Simulation of the interaction between a 2G HTS stack and a traveling inhomogeneous magnetic field

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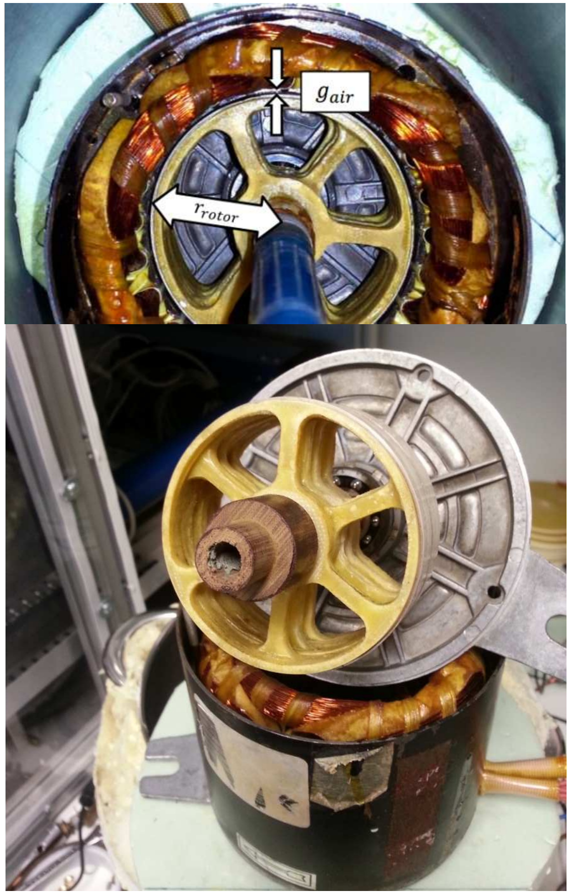
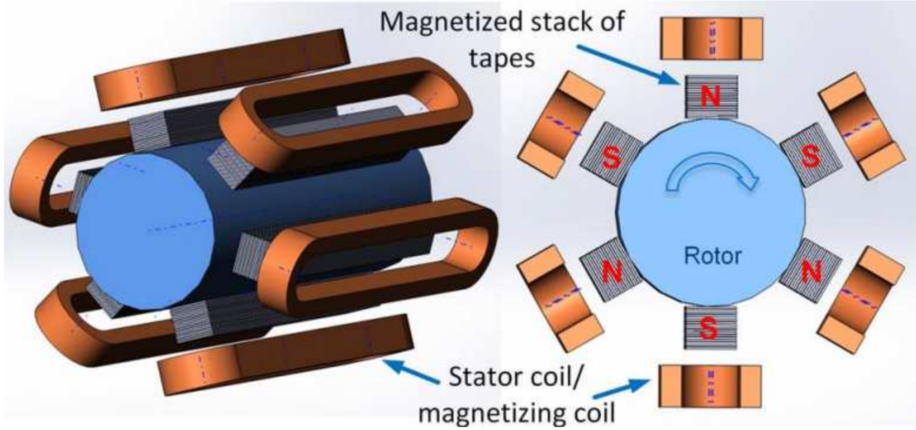
Outline

- Motivation
- Objectives
- Introduction
- The model
- Results
- Final Considerations

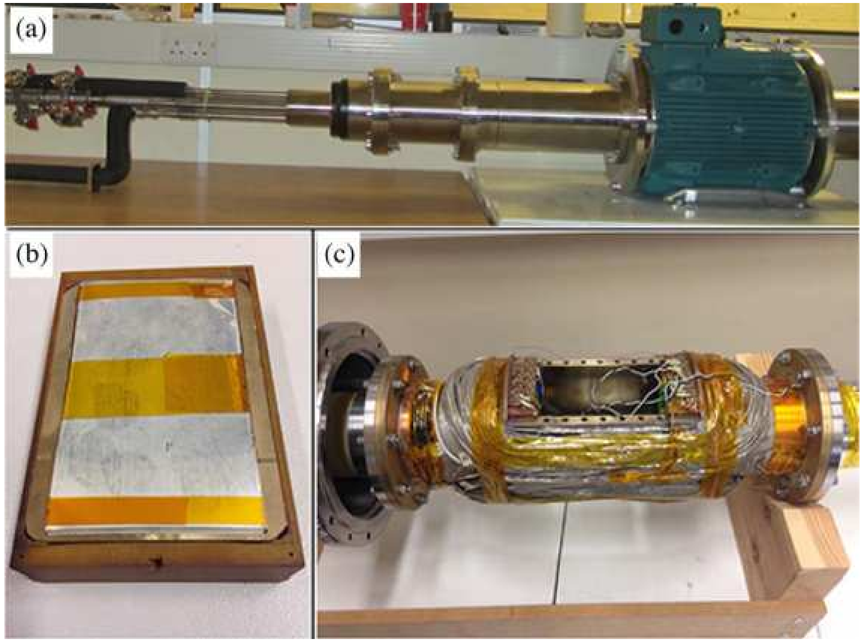
Motivation: Electric Machines with stacks of 2G tapes



X. Granados *et. al*. EUCAS-2015, Lyon.



A. Patel *et. al., IEEE Trans. on App. Supercond.,* 25 (3), 2015.



M. Baghdadi *et al., IEEE Trans. on App. Supercond.,* 25 (3), 2015

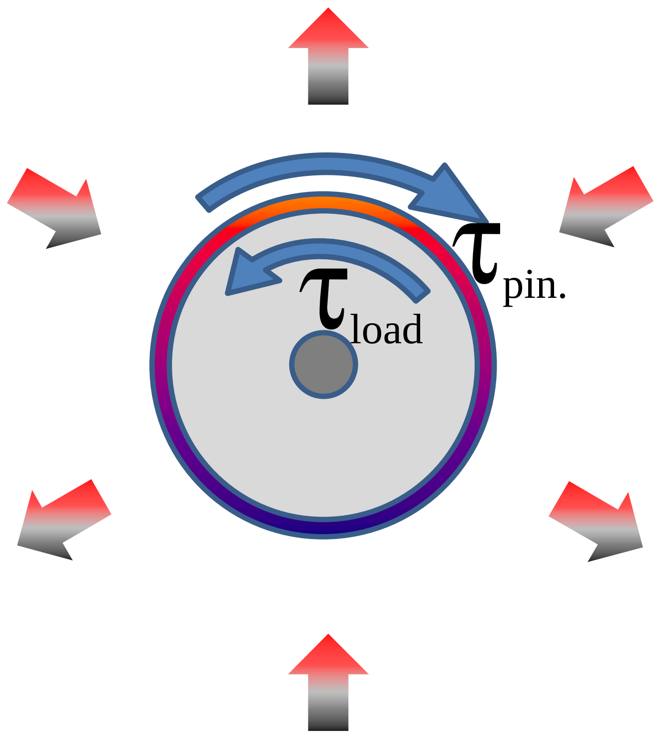
Objectives

- To simulate the interaction between a travelling inhomogeneous magnetic field and a 2G tape HTS stack
- To compare the simulated results with measurements
- To extrapolate the model to investigate the influence of some parameters change

Trapped field motors

The magnetic field rotates and the superconductor magnetizes (partially or fully) according to the applied magnetic field

Two poles 3 phases machine



$$\tau_{load} < \tau_{pinning}$$

A) Synchronous machine (no losses in steady state)

•the resistant torque is smaller than that allowed by the electromagnetic forces and the pinning of the magnetic flux;

•The rotor moves in the synchronous speed;

$$\tau_{load} > \tau_{pinning}$$

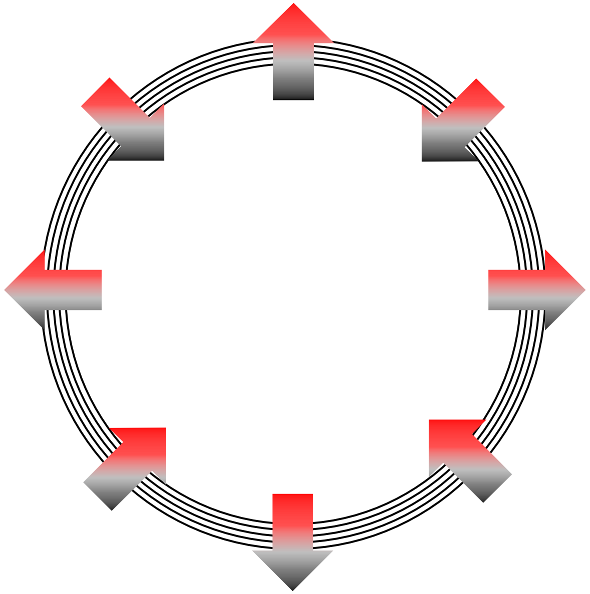
B) Hysteresis machine (Losses)

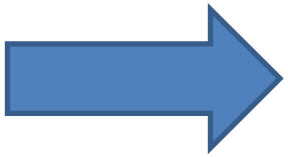
•the resistant torque is larger than that allowed by pinning of the flux and the electromagnetic forces;

•The rotor moves slower than the synchronous speed (there is a slip);

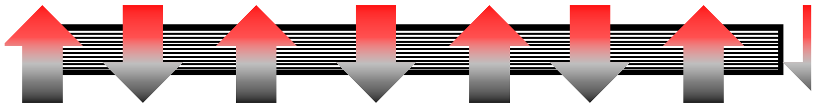
2G HTS Electric Motors

The rotational machine



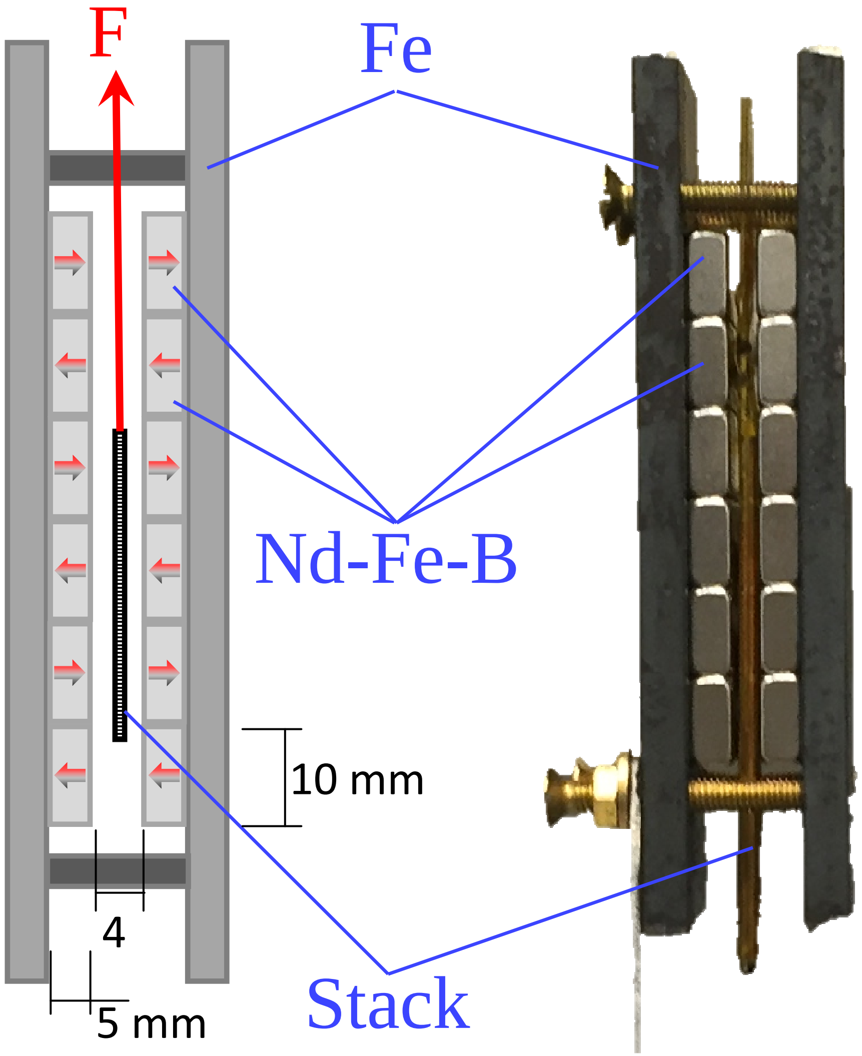


Linear case studied here



Studied System

Schematic | Exp. set up

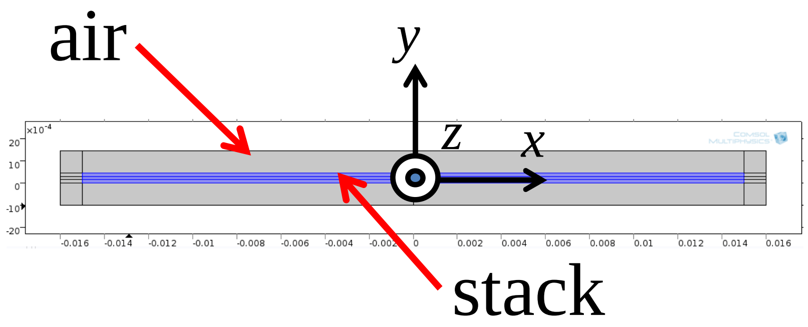


Stack

SuperPower
SF12050-AP (2013)
$I_{c\ av.}$ = 281 A (Self Field, 77 K)
n = 35 (Self Field, 77 K)
9 layers
Width = 12 mm
Length = 30 mm
Thickness total = 510 µm

The H-formulation (2D)

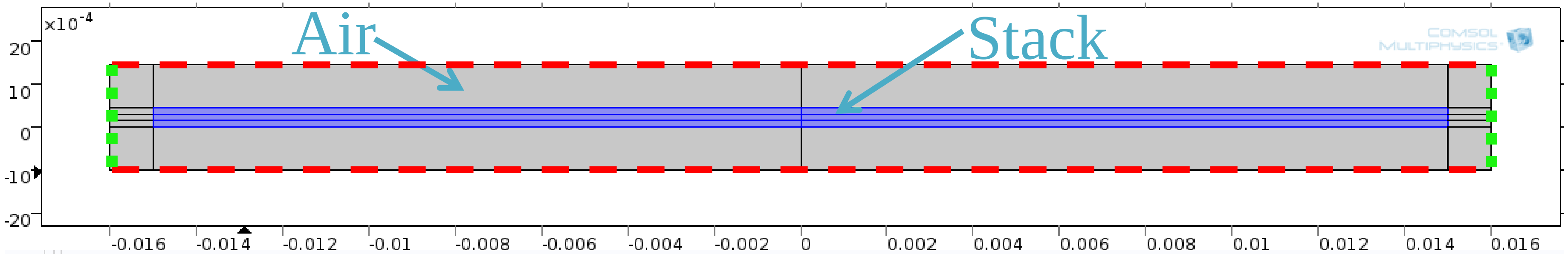
$$H_z = E_x = E_y = J_x = J_y = 0$$



$$\rho = \frac{1}{\sigma} = \frac{E_c}{J_c}\left|\frac{E}{E_c}\right|^{1-1/n} = \boxed{\frac{E_c}{J_c}\left|\frac{J}{J_c}\right|^{n-1}}.$$

$$\left.\begin{aligned} &\mu\frac{\partial \vec{H}}{\partial t} + \nabla \times \vec{E} = \vec{0}, \\ &\vec{J} = \nabla \times \vec{H}. \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} &\mu\frac{\partial H_x}{\partial t} + \frac{\partial E_z}{\partial y} = 0, \\ &\mu\frac{\partial H_y}{\partial t} - \frac{\partial E_z}{\partial x} = 0, \\ &J_z = \frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y}. \\ &E_z = \rho\, J_z \\ &J_z = J_c(B) \end{aligned}\right.$$

The H-formulation (2D): FEM-BEM



H-Formulation with edge elements: boundary conditions

Red dashed line:

$$H_x = H_{x\,\text{ext.}} + H_{x\,\text{HTS}}$$

By analytic equation

By Biot-Savart's law:

$$-\frac{1}{2\pi}\int_{-b}^{b}\int_{-a}^{a} Jz(x,y)\,\frac{\Delta y}{r^2}\,\mathrm{d}x\,\mathrm{d}y$$

Green dotted line:

$$H_y = H_{y\,\text{ext.}} + H_{y\,\text{HTS}}$$

By analytic equation

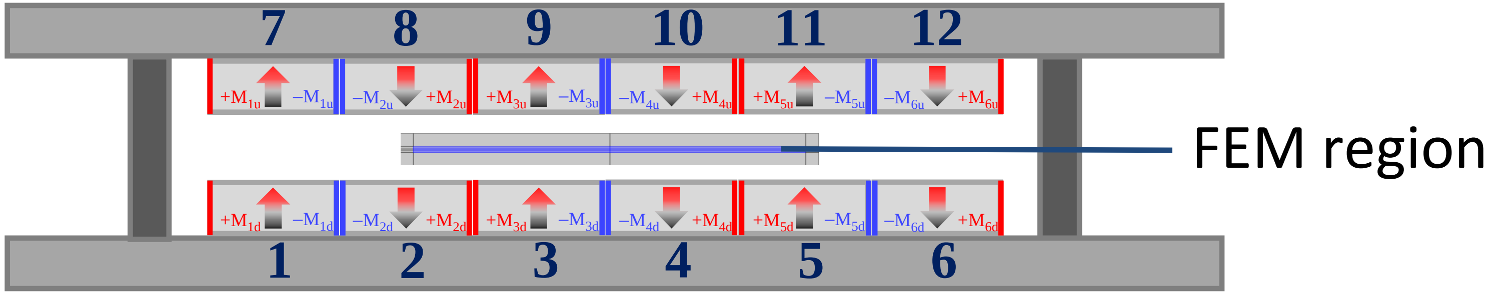
By Biot-Savart's law:

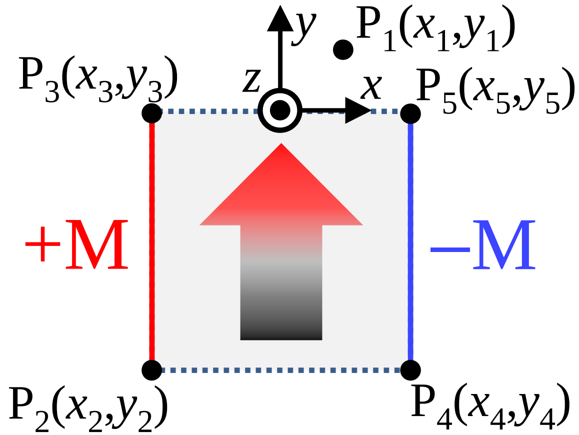
$$\frac{1}{2\pi}\int_{-b}^{b}\int_{-a}^{a} Jz(x,y)\,\frac{\Delta x}{r^2}\,\mathrm{d}x\,\mathrm{d}y.$$

[1] F. Sass, Ph.D. Thesis, UFRJ, 2015.

[2] F. Sass, G. Sotelo, R. de Andrade, F. Sirois: SuST, 28 (2015) 125012.

Permanent Magnets Analytic Equations





H_x ext

$$H_x(x,y) = \frac{M}{4\pi} \ln \frac{[(y_1-y_3)^2+(x_1-x_3)^2][(y_1-y_4)^2+(x_1-x_4)^2]}{[(y_1-y_2)^2+(x_1-x_2)^2][(y_1-y_5)^2+(x_1-x_5)^2]}$$

H_y ext

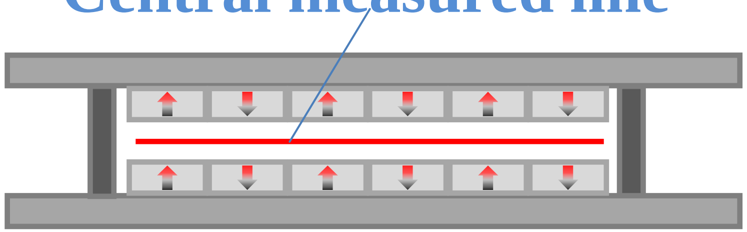
$$H_y(x,y) = -\frac{M}{2\pi}\arctan\left(\frac{y_1-y_3}{x_1-x_3}\right) + \frac{M}{2\pi}\arctan\left(\frac{y_1-y_2}{x_1-x_2}\right) - \frac{M}{2\pi}\arctan\left(\frac{y_1-y_4}{x_1-x_4}\right) + \frac{M}{2\pi}\arctan\left(\frac{y_1-y_5}{x_1-x_5}\right)$$

[1] F. Sass, Ph.D. Thesis, UFRJ, 2015.

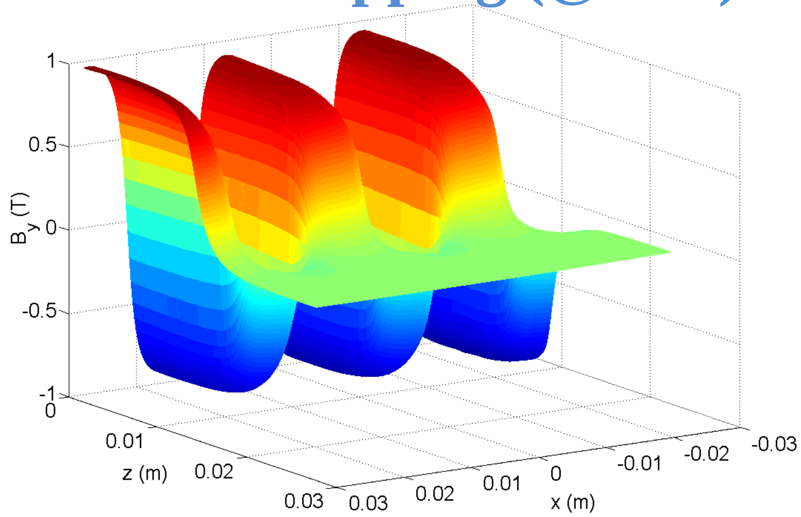
[2] F. Sass, G. Sotelo, R. de Andrade, F. Sirois: SuST, 28 (2015) 125012.

Magnetic Field Results

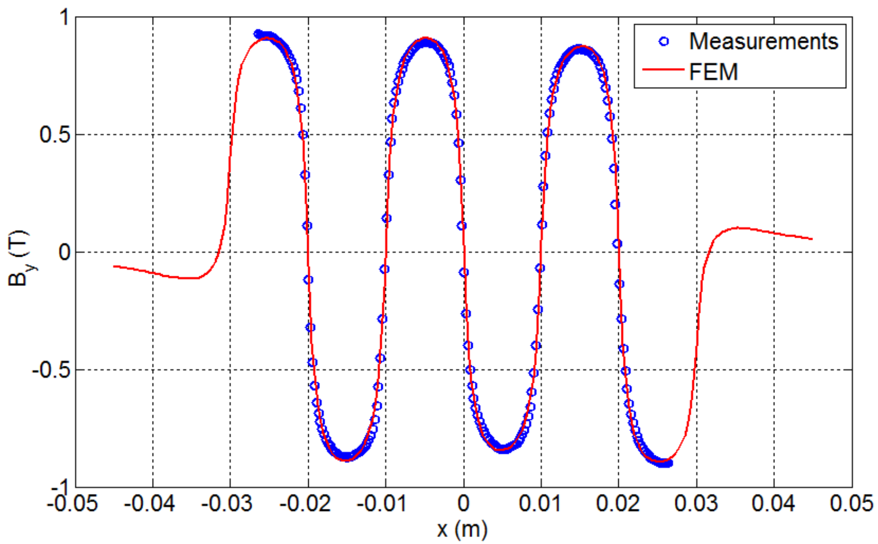
Central measured line

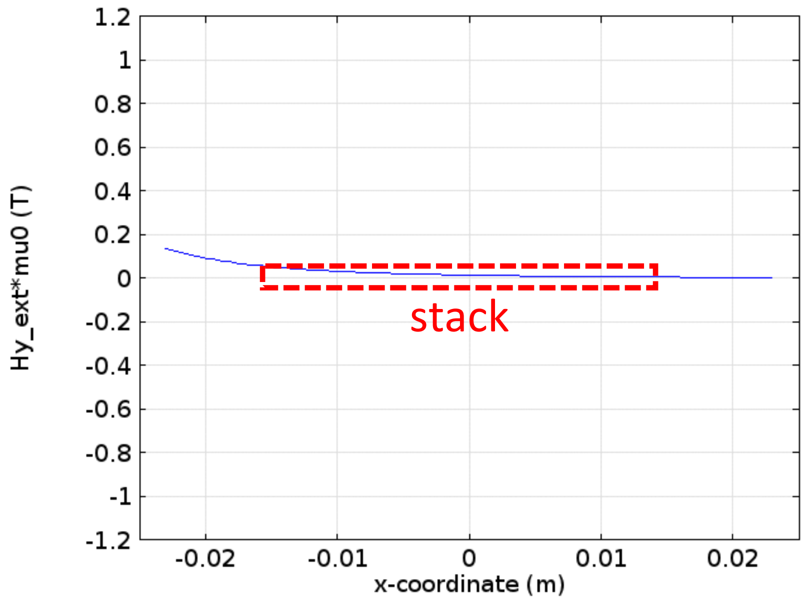


Hall mapping (@77K)



Adjusted External Field (@77K)

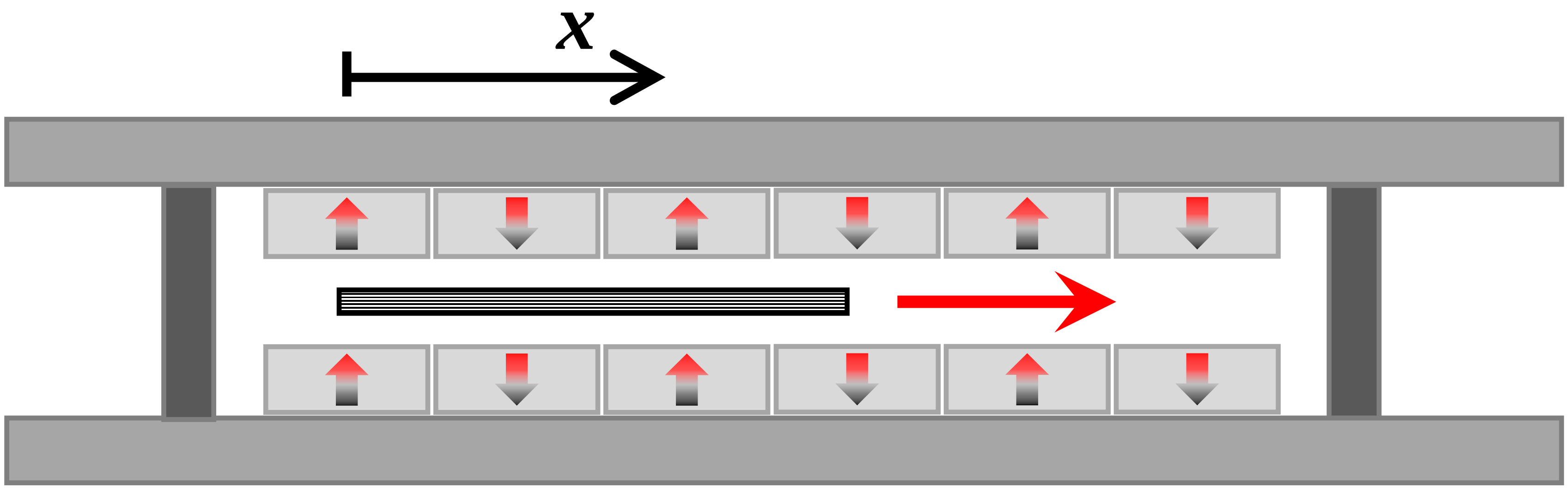




Results

Stack displacement

The stack was displaced at a constant speed:

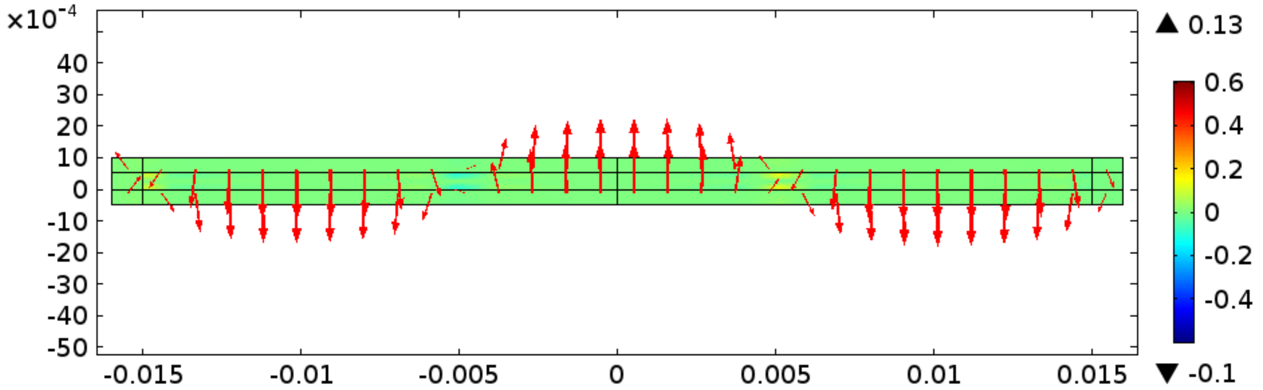


Two speeds were measured to be compared with simulations:

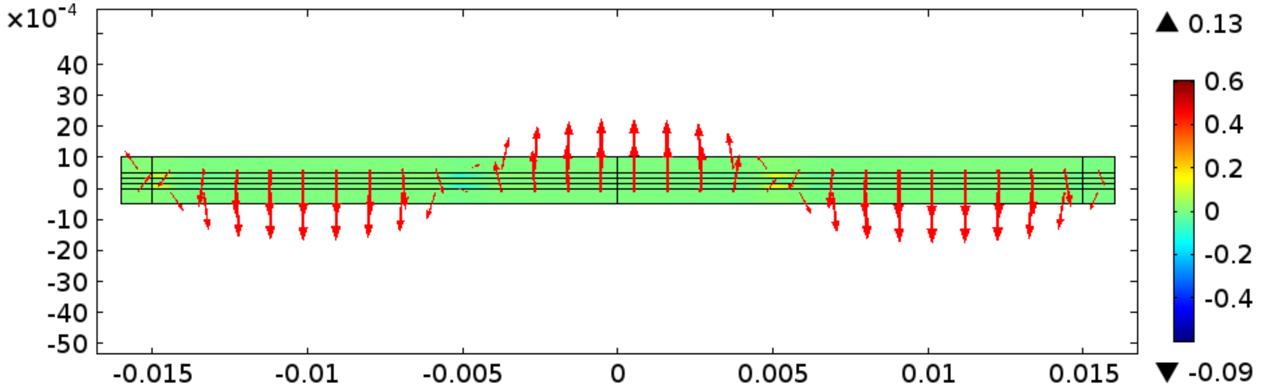
$v_1 = 0.344$ mm/s;

$v_2 = 0.2066$ mm/s.

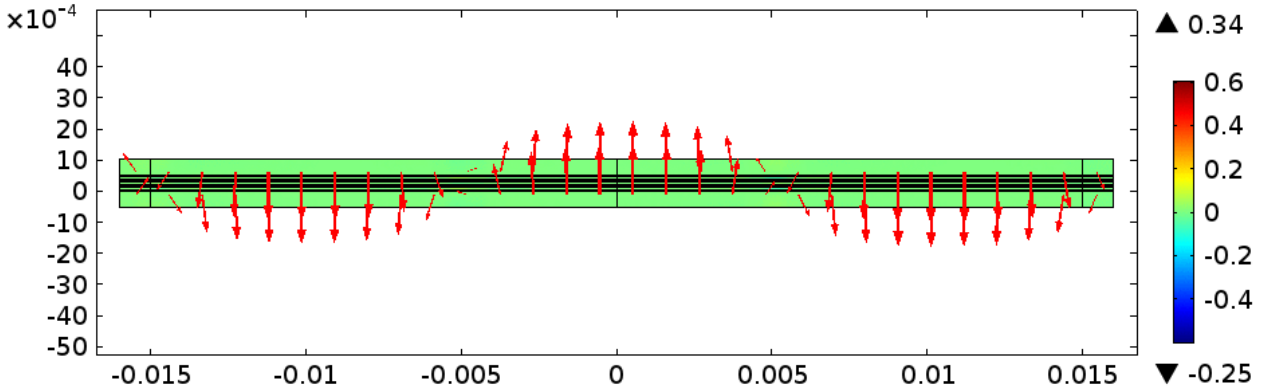
Homogenized domains and induced currents



1 Domain

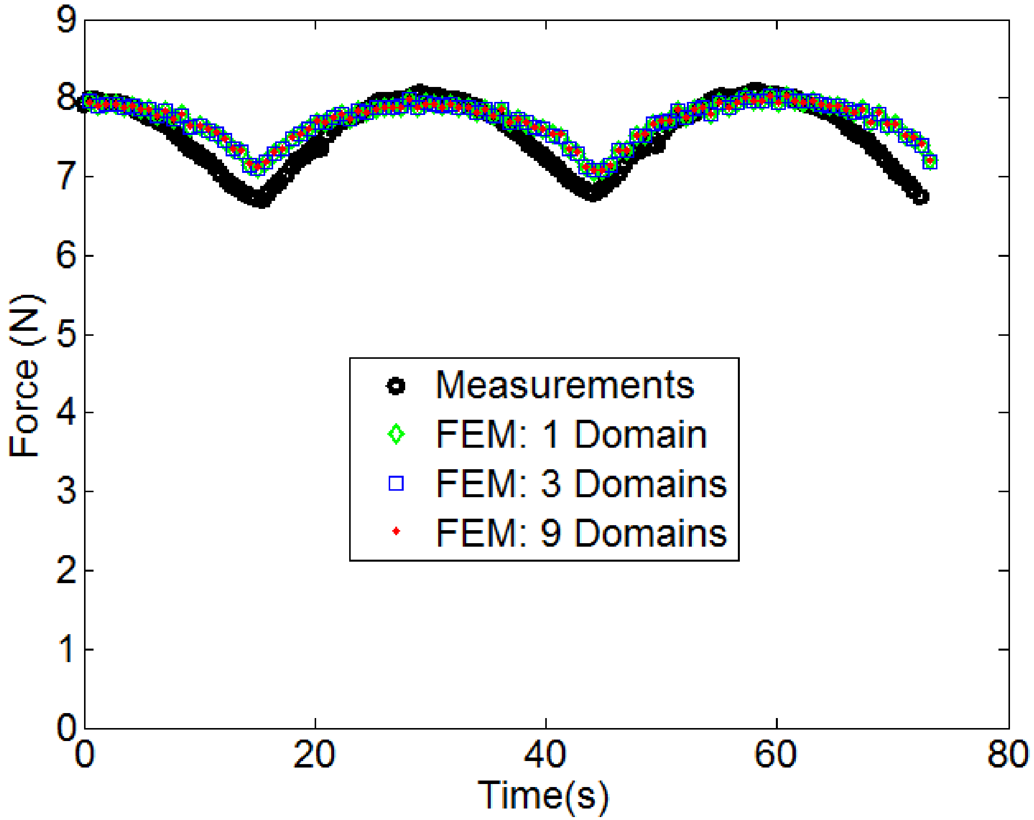


3 Domains



9 Domains

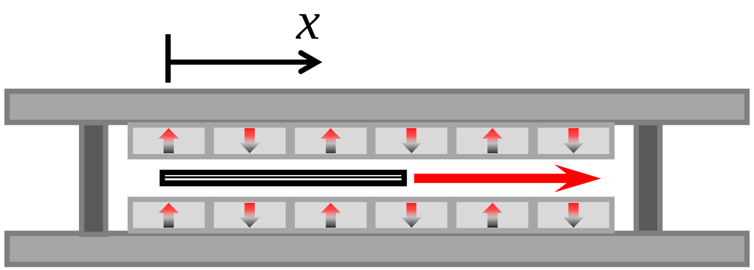
Force Results: v = 0.344 mm/s



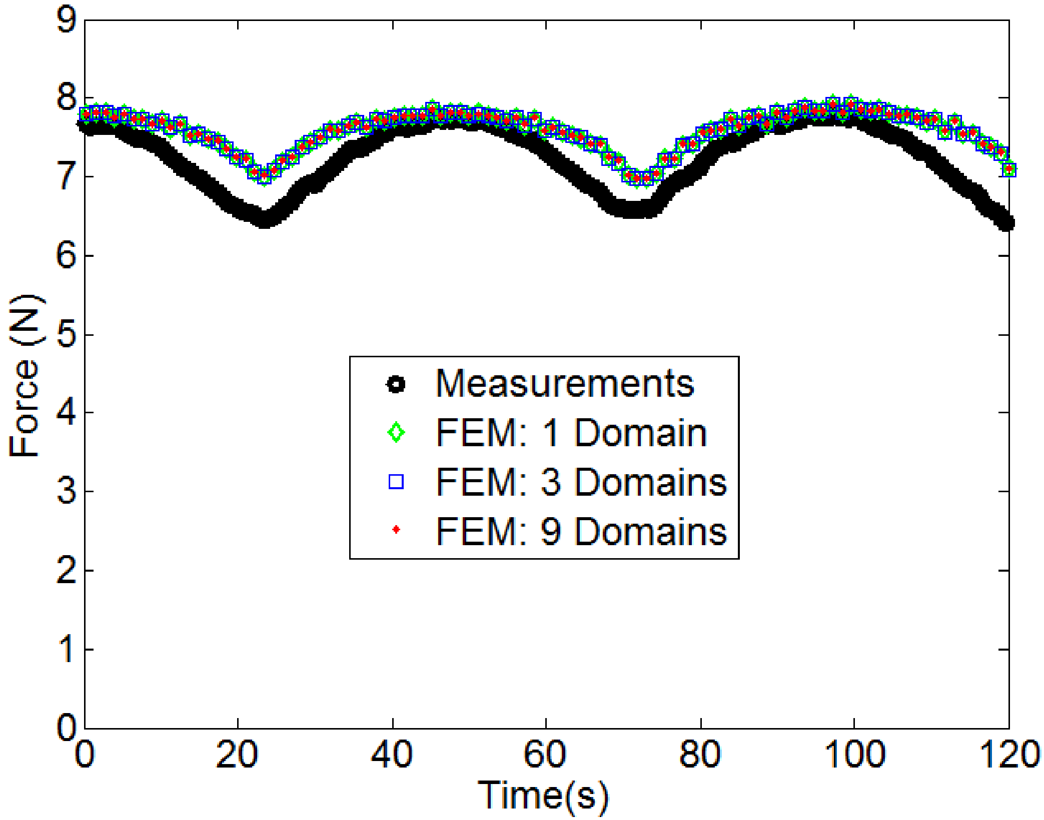
I_c = 281 A
n = 35

Domains	DOF	Comp. time
1	1035	32.7 min
3	1035	77 min
9	1689	123 min

i7, 3.9GHz, 16 Gb RAM



Force Results: v = 0.207 mm/s

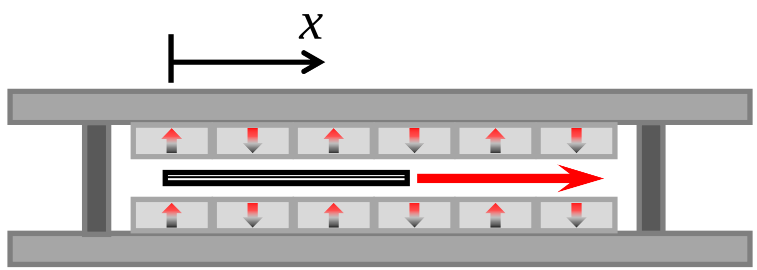


I_c = 281 A

n = 35

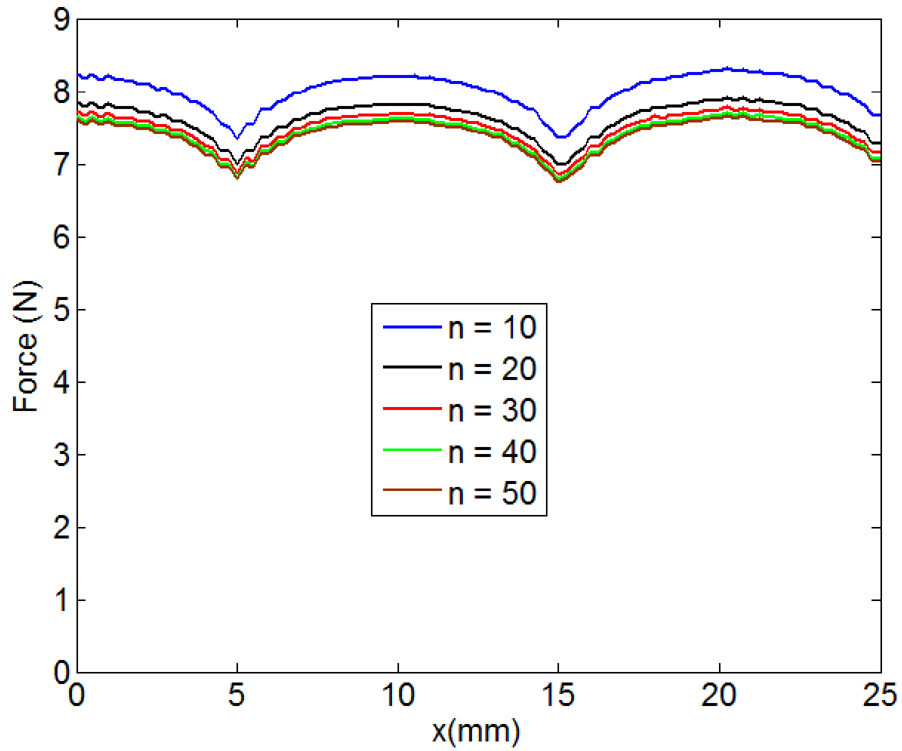
Domains	DOF	Comp. time
1	1035	35.4 min
3	1035	83 min
9	1689	145 min

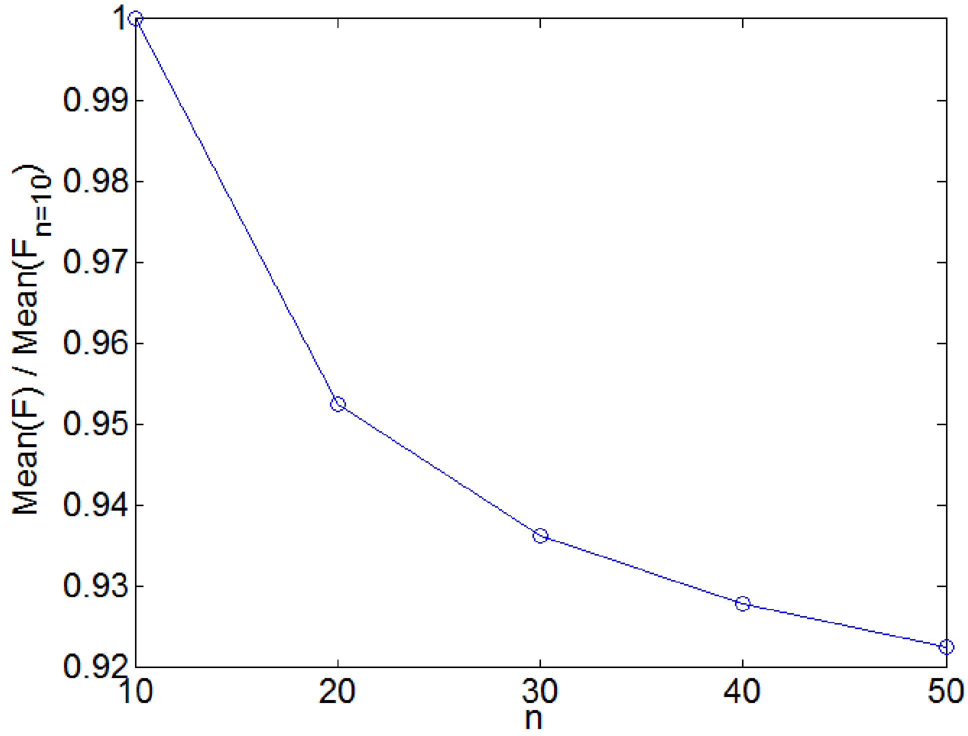
i7, 3.9GHz, 16 Gb RAM

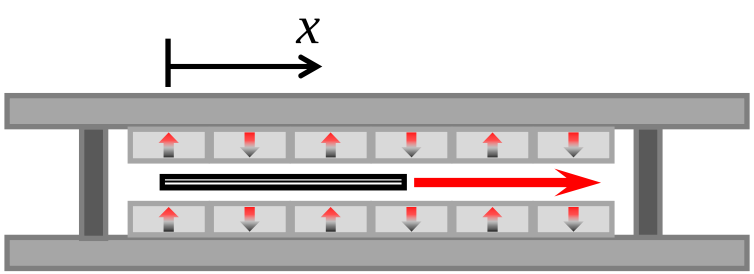


Force Results: n influence

I_c = 270 A
v = 0.344 mm/s



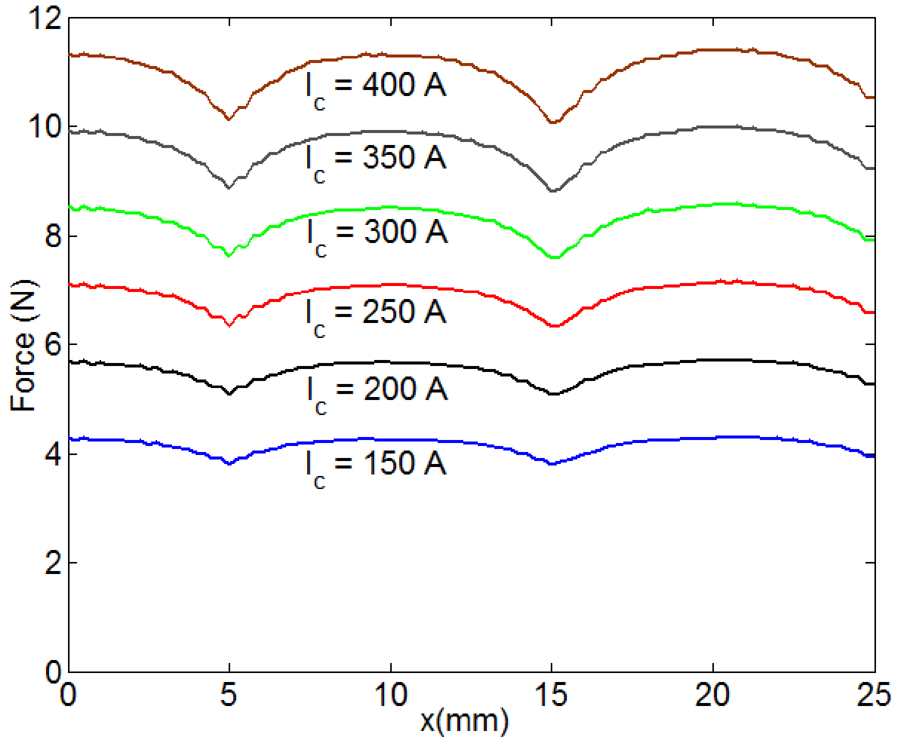


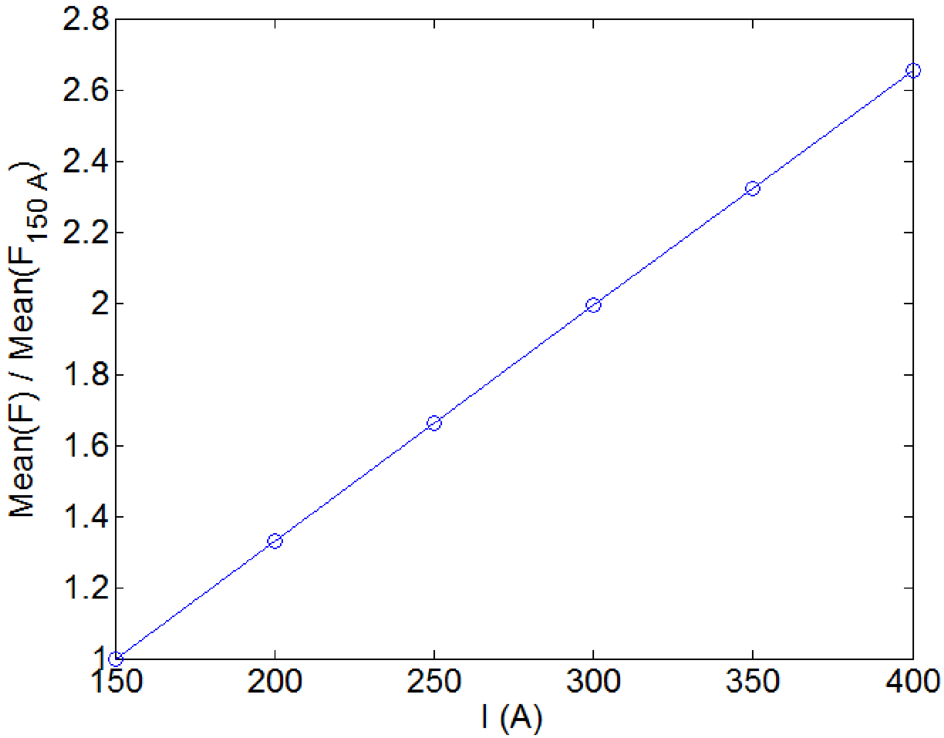


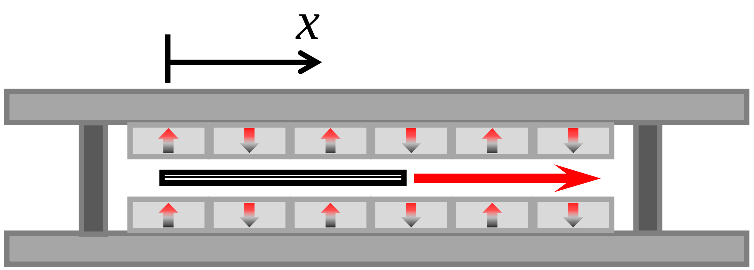
Force Results: I_c influence

n = 35

v = 0.344 mm/s



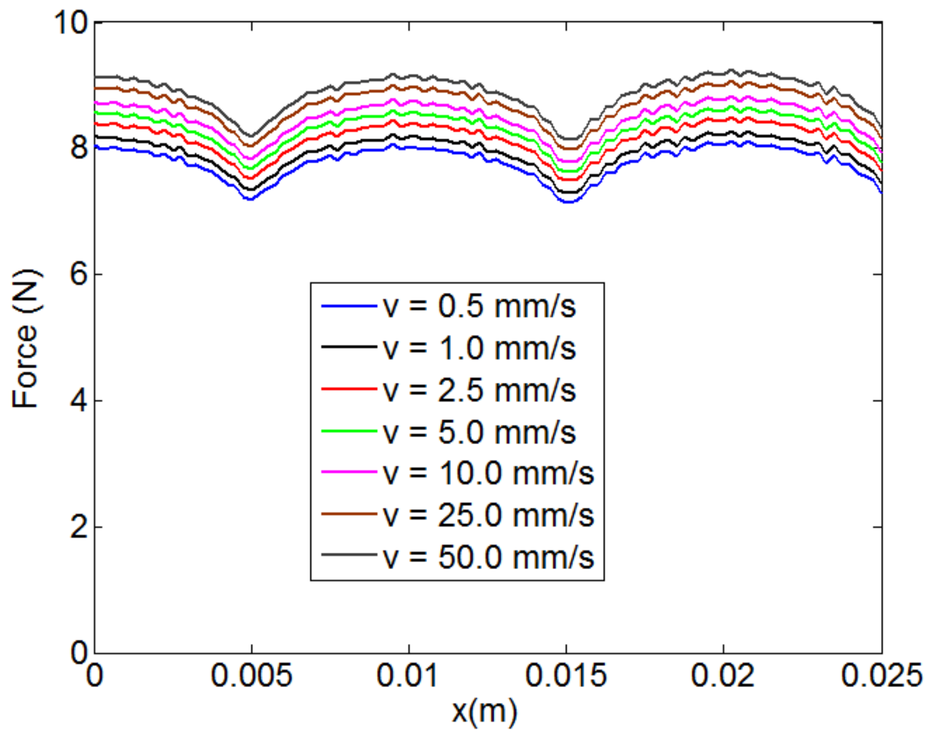


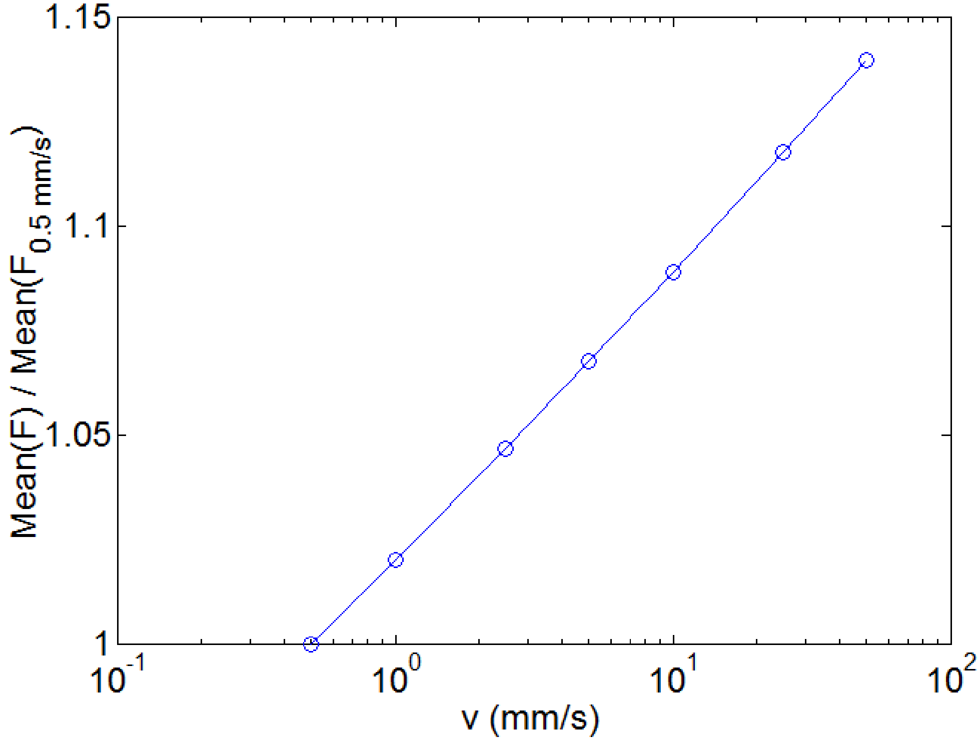


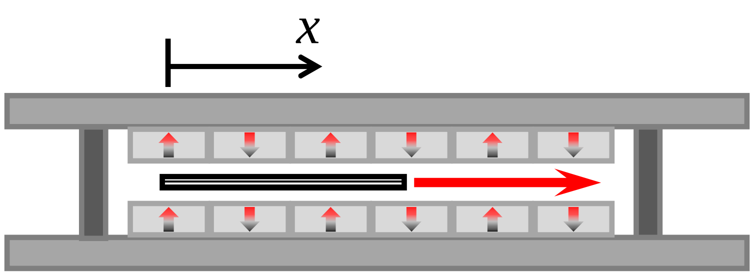
Force Results: speed influence

I_c = 281 A

n = 35







Final Considerations

- The H-formulation with FEM-BEM is an interesting way for modelling the interaction between a traveling magnetic field and a stack of 2G HTS tapes
- The model can be applied to the project HTS machines (stacks or bulks)
- It was possible to calculate very fast the proposed problem (~30 min, 1 domain)
- The model was extrapolated and some parameters were changed to investigate their influence into the force

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