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LNCMI

2D axisymmetric modeling of the HTS Insert Nougat in a background magnetic field generated by resistive magnet

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*In the frame of the **European project EMFL**:*

- *new simulation activity on superconductor magnets in the **LNCMI** to accompany the development of Metal-as-Insulation HTS insert.*
- *using **Feel++**, an open source finite element library and developing specific tools in collaboration with **IRMA** University of Strasbourg.*

Feel++ : Finite Element Embedded Library

https://docs.feelpp.org

- Open source C++ library
- Multi-physics toolboxes
- Seamless parallel computing

Toolbox Coefficient Form PDEs

PDE represented by its coefficient from a general form equation:

$$d\frac{\partial u}{\partial t} + \nabla \cdot (-c\nabla u - \alpha u + \gamma) + \beta \cdot \nabla u + au = f \quad \text{in } \Omega$$

Feelpp HTS

Documentation of HTS models from htsmodelling.com reproduced with Feelpp CFPDES

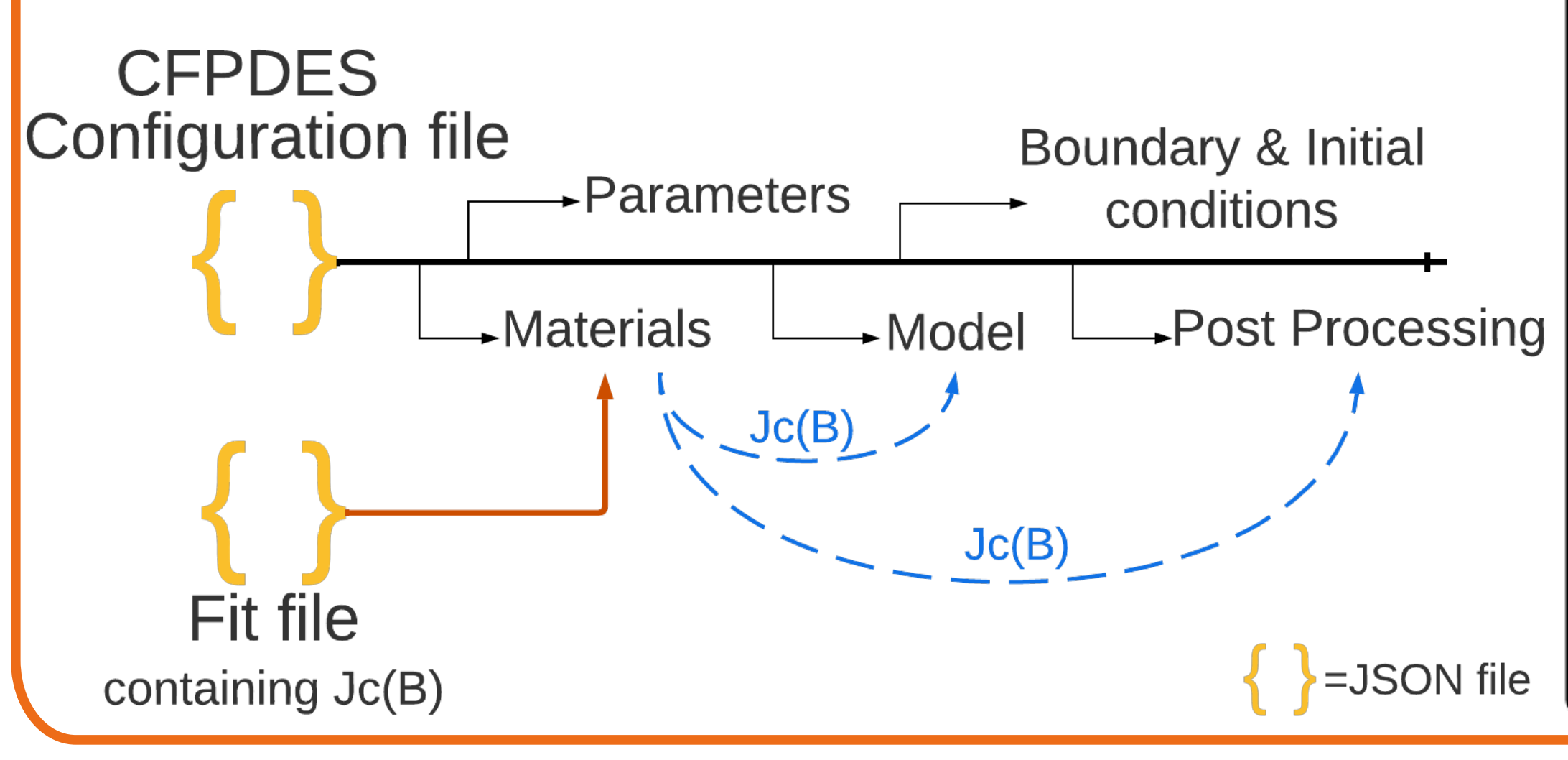
- **HTS bulk cylinder** model with an external field (2D, Axi)
- **HTS wire** model with transported current (2D)
- **Roebel cables** model (estimate critical current, 2D)
- **HTS tapes** model with transported current (2D, Axi)

Exchangeable critical current density fits

HTS tapes → anisotropic → critical current density depends on

- magnitude of **B**
- orientation of **B**

⇒ Mathematical fit models for $J_c(\mathbf{B})$



{ } Example fit file : hilton_fit.json

```
{
    "k0": 8870.0,
    "k1": 18500.0,
    "alpha0": 1.3,
    "alpha1": 0.809,
    "beta0": 13.8,
    "beta1": 13.8,
    "gama1": 0,
    "c1": 2.15,
    "normB": "sqrt((-magnetic_grad_Atheta_rt_1)^2
      +(magnetic_grad_Atheta_rt_0+magnetic_Atheta_rt/x)^2
      ):magnetic_grad_Atheta_rt_0
      :magnetic_grad_Atheta_rt_1:magnetic_Atheta_rt:x",
    "theta": "atan2((magnetic_grad_Atheta_rt_0
      +magnetic_Atheta_rt/x),(-magnetic_grad_Atheta_rt_1
      )):magnetic_grad_Atheta_rt_0
      :magnetic_grad_Atheta_rt_1:magnetic_Atheta_rt:x",
    "omega1": "c1*( normB + (1.0/c1)^(5/3) )^(3/5):c1
      :normB",
    "IcB": "k0/(normB+beta0)^alpha0 + k1/(normB+beta1
      )^alpha1 *( omega1^2 * cos(theta-gama1)^2 + sin
      (theta-gama1)^2 )^(-0.5):normB:theta:k0:k1:alpha0
      :alpha1:beta0:beta1:omega1:gama1",
    "JcB": "IcB/t_tape/h_tape:IcB:t_tape:h_tape",
    "j_th": "JcB*p*(t_tape/t_cell):t_tape:t_cell:JcB:p"
}
```

Models & Formulations for HTS materials

FEM models based on different formulations of Maxwell's equations:
→ the **A-V** formulation, the **H** formulation or more recently, the **T-A** formulation.

The electrical resistivity of the HTS material is defined by the **E-J power law**:

$$\mathbf{E} = \rho_{\text{HTS}}\mathbf{J} = \frac{E_c}{J_c(\mathbf{B})}\left|\frac{J}{J_c(\mathbf{B})}\right|^{n-1}\mathbf{J}$$

T-A Formulation

B, the magnetic flux density (T)

$$\mathbf{B} = \nabla \times \mathbf{A}$$

J, the current density (A/m²)

$$\mathbf{J} = \nabla \times \mathbf{T}$$

Main assumption: thin superconducting layer of HTS tapes can be modeled as 1D elements.

Formulation:

$$\nabla \times \nabla \times \mathbf{A} = \mu\mathbf{J}$$

$$\nabla \times \rho\nabla \times \mathbf{T} = -\frac{\partial \mathbf{B}}{\partial t}$$

Imposing the transport current:

The transport current can be written as Dirichlet boundary conditions for **T**

$$\mathbf{I} = \int_S \mathbf{J}\,dS = \int_S \nabla \times \mathbf{T}\,dS = \oint_{\partial S} \mathbf{T}\,dl$$

$$\mathbf{I} = (\mathbf{T}_1 - \mathbf{T}_2)\delta$$

with **T1** and **T2** the potentials at the extremities of the 1D layer

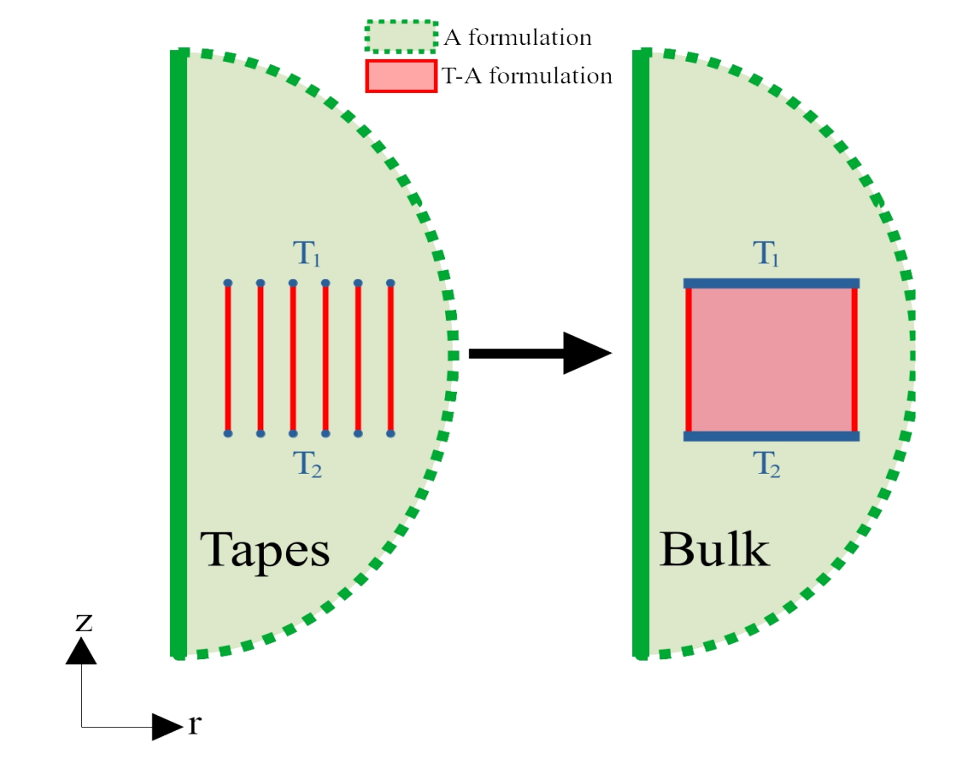
Axisymmetric coordinates

Formulation in cylindrical coordinates *(r,z)*:

$$\begin{cases} -\nabla^2\mathbf{A}_\theta + \frac{1}{r^2}\mathbf{A}_\theta & = \mu\frac{\partial \mathbf{T}_r}{\partial z} \\ -\begin{pmatrix} 0 & 0 \\ 0 & \rho \end{pmatrix}\nabla^2\mathbf{T}_r & = \frac{\partial(\partial_z \mathbf{A}_\theta)}{\partial t} \end{cases}$$

$$\text{with } \nabla^2 = \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right) + \frac{\partial^2}{\partial z^2}$$

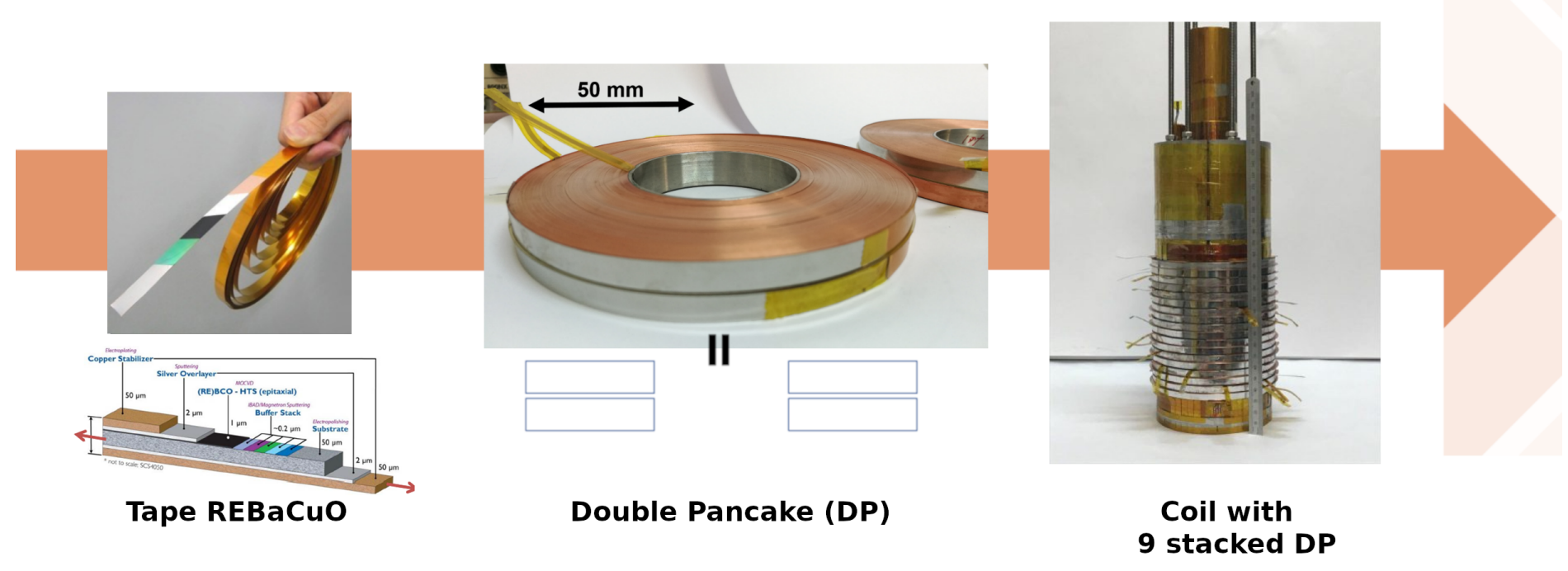
Homogeneous method



Simplification of the geometry from 1D tapes to 2D anisotropic bulk.

Nougat HTS Insert

Geometry of the Insert



Tape REBaCuO

Double Pancake (DP)

Coil with
9 stacked DP

Parameters	Value
Double Pancakes	9
Turns per Pancake	290
HTS Tape width	6 mm
HTS Tape thickness	75 μm
MI thickness	30 μm
Winding inner diameter	50 mm
Winding outer diameter	109.4 mm

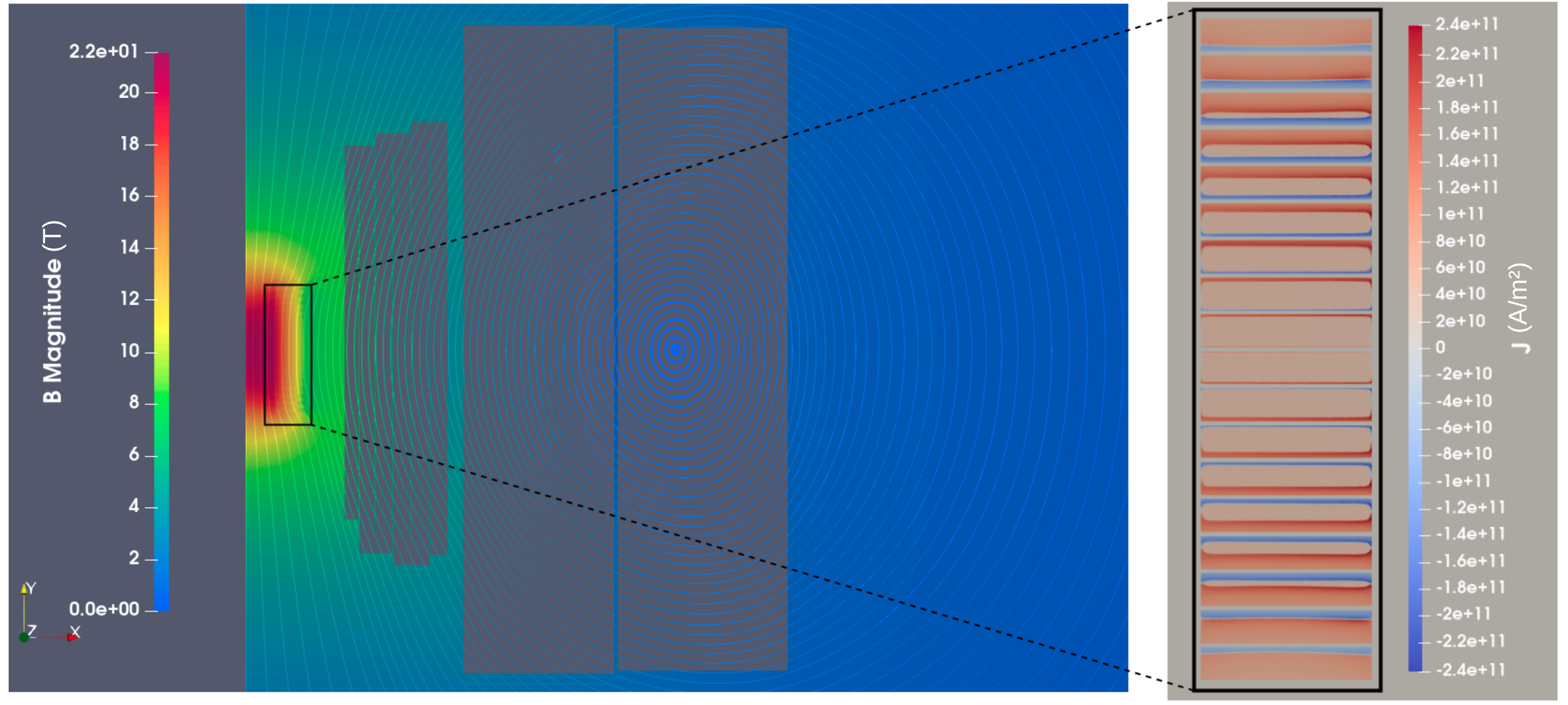
Resistive external field : 170 mm configuration (6 Helices and 2 Bitters coils)

Transient Simulation

- T-A Homogeneous formulation
  Ref. Edgar Berrospe-Juarez et al 2019 Supercond. Sci. Technol. 32 065003
- Axisymmetric coordinates
- HTS temperature: 4.2°K
- External resistive field: 8T (12 000 A in the Helices and in the Bitter coils)
- Ramping up the current in the HTS to 300 A after stabilization of resistive field

Computation time
Parallel 32 cores
2.75h for 160 time steps

Magnetic flux density (T) *HTS current density (A/m²)*



with current of 300 A in the HTS insert & background field of 8T (6 Helices & 2 Bitter coils)

Estimating the critical current

Self consistent algorithm for estimating Ic of the Nougat insert:

Ref. V Zermeño et al 2015 Supercond. Sci. Technol. 28 085004

- Stationary **A** formulation

$$\nabla \times \nabla \times \mathbf{A} = \mu\mathbf{J}$$

- Modified **E-J** power law

$$\mathbf{J} = J_c(\mathbf{B})P$$

- Iterative algorithm testing different I

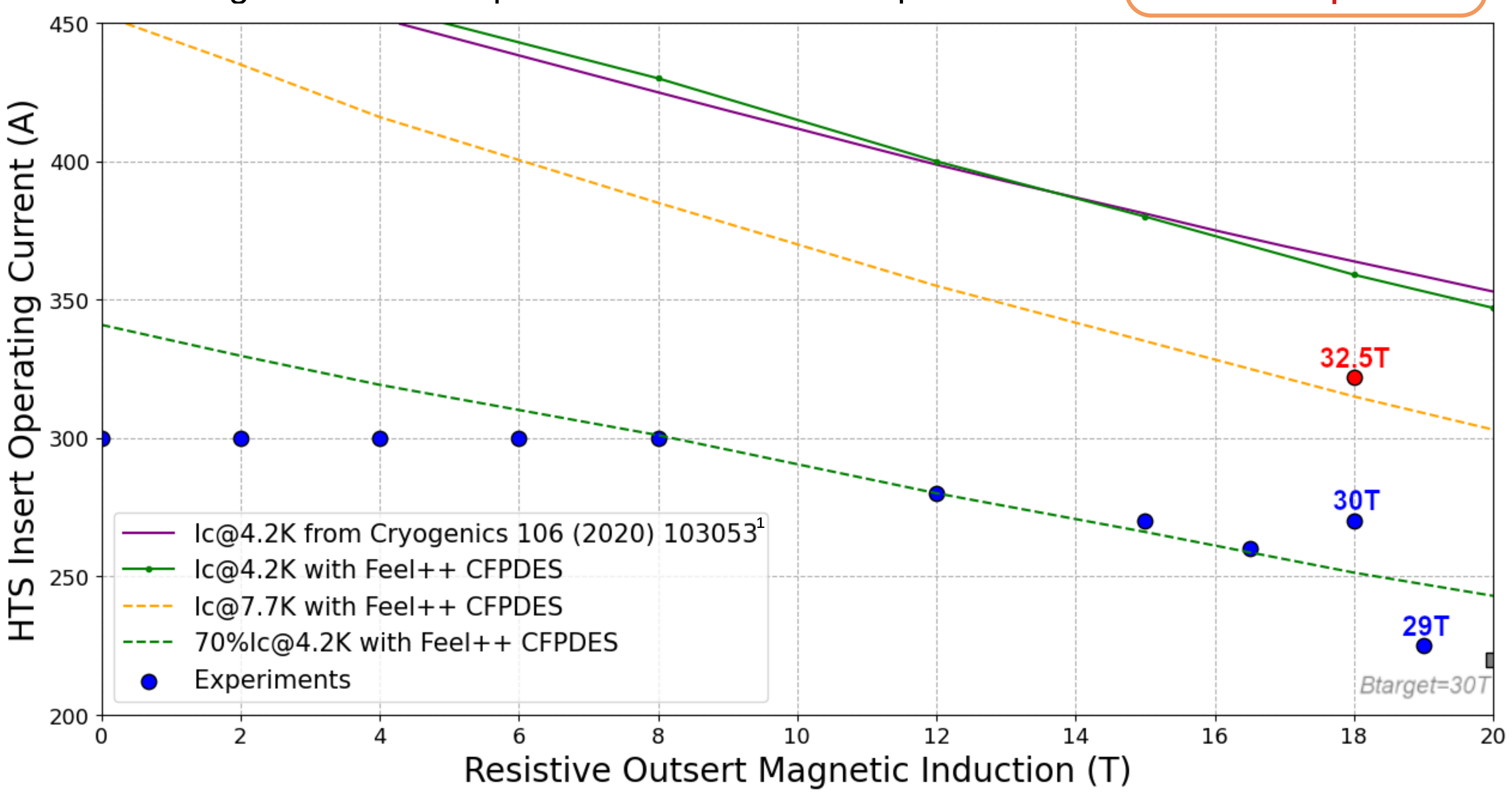
$$\mathbf{I} = P_i \int_{\Omega_i} J_c(\mathbf{B})d\Omega_i$$

where Ω_i is the domain of the ith tape.

Calculation with different values of resistive external field:

Resistive outsert: 6 Helices and 2 Bitters coils
HTS Nougat Insert: 9 dbl-pancakes with 290 turns/pancake

Computation time
Parallel 32 cores
~4h for **9 external B fields**
for **5220 tapes**



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[1] P. Fazilleau, X. Chaud, F. Debray, T. Lecrevisse & J. Song. 38 mm diameter cold bore metal-as-insulation HTS insert reached 32.5 T in a background magnetic field generated by resistive magnet. Cryogenics. 106. 103053. 10.1016/j.cryogenics.2020.103053.

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