HTS 2020 Modelling

UNIVERSITÉ DE LORRAINE

G.R.E.E.N.

2D and 3D validation of a hybrid method based on A and H formulations for Pulsed Field Magnetization

Jakub KAPEK, Kévin BERGER, Jean LÉVÊQUE

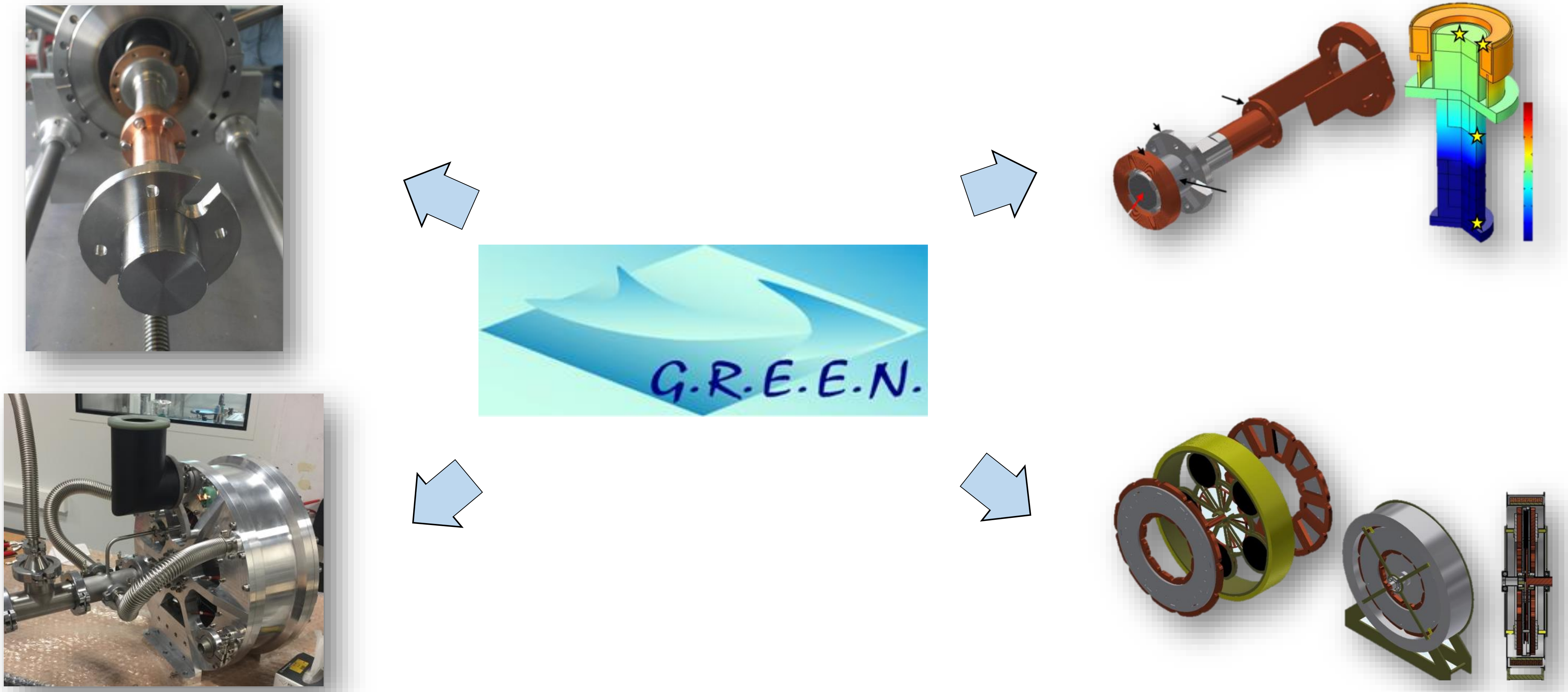
Outlines

1. Introduction

2. Formulation **A – H**

3. Validation of the formulation **A – H**

4. Summary



Examples of projects carried out in the GREEN laboratory

1. Introduction

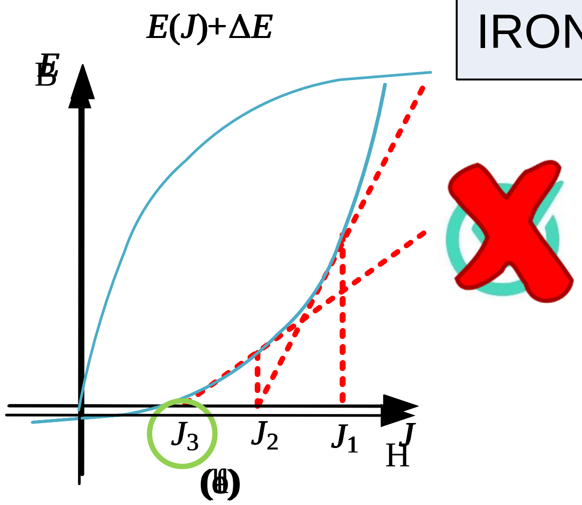
$$\frac{\partial \mu(\mathbf{H})\mathbf{H}}{\partial t} + \nabla \times (\rho \nabla \times \mathbf{H}) = 0$$

$$\begin{cases} \mathbf{E} = \rho \mathbf{J} \\ \mathbf{J} = \nabla \times \mathbf{H} \\ \nabla \times \mathbf{E} = -\dfrac{\partial \mathbf{B}}{\partial t} \\ \mathbf{B} = \mu(\mathbf{H})\mathbf{H} \end{cases}$$

Formulation **H**

Newton's method

IRON



- Recommended for superconductor problems

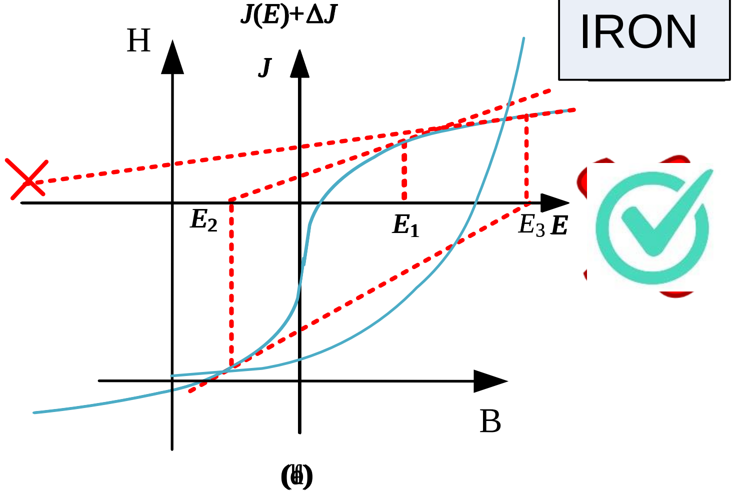
$$\sigma \frac{\partial \mathbf{A}}{\partial t} + \nabla \times \left(\frac{1}{\mu(\mathbf{B})} \nabla \times \mathbf{A} \right) = 0$$

$$\begin{cases} \mathbf{B} = \nabla \times \mathbf{A} \\ \nabla \times \mathbf{H} = \mathbf{J} \\ \mathbf{J} = \sigma \mathbf{E} \\ \mathbf{E} = -\dfrac{\partial \mathbf{A}}{\partial t} \end{cases}$$

Formulation **A**

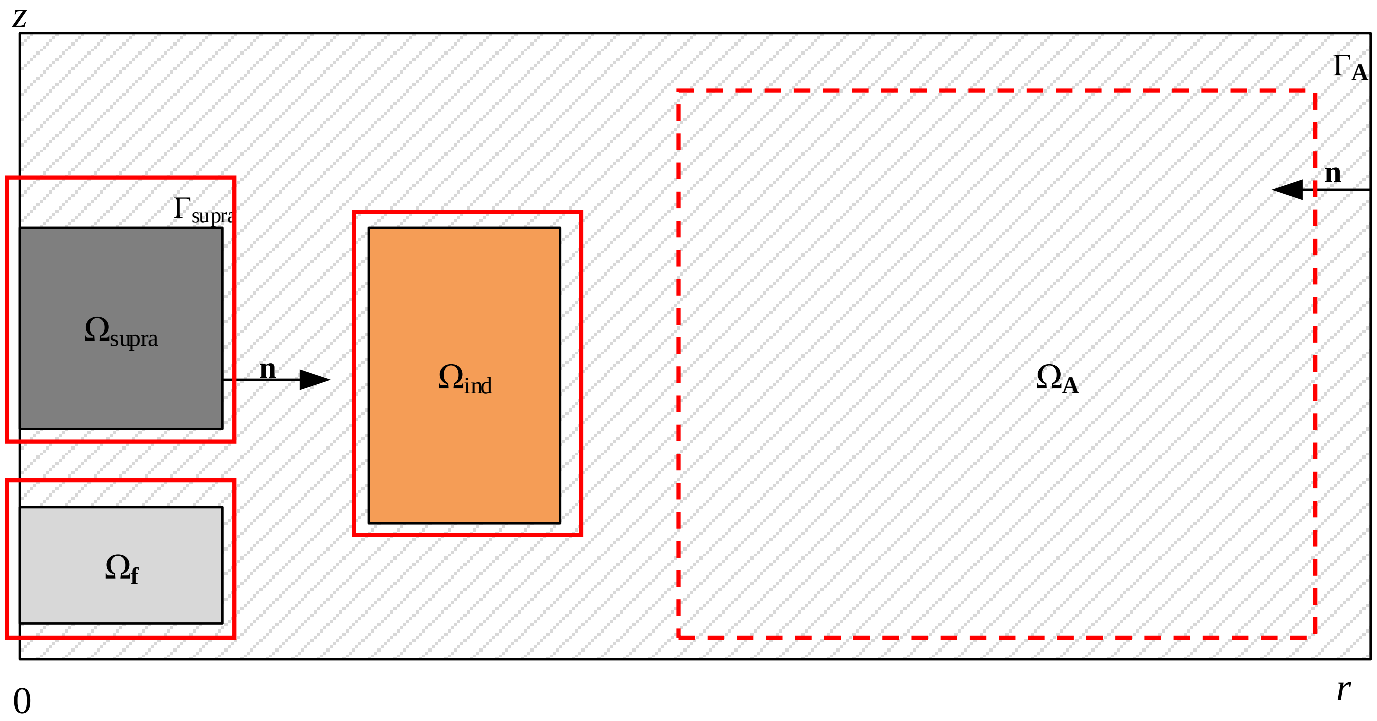
Newton's method

IRON



- Recommended for problems with ferromagnetic materials

2. Formulation A – H



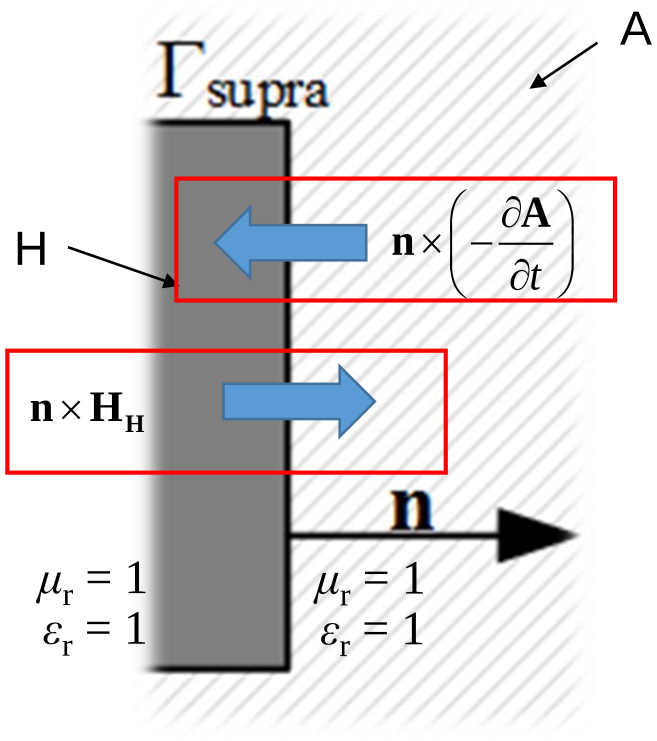
Example of a model to apply the **A-H** formulation.

Formulation en **A – H :**

$$\begin{cases} \nabla \times \left(\dfrac{1}{\mu_0} \nabla \times \mathbf{A} \right) = \mathbf{J}_{app}, & \text{dans } \Omega_{ind}, \\ \nabla \times \left(\dfrac{1}{\mu(\mathbf{B})} \nabla \times \mathbf{A} \right) = 0, & \text{dans } \Omega_f, \\ \nabla \times \left(\dfrac{1}{\mu_0} \nabla \times \mathbf{A} \right) = 0, & \text{dans } \Omega_{\mathbf{A}}, \end{cases}$$

$$\left\{ \mu_0 \frac{\partial \mathbf{H}}{\partial t} + \nabla \times \left(\rho \nabla \times \mathbf{H} \right) = 0, \quad \text{dans } \Omega_{supra} \right.$$

2. Formulation A – H



Interface conditions for electromagnetic fields between two different media:

$$\mathbf{n}\cdot(\mathbf{B}_A - \mathbf{B}_H) = 0$$
$$\mathbf{n}\times(\mathbf{E}_A - \mathbf{E}_H) = 0$$
$$\mathbf{n}\cdot(\mathbf{D}_A - \mathbf{D}_H) = 0$$
$$\mathbf{n}\times(\mathbf{H}_A - \mathbf{H}_H) = 0$$

$\mu_r = 1$
$\varepsilon_r = 1$

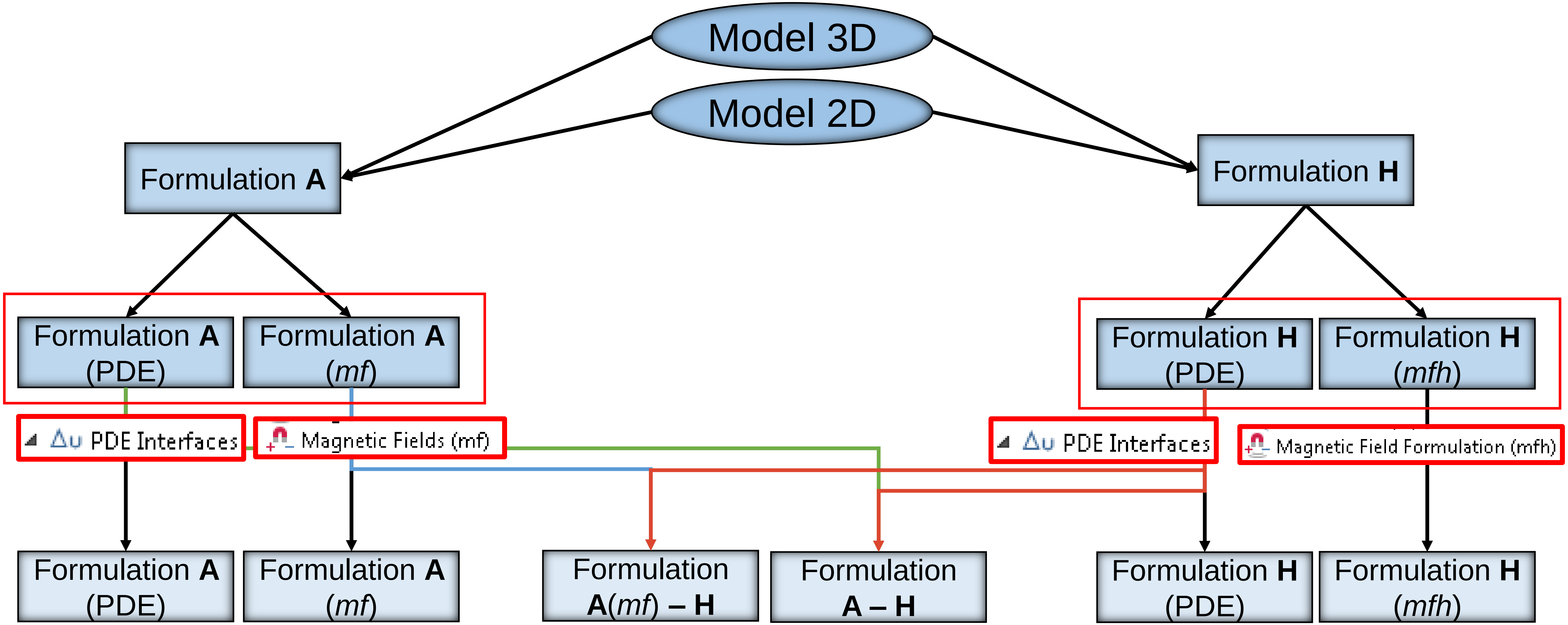
$$\mathbf{n}\cdot(\nabla\times\mathbf{A} - \mu\mathbf{H}_H) = 0$$
$$\mathbf{n}\times(-\partial_t\mathbf{A} - \rho\nabla\times\mathbf{H}_H) = 0$$
$$\mathbf{n}\cdot(-\sigma\partial_t\mathbf{A} - \nabla\times\mathbf{H}_H) = 0$$
$$\mathbf{n}\times\left(\frac{1}{\mu}\nabla\times\mathbf{A} - \mathbf{H}_H\right) = 0$$

Coupling :

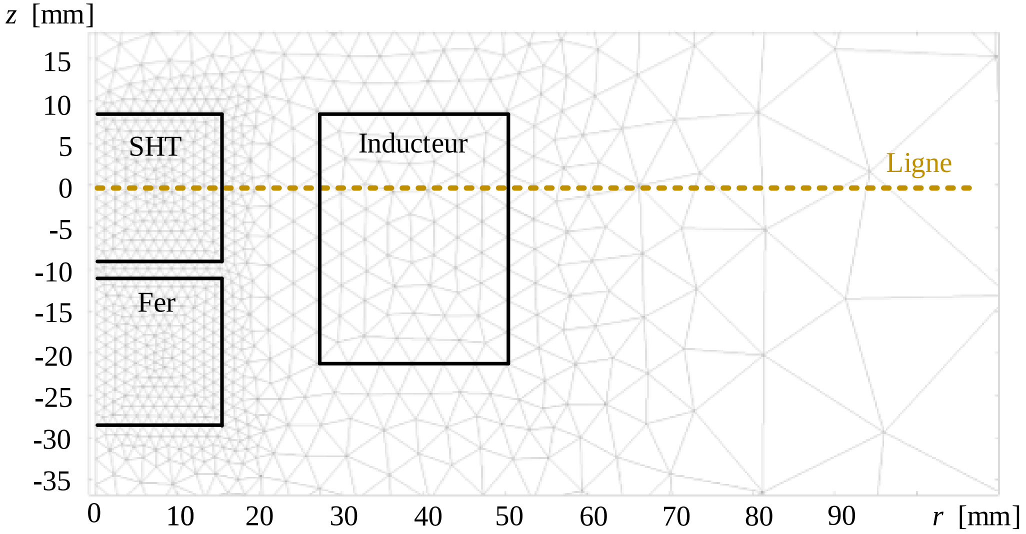
$$\mathbf{n}\times\mathbf{H}_H \rightarrow \mathbf{n}\times\left(\frac{1}{\mu}(\nabla\times\mathbf{A})\right)$$

$$\mathbf{n}\times\left(-\frac{\partial\mathbf{A}}{\partial t}\right) \rightarrow \mathbf{n}\times\left(\rho(\nabla\times\mathbf{H}_H)\right)$$

3. Validation of the formulation A – H



3. Validation of the formulation A – H, 2D

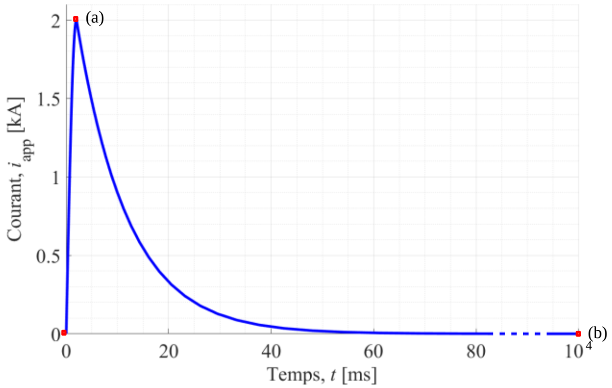


2D axisymmetric problem used to verify the **A – H** formulation.

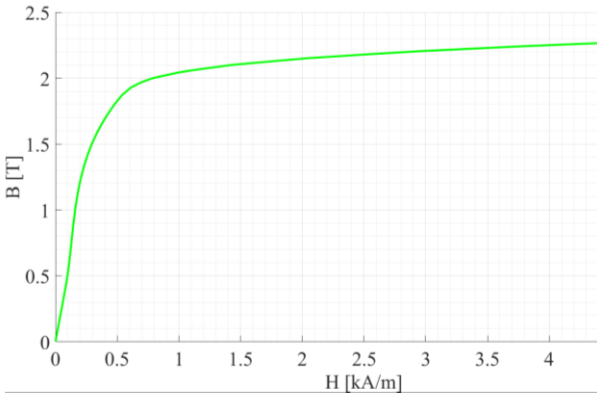
Electrical and magnetic parameters of the materials used for the verification of the formulation **A – H**.

Symbol	Materials	Electrical parameters	Magnetic parameters
Ω_{supra}	SHT	$\rho = \frac{E_c}{J_c(B)}\left(\frac{\lVert \mathbf{J} \rVert}{J_c(B)}\right)^{n(B)-1}$ 1) ou $\sigma = \frac{J_c(B)}{E_{c0}}\left(\frac{\lVert \mathbf{E} \rVert}{E_{c0}}\right)^{\frac{1-n(B)}{n(B)}}$ 2) $n=21,\ E_c = 1\ \mu\text{V/cm},\ J_c = 100\ \text{A/mm}^2$	$\mu_r = 1$
Ω_{ind}	Cuivre	$\rho = 1\ \Omega\cdot\text{m}$ 1) ou 2) $\sigma = 0\ \text{S/m}$	$\mu_r = 1$
Ω_{fer}	Fer	$\rho = 1\ \Omega\cdot\text{m}$ 1) ou 2) $\sigma = 0\ \text{S/m}$	$\mu_r = f(\mathbf{H})$ 1) ou $\mu_r = f(\mathbf{B})$ 2)
Ω_A	Air	$\rho = 1\ \Omega\cdot\text{m}$ 1) ou 2) $\sigma = 0\ \text{S/m}$	$\mu_r = 1$

1) for the formulation in H, 2) for the formulation in A

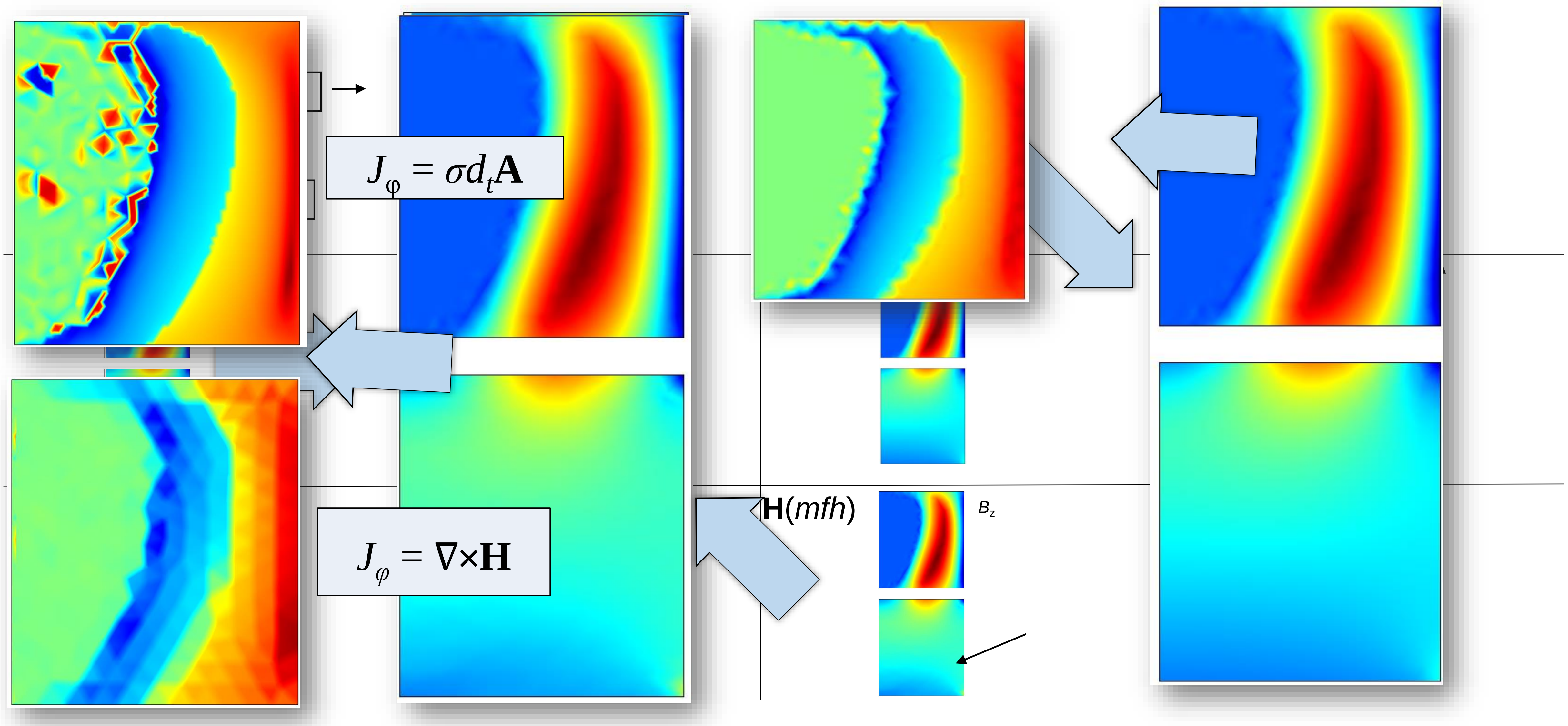


Form of the current in the inductor.



B(H) curve shape of iron-cobalt material.

3. Validation of the formulation A – H, 2D

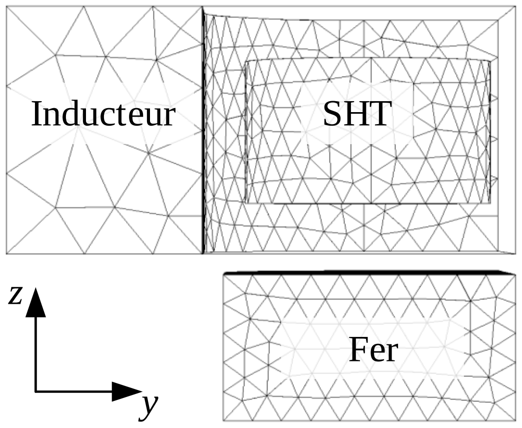


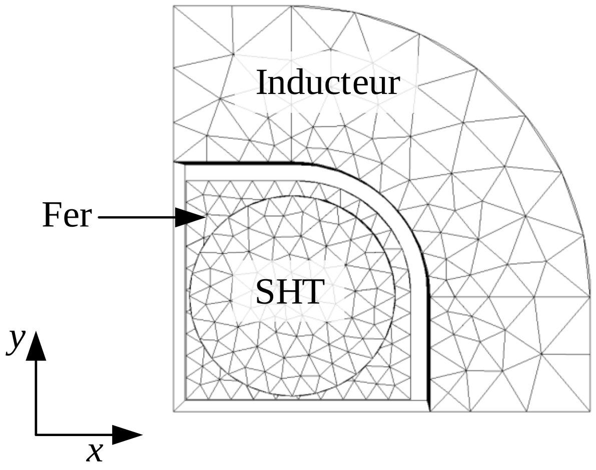
3. Validation of the formulation A – H, 2D

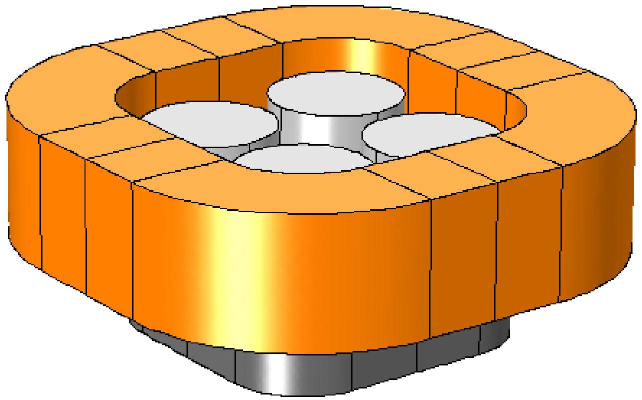
Comparison of computation time and number of degrees of freedom for a 2D axisymmetric problem.

Formulation	Calculation time	Number of degrees of freedom (DDL)
Formulation **A** – **H**	3 min 7 s	5 244
Formulation **A**(*mf*) – **H**	3 min 0 s	5 244
Formulation **A**	28 s	4 150
Formulation **A**(*mf*)	21 s	4 150
Formulation **H**	9 min 49 s	10 242
Formulation **H**(*mfh*)	12 min 14 s	10 242

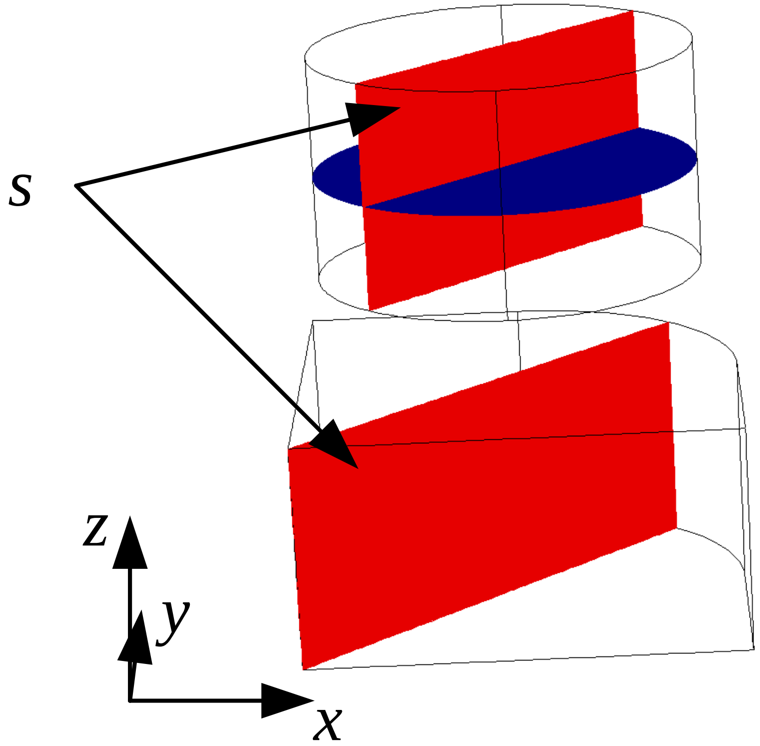
3. Validation of the formulation A – H, 3D





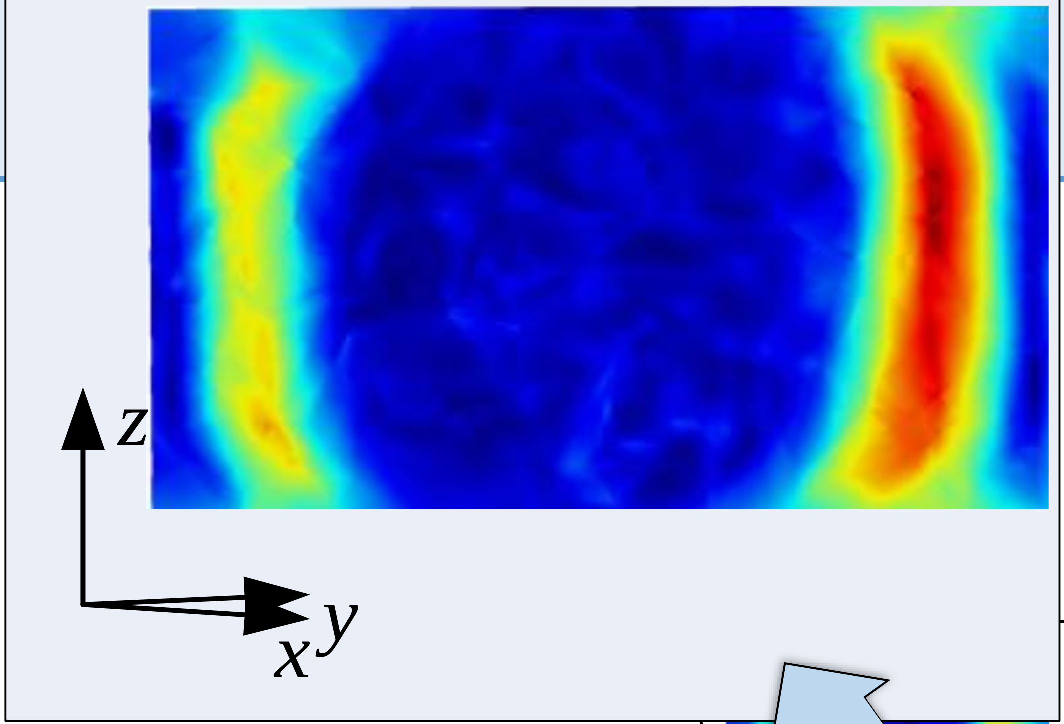


3D model for magnetization of superconductors



The s-plane cuts both the superconductor and the iron.

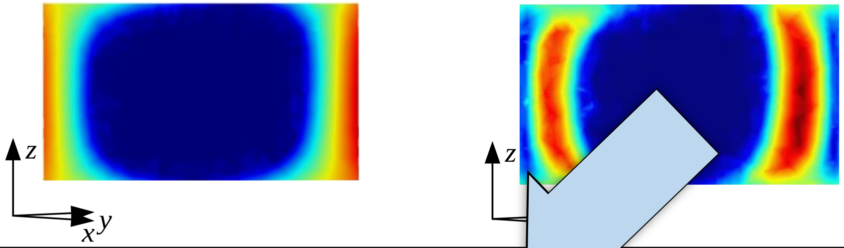
on A – H, 3D

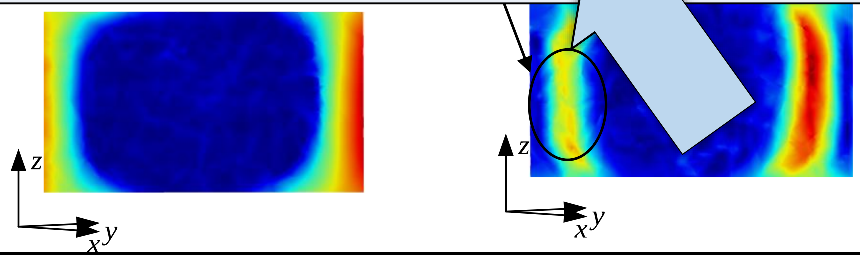


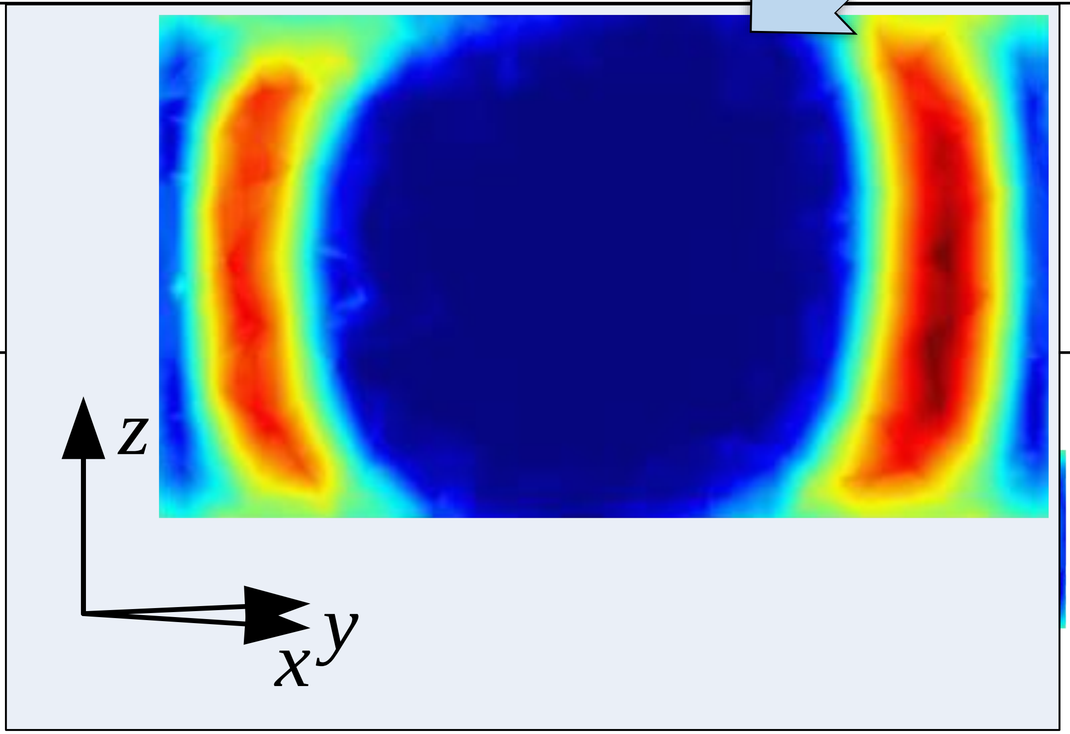
A(*mf*) – H

$\mathbf{B}_1$, t = 2 ms

$\mathbf{B}_2$, t = 100 ms



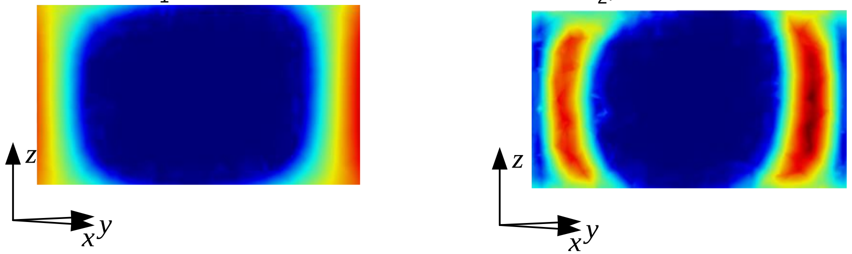




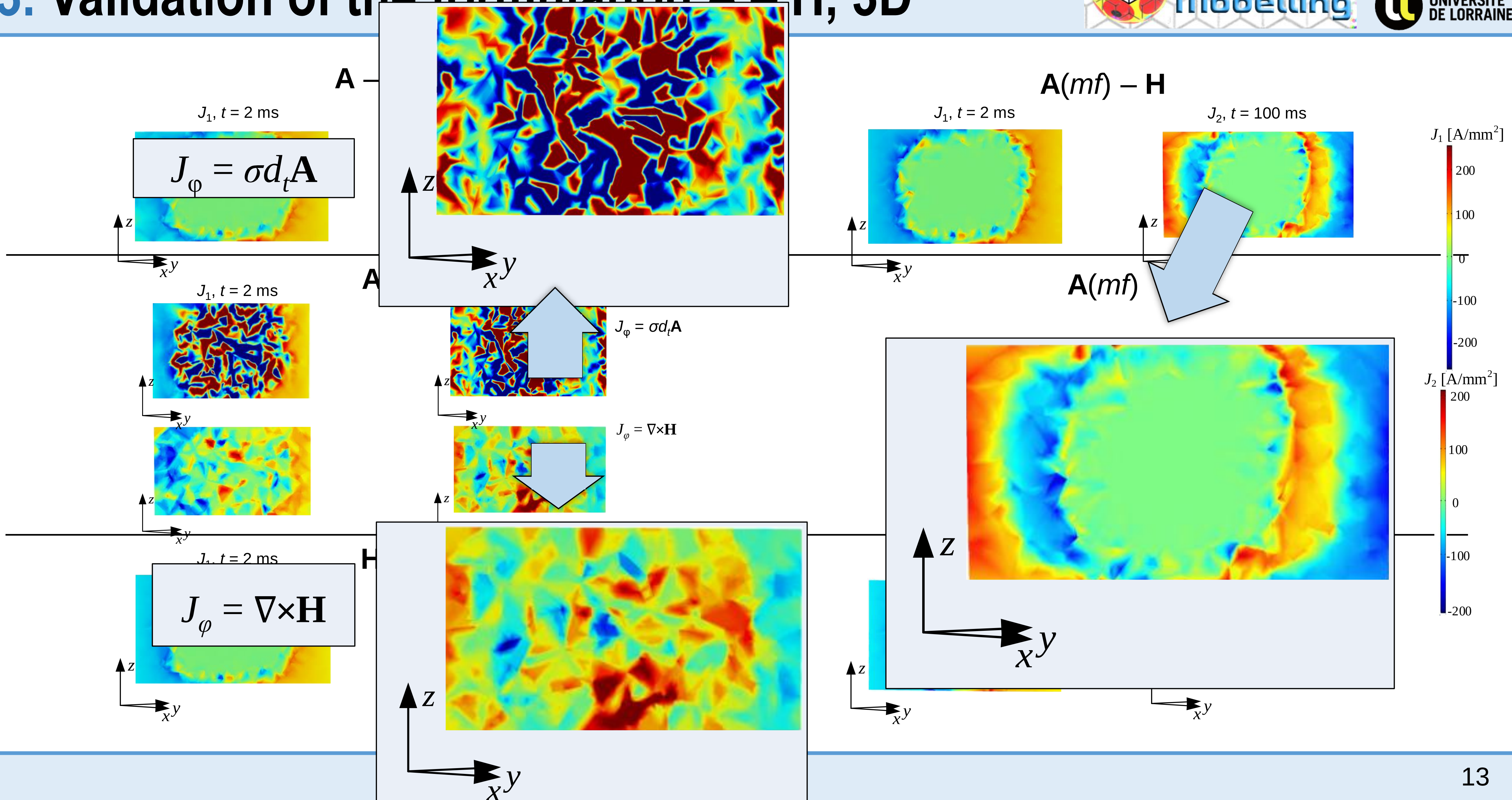
H

$\mathbf{B}_1$, t = 2 ms

$\mathbf{B}_2$, t = 100 ms



3. Validation of the formulation A – H, 3D



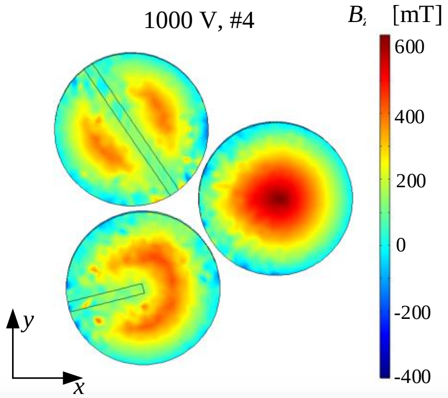
3. Validation of the formulation A – H, 3D

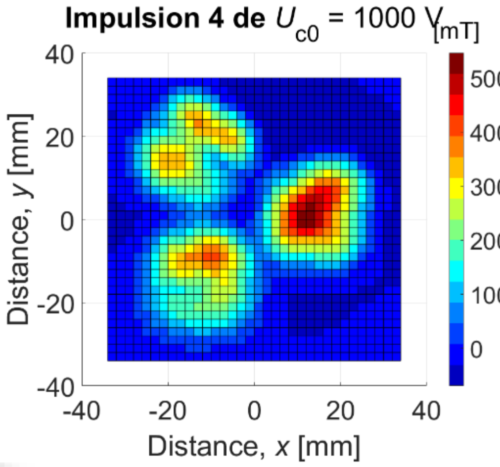
Comparison of the computation time and the number of degrees of freedom for a 3D problem.

Formulation	Calculation time	Number of degrees of freedom (DDL)
Formulation **A – H**	7 h 20 min 42 sec	141 132
Formulation **A**(*mf*) – **H**	1 j 0 h 8 min 44 sec	199 704
Formulation **A**	1 j 9 h 27 min 29 sec	126 447
Formulation **A**(*mf*)	Not solved	196 264
Formulation **H**	4 h 7 min 25 sec	196 264
Formulation **H**(*mfh*)	5 h 22 min 28 sec	196 264

6. Summary

1. The **A – H** formulation in 2D and 3D has been presented
2. Good convergence with superconductors
3. Potential use in modeling magnetization problems or superconducting electric motors
4. The **A – H** formulation was combined with a thermal model and used to simulate the magnetization process of 3 HTS





Thank you for your attention