Towards a 3D Thermal-Electrodynamic Simulation of Non-Insulated ReBCO Coils: The H-FoSTER Model

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Introduction

With the growing interest in **High-Temperature Superconductors** (**HTS**), **non-insulated magnets** are under development to study if this technology can work, as it would have several advantages:

- They might make **quench protection easier ➔** critical for HTS!
- They potentially operate at **higher current densities**, resulting in **more compact magnet designs**.

However, in non-insulated magnets, we **always need to know where the current is flowing** in order to:

- Guarantee the **quality** of the generated **magnetic field**
- Know the distribution of **mechanical stresses**
- Identify **hot spots** and **stress peaks** during quenches

Hence, develop a **3D numerical model** able to capture the **current dynamics** in non-insulated magnets is **crucial**. The **H-φ** formulation has been for year the **benchmark** to simulate superconductors, but it is very **computationally expensive** when we need to deal with the **highly anisotropic** and **non-linear behaviour** of **HTS** tapes.

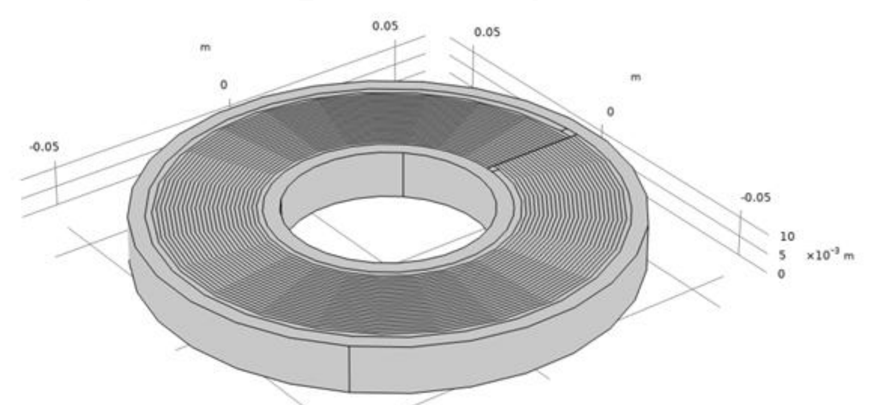
Goal: develop an **efficient 3D model** that describes the **complex electrodynamics** of **non-insulated HTS Pancake Coils.**

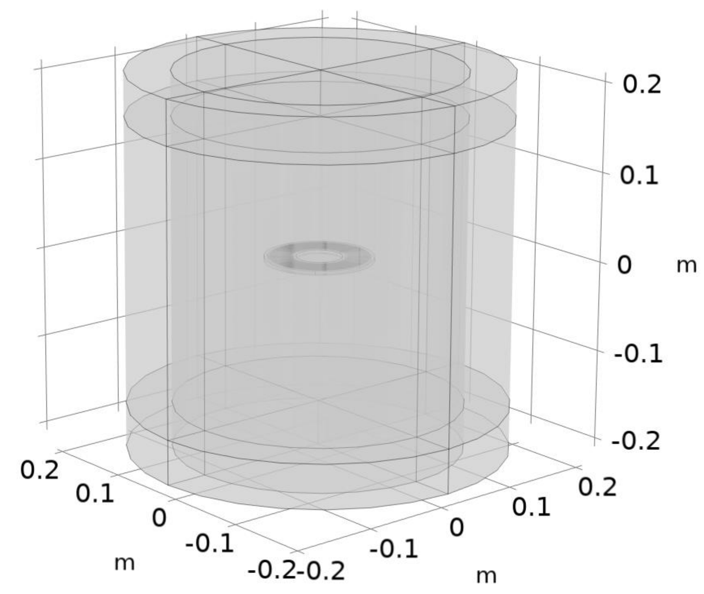
H-FoSTER: a Hybrid Formulation for the Simulation of Thermo-Electrodynamics in ReBCO magnets

Starting point: the total electric field is the sum of two contributions ➔ $E = \underbrace{-\nabla V}_{\text{Electrostatic}} \underbrace{-\frac{\partial A}{\partial t}}_{\text{Magnetic}}$. Hence, the model deals with **two separate modules**:

3D FEM Magnetic

- Defined on the **fully 3D Domain**
- Computes the **magnetic vector potential A**

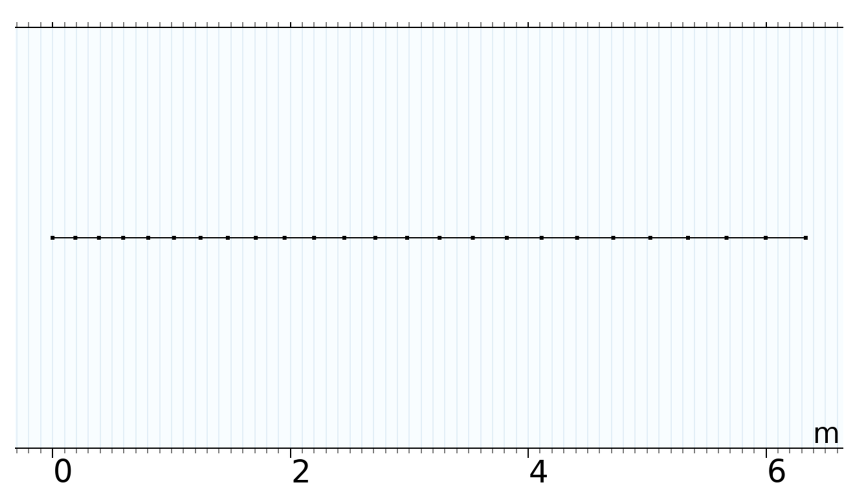




1D FEM + 2D FD Electric

- Defined only on the **1D Domain** representing the **unwound tape**
- Computes the **current density J** and the **electric potential V**

➢ ***Longitudinal current** with **Finite Element Method (FEM)**, **azimuthal** and **z-direction current** with **Finite Differences (FD)**.*

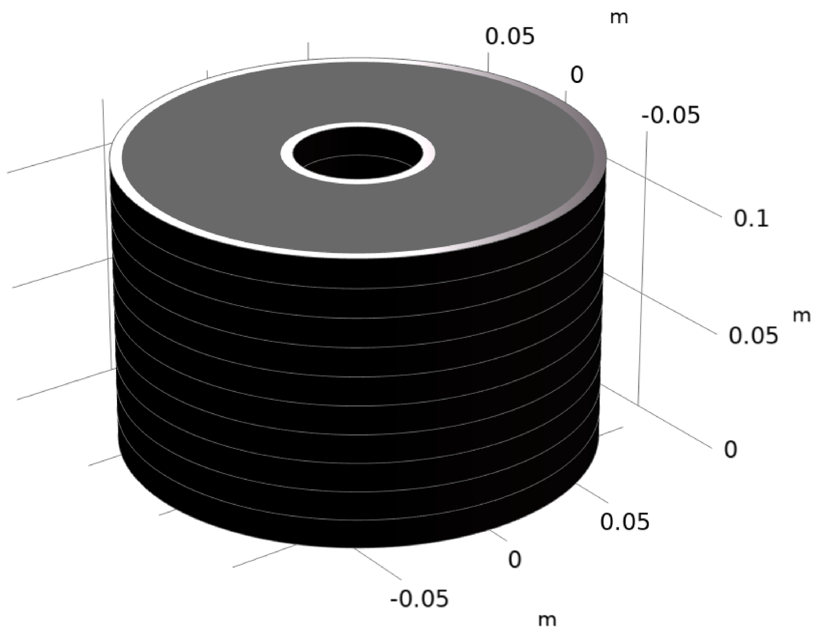


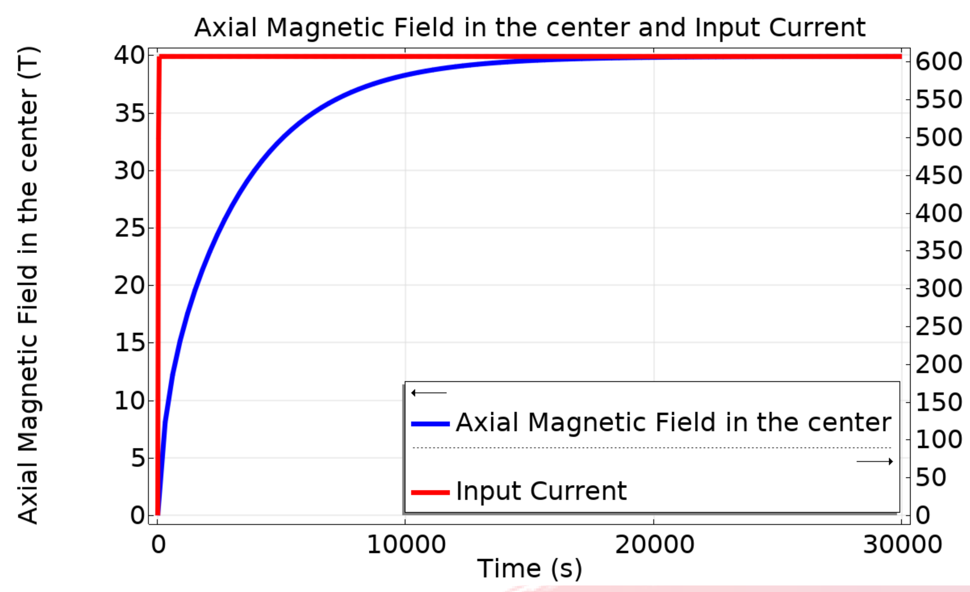
When compared to the classical **H-φ approach** (accurate but computationally heavy), this method is **less demanding** for solving 3D problems, thus offering a **reduced computational time.**

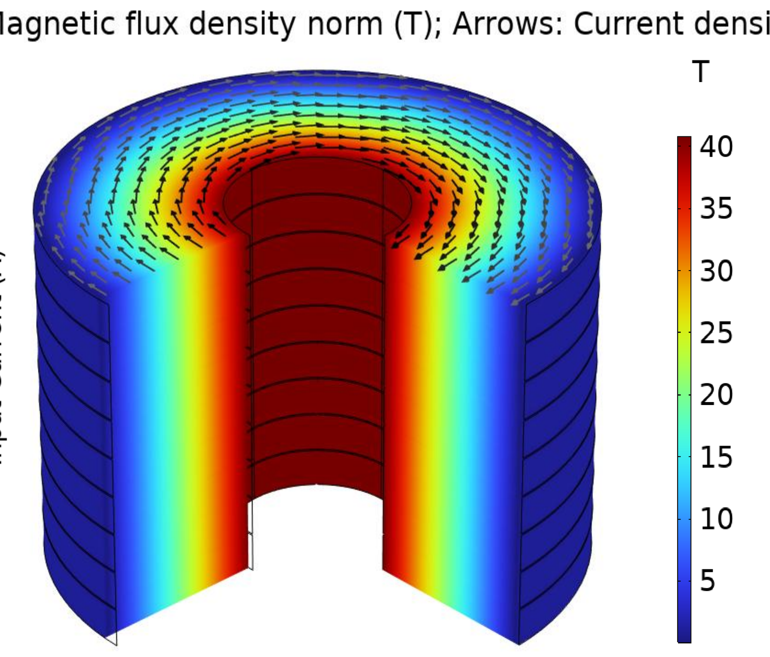
Application: the Energization of the Muon Collider 40 T Solenoid

The entire simulation (**30000 seconds**) needs **~3 hours on a regular PC!**

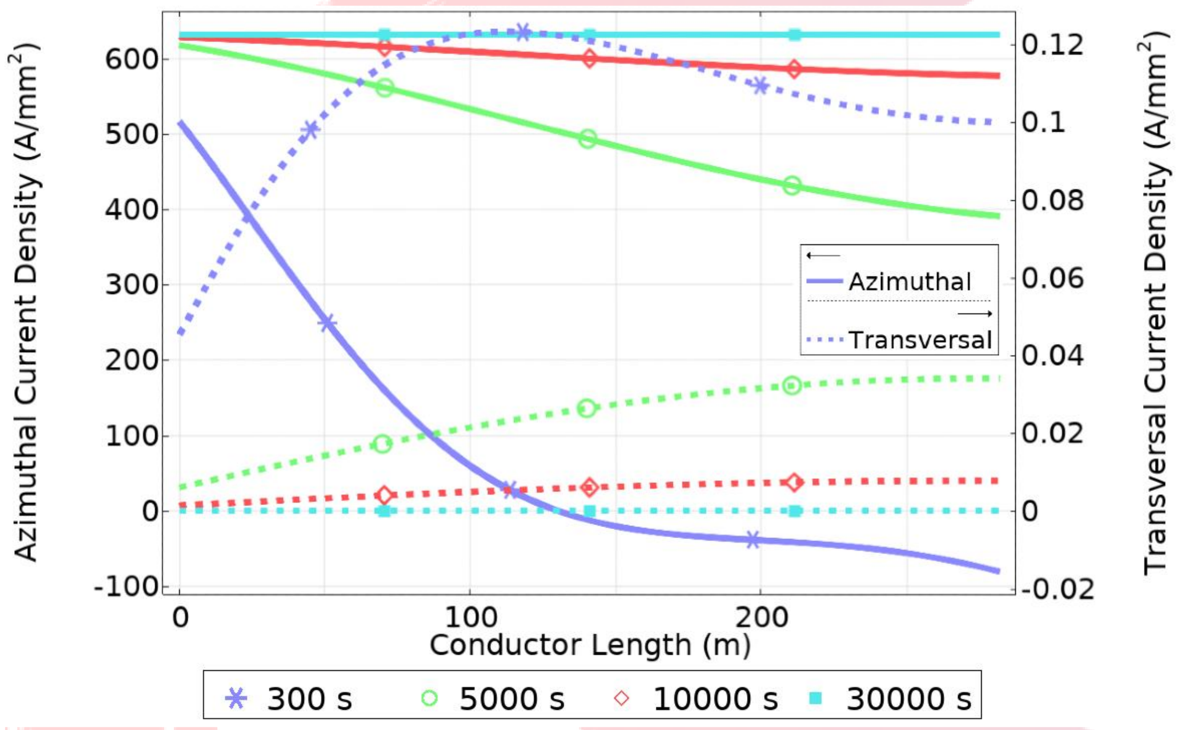
- **Infinite** number of identical **3D** pancakes (by means of **periodic boundary conditions**)
- Coil winding thickness **6 cm**
- Tape thickness **80** μm
- **750 layers** of conductor (each layer simulated)
- Tape width **12 mm**
- **Turn-to-turn contact resistance 10** $\mu\Omega\ cm^2$
- **2 mm** of air between coils
- Max current **607 A**
- Current injected **radially** from the **outermost layer**
- **30000 seconds** simulated
- **Joints** made by few turns of **non-superconducting tape (Cu + Ha)**







With this value **of turn-to-turn contact resistance**, after **16000 s (~4.5 hours)** the solenoid generates **39.6 T**, corresponding to **99%** of the injected current flowing **azimuthally**.



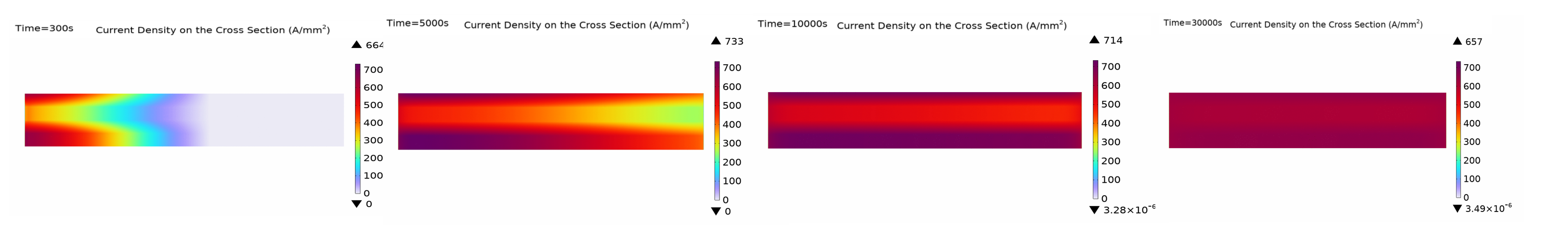
The model is able to compute both the **azimuthal** and the **transversal current density distribution through the entire length of the conductor**, from the innermost to the outermost turn.

Azimuthal ➔ current parallel to the tape

Transversal ➔ current perpendicular to the tape (turn-to-turn)

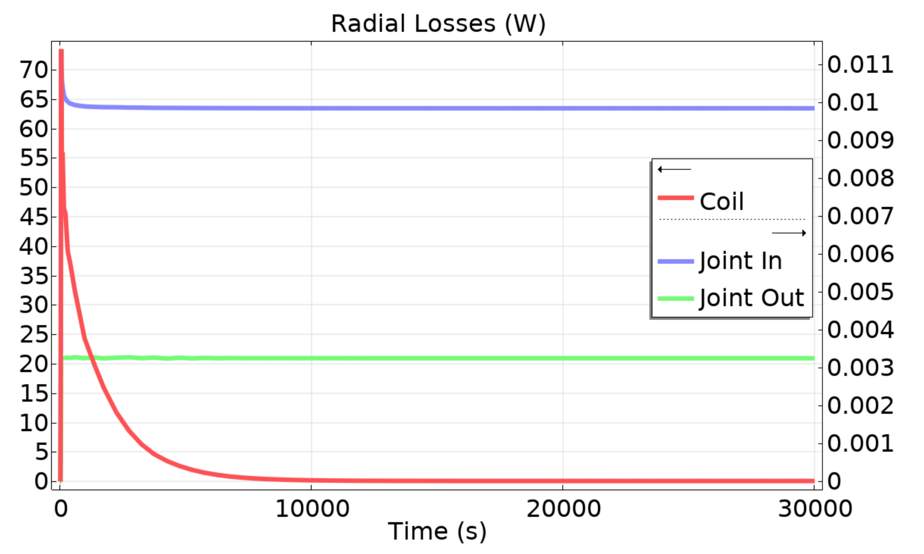
Initially, **most** of the **current flows transversely** through the tape, due to **inductive effects**, which generate a **voltage difference between the innermost and the outermost turn**. In the later stages, **inductive effects diminish**, hence most of the **current flows azimuthally**, **generating** the expected **magnetic field**.

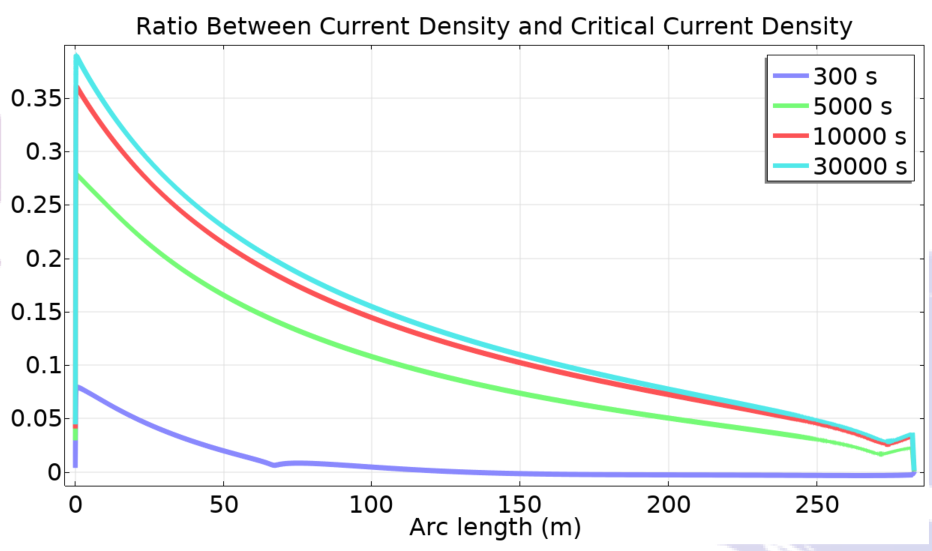
The model can compute the **screening currents** in the magnet (**for each layer**). This can be observed by plotting the **current density distribution** on one of the magnet's cross-sections:



At the beginning, **screening currents** appear to **straighten the field lines** that are bent on the edges, while they **disappear at the end of the simulation** since there are **no more inductive effects** at the steady state.

The model computes losses easily as well. Although the thermal behaviour is not modeled here, it is interesting to look at their evolution over time. The **losses** increase to a peak value of around **70 W** and they decay exponentially to zero as time progresses. Joints do not play a major role here.

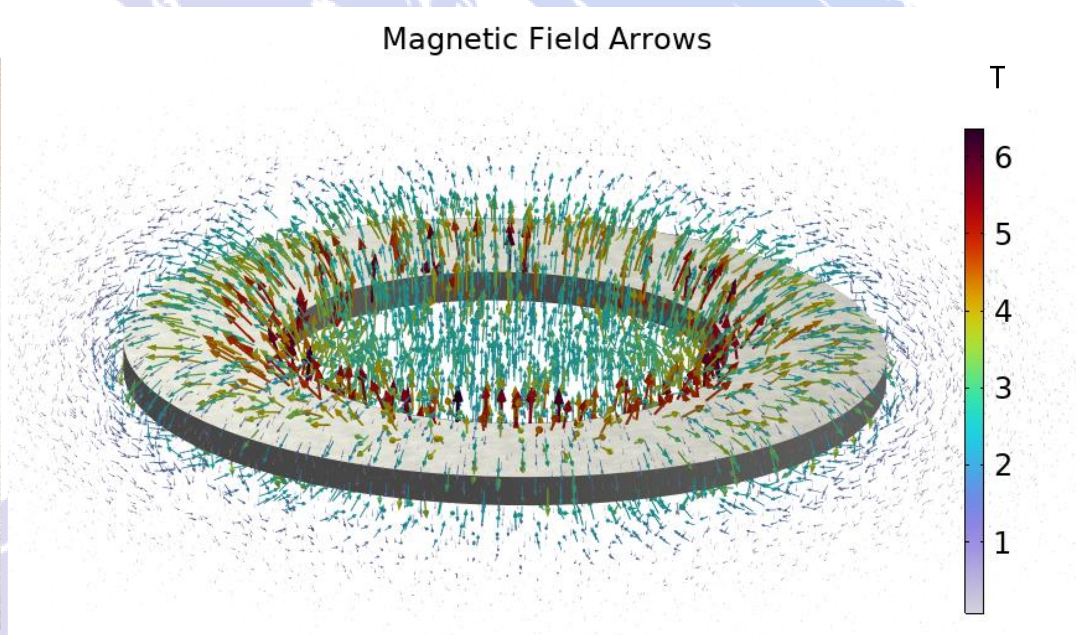




Only **radial losses are plotted**, as **longitudinal losses** are **basically zero** since the tape remains **far from the critical current** for the entire simulation: **the J over J_c ratio never exceeds 40%**!

Validation with experimental results will start soon!

Soldered Pancake, 276 turns
(courtesy of M. A. Hafiz and G. Scarantino)



Simulation of the **same pancake** (600 A input current)

The work is still ongoing!

- ✅ Screening Currents
- ✅ Electrical Joints
- ➢ Thermal effects

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