



HAL
open science

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

Jeremie Muzet, Vincent Chabannes, Christophe Prud'Homme, Christophe Trophime, Xavier Chaud

► To cite this version:

Jeremie Muzet, Vincent Chabannes, Christophe Prud'Homme, Christophe Trophime, Xavier Chaud. 2D axisymmetric modeling of the HTS Insert Nougat in a background magnetic field generated by resistive magnet.. International Conference on Magnet Technology (MT-28), Sep 2023, Aix-en- Provence, France. , 106. hal-04220944

HAL Id: hal-04220944

<https://cnrs.hal.science/hal-04220944>

Submitted on 29 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



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



J. Muzet¹, V. Chabannes², C. Prud'Homme², C. Trophime¹, X. Chaud¹.

¹ Laboratoire National des Champs Magnétiques Intenses, CNRS, UPR 3228, Grenoble, France
² Institut de Recherche Mathématique Avancée, Univ Strasbourg, UMR 7501, Strasbourg, France

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)



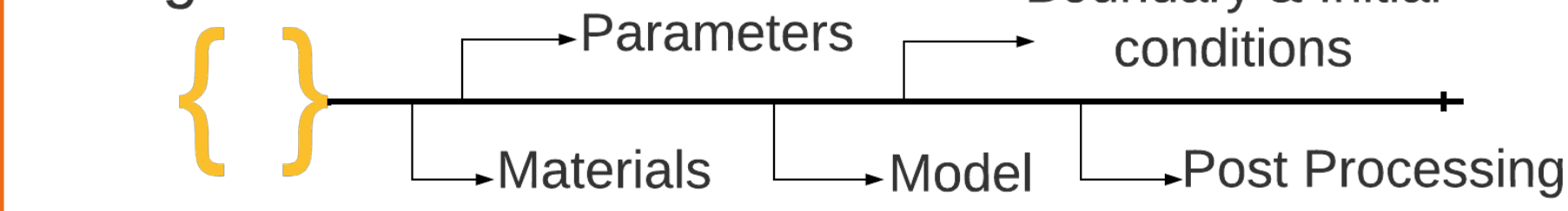
Exchangeable critical current density fits

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 $J_c(\mathbf{B})$

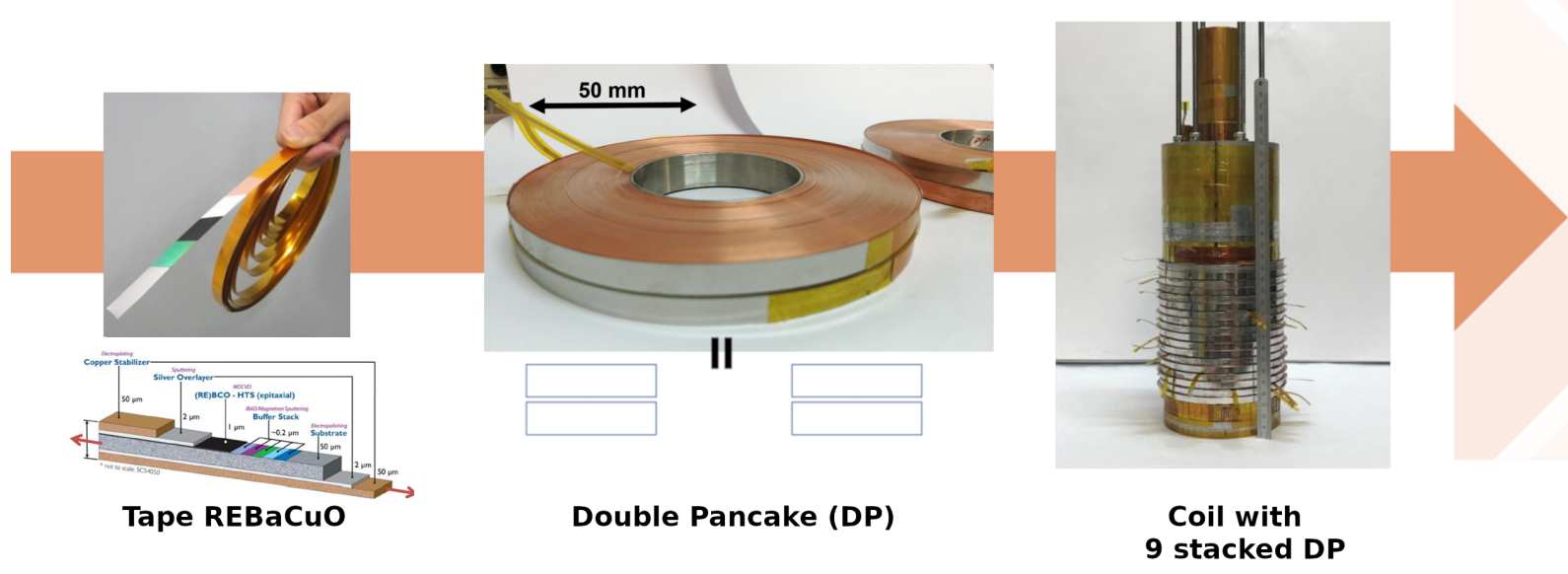
JSON file

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 }
```

Nougat HTS Insert

Geometry of the Insert



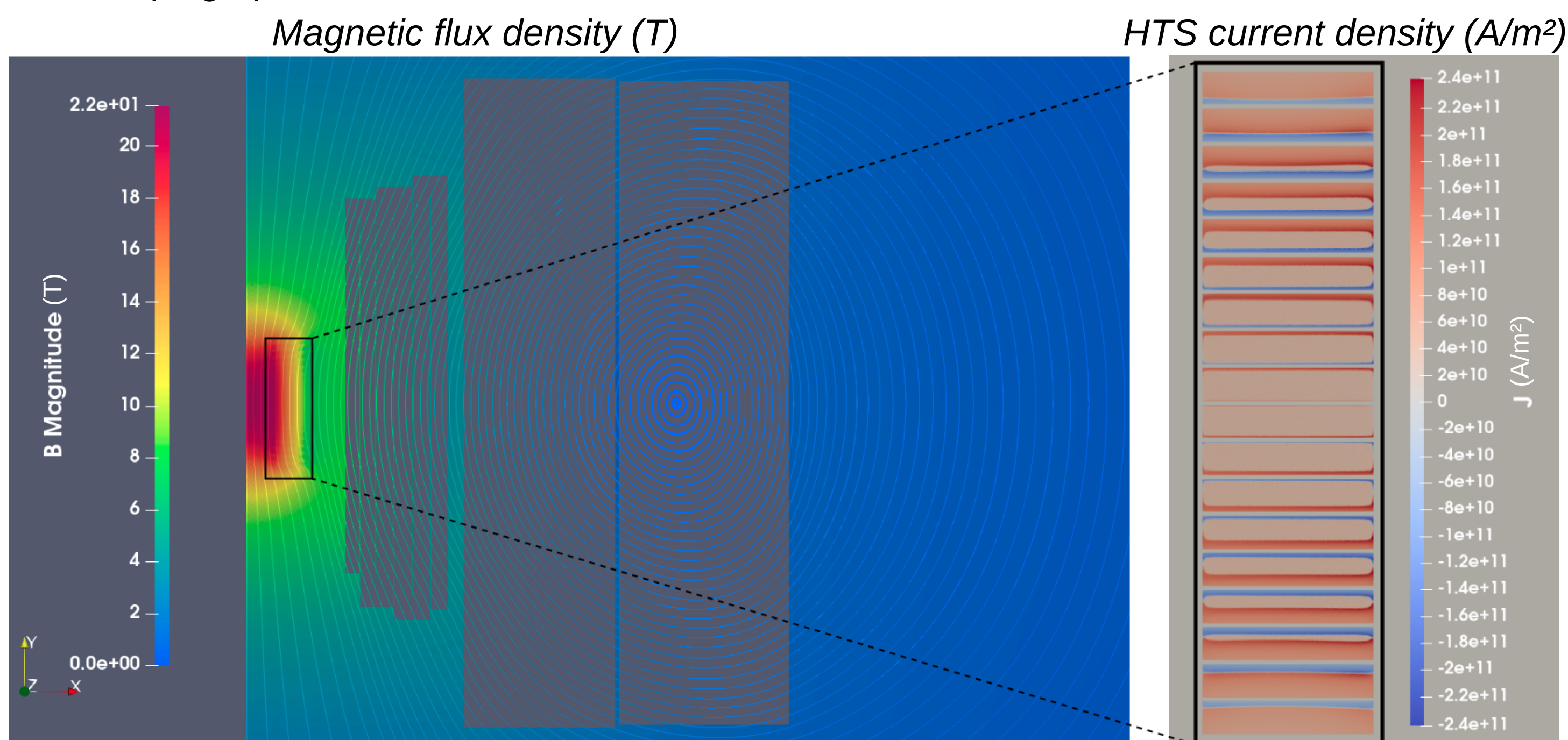
Parameters	Value
Double Pancakes	9
Turns per Pancake	290
HTS Tape width	6 mm
HTS Tape thickness	75 μm
MI thickness	30 μm
Winding inner diameter	50 mm
Winding outer diameter	109.4 mm

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)

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

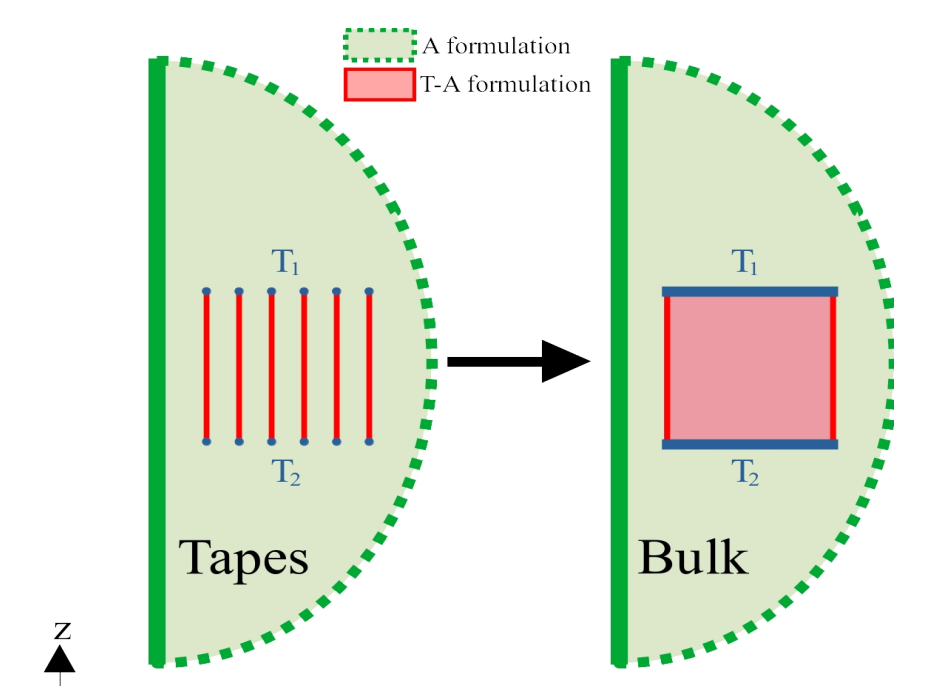
Axisymmetric coordinates

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.

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

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

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

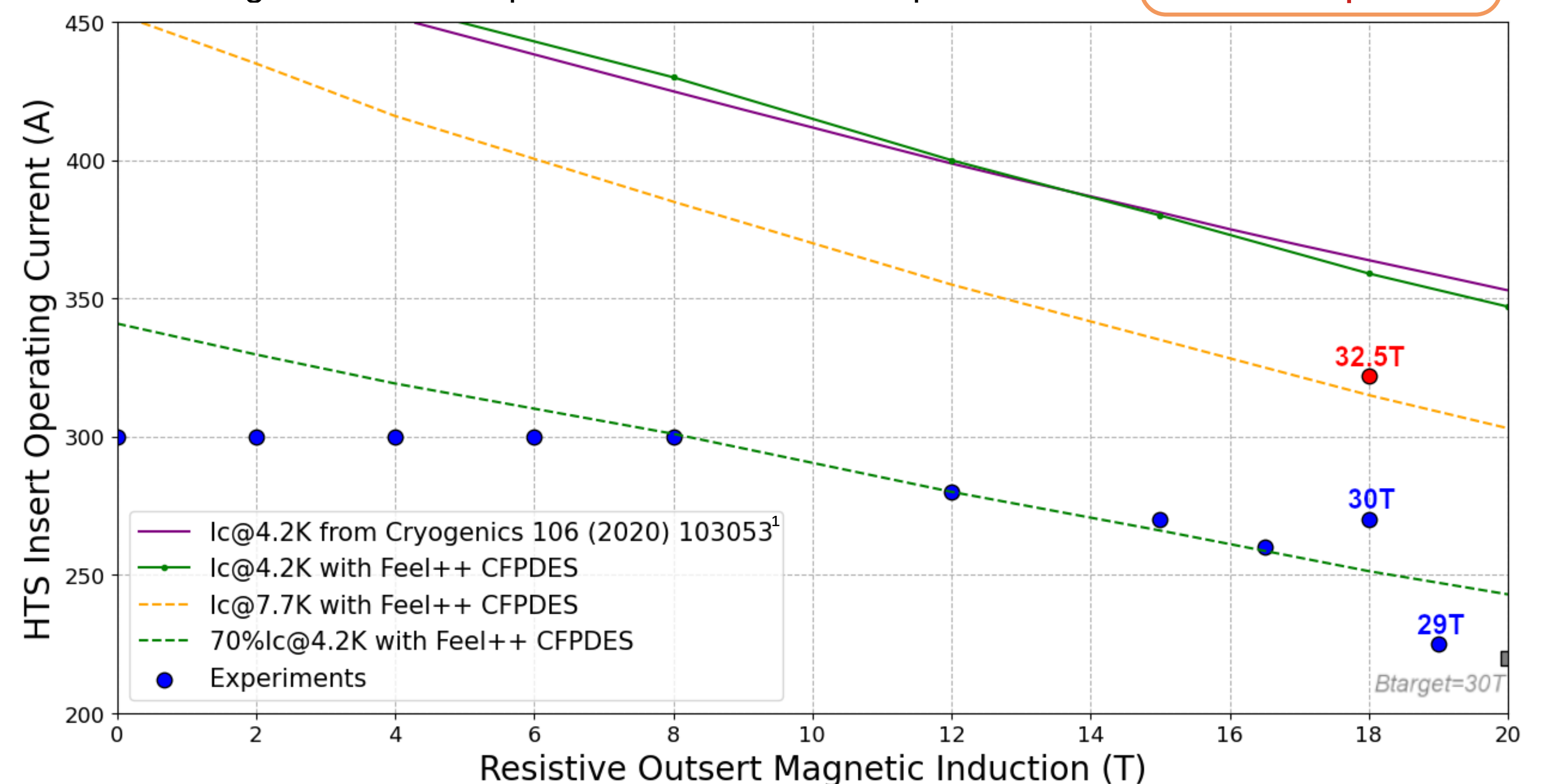
where Ω_i is the domain of the i th tape.

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.