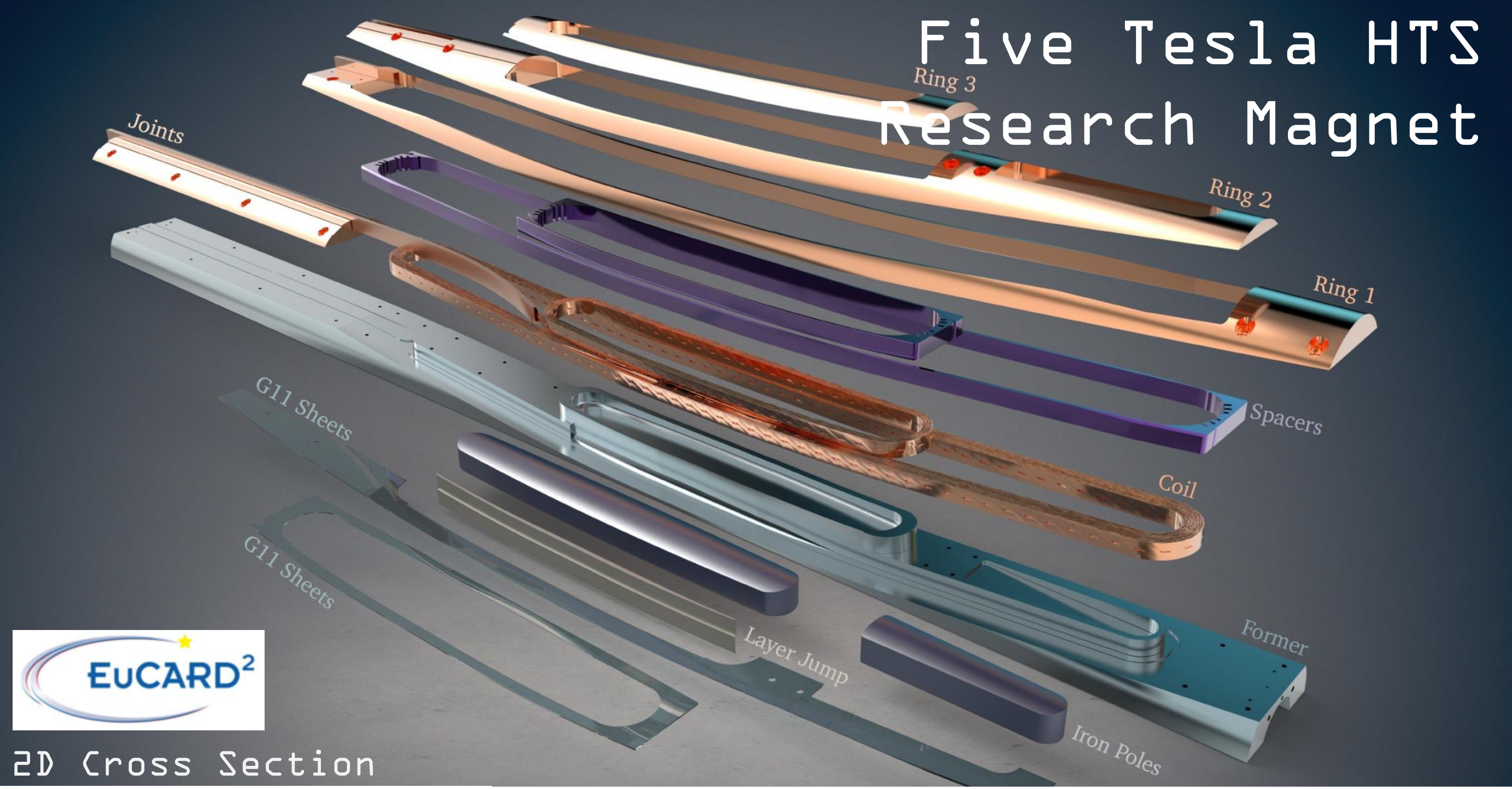
Modelling of HTS ReBCO Cables and Coils

Normal Zone Development and Field quality

EuCARD2, WP10 general meeting, 3 May 2016

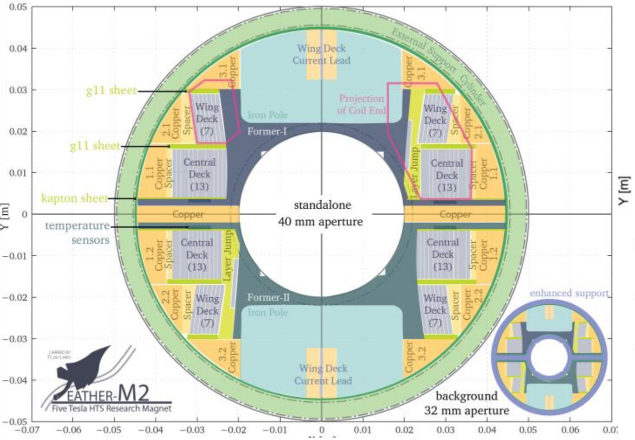
Jeroen van Nugteren

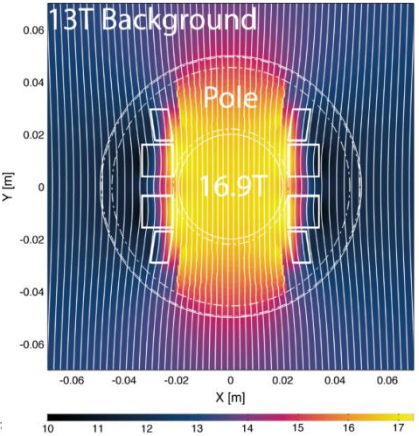
Five Tesla HTS Research Magnet

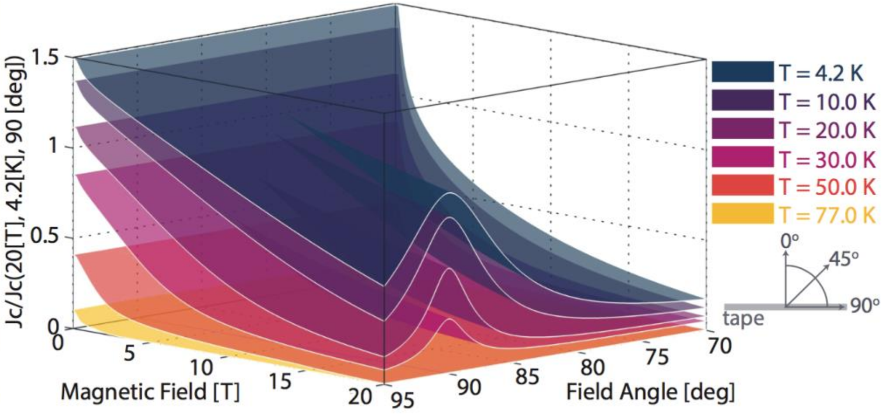


EuCARD²

2D Cross Section

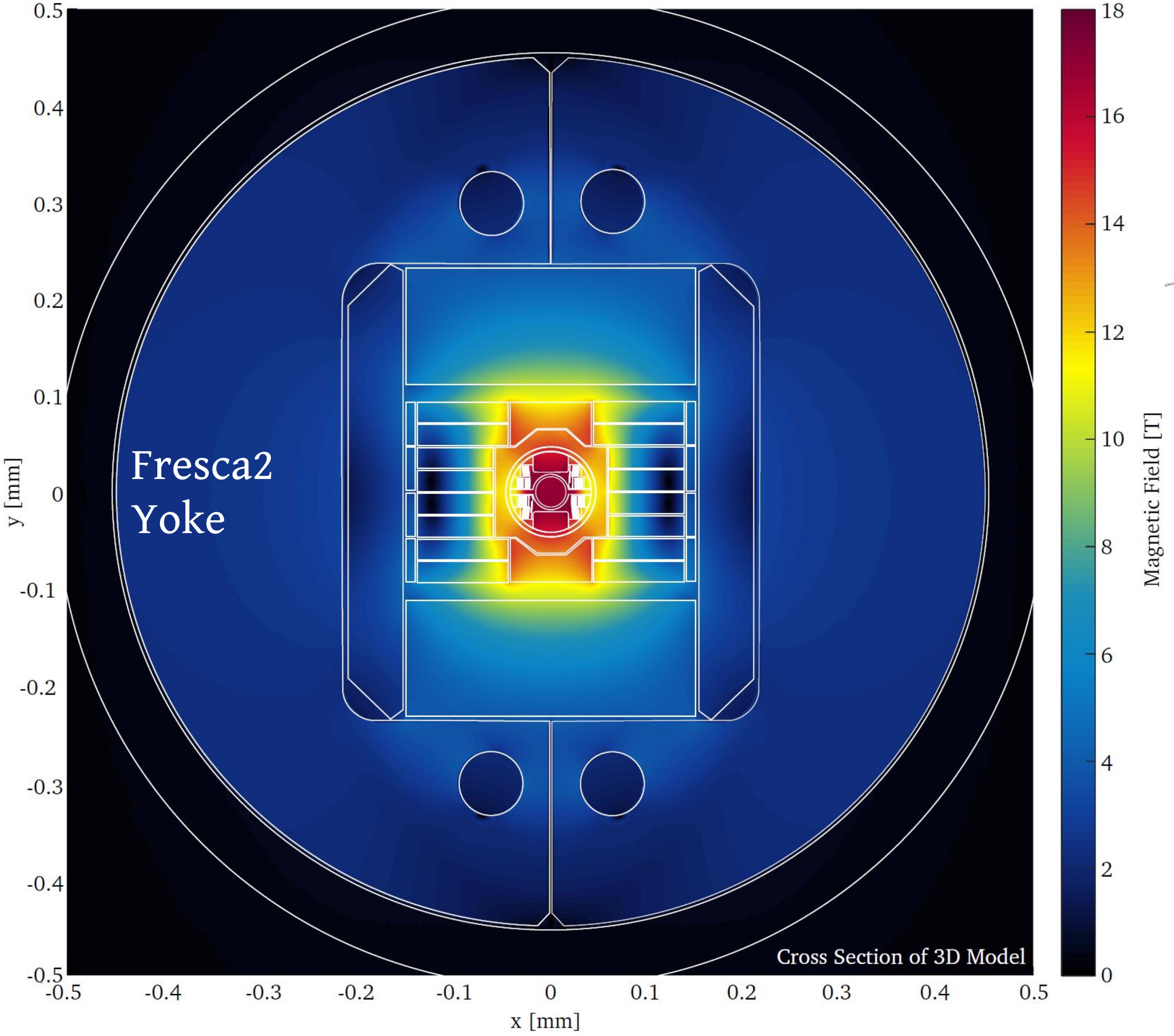


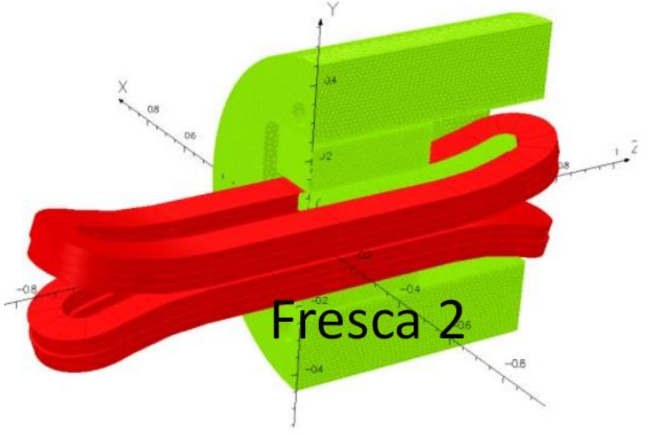


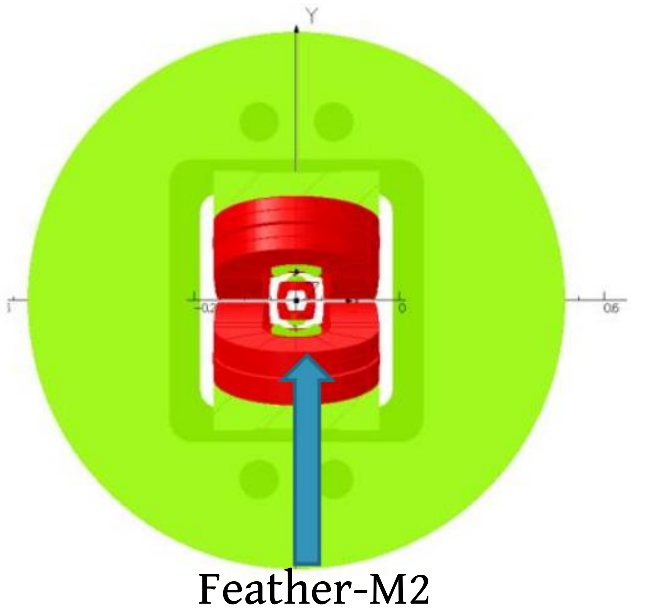


FRESCA2 Operation

- Cobham Opera model of Feather2 and Fresca2 combined
- No peak field enhancement found on outsert(?)

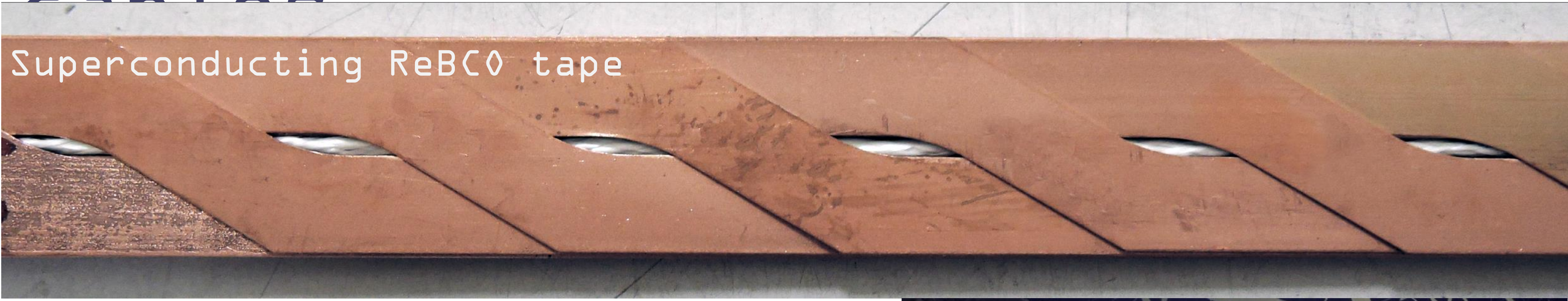


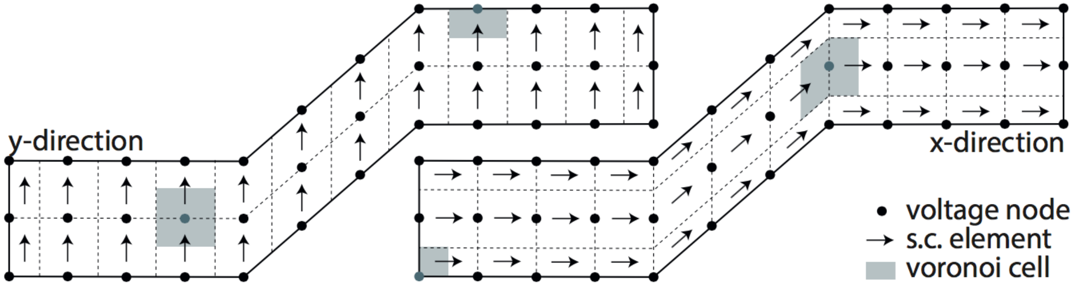




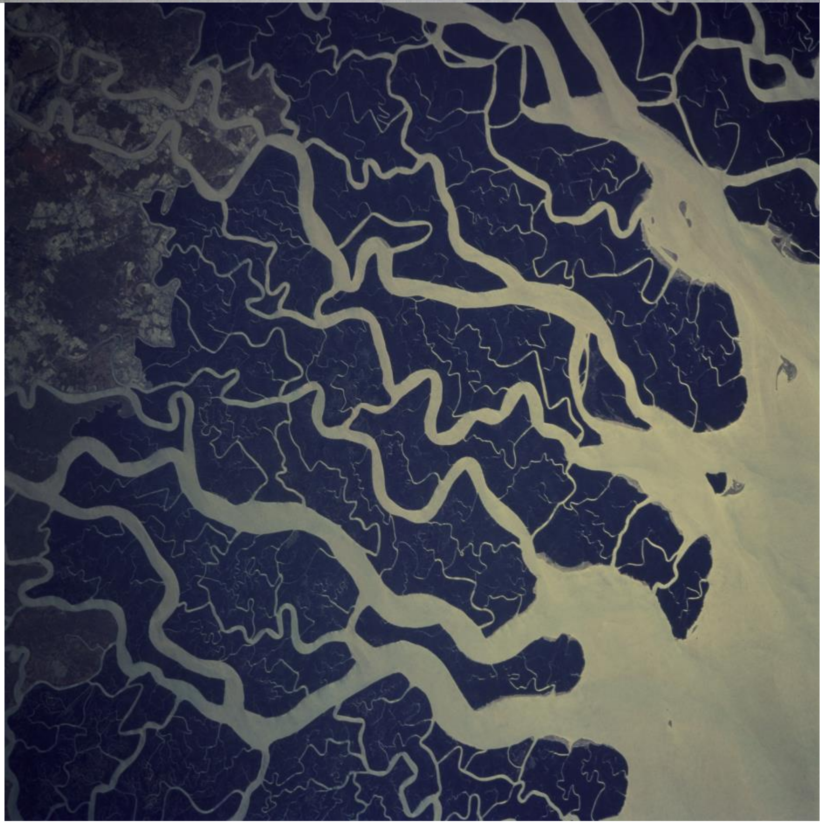
Electrical Network Model for ReBCO HTS cables

Roebel Ca





- Two main unknowns for ReBCO coated conductor:
  1. **Magnetization** - wide tapes act as mono-filaments allowing for large magnetization currents and uncertainty in the position of the current. What is the effect on field quality?
  2. **Quench** - High Minimal Quench Energies (MQE) but slow normal



System of Equations

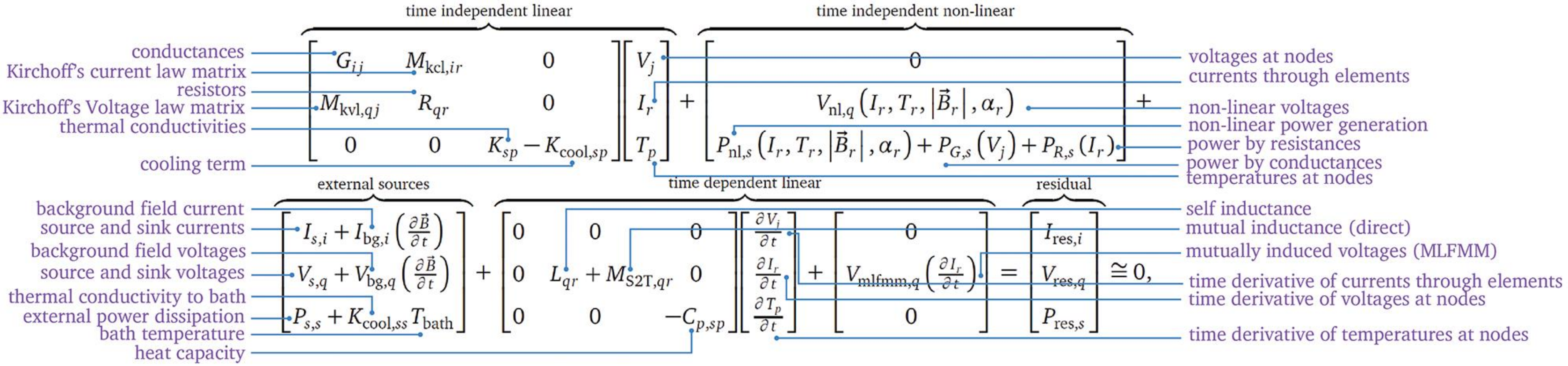
- Tape surface modelled as a (PEEC) network of superconducting elements and nodes
- System of equations is shown below
  - First row represents Kirchoff's current law
  - Second row represents Kirchoff's voltage law
  - Third row represents the Heat Equation

GPU for MLFMM


source: www.pcgamer.com

matrix differential algebraic equation (DAE)

A transient evolution of the currents, voltages and temperatures is found by solving the following system of equations. The first row is Kirchoffs current law, the second is Kirchoff's voltage law and the third is the discretized heat equation.



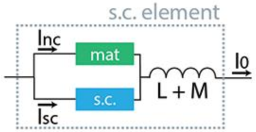
$$\overbrace{\begin{bmatrix} G_{ij} & M_{\mathrm{kcl},ir} & 0 \\ M_{\mathrm{kvl},qj} & R_{qr} & 0 \\ 0 & 0 & K_{sp}-K_{\mathrm{cool},sp} \end{bmatrix}\begin{bmatrix} V_j \\ I_r \\ T_p \end{bmatrix}}^{\text{time independent linear}} + \overbrace{\begin{bmatrix} 0 \\ V_{\mathrm{nl},q}\left(I_r, T_r, \left|\vec{B}_r\right|,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

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

current sharing

The superconducting elements are modelled as a superconductor in parallel with the matrix

$$I_0 - \frac{E_0}{\rho(B,T)}\left[\frac{I_{sc}}{I_c(B,T,\alpha)}\right]^N - I_{sc} = 0$$



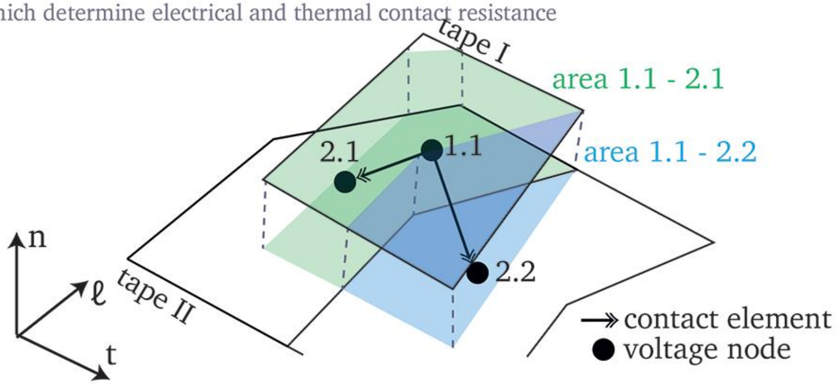
self inductance

$$L_{ribbon} = 0.002\left[\log\left(\frac{2\ell}{w+t}\right) + 0.5 + 0.235\left(\frac{w+t}{\ell}\right)\right],$$

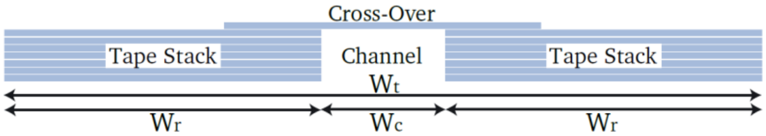
$$L_{\mathrm{wire}} = 2\ell\left[\log\left(\frac{2\ell}{d}\left(1+\sqrt{1+\left[\frac{d}{2\ell}\right]^2}\right)\right) - \sqrt{1+\left[\frac{d}{2\ell}\right]^2} + \frac{\mu}{4} + \frac{d}{2\ell}\right],$$

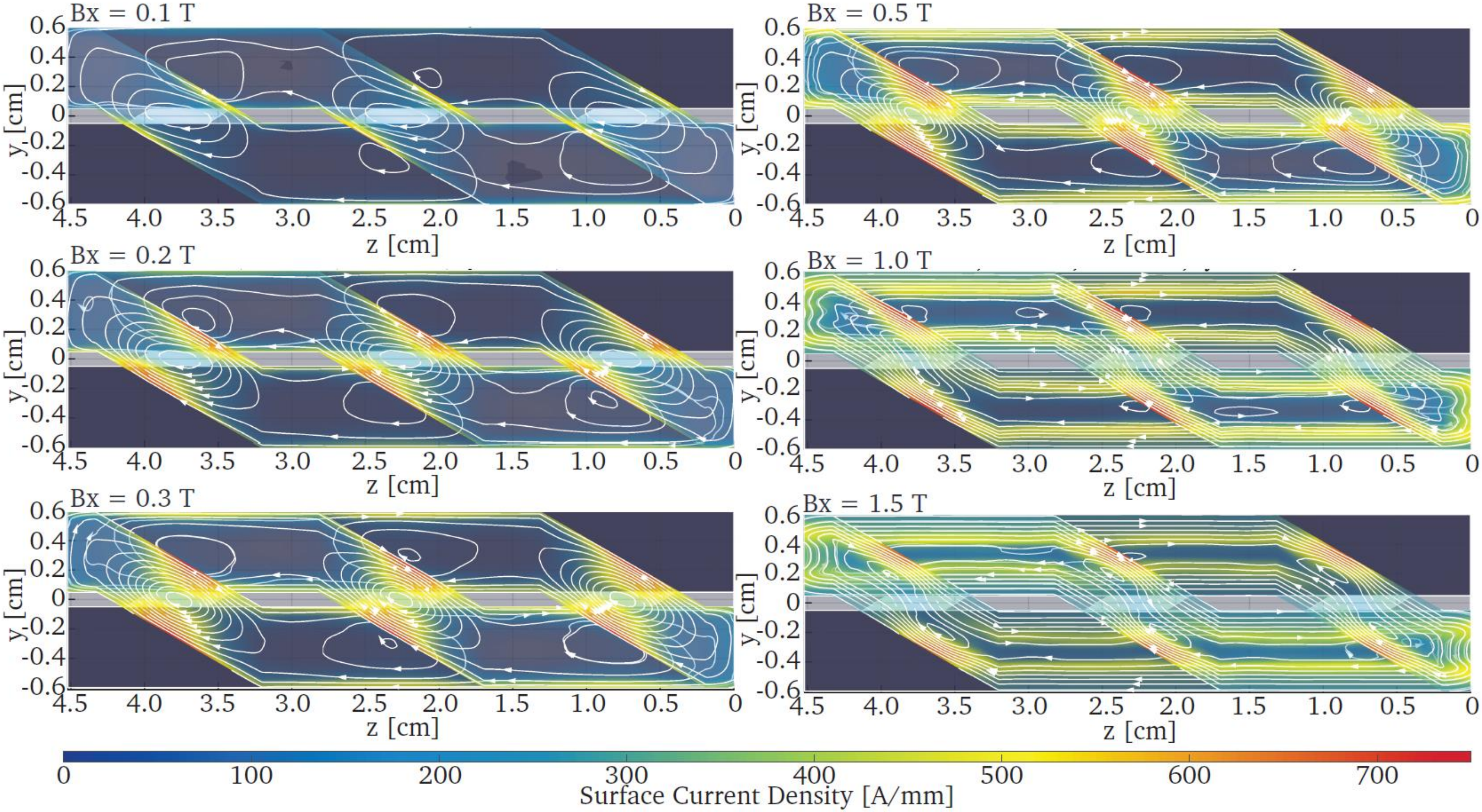
contact Elements

voronoi cells are used to calculate the contact areas which determine electrical and thermal contact resistance



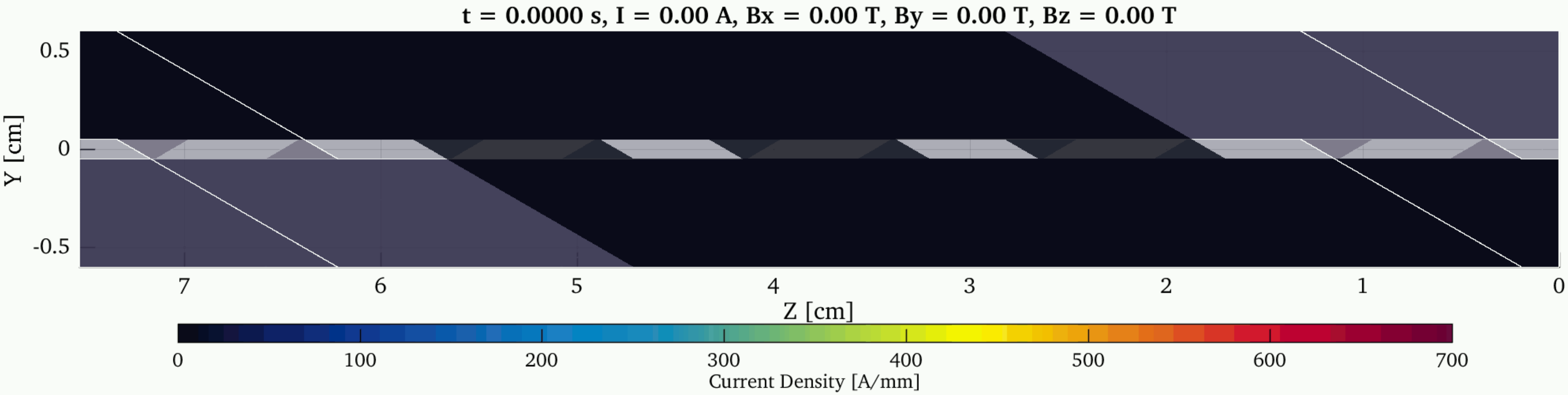
Initial Benchmarking-1



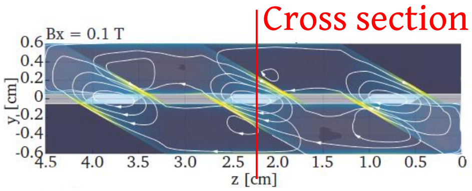


- Screening currents are calculated at in a time varying (sinusoidal) background field
- Flux penetrates first at cross-over (at ~0.3T) then in the tape stack (~1.5T)
- Similar profiles should be found when a field off-set is applied (but at lower critical current)

Initial Benchmarking-1



Initial Benchmarking-2



- Current and thus flux fills from edges of tapes as expected from the Bean critical state model

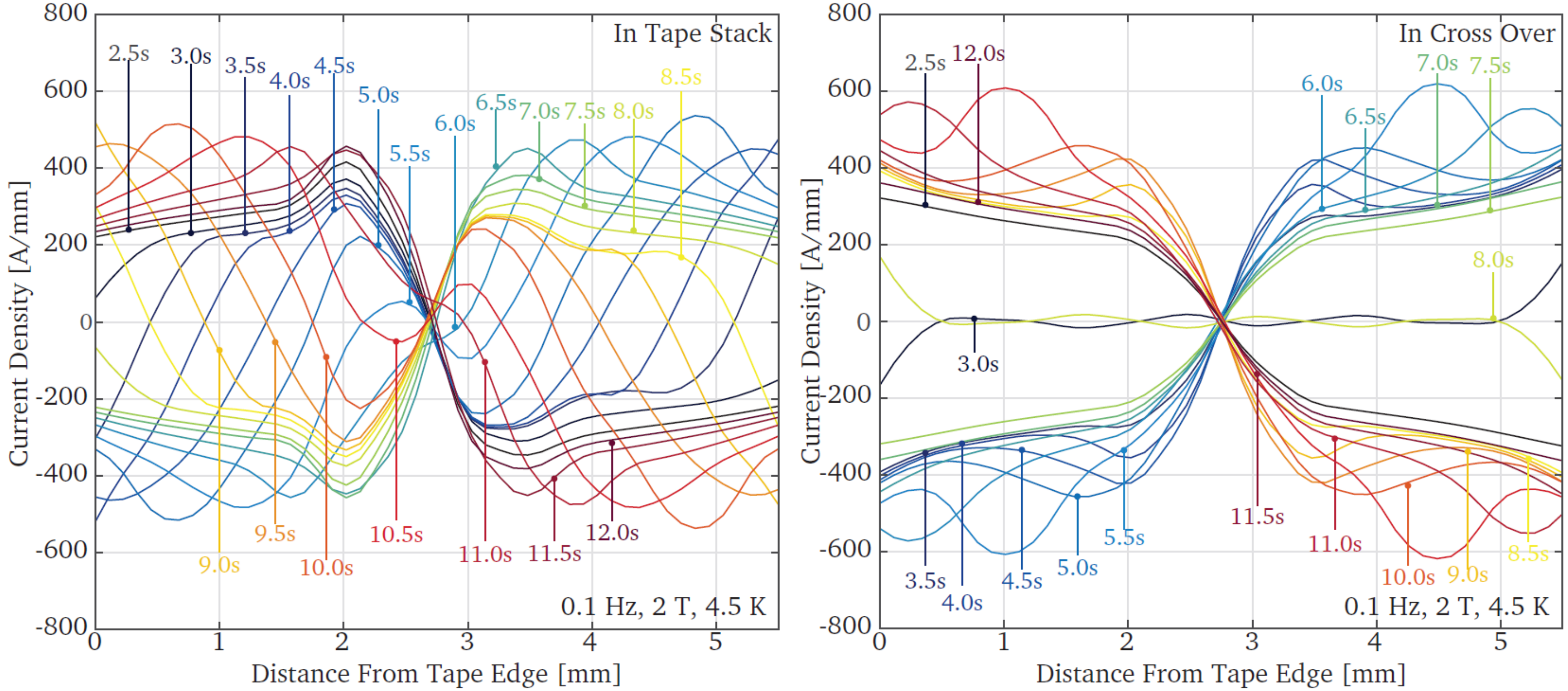
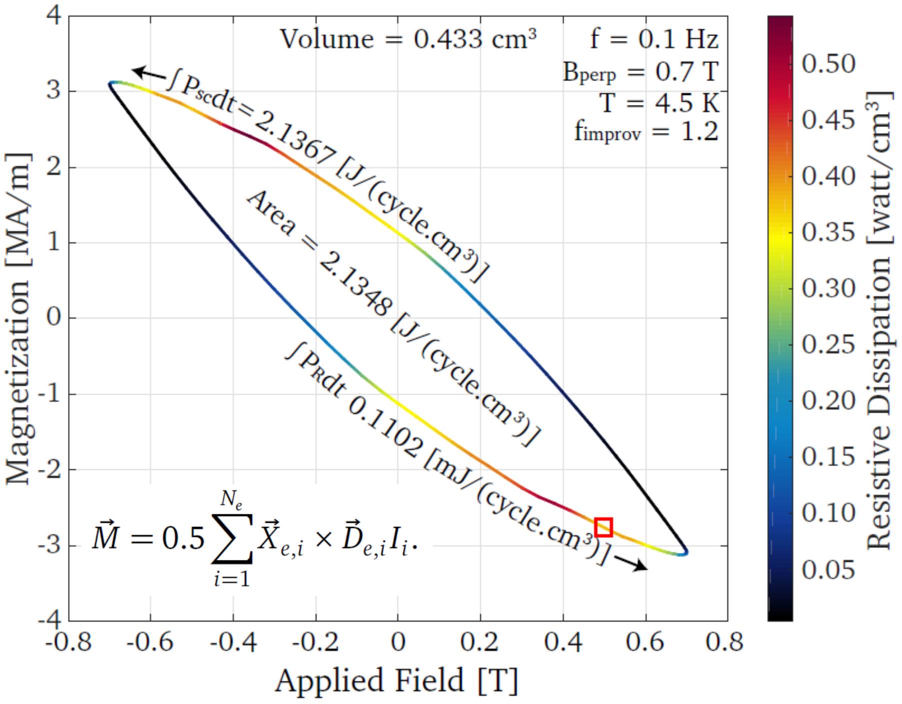
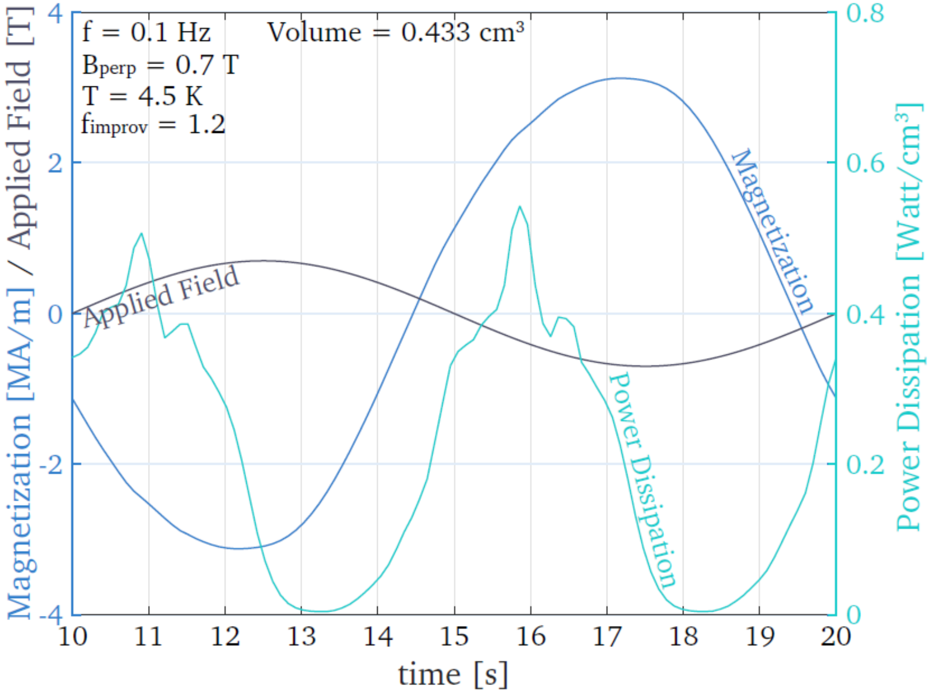


Figure 4.2: *Calculated screening current profiles for a Roebel cable, assembled from SuperPower tapes (improvement factor* 1.2 *over the Fujikura scaling relation). The profiles are shown as function of time (denoted with colored markers), in a cross section in the xy plane at* $z = 22.6\,\text{mm}$ *for a tape located in the stack (left) and for a tape that is crossing over (right). The profiles are calculated for an perpendicular applied field with an amplitude of* 2.0 T *and a frequency of* 0.1 Hz*. The operating temperature, needed for determining the critical surface, is set at* 4.5 K.

Initial Benchmarking-3

Comsol Check
3 MA/m

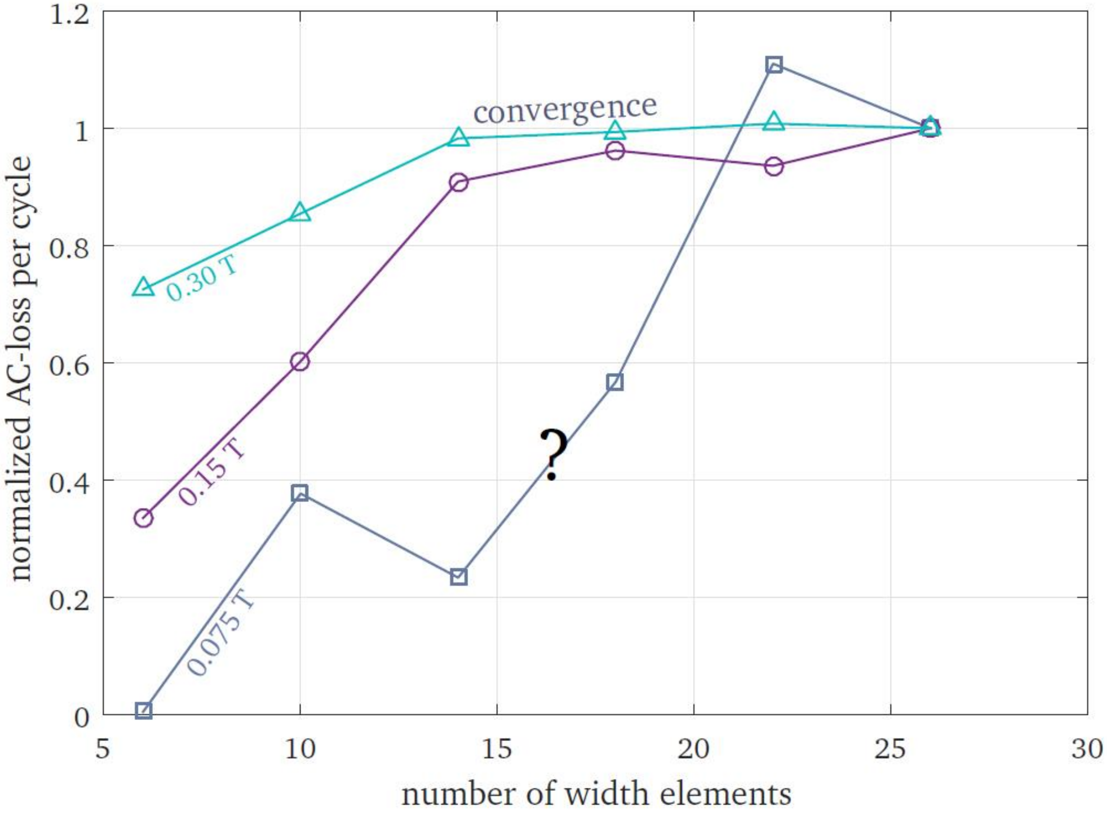


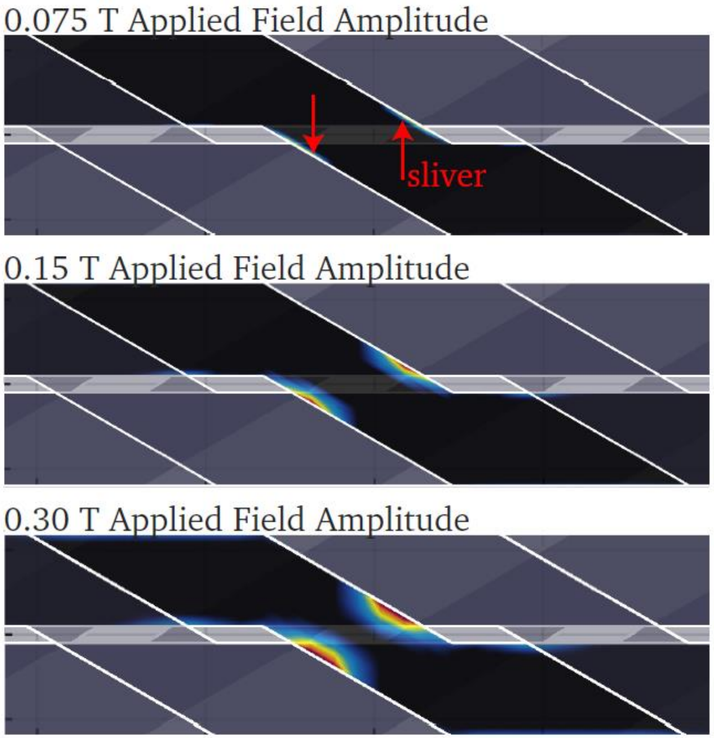


Two methods for calculating loss per cycle:

1. *Loop Area* - The loss per cycle should be equal to the area of the hysteresis loop. The area is determined using the Matlab build in polyarea function.
2. *Power Integration* - The loss per cycle is determined by integrating the resistive power dissipation of all the elements in the network. The inductive voltages and thus power are ignored. In this case hysteresis losses can be distinguished from coupling losses by calculating the power separately for the superconducting elements and for the normal conducting elements respectively. Also the location of the losses can be determined.

Initial Benchmarking-4




0.075 T Applied Field Amplitude

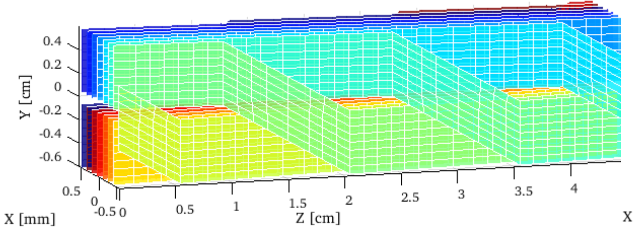
0.15 T Applied Field Amplitude

0.30 T Applied Field Amplitude

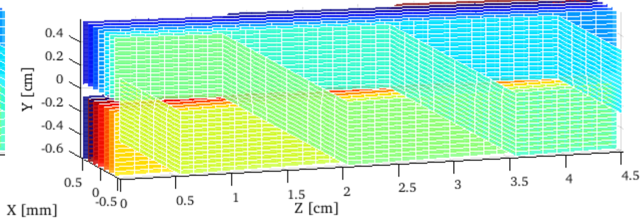
AC-loss Locality [J/(cycle.m²)]
(color on different scale)

- Number of elements determines accuracy of the solution: convergence at high end
- At low field the losses are located at the very edge of the cable (see picture) making convergence more difficult

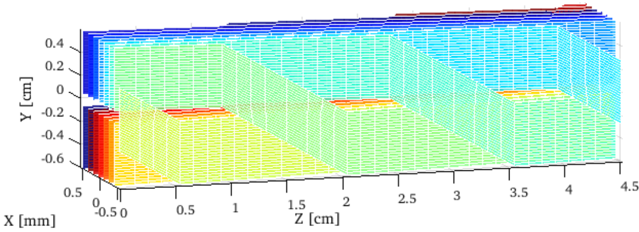
8 elements



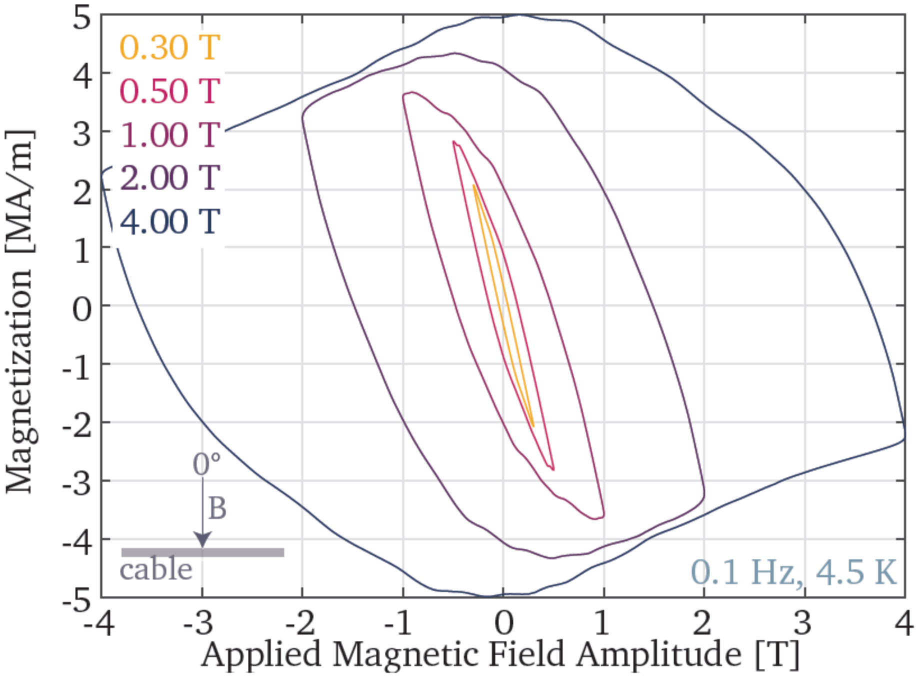
14 elements

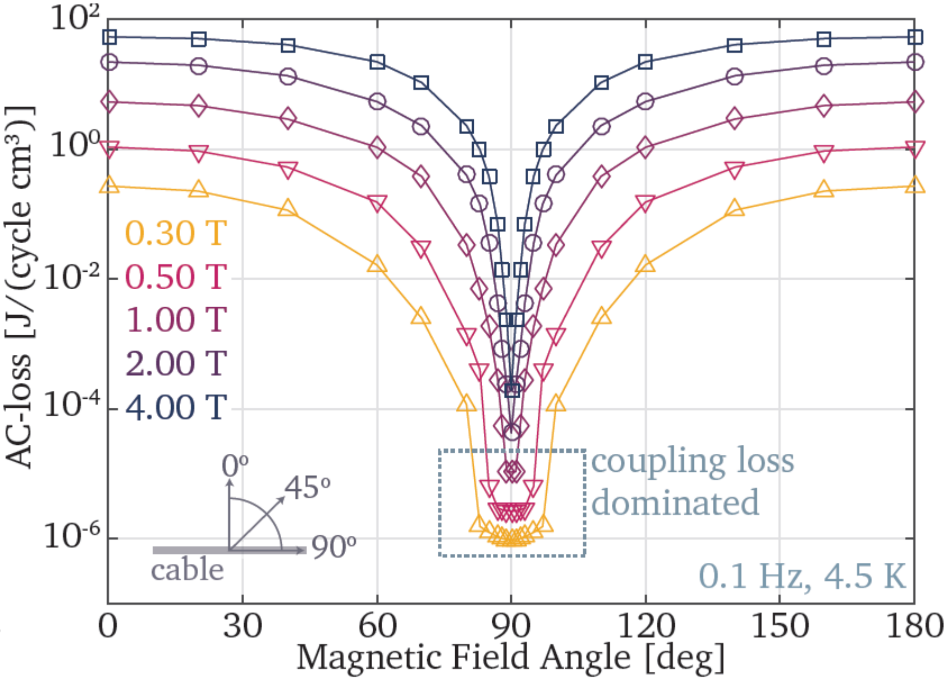


24 elements



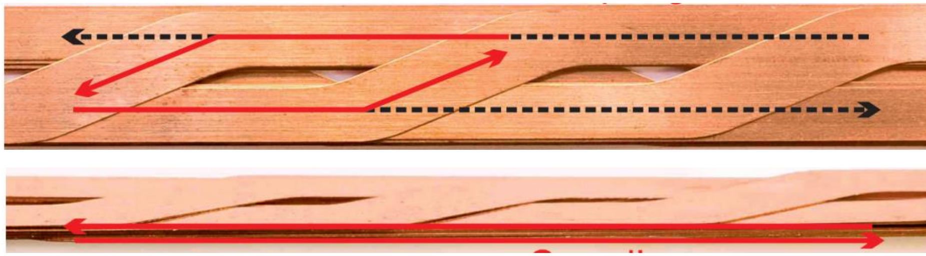
Electrical Validation of the Model-1





Hysteresis

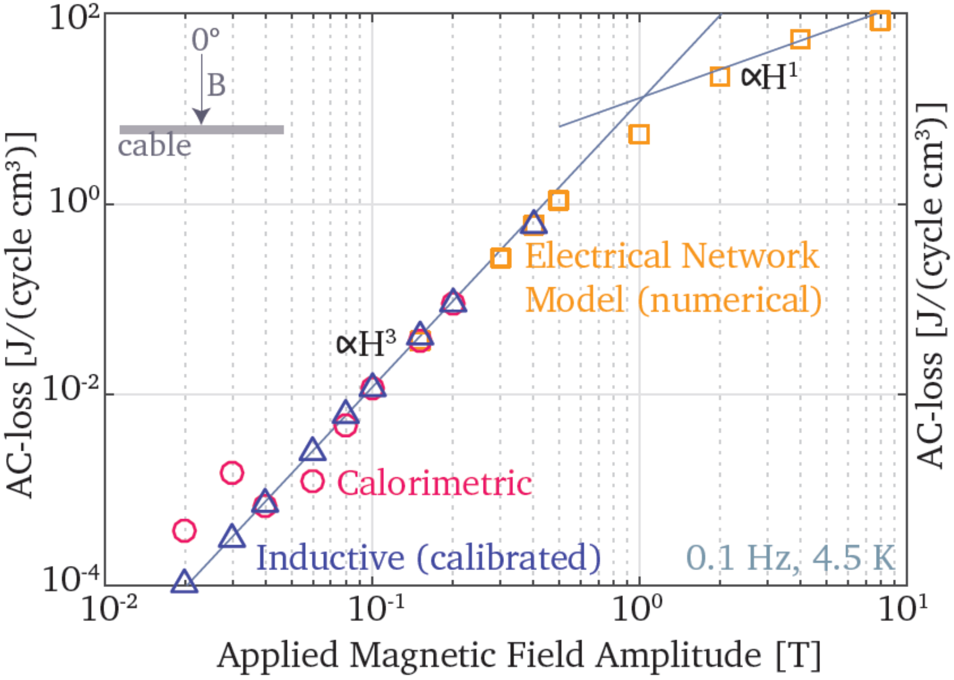
Coupling

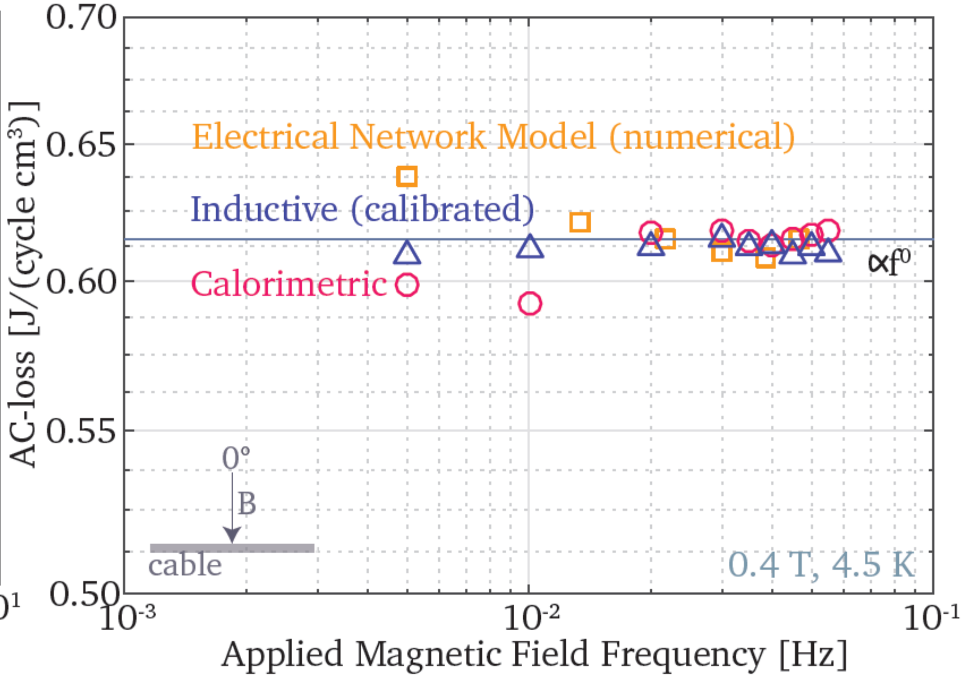


Numerical Prediction:

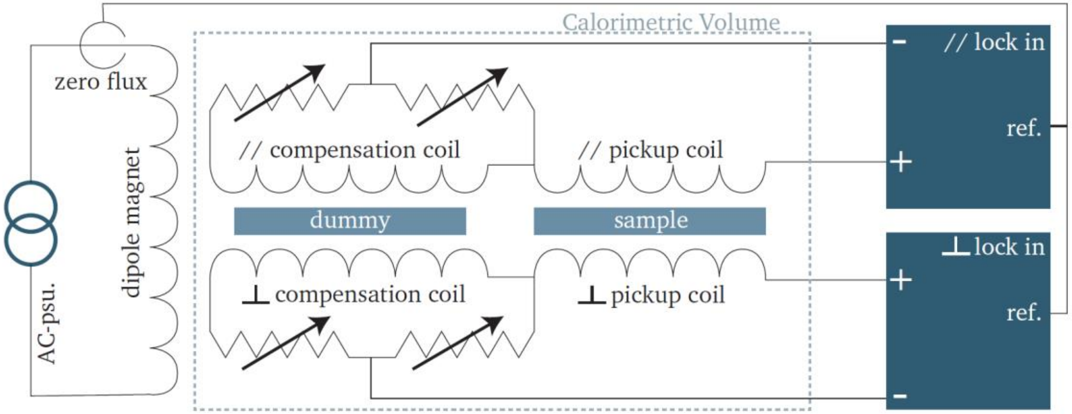
1. Hysteresis dominates in perpendicular applied field
2. Coupling loss dominates in parallel applied field

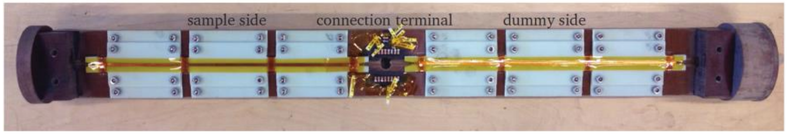
Electrical Validation of the Model-2





- Hysteresis losses are measured in the perpendicular applied field direction
- Very good quantitative agreement found between measurement and model





$$Q = \mu_0 \int \vec{M} \cdot d\vec{H} = \frac{1}{2f}\left[\left(\frac{V_i H_0}{F A_e}\right)_{\perp} + \left(\frac{V_i H_0}{F A_e}\right)_{\parallel}\right],$$

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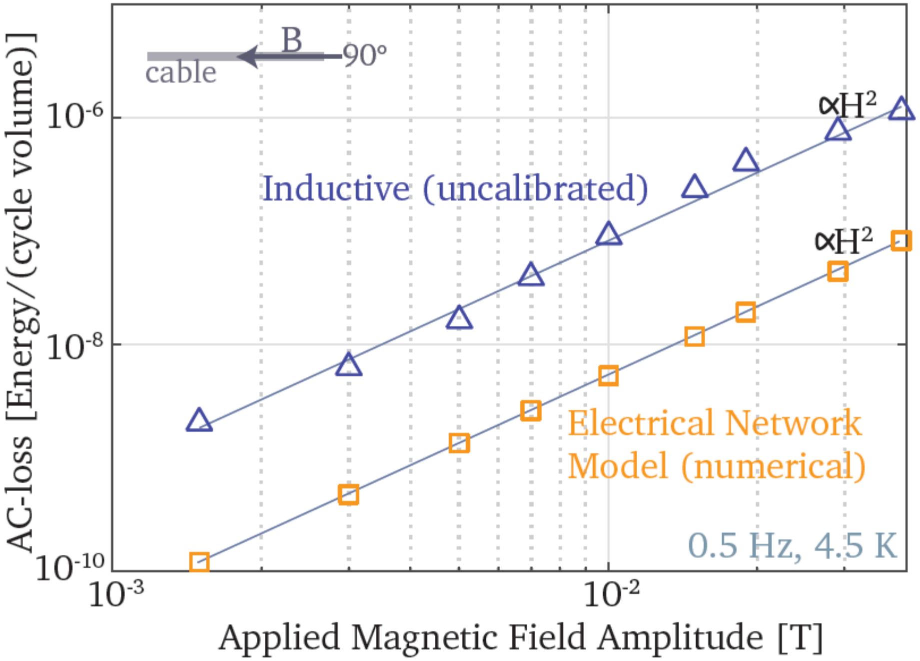
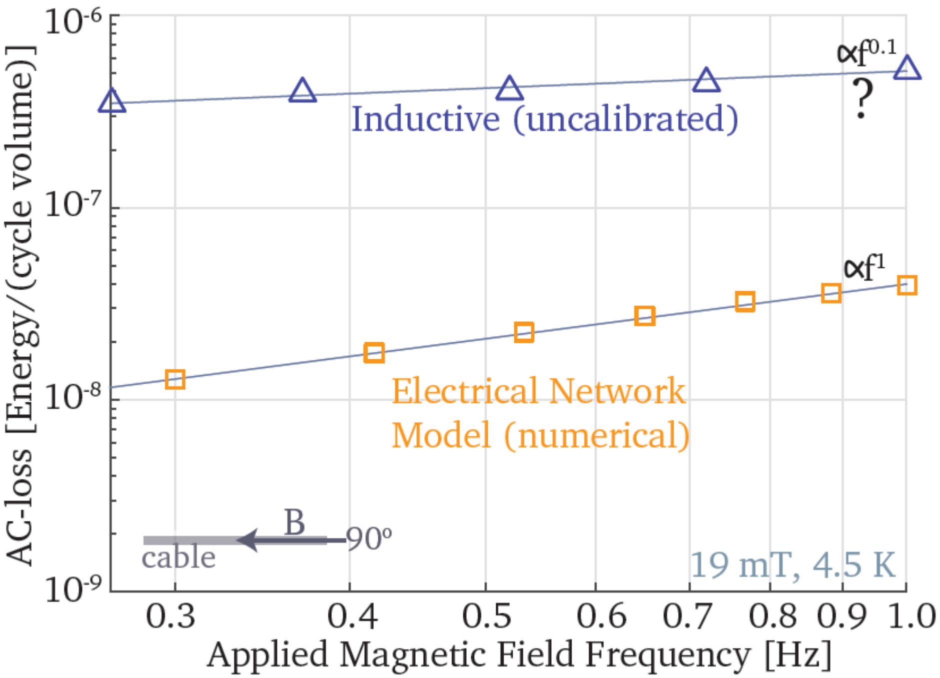
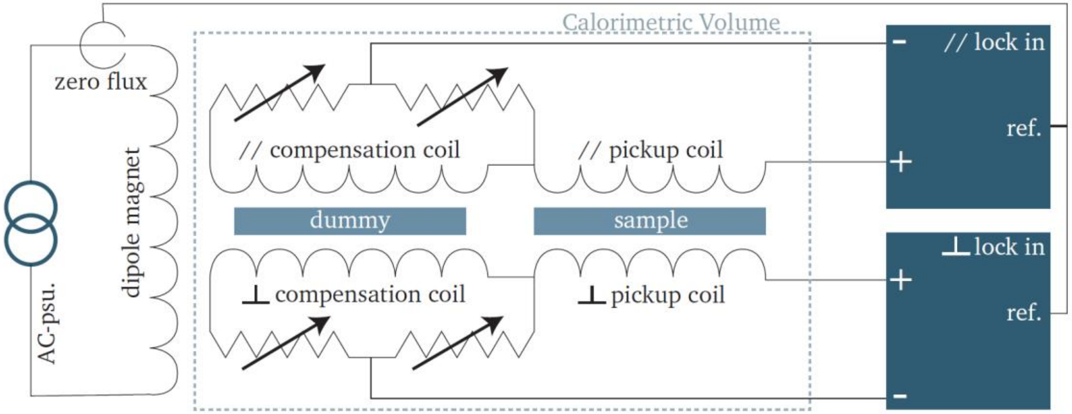
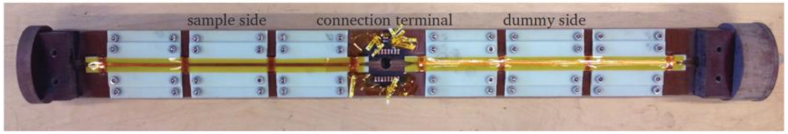
Electrical Validation of the Model-3





- Coupling losses are measured in the parallel applied field direction
- Only qualitative agreement between model and measurement (unknown fill factor)





$$Q = \mu_0 \int \vec{M} \cdot d\vec{H} = \frac{1}{2f}\left[\left(\frac{V_i H_0}{F A_e}\right)_{\perp} + \left(\frac{V_i H_0}{F A_e}\right)_{\parallel}\right],$$

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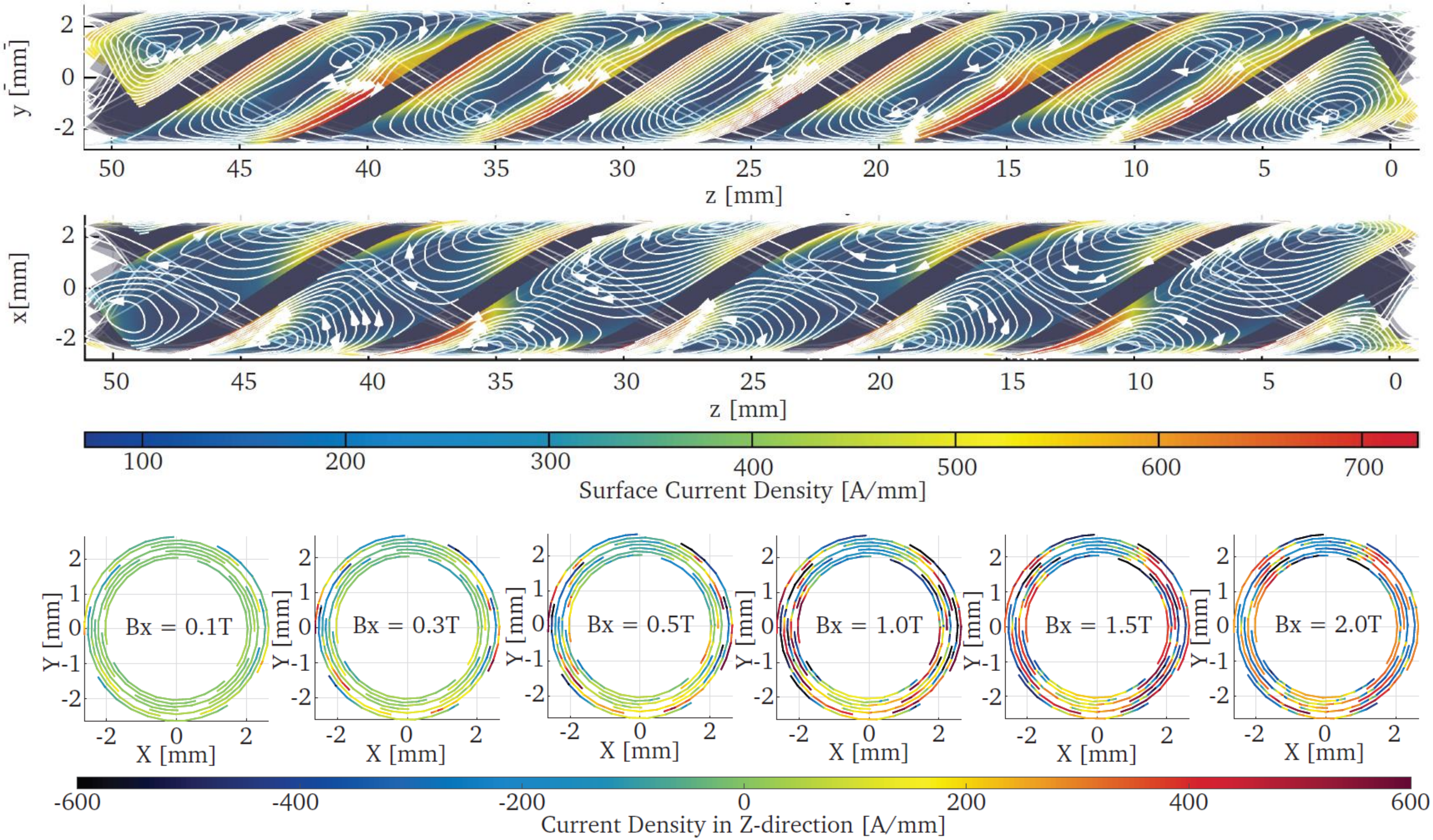
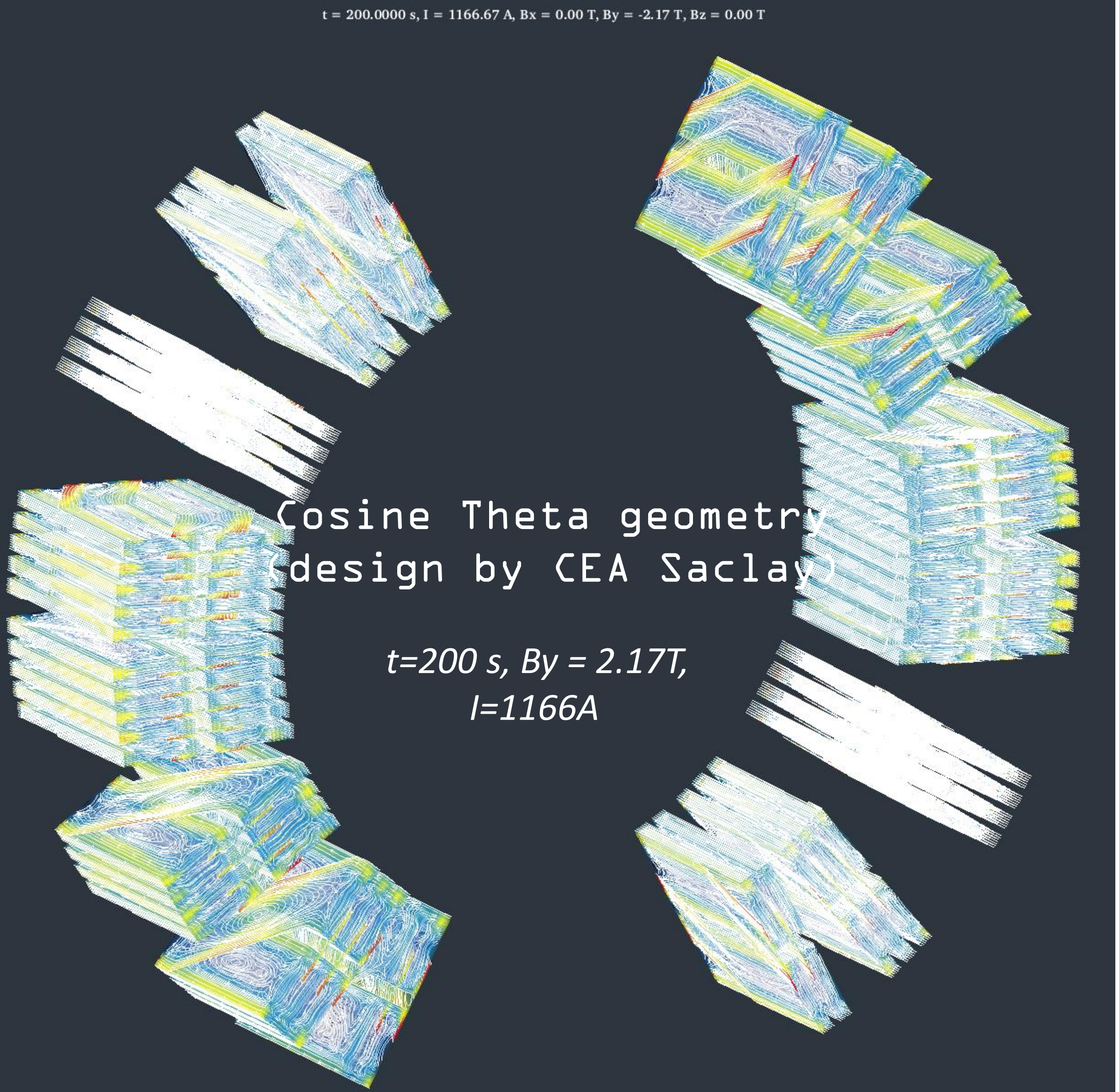
Screening Currents in CoRC



- No angular dependence obviously, to be continued!
- Discussion point: how should I fairly compare different cables A/m, Am^2, which geometries?
    - In essence what to keep constant between the geometries

Full Coil Simulatio

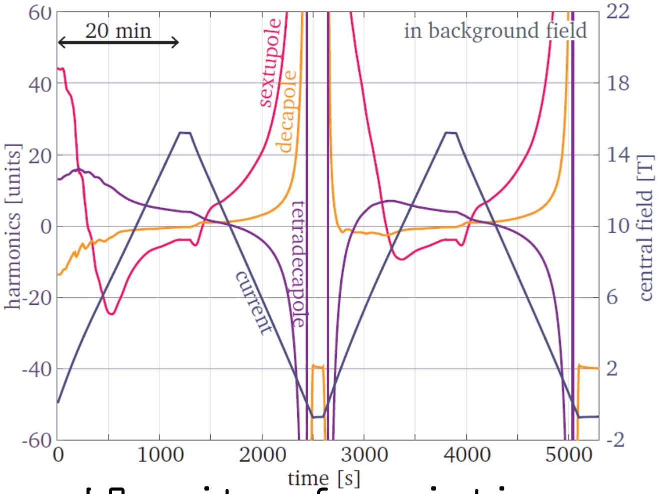


Cosine Theta geometry
(design by CEA Saclay)

t=200 s, By = 2.17T,
I=1166A

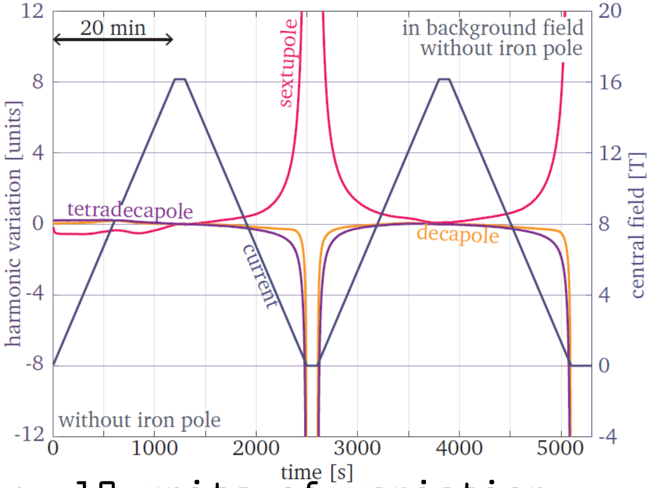
- quasi 3D cross section analysis with two full cycles takes about 1 month of

Cosine Theta (CEA)



- 60 units of variation (in 13T bg)
- High magnetization currents
- Cancelled by angle

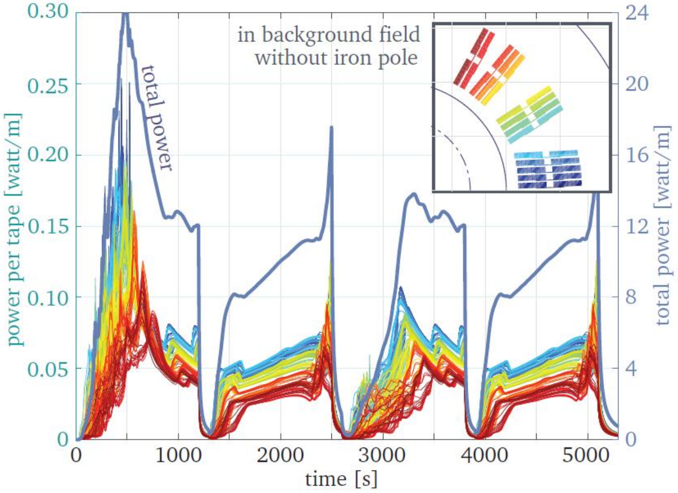
Aligned Block

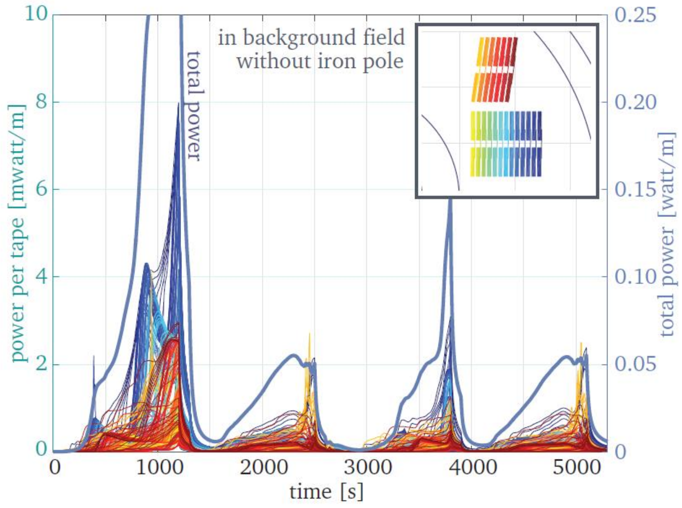


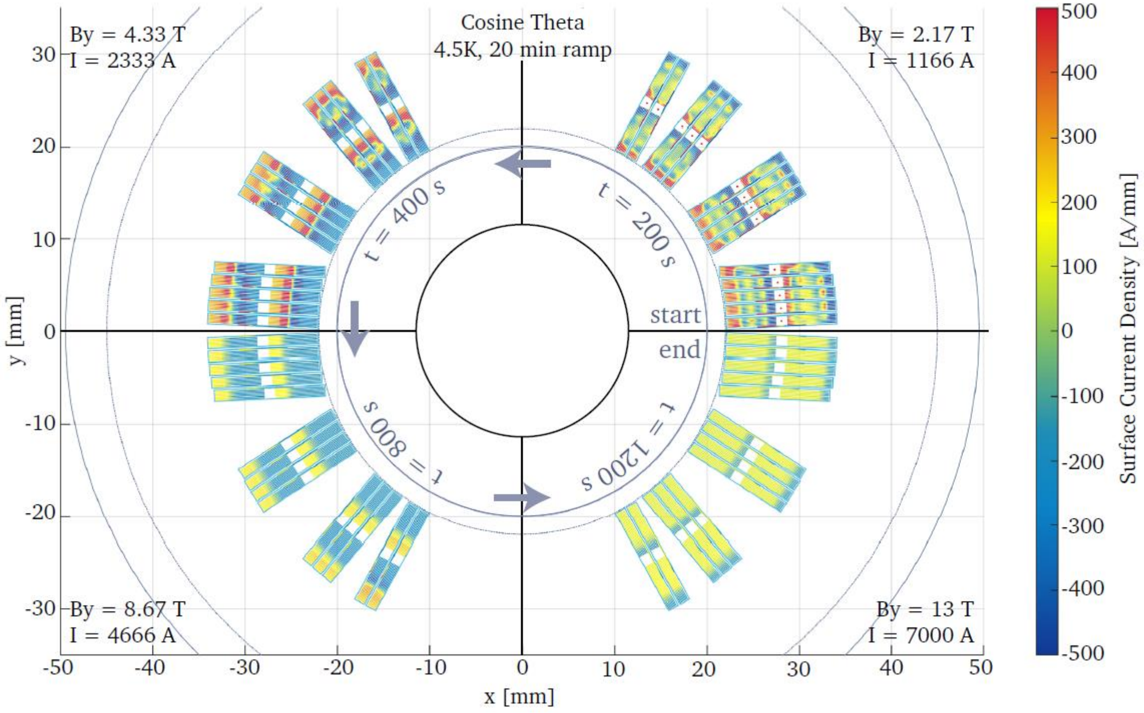
- 10 units of variation (in 13T bg)
- Low or no magnetization

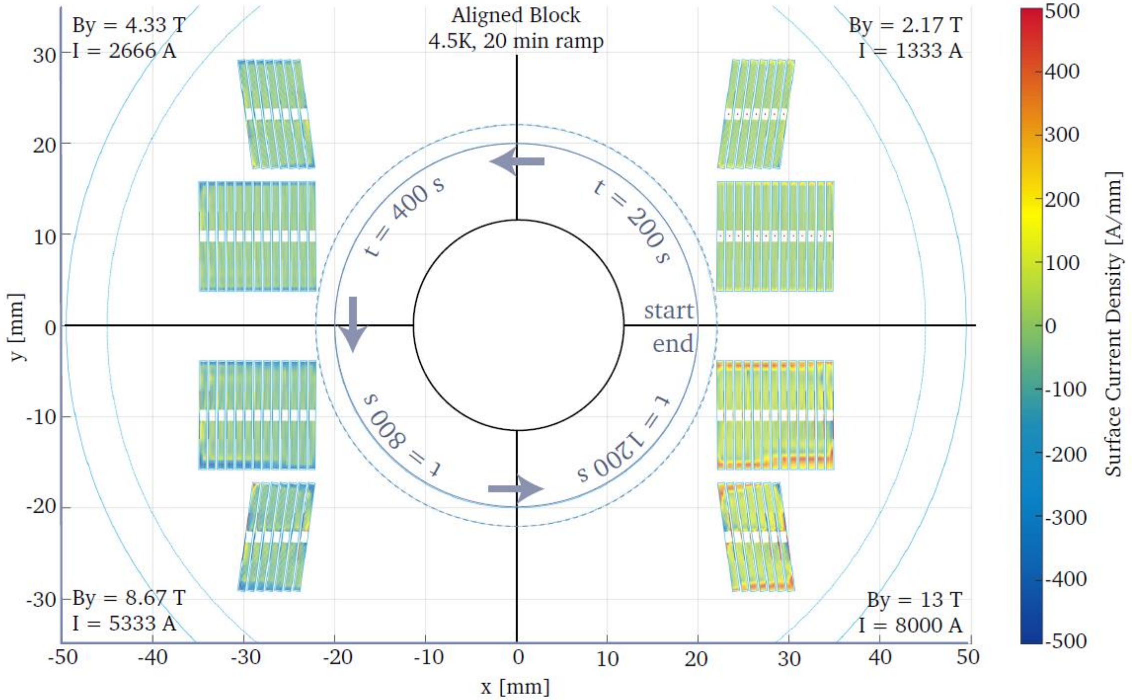
Full Coil Simulations-2

Coil AC-Loss power dissipation very high for cosine theta





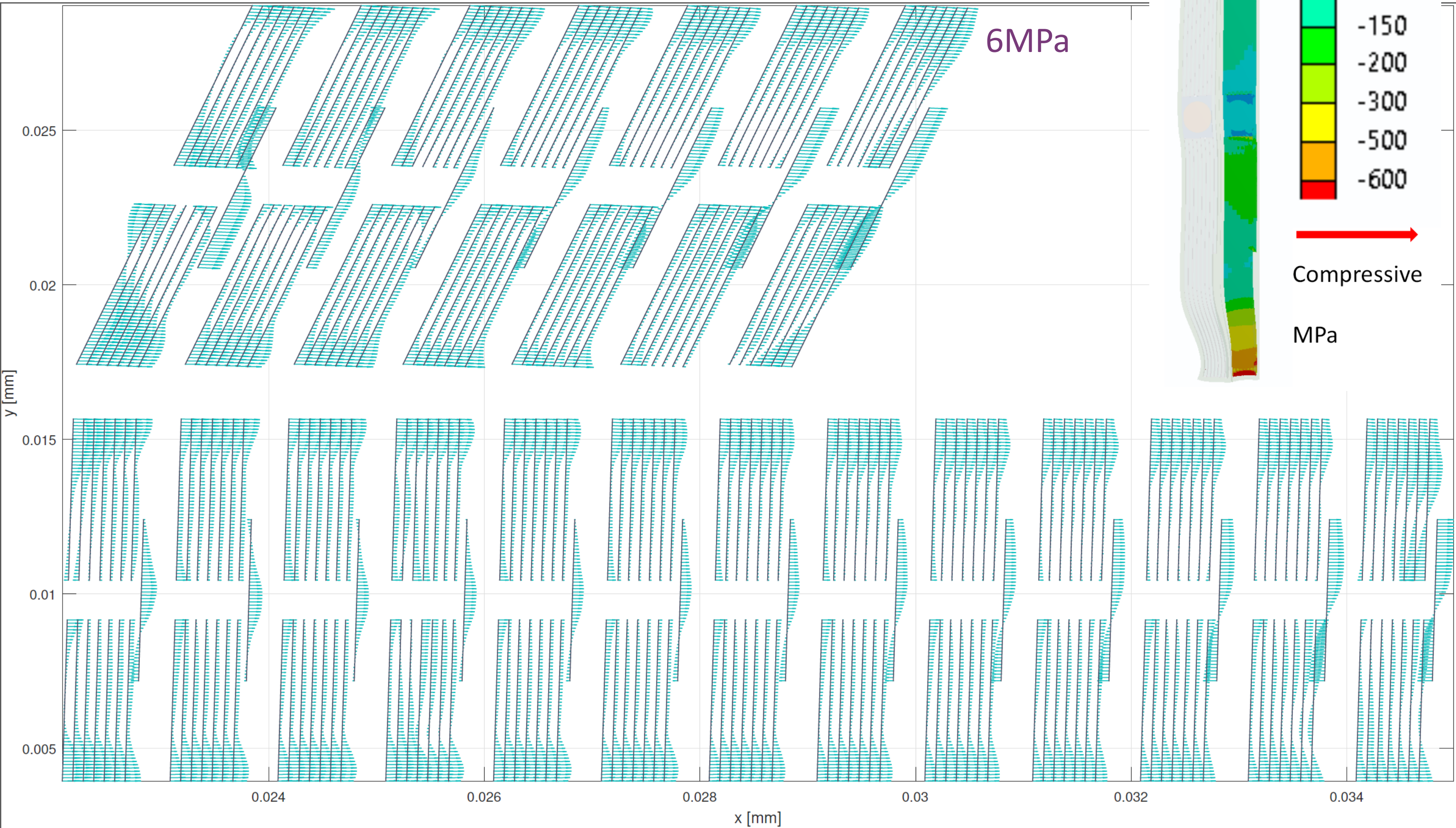




Full Coil Simulations-3

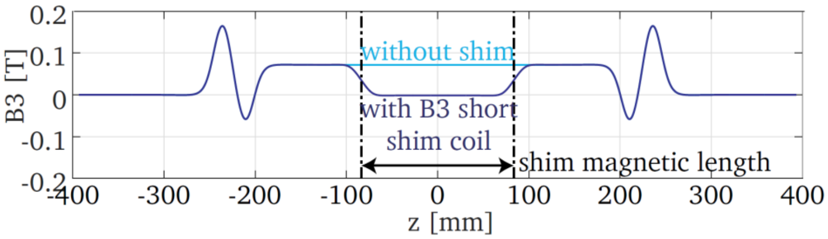
- Inhomogeneous force distribution (shown for 13T background field, 4.5K)
- Around 6MPa Lorentz pressure on edges of coil pack (on each tape!)
- Input for mechanical model of J. Murtomaki

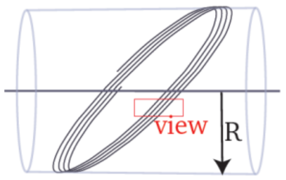
Horizontal Stress distribution Mpa (deformed shape magnified 16x)

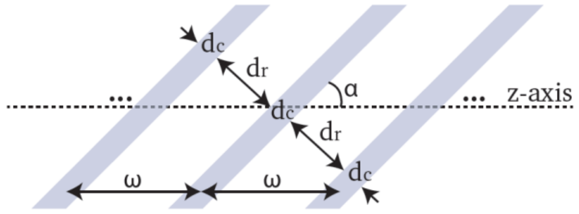


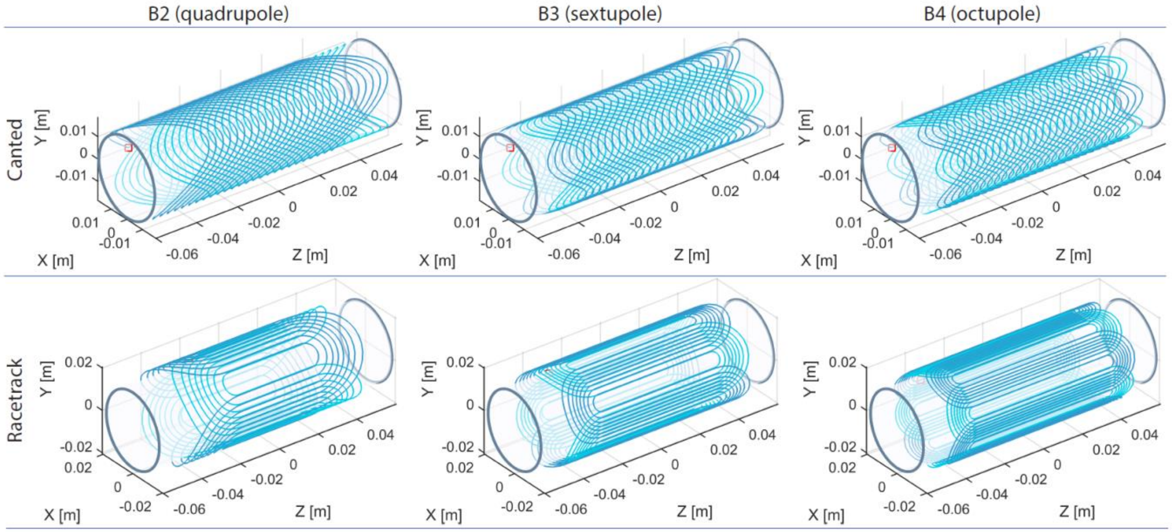
Persistent Current Shim Coils

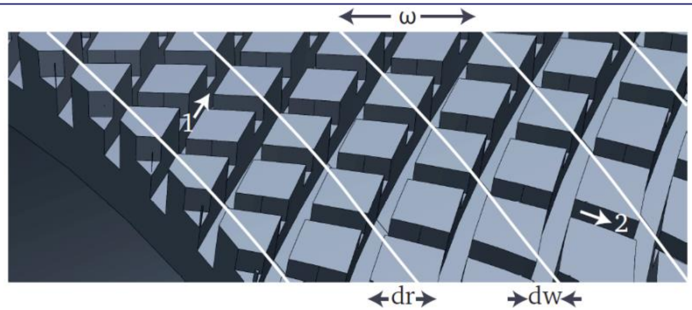
- Possible solution for fixing field quality in (but not limited to) HTS magnets could be the inclusion of persistent current shim coils
  - By topology the current induced in the resistanceless shim coil cancels out only one harmonic component of the field, independent of the origin, acting as a filter
  - This should fix both static and dynamic field quality of any magnet
  - Drawback is that it takes up valuable real estate in the aperture
  - Possible manufacturing methods are under consideration

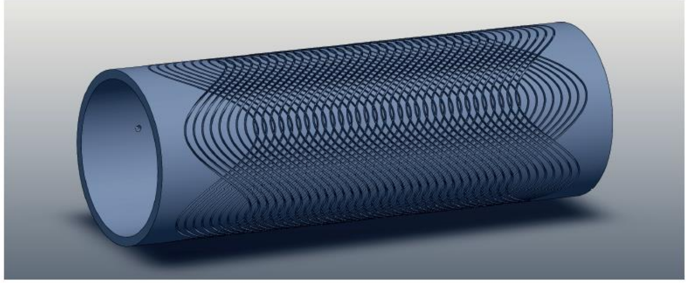




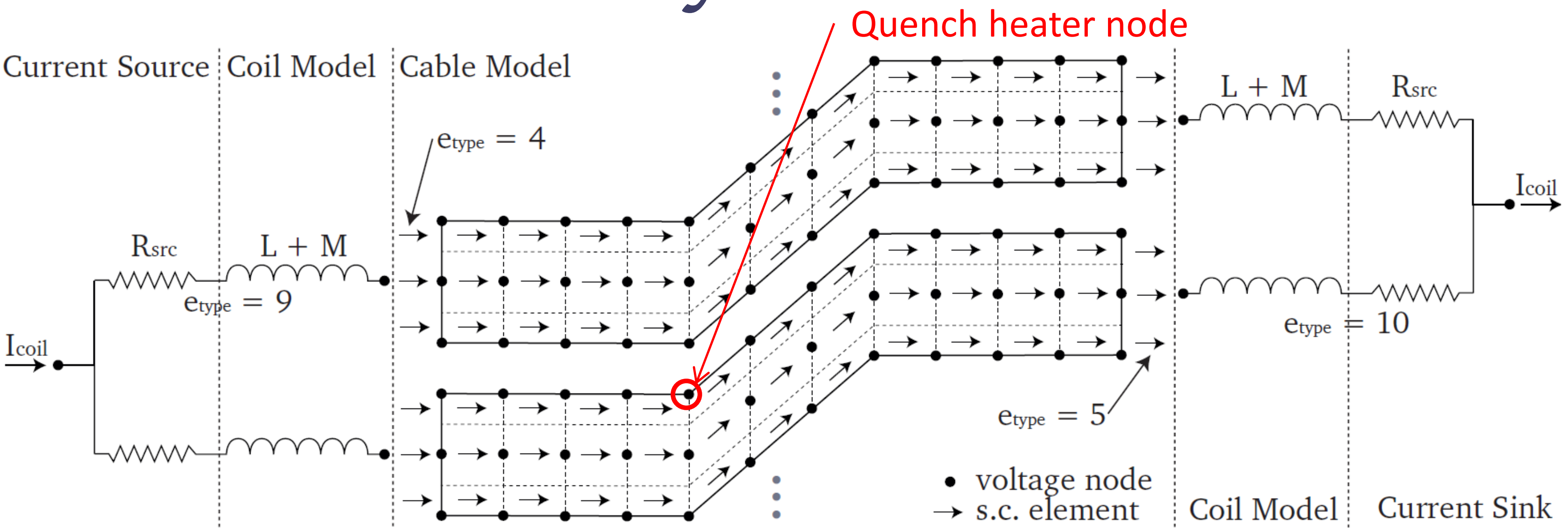








Normal Zone Analysis-1



- To model the quench the ends of the cable are connected to a current source and sink
- Extra nodes and elements allow for current redistribution
- The coil's inductance matrix (FM2) is added to the entrance elements
- A heater pulse is fired at the corner node of a cross over
- Duration of the heater pulse is arbitrarily set at 50ms (needs discussion), mainly determines drift phase

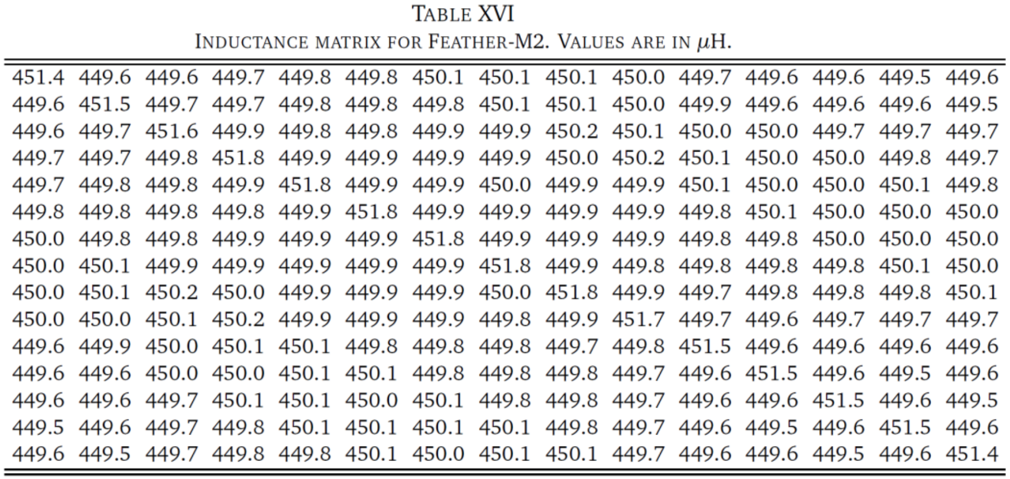
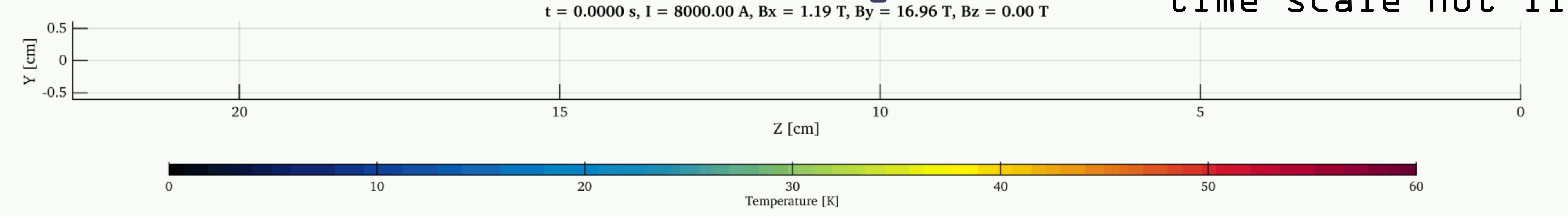


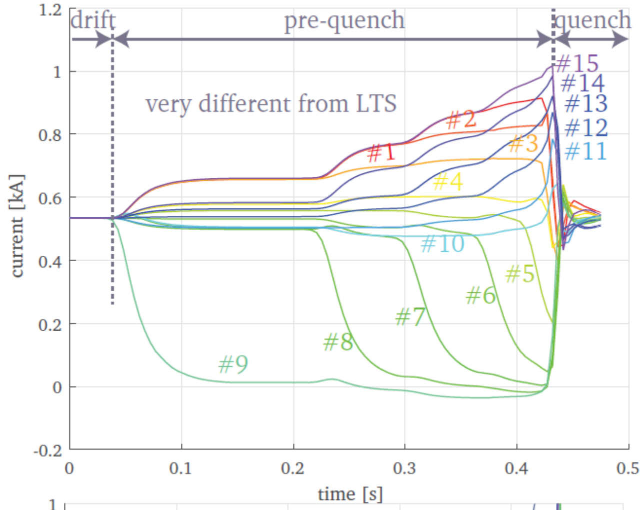
TABLE XVI
INDUCTANCE MATRIX FOR FEATHER-M2. VALUES ARE IN μH.

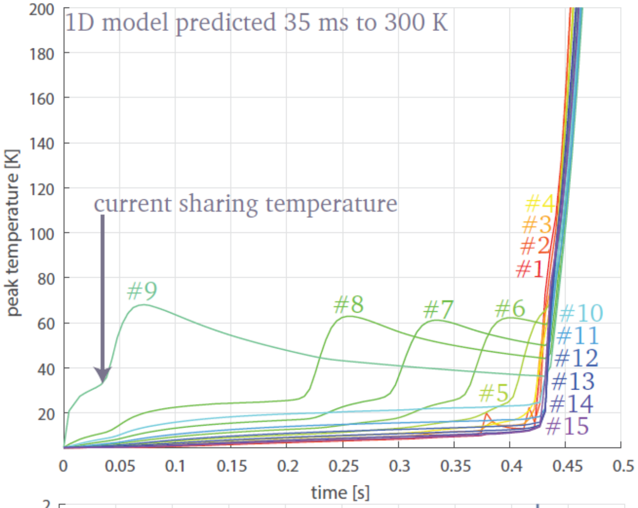
451.4	449.6	449.6	449.7	449.8	449.8	450.1	450.1	450.1	450.0	449.7	449.6	449.6	449.5	449.6
449.6	451.5	449.7	449.7	449.8	449.8	449.8	450.1	450.1	450.0	449.9	449.6	449.6	449.6	449.5
449.6	449.7	451.6	449.9	449.8	449.8	449.9	449.9	450.2	450.1	450.0	450.0	449.7	449.7	449.7
449.7	449.7	449.8	451.8	449.9	449.9	449.9	449.9	450.0	450.2	450.1	450.0	450.0	449.8	449.7
449.7	449.8	449.8	449.9	451.8	449.9	449.9	450.0	449.9	449.9	450.1	450.0	450.0	450.1	449.8
449.8	449.8	449.8	449.8	449.9	451.8	449.9	449.9	449.9	449.9	449.8	450.1	450.0	450.0	450.0
450.0	449.8	449.8	449.9	449.9	449.9	451.8	449.9	449.9	449.9	449.8	449.8	450.0	450.0	450.0
450.0	450.1	449.9	449.9	449.9	449.9	449.9	451.8	449.9	449.8	449.8	449.8	449.8	450.1	450.0
450.0	450.1	450.2	450.0	449.9	449.9	449.9	450.0	451.8	449.9	449.7	449.8	449.8	449.8	450.1
450.0	450.0	450.1	450.2	449.9	449.9	449.9	449.8	449.9	451.7	449.7	449.6	449.7	449.7	449.7
449.6	449.9	450.0	450.1	450.1	449.8	449.8	449.8	449.7	449.8	451.5	449.6	449.6	449.6	449.6
449.6	449.6	450.0	450.0	450.1	450.1	449.8	449.8	449.8	449.7	449.6	451.5	449.6	449.5	449.6
449.6	449.6	449.7	450.1	450.1	450.0	450.1	449.8	449.8	449.7	449.6	449.6	451.5	449.6	449.5
449.5	449.6	449.7	449.8	450.1	450.1	450.1	450.1	449.8	449.7	449.6	449.5	449.6	451.5	449.6
449.6	449.5	449.7	449.8	449.8	450.1	450.0	450.1	450.1	449.7	449.6	449.6	449.5	449.6	451.4

Normal Zone Analysis-2

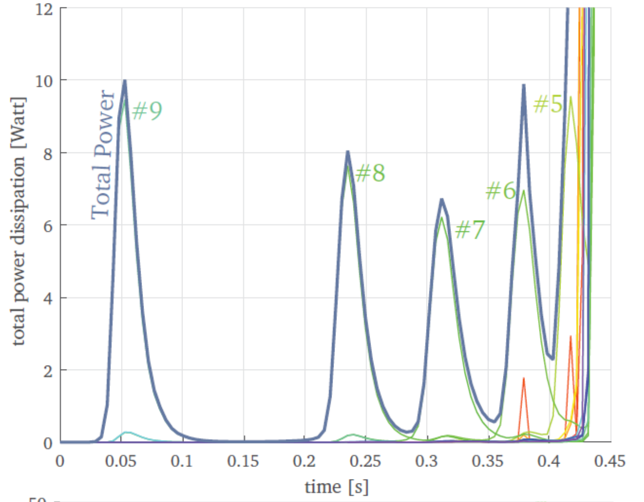
time scale not li

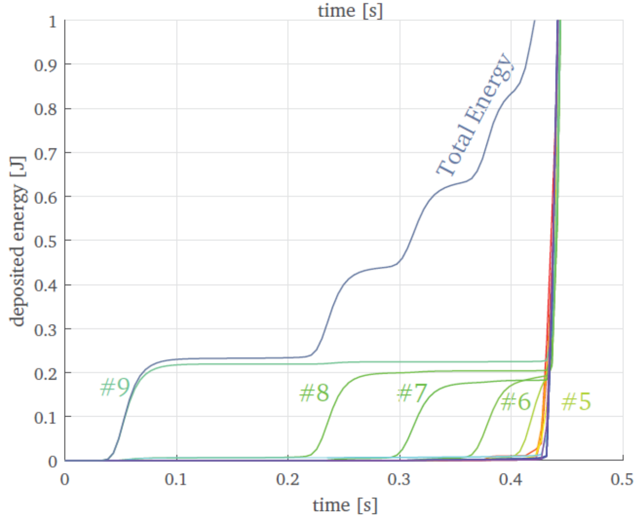

t = 0.0000 s, I = 8000.00 A, Bx = 1.19 T, By = 16.96 T, Bz = 0.00 T

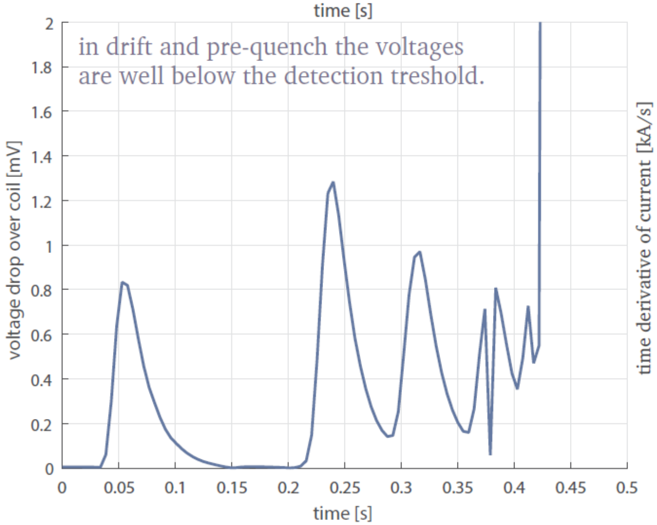

very different from LTS

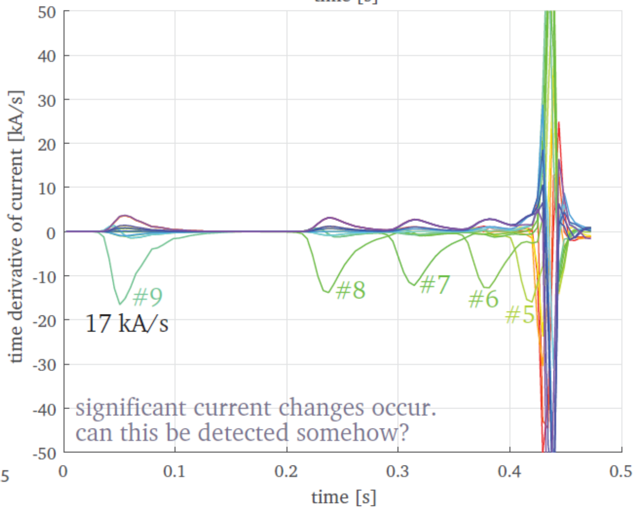

1D model predicted 35 ms to 300 K

current sharing temperature





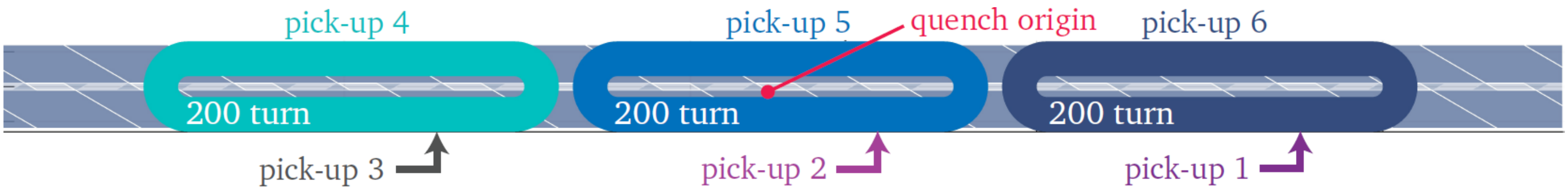

in drift and pre-quench the voltages are well below the detection treshold.

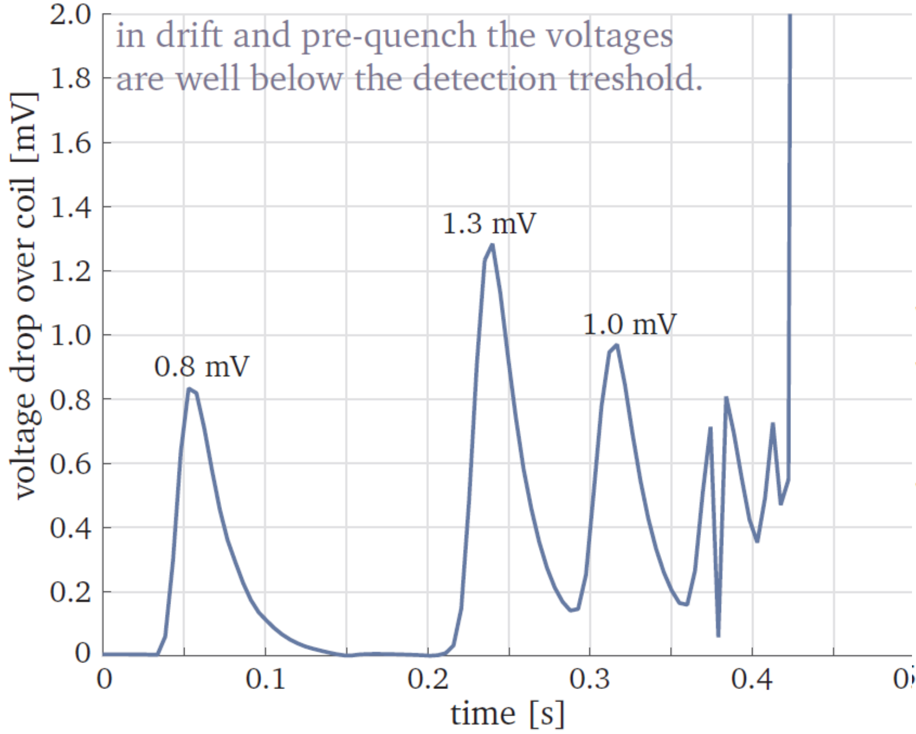

17 kA/s

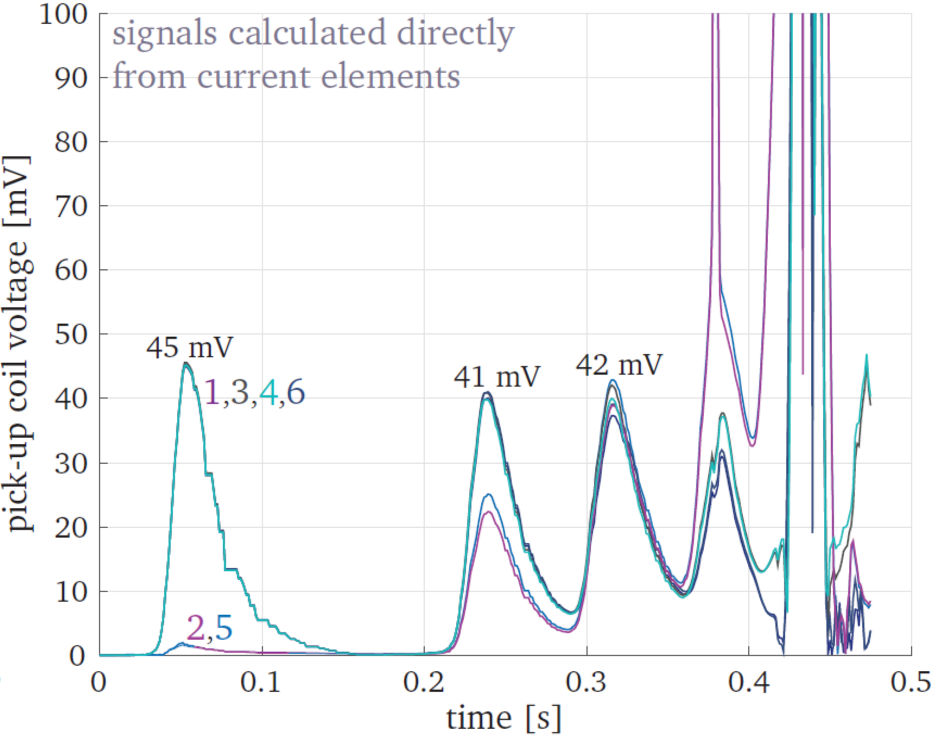
significant current changes occur.
can this be detected somehow?

- Single quench case in Roebel cable takes about 1 day to calculate.

Normal Zone Analyisis-3

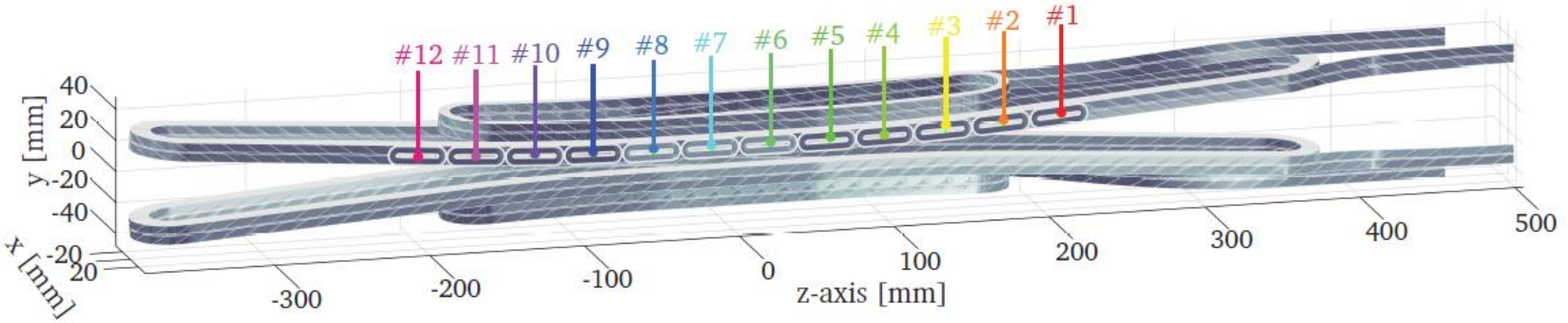


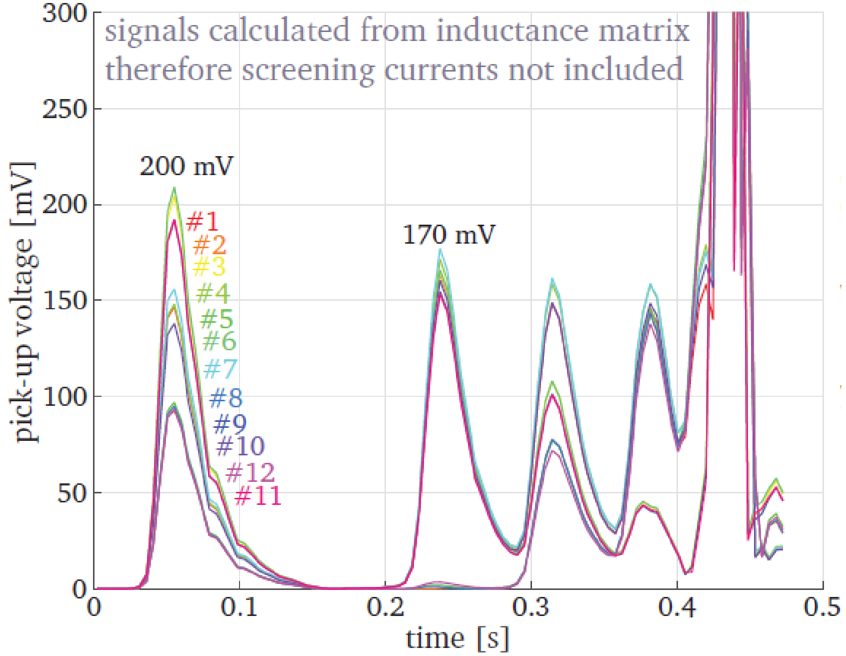

in drift and pre-quench the voltages are well below the detection treshold.

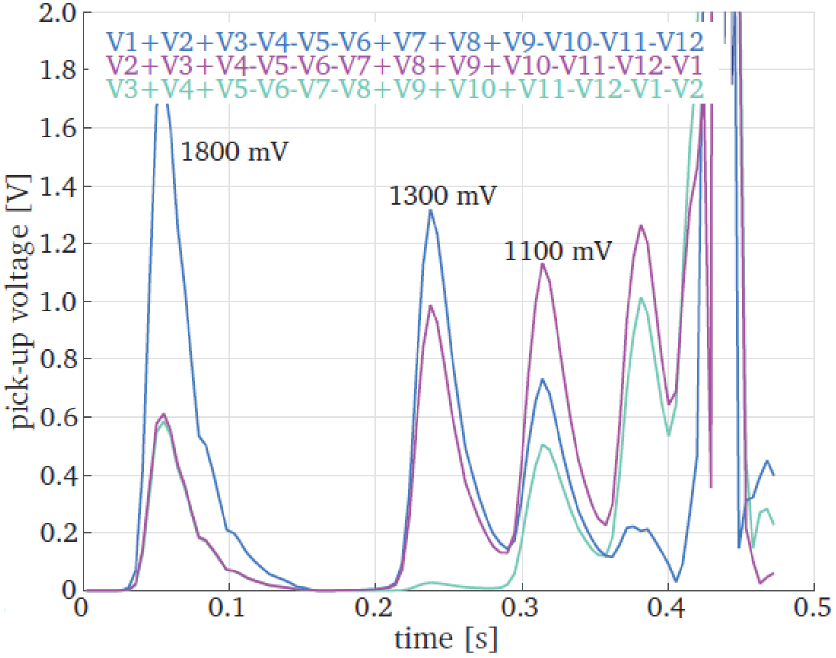

signals calculated directly from current elements

- If we can detect current distribution with pickup coils we can detect the pre-quench 0.5s before the quench
- The location of the pick-up coils is important
- Signals from the array can be added (in a smart way) such that the signals are even higher

Normal Zone Analysis-4

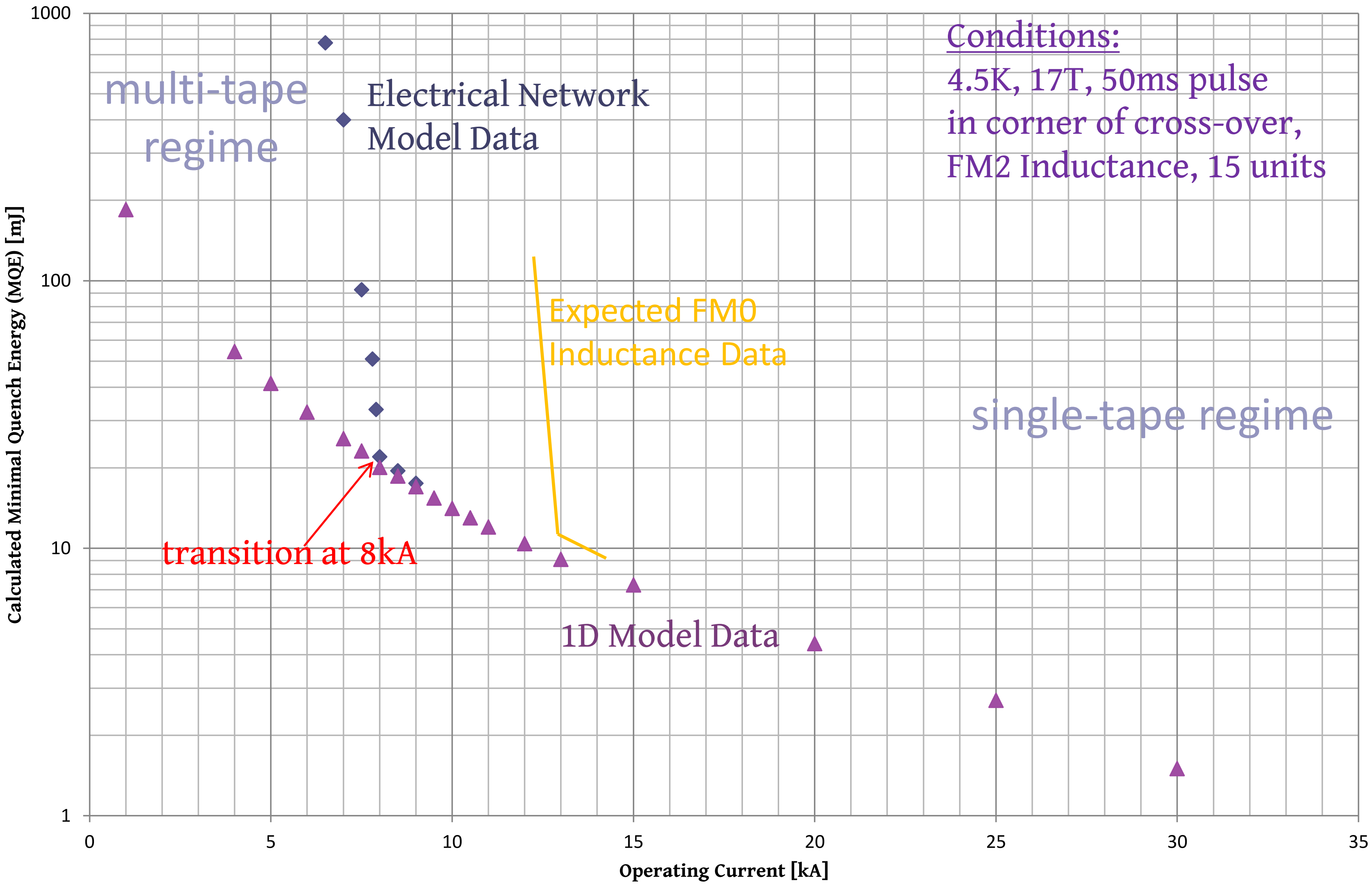






- On the Feather-M2 coil pick-up coils can be added on the outside or inside of the coil pack
- Calculated added signals exceed 1.8V. This is an overestimate because:
  - the shielding of the signal due to screening currents in the coil itself is not included in this calculation
  - Also it is assumed that the redistribution happens over the full length of the cable
- Reduction of number of turns is probably possible

Normal Zone Analysis-5



Conditions:
4.5K, 17T, 50ms pulse
in corner of cross-over,
FM2 Inductance, 15 units

Conclusion

1. Magnetization and Field Quality
   - Electrical part of the model validated using measurement data from Twente University
   - Able to predict screening currents in ReBCO coated conductor cables and cross sectional coils (given a month of computation time)
   - Approximately 10 units for Aligned Block and 60 units for Cosine theta in background field (still running standalone case)
   - Very high AC-losses in Cosine Theta configuration (25 Watts/m), almost none in Aligned Block
   - Non-homogeneous force distribution (under study by Jaakko)
2. Normal Zone Development and Detection
   - Thermal part of the model validated using MQE data from 1D model (in single strand regime)
   - Able to predict quench propagation in ReBCO coated conductor cables
   - Coil inductance and contact resistance (inter-strand) have influence on current redistribution and thus quench (however provided that there is margin left in the tapes, always a cascading effect if observed)
   - Pickup-coils are a very effective way of detecting a normal zone in the pre-quench phase (0.5s before a real quench happens)

- Data mining constantly ongoing and more results can be expected!
- Thesis writing status (chapter wise): Feather (90%), Electrical Network Model (100%), Magnetization (60%), Normal zones (20%), Layout study (10%)

Thank You for Your Attention