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

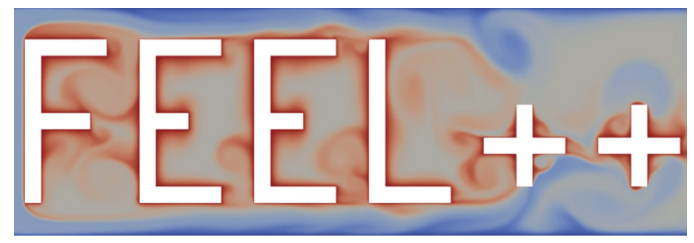


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In the frame of the **European project EMFL**:

- 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:

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

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)



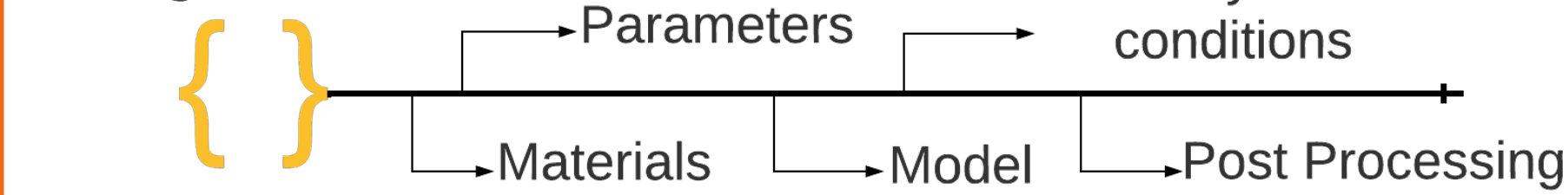
Exchangeable critical current density fits

HTS tapes → anisotropic → critical current density depends on

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

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

CFPDES Configuration file



Fit file containing $J_c(\mathbf{B})$

Example fit file : hilton_fit.json

```
1 {
2   "k0": 8870.0,
3   "k1": 18500.0,
4   "alpha0": 1.3,
5   "alpha1": 0.889,
6   "beta0": 13.8,
7   "beta1": 13.8,
8   "gamma1": 0,
9   "c1": 2.15,
10  "normB": "sqrt((-magnetic_grad_Atheta_rt_1)^2
11  +magnetic_grad_Atheta_rt_0+magnetic_grad_Atheta_rt_x)^2
12  );magnetic_grad_Atheta_rt_0
13  :magnetic_grad_Atheta_rt_1:magnetic_grad_Atheta_rt_x";
14  "theta": "atan2(magnetic_grad_Atheta_rt_0
15  +magnetic_grad_Atheta_rt_1,(-magnetic_grad_Atheta_rt_1
16  ));magnetic_grad_Atheta_rt_0
17  :magnetic_grad_Atheta_rt_1:magnetic_grad_Atheta_rt_x";
18  "omega1": "c1*(normB + (1.0/c1)^(5/3))^(3/5);c1
19  :normB";
20  "icB": "k0/(normB+beta0)^alpha0 + k1/(normB+beta1
21  )^alpha1 * ( omega1^2 * cos(theta-gamma1)^2 + sin
22  (theta-gamma1)^2 )^(0.5);normB:theta:k0:k1:alpha0
23  :alpha1:beta0:beta1:omega1:gamma1";
24  "jCB": "icB/t_tape/h_tape:icB:t_tape:h_tape";
25  "j_th": "jCB*p*(t_tape/t_cell):t_tape:t_cell:jCB:p";
26 }
```

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:

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

T-A Formulation

\mathbf{B} , the magnetic flux density (T)

\mathbf{J} , the current density (A/m²)

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

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

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 \mathbf{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 \mathbf{T}_1 and \mathbf{T}_2 the potentials at the extremities of the 1D layer

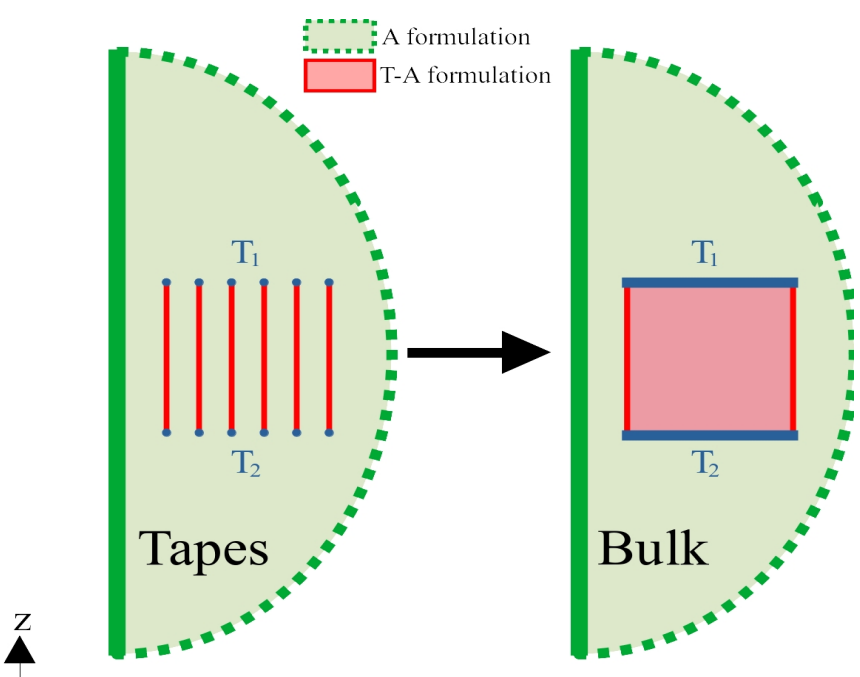
Axisymmetric coordinates

Formulation in cylindrical coordinates (r, z):

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

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

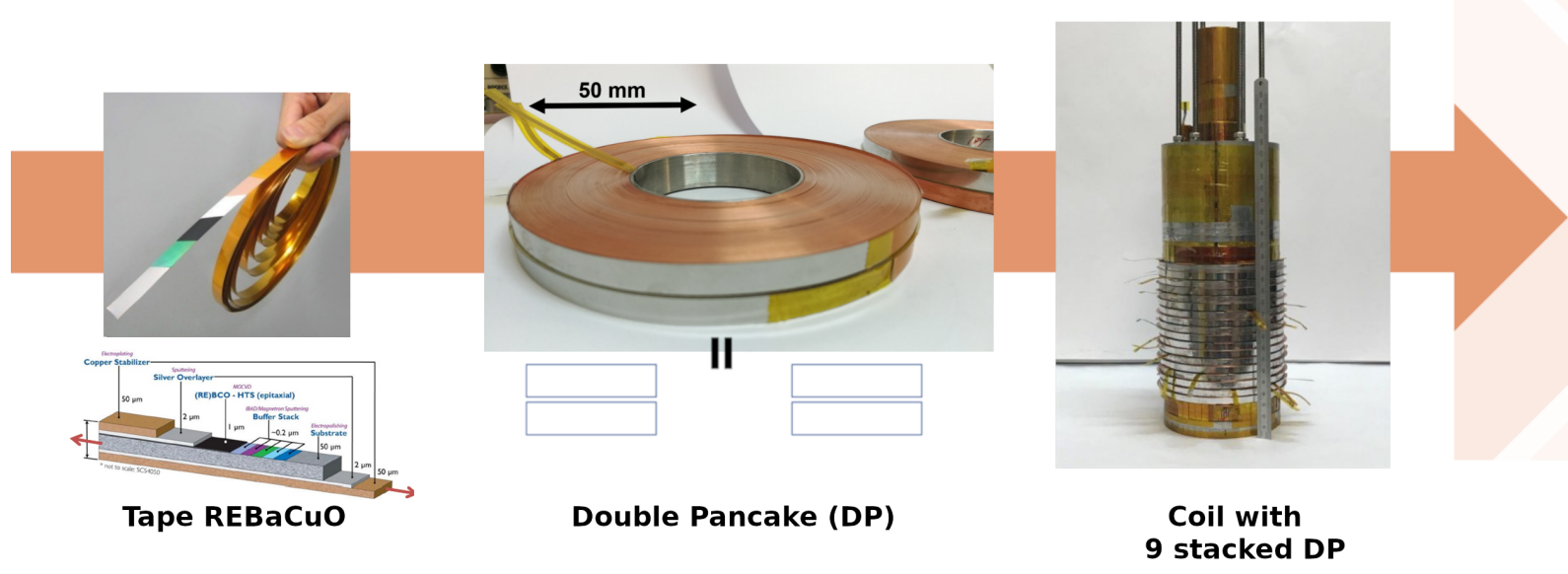
Homogeneous method



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

Nougat HTS Insert

Geometry of the Insert



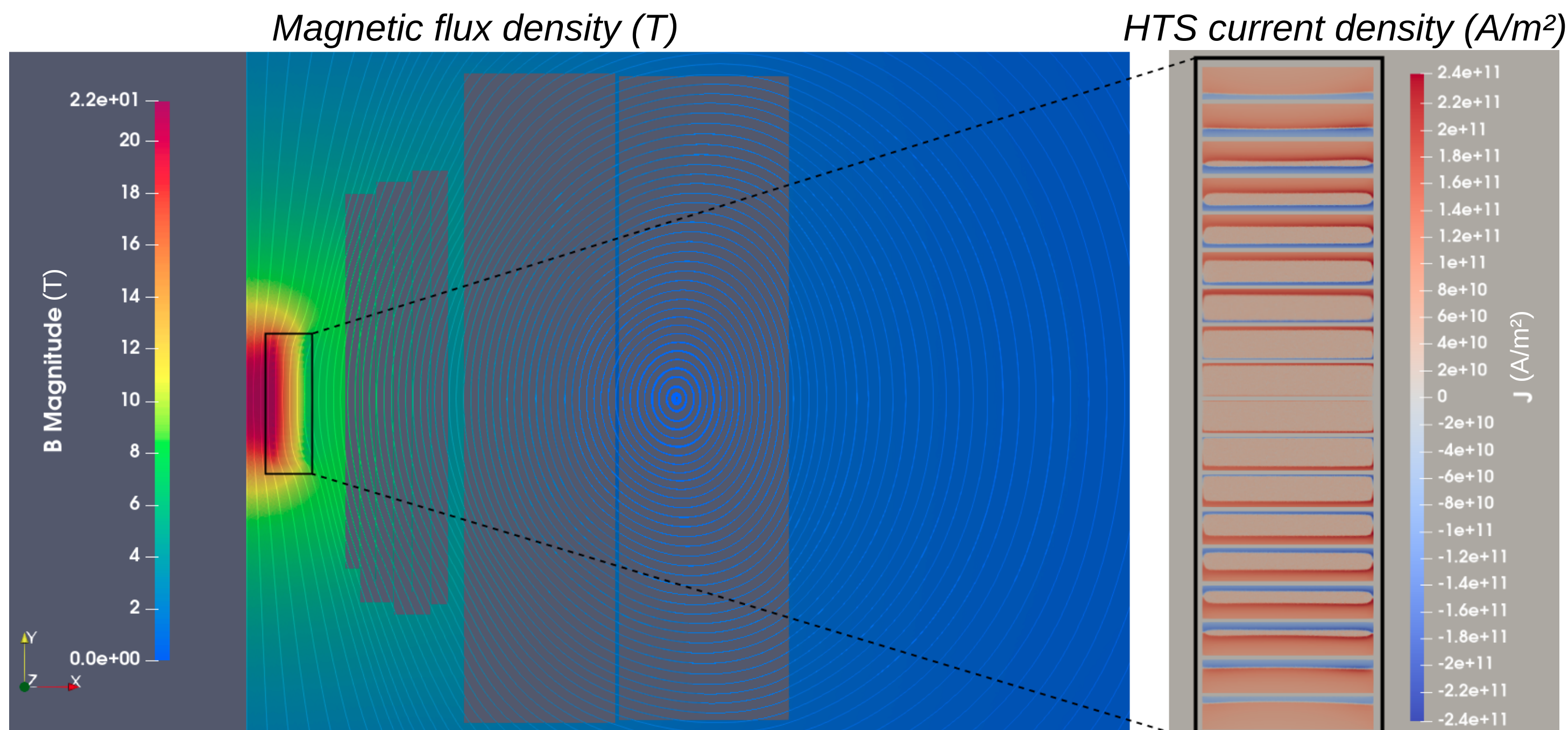
Parameters	Value
Double Pancakes	9
Turns per Pancake	290
HTS Tape width	6 mm
HTS Tape thickness	75 μm
MI thickness	30 μm
Winding inner diameter	50 mm
Winding outer diameter	109.4 mm

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



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 I_c of the Nougat insert:

Ref. V Zermeno 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

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

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

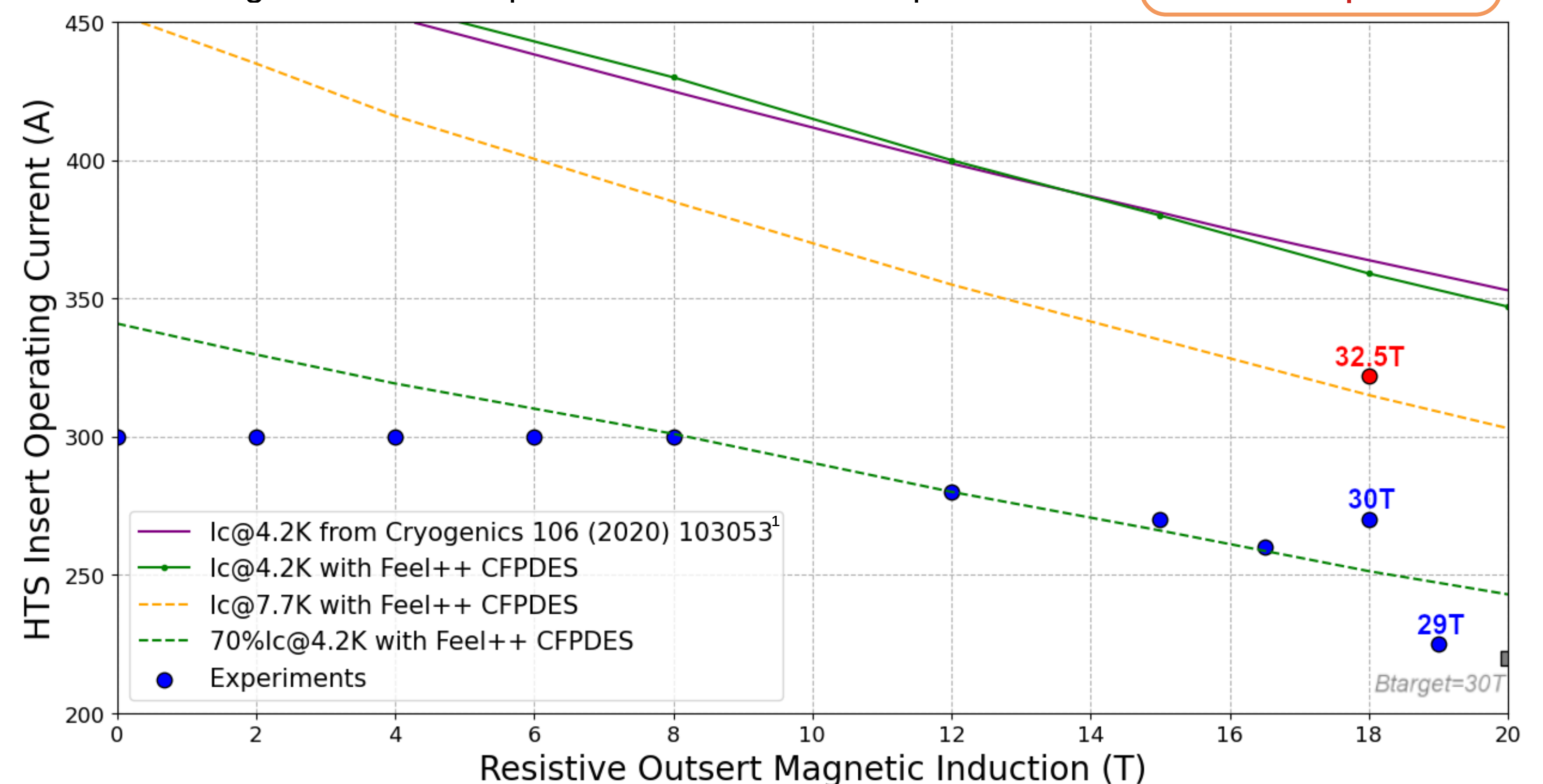
where Ω_i is the domain of the i th tape.

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



¹P. 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.