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# Multiscale Modelling of Nonlinear Eddy Current Problems Using the $h$ -conforming Formulation

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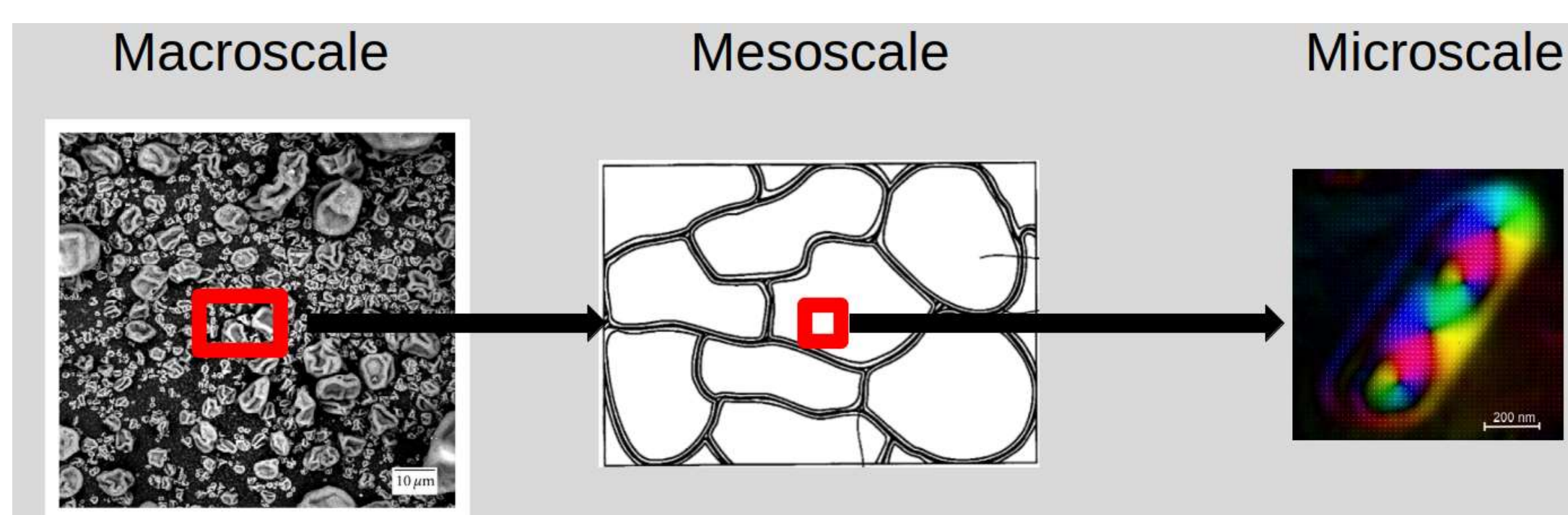
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## Abstract

This paper deals with an  $h$ -conforming multiscale formulation for nonlinear eddy current problems in idealized soft magnetic composites using the heterogeneous multiscale method. The classical  $h$ - $\phi$  formulation is recalled before presenting the different components of the  $h$ - $\phi$  multiscale formulation including the governing weak forms, the upscaling of quantities of interest and details some on the numerical implementation. Validation results are then presented before a conclusion.

## 1. Introduction

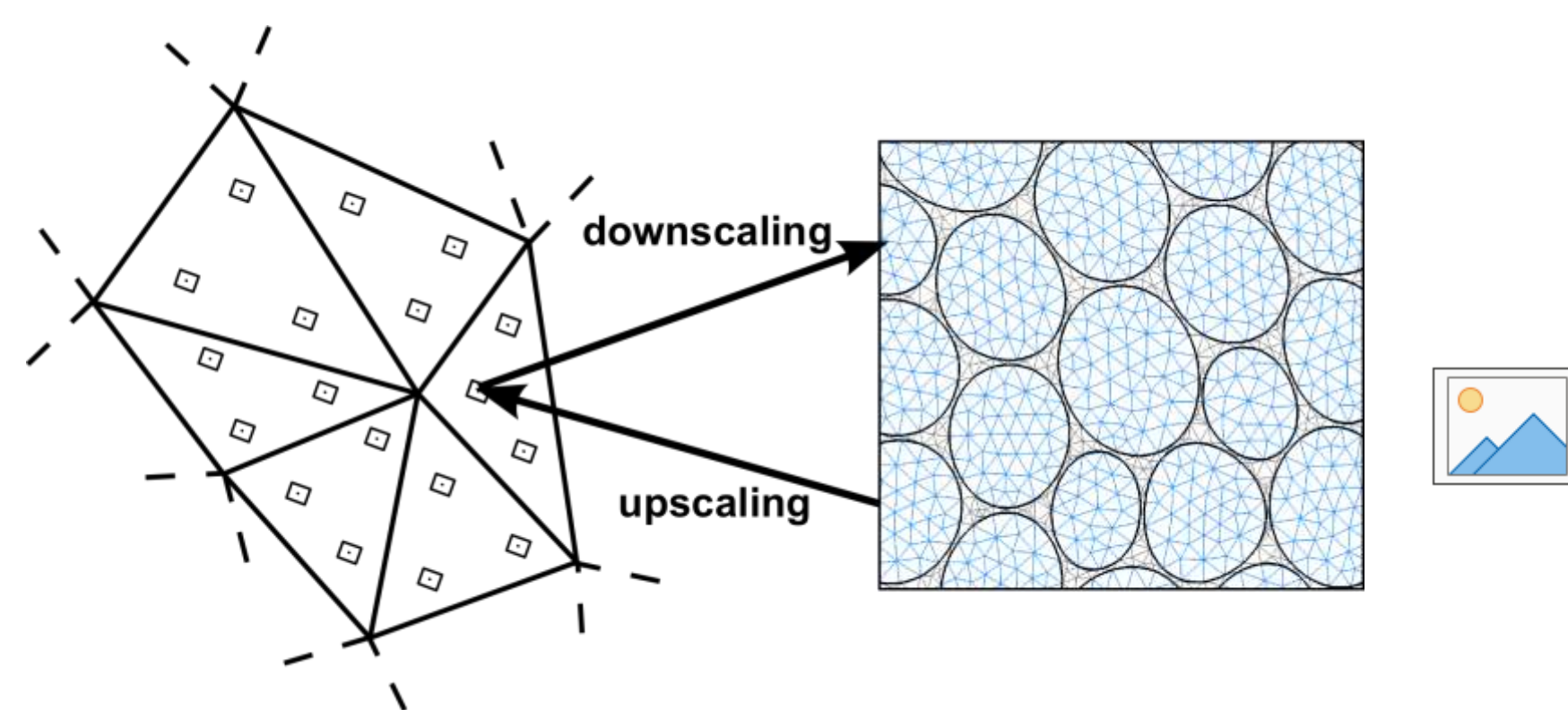
- Electrical devices with soft magnetic composites (SMC) can operate at higher frequencies with reduced eddy current losses.
- SMC exhibit isotropic nonlinear/hysteretic behaviour.
- Classical numerical methods such as FEM are too costly and multiscale methods are more convenient to characterize SMC. In this research work, we used the heterogeneous multiscale method (HMM).



## 3. Multiscale formulation

### Scale separation :

Length of the microstructure  $\ll$  length of device / characteristic length of external loadings.



- At each iteration: 1 macroproblem and many microproblems (1 per Gauss point of the Macro mesh). Couple these problems (**upscaling-downscaling**).

### Strong form :

• **Macro** :  $\text{curl}_x \mathbf{h}_M = \mathbf{j}_M$ ,  $\text{curl}_x \mathbf{e}_M = -\partial_t \mathbf{b}_M$ ,

$$\mathbf{b}_M = \mathcal{B}_M(\mathbf{h}_M), \mathbf{e}_M = \rho \mathbf{j}_M = \rho \text{curl}_x \mathbf{h}_M.$$

• **Meso** :  $\text{curl}_y \mathbf{h}_c = \mathbf{j}_c$ ,  $\text{curl}_y (\mathbf{e}_c - \kappa \partial_t \mathcal{B}_M \times \mathbf{y}) = -\partial_t \mathbf{b}_m$ ,

$$\mathbf{b}_m = \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c), \mathbf{e}_c = \rho \mathbf{j}_c = \rho \text{curl}_y \mathbf{h}_c.$$

### Weak form :

• **Macro** :  $\left( \frac{\partial}{\partial t} \mathcal{B}_M(\mathbf{h}_M), \mathbf{v}_M \right)_{\Omega} + \left( \rho \text{curl}_x \mathbf{h}_M, \text{curl}_x \mathbf{v}_M \right)_{\Omega_c} + \sum_{i \in \mathcal{C}} \mathcal{I}_i V_i = 0.$

• **Meso 1** :  $\left( \frac{\partial}{\partial t} \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c), \mathbf{v}_c \right)_{\Omega_m} + \left( \rho \text{curl}_y \mathbf{h}_c, \text{curl}_y \mathbf{v}_c \right)_{\Omega_{mc}} = \left( \kappa \sigma \partial_t \mathcal{B}_M \times \mathbf{y}, \text{curl}_y \mathbf{v}_c \right)_{\Omega_{mc}}$

• **Meso 2** :  $\left( \mathcal{B}(\mathbf{h}_M + \text{grad}_y \phi_c), \text{grad}_y \phi_c' \right)_{\Omega_m} = 0$

### Upscaling :

Upscaling of  $\mathcal{B}_M$  using Meso 1:  $\mathcal{B}_M = \frac{1}{|\Omega_m|} \iiint_{\Omega_m} \mathcal{B}(\mathbf{h}_M + \mathbf{h}_c)$

Upscaling of  $\frac{\partial \mathcal{B}_M}{\partial t}$  using problem Meso 2 and the finite difference method.

### Implementation :

- Temporal discretization using the Backward Euler method
- Nonlinear problem solved using a relaxed Newton-Raphson scheme

## Conclusions:

- HMM yields accurate local fields and global quantities (Joule losses, voltage, etc.) for nonlinear eddy current problems with idealized SMC.
- $\mathcal{B}_M$  is upscaled using fields of the magnetodynamic problem whereas  $\frac{\partial \mathcal{B}_M}{\partial t}$  is obtained using fields of the magnetostatic problem.
- Adaptive relaxation should be used for the convergence of the nonlinear meso-problems and of macro-problem (if there is too much saturation).
- The HMM algorithm scales very well on clusters.

## 2. Classical formulation

- Maxwell's equations and constitutive law:

$$\text{curl} \mathbf{h}^\varepsilon = \mathbf{j}^\varepsilon, \text{curl} \mathbf{e}^\varepsilon = -\partial_t \mathbf{b}^\varepsilon,$$

$$\mathbf{b}^\varepsilon = \mathcal{B}(\mathbf{h}^\varepsilon), \mathbf{e}^\varepsilon = \rho^\varepsilon \mathbf{j}^\varepsilon = \rho^\varepsilon \text{curl} \mathbf{h}^\varepsilon.$$

- Weak form:  $\left( \frac{\partial}{\partial t} \mathcal{B}(\mathbf{h}^\varepsilon), \mathbf{v} \right)_{\Omega} + \left( \rho^\varepsilon \text{curl} \mathbf{h}^\varepsilon, \text{curl} \mathbf{v} \right)_{\Omega_c} + \sum_{i \in \mathcal{C}} \mathcal{I}_i V_i = 0.$

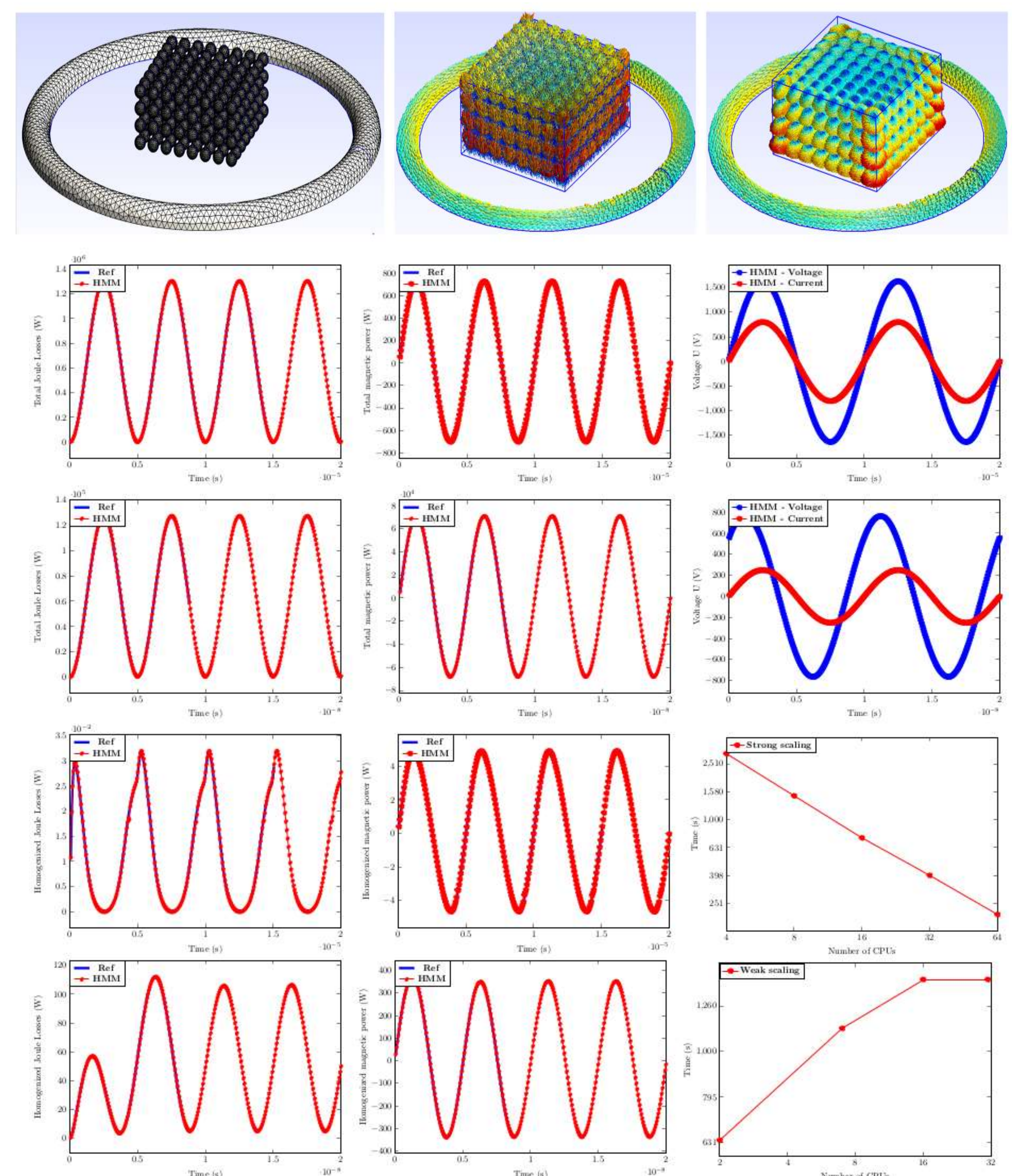
- Discretization of the magnetic field:

$$\mathbf{h}^\varepsilon(\mathbf{x}) = \sum_{e \in \Omega_c} h_e \mathbf{S}_e(\mathbf{x}) + \sum_{n \in \Omega_c^c} \phi_n \text{grad} S_n(\mathbf{x}) + \sum_{i \in \mathcal{C}} \mathcal{I}_i \mathbf{c}_i(\mathbf{x})$$

## 4. Numerical Results

**Geometry** : 8 x 8 x 8 conductive spheres (radius  $r = 40\mu\text{m}$ ) surrounded by a massive inductor.

**Material laws** : conductivity  $\sigma = 10^7 \text{Sm}$ , nonlinear Fröhlich-Kennely law.



## Perspectives :

- Use of the HMM method to model closed magnetic circuits such as the transformers.
- Extension of the formulation to account for macroscale currents (e.g., problems with macroscale displacement currents).
- Use of the model order reduction (MOR) for further reduction of the computational cost.