Update on Feather-M2.3-4 *(KIT, Bruker)*

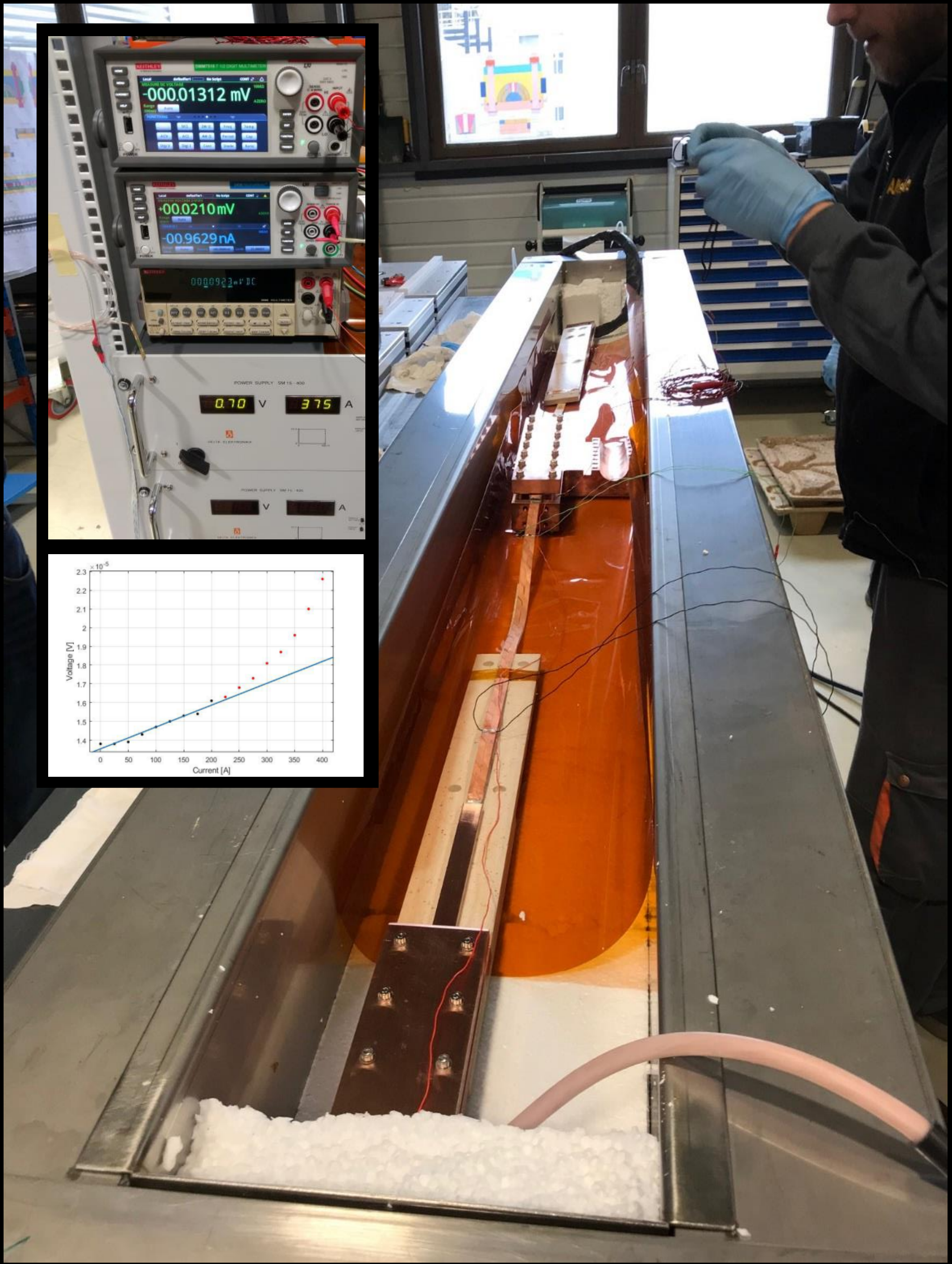
Preparation of Instrumentation Plate

Instrumentation Plate

1XCopper Wire
2XDistributed Fiber
1XBrag Fiber

UV-Sensitive Glue

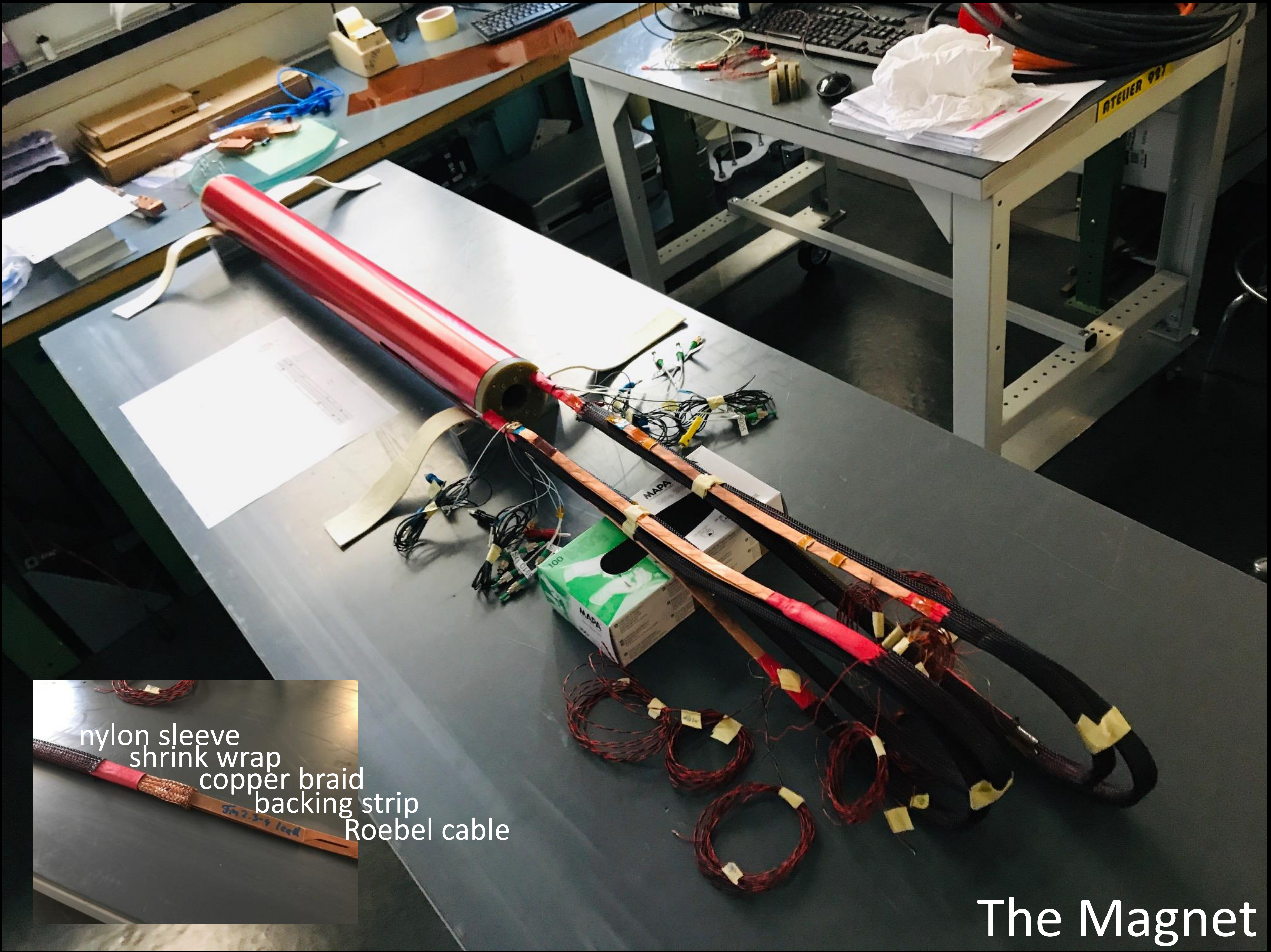
Coil Winding

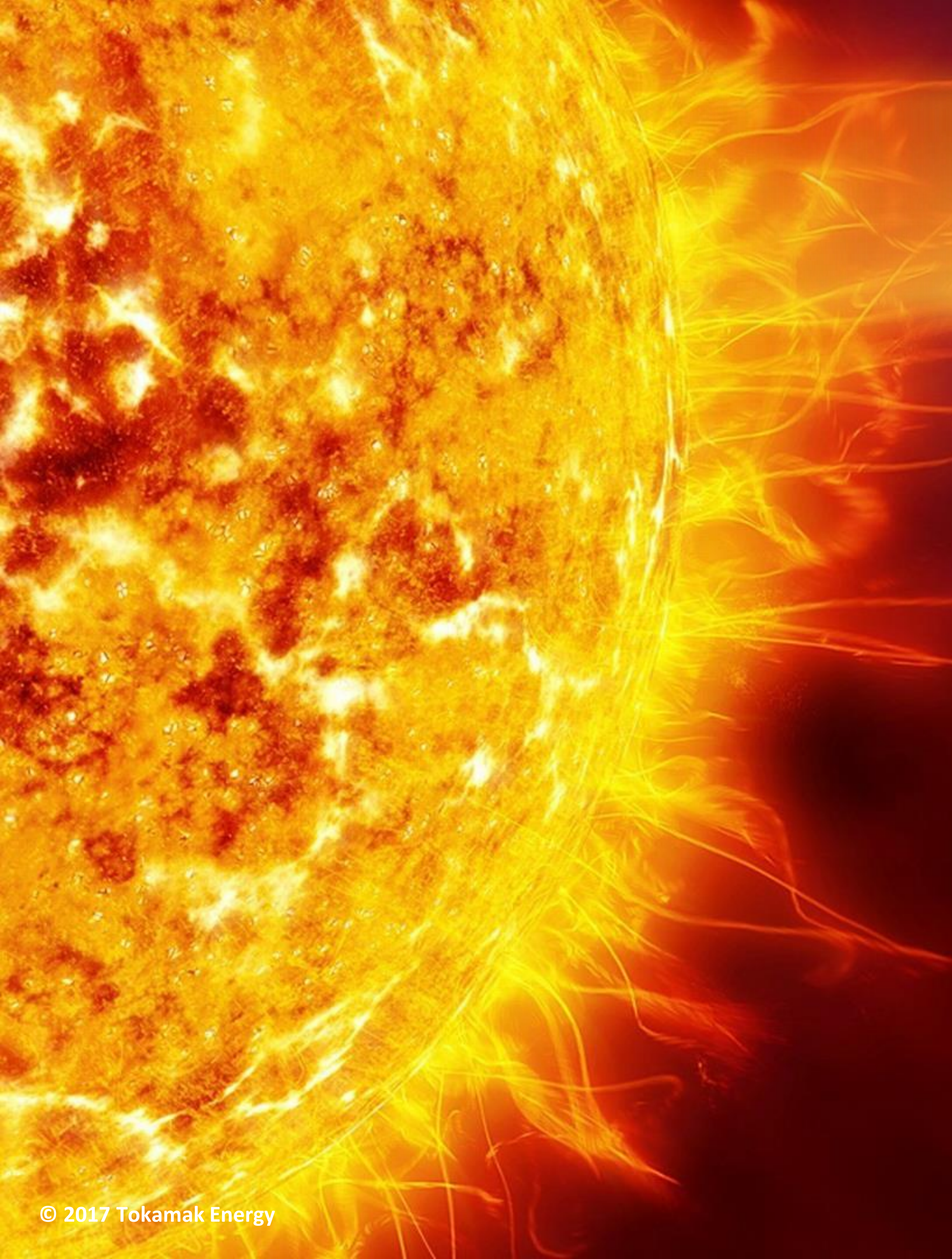


Joint resistance is 10 nOhm at 77 K
Low critical current (artificial pinning?)

Joint Test

The Magnet


nylon sleeve
shrink wrap
copper braid
backing strip
Roebel cable



Large Tuned Insulation HTS Magnets

CERN // Tokamak Energy
June 2019

J. van Nugteren, R. Slade, L. Rossi,
R. Bateman, G. Brittles, G. Kirby,
M. Kruip, B. van Nugteren, M. Wilson

Introduction and Outline

- Why collaboration? We have common goal: Need a big HTS magnet to work reliably.
- Understanding non-insulation coils using my network model ElMaTh (Electro-Magnetic and Thermal).
- First need proper validation before we can make predictions.
- Then scale up to larger magnets.

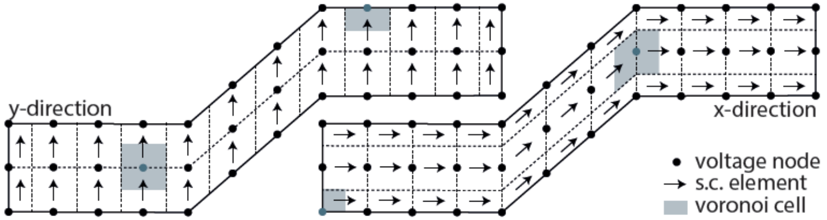
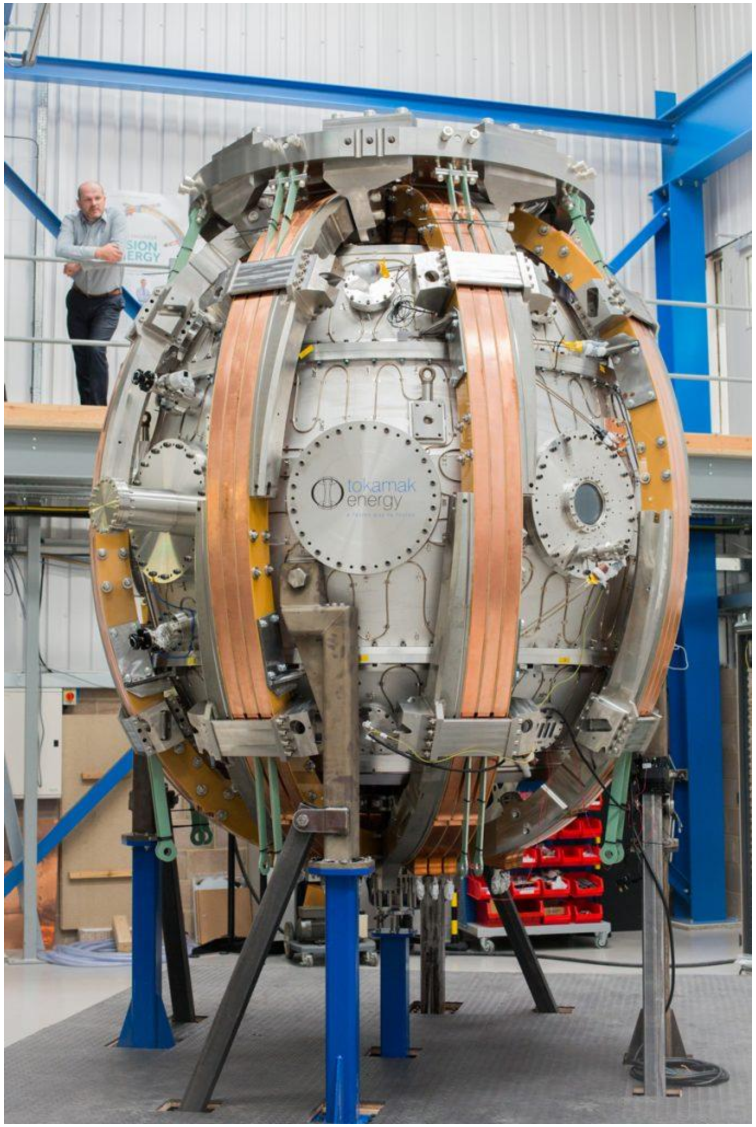
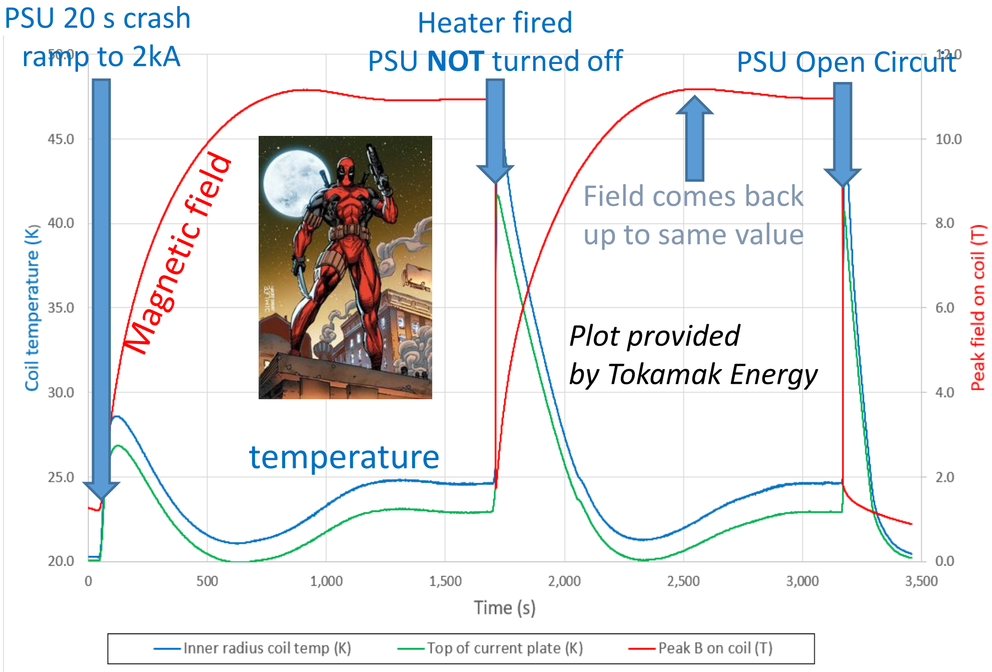


Fig. 1. Electrical network geometry with superconducting elements, shown separately for x and y directions, and voltage nodes. For clarity a very coarse version of the network is shown. For a couple of nodes the Voronoi cells used for the determination of the tape-to-tape contact areas are shown.



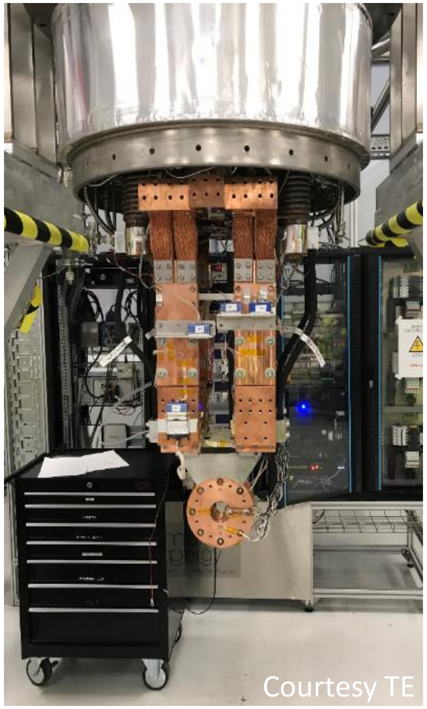
Tokamak’s QA Coils

- Tokamak has constructed and tested a large set of double pancake solder potted QA coils.
- The purpose of the programme was to learn about coil winding, joints, consolidation, instrumentation, testing, validation of models etc.
- The results are quite remarkable and thus the question arose: can we somehow use NI coils for large magnets as well?



Plot provided by Tokamak Energy

Deadpool, whose real name is Wade Wilson, is a disfigured mercenary with the superhuman ability of an accelerated healing factor and physical prowess.

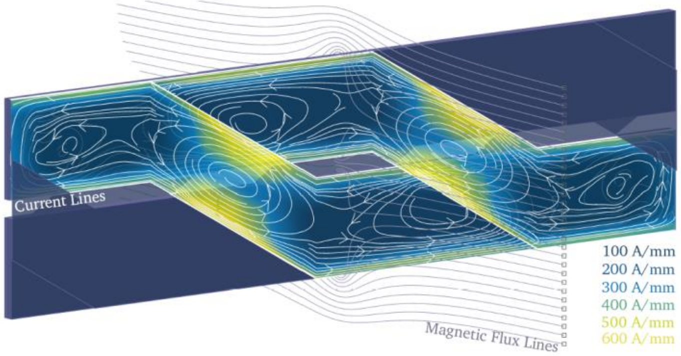

Courtesy TE

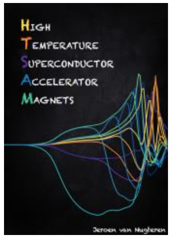

Courtesy TE

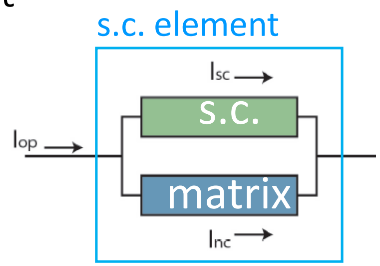

Courtesy TE

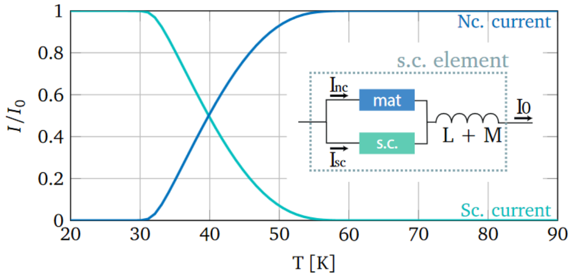
Network Representation

- The coils are modelled using a pre-existing network solver ElMaTh.
- The tapes are approximated using infinitely thin line elements. This implies that screening currents are excluded from the model.
- The contact between the tapes in the cable is modelled using contact conductances (stored in G_{ij}).
- The non-linear voltage of the superconducting elements is calculated using a parallel path model.



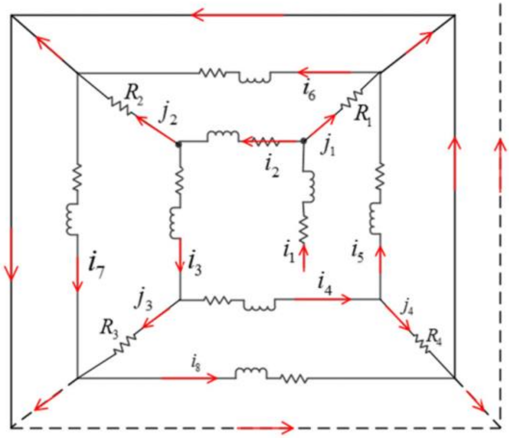






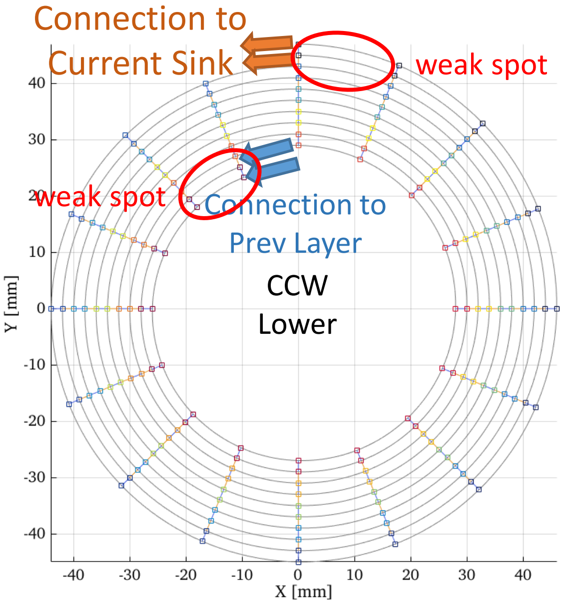
$$\overbrace{\begin{bmatrix} \boxed{G_{ij}} & M_{\mathrm{kcl},ir} & 0 \\ M_{\mathrm{kvl},qj} & R_{qr} & 0 \\ 0 & 0 & K_{sp}-K_{\mathrm{cool},sp} \end{bmatrix} \begin{bmatrix} V_j \\ I_r \\ T_p \end{bmatrix}}^{\text{time independent linear}} + \overbrace{\begin{bmatrix} 0 \\ \boxed{V_{\mathrm{nl},q}\left(I_r, T_r, \left|\vec{B}_r\right|, \alpha_r\right)} \\ P_{\mathrm{nl},s}\left(I_r, T_r, \left|\vec{B}_r\right|, \alpha_r\right) + P_{G,s}\left(V_j\right) + P_{R,s}\left(I_r\right) \end{bmatrix}}^{\text{time independent non-linear}} +$$

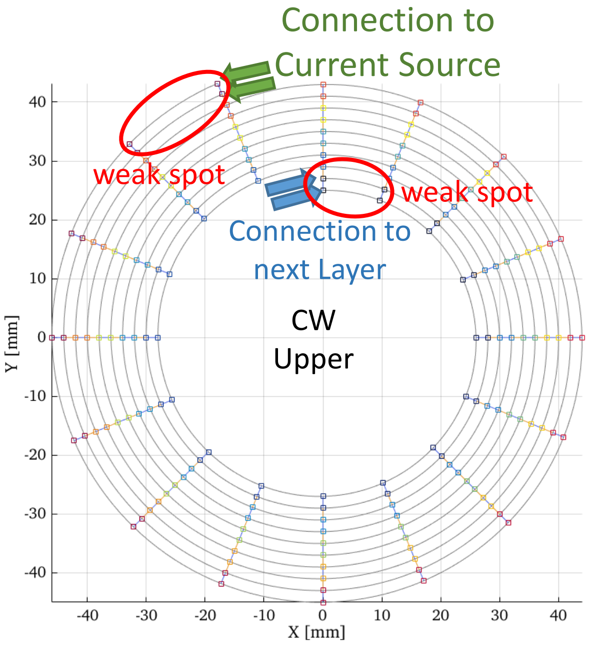
$$\overbrace{\begin{bmatrix} I_{s,i} + I_{\mathrm{bg},i}\left(\frac{\partial \vec{B}}{\partial t}\right) \\ V_{s,q} + V_{\mathrm{bg},q}\left(\frac{\partial \vec{B}}{\partial t}\right) \\ P_{s,s} + K_{\mathrm{cool},ss} T_{\mathrm{bath}} \end{bmatrix}}^{\text{external sources}} + \overbrace{\begin{bmatrix} 0 & 0 & 0 \\ 0 & L_{qr} + M_{\mathrm{S2T},qr} & 0 \\ 0 & 0 & -C_{p,sp} \end{bmatrix} \begin{bmatrix} \frac{\partial V_j}{\partial t} \\ \frac{\partial I_r}{\partial t} \\ \frac{\partial T_p}{\partial t} \end{bmatrix} + \begin{bmatrix} 0 \\ V_{\mathrm{mlfmm},q}\left(\frac{\partial I_r}{\partial t}\right) \\ 0 \end{bmatrix}}^{\text{time dependent linear}} = \overbrace{\begin{bmatrix} I_{\mathrm{res},i} \\ V_{\mathrm{res},q} \\ P_{\mathrm{res},s} \end{bmatrix}}^{\text{residual}} \cong \vec{0},$$

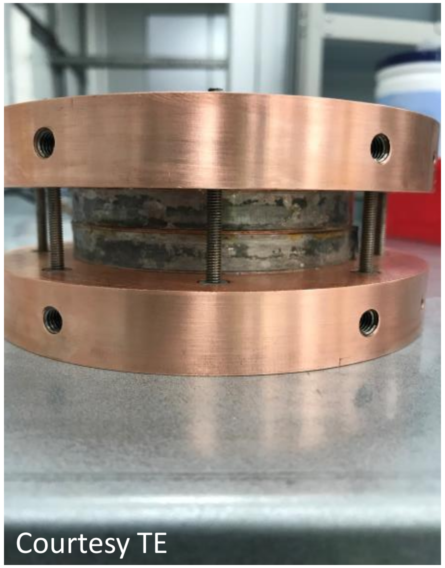


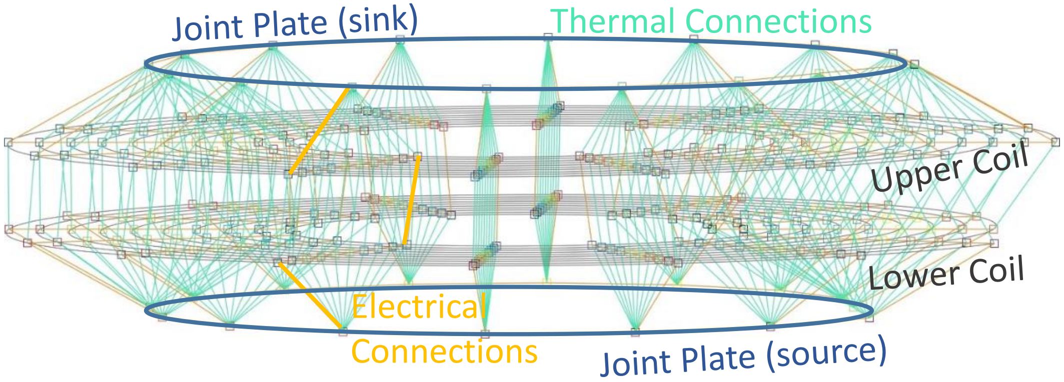
Wang et el. picture and approach

NI Coil Network I



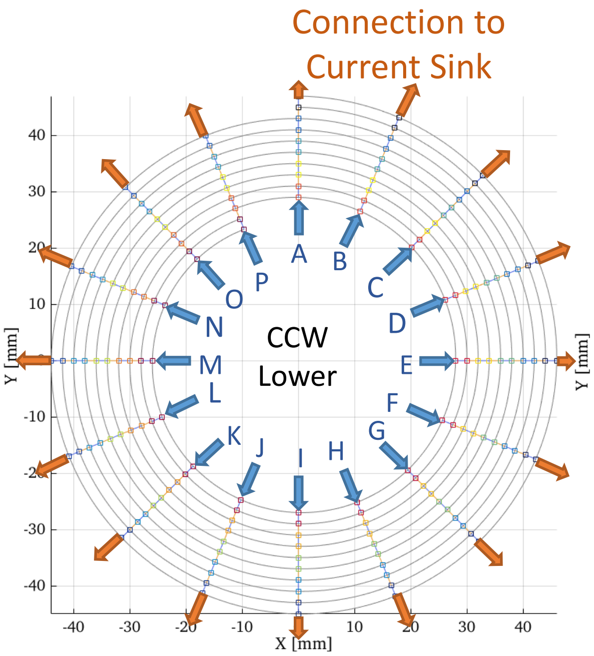


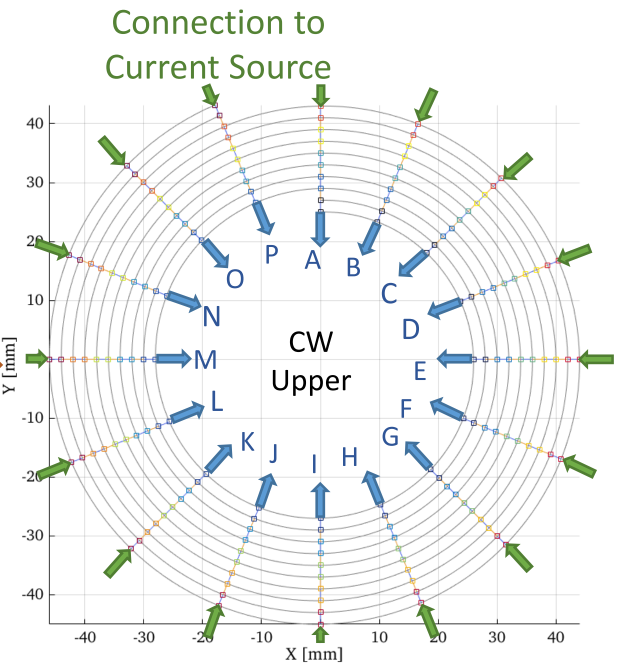

Courtesy TE

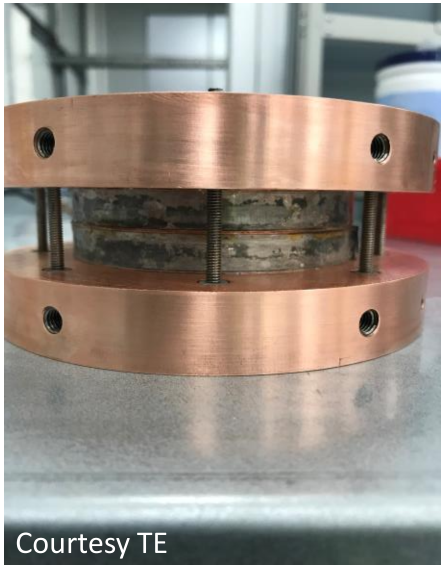


- The Coils are Represented by a 3D network consisting of line elements and nodes.
- Here we see an earlier version of the network.
- Many quenches occurred pre-maturely at the indicated locations.

NI Coil Network II



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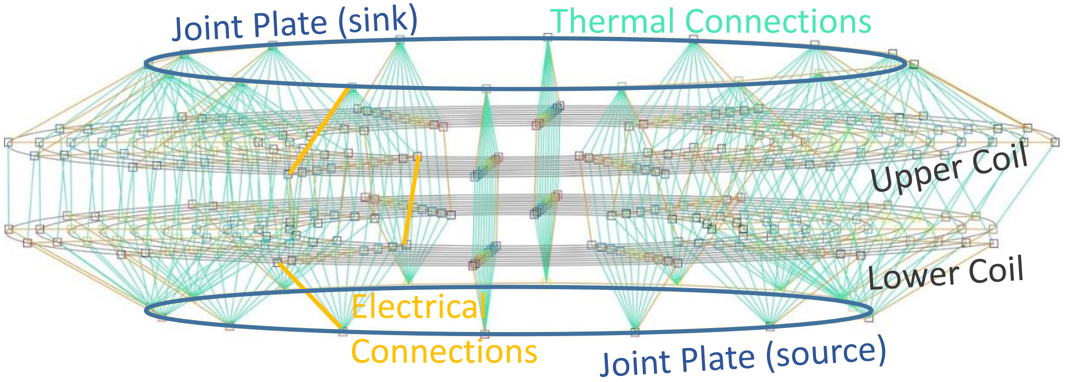
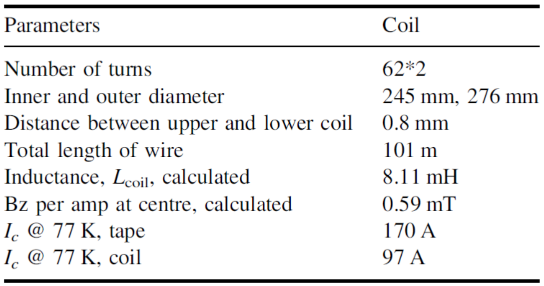


- The Coils are Represented by a network consisting of line elements and nodes.
- Ring joints must be connected to a large part of the innermost and outermost turn of each pancake.

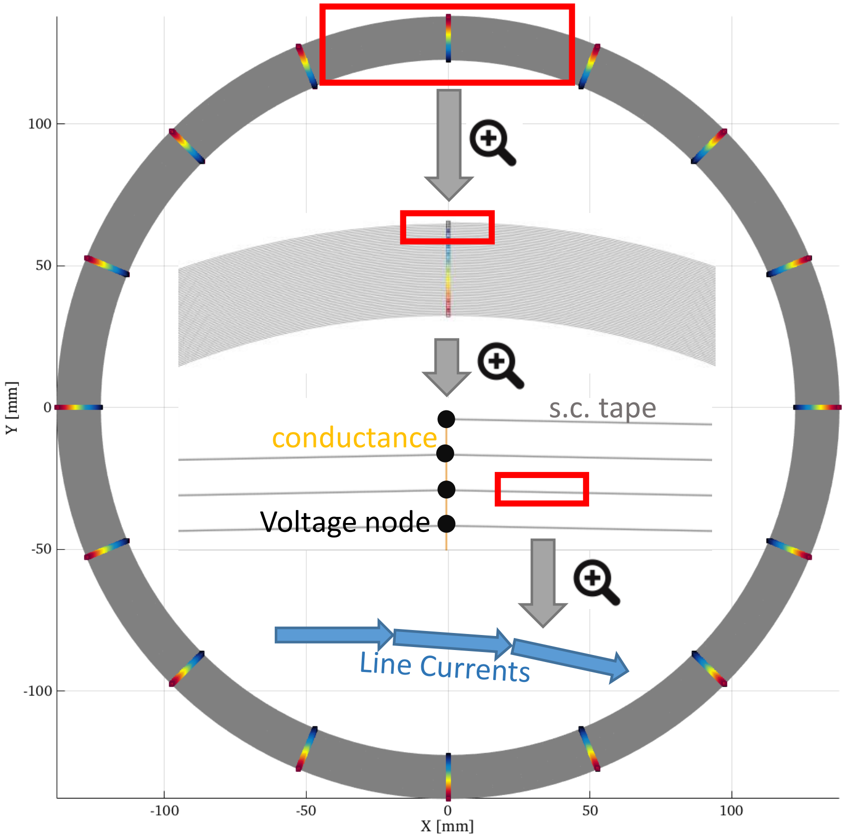
Modelling Wang et al. NI Coil

- In the paper of Wang et al. a well characterised (both numerically and experimentally) NI coil is found.
- The provided data is used for initial validation of the model.
- Below the network representation of the wang et al. coil.
- Turn to turn contact resistance is given as: 2.75 nΩm^2

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



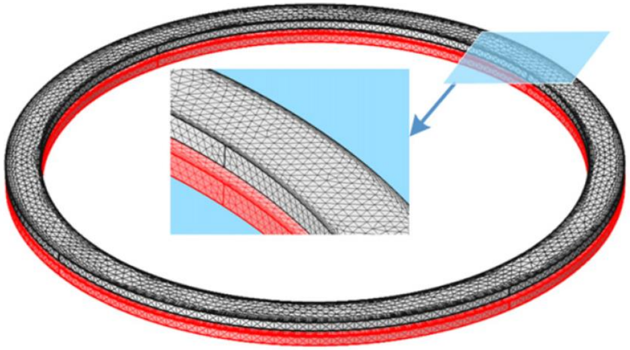
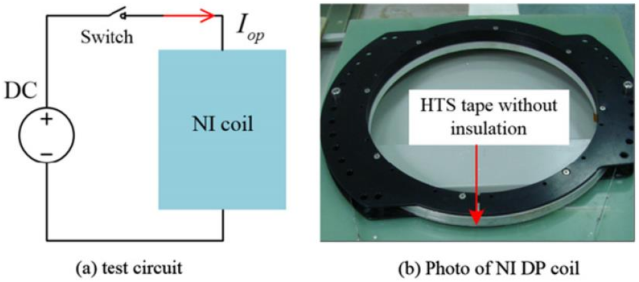


Figure 4. The FEM model of the DP coil to calculate the induced magnetic field.



(a) test circuit

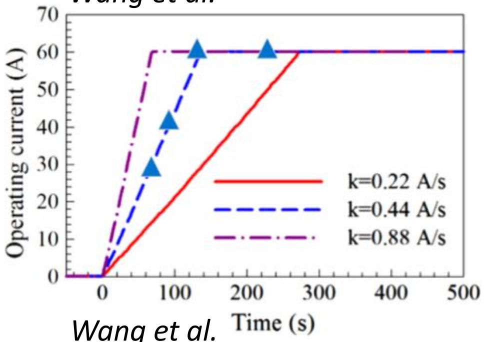
(b) Photo of NI DP coil

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

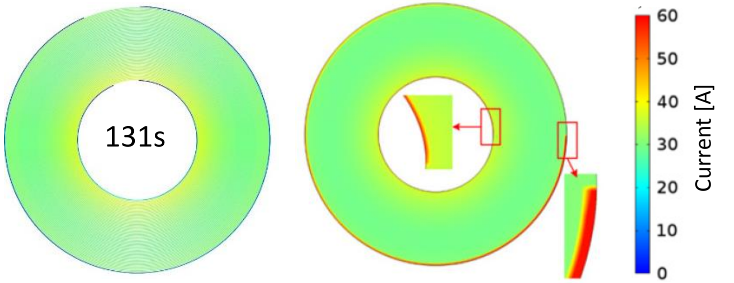
Wang Coil Comparing Results

- The coil was tested at various ramp-rates: 0.22, 0.44 and 0.88A/s.
- The voltage drop over the coil and magnetic field at the coil centre match very well.
- The calculated spiral current and radial currents look identical at 91, 131 and 200 s (provided by paper).
- Similar results found for fast discharge (open circuit) test.
- This validates the electro-magnetic part of the network model.

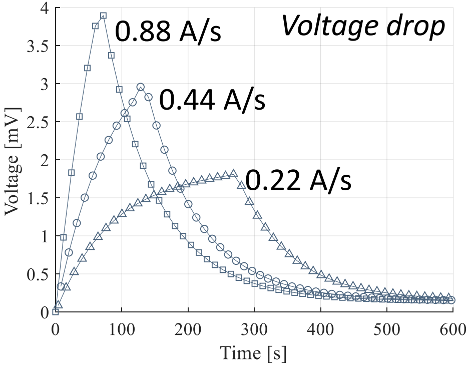
Wang et al.



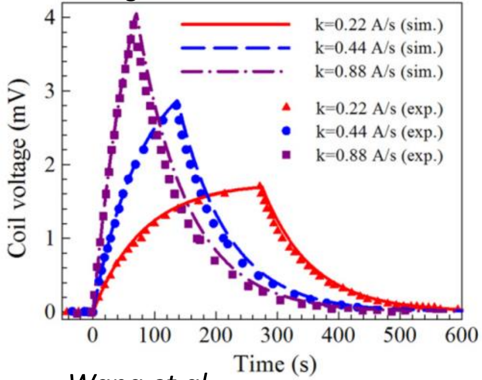
Spiral current *



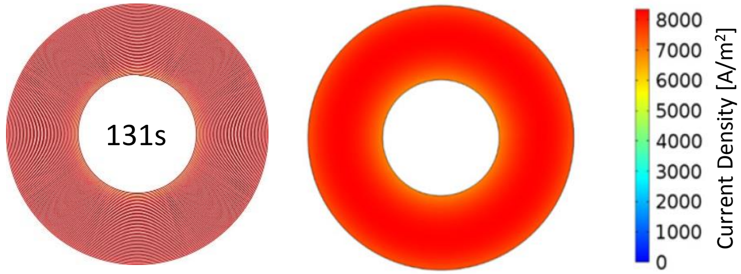
ElMaTh



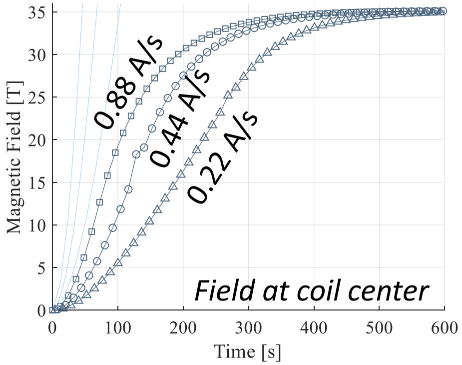
Wang et al.



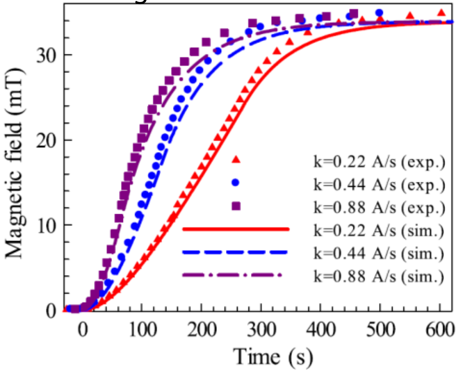
Radial current*



ElMaTh



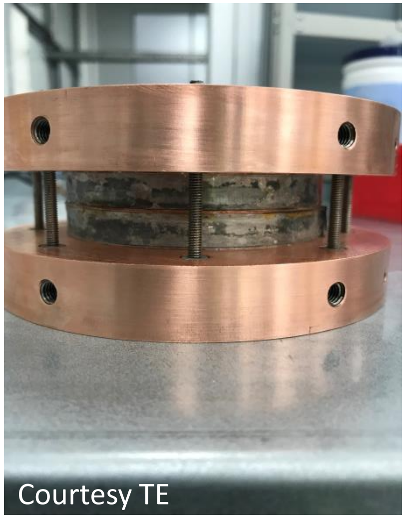
Wang et al.



*Coil radiuses re-scaled for better representation

Modelling QA Coil

- 128 Turns with type-0 tape pair
- 50 mm inner diameter, 100 mm outer diameter
- Fully solder potted (both turn2turn and tape2tape):
  - Resistance: 450 nΩ cm^2 (from Fleiter et al.)
  - Thermal conductivity: 10.8 kW K^{-1} m^{-1}
- Tape and scaling relation from Shanghai Superconductors
- Operating temperature 20 K on cryocooler



Courtesy TE

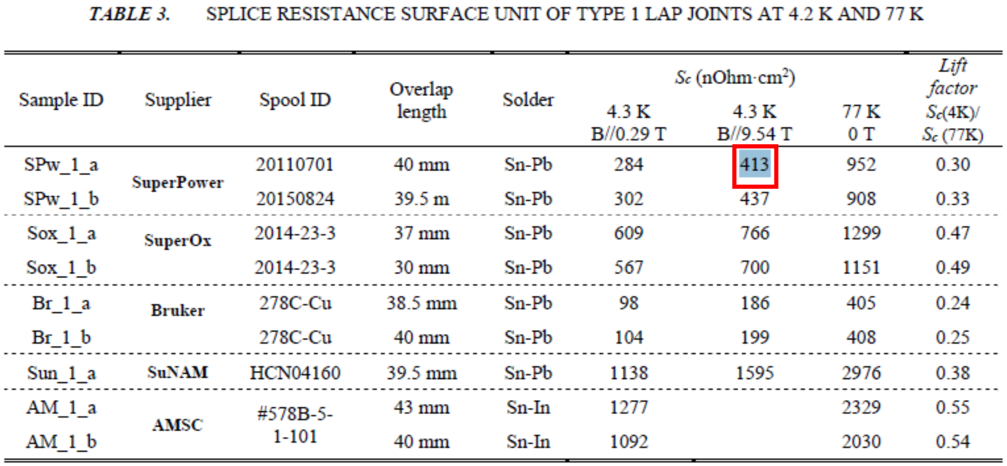
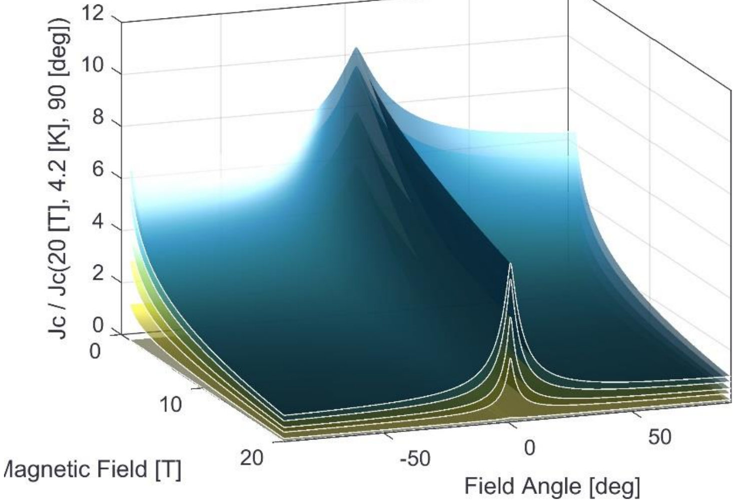


TABLE 3. SPLICE RESISTANCE SURFACE UNIT OF TYPE 1 LAP JOINTS AT 4.2 K AND 77 K

Sample ID	Supplier	Spool ID	Overlap length	Solder	S_c (nOhm·cm²)			*Lift factor*
					4.3 K B//0.29 T	4.3 K B//9.54 T	77 K 0 T	S_c(4K)/ S_c (77K)
SPw_1_a	**SuperPower**	20110701	40 mm	Sn-Pb	284	413	952	0.30
SPw_1_b		20150824	39.5 m	Sn-Pb	302	437	908	0.33
Sox_1_a	**SuperOx**	2014-23-3	37 mm	Sn-Pb	609	766	1299	0.47
Sox_1_b		2014-23-3	30 mm	Sn-Pb	567	700	1151	0.49
Br_1_a	**Bruker**	278C-Cu	38.5 mm	Sn-Pb	98	186	405	0.24
Br_1_b		278C-Cu	40 mm	Sn-Pb	104	199	408	0.25
Sun_1_a	**SuNAM**	HCN04160	39.5 mm	Sn-Pb	1138	1595	2976	0.38
AM_1_a	**AMSC**	#578B-5-1-101	43 mm	Sn-In	1277		2329	0.55
AM_1_b			40 mm	Sn-In	1092		2030	0.54

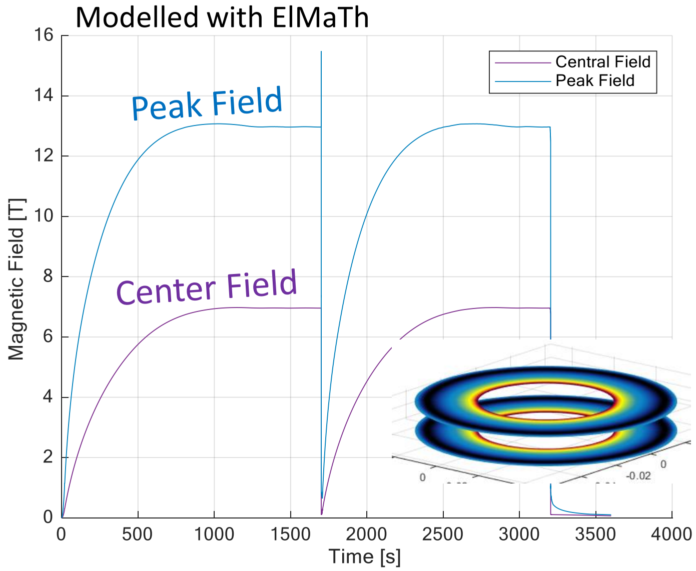
From: J. Fleiter and A. Ballarino. "In-Field Resistance of REBCO Electrical Joints at 4.2 K". CERN Internal Note 2015-10, EDMS Nr: 1562549

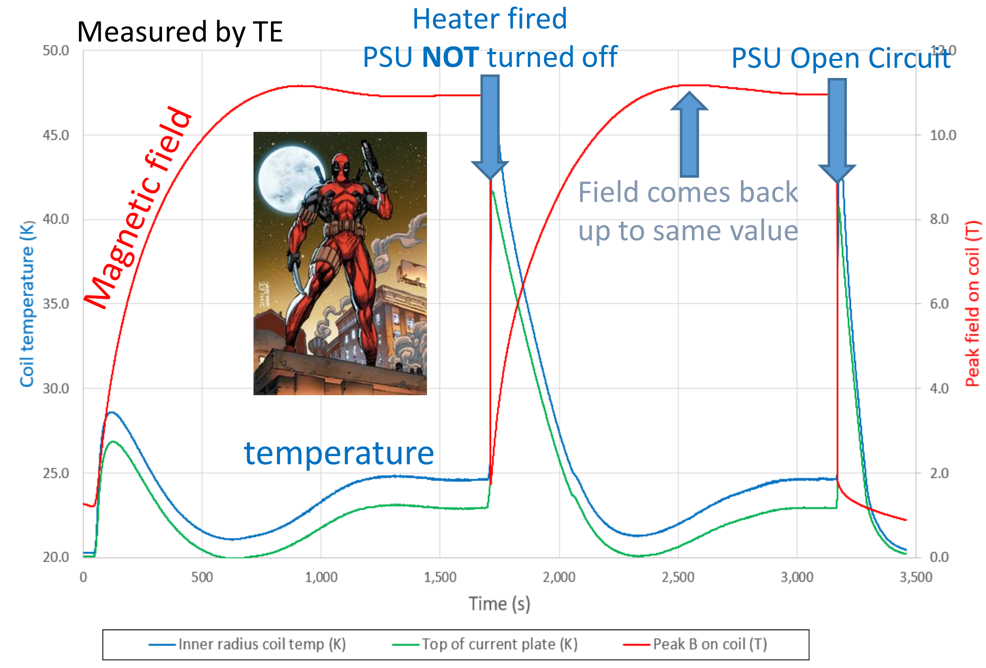
Shanghai Angular/Temperature/Field Dependent Critical Current

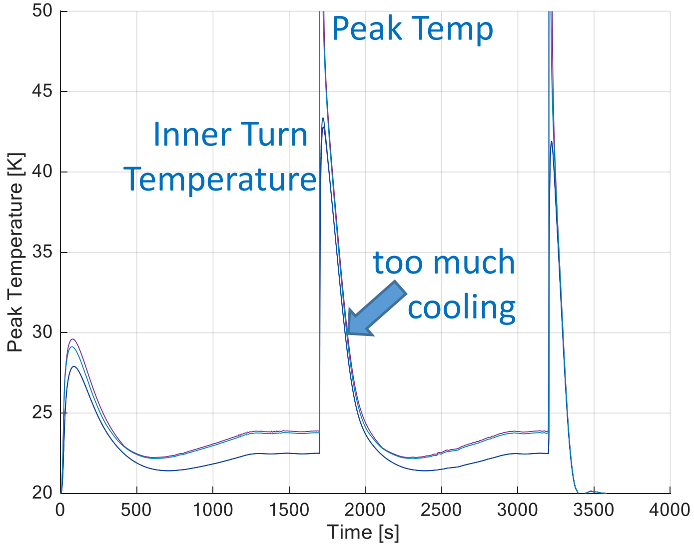


QA Coil Analysis

- Can we reproduce the test of the tokamak deadpool QA coil?
- The difficulty lies in the cooling term, which is constant W/(Km^2). We decided to use fitting for this parameter.
- Reasonable agreement is found between the model and the measurement in terms of Voltage drop, Central Field, Temperature.

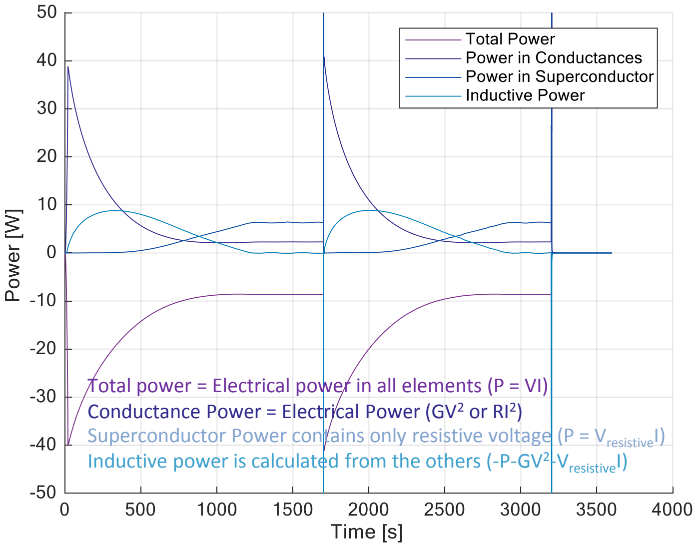






Energy Balance Check

- In the model we can calculate the power dissipation in each of the elements.
- The integral over the resistive power in the elements should be equal to the energy supplied by the power supply.
- The energy balance checks out, strengthening our confidence in the model.

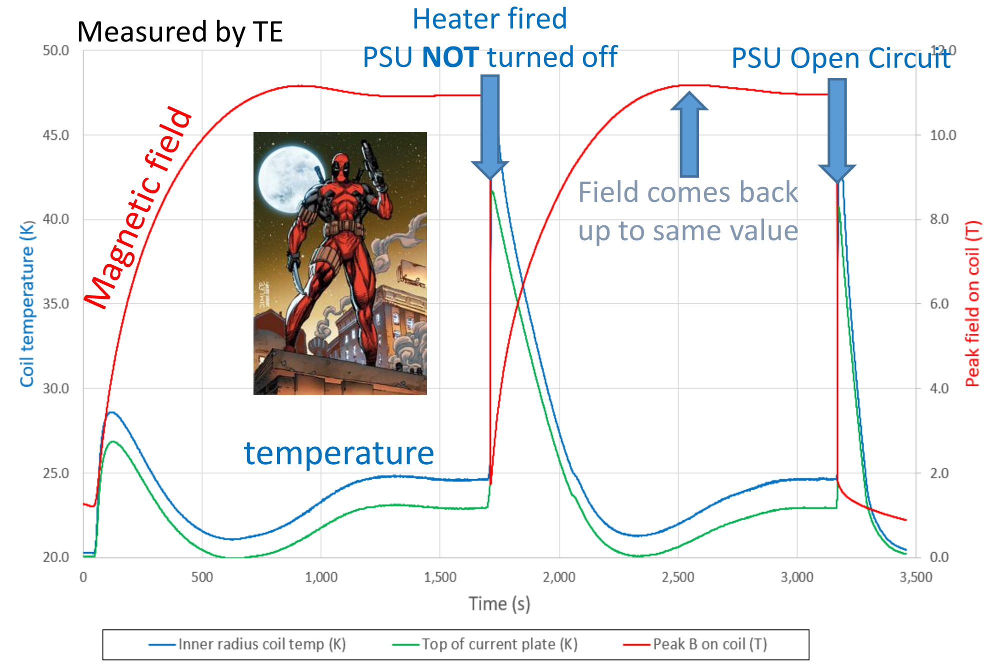


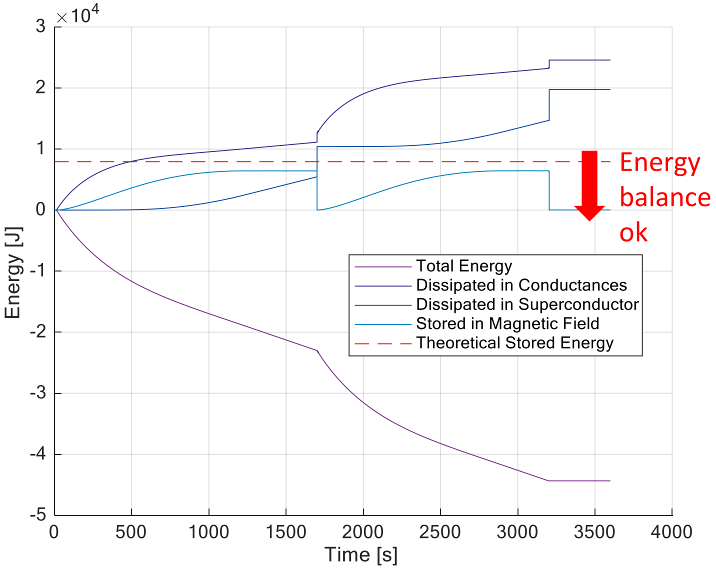
Total power = Electrical power in all elements (P = VI)

Conductance Power = Electrical Power (GV^2 or RI^2)

Superconductor Power contains only resistive voltage ($P = V_{resistive}I$)

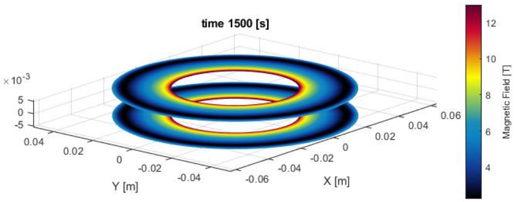
Inductive power is calculated from the others ($-P-GV^2-V_{resistive}I$)



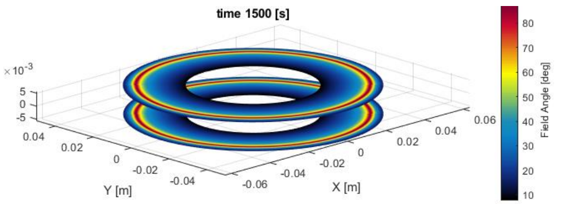


Self Grading Confirmed

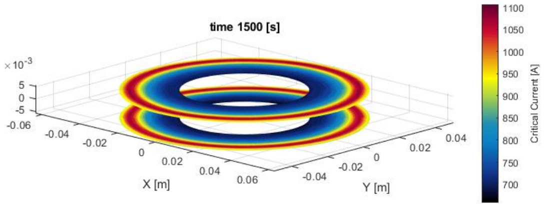
- By reverse engineering the measurements from the Hall probes. It was suspected that the entire coil runs at the short sample.
- The network model confirms this. The turns fill up until critical current reached then bleed off the remaining current radially.
- This unique behaviour is ONLY possible in a solder potted coil.



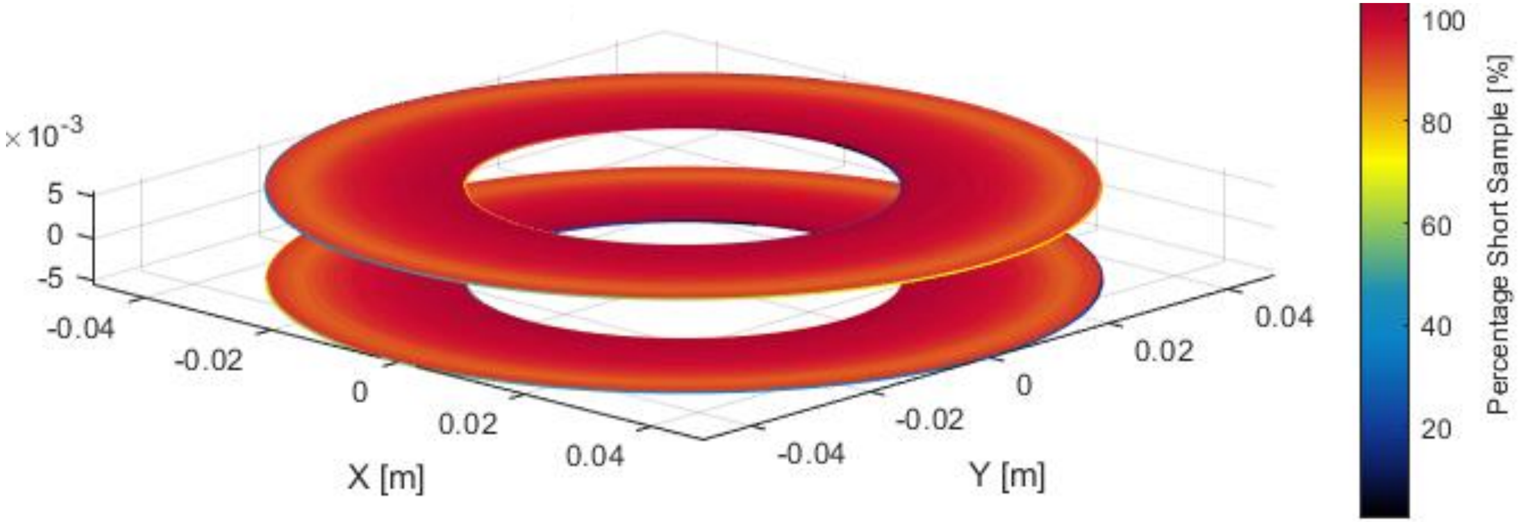
magnetic field



magnetic field angle

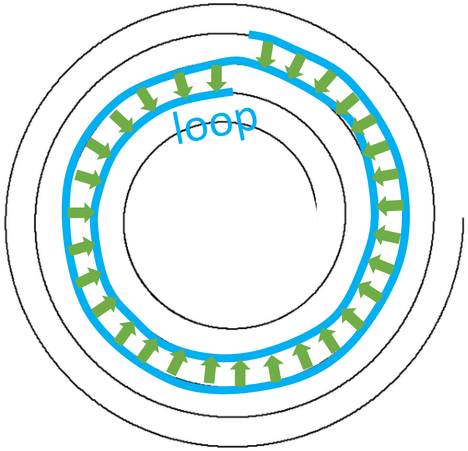


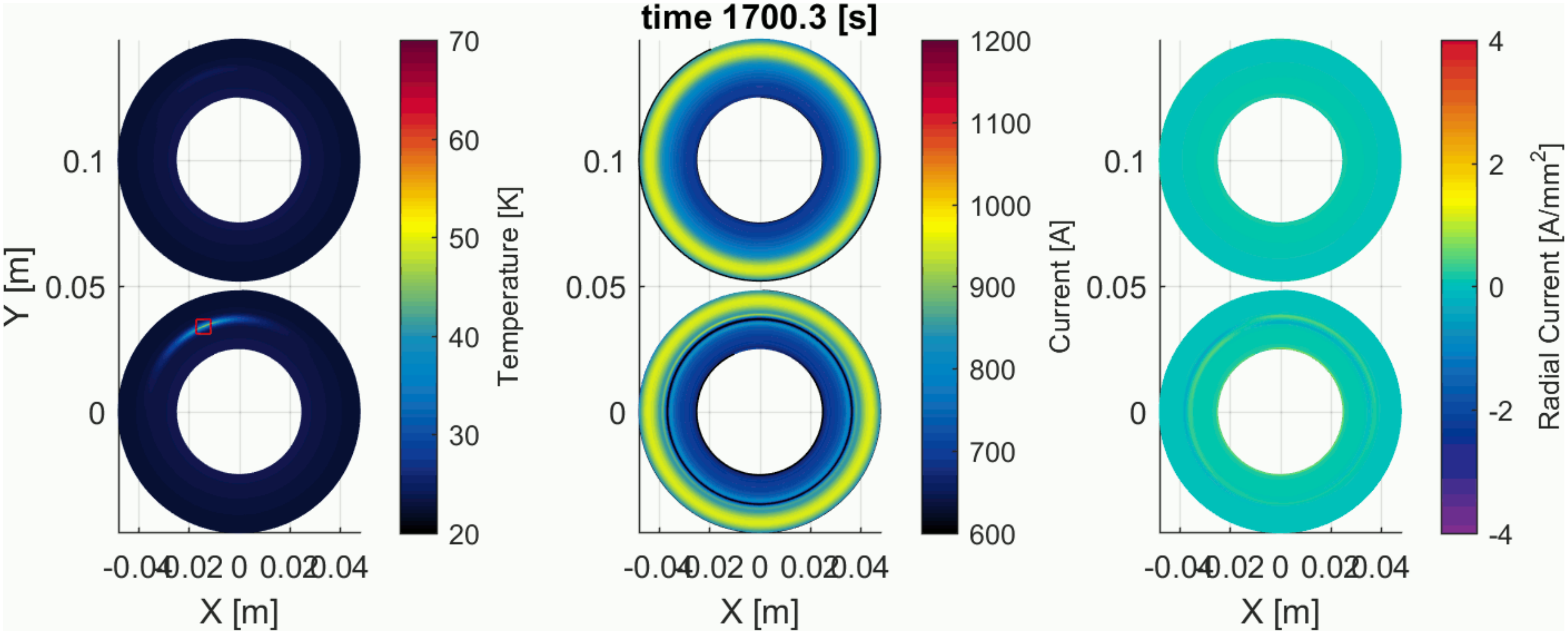
critical current



QA Coil Quench

- The model can offer valuable insight in what happens during the quench
- Due to the very low turn-to-turn resistance each turn can be seen as a loop (closed on itself)
- In case of a normal zone. The current is inductively transferred to the neighbouring loops causing them to quench as well.
- This causes a “shockwave” to propagate throughout the coil effectively discharging the spiralling current in 100 ms.

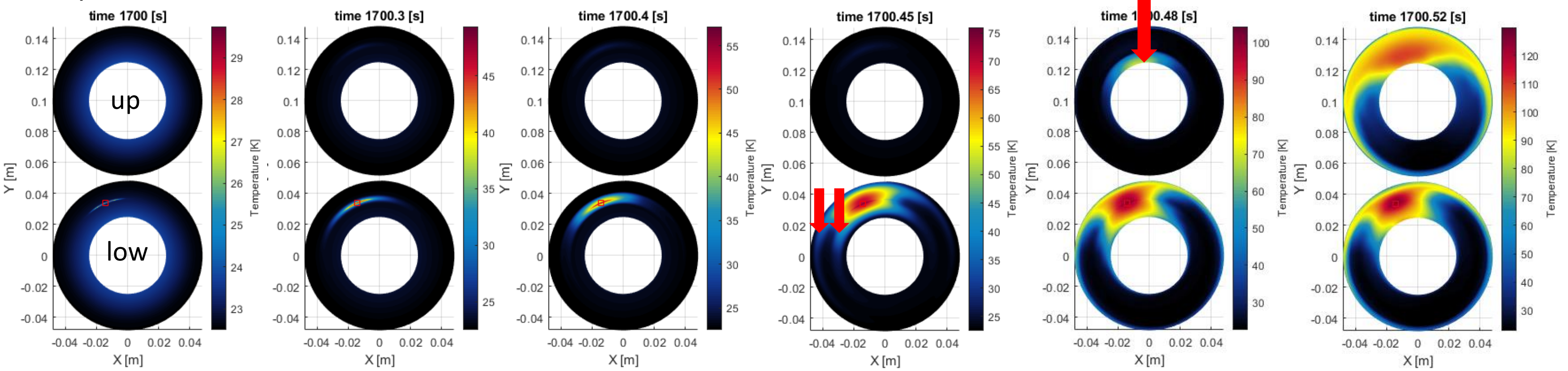




QA Coil Quench (backup)

- Back-up slide in case movie fails.

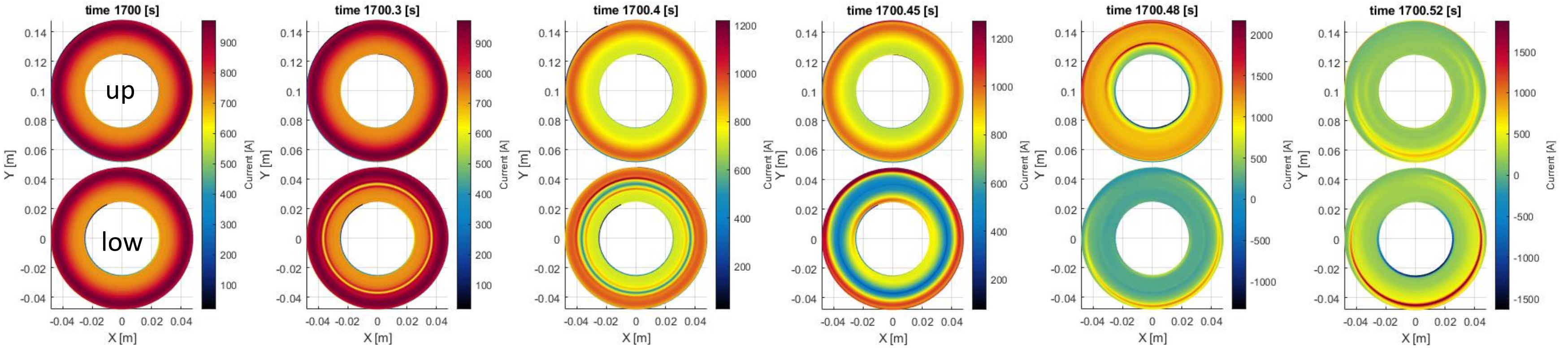
Temperature



Quench jump through joint

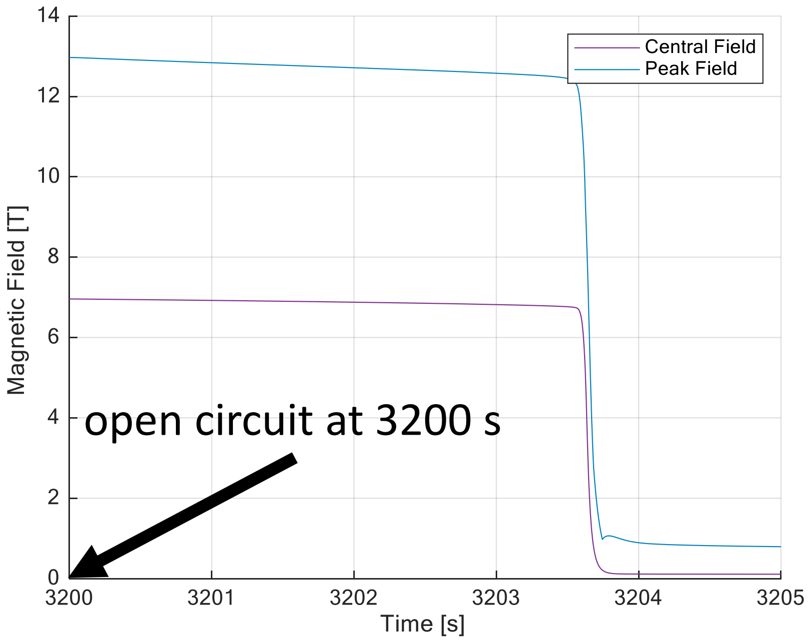
check these tails

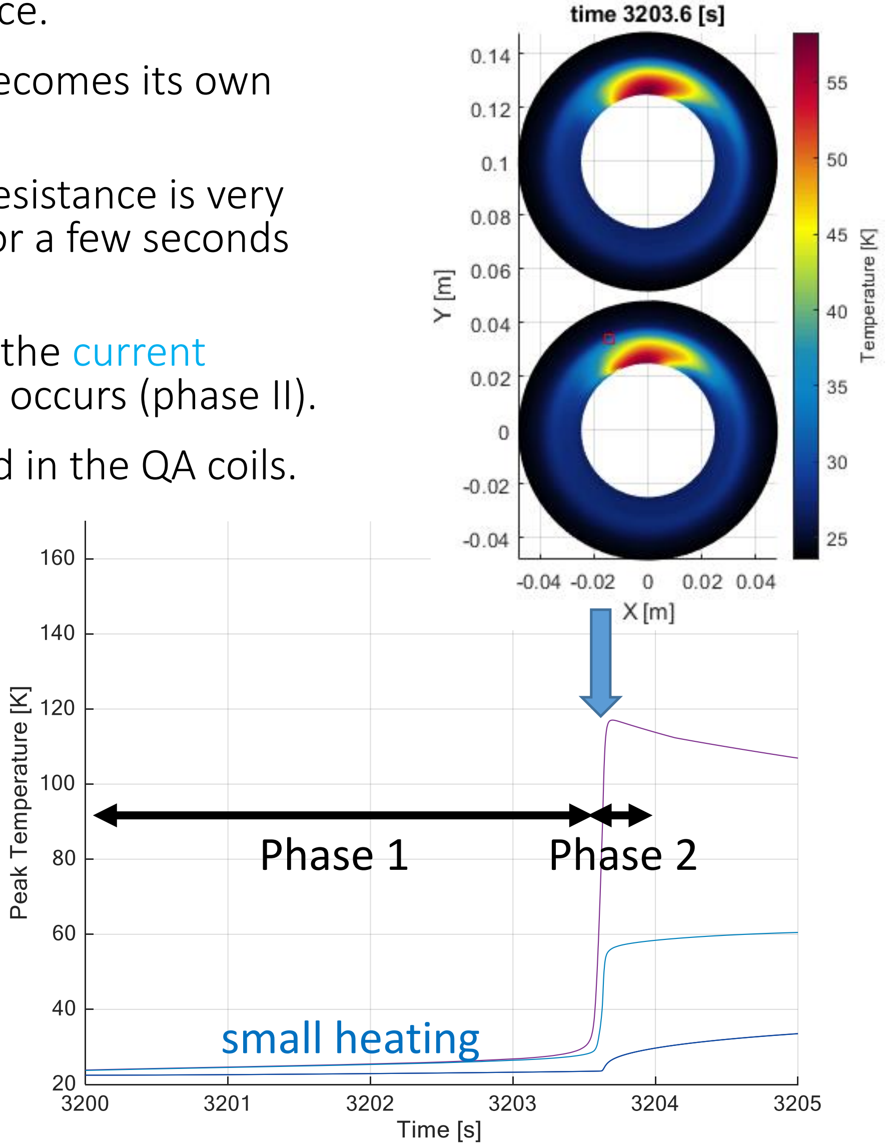
Current



QA Coil Discharge

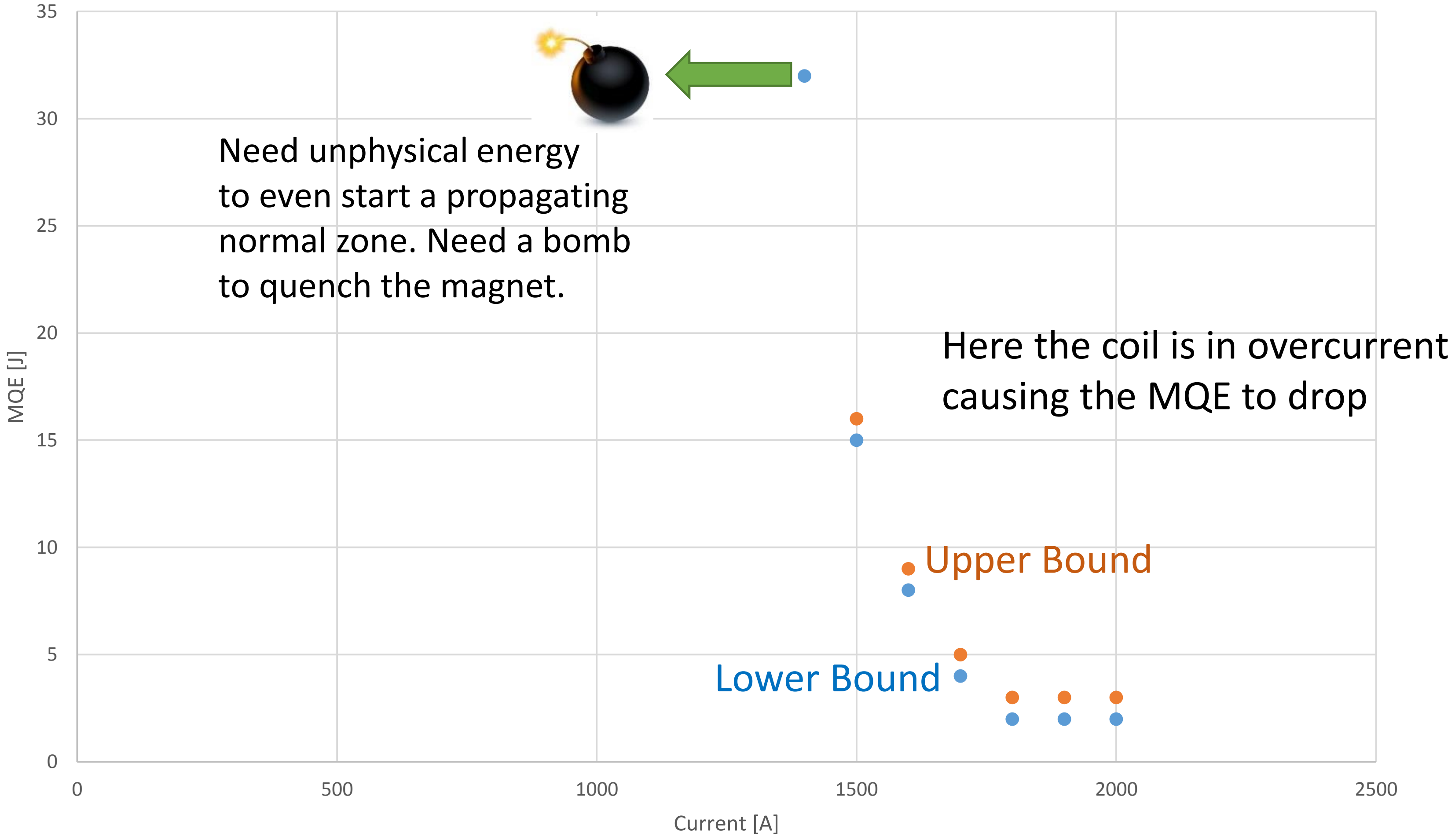
- When the circuit is opened the current is forced to return radially through the turn-to-turn resistance.
- In this scenario, the magnet effectively becomes its own dump resistor.
- However, due to the solder potting this resistance is very low. This causes the magnet to heat up for a few seconds (phase I).
- Then the superconductor is pushed over the current sharing temperature and a fast discharge occurs (phase II).
- This delayed behaviour was also observed in the QA coils.





QA Coil MQE Calculation

- Perhaps after talking about quench so much you have the impression that these coils quench easily. To prove otherwise see MQE vs Operating current below.

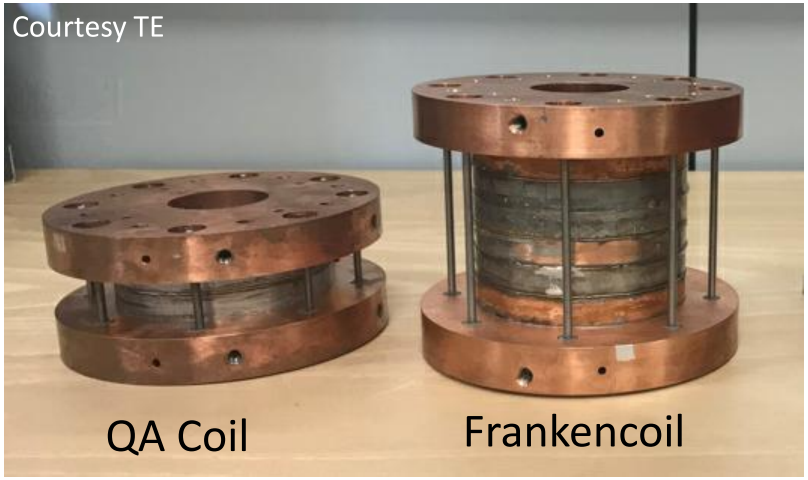


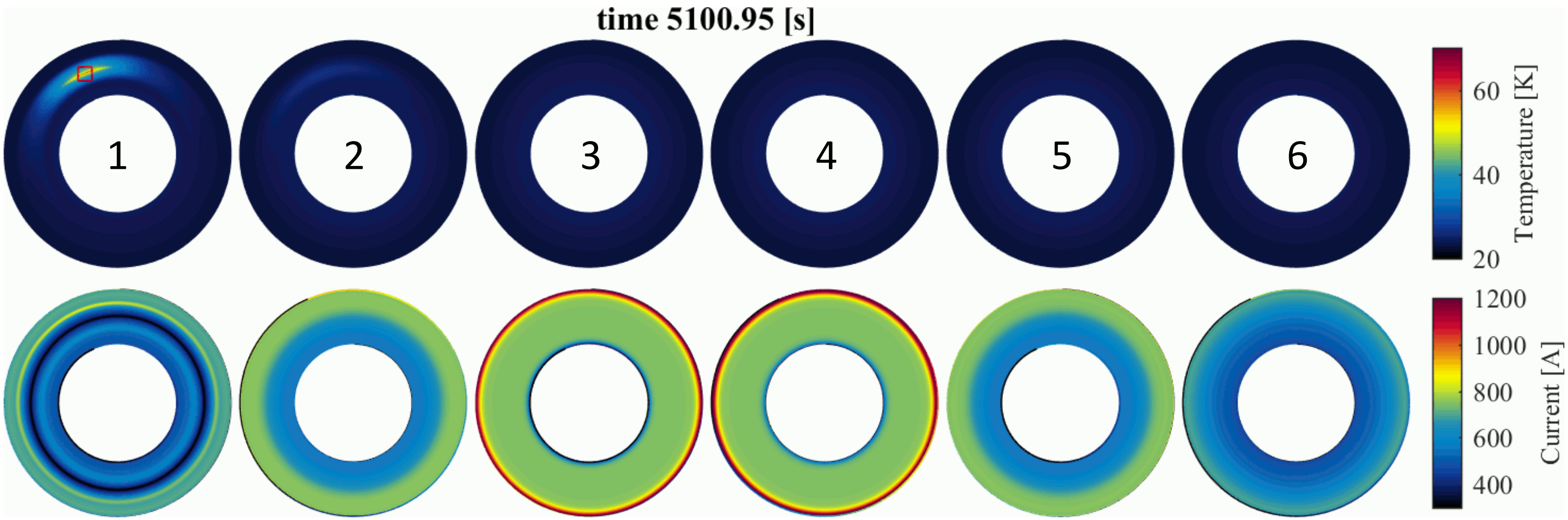
Need unphysical energy to even start a propagating normal zone. Need a bomb to quench the magnet.

Here the coil is in overcurrent causing the MQE to drop

Franken Coil Quench

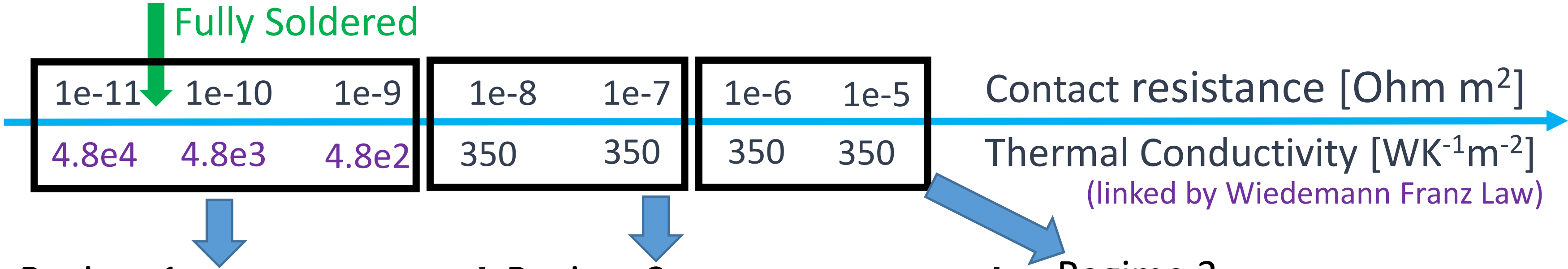
- Tokamak has performed further tests in which multiple QA coils are stacked up (nicknamed “Frankencoil”).
- See below the modelled quench propagation for this case.
- Due to inductive transfer, the current in the last coil looks dangerously high for mechanics. High field solenoid people be warned.
- BUT THE COIL SURVIVED!


Courtesy TE



Turn-to-Turn Resistance

- It is clear that the turn to turn resistance is an important parameter leaving to wonder if there is some sort of optimum.
- A parametric sweep is performed using QA coil geometry and it seems there is more-or-less three regimes present.

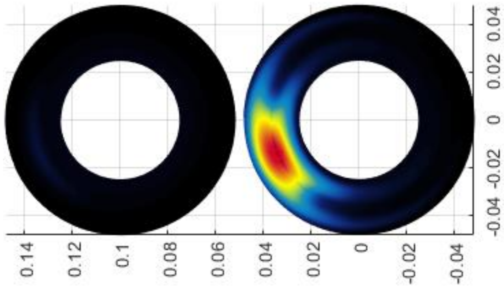


Fully Soldered

Contact resistance [Ohm m^2]	1e-11	1e-10	1e-9	1e-8	1e-7	1e-6	1e-5
Thermal Conductivity [WK^{-1}m^{-2}]	4.8e4	4.8e3	4.8e2	350	350	350	350

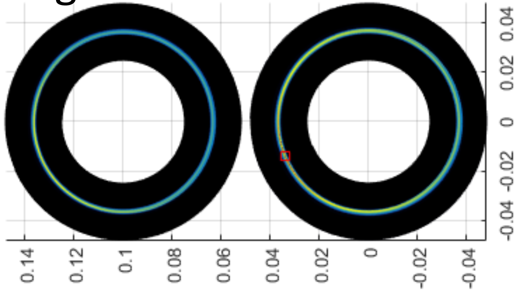
(linked by Wiedemann Franz Law)

Regime 1.



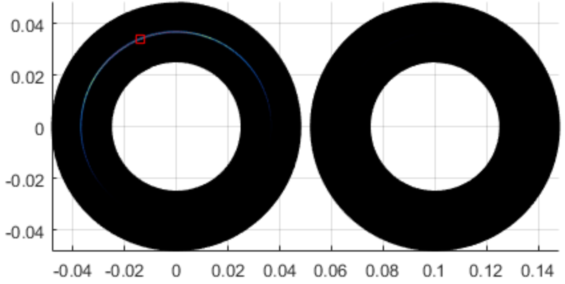
- Instant Discharge (Shockwave).
- Dominated by inductance.
- Quench propagates radially.
- PSU shutdown not needed.

Regime 2.



- Long Duration turn2turn propagation. Slowly collapsing the magnetic field.
- Dominated by resistance.
- Magnetic Energy is dissipated along length of coil.
- PSU shutdown needed.

Regime 3.

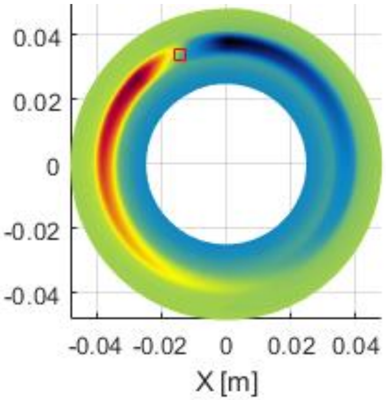


- Instant burnout!
- Quench does NOT spread.
- Need pre-quench detection or very fast (40 ms) detection/protection.
- Fast internal dump perhaps still possible.

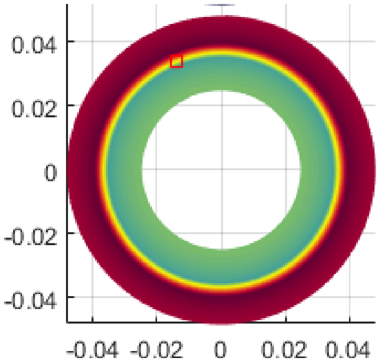
A Good Analogy

- The difference between the regimes is also clearly visible in voltage.
- For the first one the voltage drop is azimuthal while for the second regime the voltage drop is radial.
- I like a good analogy. So here is one …

Regime 1 Quench



Regime 2 Quench

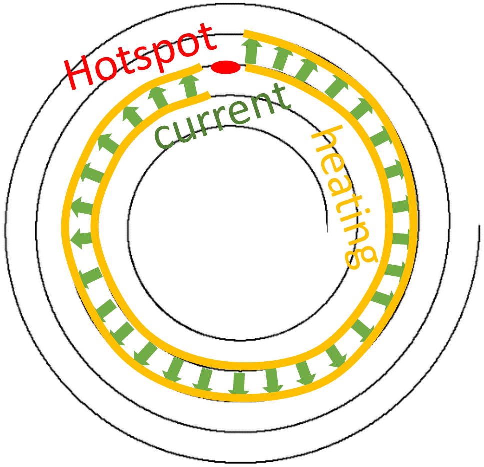


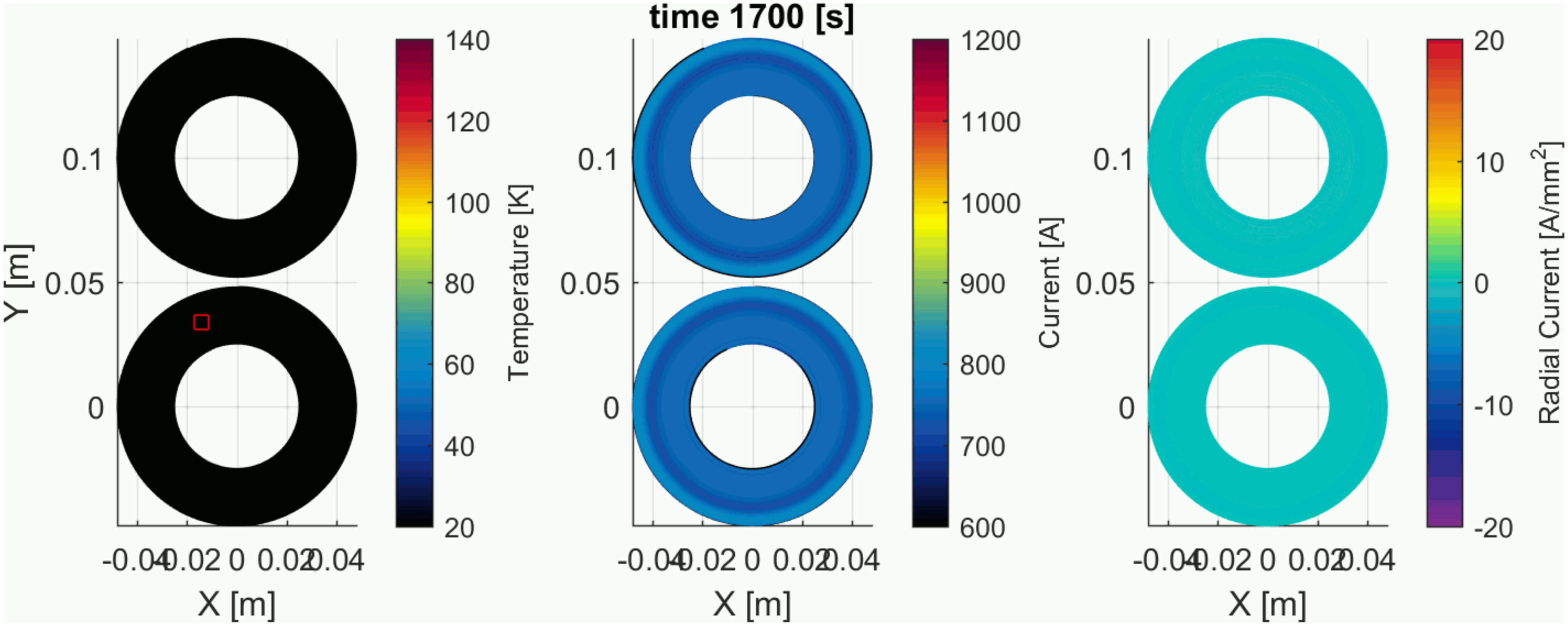
Think of stirring your coffee and stop suddenly. The momentum of the coffee is the inductance.

Like the water intake at a dam. The water/current keeps flowing continuously over the edge.

Intermediate Resistance

- In the second regime we see a completely different phenomenon. As the turn-to-turn resistance is too high for inductive current transfer.
- Here the current wants to skip the turn with the normal zone in it. Causing heating all the way round the coil.
- After initial decay, in which the turn dissipates its own stored energy, the only heating left is coming from the powers supply (diode good idea).





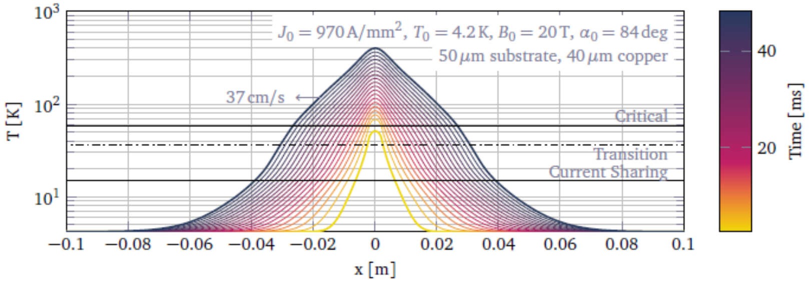
Tuned Insulation

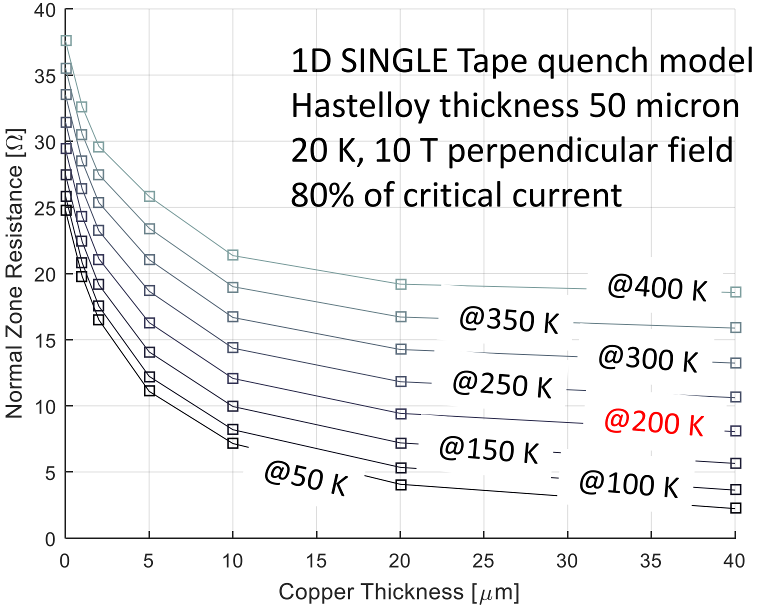
- Now that we understand what happens we can optimise this for our purposes.
- For the current to be able to skip a turn the R_{t2t} must be much less than R_{nz}

$$\not{f} = \frac{1}{120} \qquad \frac{\rho_{t2t}}{\ell_c w_{tp}} = R_{t2t} = R_{nz}\not{f}$$

- The R_{nz} can be found with a 1D NZP model. It seems to almost uniquely depend on the copper thickness (and number of tapes in the cable).
- Here ℓ_c is the length of the coil. So the turn to turn resistance depends on the coil size.
- Also the heat capacity of the turn must be sufficient to take its stored magnetic energy.

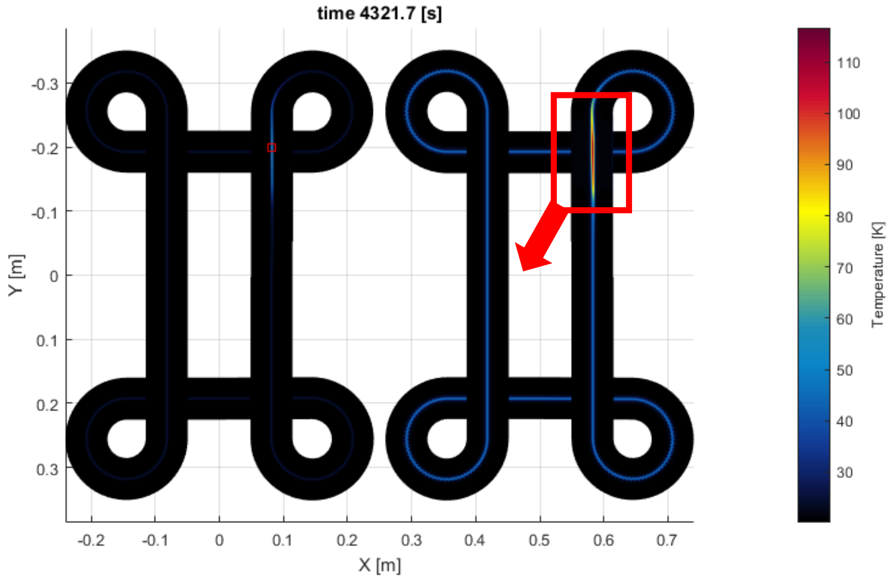
$$\frac{L_c {I_{op}}^2}{2N_{turn}} = E_t = N_{tp}\ell_c w_{tp}\sum_i D_i d_i \int_{T_{op}}^{T^*} C_{pi}$$

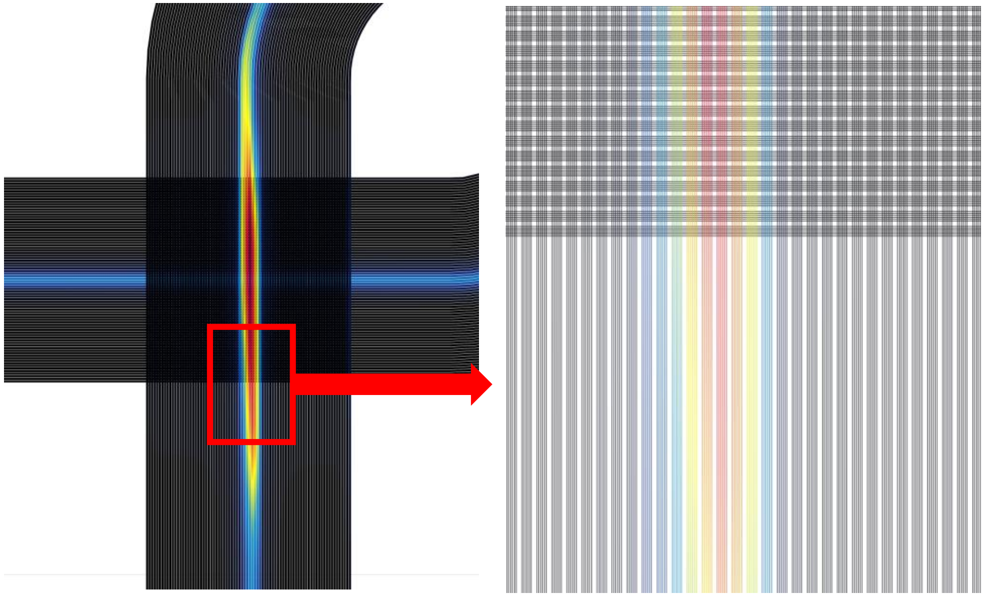




Scale Up

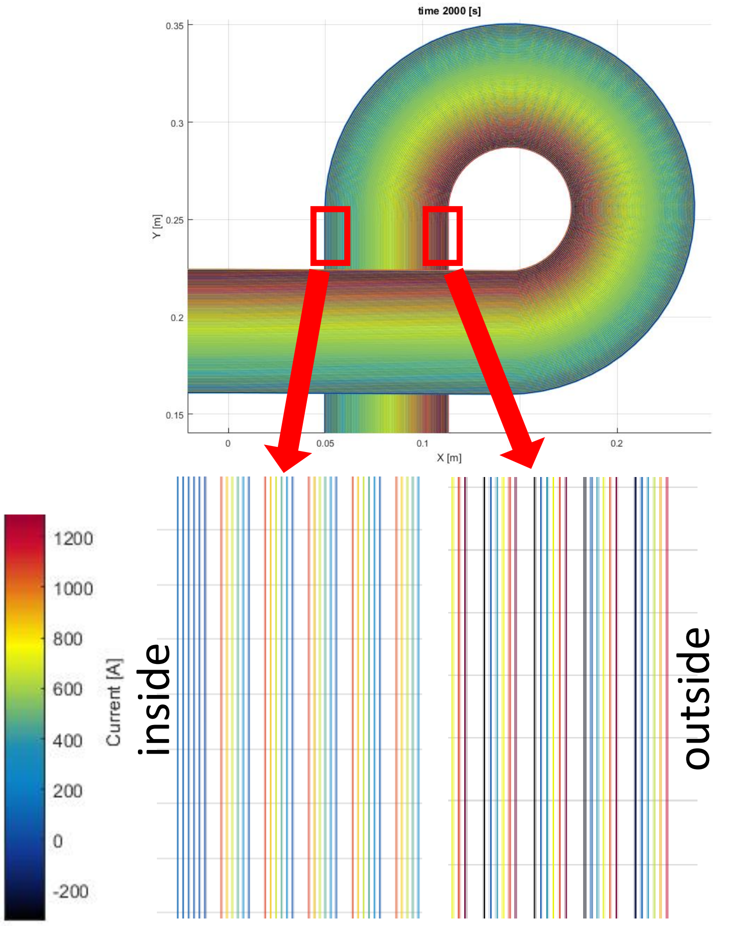
- Can tuned insulation coil be scaled up?
- Initial modelling suggests that this is indeed the case.
- The energy of the quenching turn is distributed fully around the magnet.
- Forces between coils are a worry. When the current comes down in an antisymmetric manner. The forces can be huge.
- Time constant for field delay i.e. L/R is only a few seconds.
- Partial insulation is not noticeable during 20 min ramp.

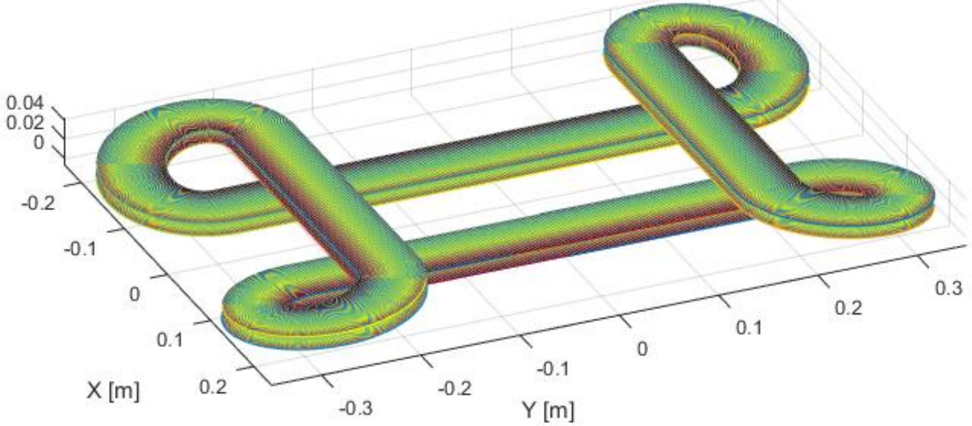




Coupling Loss

- Parallel tapes for mitigating defects and other disturbances are required.
- Stack of tapes much easier to achieve than Roebel cable.
- But what about coupling losses?
- Despite common belief:
  - The current does not flow all the way to the joint and back (in fact there is no joint).
  - During a constant ramp most losses are dissipated inside the superconducting elements (due to over current).
  - The power dissipation for (slow) 1 hour ramp is 0.4 W -> at 20 K this is **nothing**.





What does all this mean?

- Solder potted coils probably best for small steady state magnets.
- For large magnets we can use tuned insulation.
- The time constants are on the order of seconds so will have little effect on slow 20 min powering cycle.
- Can expect to get some snapback.
- Pre-quench detection still preferred. Use inductive backing wire etc.
- Partial insulation as final measure to delay the quench.
- Then after detection use the partial insulation for fast discharge.
- Need practical solution for partial insulation layer.

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Thank you!