Muon Collider Magnet Design Second Workshop

Charging, losses and quench in (NI) HTS magnets

S. Sorti on behalf of LASA HTS team

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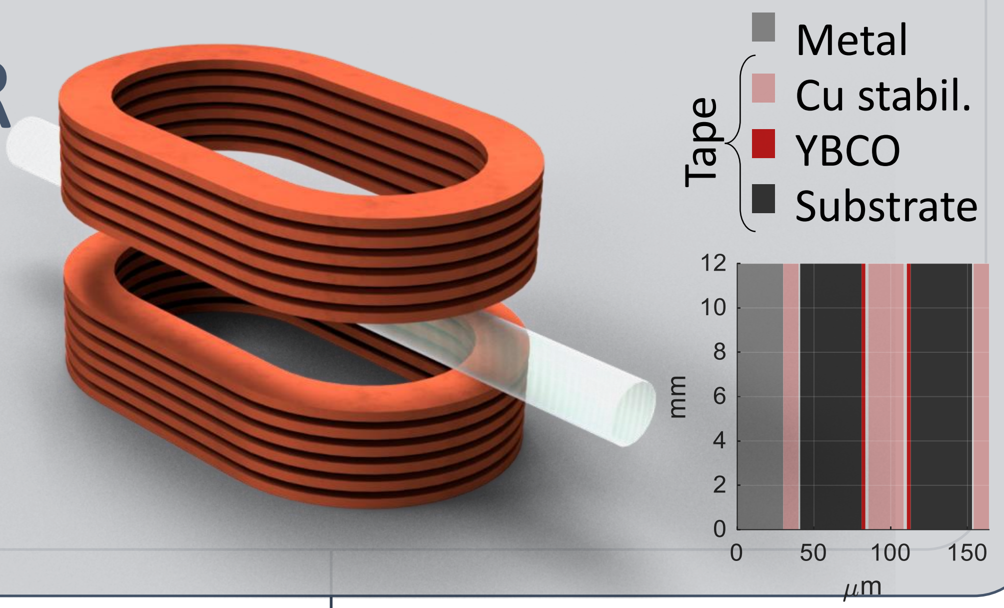
Motivation, objectives, and summary

- To **contribute to the discussion** about assumptions, parameters, models and strategies for the design of MuCol dipole and c.f. magnets
- **Mainly sharing LASA experience**, plus what we have learnt from many experts → not a seminar, a lot of topics are better covered by others (like INS coils)
- The presentation will cover:
  1. Charging and losses for Non-insulated coils
     1. Lumped formula for preliminary design
     2. More advanced models
  2. How Non-insulated coils quench
     1. Phenomenology of NI quench (ESMA example)
  3. Grounds for future activities

LASA research on HTS Framework

PNRR
IRIS



HFM & MuCol

Magnet design and forecasted prototypes

Small Coils

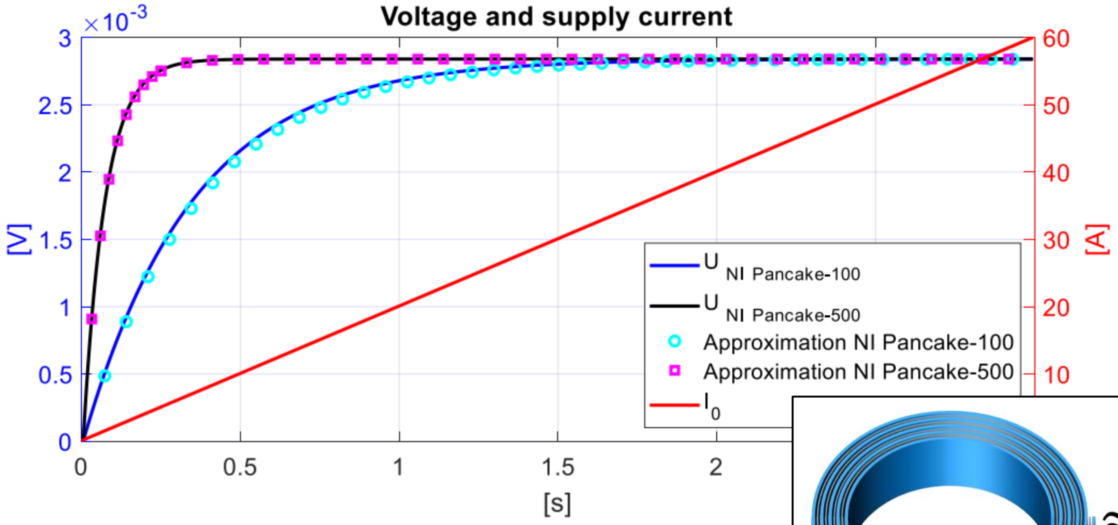
Purchasing machines

Conductor properties

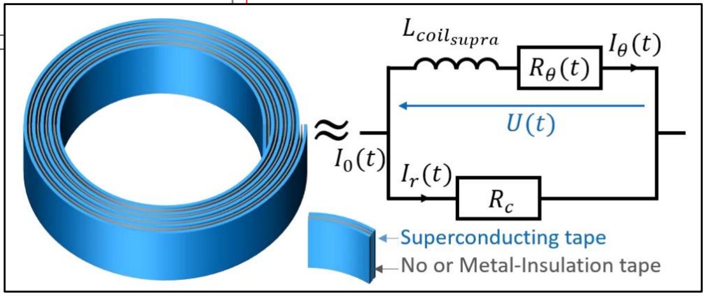
Quench simulations

Charging of NI coils

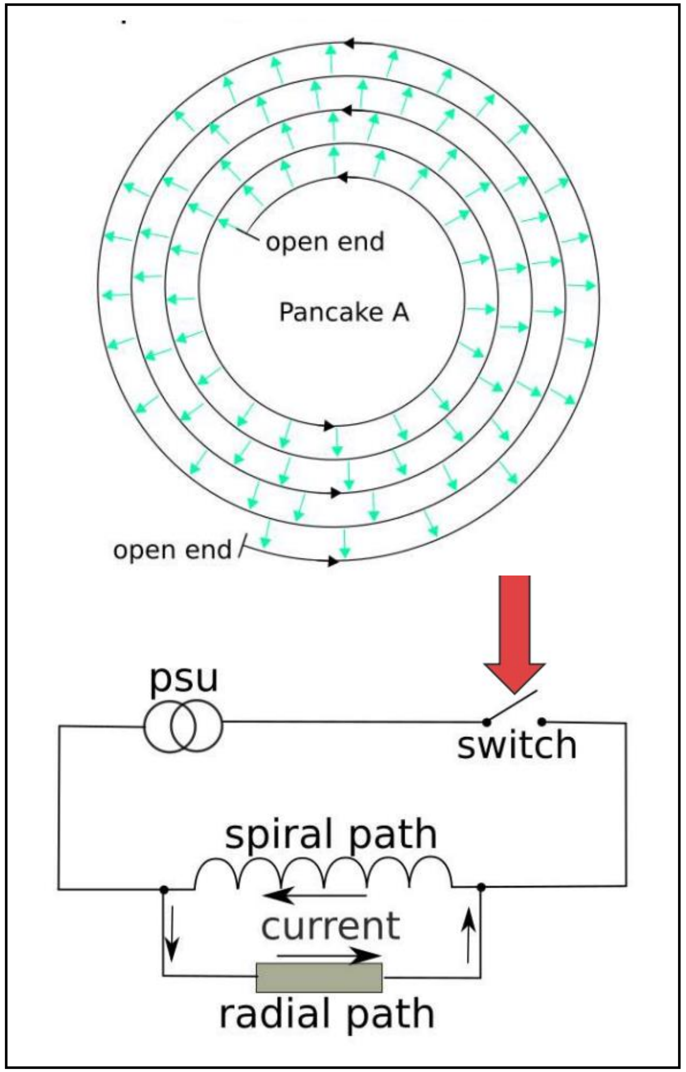
- The main phenomena is straightforward: current flows radially during transients (including open circuits).
- Far from superconductor saturation, **lumped models are pretty good**, also quantitively



Reprinted from C. Genot, Numerical and experimental studies for the optimization and protection of NI-MI HTS coils



Courtesy of Jeroen van Nugteren

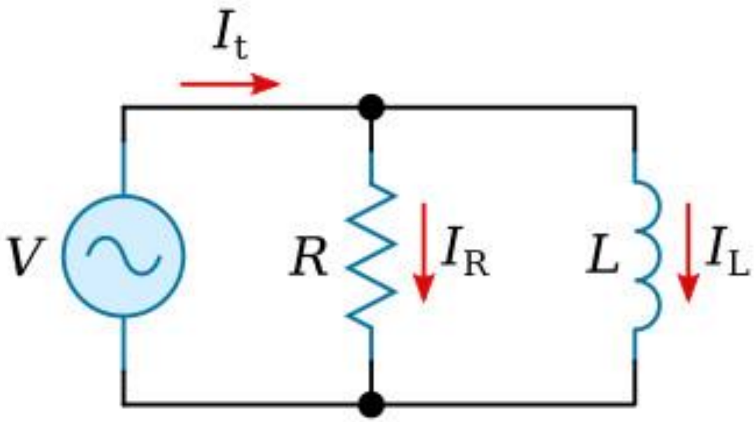


Charging of NI coils: lumped formula

- We start with this:
  1. Fixed geometry, you fix $L \sim L_0 n^2$ being n number of turns
  2. Radial resistance is the series of turn-resistances $R \sim R_0 n$
  3. After $\tau = \frac{L_0}{R_0} n$ transient, $\frac{dI_r}{dt} = 0$ so $\frac{dI_L}{dt} = \frac{dI_t}{dt}$
  4. Can write:
     $$P = \frac{V^2}{R} = \sim \frac{\left(\mathrm{L}\frac{dI_t}{dt}\right)^2}{R} = \frac{\left(n^2 L_0 \frac{dI_{t,0}}{ndt}\right)^2}{nR_0} \sim \frac{\left(L_0 I_{t,0}\right)^2}{R_0} \frac{n}{T^2}$$
  5. This may **shift the focus**. Example: nominal ESMA 20 K cryocooled, limiting I_t for current leads heat
     L ~ 5.5 H, R ~ 20 mΩ → $\tau = 5$ minutes
     but P = 15 W at 0.1 A/s → $T = 3$ h

Bottleneck never been charging tau but heat!

Quantities 0 are the ones for a single-turn magnet

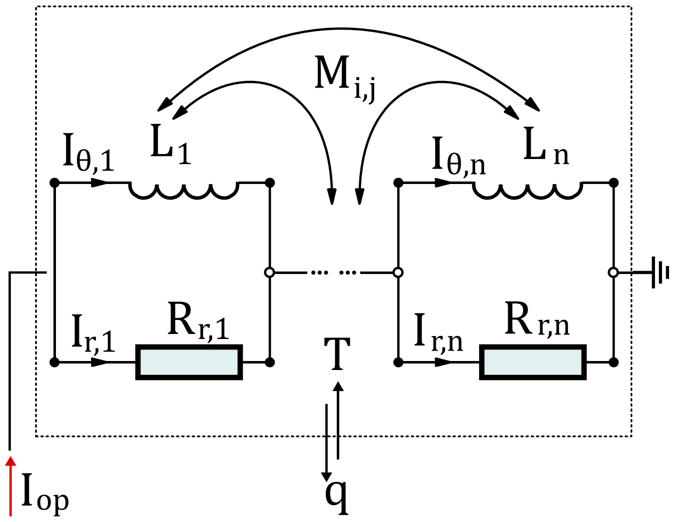


$$\mathrm{V} = \mathrm{L}\frac{dI_L}{dt} = RI_R$$

Charging of NI coils: lumped formula

L. Balconi work

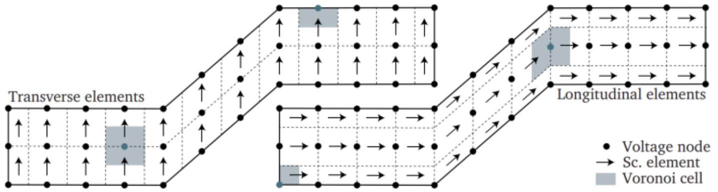
- For more complex geometries, one element per coil can be introduced
  - In addition, 0D model for cooling if needed
  - Successfully employed, for instance, in
    Magnus Dam *et al* 2023 *Supercond. Sci. Technol.* **36** 014007
    (experimental validation on a NI coil)
  - We used it for a specific application (see later)



$$\frac{d\boldsymbol{I}_\theta(t)}{dt} = [L]^{-1}[R_r] \cdot \left(\boldsymbol{I}_{PS}(t) - \boldsymbol{I}_\theta(t)\right)$$

- Indeed, radial-current losses are only half of the story, as we have also **magnetization *M* losses**, still, from our (very limited experience, see later)
  - Magnetization is comparable to r.c. losses in the first ramp
  - Magnetization is just a fraction of r.c. losses in following cycles
  - Still, it really depends on the scenario, cannot take it for any case

Charging of NI coils: numerical models



- Evolution of lumped multi-coil model is the **Partial Equivalent Element Circuit** (PEEC).
  Not so useful for charging only, can be expanded to account for ***M***, too.
  →Example: *Racoon from Little Beast Engineering* (also for quench)
  not available per-se, part of consultancy services.

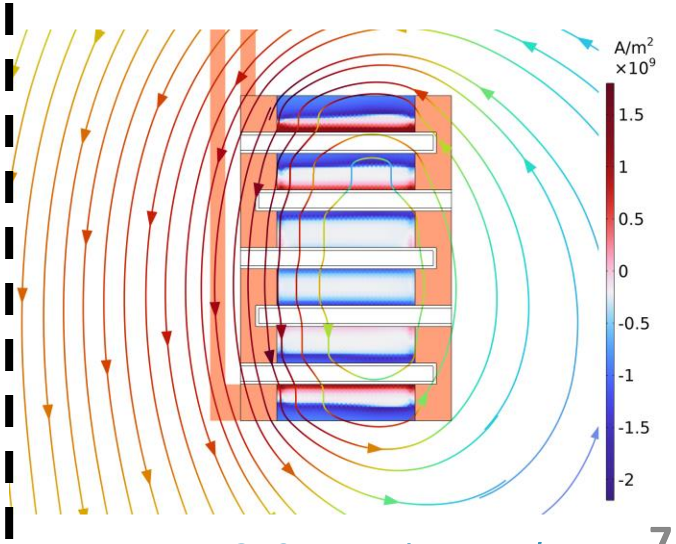
- Can exploit **commercial FEM** too (COMSOL). We are working, for 2D axisymmetric cases, with the following (R. C. Mataira *et al* 2020 *Supercond. Sci. Technol.* **33** 08LT01):
  - Full H formulation (cannot couple with φ), solving 3D components
  - Local anisotropic, nonlinear resistivity tensor
  - Ongoing improvements idea:

Mesh homogeneization	Verified
Quench model	Possible
2D linear model	To be investigated

$$\boldsymbol{\rho}_{\text{coil}} = \begin{pmatrix} \rho_{rr} & \rho_{r\phi} & 0 \\ \rho_{\phi r} & \rho_{\phi\phi} & 0 \\ 0 & 0 & \rho_z \end{pmatrix}_{\hat{r},\hat{\phi},\hat{z}},$$

components are

$$\rho_{rr} = \rho_n \cos^2(\alpha) + \rho_{\text{tape}} \sin^2(\alpha),$$
$$\rho_{r\phi} = \rho_{\phi r} = \frac{1}{2}(-\rho_n + \rho_{\text{tape}}) \sin(2\alpha),$$
$$\rho_{\phi\phi} = \rho_{\text{tape}} \cos^2(\alpha) + \rho_n \sin^2(\alpha).$$

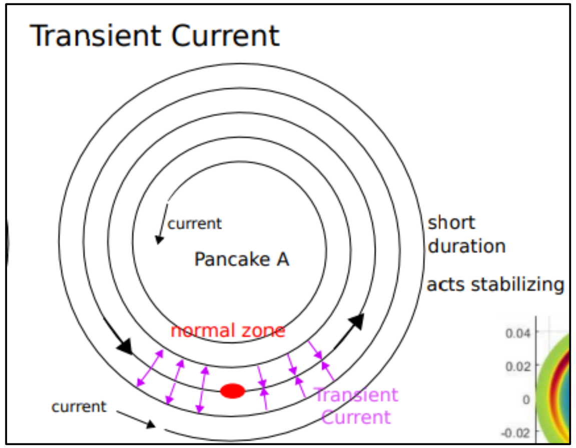


G. Scarantino work

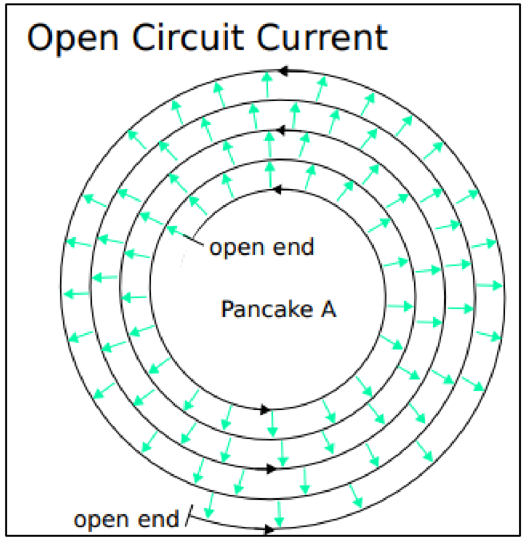
From charging to quench of NI coils

- Pretty simple tools exist, and we are using them at LASA, for the charging of NI (or related technologies) coils. **Analytical are fine** for general overviews (magnet maps/graphs to span design space), then can refine estimations with PEEC/FEM.
- Things get complicated with quench. To our knowledge, no simple tools exist for this scope. The reason is the **complex mechanism** of NI coil quench.
- **Main point** about NI-like quench: *transfer[ing] of the overheating (quench) issue of insulated coils to a mechanical issue due to new unbalanced and torque forces*
  (Thibault Lécrevisse *et al* 2022 *Supercond. Sci. Technol.* **35** 074004)

Generalities about quench of NI coils



- When the radial resistance is **low** (soldered NI), quench propagation would be by normal zone heating, but current easily bypass it with low losses.
  Small coils are self-protected, i.e. NZ never propagates as all current goes radial without heating enough.



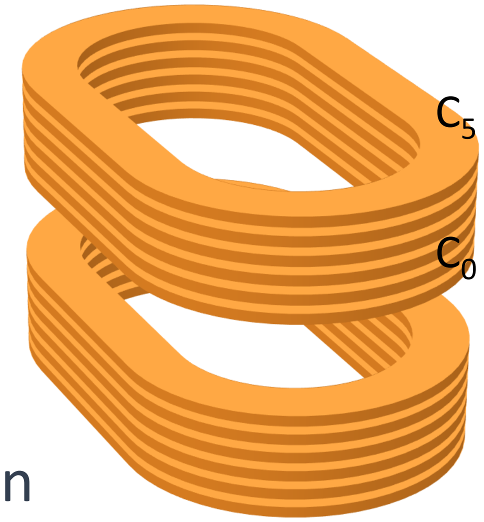
- When radial resistance is **high** (MI high-res), the resistance of the normal zone not enough to push enough transport current into the radial path.
  Must act, like opening the circuit breaker to force it, leading to a somehow self-quench-heater at the cost of large voltages over the coil.

- When radial resistance is in **between**, superimposition. Both propagation (NZ and radial) can even take spiral paths. Hybrid protection, should open the circuit but with a "relaxed" quench detection (heat is spreading)

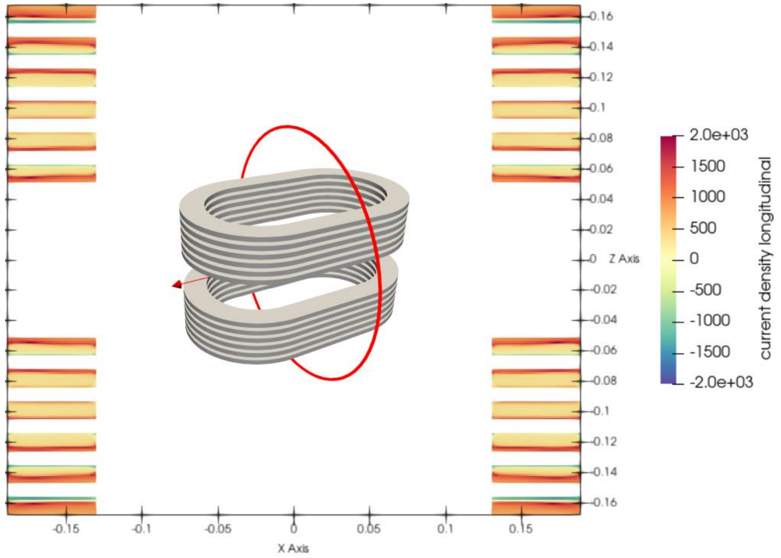
And this is only for electrical resistivity. Then we have the combination with thermal resistivity and the mechanical effects!

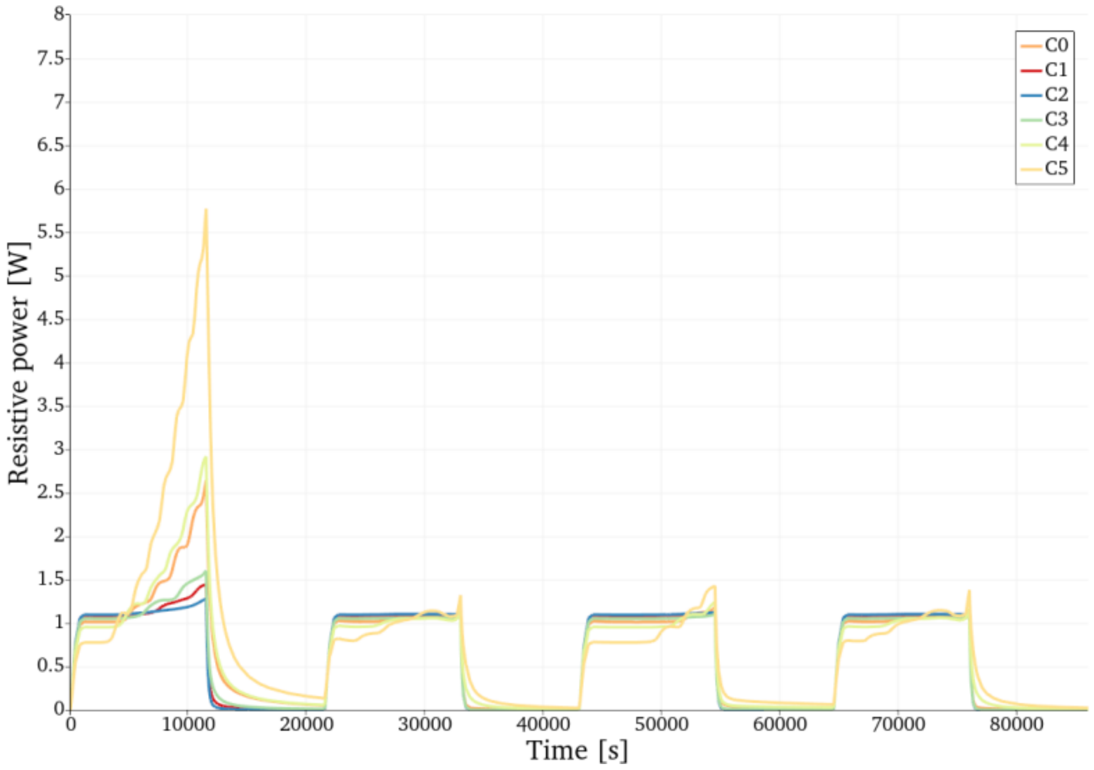
ESMA example, AC losses

- Good validation of model,
  12 W for T = 3.2 h
- Confirmation of reduced contribution from magnetization (power called “resistive” but takes it all). Tape is not saturating, thus lower overall loop.



Parameter	Unit	Value
Central field	tesla	10
Current for 10 T	A	1150
Free bore dimensions	mm	⌀70
Coil Mechanical length	mm	600
Good field region uniformity	N/A	1.5%
Good field region extension	mm	H50xV30xL400
Operating temperature	K	20

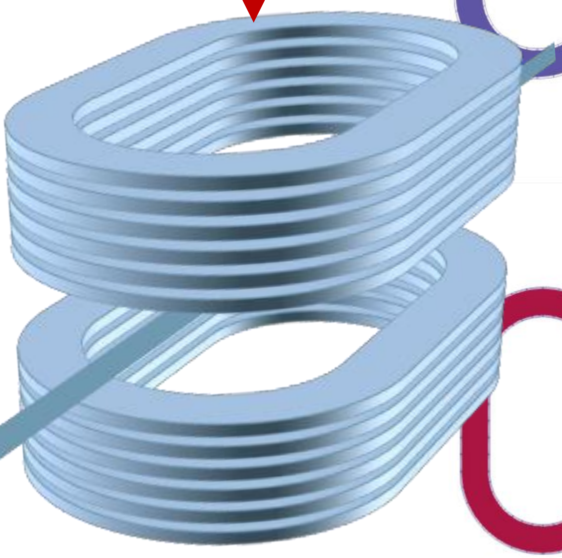


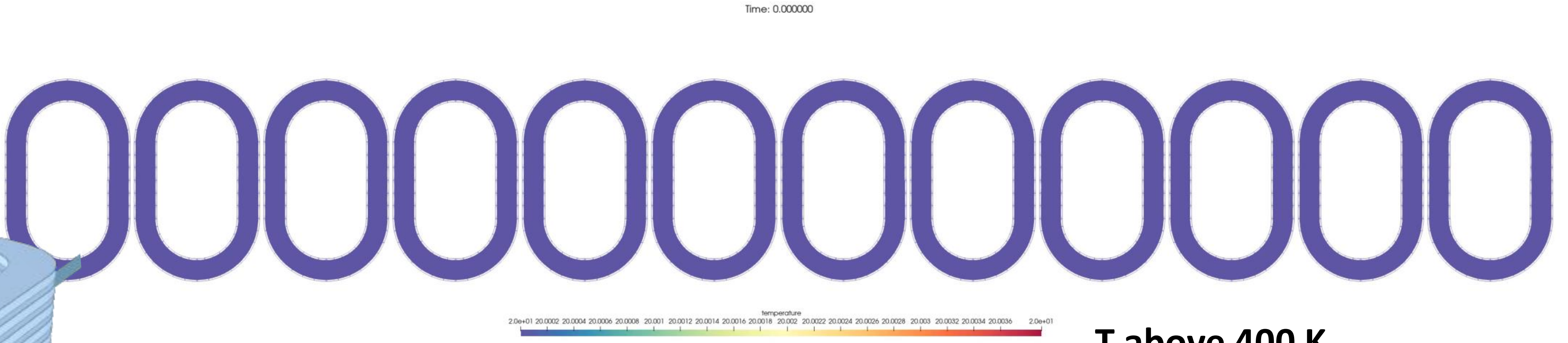


ESMA example

- Contact resistivity of the order of 1 mΩcm^2 with artificial heater

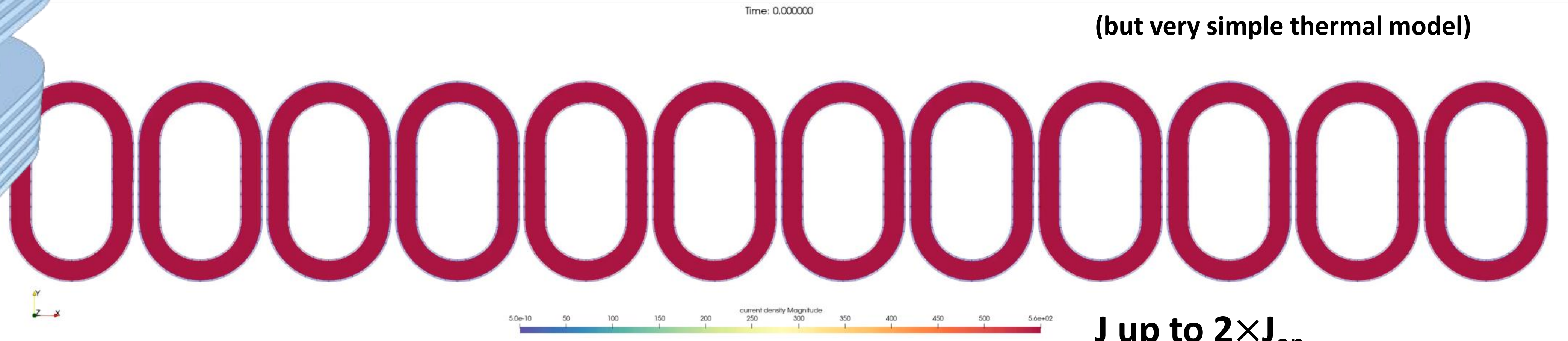
40 W X 0.1 s





T above 400 K

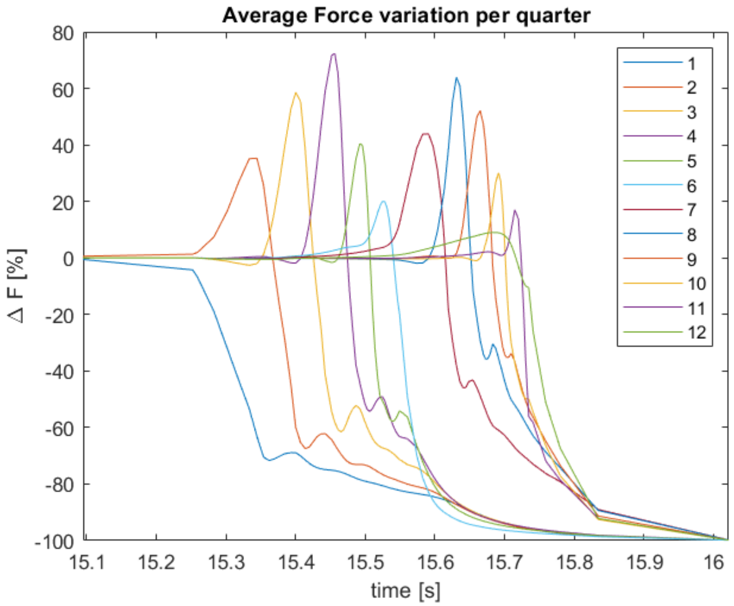
(but very simple thermal model)

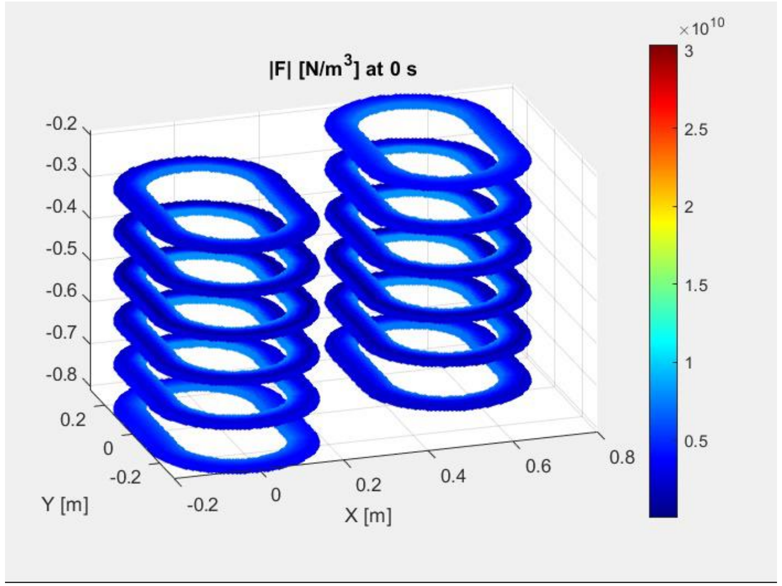


J up to 2×J_{op}

ESMA example

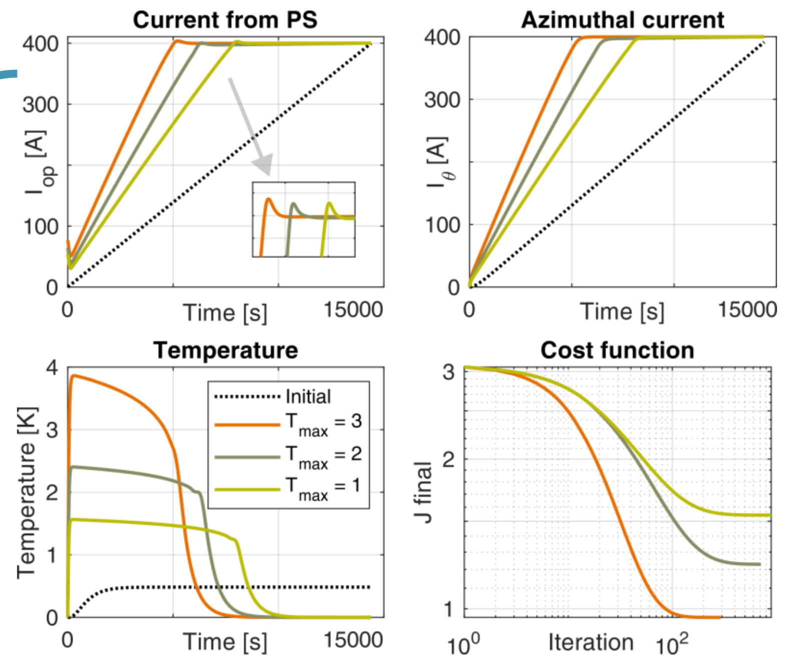
- Still, worst aspect is **mechanics**, due to the shock-wave. Mitigation already in place (reinforcement).
- Detection & discharge with magnet shut down (a few V on coils, no dump) . Not much more can be done, main parameter remain τ for E extraction, so this scheme always a bit on the edge.
  → **early detection** as it takes seconds of drifting (non-disclosable yet, series of sensors)
- Other scenarios (insufficient cooling, coil degradation, etc) to be **mitigated in operation**
- Other approaches may regard better R_{ct} tuning and/or energy extraction (magnetic dam?)

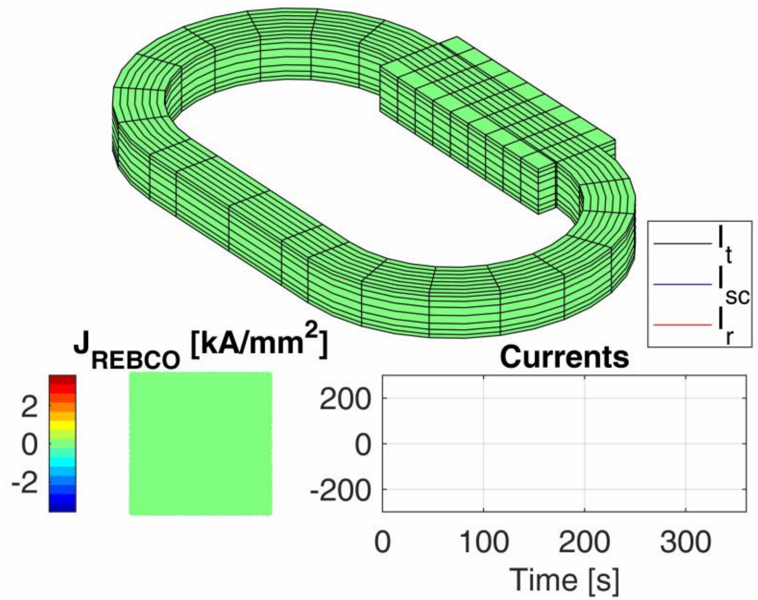




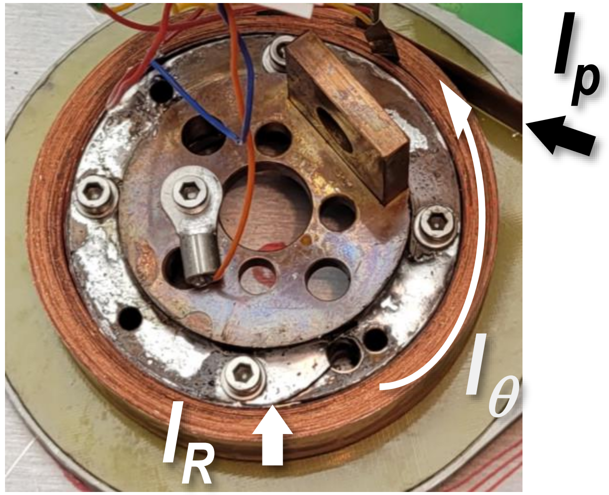
Ongoing activities

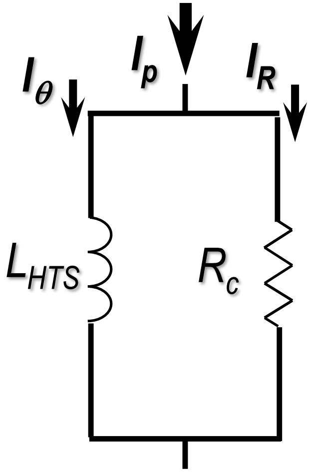
- Modelling in COMSOL for NI charging (future 2D linear, quench,…), for RFMFTF in IMCC, by G. Scarantino
- Modelling analytic + COMSOL for insulated HTS (see F. Mariani talk)
- Automation studies for NI and INS coils (in-house codes)
- Ideas about REBCO-oriented magnet design optimization





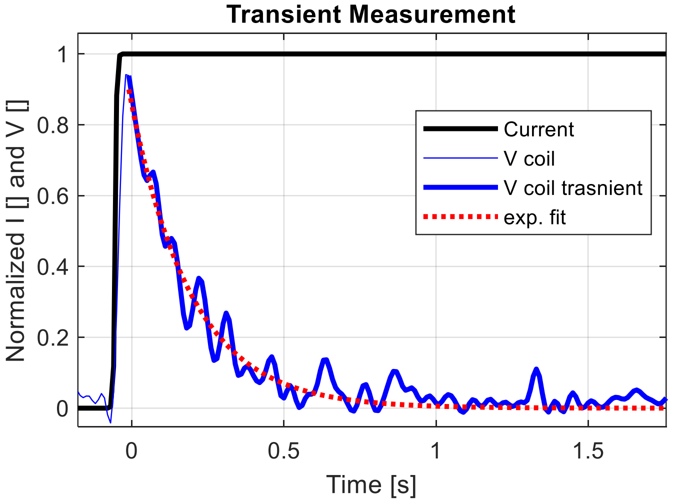
Ongoing activities: 2023/2024 campaign closed, now new one

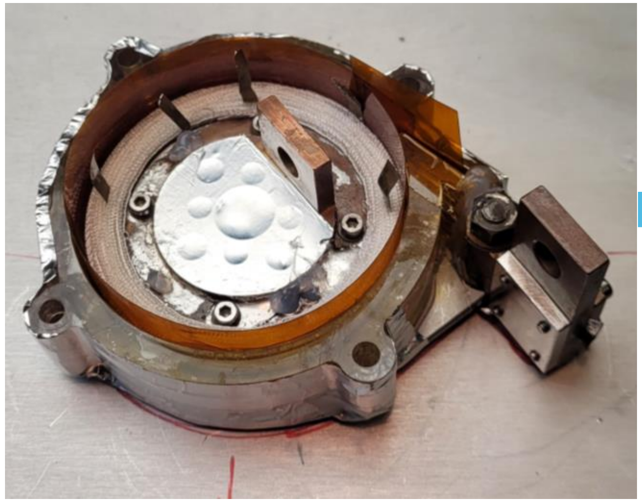




$$V(t) = V_0 e^{-\frac{t}{\tau}}$$

$$\tau = \frac{L_{HTS}}{R_c}$$





> 150 GΩ
@ 2.5 kV

Opportunities for IMCC

- Charging can easily become part of early evaluations if needed. ESMA-like magnets may hope to get limited ***M*** losses
- For protection, fast-running models are missing for quench propagation. Maybe some estimations can be drawn (about costs for pre-quench detection systems?)
- We could select some models to be further developed, aiming at mid-speed models (like Comsol 2D).
- In parallel to that, experimental validation.