3D quench modeling of 2G HTS using T-A formulation and COMSOL

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Outlines

- Introduction to T-A formulation
- **Quench model based on T-A formula**
- Electromagnetic validation of T-A model
- **Application of 3D T-A quench model on CORC cable**

Introduction: T-A formulation[1]

- Thin shell approximation: the thickness of tape is neglected.
- T-formulation is applied in superconductor domain: current distribution.
- A-formulation is applied in all domain, field distribution.

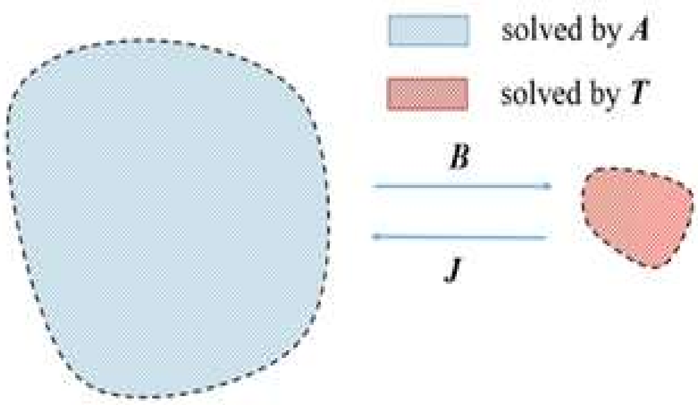
T-formulation
(**PDE**, COMSOL)

$$\mathbf{J} = \nabla \times (T\mathbf{n}) \qquad \nabla \times \boldsymbol{E} = \frac{\partial B}{\partial t}$$

$$\mathbf{E}(\mathbf{J}) = E_0 \left(\frac{|\mathbf{J}|}{J_c(\mathbf{B}, T_h)} \right)^n \frac{\mathbf{J}}{J_c(\mathbf{B}, T_h)}$$

A-formulation
(**mf**, COMSOL)

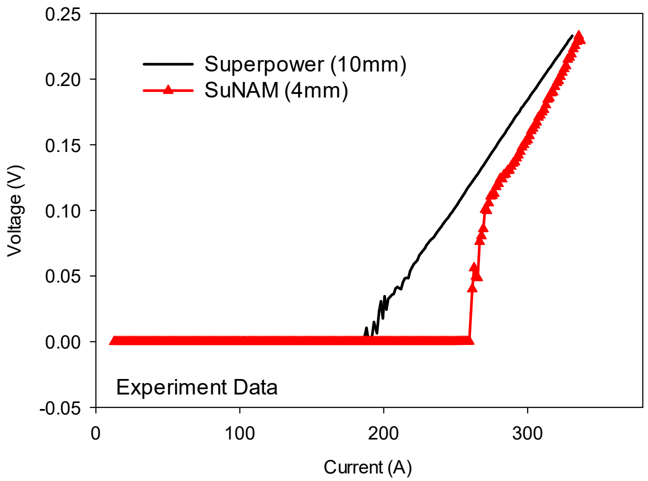
$$\nabla \times \nabla \times \boldsymbol{A} = \boldsymbol{\mu_0}\, \boldsymbol{J}$$



[1] 2017 Supercond. Sci. Technol. 30 024005

Thermal coupling

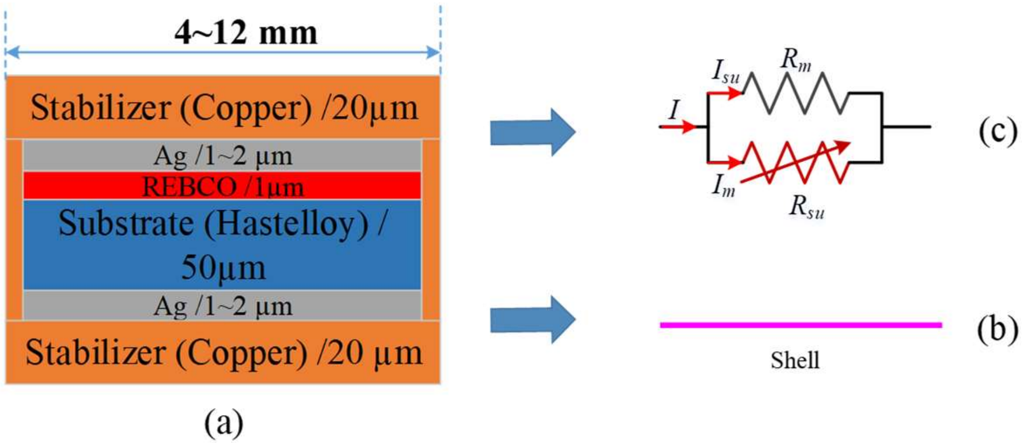
- Coupling **thermal model on shell to T-A formulation model**

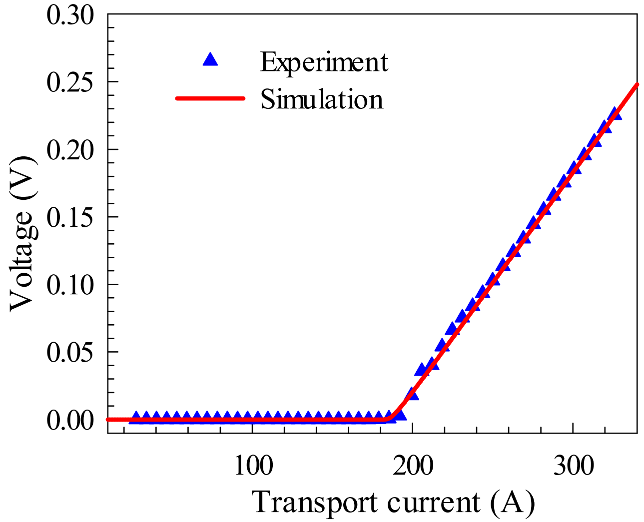


✓ **Model approximation 1**: the coated conductor is also equivalent to thin shell in thermal model.

✓ **Model approximation 2**: the 2G HTS tape is equivalent to two parallel resistances: superconductors and metals.

✓ **Overcurrent U-I behavior** of 2G HTS tape: this approximated model matches well with tapes with thick Cu stabilizers, which need more tests.





T-A quench model

- **Governing equations**:

T-A model

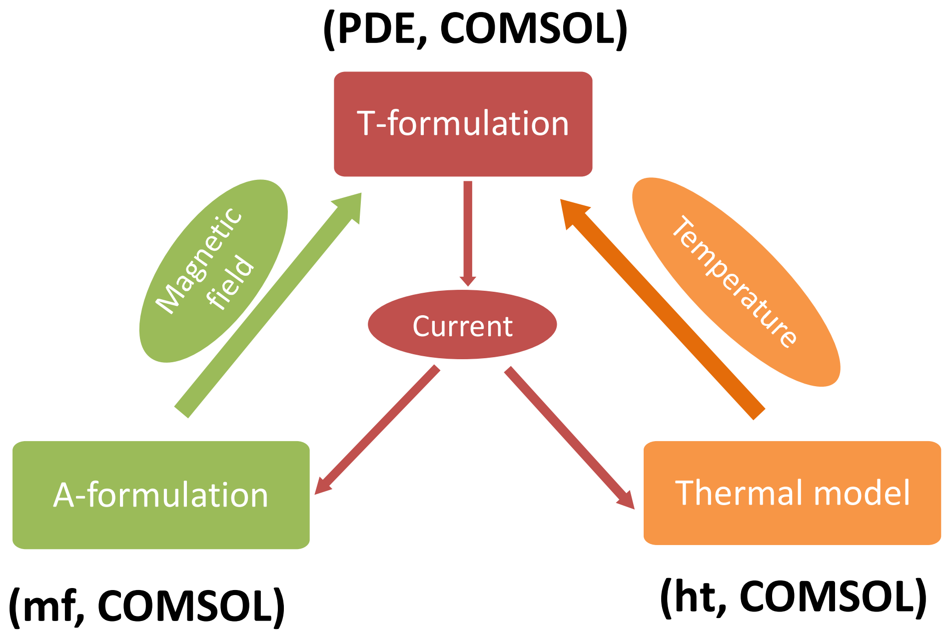
$$\nabla \times \boldsymbol{E}(\nabla \times \boldsymbol{T}) = \frac{\partial B}{\partial t}$$
$$\nabla \times \nabla \times \boldsymbol{A} = \boldsymbol{\mu_0 J}$$

$$J_{cT}(T_h) = \begin{cases} \left(\dfrac{T_c - T_h}{T_c - T_o} \right)^{\beta} & if \;\; T_h < T_c \\ 0 & if \;\; T_h \geq T_c \end{cases}$$

$$\mathbf{J}_c(\mathbf{B}) = \frac{I_{co}}{S_c} \cdot J_{cT}(T_k) \cdot J_{cB}(B_{par}, B_{per})$$

Thermal model on shell

$$\begin{cases} \rho C_p \dfrac{\partial T_h}{\partial t} - k\nabla_t \cdot (\nabla_t T_h) = \dfrac{Q}{d_s} \\ \mathbf{n} \cdot (-k\nabla T_h) = h(T_h - T_e) \end{cases}$$

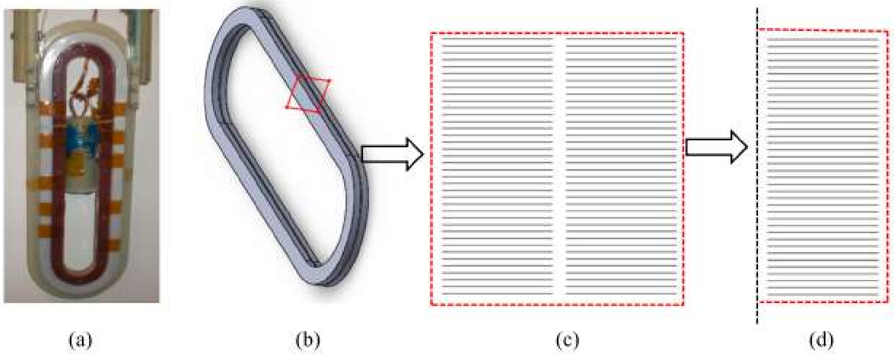


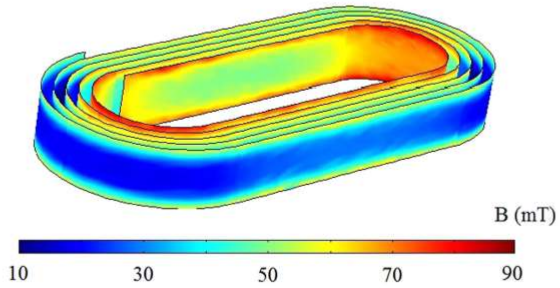
T-A quench model

Advantages:

1. Thin strip approximation reduce dimension:

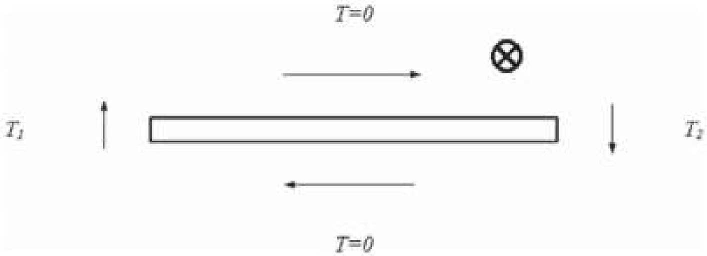
   Smaller degree of freedom, faster computation





2. Solvable by commercial finite element software, e.g. **Comsol**:

   Easy to apply stimulations: current and magnetic field



$$I = (T_1 - T_2) \cdot d,$$

[2] 2017 Supercond. Sci. Technol. 30 024005

Model validation(electromagnetic)

- **T-A compares to *H*-formulation : Good agreement [3].**

Pancake coil with 2000 turns, AC transport current.

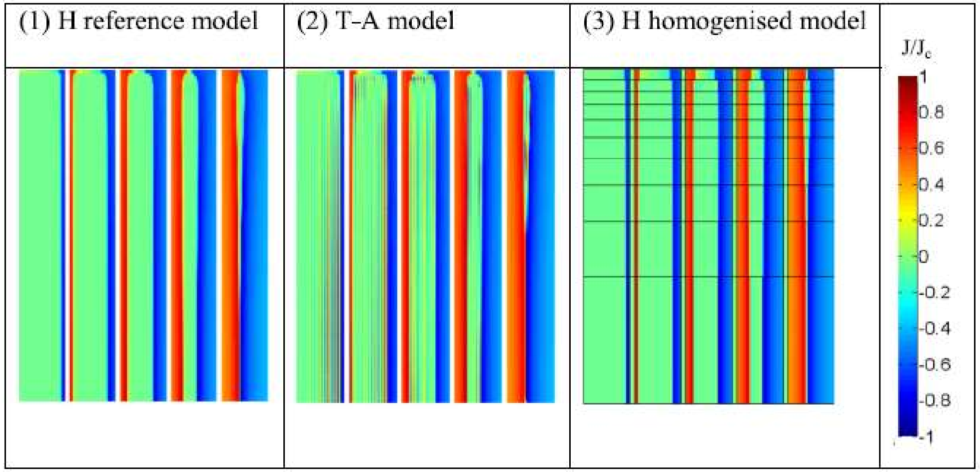
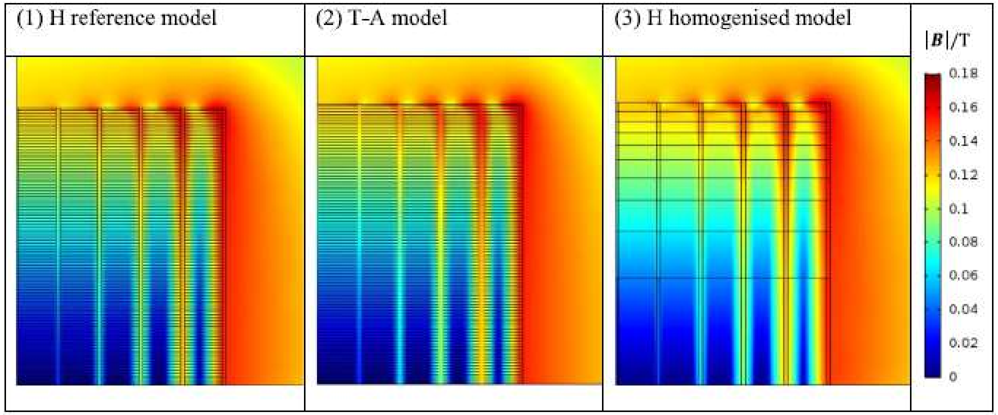


FIG. 14. Simulation results of current density distribution of the 2000 turns coils at a transport current of 11 A when t = 0.015 s. For simplification reason, only 1/4 part of the coil is simulated here based on coil symmetry.



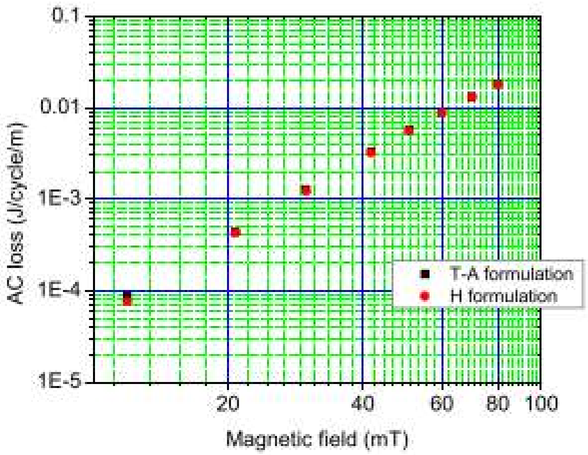


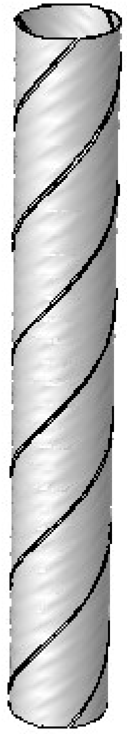
FIG. 8. AC loss comparison of the superconducting stack under different perpendicular magnetic fields.

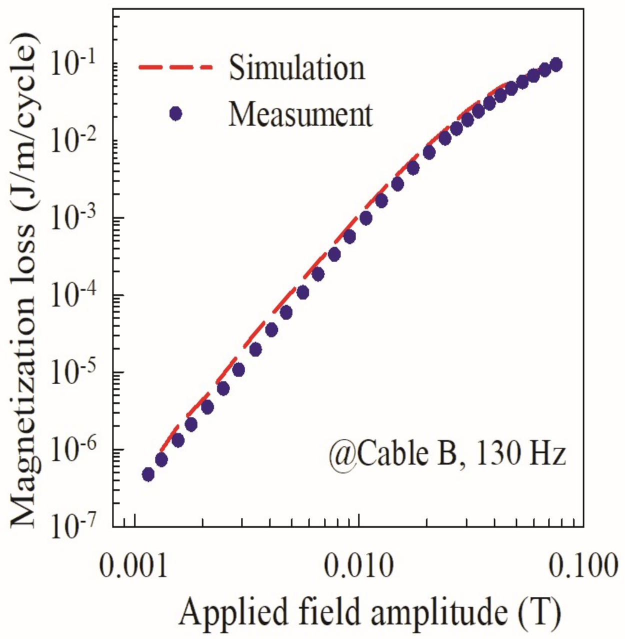
[3]Journal of Applied Physics 122 (4), 043903

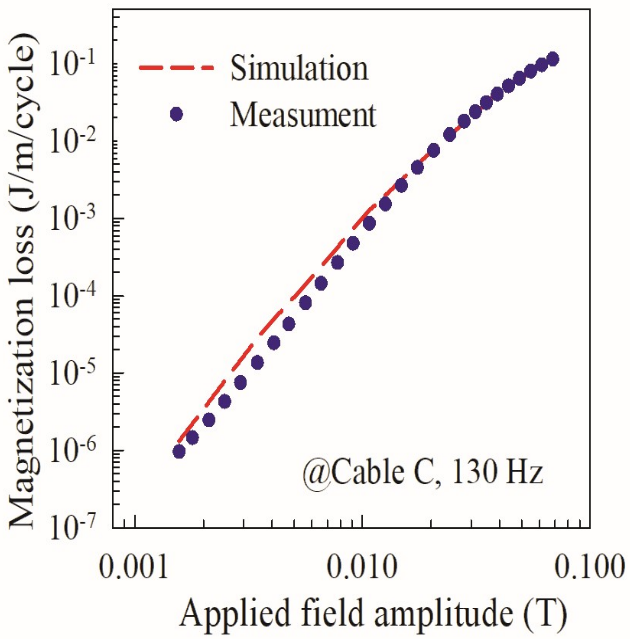
Model validation(electromagnetic)

- 3D T-A model compares to measurement:

  Magnetization loss of CORC cable induced by external magnetic field.
  two layers, REBCO conductor, frequency of external field 130 Hz*

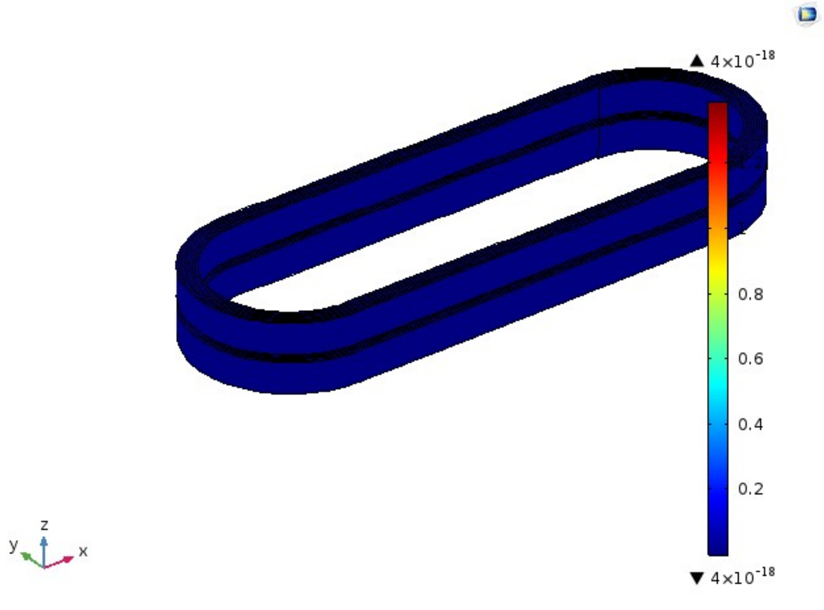


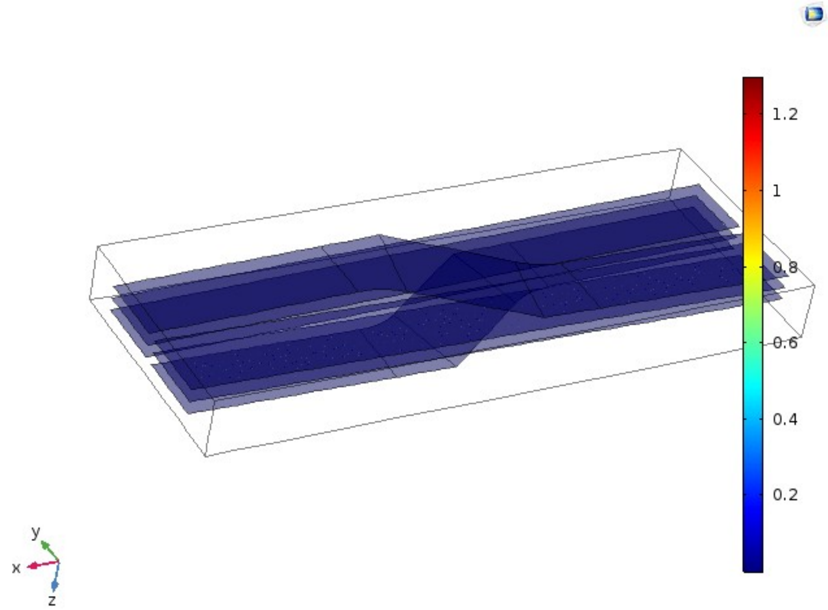


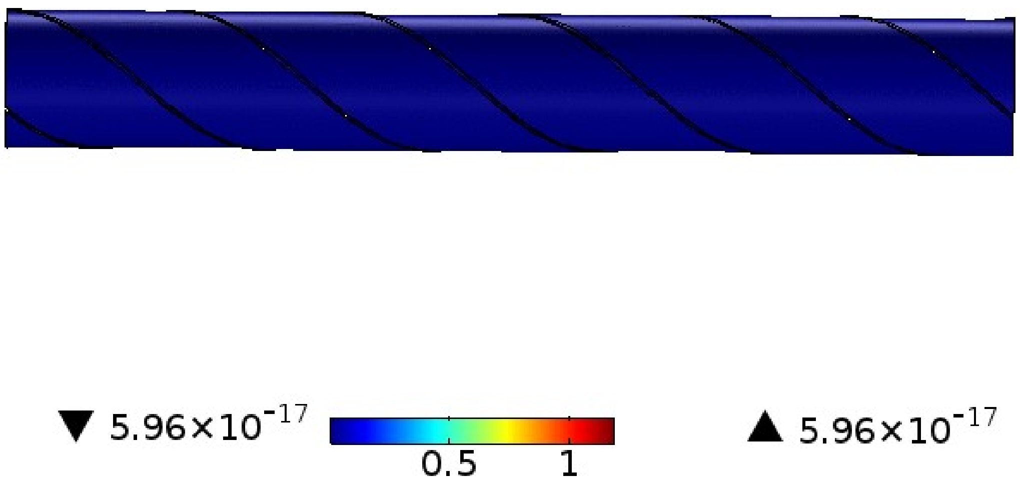


* Measurement data is provided by Dr Grilli, KIT.

3D T-A formula application



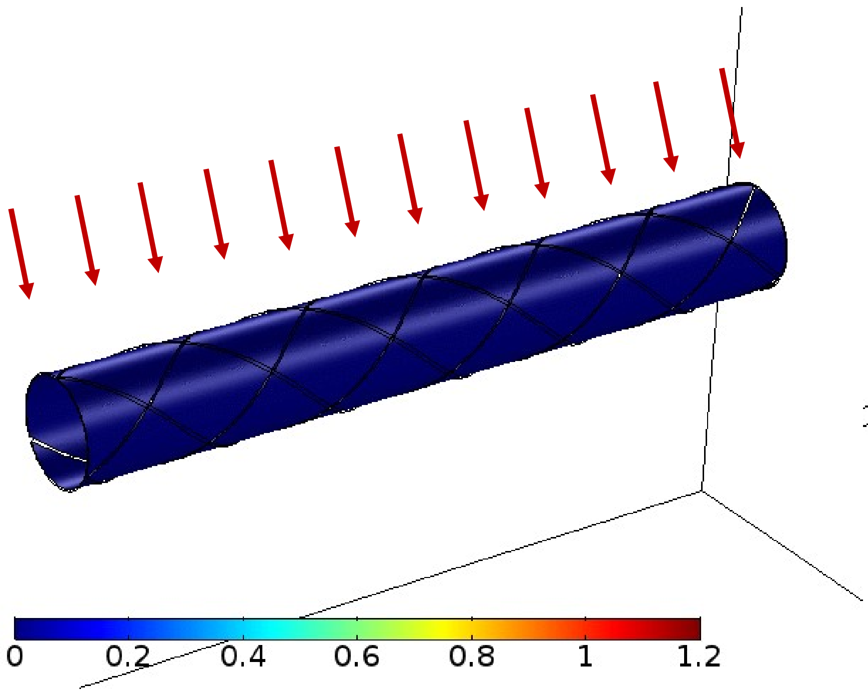




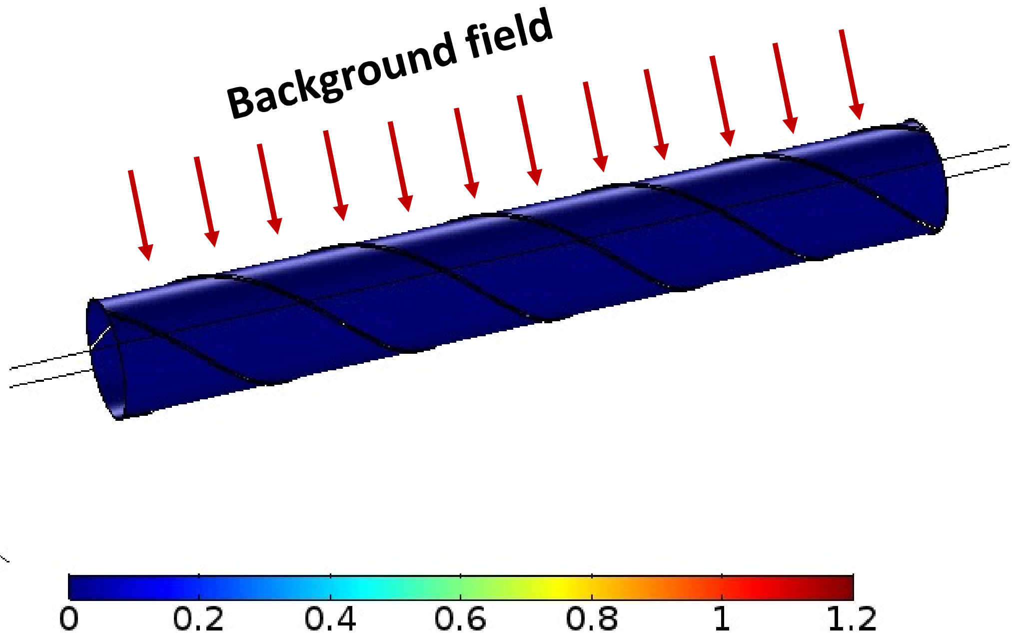
3D T-A formula application

CORC cable with two layer in background field 130 Hz, 20.5 mT: inner layer

Opposite winding direction



Same winding direction

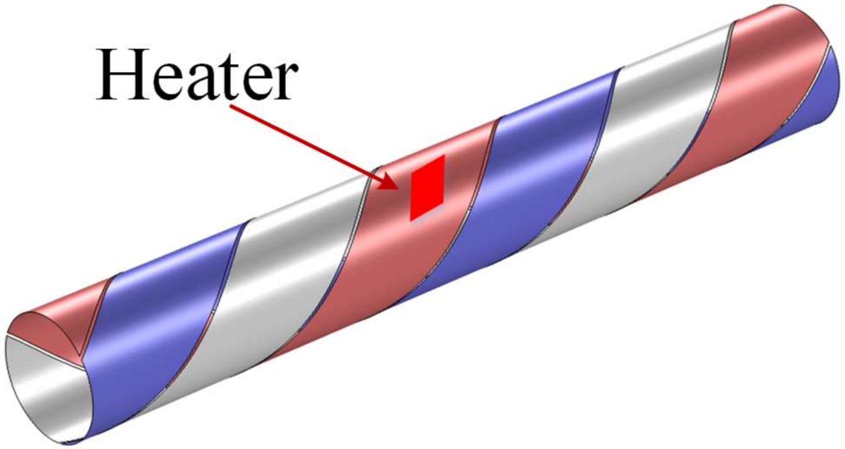


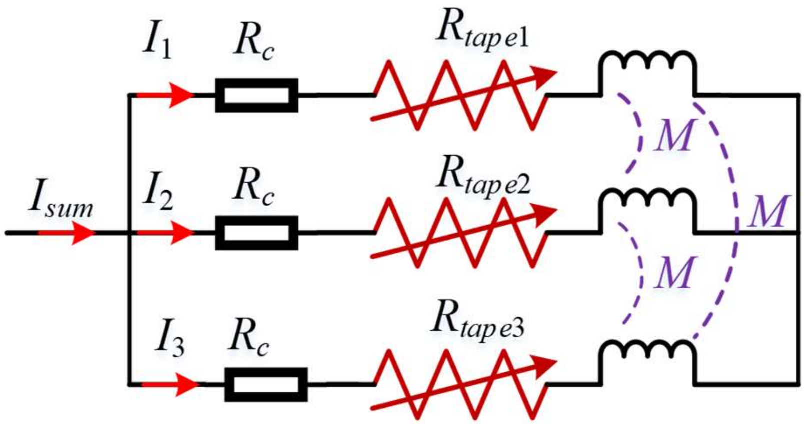
Normalized current density

3D T-A quench model for CORC cable

- **Coupled with a circuit model, which is to calculate the current redistribution among tapes.**
- **Hot-spot induced quench is studied using the model**

$$\begin{cases} u_k = I_k(R_c + R_{tape,k}) + \sum_{n=1}^{3} \frac{dI_n}{dt} M_{k,n} \\ u_1 = u_2 = u_3 \\ I_{sum} = I_1 + I_2 + I_3 \\ k = 1, 2, 3 \end{cases}$$





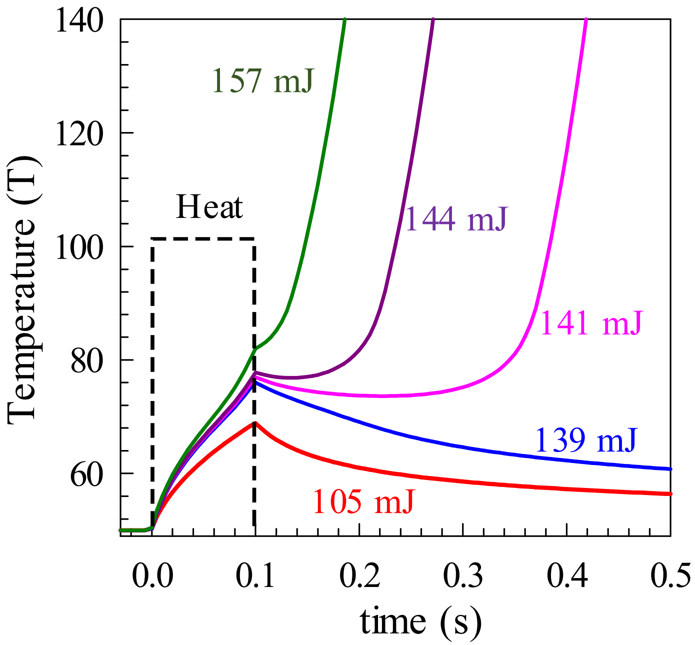
Circuit model for CORC cable

3D T-A quench model for CORC cable

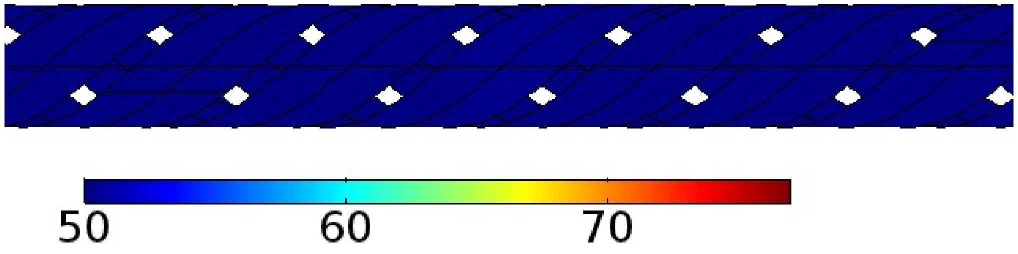
- **Hot spot and recovery.**
- **Not current redistribution among turns.**

$$Rc = \infty$$

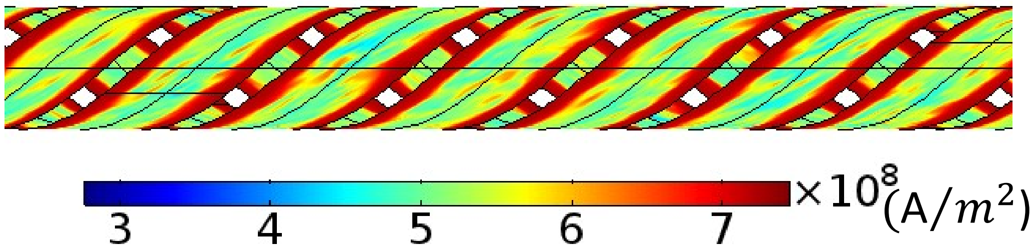
- external heat disturbance 139 mJ, transport current 200A



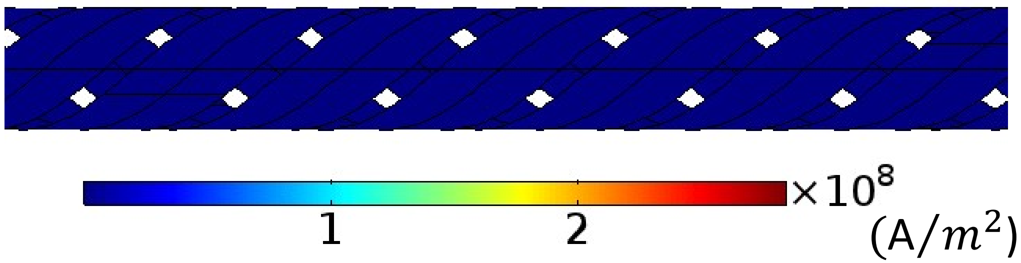
Temperature (K)



Current density in superconducting layer



Current density in metallic layers

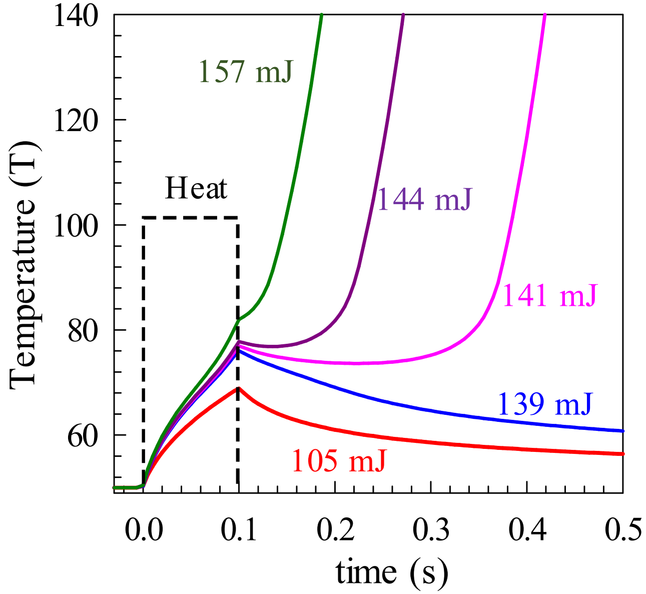


3D T-A quench model for CORC cable

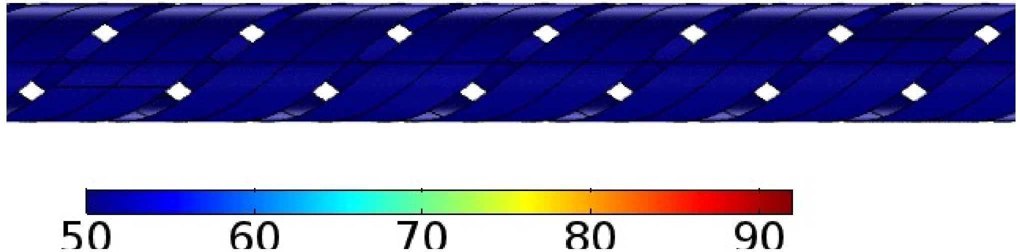
- **Quench induced by hot spot.**
- **Not current redistribution among turns.**

$$Rc = \infty$$

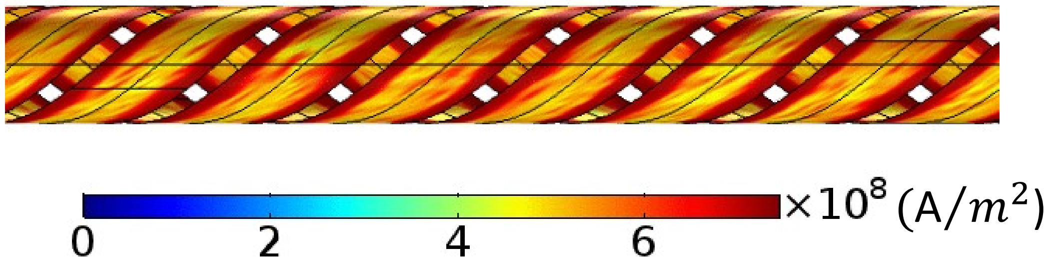
- external heat disturbance 144 mJ, transport current 200A



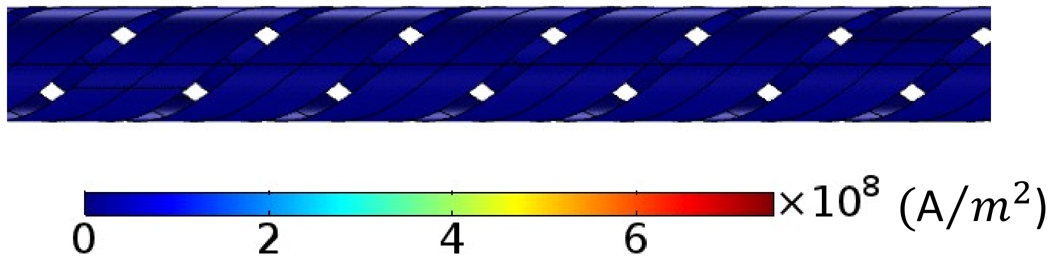
Temperature (K)



Current density in superconducting layer

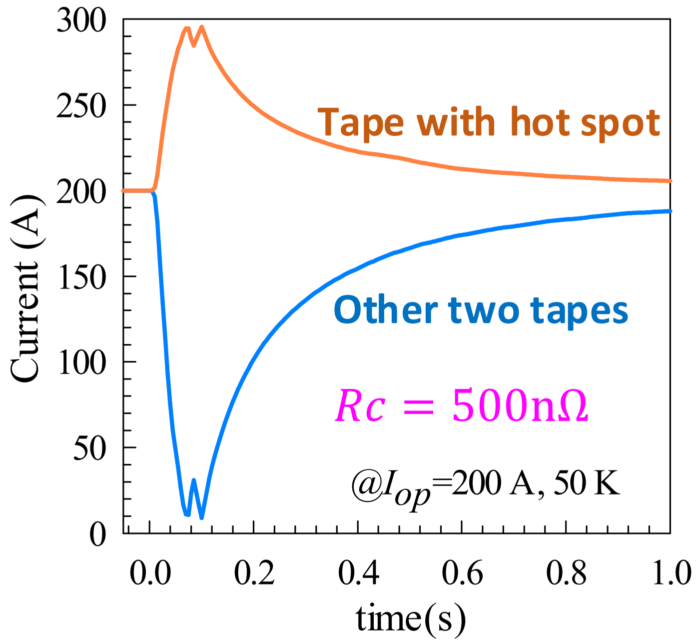


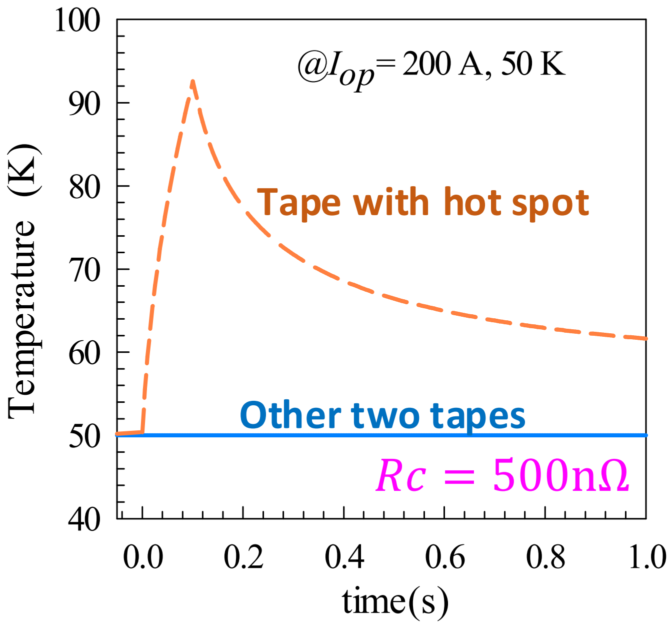
Current density in metallic layers

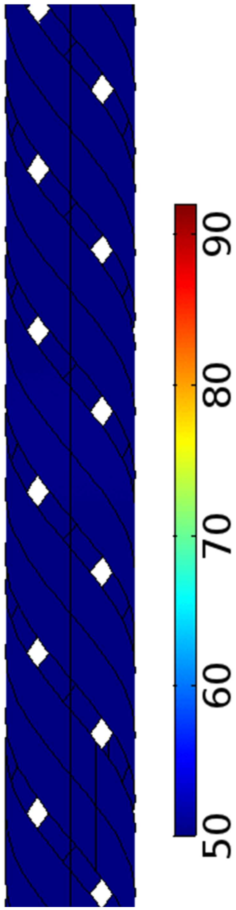


3D T-A quench model for CORC cable

- **Hot spot and recovery.**
- **Current redistributed among turns through terminal contact resistance.** 100~1000 nΩ [3]
- NO quench happens with two times external heat disturbance 280 mJ. Thermal stability is enhanced significantly.



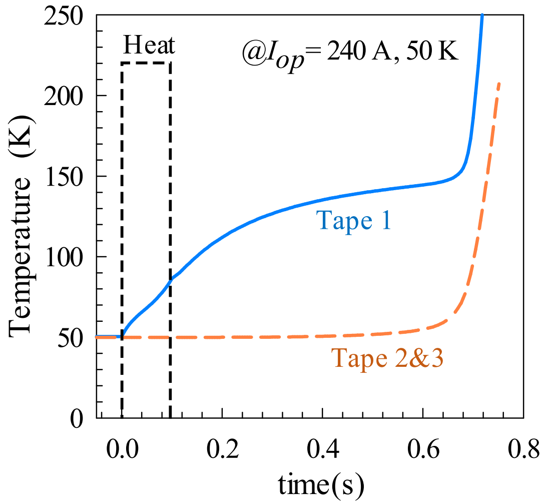


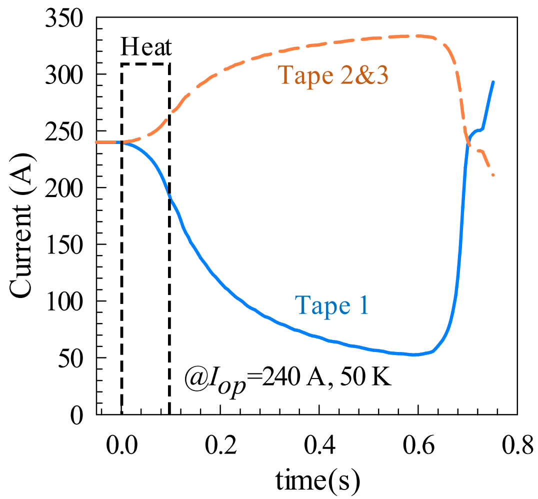


3. **G P Willering** *et al* 2015 *Supercond. Sci. Technol.* **28** 035001

3D T-A quench model for CORC cable

- **Quench induced by hot spot.**
  - Increasing the terminal resistance to
    $Rc = 200\ \mathrm{u\Omega}$
  - Hot spot in one tape can induce a overcurrent quench on the other two tapes through current redistribution among individual tapes.
  - **Lower terminal resistance leads to higher thermal stability during hot spot quench.**





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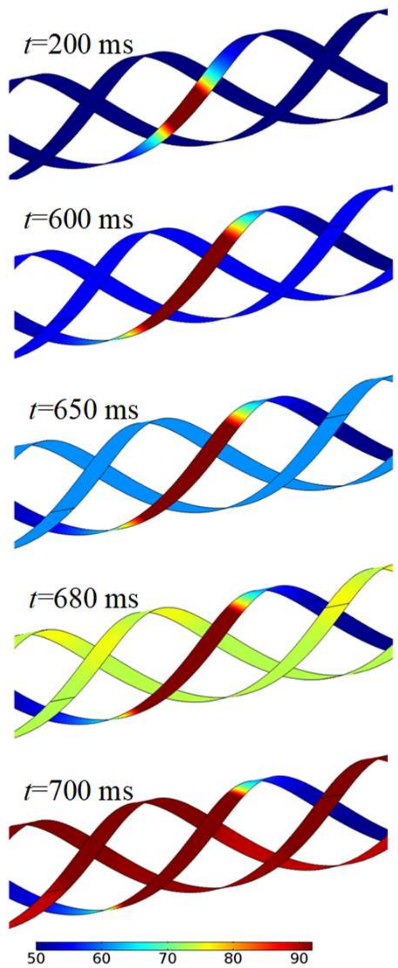

3D T-A Quench model applications:

- Extremely efficient in 3D calculation for current, AC losses, temperature
  especially for a 3D geometry.
  - ✓ Quench behaviour
  - ✓ Current redistribution of YBCO cables via terminals
  - ✓ Easily add cooling condition and other heat sources.
  - ✓ Easily extend to Roebel cable and insulated coils

- Issues needs to be solved:
  - ✓ Current redistribution through tape-to-tape contacts.

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Thanks very much for attention

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