Screening Currents and Hysteresis Losses in the REBCO Insert of the 32 T All-Superconducting Magnet Using T-A Homogenous Model

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- Mark Bird (NHMFL)

Introduction

- Development of an electromagnetic model for the 32 T all-superconducting magnet (NHMFL, Florida).
- The magnet consists of a 17 T HTS insert and a 15 T LTS outsert.
- The current density and the hysteresis losses are estimated in the **HTS insert**.
- The LTS outsert is modeled as 5 concentric coils in which uniform current densities are impressed .

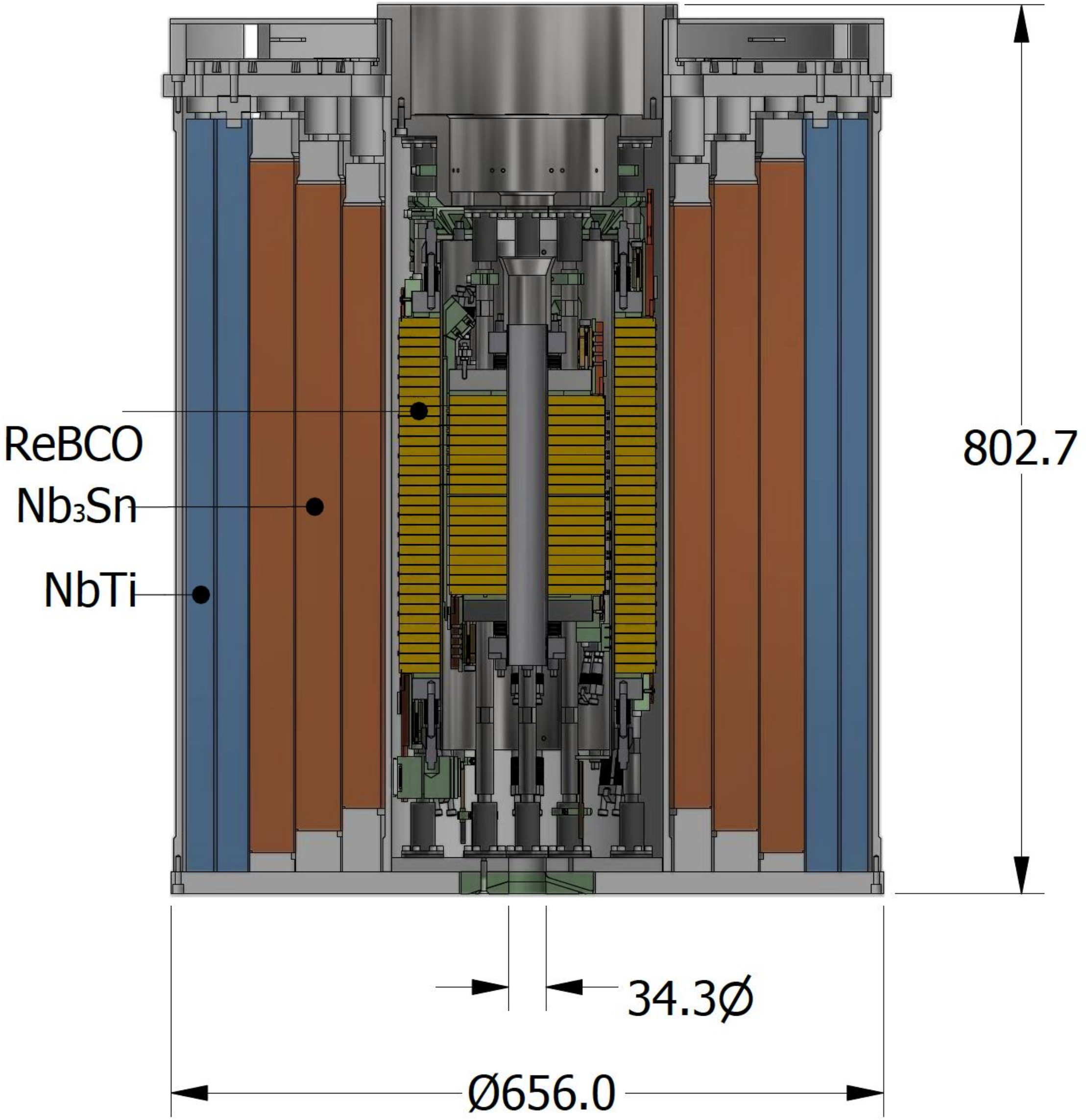

Figure 1.

The Challenge

TABLE I
32 T ALL-SUPERCONDUCTOR INSERT'S PARAMETERS

Parameter	Coil 1	Coil 2
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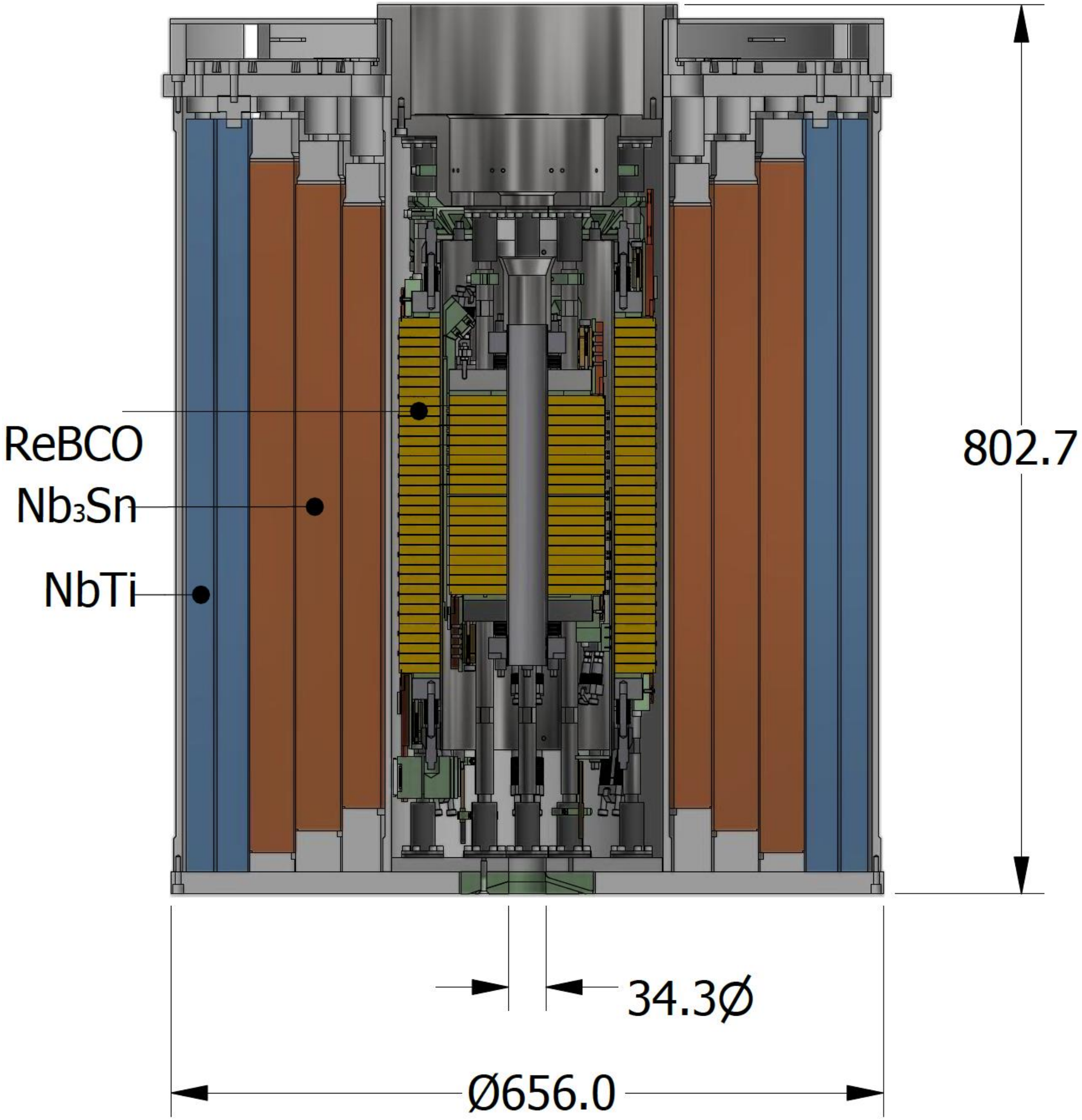
Height [mm]	178	320.4
Pancakes	40	72
Turns/Pancake	253	145



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20560 REBCO turns

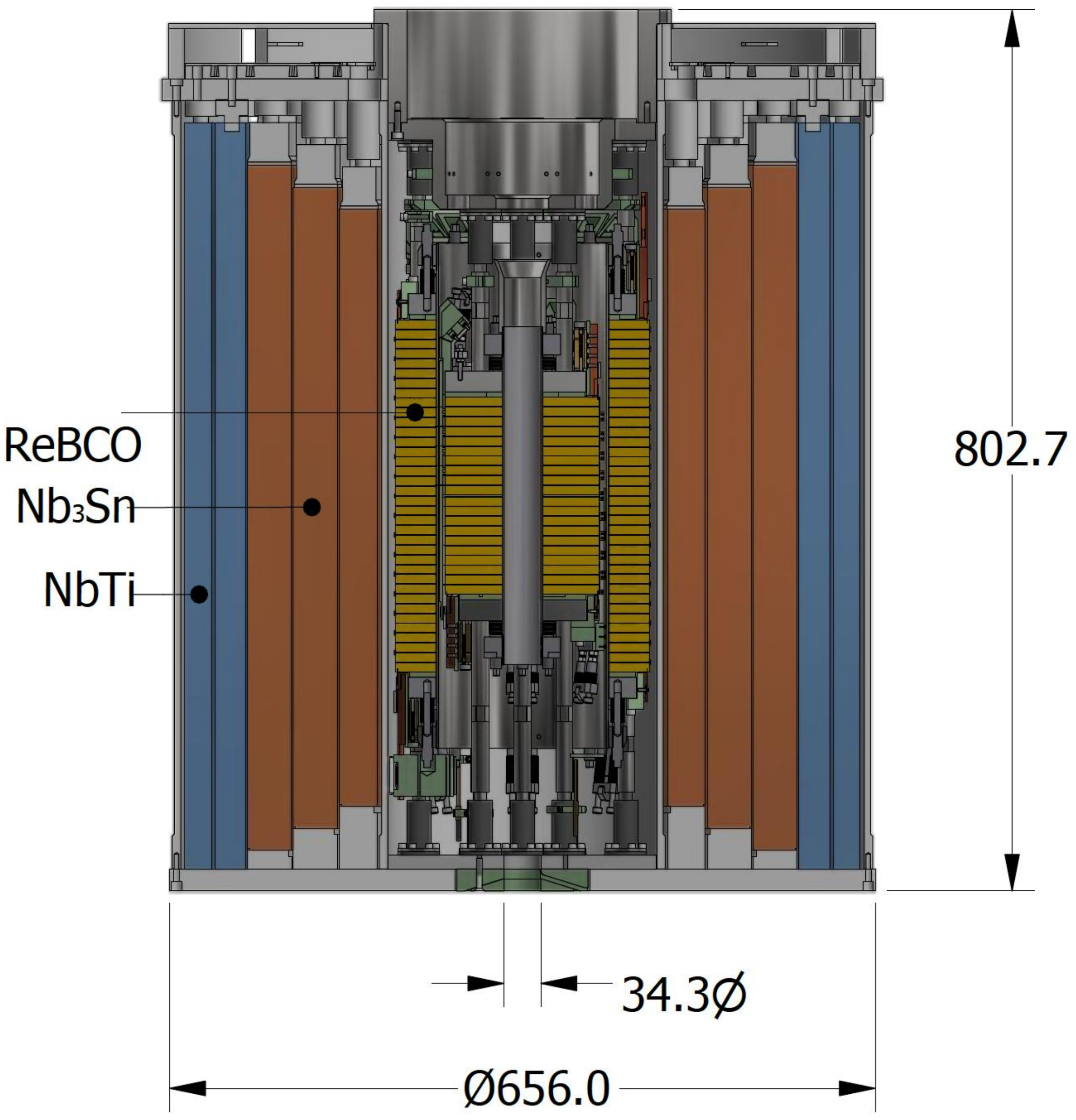

Figure 1.

The Challenge - The Strategies

- The well-known *H* formulation (FEM), proposed by Brambilla *et al.* [1], requires a huge amount of computational resources.
- The Minimum Electromagnetic Entropy Production (MEMEP) method, proposed by Pardo [2], has been applied to stacks having up to 40,000 turns.
- The homogenization together with the *H* formulation, proposed by Zermeño *et al*. [3].
    - Smaller size prototype coils of the 32 T magnet, proposed by Xia *et al*. [4].
    - Inner coil (coil 1) of the HTS insert 32 T magnet, proposed by Xia *et al*. [5].
- The Iterative multi-scale method together with the *H* formulation, proposed by Berrospe *et al*. [6]
    - Full HTS insert model of the 32 T magnet without the LTS outsert, proposed by Berrospe *et al*. [7].
- The *T-A* formulation (FEM), proposed by Zhang *et al*. [8] and Liang *et al*. [9].

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- The *T-A* formulation (FEM), proposed by Zhang *et al*. [8] and Liang *et al*. [9].

- **The homogenization together with the *T-A* formulation proposed by Berrospe *et al*. [10].**
    - **Full HTS insert model of the 32 T magnet without the LTS outsert, presented here.**

T-A Formulation

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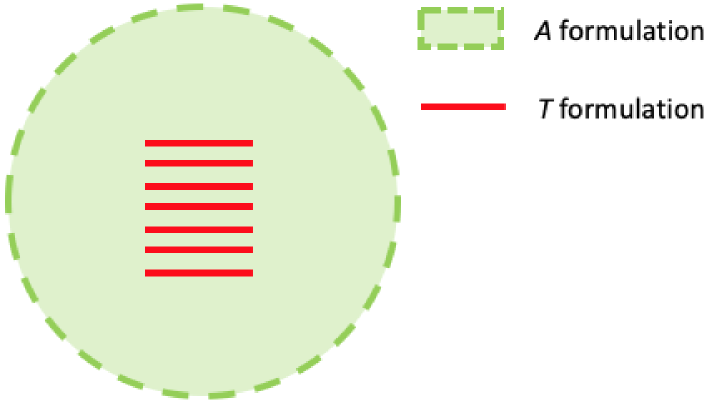

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- The *T-A* formulation combines the *T* and the *A* formulations.
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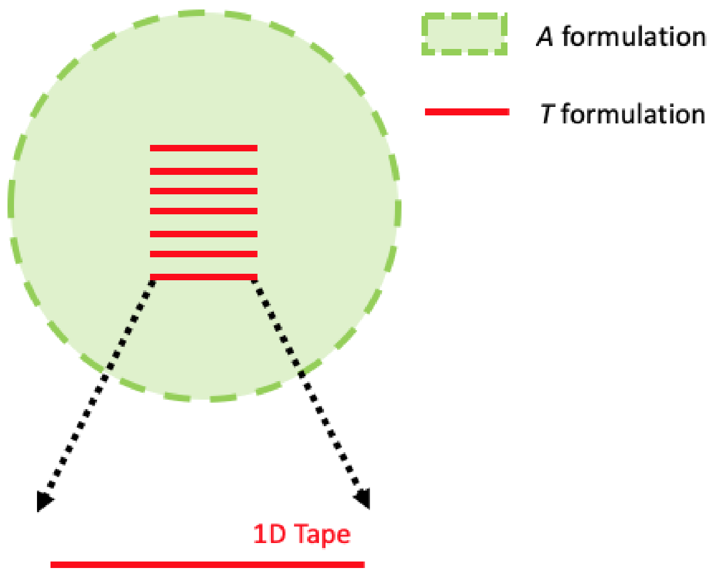

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$$\nabla^2 A_z = -\mu J_z$$

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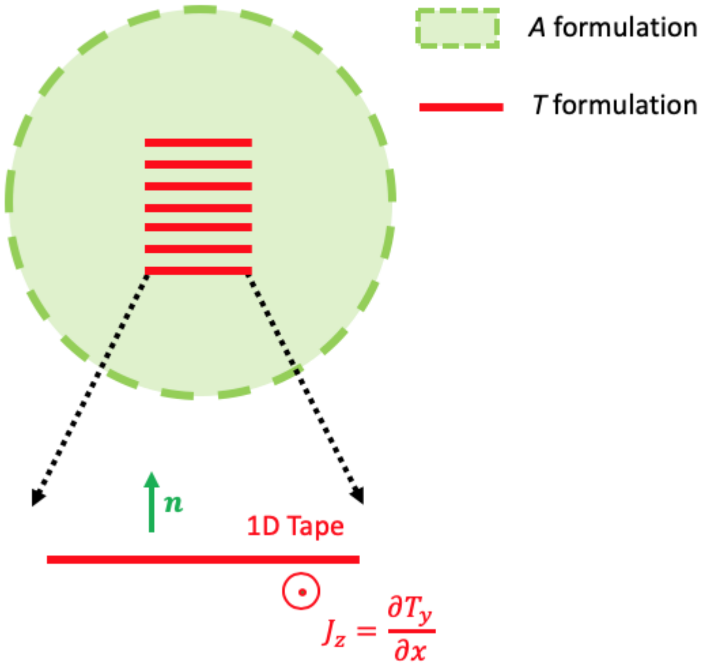

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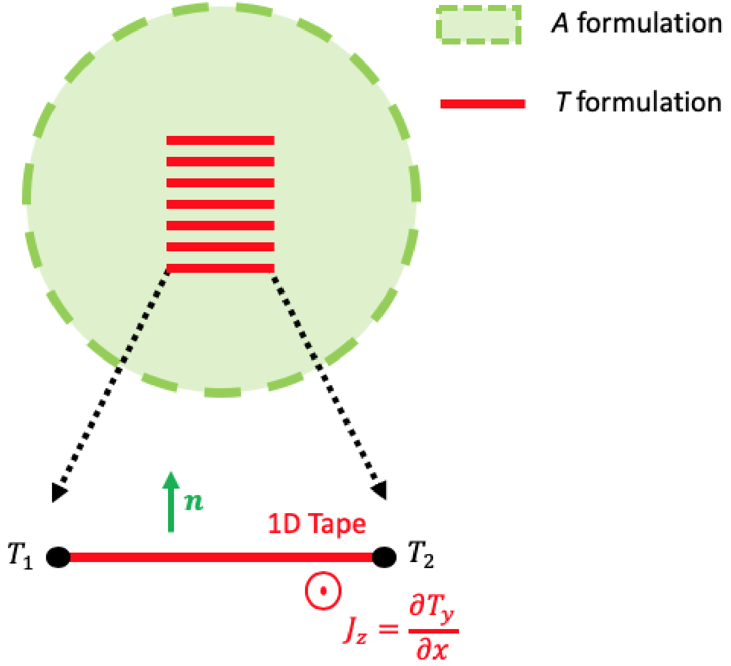
- The transport current is impressed by means of the boundary conditions for *T*.

$$I = (T_1 - T_2)\delta$$



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- The surface current density *K* appears in the *A* formulation as a Neumann boundary condition.

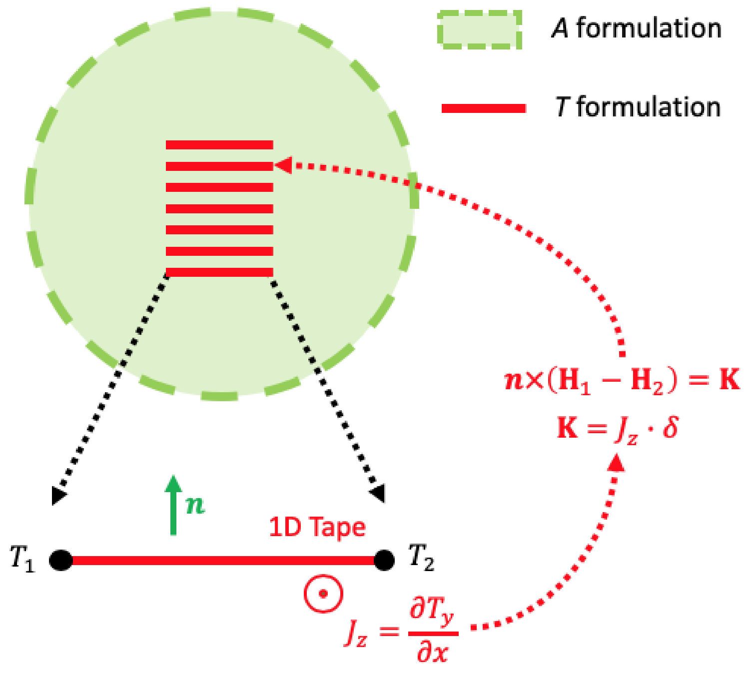
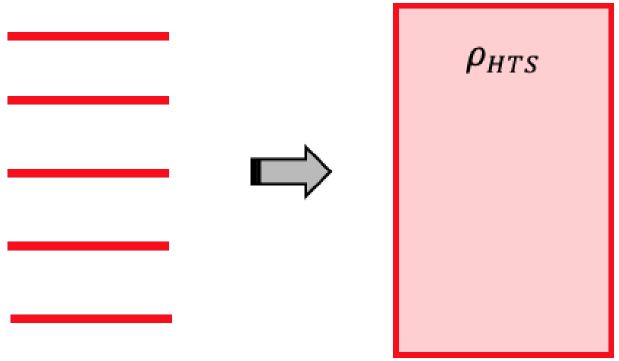


Figure 2.

T-A Homogeneous

- The homogenization tranforms a HTS tapes stack into an anisotropic bulk.



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- The homogenization tranforms a HTS tapes stack into an anisotropic bulk.
- *T* is exclusively defined inside the bulk.
- The influence of B_x in T is neglected, therefore T is forced to have only one component.

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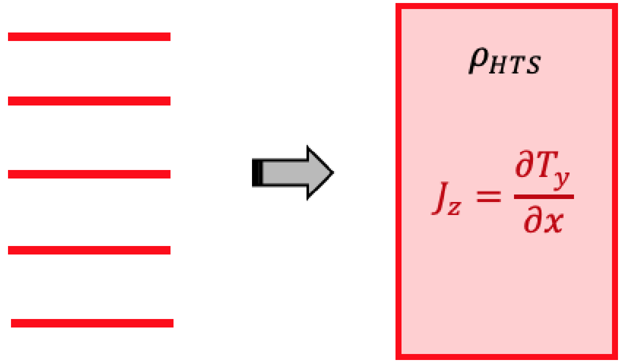

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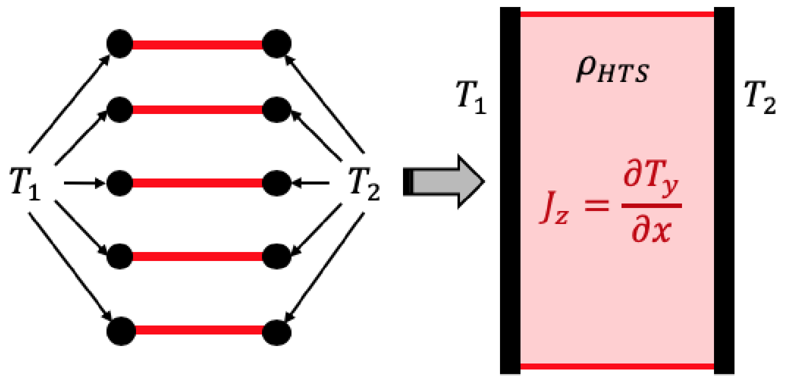

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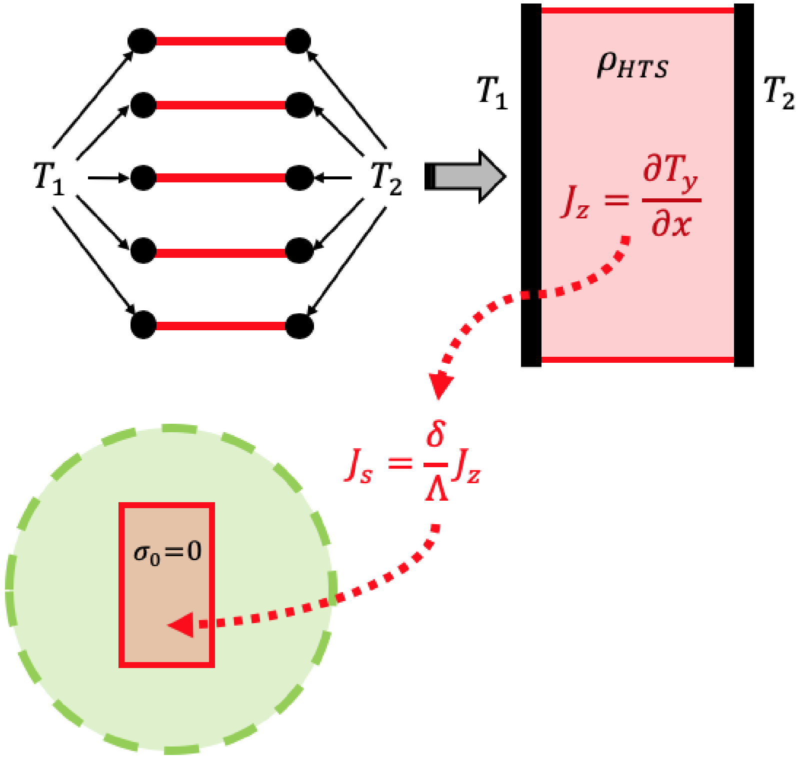

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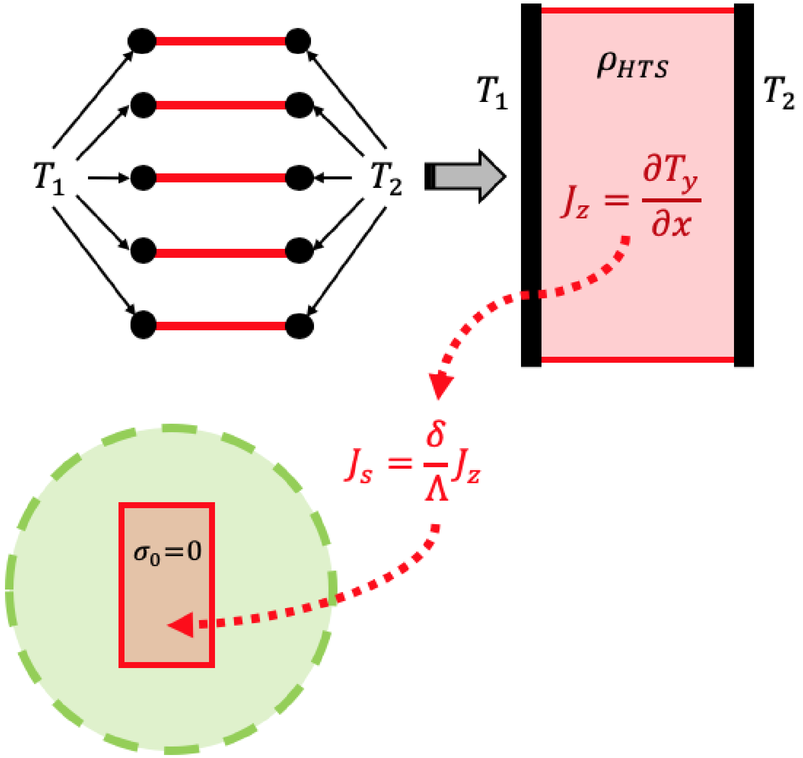

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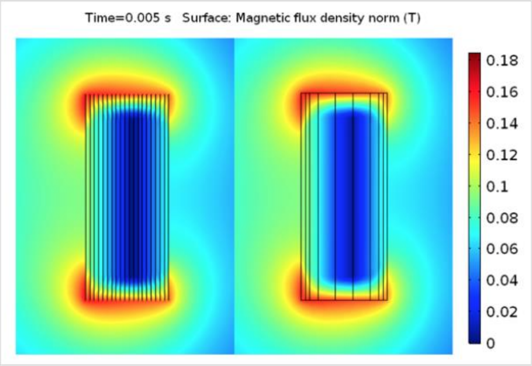
- Small examples of the code are available on-line. http://www.htsmodelling.com/

HTS MODELLING WORKGROUP | Modelling of High Temperature Superconductors (HTS)

T-A multi-scale and homogeneous models for the *Benchmark #3* (shared by Edgar Berrospe, National Autonomous University of Mexico, Mexico). These two models address the analysis of the Benchmark #3, a 20 HTS tapes stack. The models show how the multi-scale and homogeneous methods are adapted to be used in conjunction with the T-A formulation. The achieved simplification in the description of the system allow to reduce the computation time.

Comsol files (version 5.2a): here.

Reference article: Edgar Berrospe-Juarez et al 2019 Supercond. Sci. Technol. 32 065003



32 T Magnet - *T-A* Homogeneous Model

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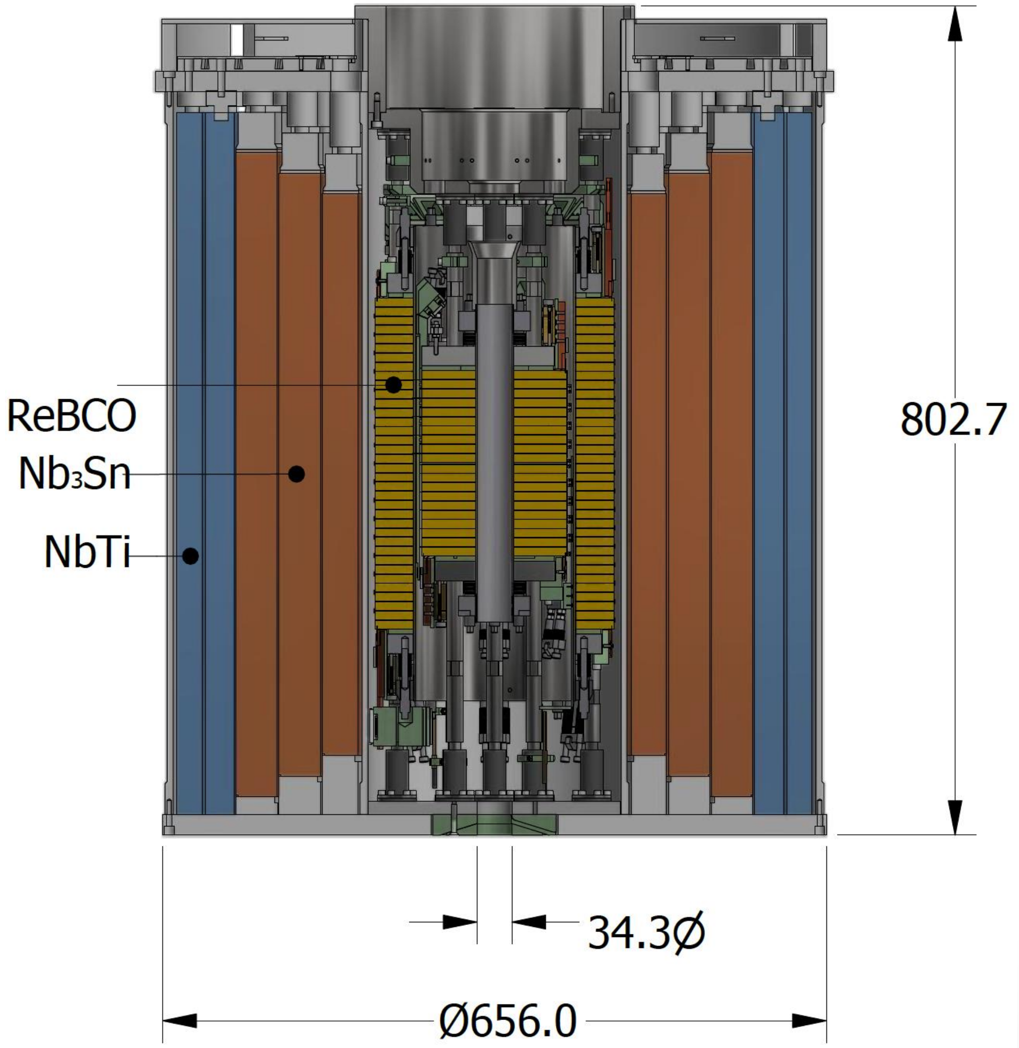

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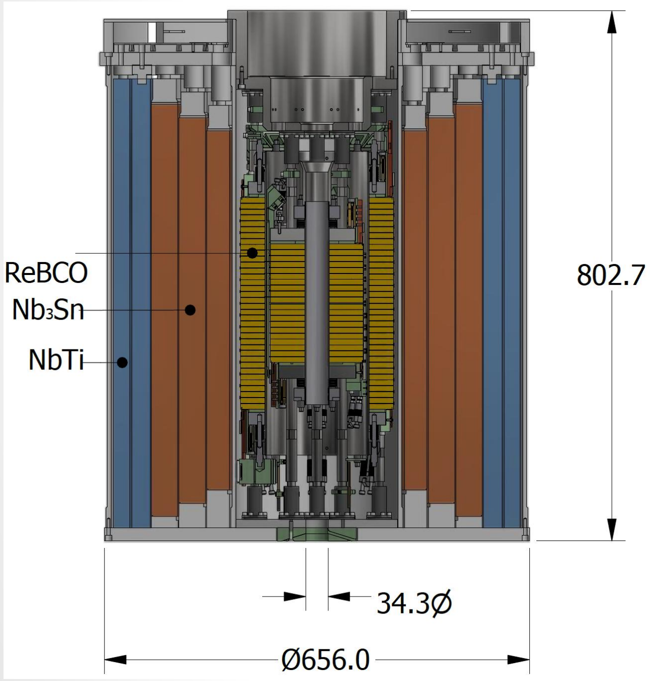

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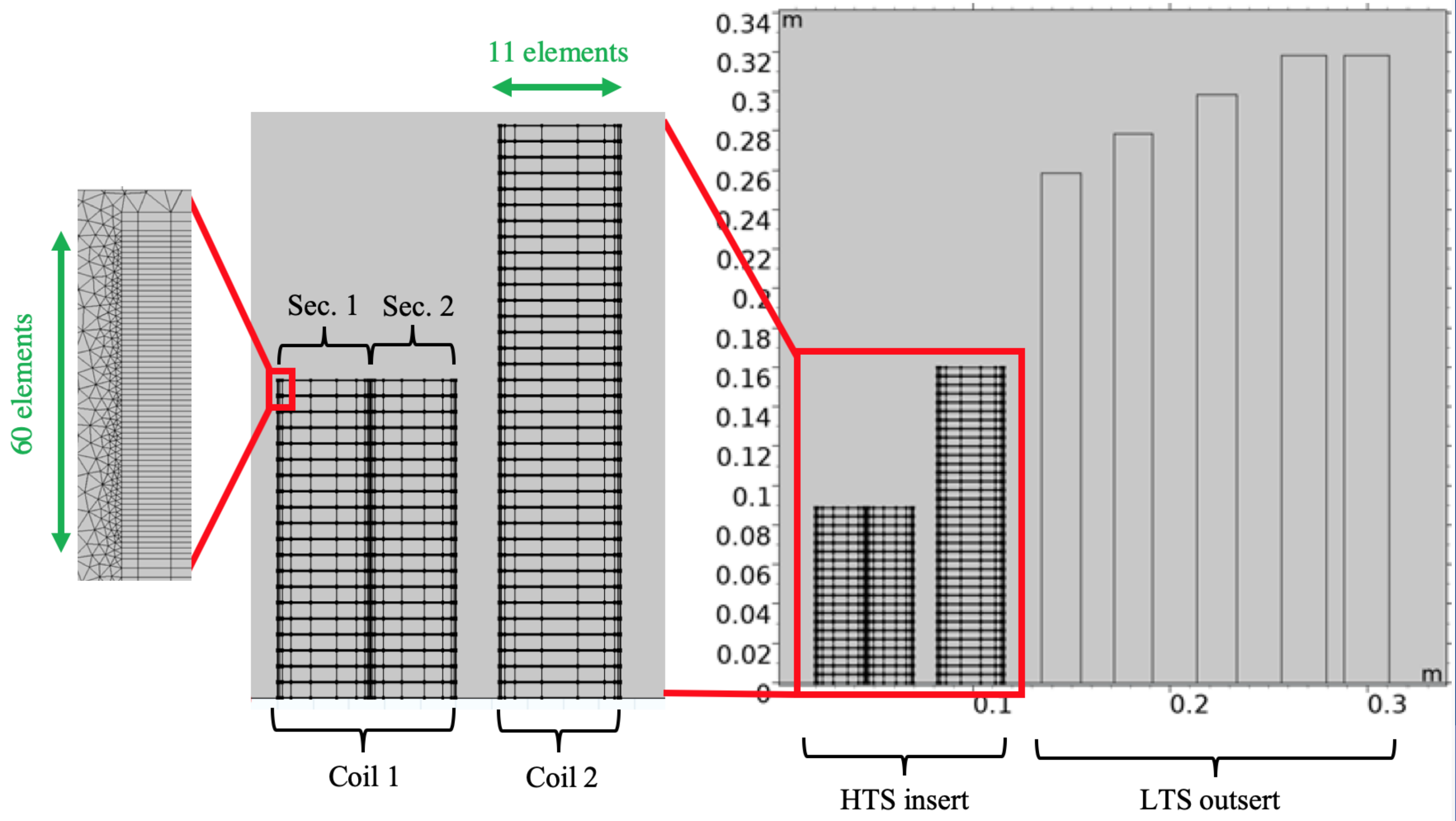

Figure 4.

32 T Magnet - *T-A* Homogeneous Model

- The LTS outsert is modeled as 5 coils with uniform current densities.

REBCO characteristics

- Pover-law model

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

- Kim-like model

$$J_c(B_r, B_z) = \frac{\beta \cdot J_{c0}}{\left(1 + \frac{\sqrt{k^2 B_z^2 + B_r^2}}{B_0}\right)^{\alpha}}$$

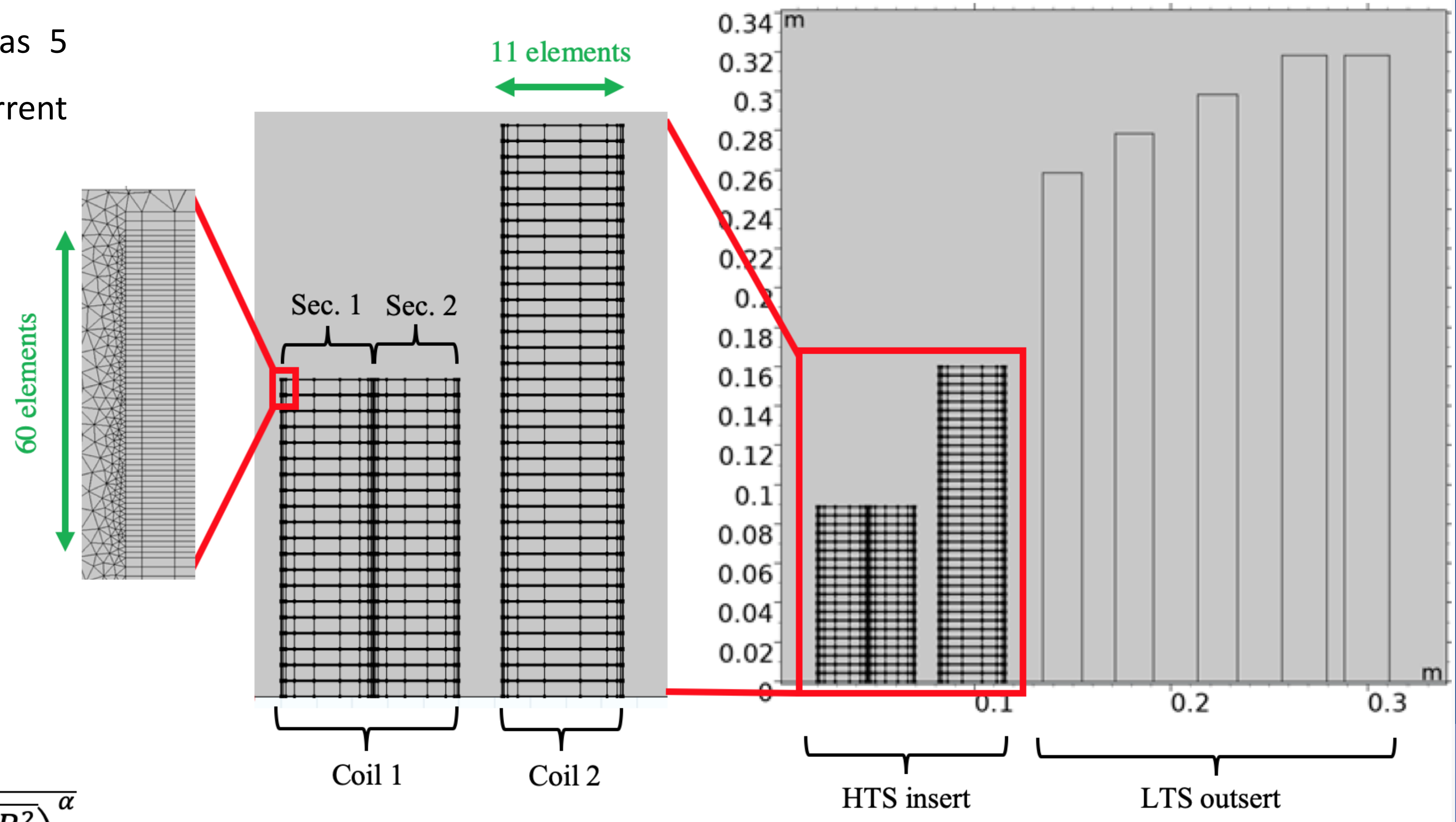

Figure 4.

32 T Magnet - *T-A* Homogeneous Model

- Both insert and outsert are charged, considering a real charge cycle.

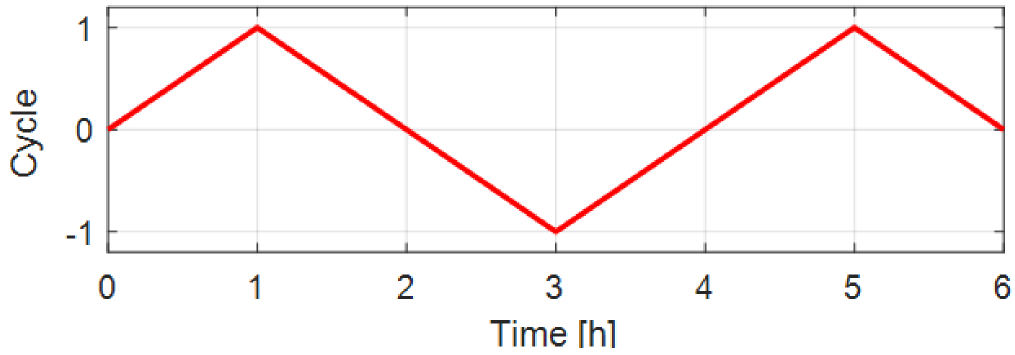

Figure 5.

32 T Magnet - *T-A* Homogeneous Model

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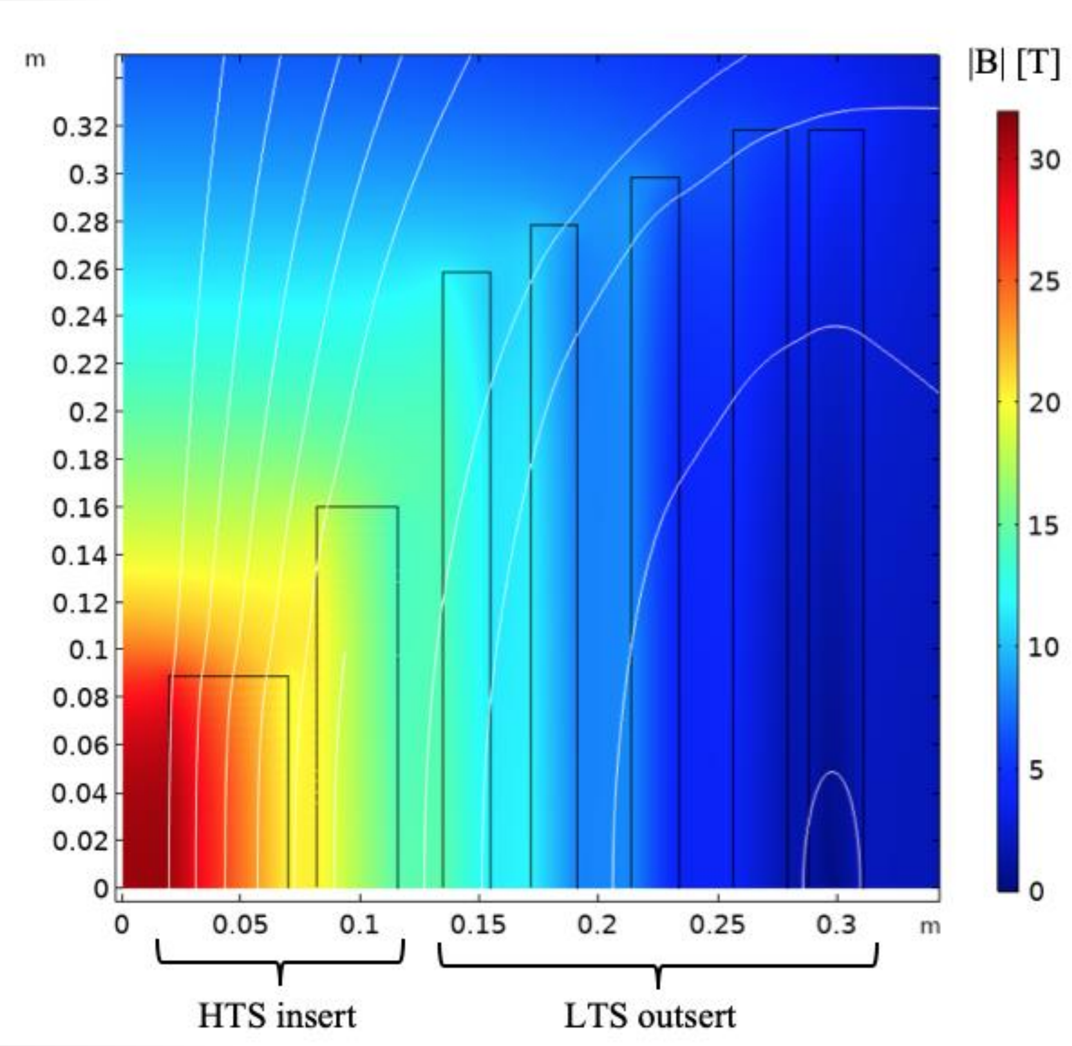
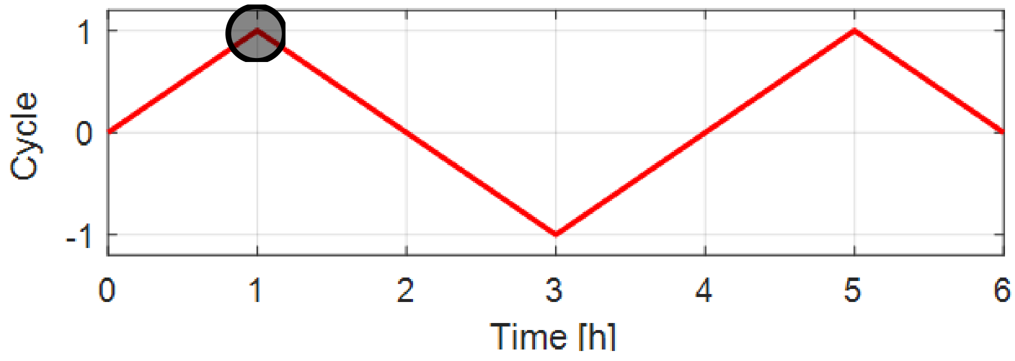


Figure 6. Magnetic field magnitude at peak current.



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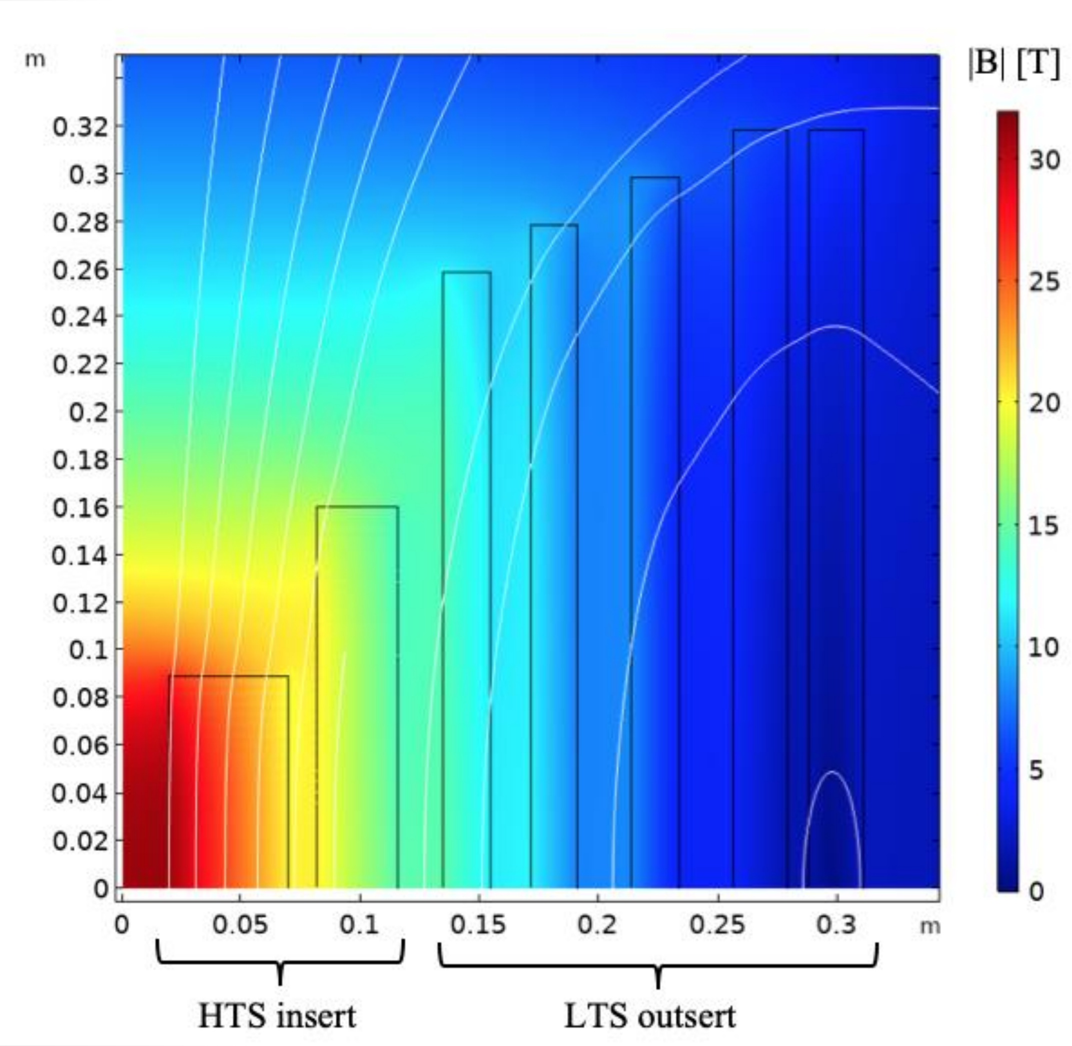

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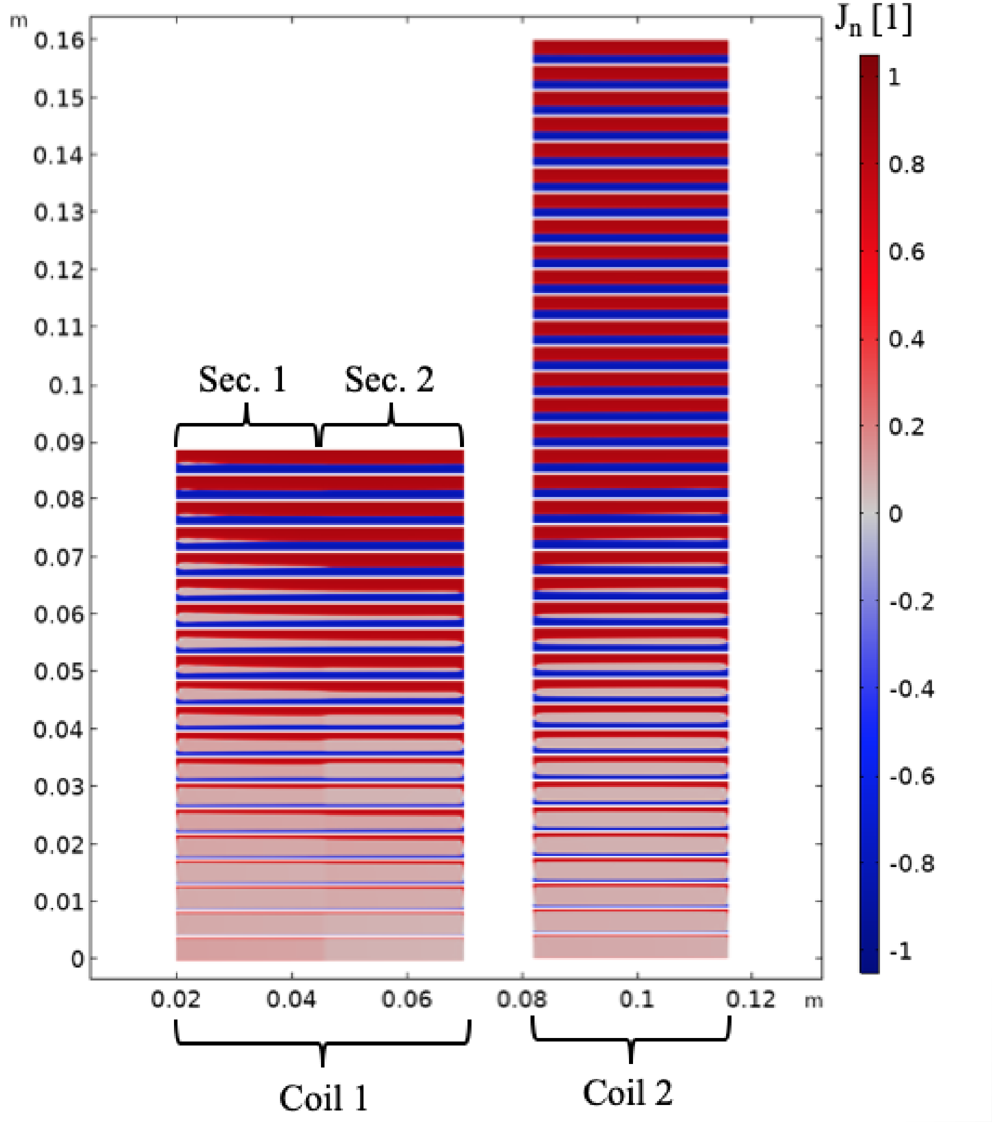


Figure 7. J at peak current in the last iterations.

32 T Magnet - *T-A* Homogeneous Model

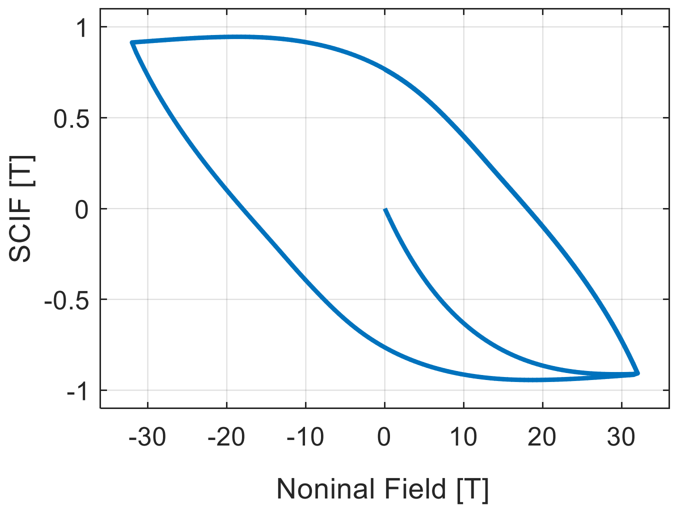
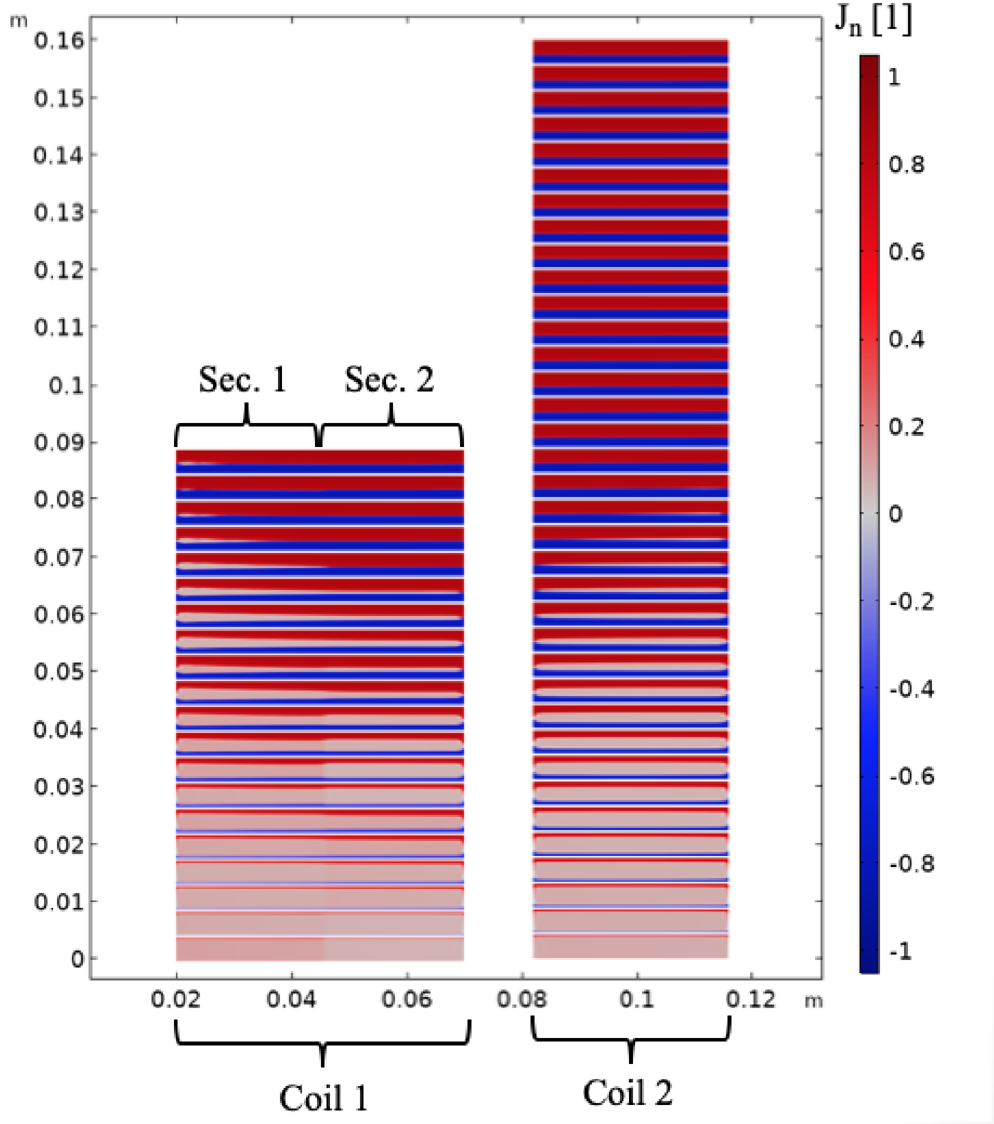


Figure 8. Screening Current Induced Field Loop.

The *J* distribution is used to compute the stresses, Kolb-Bond *et al. Mon-Af-Po1.11-05: Stress analysis of the 32 T superconducting magnet at the MagLab including screening current effects* [11].



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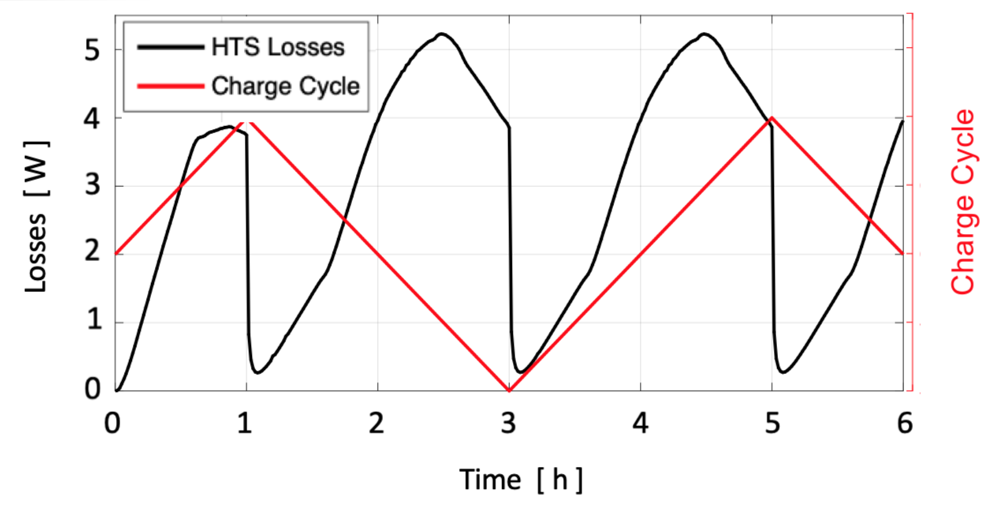


Figure 9. Instantaneous losses and charge cycle

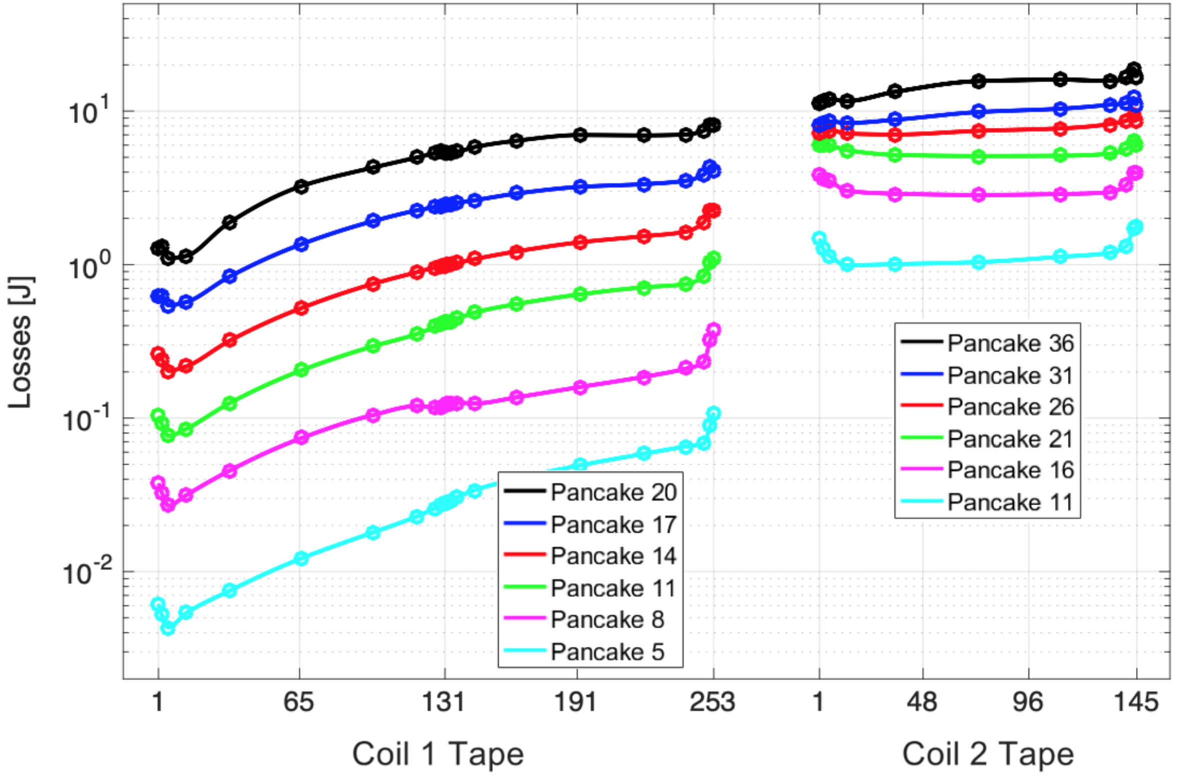
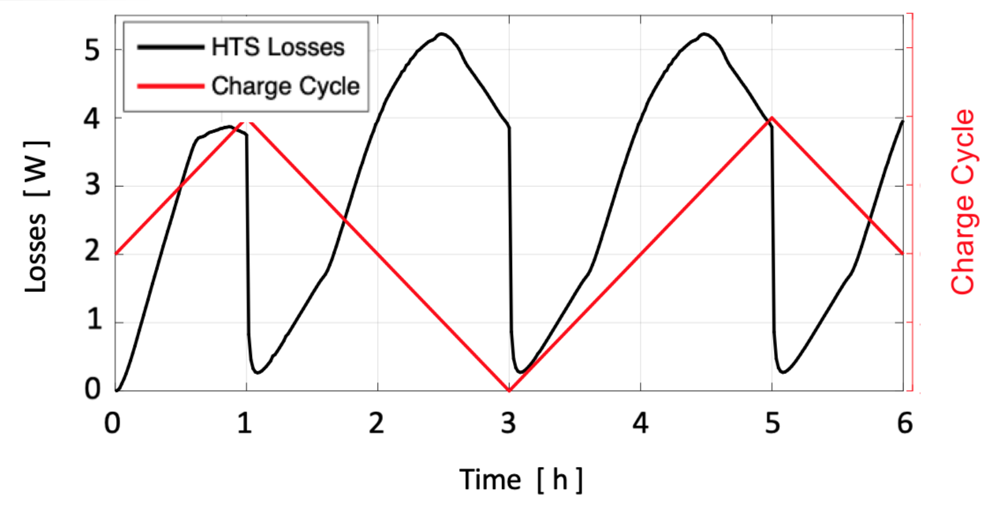


Figure 10. Losses in selected pancakes

32 T Magnet - *T-A* Homogeneous Model



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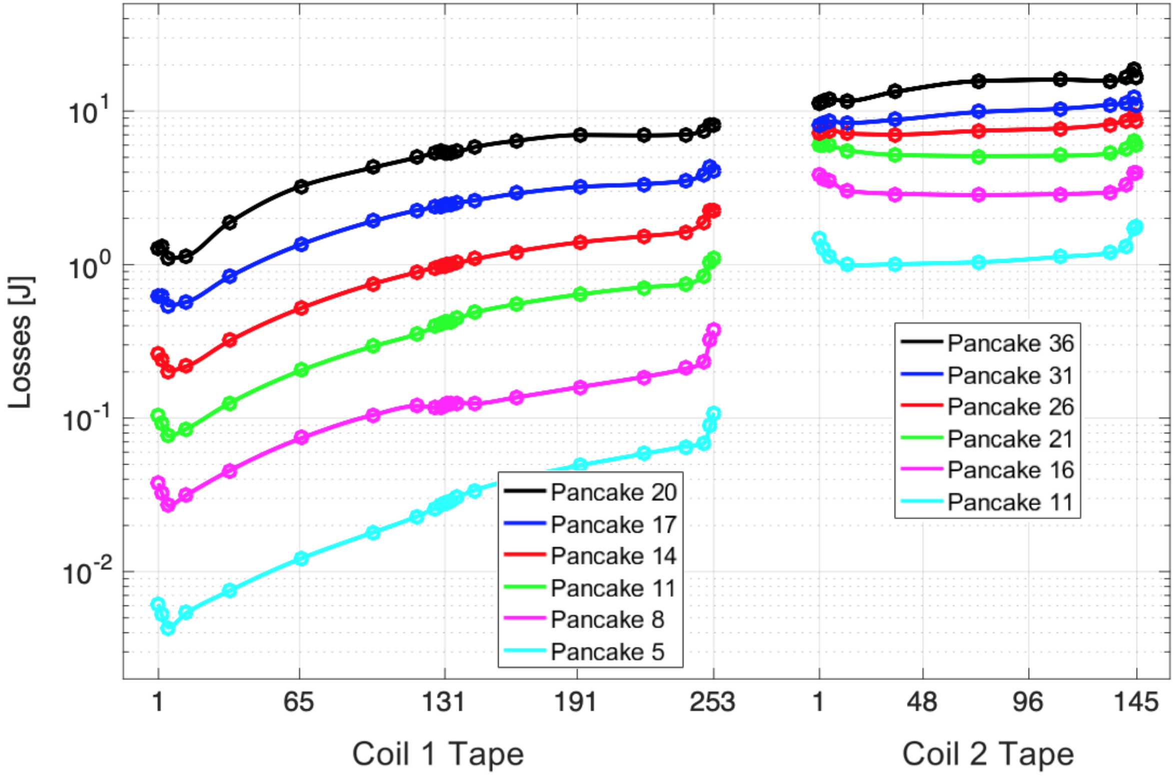

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Computation time

- Multi-scale **19 days** (without the LTS outsert field).
- Homogeneous **4 h 15 min.**

Thank you very much!

References

[1] R. Brambilla, F. Grilli, and L. Martini, "Development of an edge-element model for AC loss computation of high-temperature superconductors," *Supercond. Sci. Technol.*, 2007.

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[10] E. Berrospe-Juarez, V. M. R. Zermeño, F. Trillaud, and F. Grilli, " Real-time simulation of large-scale HTS systems: multi-scale and homogeneous models using the T–A formulation ," *Supercond. Sci. Technol.*, 2019.

[11] D. Kolb-Bond, *et al.*, "Computation of Strains due to Screening Currents in REBCO Magnets at the NHMFL", presented, MT-26, Mon-Af-Po1.11-05, Vancouver, BC, Canada, Sept. 23 – 27, 2019.