Chats 2019

Applied Superconductivity

Summary of the Workshop

09-12 July 2019

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(*) ce

(**) Bundesministerium für Bildung und Forschung

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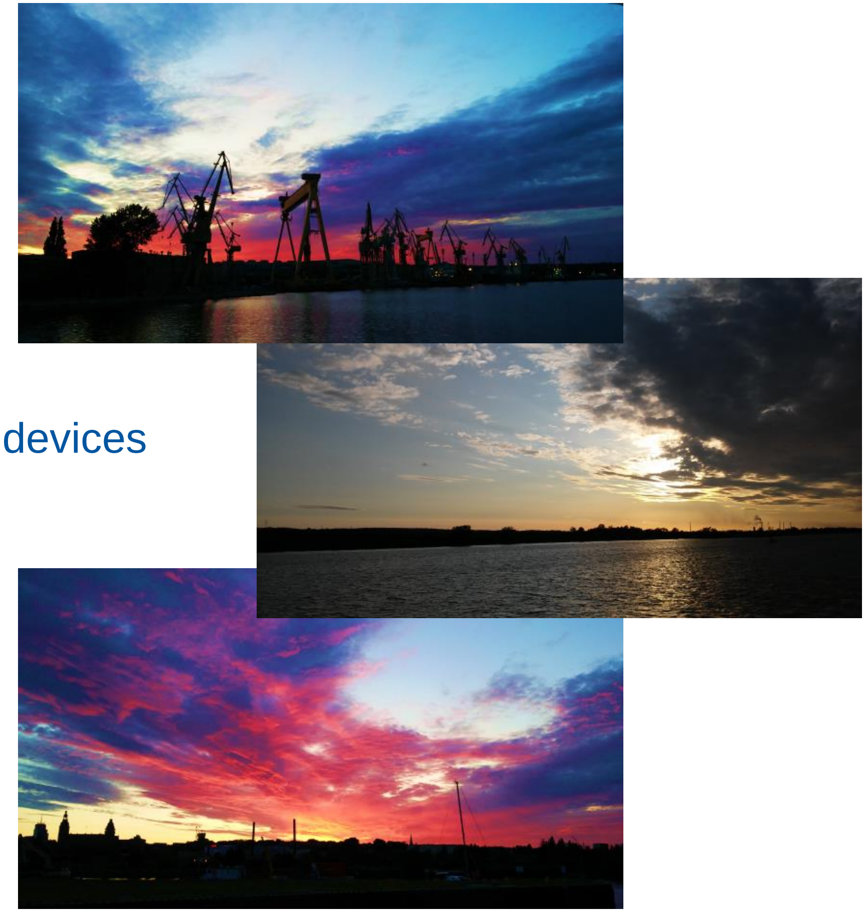
(*) The ‘Excellence Initiative’ of the German Government and by the Graduate School of Computational Engineering at TU Darmstadt;
(**) The Gentner program of the German Federal Ministry of Education and Research (grant no. 05E12CHA).

Overwiew

Presentations available at https://indico.cern.ch/event/776034/

9-12 July 2019, Szczecin, Poland
~ 40 participants



Numerical methods

- Electro mechanical modelling
- Electro-thermal modelling
- Electromagnetics
- Multiphysics modelling of superconducting devices
- Experimental results for modelling

Quench Analysis

- Quench in HTS conductors
- Quench and thermo-hydraulic LTS

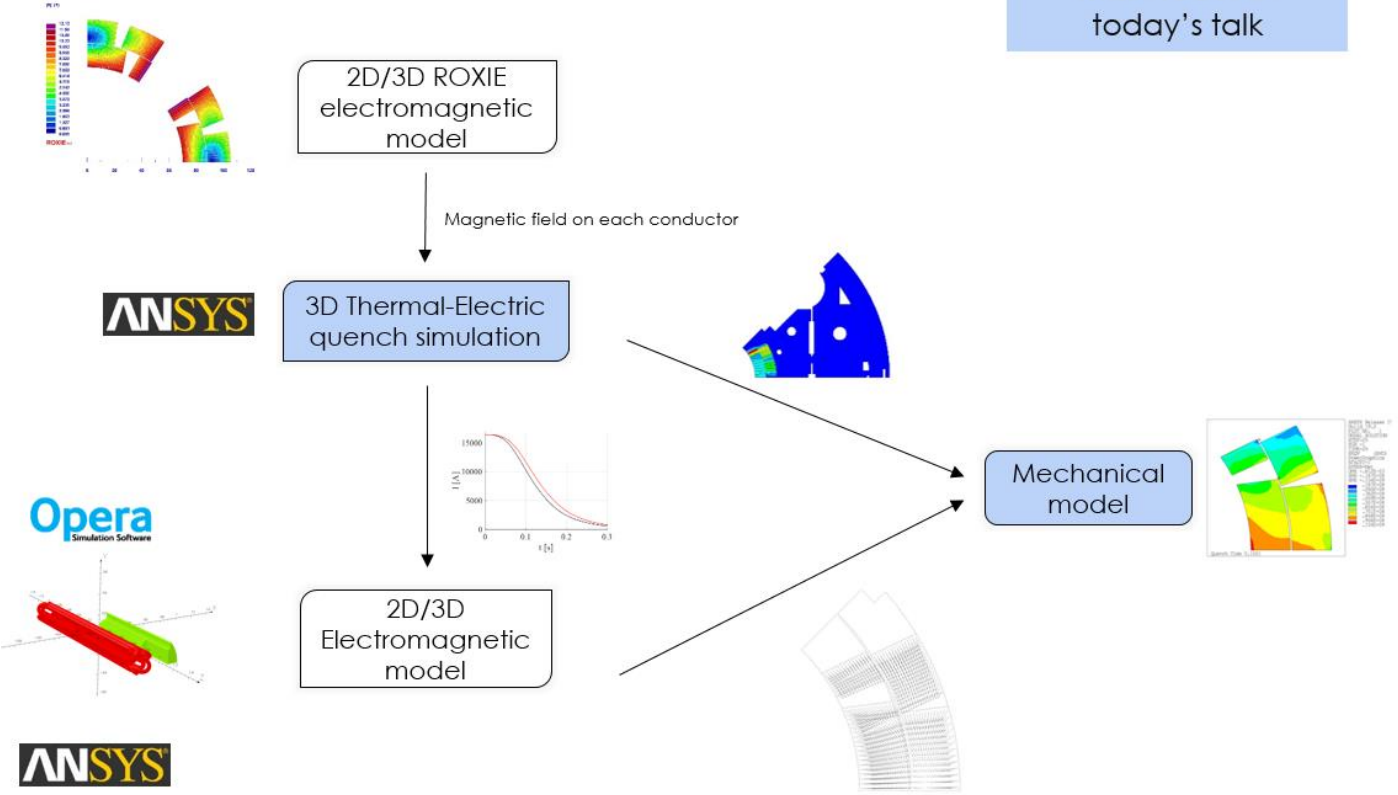
Cryogenic systems

- Thermo-hydraulic and cryogenics

Selected contribution 01

Motivation: Analysis of thermo-mechanical stresses in conductors during quench

Modelling strategy



Main focus of today's talk

2D/3D ROXIE electromagnetic model

Magnetic field on each conductor

3D Thermal-Electric quench simulation

2D/3D Electromagnetic model

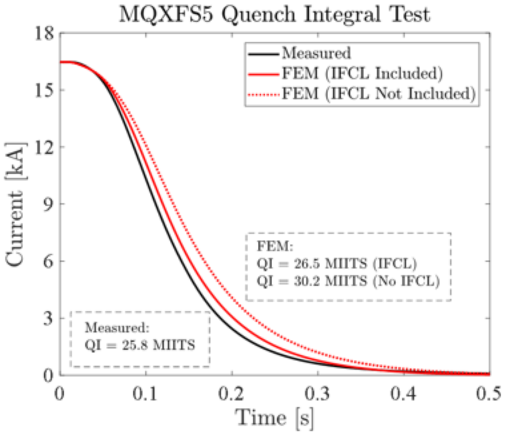
Mechanical model

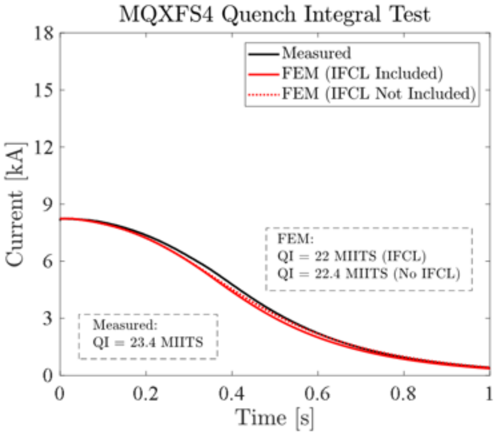
Model results and validation

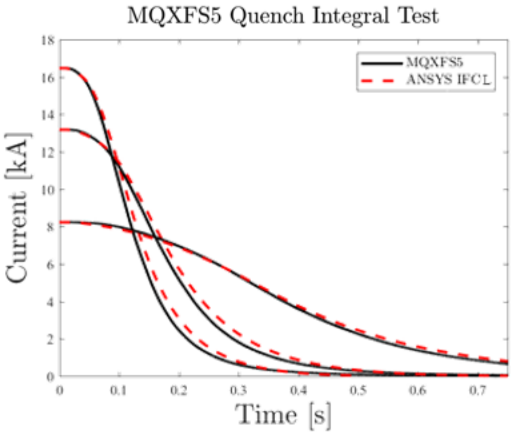
Simulation results obtained under the explained assumptions. An "error bar" should be always considered!

The model could be validated using the extensive experimental campaign for MQXFS magnets:

Quench Integral (QI) tests





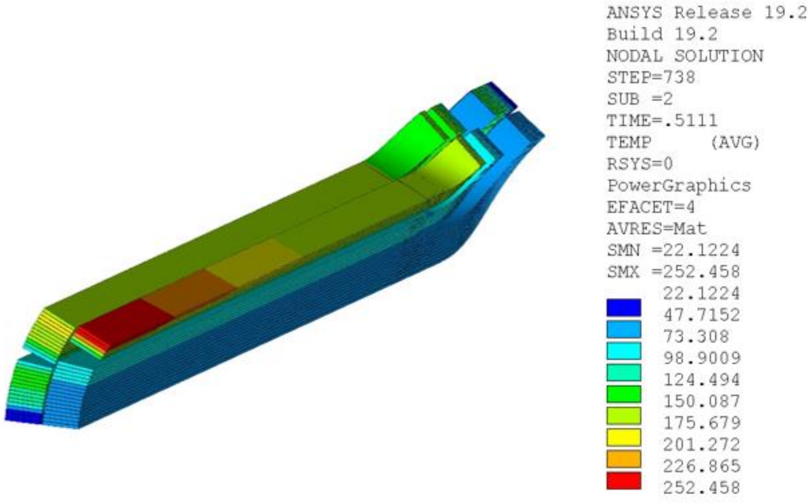


QI ~ Less than 10% difference w.r.t. experimental data in all tests

On the magnet mechanics during a quench: Three-Dimensional Finite Element Analysis Of a Quench Heater Protected Magnet

Jose Ferradas et al. - CERN

Nominal current training quench



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Build 19.2
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SUB =2
TIME=.5111
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RSYS=0
PowerGraphics
EFACET=4
AVRES=Mat
SMN =22.1224
SMX =252.458
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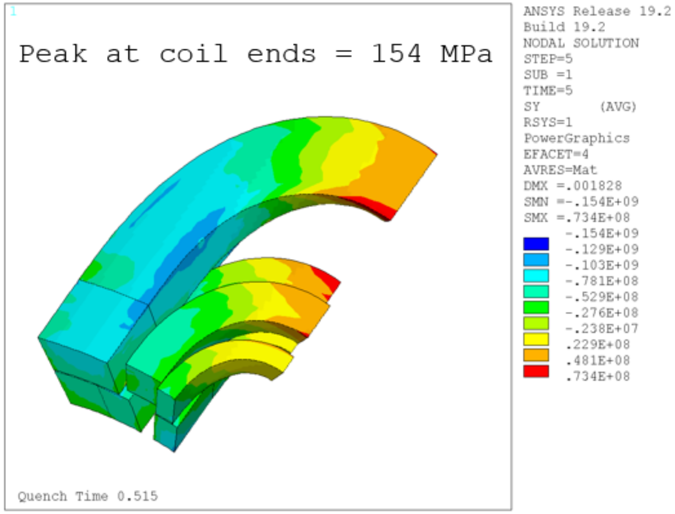
     47.7152
     73.308
     98.9009
     124.494
     150.087
     175.679
     201.272
     226.865
     252.458
```

Temperature



Peak at coil ends = 154 MPa

Quench Time 0.515

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TIME=5
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RSYS=1
PowerGraphics
EFACET=4
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SMX =.734E+08
     -.154E+09
     -.129E+09
     -.103E+09
     -.781E+08
     -.529E+08
     -.276E+08
     -.238E+07
     .229E+08
     .481E+08
     .734E+08
```

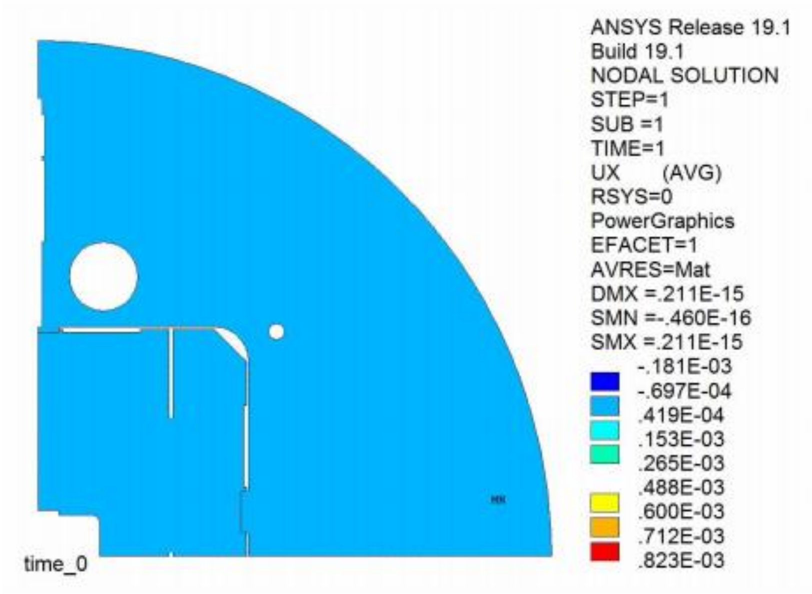
Azimuthal stress

- A methodology for the 2D and 3D study of the magnet mechanics during a quench has been presented.
- It uses a combination of finite element models in ANSYS APDL with other usual tools used in the magnet community.
- The different models have been validated with experimental measurements separately.

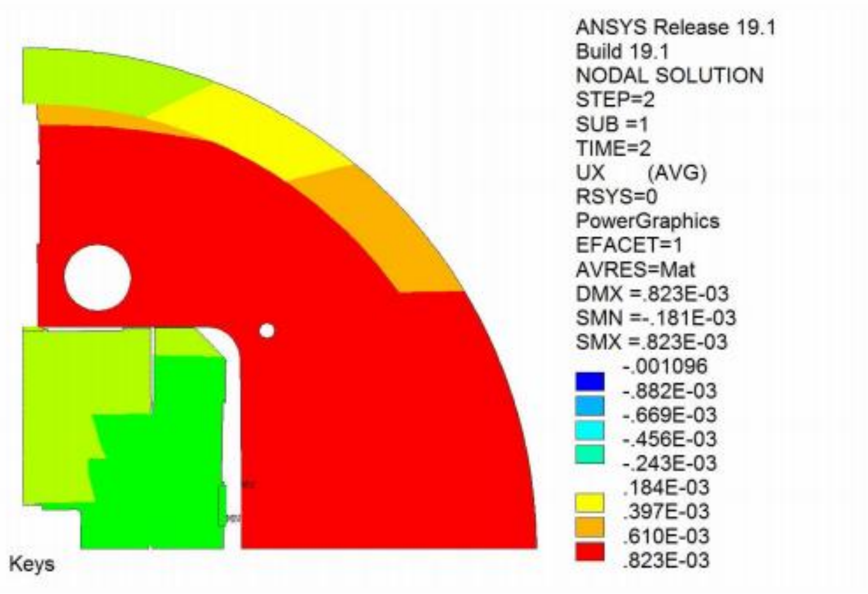
Selected contribution 02

Motivation: Influence of magnetic forces on the magnet mechanical behaviour

Calculation example (HEPdipo magnet – forces in the iron):



Lateral pre-load of 1 mm using bladders and Keys technology



Effect of the thermal contraction from 300 to 4.2 K on the horizontal displacement

High Field Magnets: Electromechanical Modeling Taking into Account Local Magnetic Forces with Iron Saturation

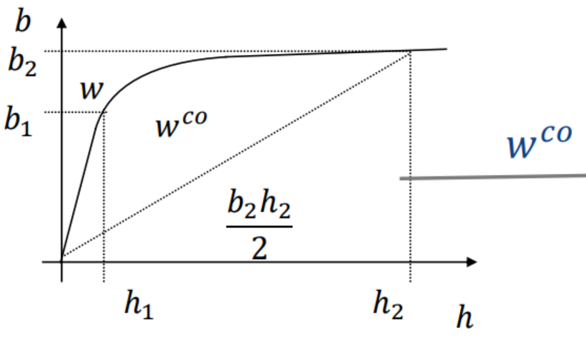
D. Martins Araujo et al. - CERN

The local distribution of magnetic forces within the iron is **unknown**!

Several formulas can be used to compute it:

- **T1** - Maxwell stress tensor
- **T2** - Virtual work principle, via calculation of the magnetic co-energy
- **T3** - M. K. Ghosh et al., IEEE Transactions on Magnetics, pp. 1–4, 2018.

$$\rightarrow T^1_{mn} = h_m b_n - \frac{1}{2}\delta_{mn}(\mathbf{h}\cdot\mathbf{b})$$

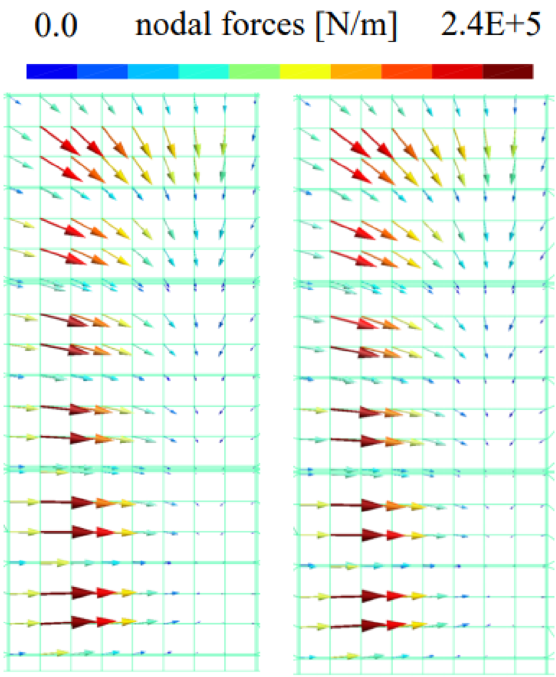


$$\rightarrow T^2_{mn} = h_m b_n - \int_0^h \mathbf{b}\cdot d\mathbf{h}$$

M. K. Ghosh *et al.*, "Proposal of Maxwell Stress Tensor for Local Force Calculation in Magnetic Body," *IEEE Transactions on Magnetics*, pp. 1–4, 2018.

$$\rightarrow T^3_{mn} = \frac{\mu_0}{\mu_0}\left(h_m b_n - \frac{1}{2}\delta_{mn}\mathbf{h}\cdot\mathbf{b}\right)$$

Lorentz forces in the coils: **T1 = T2 = T3** (linear magnetic material)



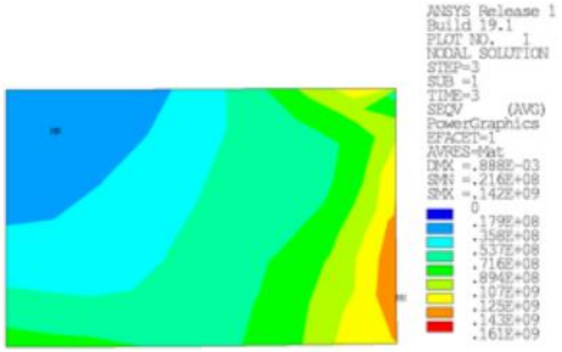
Lorentz MST

MN/m 1/4 model	Fx	Fy
Inner coil	5.35	- 0.03
Inter coil	4.69	- 2.0
Outer coil	4.13	- 5.11

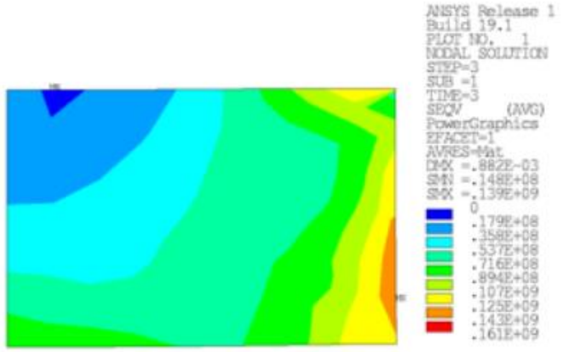
Very similar results using Lorentz and Maxwell Stress Tensors

The compatibility between forces on coils computed by Lorentz formula and Maxwell Stress Tensor was proved.

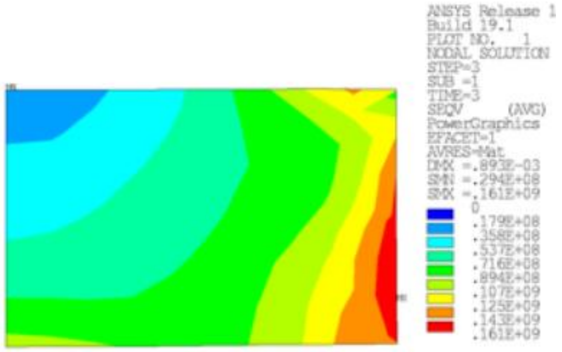
Powering to 15 T at 4.2 K: Iron pole of the inter coil



T1



T2



T3

Maximum difference of **15%** on the horizontal stress for the iron pole of the outer coil

The effect on the iron stress is limited because the model is symmetric

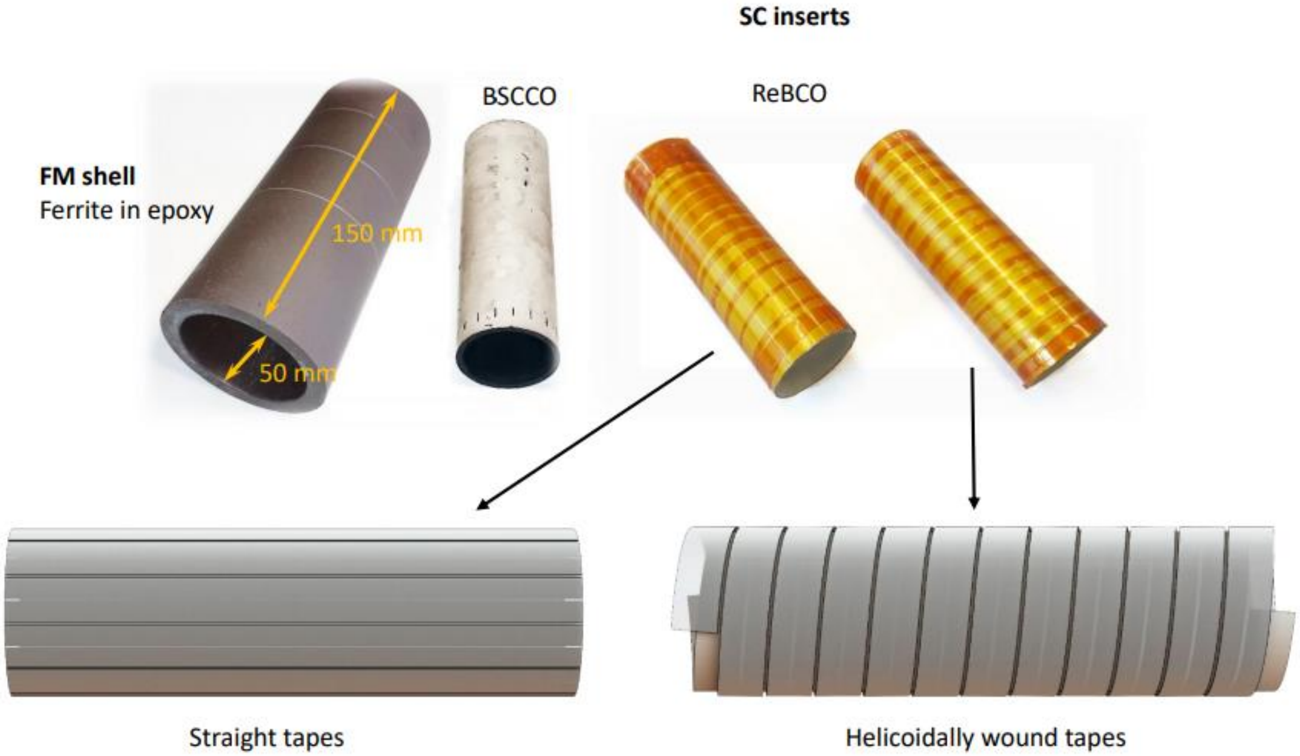
If a free movement is allowed the stress may increase even more

Commercial software (Ansys, Opera) uses T1.

When using T2 or T3 the stress on iron poles is higher

Selected contribution 03

Motivation: Simulation of magnetic cloaks based on HTS superconductors



Issue: Nonlinear behavior of (E-J) characteristics

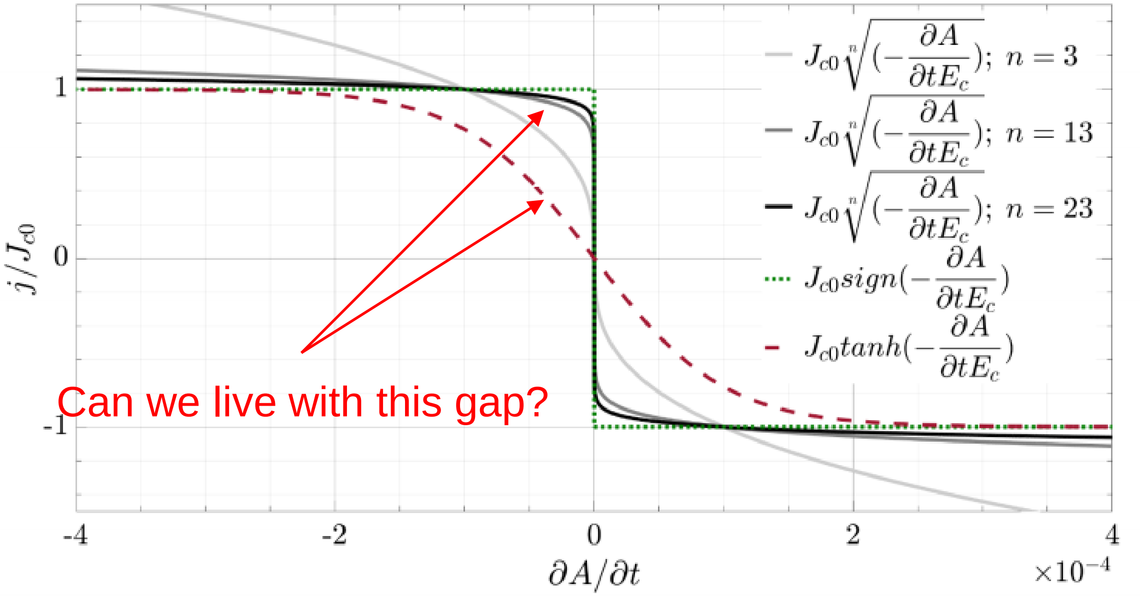
- Smooth-it out!

$$\vec{j} = J_{c0}\sqrt[n]{-\frac{\partial \vec{A}}{\partial t E_c}}$$

$$\vec{j} = J_{c0}\,sign\left(-\frac{\partial \vec{A}}{\partial t E_c}\right)$$

The alternative function
proposed by A. Campbell[2]

$$\boldsymbol{\vec{j} = J_{c0}\,tanh\left(-\frac{\partial \vec{A}}{\partial t E_c}\right)} \qquad \textbf{(7)}$$

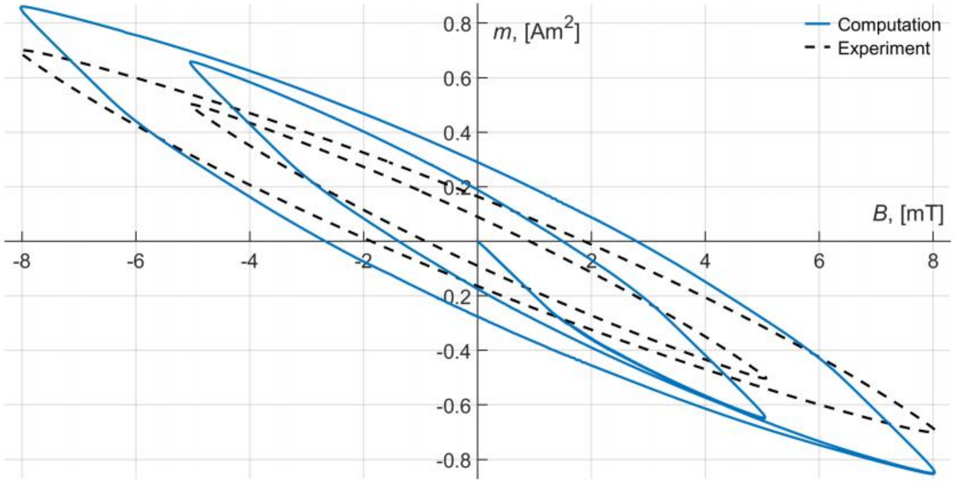


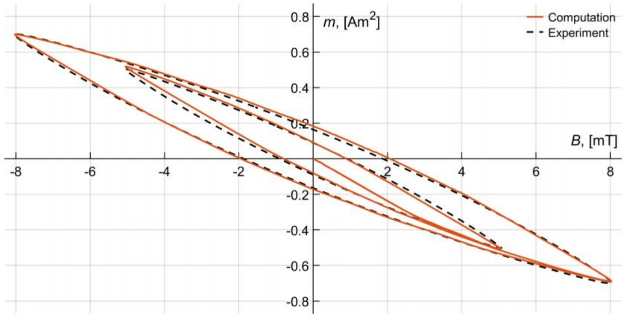
Can we live with this gap?

A-formulation method for full 3D FEM computation of the superconductor magnetization

Solovyov Mykola et al. - Institute of Electrical Engineering Slovak Academy of Sciences

Comparable areas, peaks shifted





Model conditioned a posteriori with measurements of current density distribution

The model shall be:

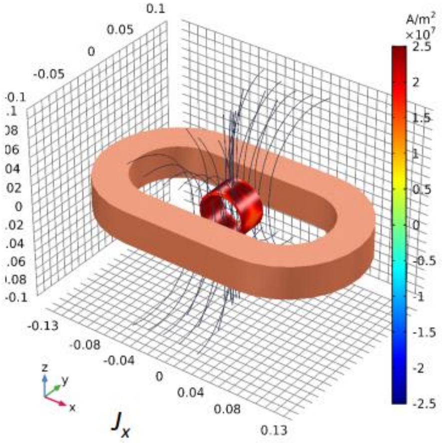
- acceptable for AC losses estimation (overestimation)
- potentially not accurate for field quality analysis

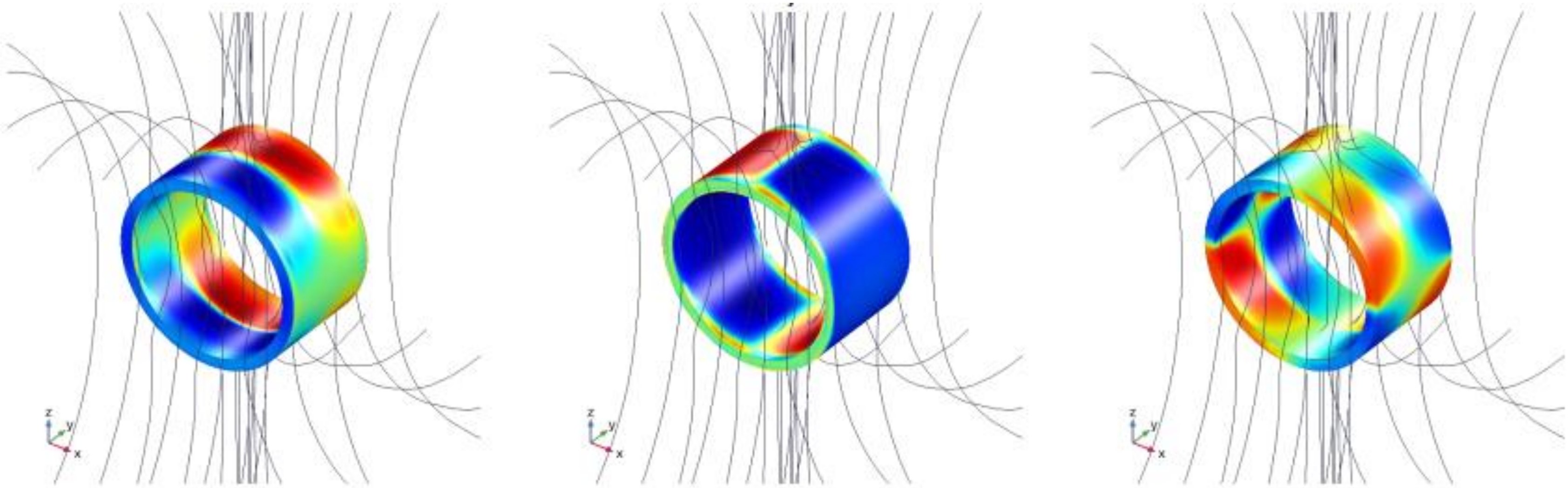
A-formulation method for full 3D FEM computation of the superconductor magnetization

Solovyov Mykola et al. - Institute of Electrical Engineering Slovak Academy of Sciences

Anyway, the results are pretty nice!

- Current density distribution within a BSCCO ring
- External field generated by pancake coil



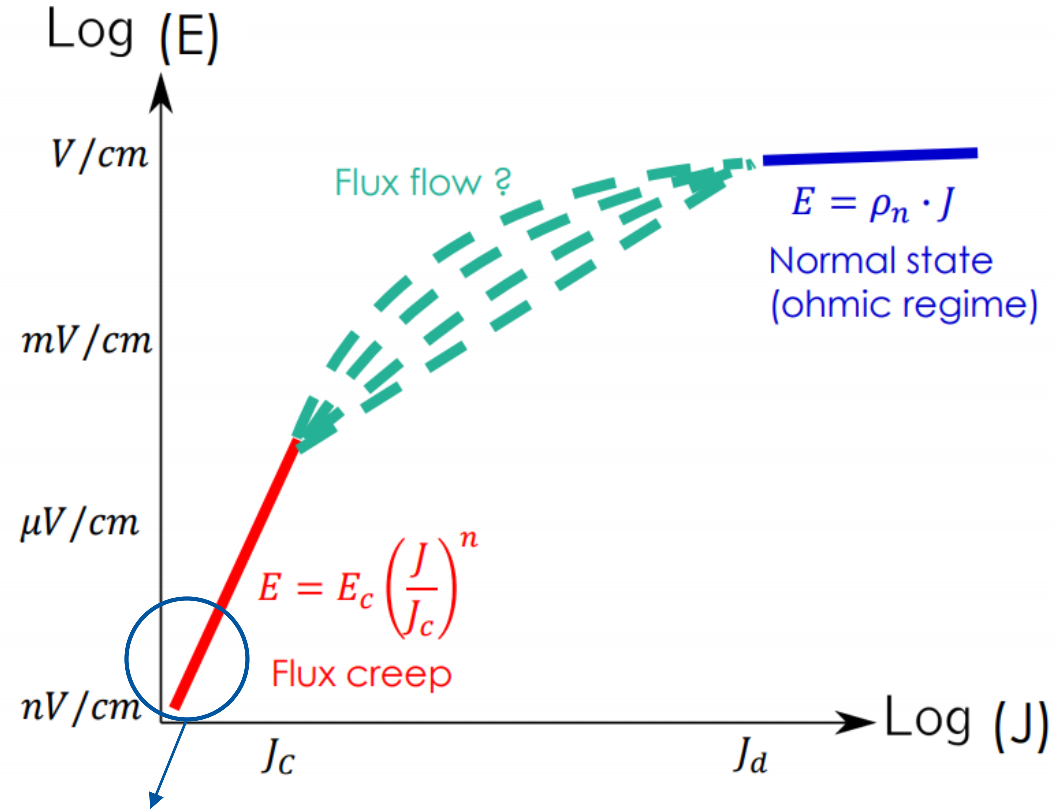


Selected contribution 04

1D and 2D finite-element approaches to extract the resistivity of the superconductor material from pulsed current measurements on HTS commercial tapes

Nicolo Riva et. al. - EPFL

Motivation: a better understanding of E-J curves



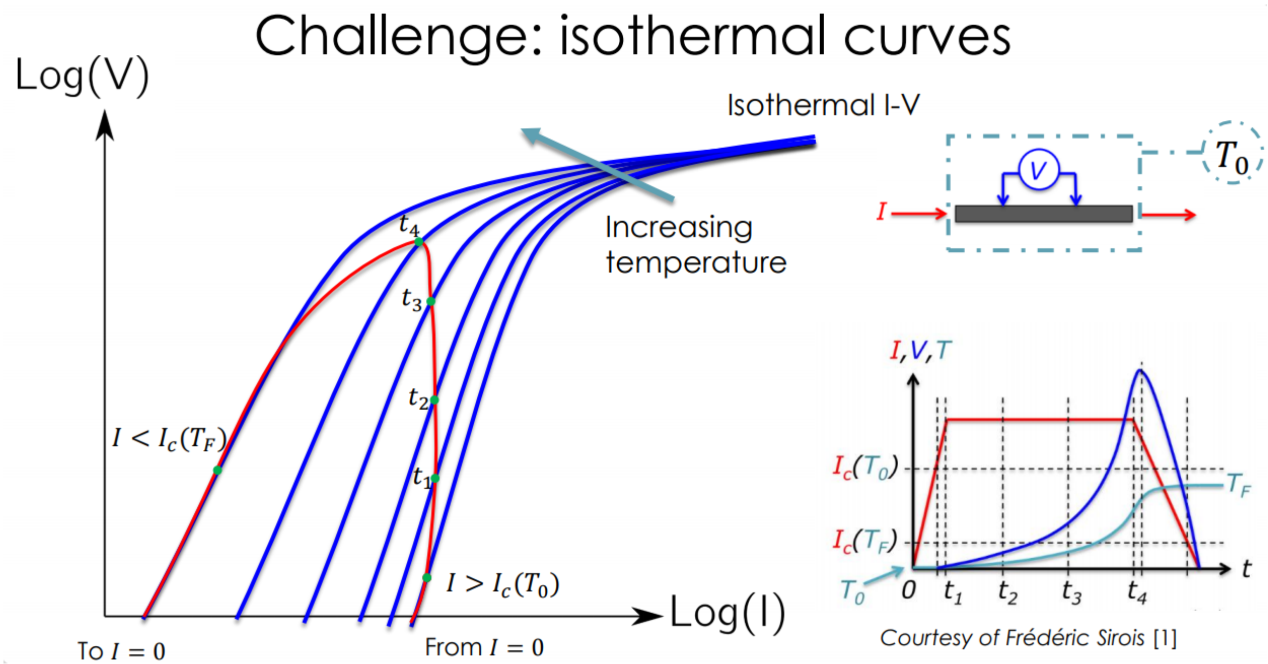
- **E-J** curve of commercial coated conductors is not always **well-known**
- Constitutive laws do not describe the **flux flow** regime
- Better understanding of **E-J** will help **design and modelling** of HTS applications (e.g. Pulsed Field Magnetization [6])

Our magnets typically work here (if they do not quench..)

Joule losses associated to the measurement (we are in flux flow regime!)

A temperature-change influences the properties of the sample

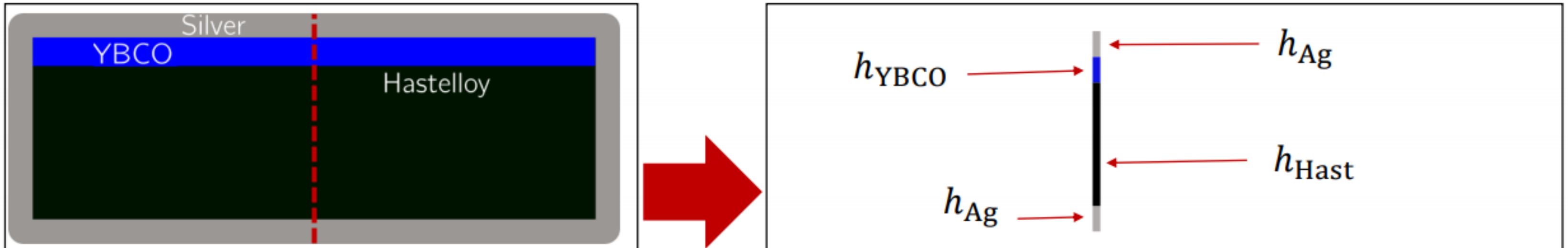
If temperature changes, what are we measuring?



Challenge: isothermal curves

Courtesy of Frédéric Sirois [1]

Model order reduction: 1D modelling



$$\rho_m(T)C_p(T)\frac{\partial T}{\partial t} + \vec{\nabla}\cdot\left(-k(T)\vec{\nabla}T\right) = J\cdot E$$

$$\rho_m(T)C_p(T)\frac{\partial T(x,t)}{\partial t} + \frac{\partial}{\partial x}\left(-k(T)\frac{\partial T(x,t)}{\partial x}\right) = J\cdot E$$

$$\boldsymbol{\rho_{YBCO} = \frac{V_{meas}(t)}{I_{\mathrm{YBCO}}(t)}\cdot\frac{S_{\mathrm{YBCO}}}{L}}$$

Constant resistivity across the superconducting layer.

Flux-flow regime → current already relaxed into the tape (saturation)

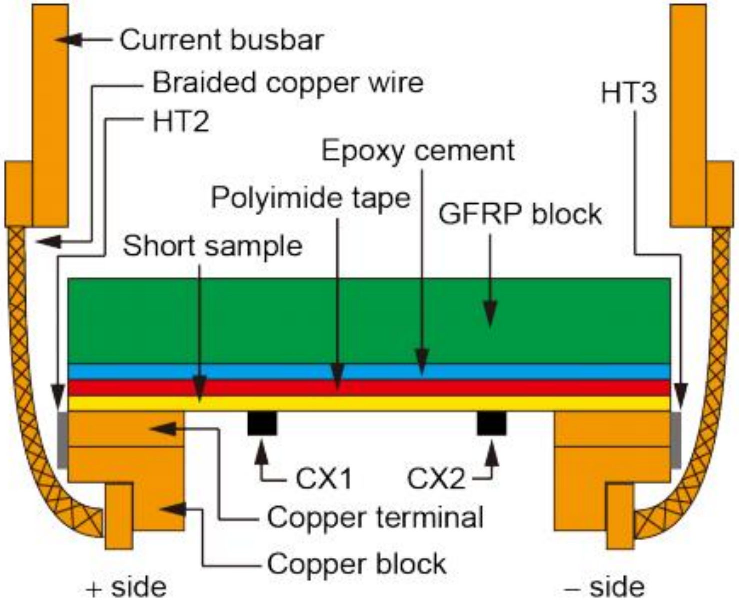
Thus, the 1D approach is valid, but only in the flux flow regime and beyond

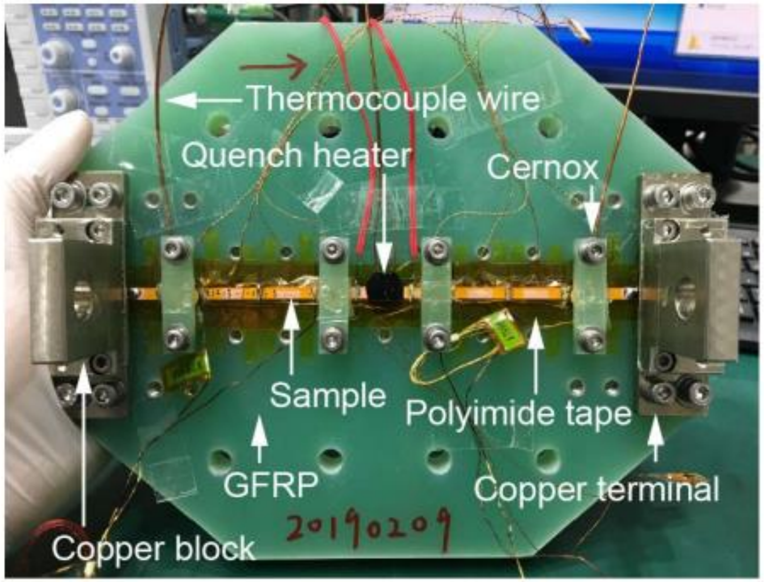
Selected contribution 05

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations

Naoyuki Amemiya et. al. - Kyoto University

Motivation: Feasibility of the classical quench detection and protection of coated-conductor magnets

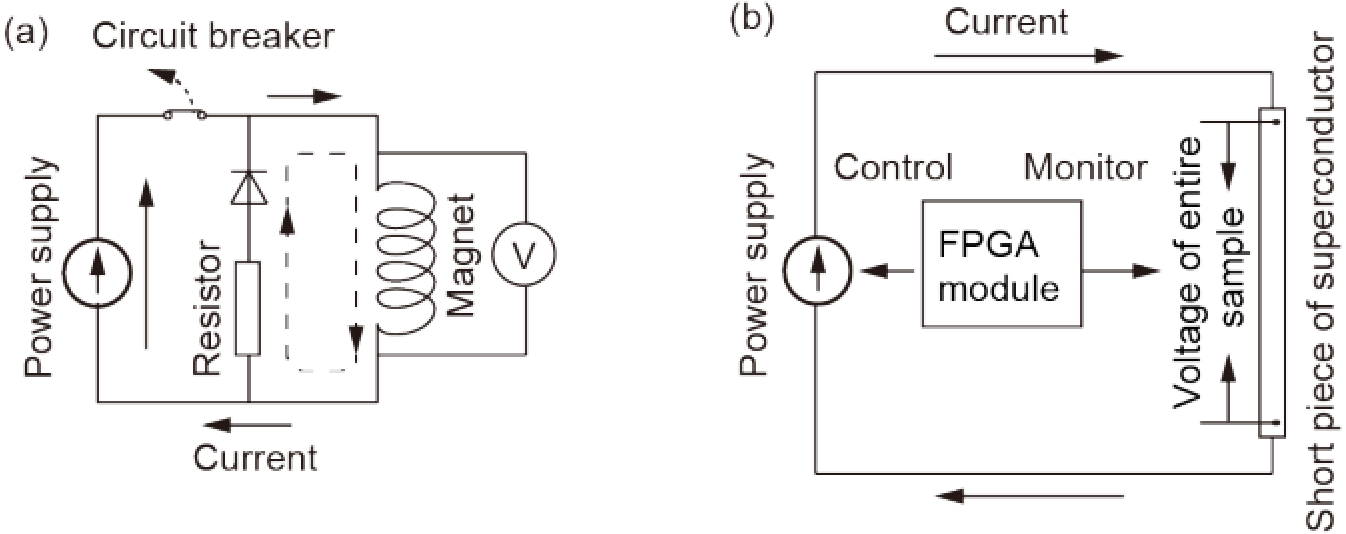




Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations

Naoyuki Amemiya et. al. - Kyoto University

Protection strategy



1 V_{th} is reached (= quench detection in a magnet)

2. Waiting time (= time required for quench detection and activation of circuit breaker),

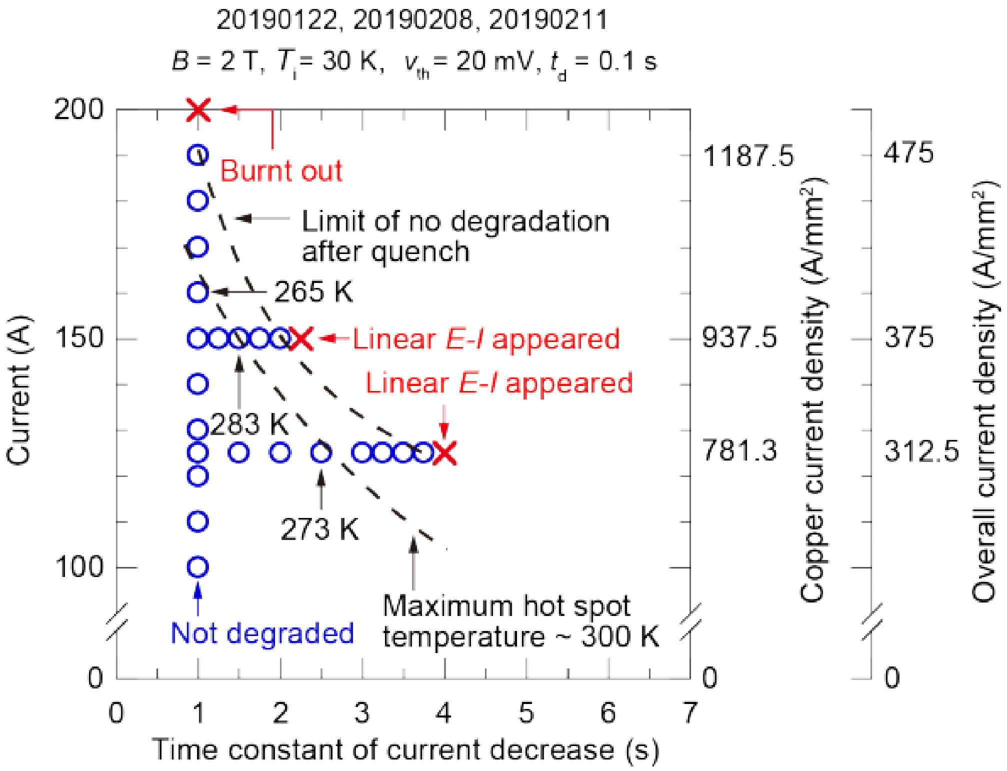
3. Power supply de-energized exponentially (=dump resistor).

Study on conditions for successful quench protections of coils wound with coated conductors by short-sample experiments and quench simulations

Naoyuki Amemiya et. al. - Kyoto University

Results

$V_{th} = 20\ \mathrm{mV}$
$t_d = 100\ \mathrm{ms}$
$i_{max} = 79\%\ i_{crit}$



Individual tapes seem to be easily protectable, even at high currents.

A time constant of 1s seems to be really conservative (PS limit?)

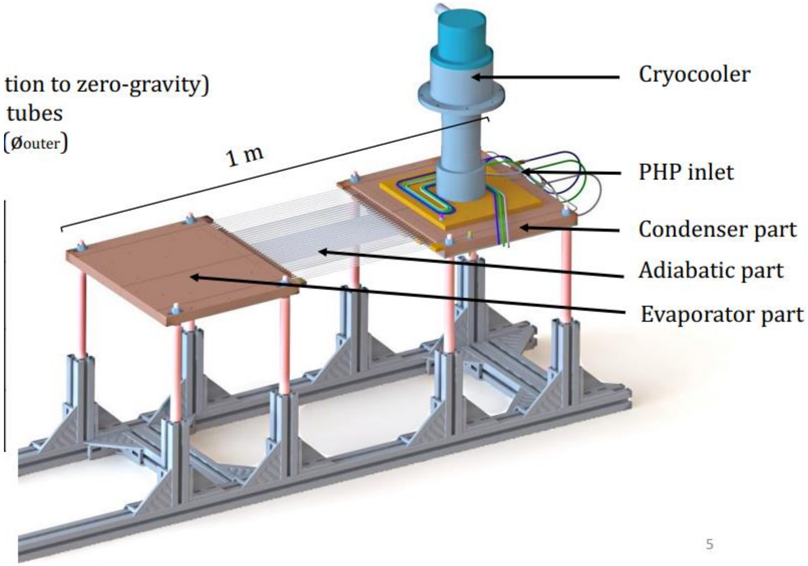
Shorter time constants for the current decay would allow for even higher currents.

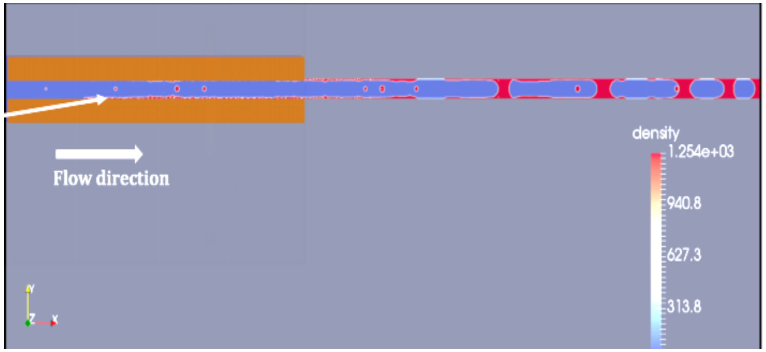
Selected contributions - Miscellanea

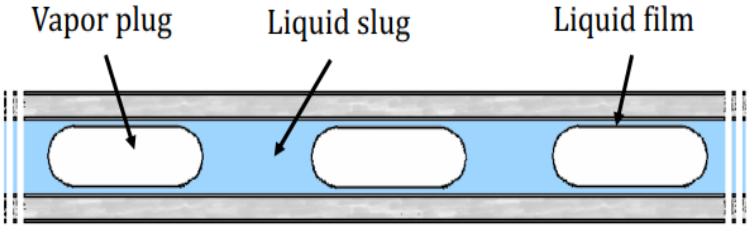
Simulation of a cryogenic capillary tube

Maria Barba et. al. - CEA Saclay

Motivation: Design of Cryogenic Pulsating Heat Pipes applied to SC magnets



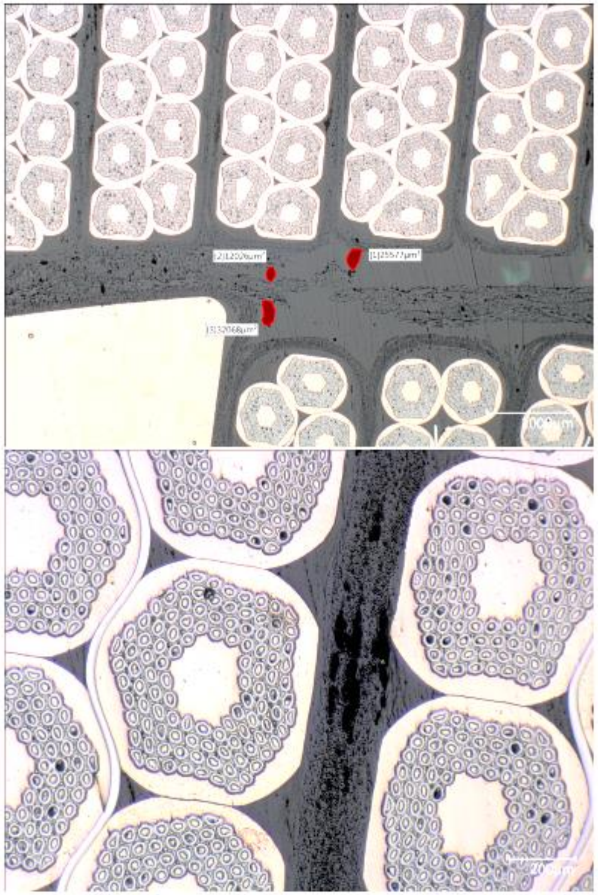


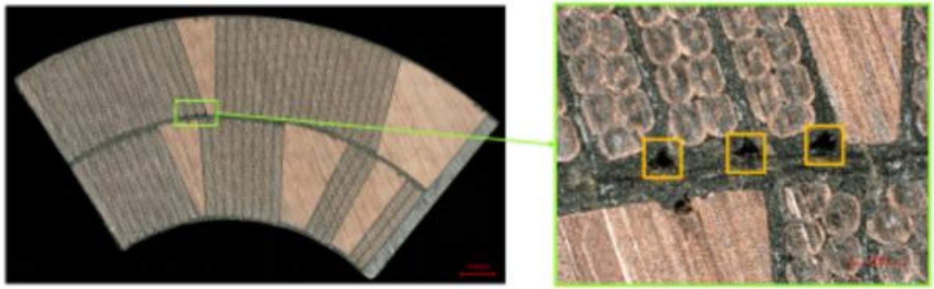


Simulations performed with Pressure-based ANSYS Fluent solver, Volume of Fluid (VOF) method, 2D axisymmetric geometry

0.5 s simulation → more than one week

Motivation: Study of thermal behavior of D11T and MQXF samples





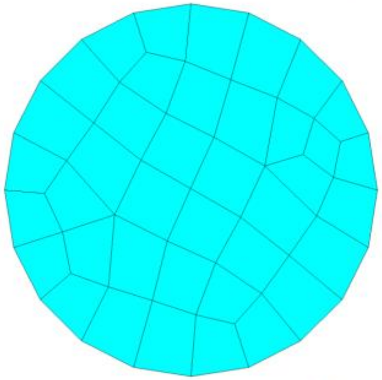
- Experimental campaign to measure thermal behavior of D11T and MQXF samples.
- Creation of a robust multi-region numerical toolkit for modeling heat transfer in complex solid-liquid systems, involving superfluid He,

User Defined Elements in ANSYS for Multiphysics Modeling of Superconducting Devices

Lucas Brouwer et. al. - LBNL

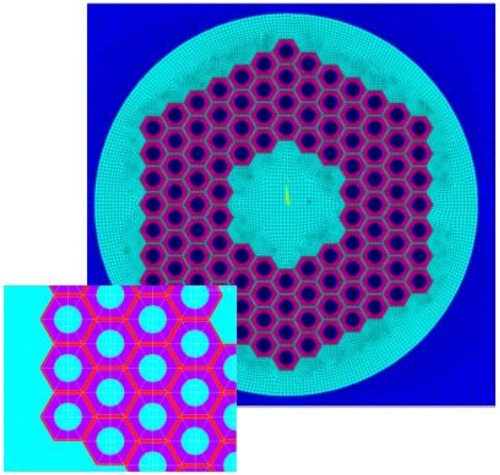
Motivation: add equivalent magnetization, quench, and material property fits to ANSYS, to run transient magneto-thermal simulations

A-curr-emf (stranded)

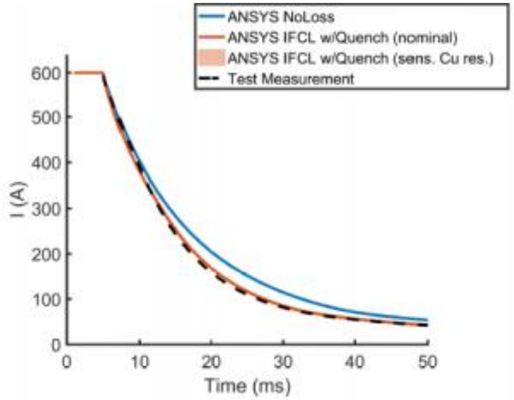


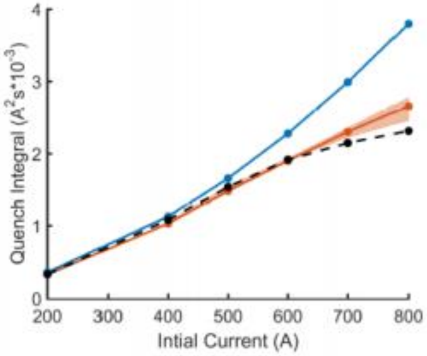
- quench and current sharing is implemented with loss term based on Jc(T,B)
- equivalent magnetization used for coupling currents (a priori current path)
- optional resistive/inductive coupling to external circuit
- use for conductor regions of NbTi, Nb_3Sn magnet models

A-V formulation with E-J power law



- conductive paths resolved by mesh
- current distribution follows from DOF solution
- use for bulk devices, filament magnetization, etc.



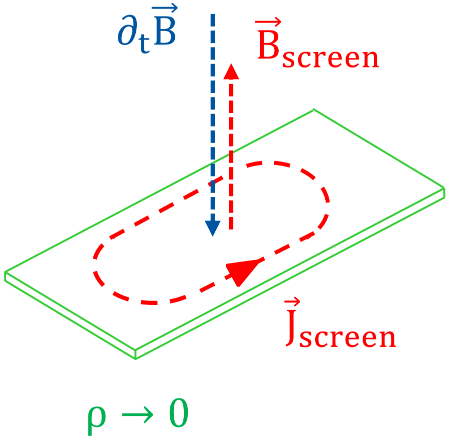


We have a first package with examples and documentation to share with the community (see http://usmdp.lbl.gov/scpack-code/ or contact me at lnbrouwer@lbl.gov)

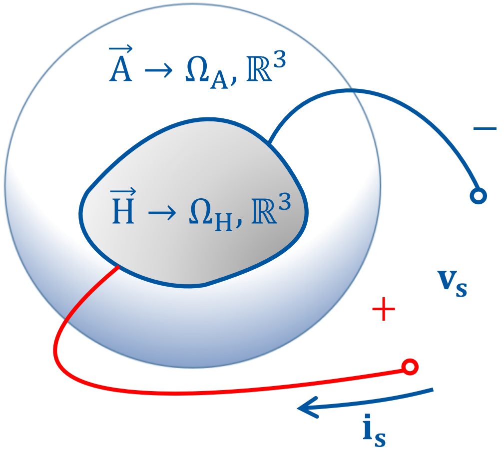
Field Quality Analysis in the HTS Dipole Insert-Magnet Feather M2 with the Finite Element Method

Lorenzo Bortot et. al. - CERN

Motivation: Characterization of screening currents in HTS tapes, coils and magnets



- Persistent magnetization
- Field quality issue, especially at low field
- Joule losses

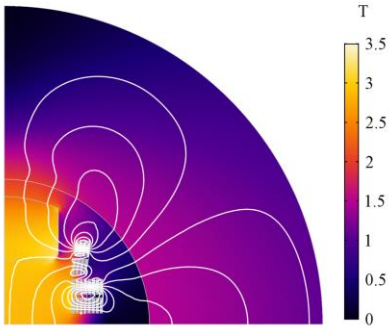


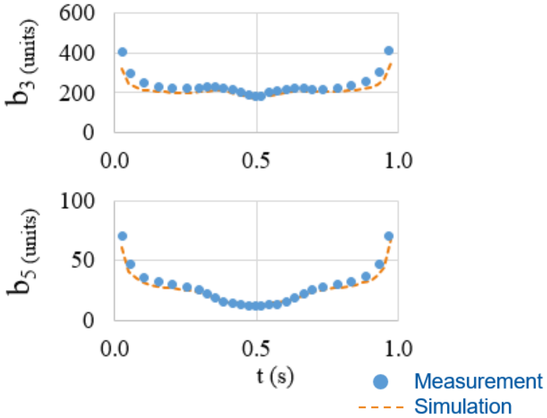
Mixed potentials

Domain decomposition

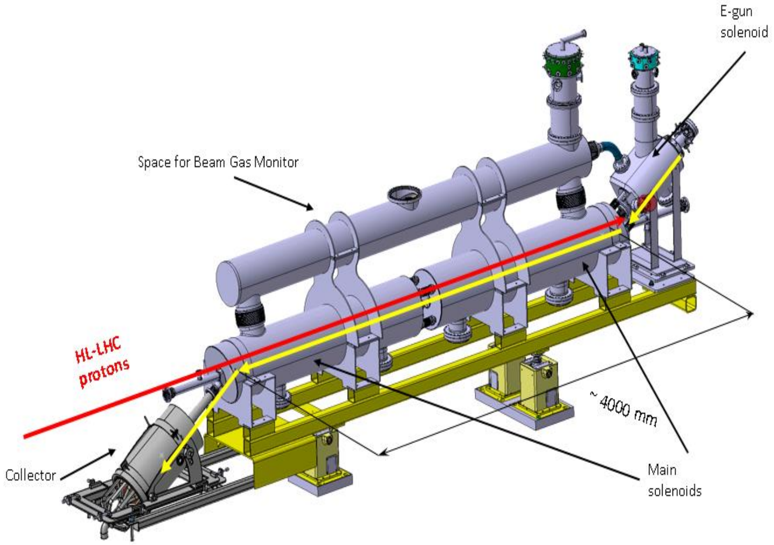
- $\vec{A}$ in Ω_A (air, iron)
  $\sigma \to 0$
- $\vec{H}$ in Ω_H (conductors)
  $\rho \to 0$

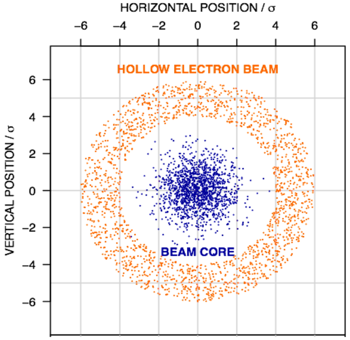
Feather M2 field quality simulations

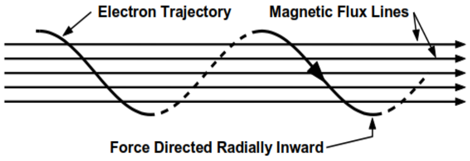




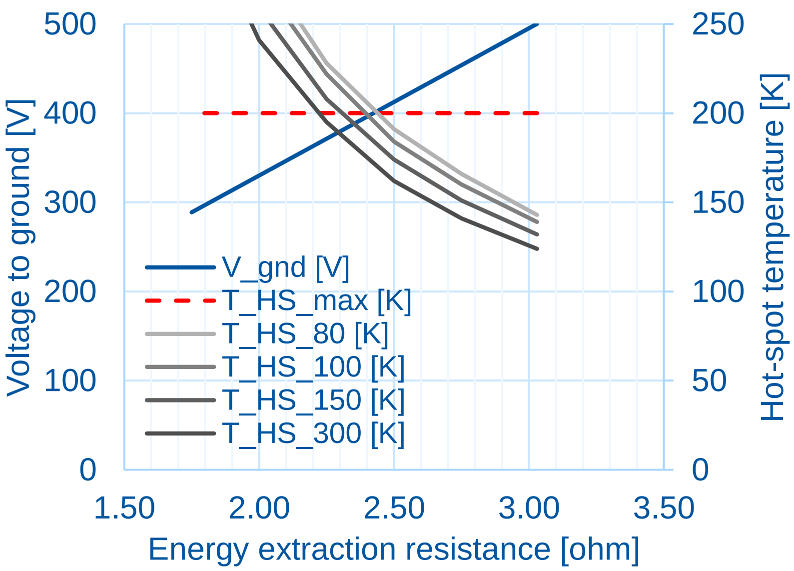
Motivation: Study the protectability of the superconducting circuits







Main Solenoid
Energy Extraction Resistance Sweep



Max T (**200 K**) and V to ground (**500 V**):
Energy extraction R from **2.46** to **3** Ω.

Thank you!