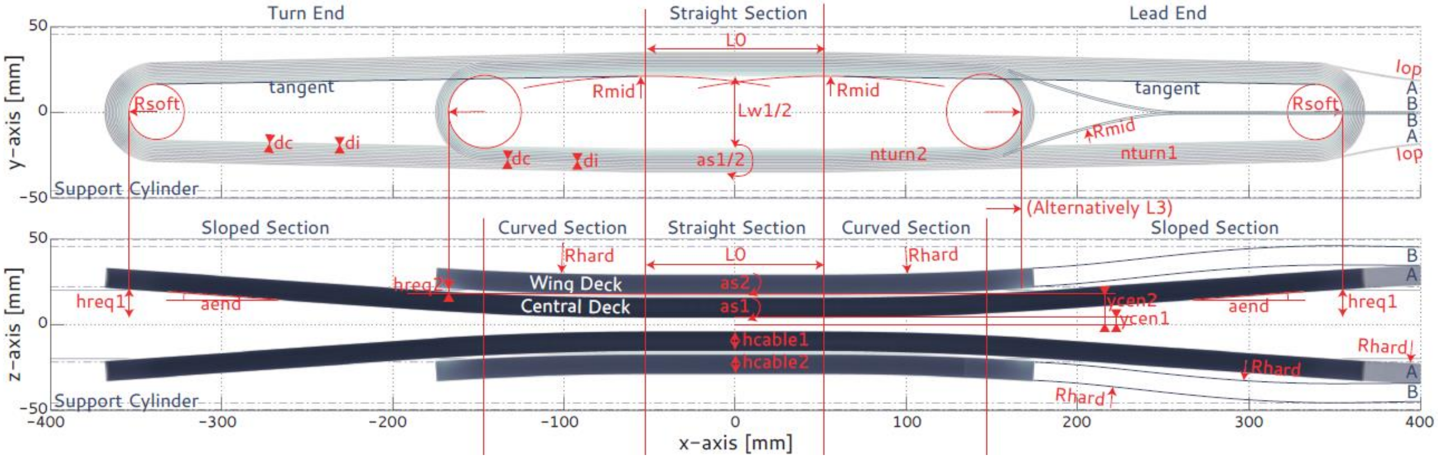
Electrical Network Model for ReBCO Cables and Coils

WAM-HTS Kyoto Japan 14-15 November 2014

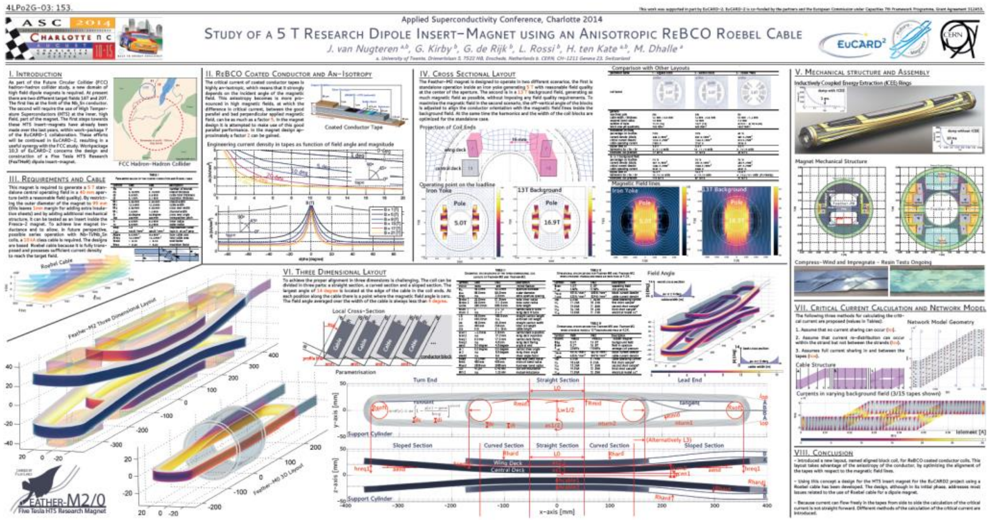
Work performed at CERN, Technology Department, Magnets, Superconductors and Cryostats group as part of the EuCARD-2 project, within the framework of a PhD. At the University of Twente, Energy Materials and Systems group.

J. van Nugteren, G. Kirby, G. de Rijk, L. Rossi, H.H.J. Ten Kate (CERN),
A. Nijhuis, K. Yagotintsev and M.M.J. Dhalle (Twente)



Introduction and Motivation

- Feather-M0/2 EuCARD-2 Magnets (presented at ASC 2014)
- Two of the present concerns with ReBCO HTS accelerator magnets
  1. Magnetization and Field Quality
  2. Quench Detection and Protection
- This lead to the development of an Electrical Network model of ReBCO cables (and coils)
- The model follows the JackPot-AC model for Cable in Conduit Conductors from the University of Twente



4LPo2G-03: 153.

Applied Superconductivity Conference, Charlotte 2014

STUDY OF A 5 T RESEARCH DIPOLE INSERT–MAGNET USING AN ANISOTROPIC REBCO ROEBEL CABLE

J. van Nugteren a,b, G. Kirby b, G. de Rijk b, L. Rossi b, H. ten Kate a,b, M. Dhallé a

I. INTRODUCTION

II. REBCO COATED CONDUCTOR AND AN-ISOTROPY

IV. CROSS SECTIONAL LAYOUT

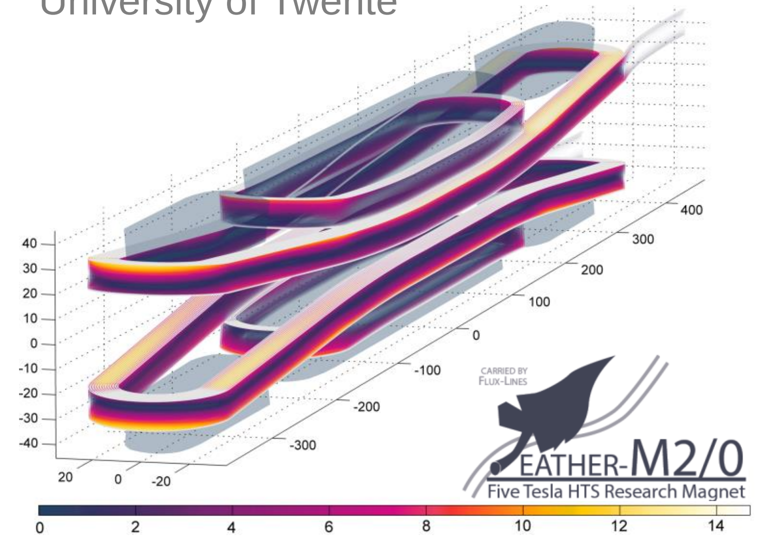
V. MECHANICAL STRUCTURE AND ASSEMBLY

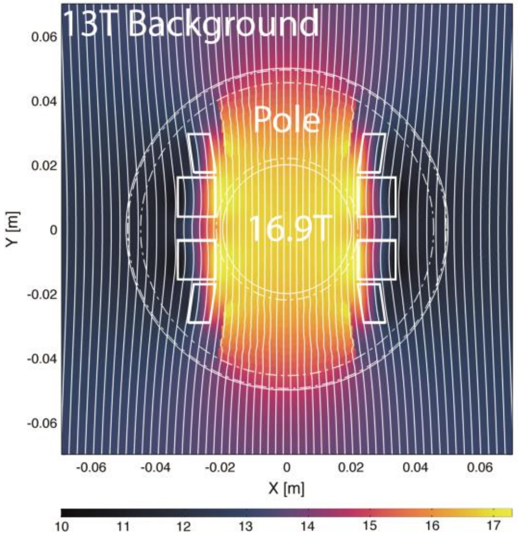
III. REQUIREMENTS AND CABLE

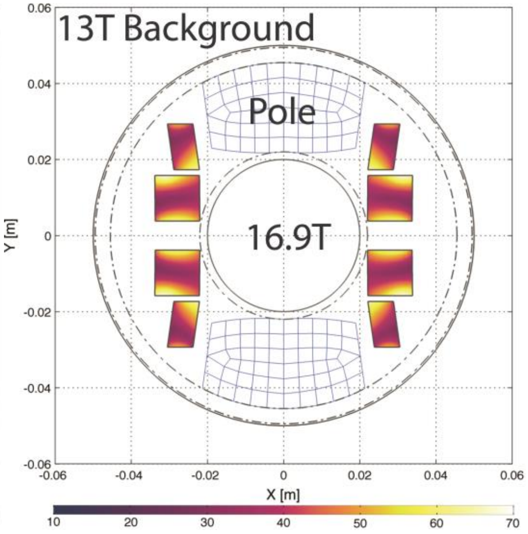
VI. THREE DIMENSIONAL LAYOUT

VII. CRITICAL CURRENT CALCULATION AND NETWORK MODEL

VIII. CONCLUSION

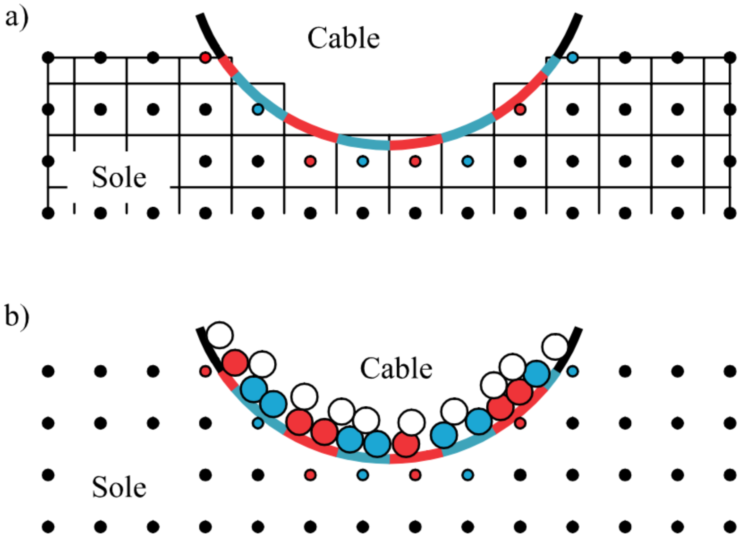






JackPot-AC

- Part of ITER project
- Calculation of current distribution in Cable in Conduit Conductors (CiCC)
- Accurate prediction of coupling losses of such cables and joints
- Allows for large number of elements
- Idea is to start from same solver setup because it is fast and solid
- Many new features needed implementation



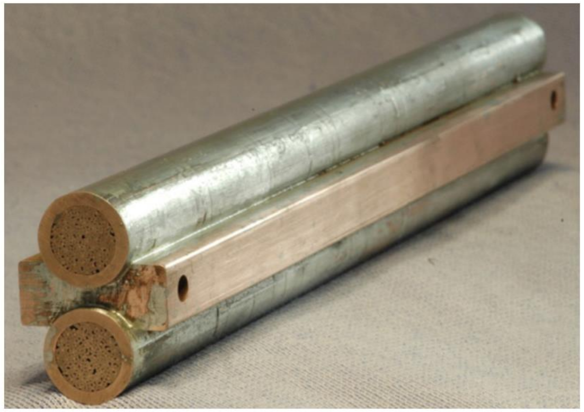


Figure 9. The mock-up joint assembly.

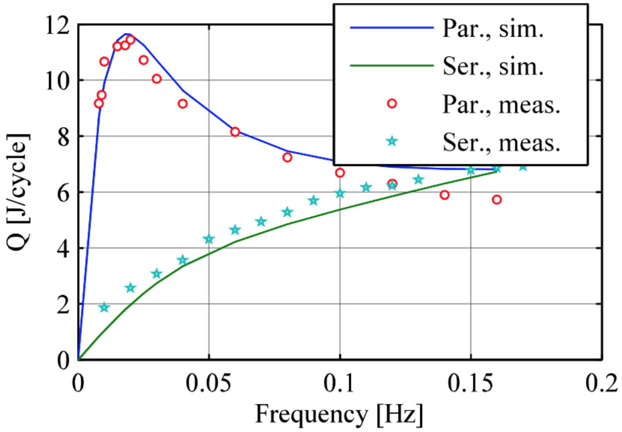
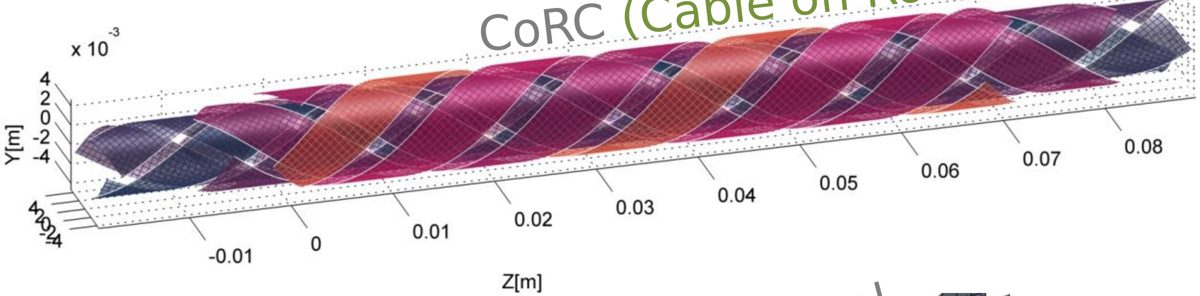


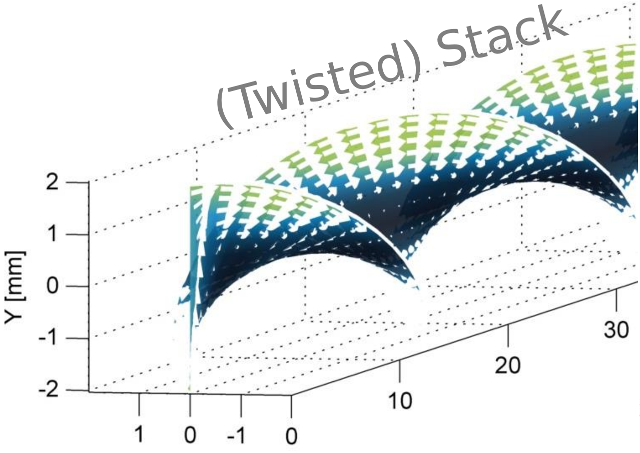
Figure 10. Measured and simulated AC loss of the joint versus frequency, under different angles of the applied AC field.

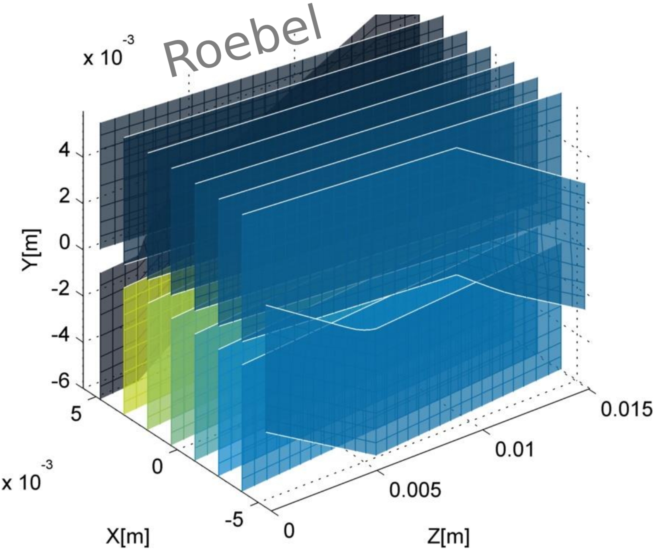
E P A van Lanen, J van Nugteren and A Nijhuis, ”Validation of a strand-level CICC-joint coupling loss model” Superconducting Science and Technology 2012, vol 25

Network Geometry

- To be able to model the hysteresis the superconducting tapes are modeled as ribbon shaped meshes of elements (PEEC)
- At this moment there are three cable geometries implemented.


CoRC (Cable on Round Core)


(Twisted) Stack


Roebel

Network Elements

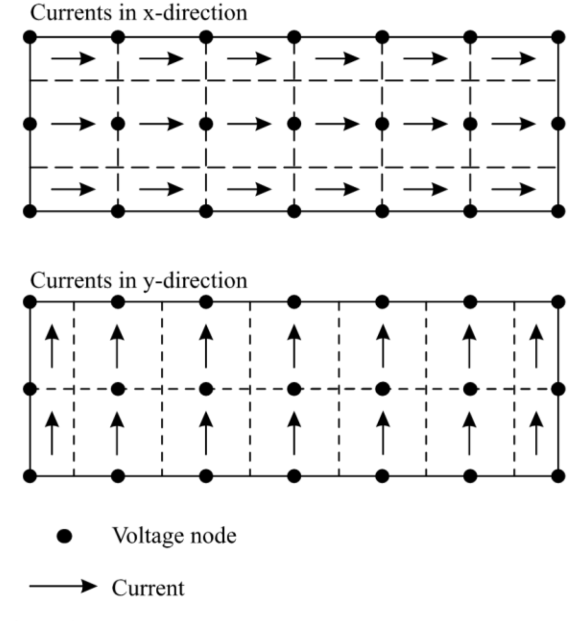
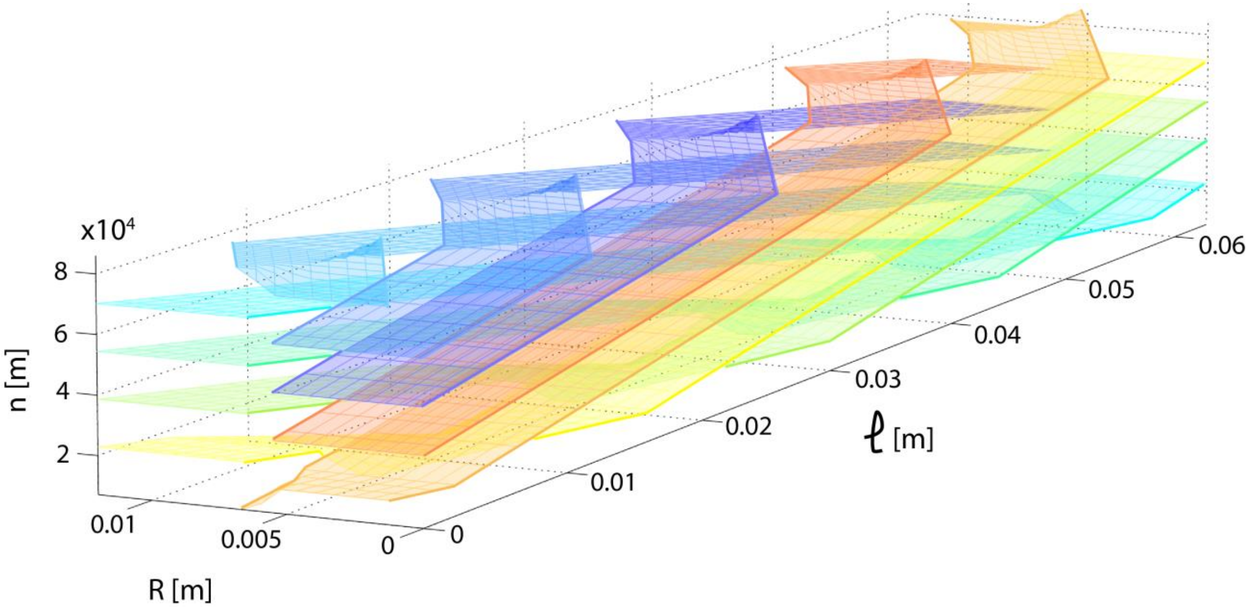


Figure 1. Schematic representation of a 2D rectangular object modelled with the PEEC method.

- Geometry consists of
  - Voltage nodes
  - Current elements

Roebel Cable

- Baseline cable geometry for EuCARD2 Feather-M2 magnet
  - 15 tapes
  - 226 mm twist pitch
- The positions of some nodes along the length of the cable are fixed
- Trajectories of tapes are calculated from unit cell



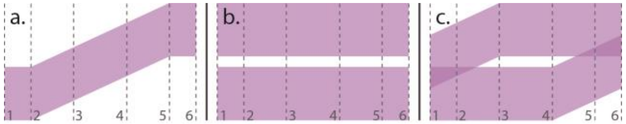
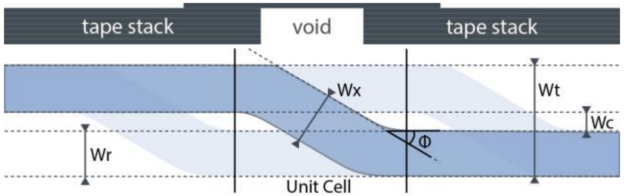


TABLE I

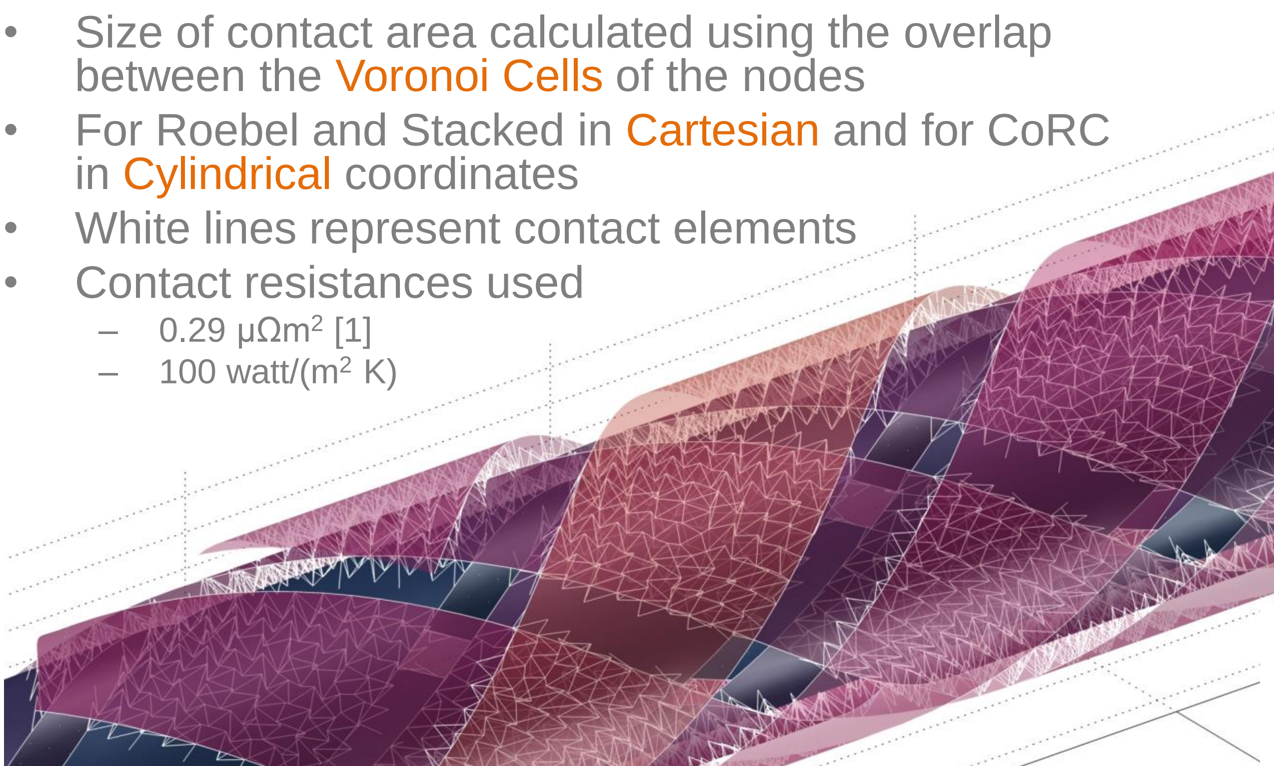
Parameter values of the coated conductor and Roebel cable.

Symbol	FM0	FM2	Description
Ns	15	15	number of strands
ds	0.10 mm	0.10 mm	strand thickness
dc	0.8 mm	0.8 mm	cable total thickness
di	0.1 mm	0.1 mm	insulation thickness
Wr	5.50 mm	5.50 mm	strand width
Wt	12.0 mm	12.0 mm	cable width
Wx	5.50 mm	5.50 mm	cross over width
Wc	1.0 mm	1.0 mm	channel width
Φ	30 degree	30 degree	cross over angle
Ltp	226 mm	226 mm	transposition pitch
ri	6.0 mm	6.0 mm	inner radius
ro	0.0 mm	0.0 mm	outer radius
$fimp$	1.0	1.5	improvement factor
$J_{20T\perp}$	$400\ \mathrm{A/mm^2}$	$600\ \mathrm{A/mm^2}$	tape Je at 20 T ⊥
$Abare$	$9.6\ \mathrm{mm^2}$	$9.6\ \mathrm{mm^2}$	bare cable area
$Ainsu$	$12.2\ \mathrm{mm^2}$	$12.2\ \mathrm{mm^2}$	total cable area
$fvoid$	~ 0.10	~ 0.10	void factor
$finsu$	~ 0.20	~ 0.20	insulation factor

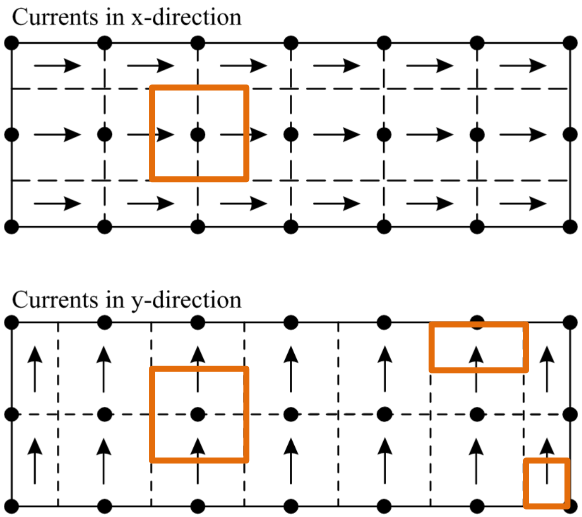


Contact Elements

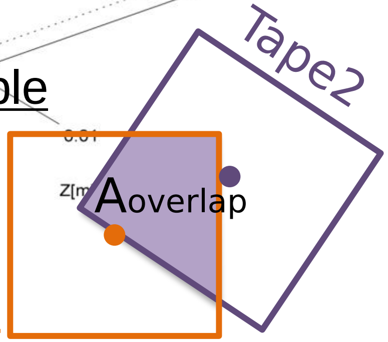
- Size of contact area calculated using the overlap between the Voronoi Cells of the nodes
- For Roebel and Stacked in Cartesian and for CoRC in Cylindrical coordinates
- White lines represent contact elements
- Contact resistances used
    - 0.29 μΩm² [1]
    - 100 watt/(m² K)



Voronoi Cell

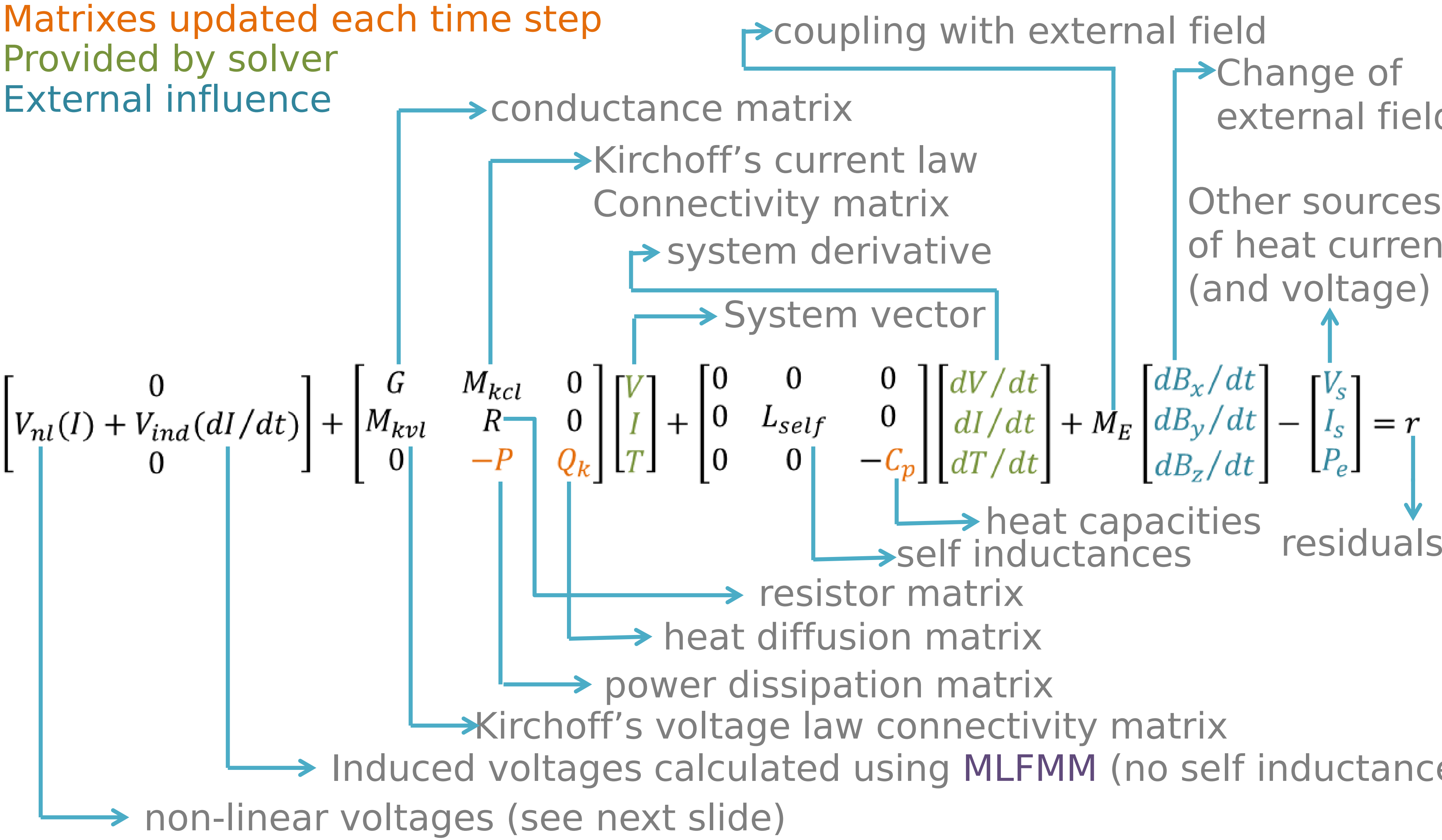


Example



[1] K. Yagotintsev, P. Gao, M. Dhalle *et al.*, "AC loss tests on CORC and stacked tape ReBCO cables," Poster presented at ASC 2014, August 2014, charlotte (SC) USA.

System of Equations



Matrixes updated each time step
Provided by solver
External influence

$$\begin{bmatrix}0\\V_{nl}(I)+V_{ind}(dI/dt)\\0\end{bmatrix}+\begin{bmatrix}G & M_{kcl} & 0\\ M_{kvl} & R & 0\\ 0 & -P & Q_k\end{bmatrix}\begin{bmatrix}V\\I\\T\end{bmatrix}+\begin{bmatrix}0&0&0\\0&L_{self}&0\\0&0&-C_p\end{bmatrix}\begin{bmatrix}dV/dt\\dI/dt\\dT/dt\end{bmatrix}+M_E\begin{bmatrix}dB_x/dt\\dB_y/dt\\dB_z/dt\end{bmatrix}-\begin{bmatrix}V_s\\I_s\\P_e\end{bmatrix}=r$$

coupling with external field

Change of
external fiel

conductance matrix

Kirchoff's current law
Connectivity matrix

system derivative

System vector

Other sources
of heat curren
(and voltage)

heat capacities

self inductances

residuals

resistor matrix

heat diffusion matrix

power dissipation matrix

Kirchoff's voltage law connectivity matrix

Induced voltages calculated using MLFMM (no self inductanc

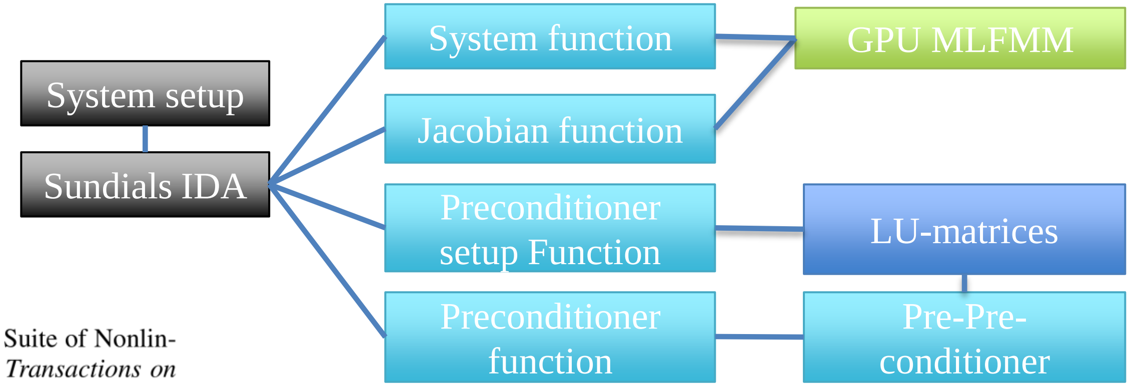
non-linear voltages (see next slide)

Solving the system

- The system is solved using the Sundials IDA solver from LLNL [1]

- Jacobian Function
  - Most derivatives are approximated using finite difference
  - The system

- Preconditioner
  - Using stabilized bi-conjugent gradient method (BICGSTAB) or generalised minimal residual method (GMRES) preconditioned by LU-matrices
  - The LU-decomposition of the system matrix is performed only when requested by IDA
  - Only for the LU the mutual inductances from the MLFMM can not included in the system



System setup

Sundials IDA

System function

Jacobian function

Preconditioner setup Function

Preconditioner function

GPU MLFMM

LU-matrices

Pre-Pre-conditioner

---

[1] A. Hindmarsh, P. Brown, K. Grant *et al.*, "SUNDIALS: Suite of Nonlinear and Differential/Algebraic Equation Solvers," *ACM Transactions on Mathematical Software*, vol. 31, no. 3, pp. 363–396, September 2005.

Non-Linear Current Sharing Model

- Current sharing refers to the current distribution between the matrix material and the superconductor provides Vnl(I)
- In the model three options are available:
  1. Pure power law (not useable for quench analysis because only valid below or just above Tcs)
  2. Linear transition between Tcs and Tc

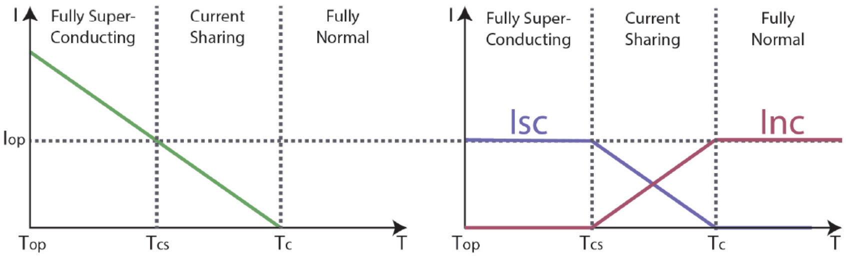
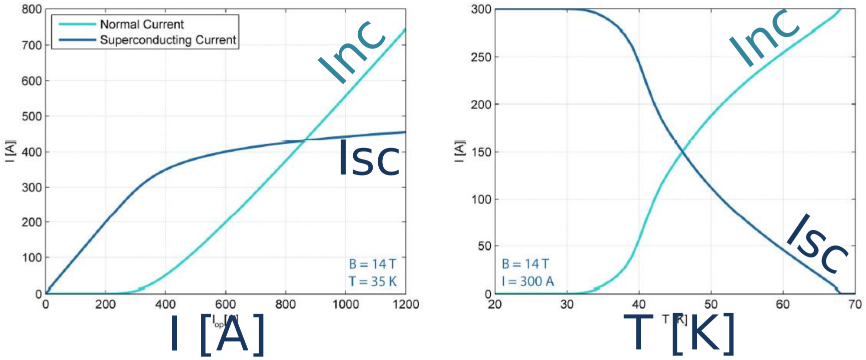
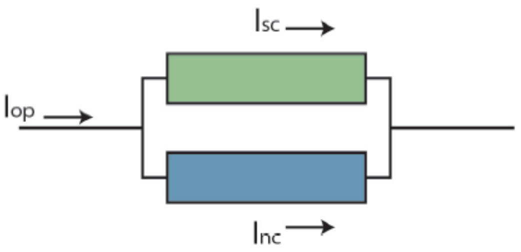


Figure 4.1: Schematic representation of current sharing in a practical superconductor (adapted from Bellis [35]).

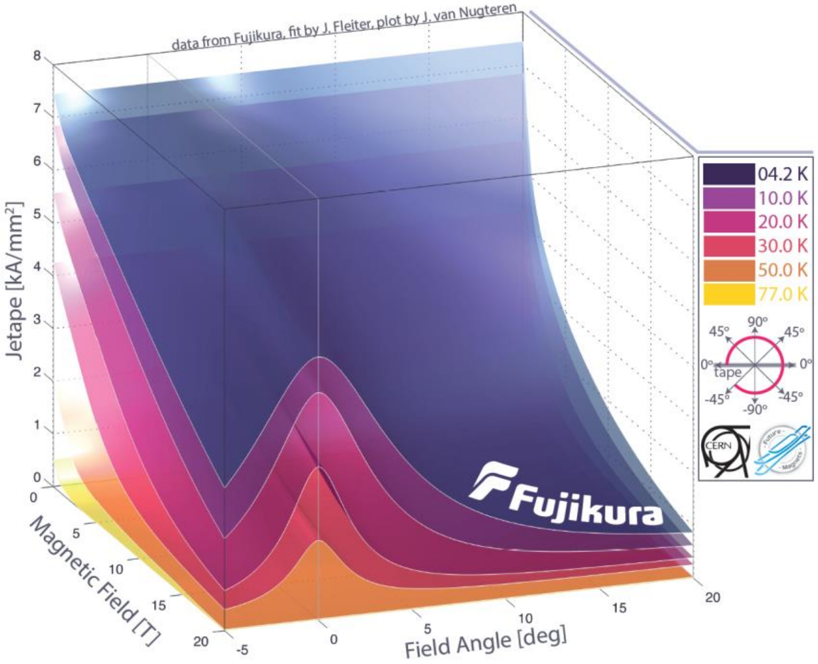
  3. Superconducting power law element in parallel with resistive (matrix) element (implicit equation)



Current Sharing

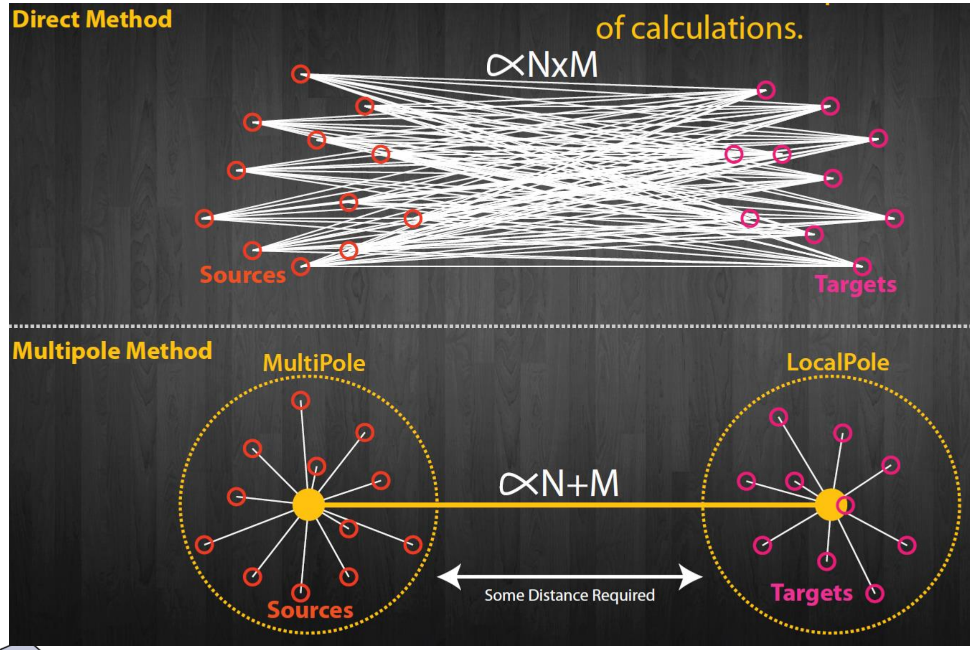


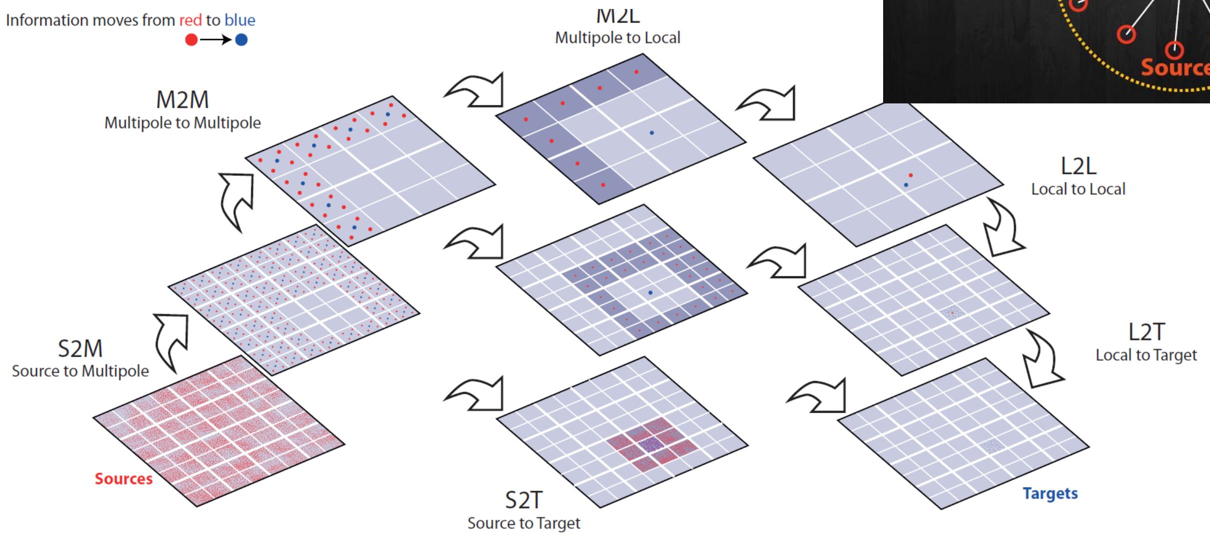
Angular Dependent Critical Current



Multi-Level Fast Multipole Method

- Multi-Level Fast Multipole Method (MLFMM) developed by Greengard and Leslie (one of the top 10 algorithms of the previous century)
- Instead of using a dense matrix the the induced voltages can be calculated at each element every time step using MLFMM
- Uses spherical harmonics (multipoles) as a “middle man” to reduce the computational complexity from O(NxM) to O(N+M)
- An octtree-grid ensures that all the interactions are included
- Implemented using highly parallelized code using NVIDIA CUDA GPU programming language



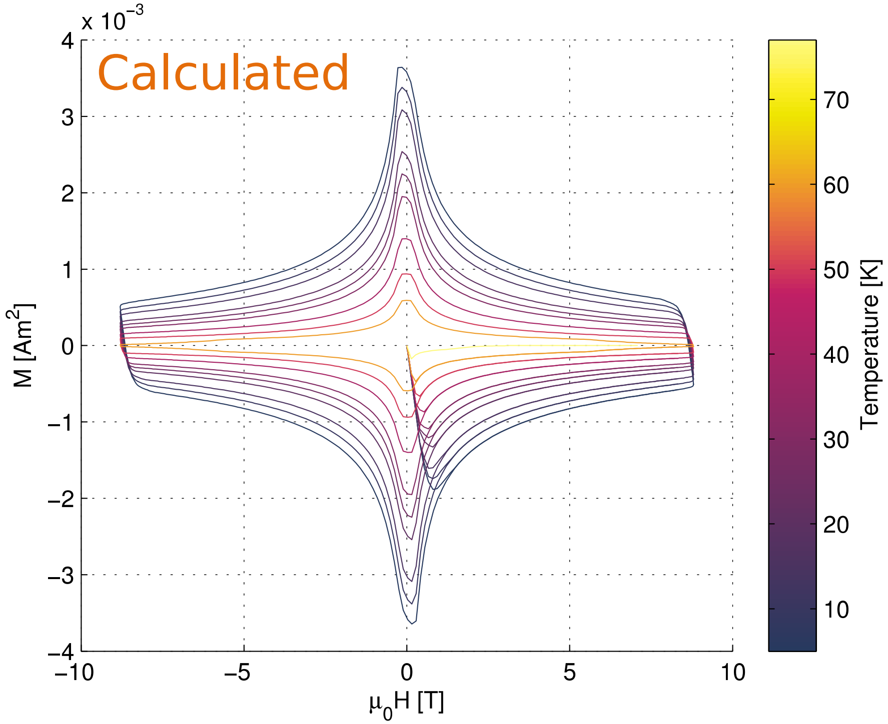


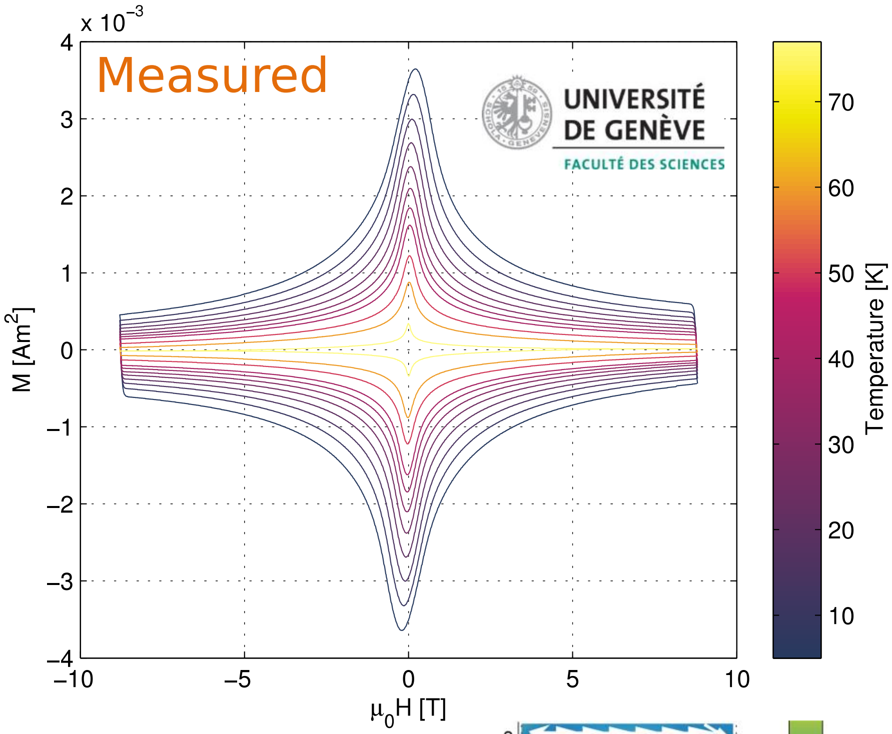

Graphics Processing Unit (GPU)

L. Greengard, “The rapid evaluation of potential fields in particle systems,” tech. rep., Cambridge, 1988.

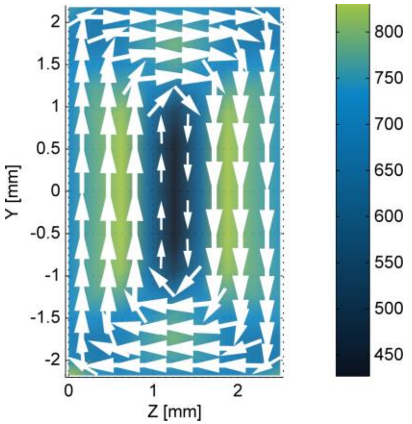
J. Kurzak and B. M. Pettitt, “Fast multipole methods for particle dynamics,” Molecular Simulation, vol. 32, no. 10-11, pp. 775–790, 2006.

Validation of Magnetisation Model



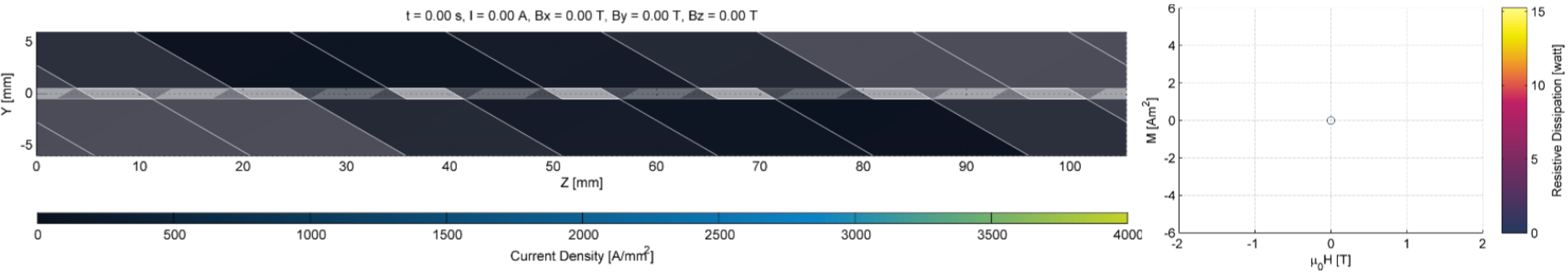


- Comparison University of Geneva Data taken with VSM
- sample size 4.4 mm x 5.1 mm x 0.16 mm but edges near cut suspected to be damaged during sample preparation
- For the calculation critical current scaled to 50 A/mm in 4.2K, 19 T perpendicular field
- Considering scaling relation used. Reasonable agreement is found between measurement and experiment.

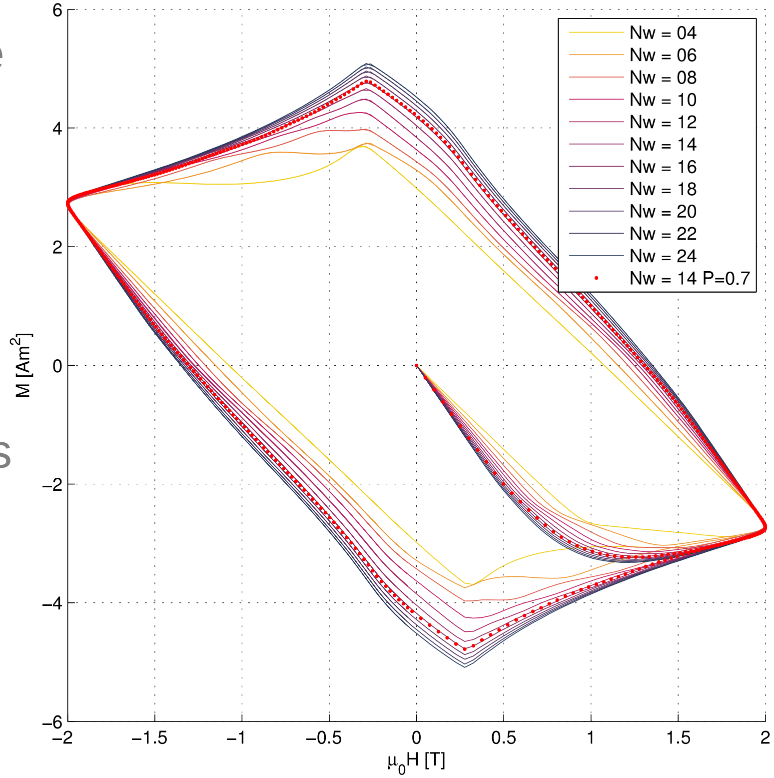


Special thanks to Carmine Senatore and the university of Geneva for sharing their measurement data!

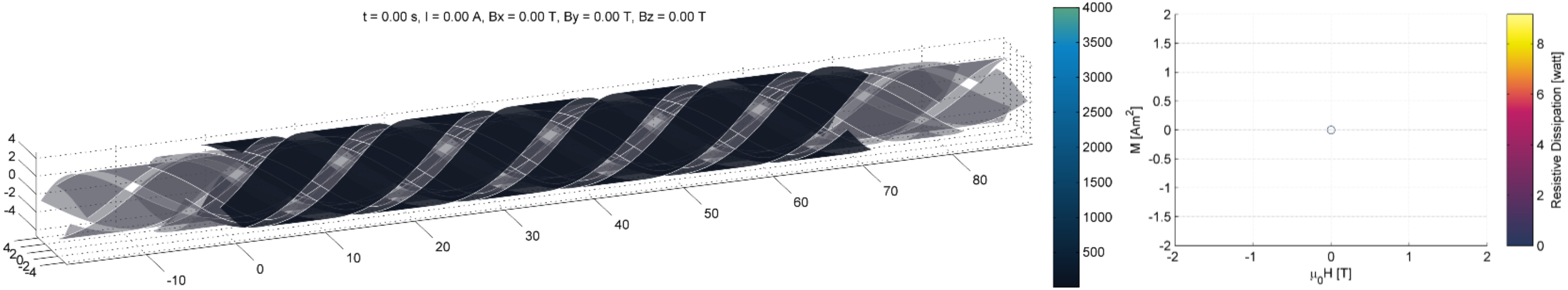
Magnetisation of Roebel Cable



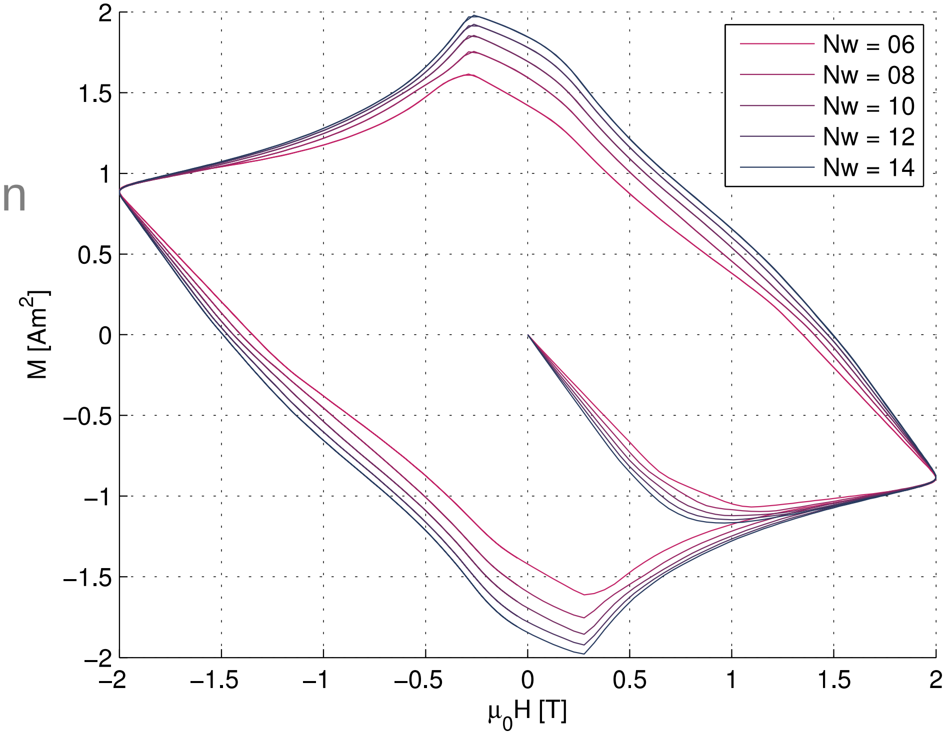
- The calculated magnetisation of a Roebel cable in -2 to 2 T sinusoidal applied field in the perpendicular direction
- Only hysteresis, almost no coupling currents observed
- Hysteresis curve as function of number of elements along width of tapes
- Studied the influence of the number of elements across the width of the tape (decided to use 14 or more)
- Measurement of hysteresis and AC-losses is on-going at the University of Twente



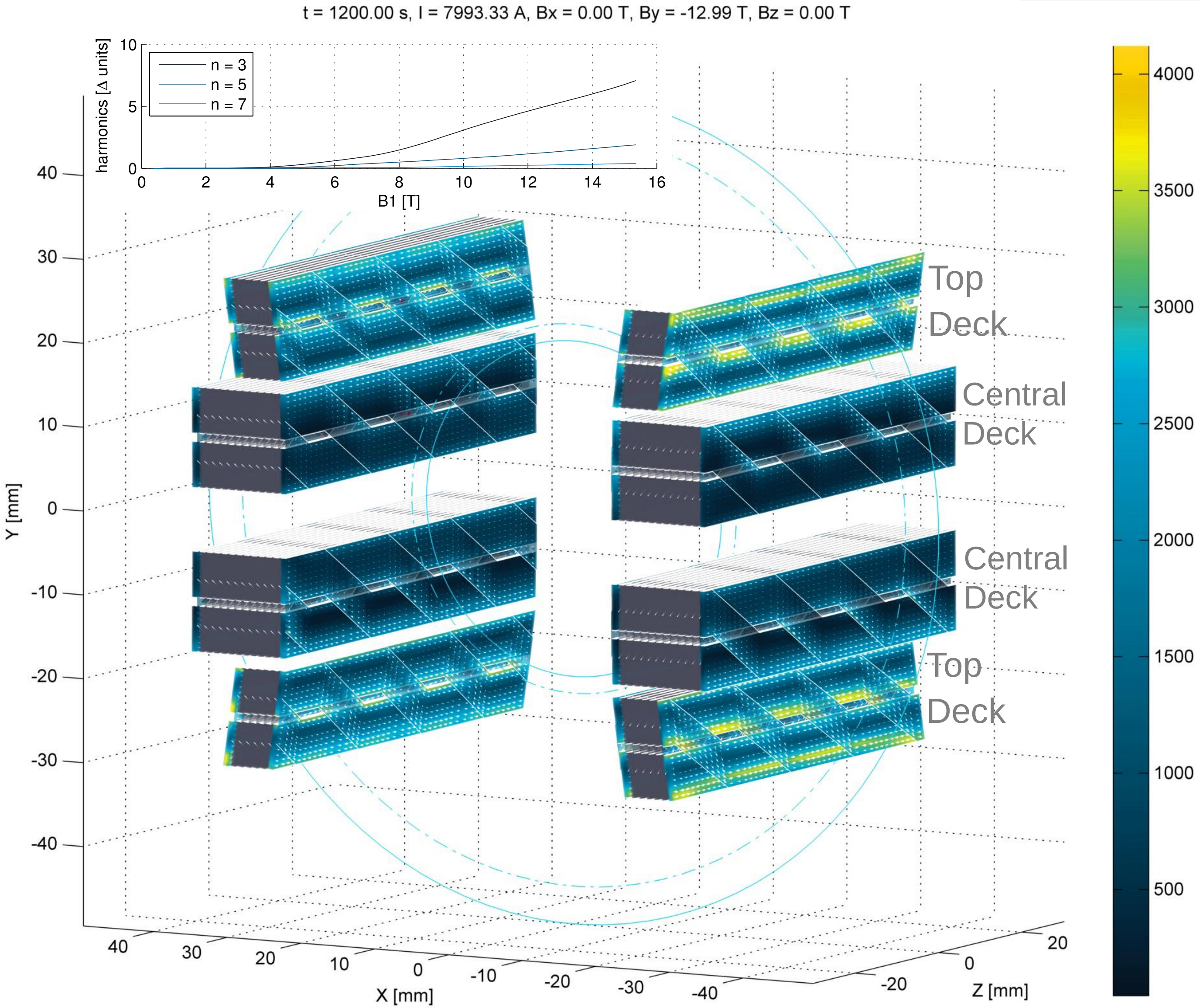
Magnetisation of CoRC Cable



- The calculated shielding currents of a CoRC cable in -2 to 2 T sinusoidal applied field in the perpendicular direction
- Almost only hysteresis observed
- CoRC strands are twisted therefore less magnetisation than Roebel in perpendicular field direction
- Similar behaviour with number of elements observed as for Roebel



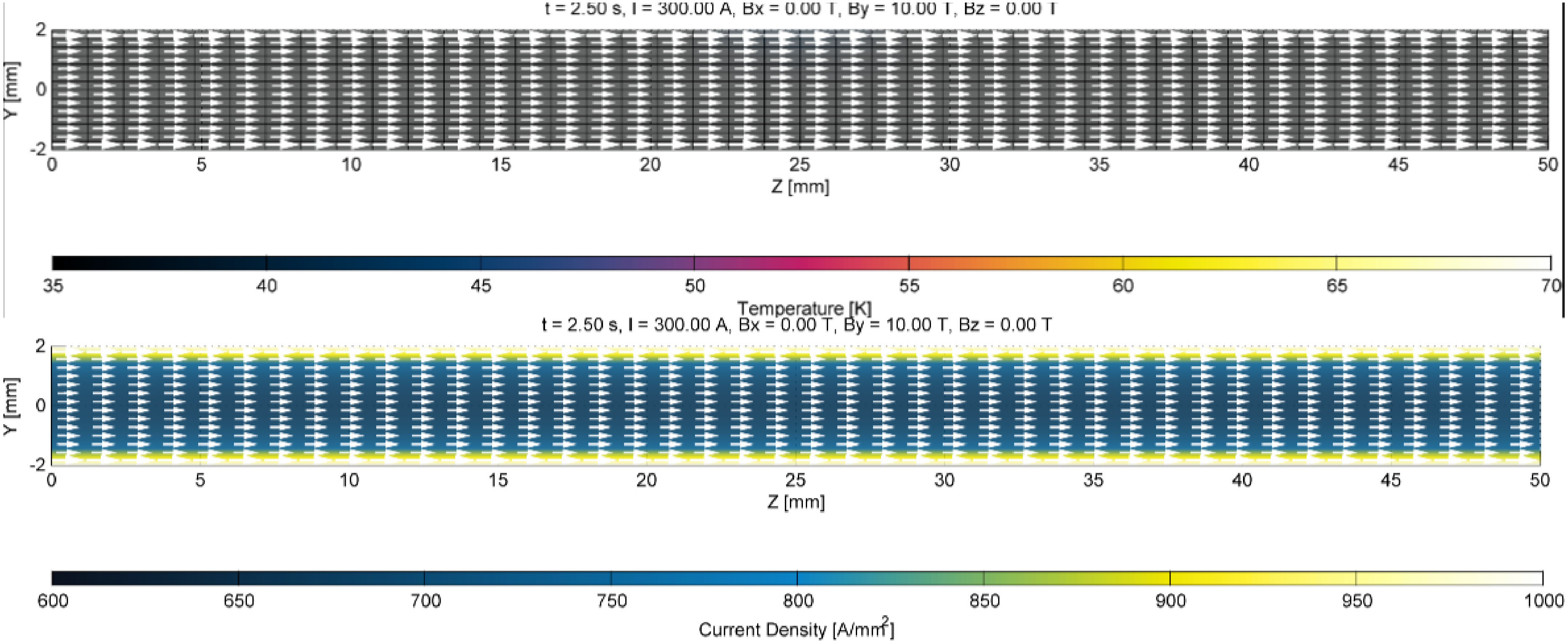
Feather–M2 Harmonics



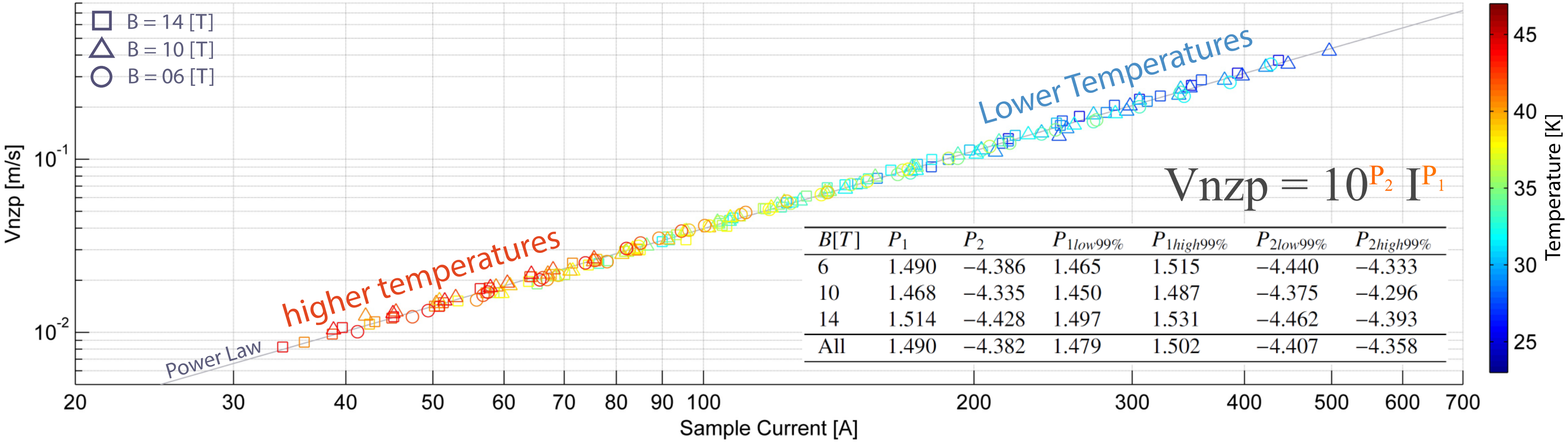
- Due to limitations of the BemFem no Iron pole (yet)
- Simultaneous ramp of Fresca2 and insert over 20 minutes (1200 s)
- Top deck generates more shielding currents due to field angle
- Harmonics at 2/3 aperture less than 10 units
- Keeping alignment during ramping could reduce the field error by a great deal

Validation of Thermal Model

- Comparison University of Twente normal zone propagation measurement data (master assignment JvN).
- As an example a quench at 35 K, 10 T parallel, 300 A in a 4 mm wide tape
- Quench was purposely initiated at edge of tape to show redistribution of current
- Propagation is, due to the redistribution of the current, much faster in width direction than longitudinal direction!



Validation of Thermal Model

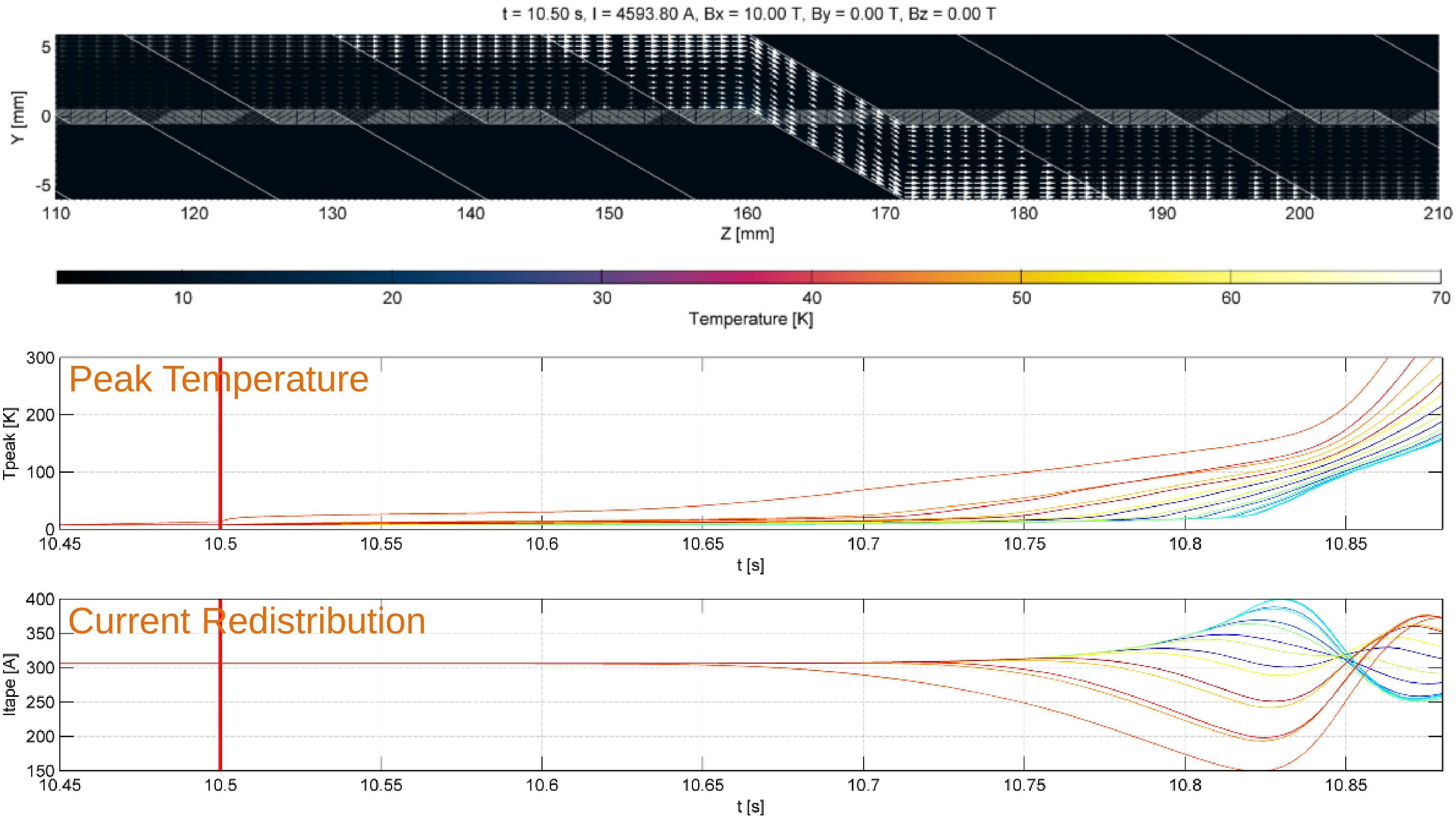


$$\mathrm{Vnzp} = 10^{P_2}\, I^{P_1}$$

$B[T]$	P_1	P_2	$P_{1low99\%}$	$P_{1high99\%}$	$P_{2low99\%}$	$P_{2high99\%}$
6	1.490	−4.386	1.465	1.515	−4.440	−4.333
10	1.468	−4.335	1.450	1.487	−4.375	−4.296
14	1.514	−4.428	1.497	1.531	−4.462	−4.393
All	1.490	−4.382	1.479	1.502	−4.407	−4.358

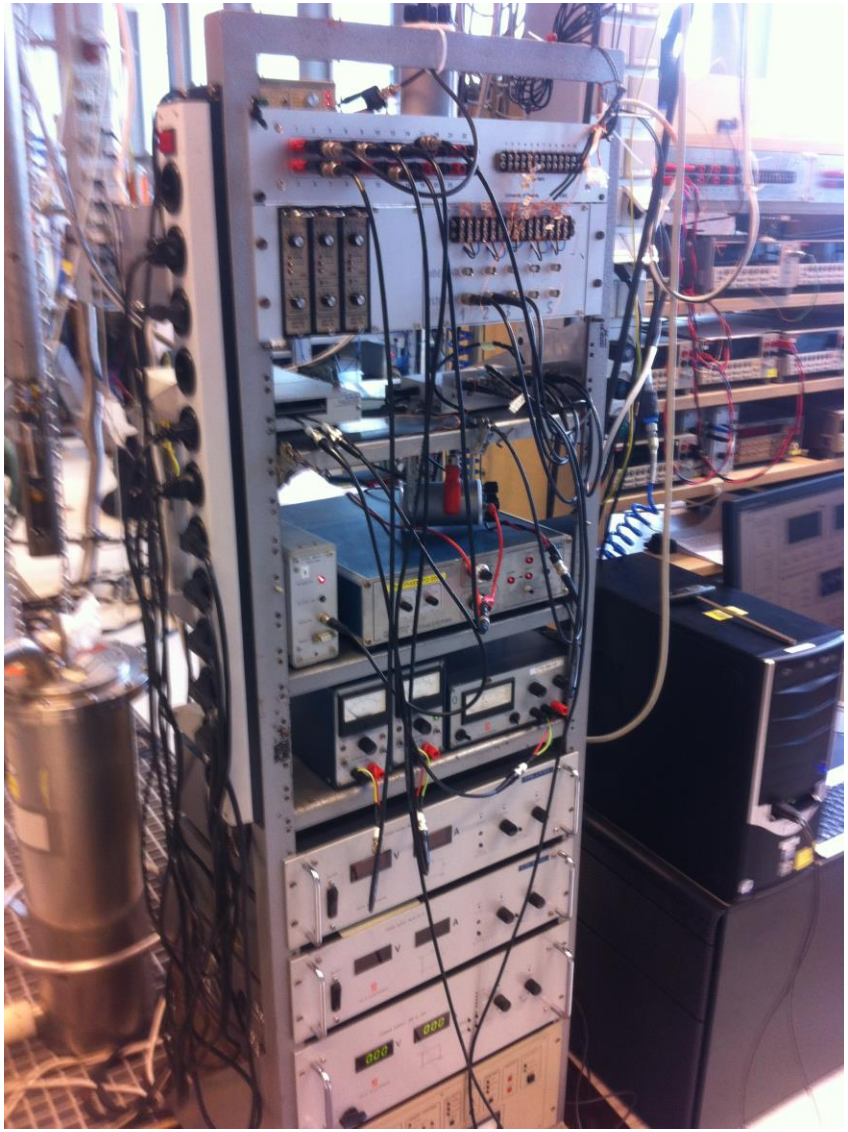
Normal Zone Propagation inside Roebel cable

- 0.4 watt heating on point after 10.5 s



Requested Experimental Input

- Additional validation of the model
  - Magnetisation and AC-losses of different cable structures, pressures and orientations
  - Quench propagation and corresponding current redistribution of different cable structures
- Electrical contact resistances
- Thermal contact resistances



Conclusion

- An electrical network model representing the tapes in ReBCO cables has been introduced
- In the model the following physics are available
  - Electrical voltages and currents
  - Heat generation and conduction

- Initial validation seems promising but waiting for more measurement data (from the University of Twente)
- Some examples were calculated for this conference but real data mining is yet to start (need validation first)

- Intend to get
  - Further analysis of the magnetisation currents and their effect on the coil harmonics.
  - Possible ramp scenarios for Feather-M2 magnet
  - Quench analysis and comparison between the different cable types

Thank you for your attention