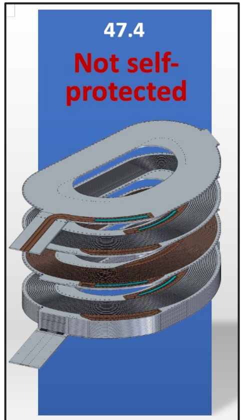
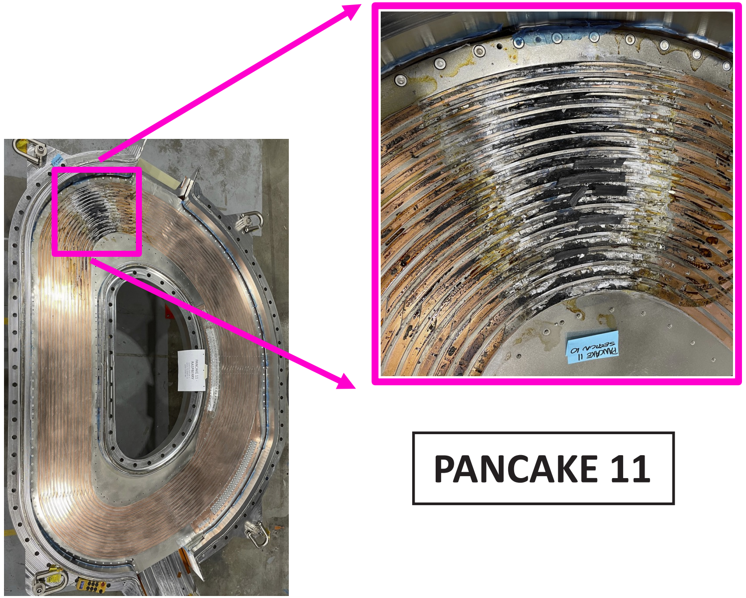
SPARC TFMC Operating at 32 kA, 16T
– found robustly stable, but not self-protected to sustained open circuit condition



SPARC TF Model Coil @40kA

Objective 2: Test self-protection response to open-circuit fault.



PANCAKE 11

Sequence:

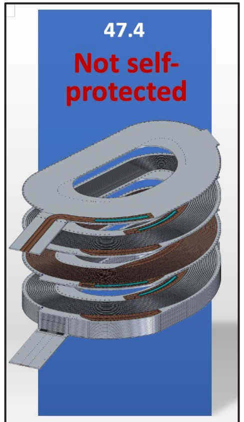
1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Result:

- Normal Zone Formation
- Inductive Quench Cascade
- "Copper Coil" Energy Dump
- **Localized hot spot and 'radial cut' burn on 7 adjacent pancakes at lowest Ic locations**

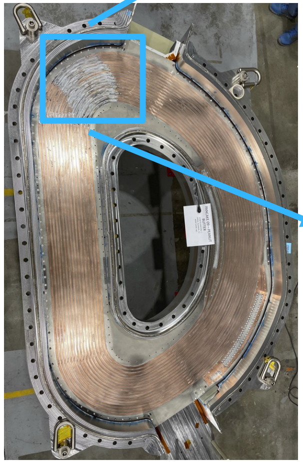
SPARC TFMC Operating at 32 kA, 16T
– found robustly stable, but not self-protected to sustained open circuit condition

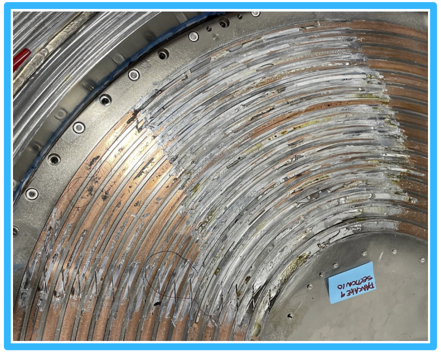
SPARC



SPARC TF Model Coil @40kA

Objective 2: Test self-protection response to open-circuit fault.





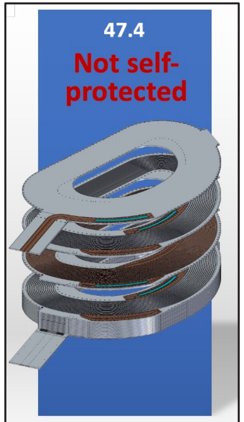
PANCAKE 9

Sequence:

1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Result:

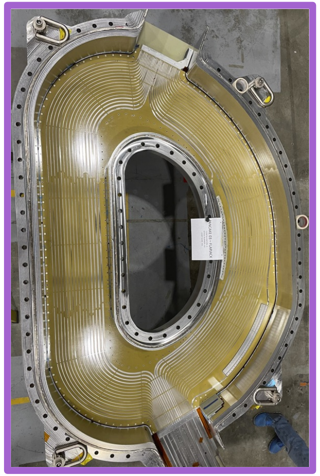
- Normal Zone Formation
- Inductive Quench Cascade
- “Copper Coil” Energy Dump
- **Localized hot spot and ‘radial cut’ burn on 7 adjacent pancakes at lowest Ic locations**
- **“Copper coil” Energy Dump not uniform on non-burned pancakes - melted solder**



SPARC TF Model Coil @40kA

SPARC TFMC Operating at 32 kA, 16T – found robustly stable, but not self-protected to sustained open circuit condition

Objective 2: Test self-protection response to open-circuit fault.



PANCAKE 3

Sequence:

1. Open-circuit at 32kA, 20K
2. Coil warms up (~26kW) from radial current flow
3. Quench after ~ 110s

Result:

- Normal Zone Formation
- Inductive Quench Cascade
- “Copper Coil” Energy Dump
- **Localized hot spot and ‘radial cut’ burn on 7 adjacent pancakes at lowest Ic locations**
- **“Copper coil” Energy Dump not uniform on non-burned pancakes - melted solder**
- **5 of 16 pancakes unaffected. Retested with no Ic loss, despite cascade currents > 60kA**

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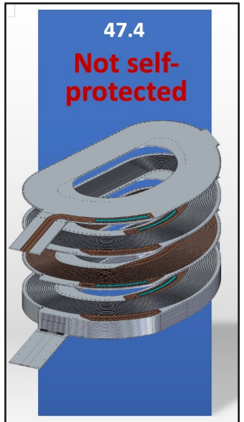
SPARC TFMC Operating at 32 kA, 16T

– found robustly stable, but not self-protected to sustained open circuit condition

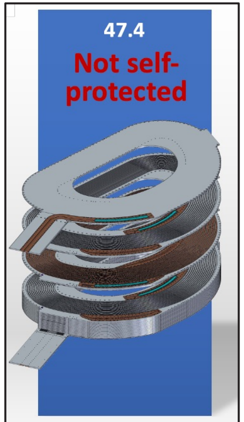


SPARC TF Model Coil
@40kA

Objective 2: Test self-protection response to open-circuit fault.

TFMC - NI Quench Self-Protection Score Card

- **Normal Zone Formation** → Hot spot and burn; radial normal zone extending across all turns
- **Inductive Quench Cascade** → No damage from Lorentz loads on non-overheated pancakes
- **'Copper Coil' Energy Dump** → Non-unform azimuthal energy deposition causing peak temperatures to exceed allowable



SPARC TF Model Coil @40kA

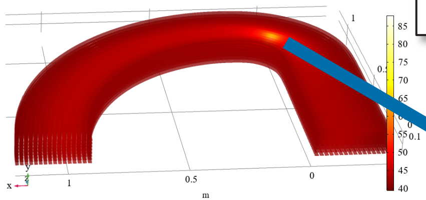
SPARC TFMC Operating at 32 kA, 16T
– found robustly stable, but not self-protected to sustained open circuit condition

Objective 2: Test self-protection response to open-circuit fault.

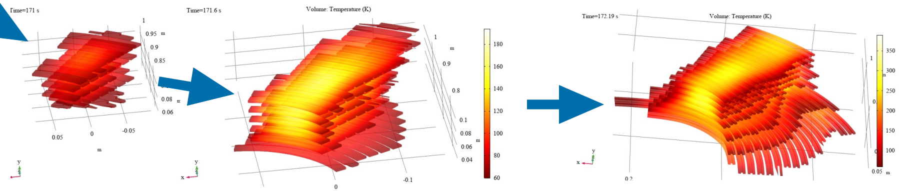
TFMC - NI Quench Self-Protection Score Card

- Normal Zone Formation → Hot spot and burn; radial normal zone extending across all turns
- Inductive Quench Cascade → No damage from Lorentz loads on non-overheated pancakes
- 'Copper Coil' Energy Dump → Non-unform azimuthal energy deposition causing peak temperatures to exceed allowable

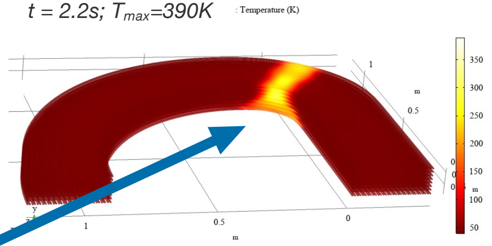
t = 0.3s; T_{max}=87K



t = 1.6s; T_{max}=190K



t = 2.2s; T_{max}=390K

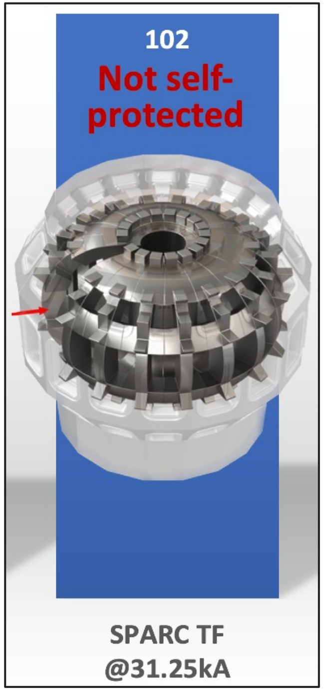


Simulation by Akdior Sattarov

***Simulation:** Formation of Radially Extended Normal Zone At Location of Minimum Ic, 30kA TFMC*

What can be done to quench protect high stored energy NI coils?

SPARC



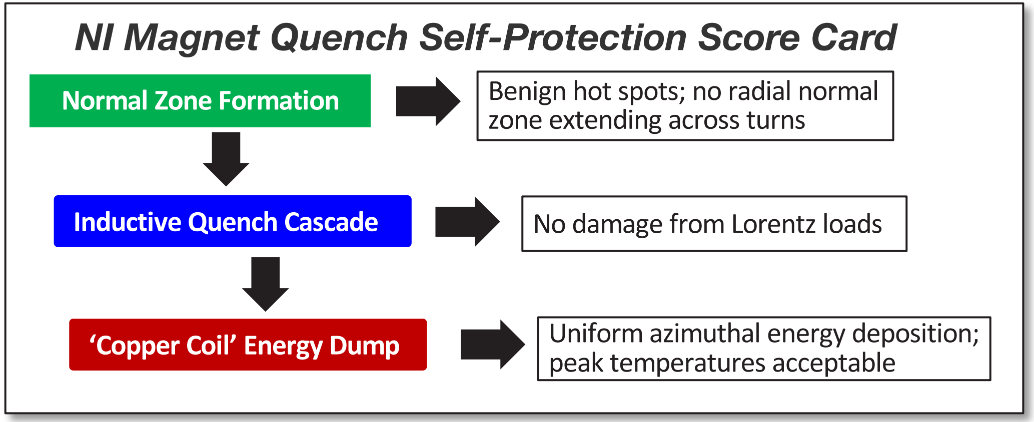
1. Fully exploit NI coil's robust stability against quench
   - Operate in deeply stable regime to provide margin for subsystem faults (e.g., loss of terminal current, loss of thermal insulation)
   - Have high reliability subsystems
2. Incorporate the means to actively trigger a quench cascade on demand
3. Ensure uniformity in EM and thermal response across coil once quench cascade is initiated

Informed by quench response of TFMC, such strategies have been implemented for quench protection of SPARC's TF magnet.

Q: "Are REBCO NI Magnets Really Self-protected?"

A: Depends on the application

- At low stored energy per conductor unit cell mass, they can be.
- But when pushed to the limit (e.g., in large bore fusion energy magnets), they are not, in general.



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End