mechanism

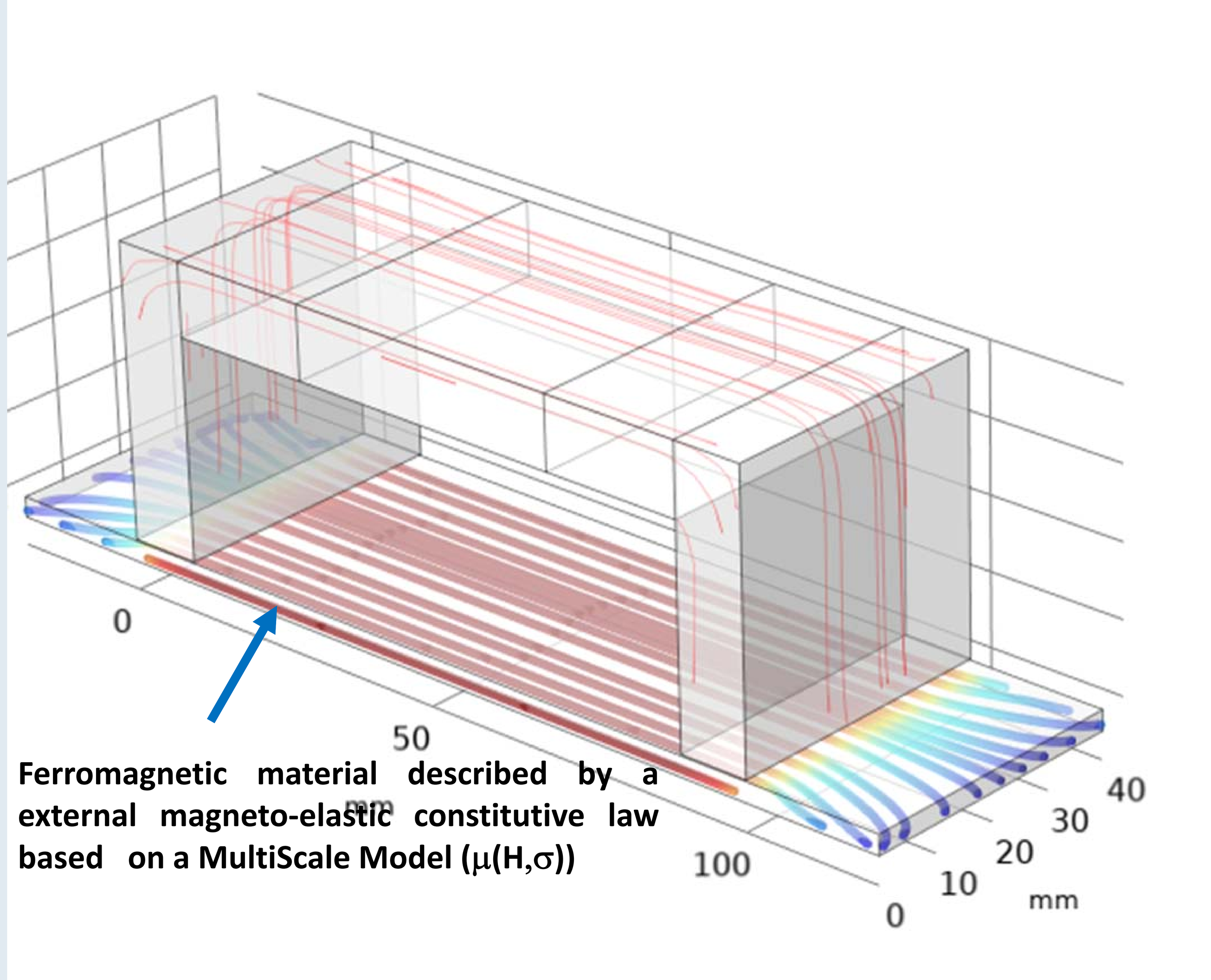

Figure 1 : magnetic flux line in the setup

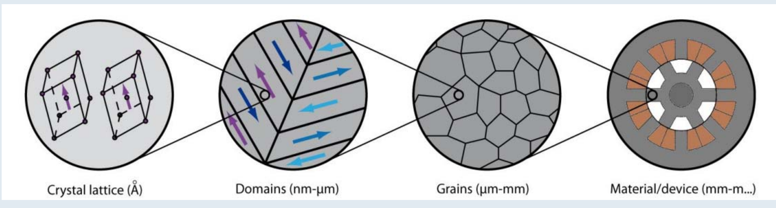

Figure 2 : Multi-Scale mechanism

Use of a magneto-elastic constitutive law for modelling a magneto-mechanical characterization setup

External C function is used to introduce a magneto-elastic constitutive law to define the characterized material behavior.

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Goal : Modelling of a ferromagnetic material characterization device in Comsol Multiphysics

- Geometry consists of a magnetic circuit exciting the ferromagnetic sample to be characterized
- Stationary study low-frequency 3D model is used (AC/DC Module) with a Scalar potential magnetic formulation (magnetic field and no current formulation) (MFNC)
- To define the characterized ferromagnetic material behaviour a magneto-elastic constitutive law must be used which relates the induction magnetic field **B** to the electromagnetic field **H** and a stress state σ. Solving the problem requires a non-linear process

$$B = \mu(H,\sigma)H$$

Comsol Multiphysics Modelling

Model used

- **Magnetic Field, No Current (MFNC) which provides H**
- **Stationary study**

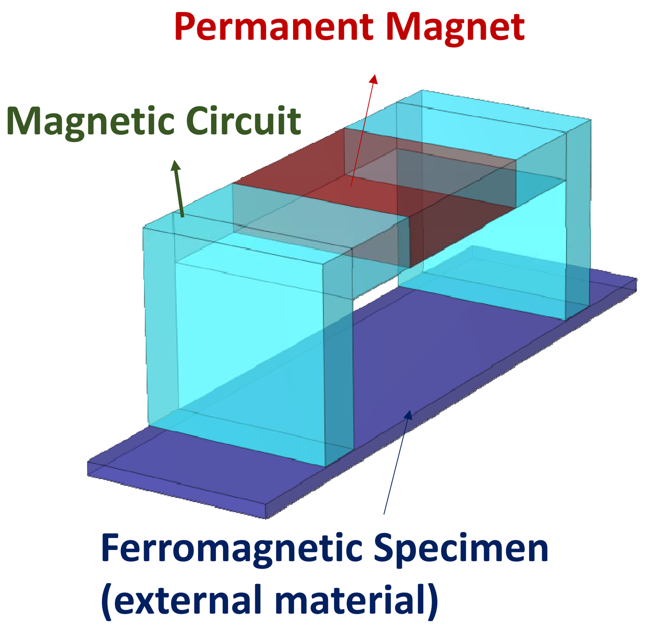

FIGURE 3 : Geometry of the Characterization device

External Material definition

- Definition of an external material in Comsol Multiphysics
- Definition of C external function implementing the Multi-Scale Model
  - **Input** : magnetic Field H, Stress along X axis and Y axis
  - **Output :** Induction magnetic B field and the components jacobian Matrix $\frac{\partial B_i}{\partial H_j}$ with I,j=1,2,3
- Use of this external material in magnetic flux conservation settings window

MultiScale Model Principle

MultiScaleModel (MSM) : In this behavioural model, the material is treated as a set of magnetic domain families. Each magnetic domain family α is defined by its magnetization M_α and its magnetostriction strain ε_α. The MSM is based on a free energy balance at the magnetic domain scale. The free energy is written as

$$W_\alpha = -\mu_o . H_\alpha . M_\alpha \; - \; \sigma : \varepsilon^\mu_\alpha \; - \; K(\alpha,\beta)^2$$

Magnetic Energy — Elastic Energy — Anisotropic Energy

The transition to the macroscopic scale is made by calculating the volume fraction of each domain family using a Boltzmann law.

$$f_\alpha = \frac{e^{(-A_s W_\alpha)}}{\int_\alpha e^{(-A s W_s)}}$$

to obtain the macroscopic magnetization $M = \langle M_\alpha \rangle = \sum_\alpha M_\alpha . f_\alpha$

The coefficients of the Boltzmann distribution are defined experimentally on an unstressed material. This constitutive law is introduced in the software by defining an external material in the dedicated menu (see fig 3) which allows to import the dynamic C library.

Results

The figure 4 left gives a constant uniform relative magnetic permeability $\mu_r(H,\sigma)$ in the specimen.

The figure 4 (middle) and the figure 4 (right) show the μ_r variation when a stress state is applied (250 MPa along the x-axis) It can be observed that in the compressive case $\mu_r(H,\sigma)$ increases between the poles where as in the tensile case $\mu_r(H,\sigma)$ decreases.

These results are consistent with the magneto-elastic behavior of ferromagnetic materials.

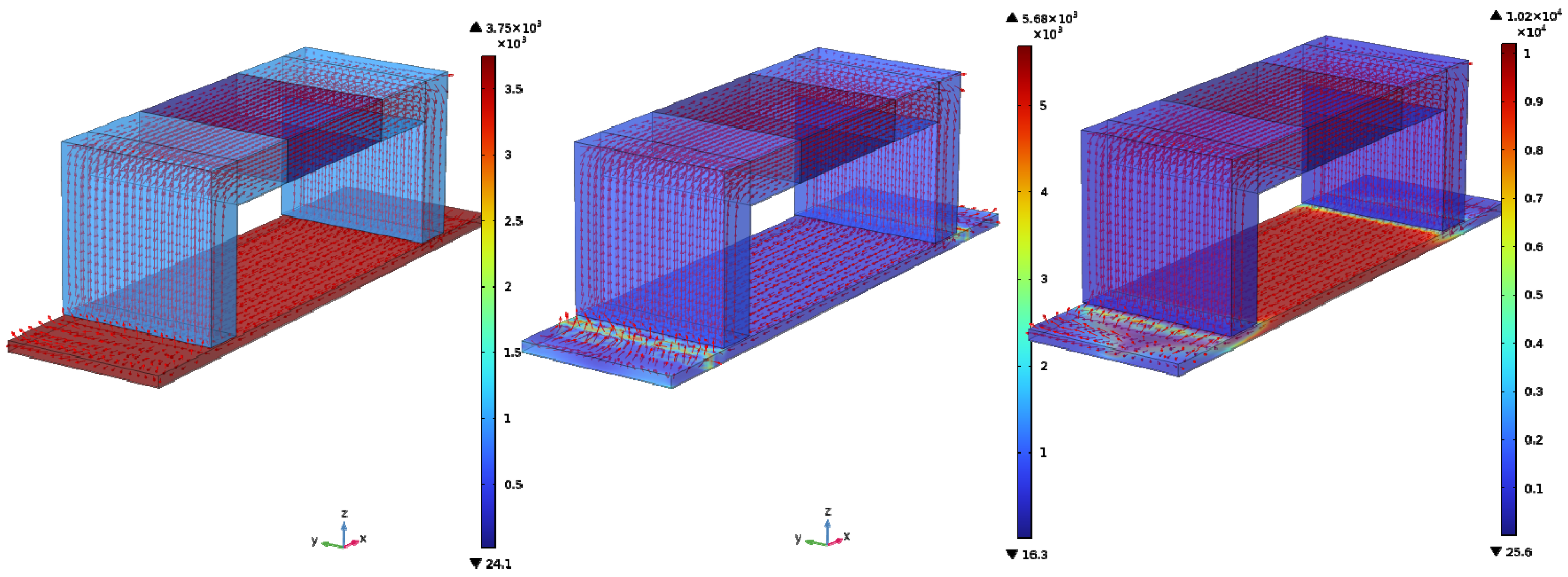

Figure 4 : Relative magnetic permeability map and magnetic induction field

left : no stress – middle : compressive stress – right : tensile stress

REFERENCES

L. Bernard and L. Daniel, "Effect of Stress on Magnetic Hysteresis Losses in a Switched Reluctance Motor: Application to Stator and Rotor Shrink Fitting," in *IEEE Transactions on Magnetics*, vol. 51, no. 9, pp. 1-13, Sept. 2015, Art no. 7002513, doi: 10.1109/TMAG.2015.2435701.

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