Good Afternoon!

Simulations of REBCO Tapes Double Crossed Loops Coils with Integral Equations Method

Flávio Goulart dos Reis Martins

Felipe Sass, Rubens de Andrade Jr.

June 29th, 2018

Laboratório de Aplicação de Supercondutores
Laboratory for Applied Superconductivity

Universidade Federal do Rio de Janeiro
Federal University of Rio de Janeiro

1. Introduction

Research background

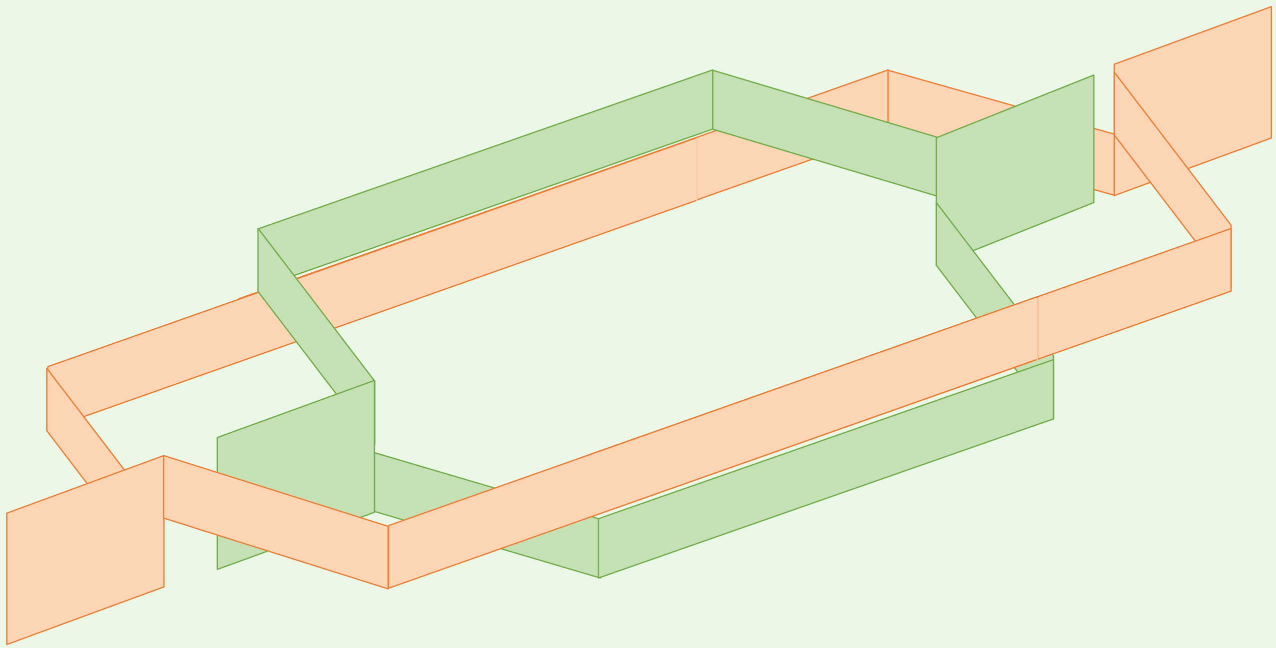
Motivations

Objectives

1.1. Background

Presented last year...

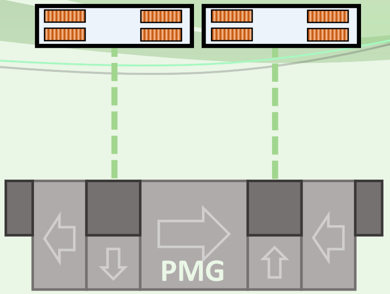
Jointless loops made from REBCO tapes: **Double Crossed Loop**



F. Martins, et al., "*A novel magnetic bearing using 2G double crossed loops*". IEEE TAS, 2018

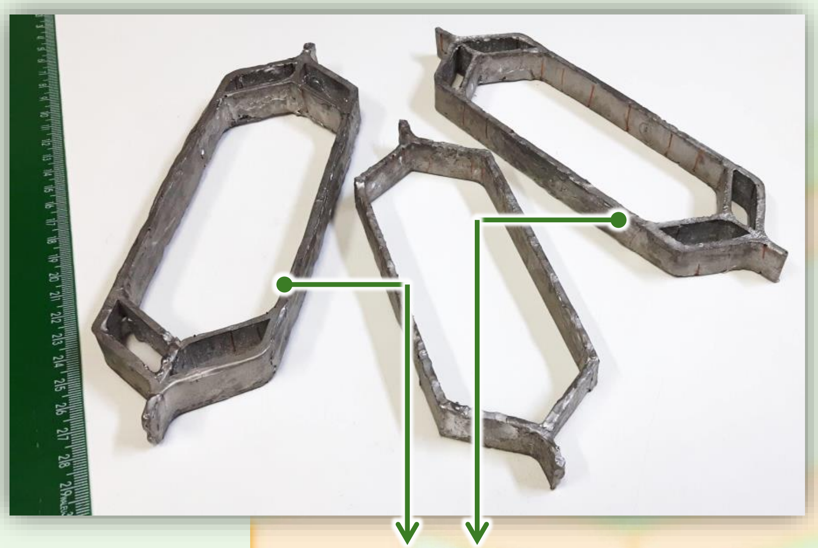
1.1. Background

Prototype SML Bearing



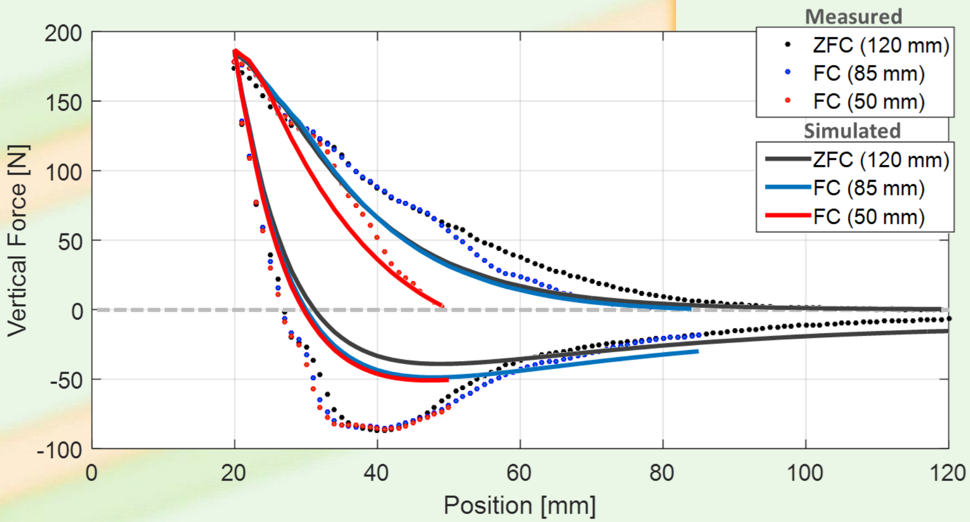
Presented last year...

Jointless loops made from REBCO tapes: **Double Crossed Loop**



First Prototype DCL Coils

20 double loops each

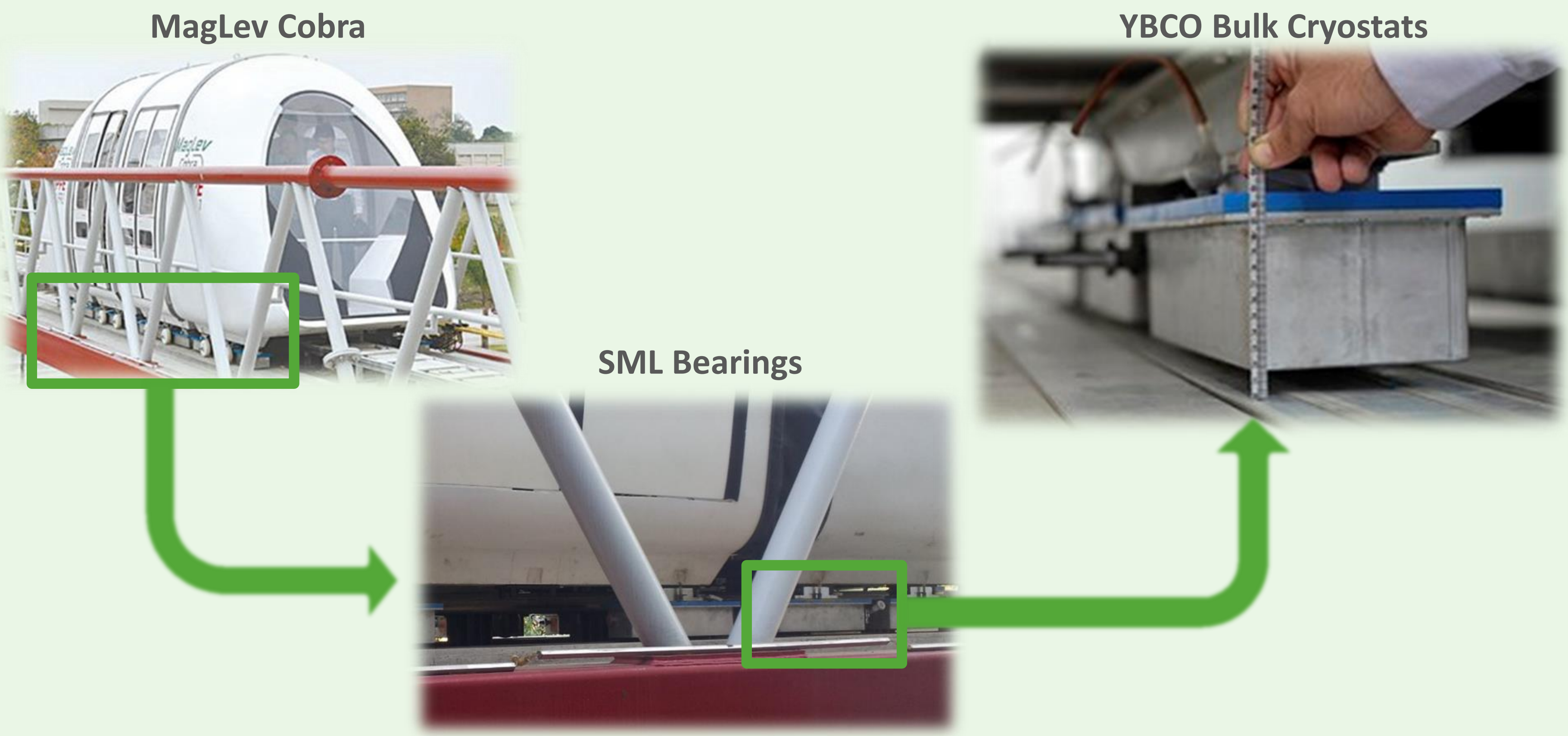


Levitation Tests and Simulations

F. Martins, et al., "*A novel magnetic bearing using 2G double crossed loops*". IEEE TAS, 2018

1.2. Motivations

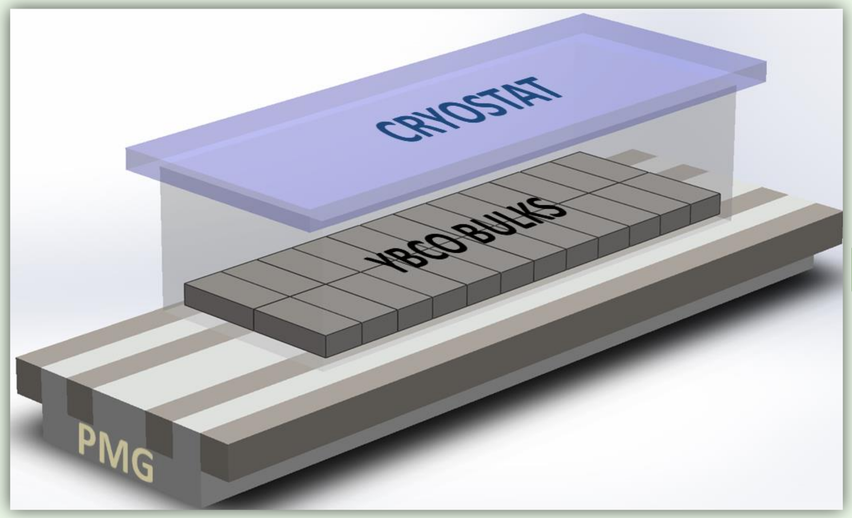
Developed for substitute YBCO bulks in levitation...



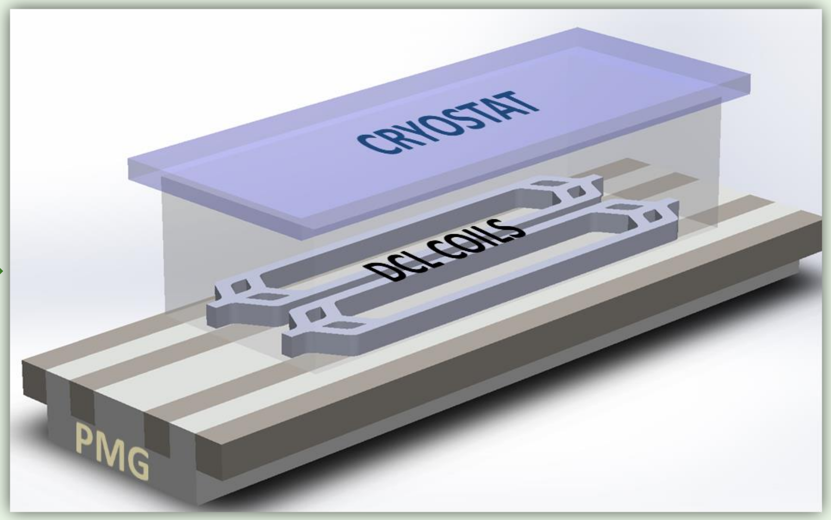
1.2. Motivations

Developed for substitute YBCO bulks in levitation...

Actual Cryostat

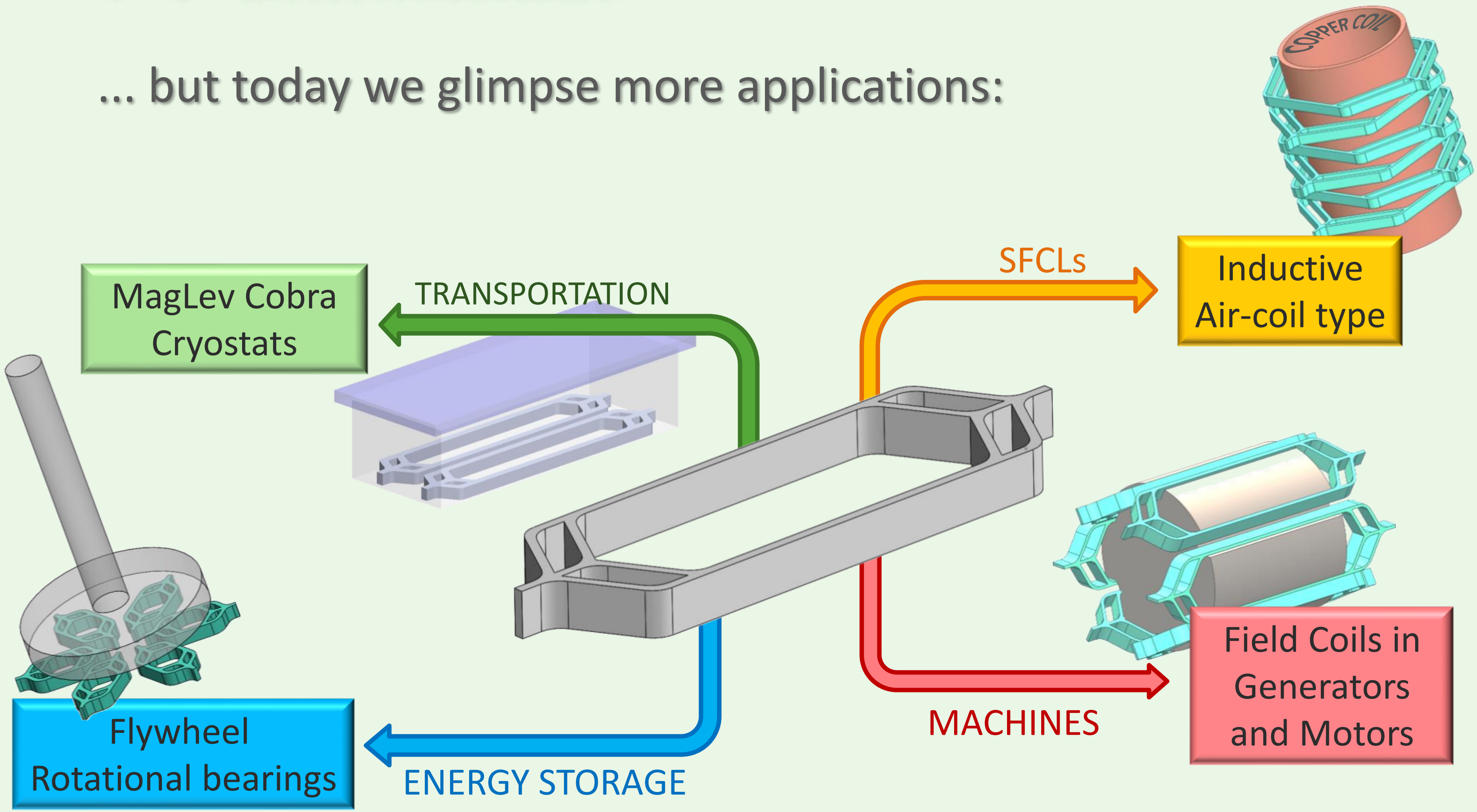


New Cryostat Concept



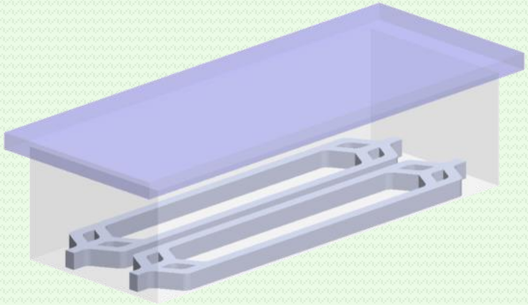
1.2. Motivations

... but today we glimpse more applications:



1.3. Objectives

In this work, we intend to:



- Simulate DCL coils as **SML bearings** for the MagLev Cobra
- Analyze some design parameters to try to enhance the (**tape consumption**)/(**levitation force**) ratio.
- Improve the simulation technique to better **reproduce** the measured results in prototypes.

2. Numerical Modelling

Integral Equations Method

Modelling the DCL Coils

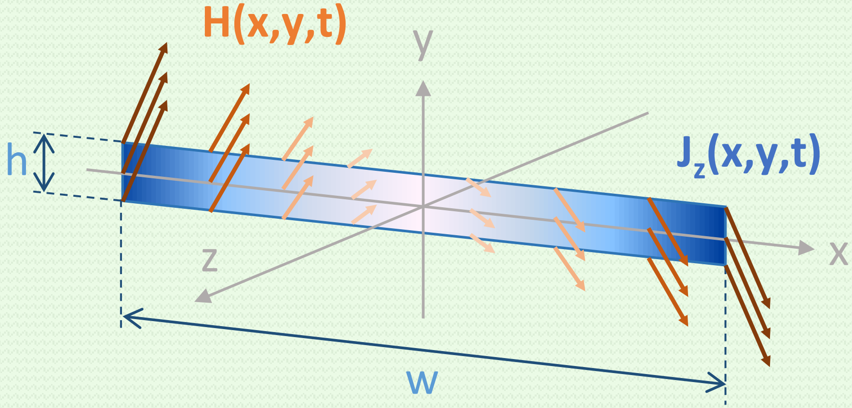
Modelling the Magnets

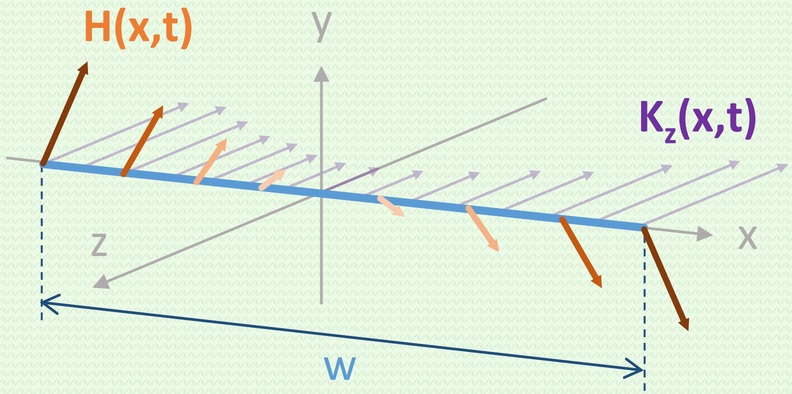
2.1. Integral Equations Method

Taking advantage of the tape's geometry by considering it a 1D current sheet: $K_z(x,t)$

$$\begin{cases} \dfrac{\partial J_z(x,y,t)}{\partial y} = 0 \\ \dfrac{\partial H(x,y,t)}{\partial y} = 0 \end{cases}$$

$$K_z(x,t) = \int_{-h/2}^{h/2} J_z(x,y,t)\,dy$$





R. Brambilla, et al., "*Integral equations for the current density in thin conductors and their solution by the finite-element method*", IEEE TAS, 2008

2.1. Integral Equations Method

The integral equation that solves $K_z(x,t)$:

$$K_z(x,t) =$$

$$\frac{\mu_0 h}{\rho}\left[\underbrace{\int_{-w/2}^{x} \dot{H}_{ext}(\xi,t)d\xi}_{\text{Induced currents due to the external field variation}} + \underbrace{\int_{-w/2}^{w/2} \frac{\dot{K}_z(u,t)}{2\pi} ln|u-x|du}_{\text{Induced currents due to the self-field variation}} - \underbrace{\int_{-w/2}^{w/2} \frac{\dot{K}_z(u,t)}{2\pi} ln|u+w/2|du}_{\text{A term independent from x attributed to the current constraint}}\right]$$

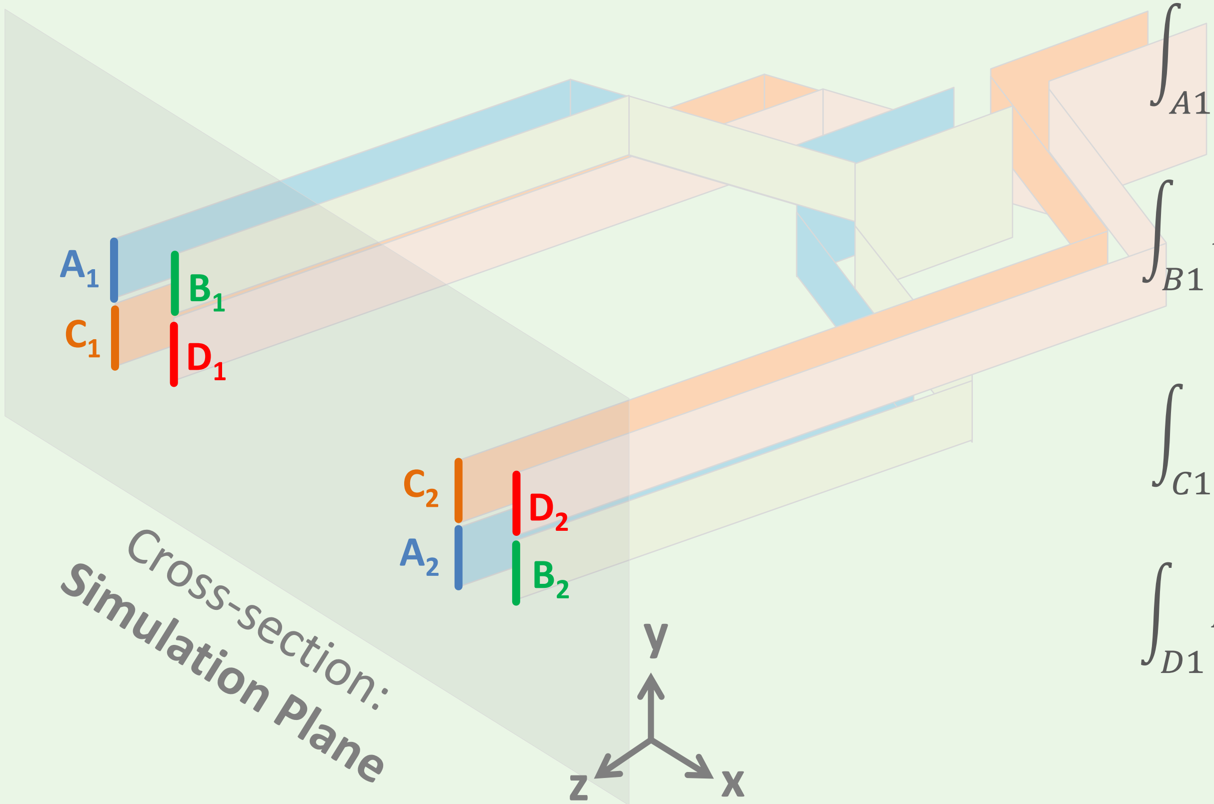
$$\rho K_z(x,t) = \tau[a(x,t) + b(x,t)] + c(t)$$

$$\rho = \frac{E_c}{J_c(B_{\|},B_{\perp})}\left(\frac{K_z(x,t)}{h\,J_c(B_{\|},B_{\perp})}\right)^{n-1} \qquad J_c(B_{\|},B_{\perp}) = \frac{J_{c0}}{\left[1+\sqrt{(kB_{\|})^2 + {B_{\perp}}^2}/B_c\right]^b}$$

F. Grilli, et al., "Self-Consistent Modeling of the Ic of HTS Devices: How Accurate Models Really Need to Be?" IEEE TAS, 2014

2.2. Modelling the DCL Coils

The current continuity constraint:



$$\int_{A1} K_{zA1}dy + \int_{A2} K_{zA2}dy = 0$$

$$\int_{B1} K_{zB1}dy + \int_{B2} K_{zB2}dy = 0$$

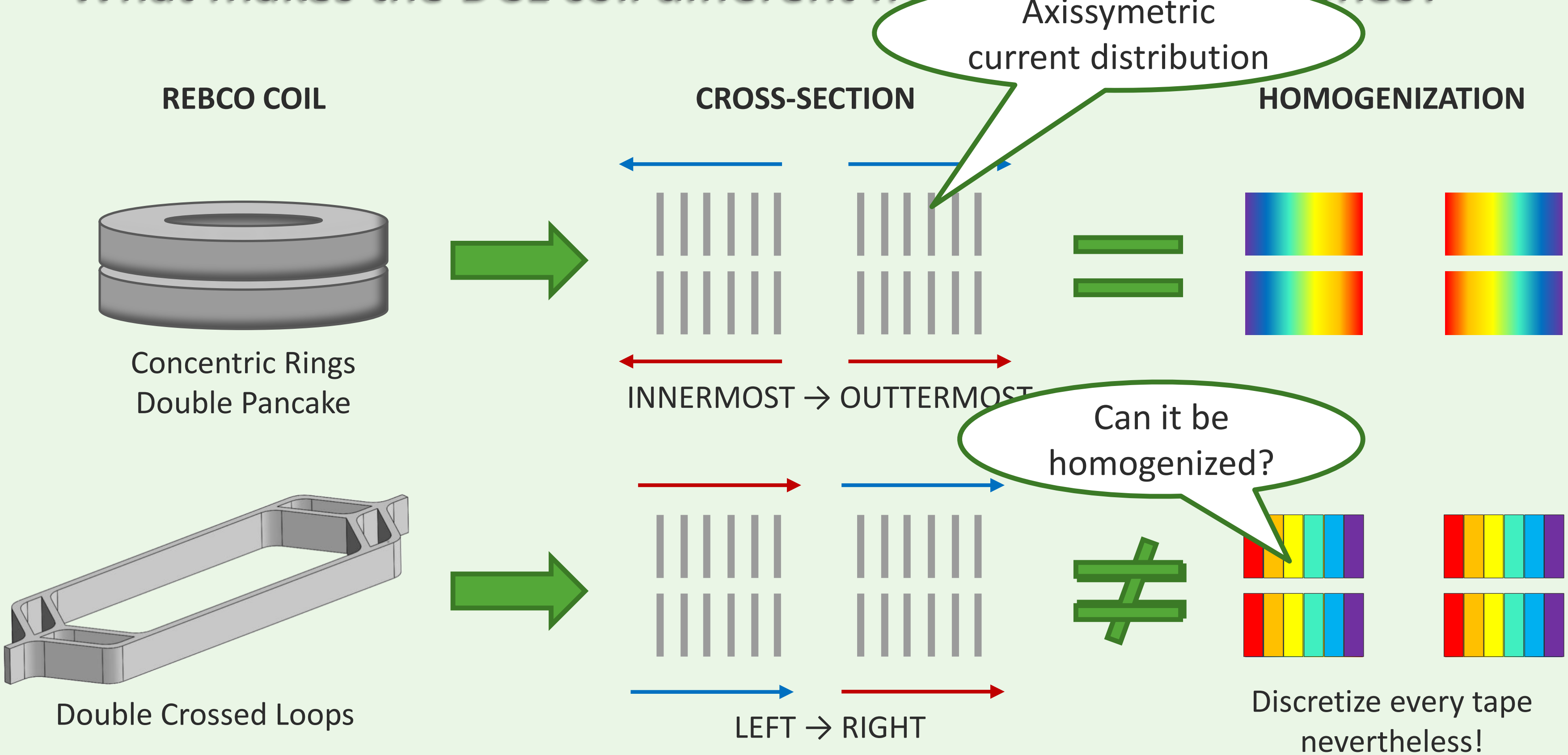
$$\int_{C1} K_{zC1}dy + \int_{C2} K_{zC2}dy = 0$$

$$\int_{D1} K_{zD1}dy + \int_{D2} K_{zD2}dy = 0$$

2.2. Modelling the DCL Coils

The current continuity constraint:

What makes the DCL coil different from conventional ones?

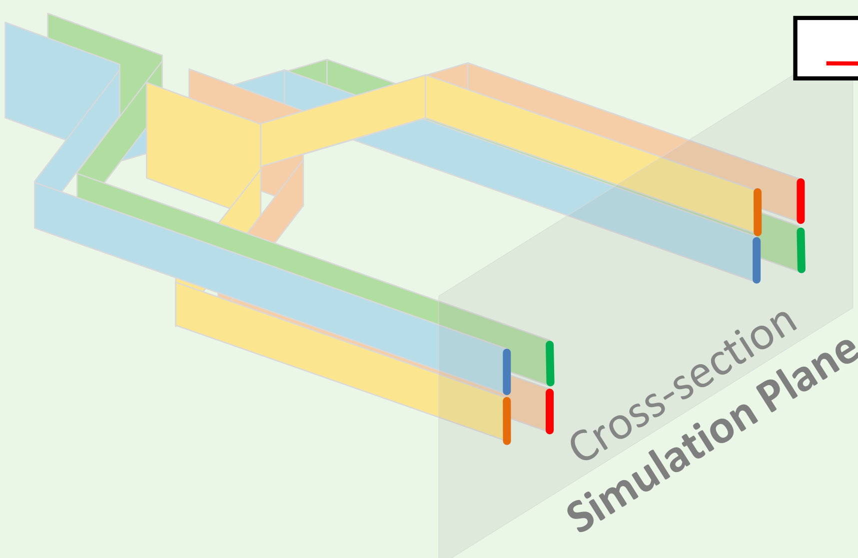


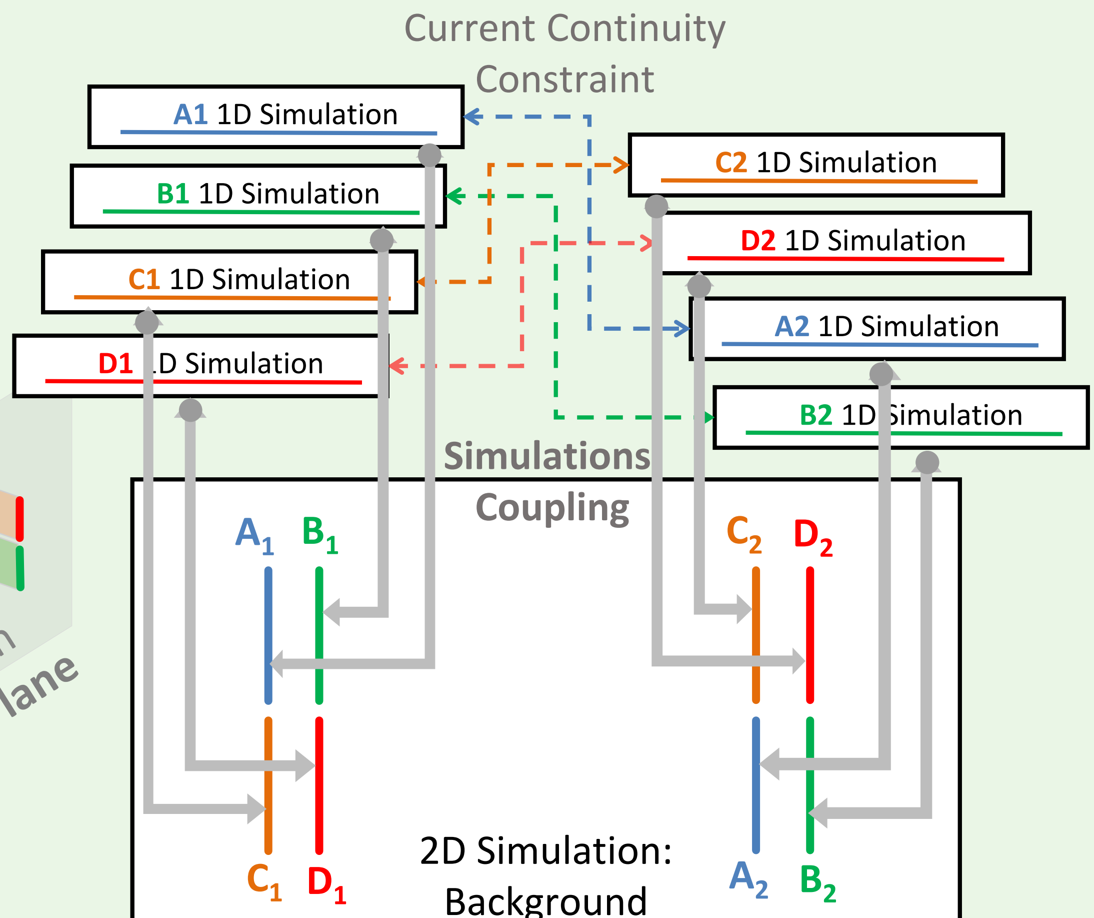
2.2. Modelling the DCL Coils

Integral Equations (IE) solved by Finite Elements (FE) method

1D and 2D coupling:

Drawback:
neglects coil head effects



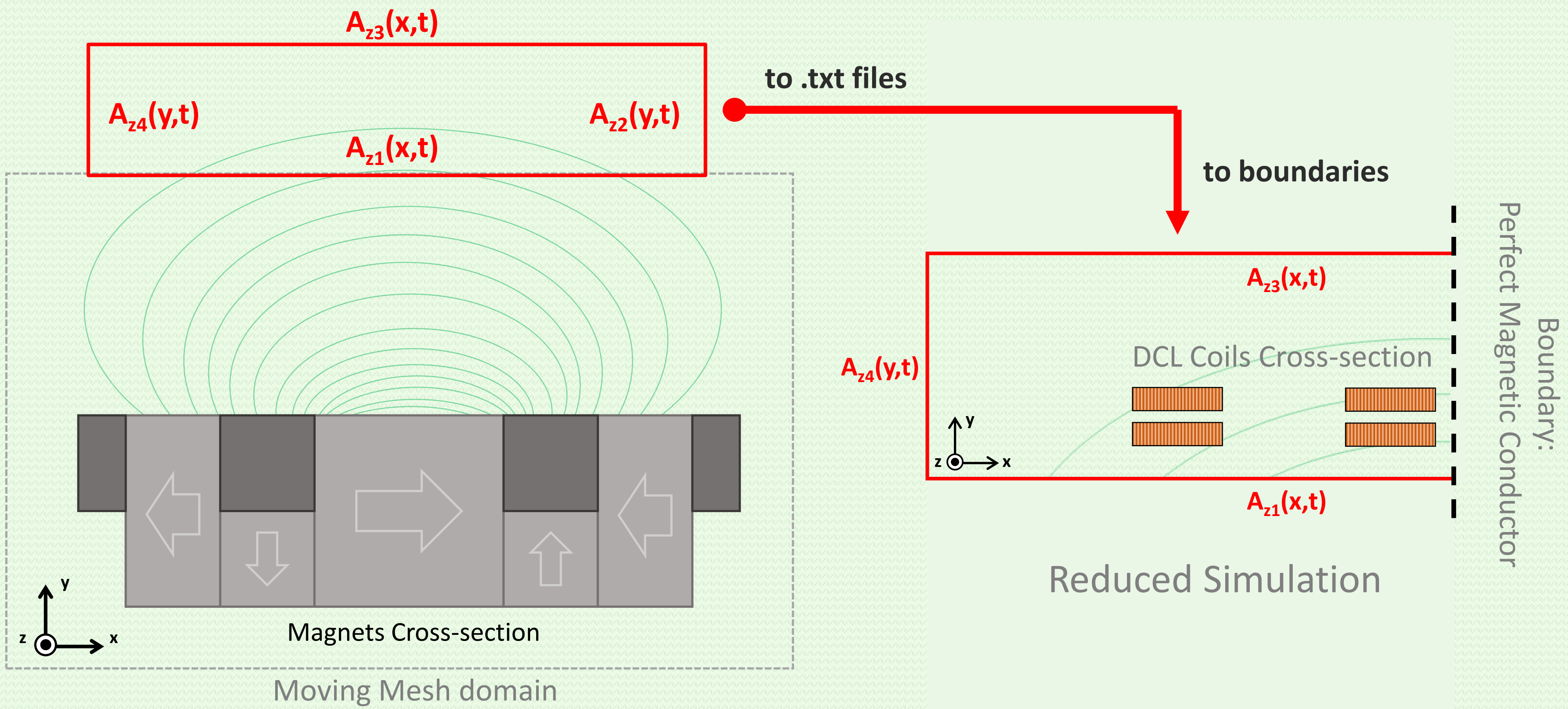


F. Grilli, et al., “*Current Density Distribution in Multiple YBCO Coated Conductors by Coupled Integral Equations*”, IEEE TAS, 2009

2.3. Modelling the Magnets

Magnets displacement: Moving Mesh = TROUBLE!

Bypassed by splitting the simulatio in two:

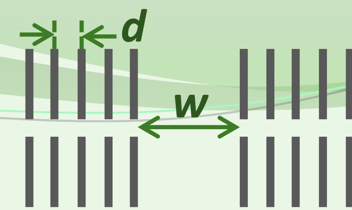


3. Results

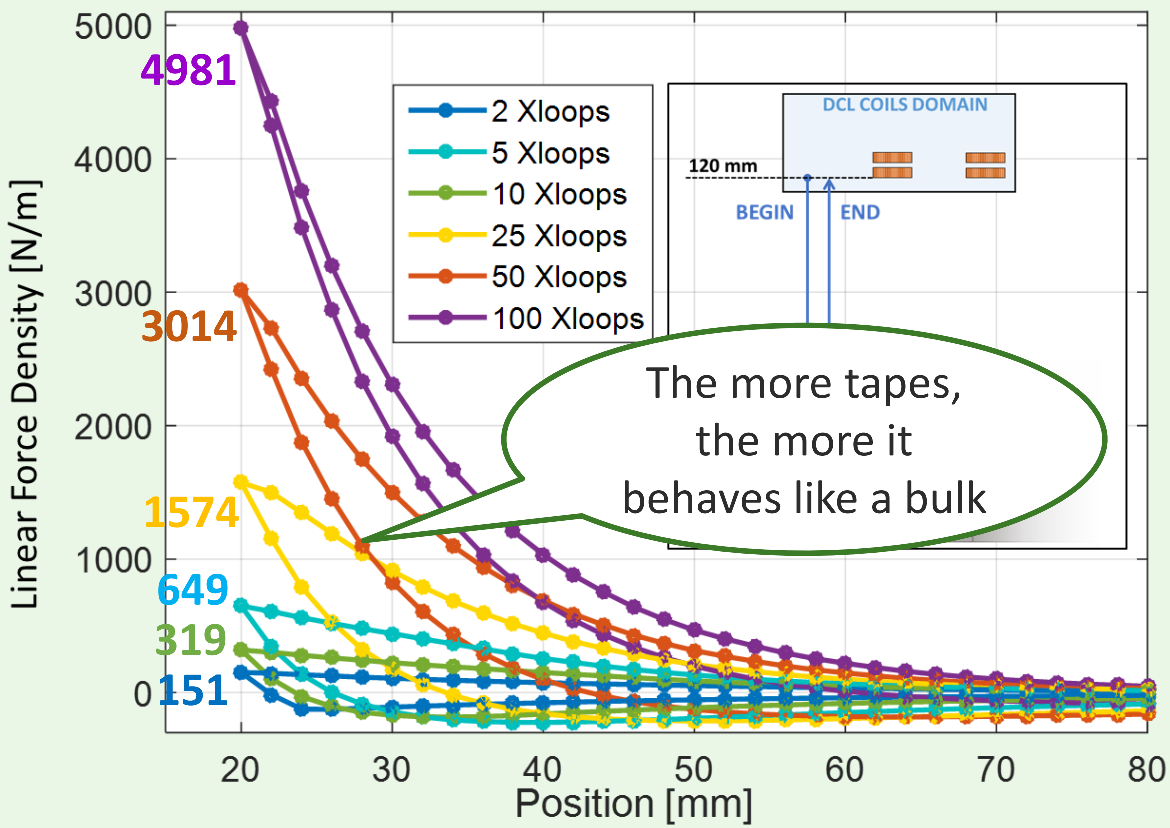
Analyzing Design Parameters

Comparing Simulations to Measurements

3.1. Design Parameters



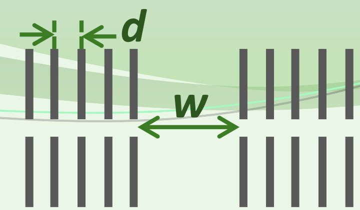
Number of Xloops (N), inner width (w), stacking factor (d)



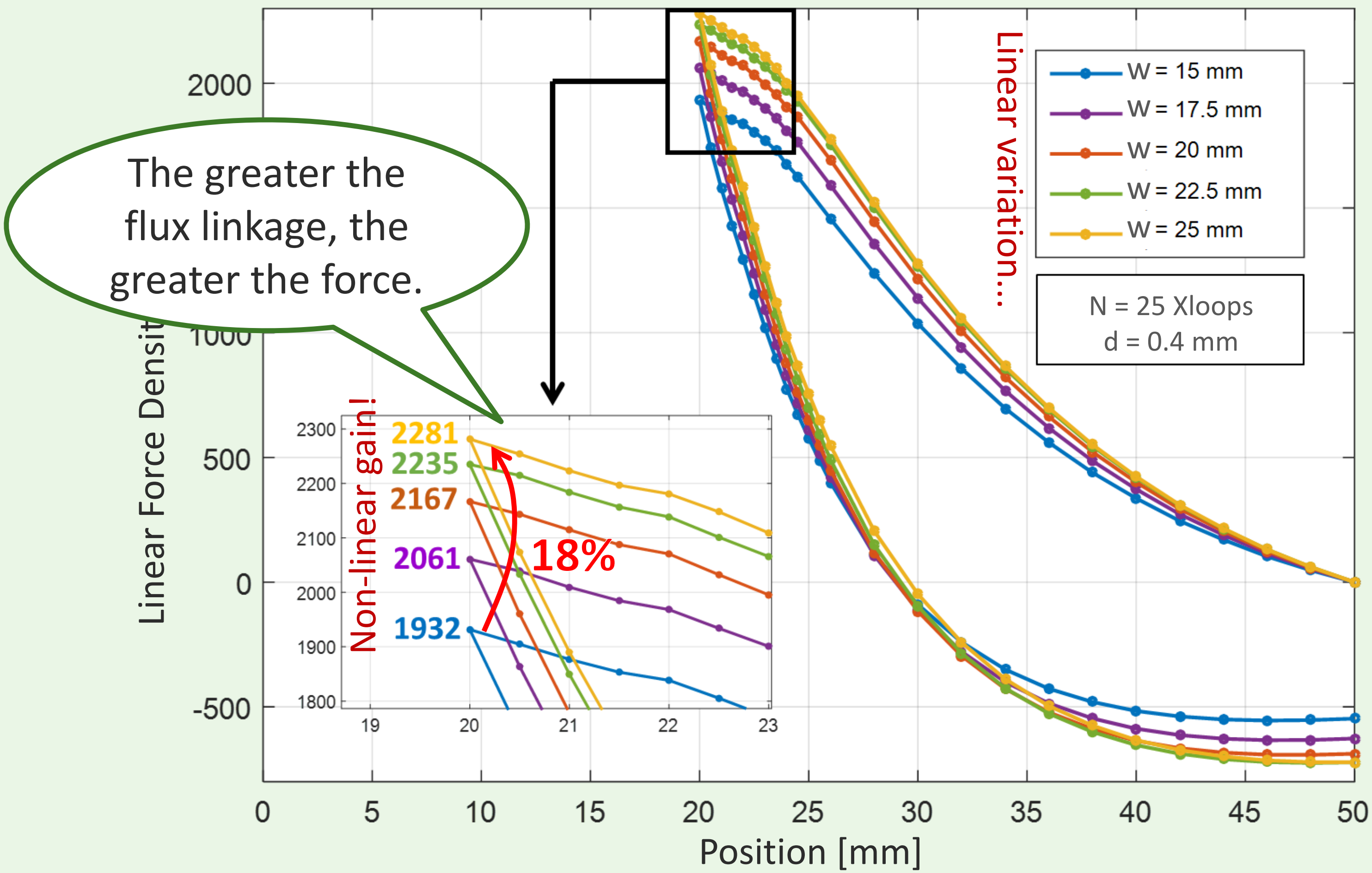
N	F at 20 mm (N / m)	F per DCL (N / m / DCL)
2	151	75,5
5	319	63,8
10	649	64,9
25	1574	63,0
50	3014	60,3
100	4981	49,8

It's not only about stacking the more tapes you could!

3.1. Design Parameters

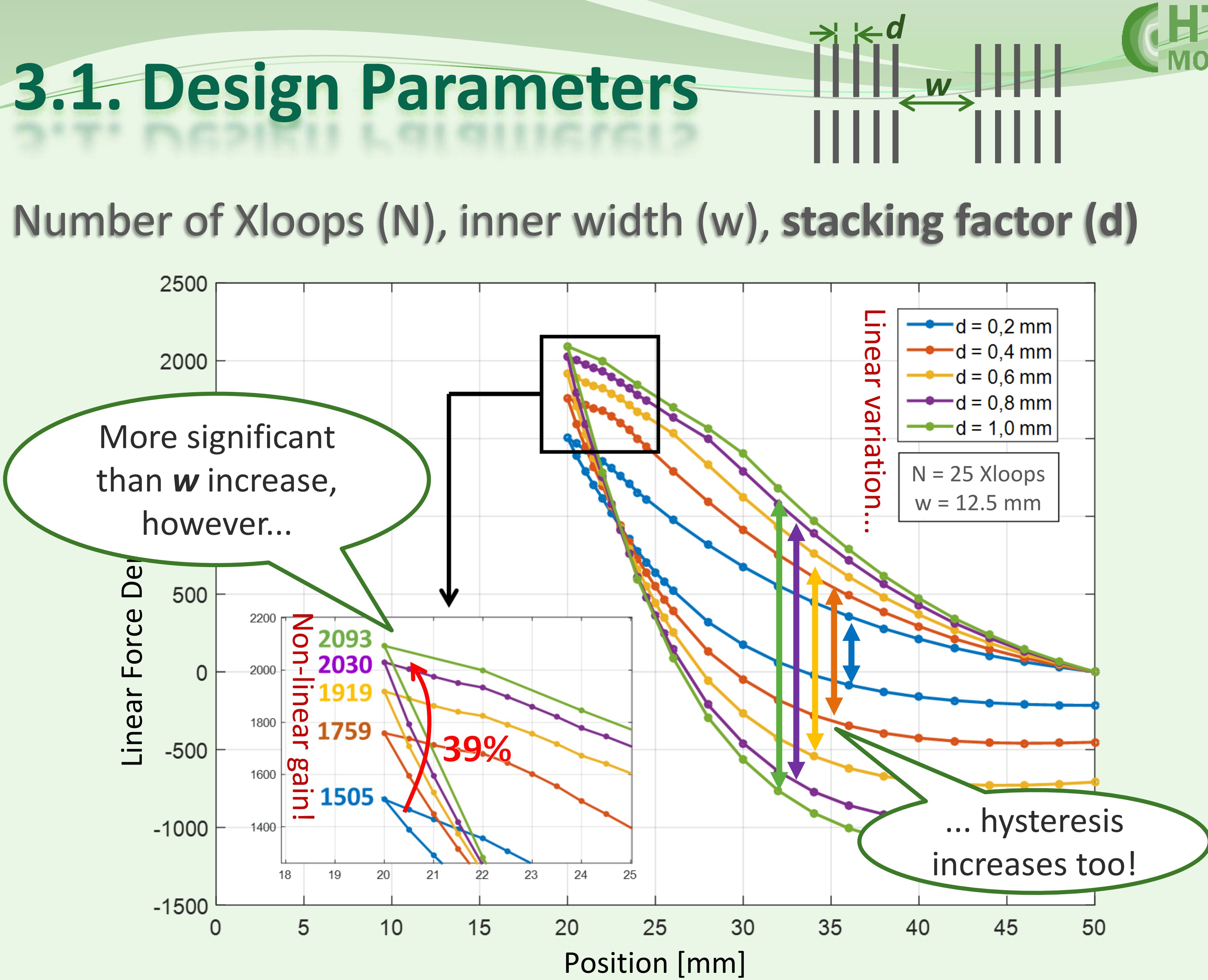


Number of Xloops (N), **inner width (w)**, stacking factor (d)



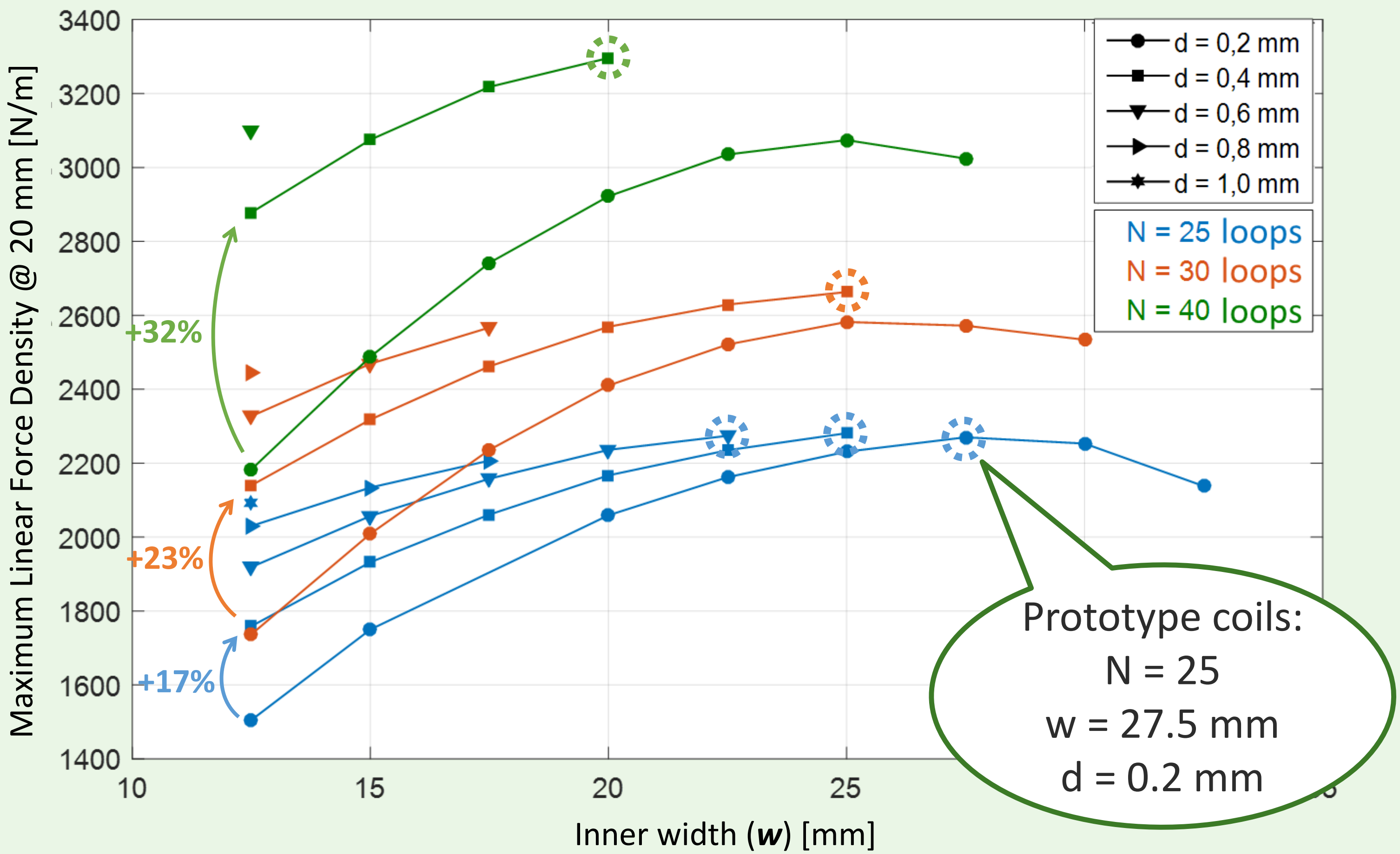
3.1. Design Parameters

Number of Xloops (N), inner width (w), **stacking factor (d)**



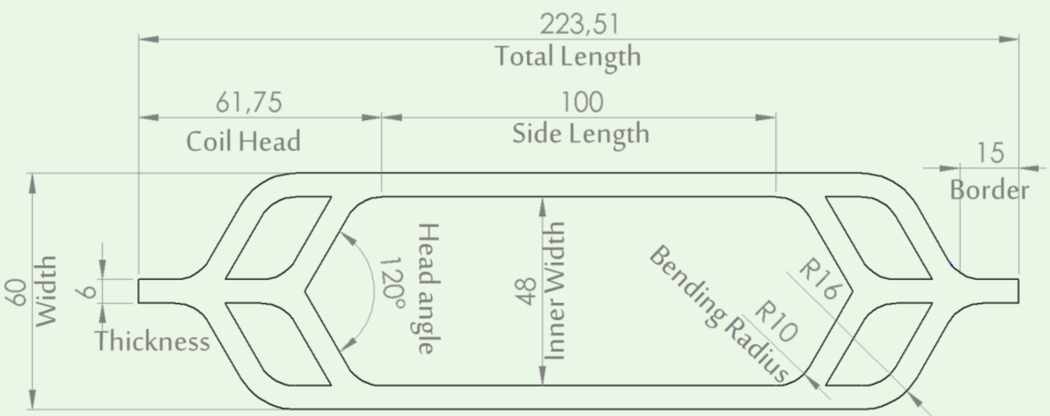
3.1. Design Parameters

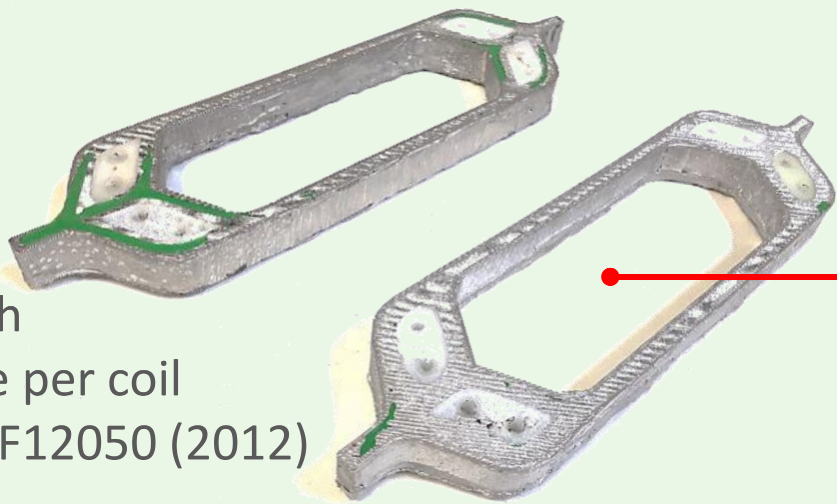
Non-linear relations led to parametric simulations (54 variations).



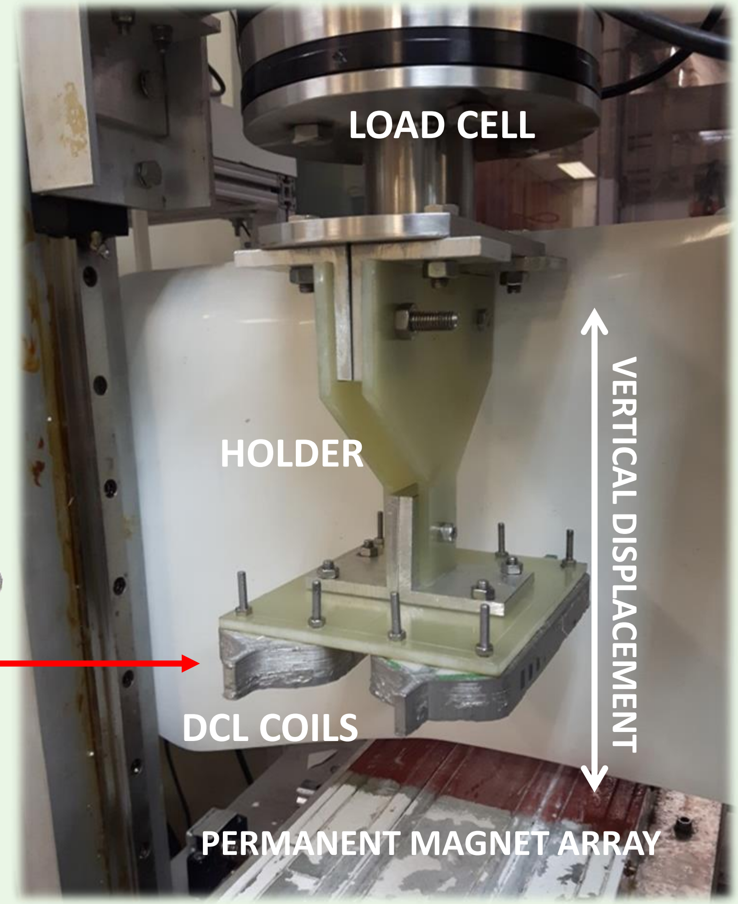
3.2. Simulations vs Measurements

Prototype tests: vertical displacement towards magnets in $_{L}N_{2}$



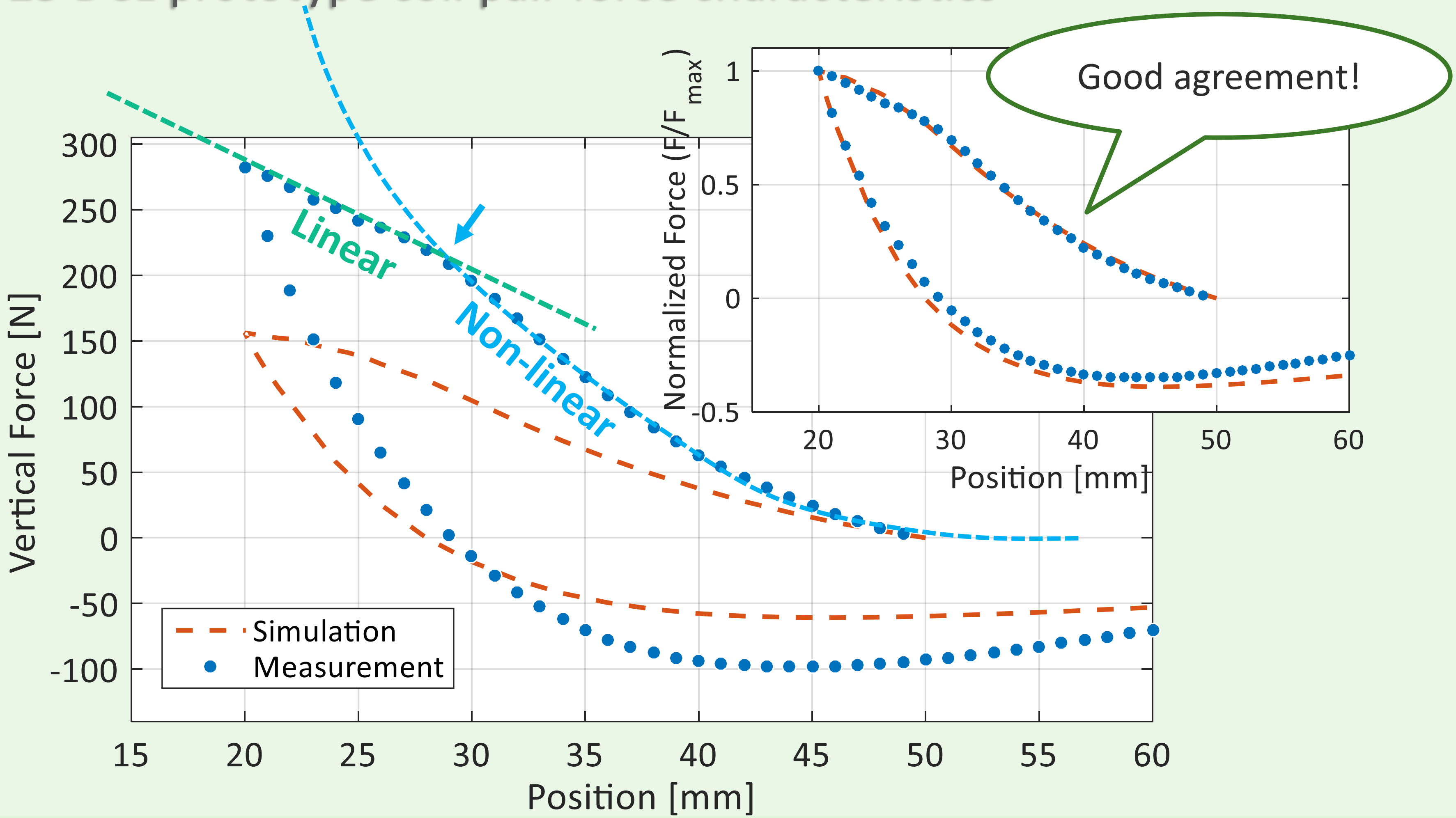


2 DCL coils
25 Xloops each
11.125 m tape per coil
SuperPower SF12050 (2012)



3.2. Simulations vs Measurements

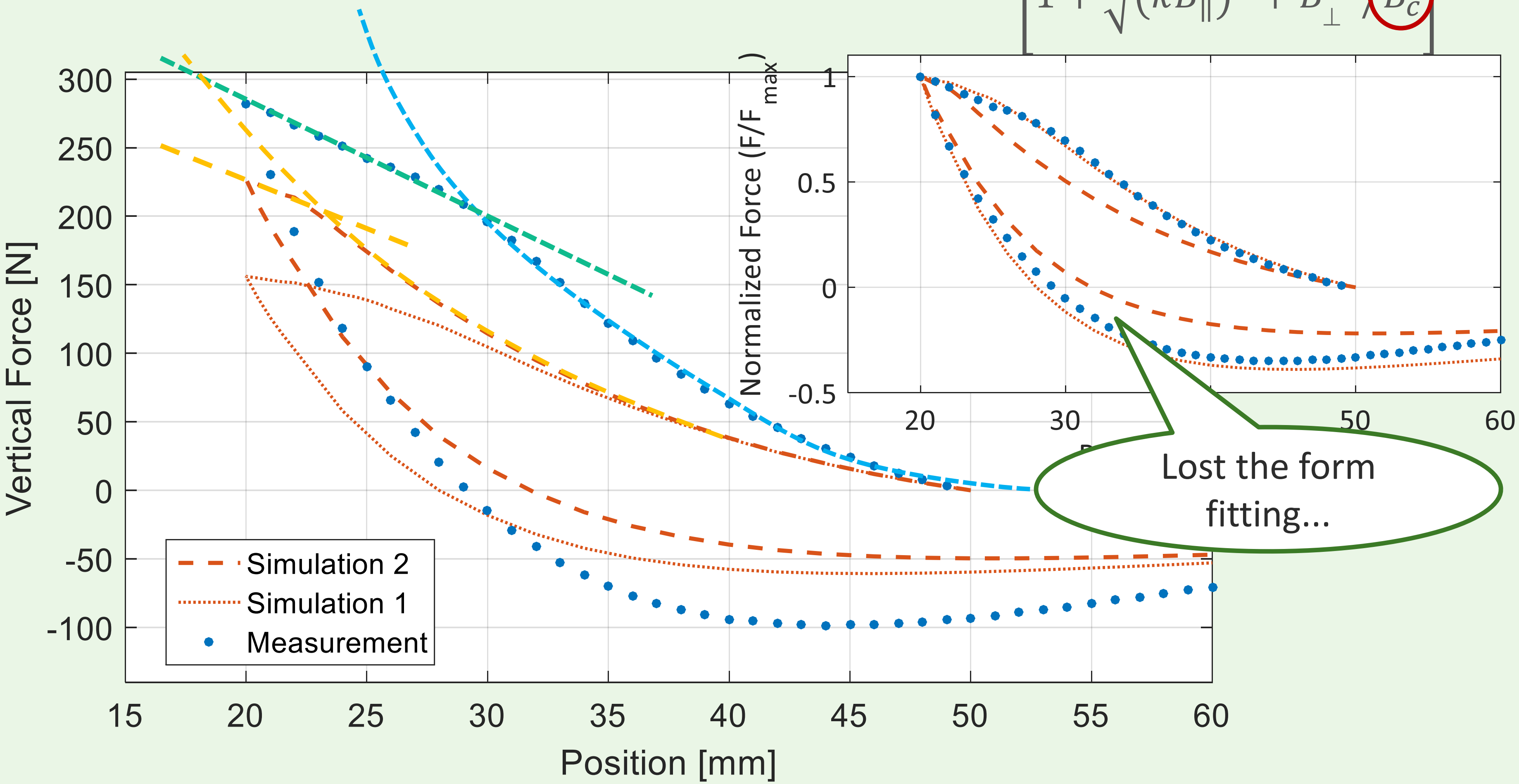
25 DCL prototype coil pair force characteristics



3.2. Simulations vs Measurements

Trying improve the agreement...

$$J_c(B_{\|}, B_{\perp}) = \frac{J_{c0}}{\left[1 + \sqrt{(kB_{\|})^2 + B_{\perp}^2}/B_c\right]^b}$$



4. Conclusions

4. Conclusions

A simulation model for DCL coils is proposed and tested for designing a SML bearing application.

- There are design variables that increase the levitation force other than simply increasing the number of tapes.
- These variables effects are non-linear. Optimization requires parametric simulations.
- The model does not match the values of the measured force, but reproduce its behavior.

4. Conclusions

Next steps (concerning simulations):

- Find a set of $J_c(B_{\|}, B_{\perp})$ parameters (or even another function) that allows a better reprodution of measured results;
- Implement a 3D simulation to allow accounting for coil head effects (leave Integral Equations?);
- Investigate other applications...

Thank you for your atention!

Flávio Goulart dos Reis Martins

flaviogrmartins@gmail.com

Laboratório de Aplicação de Supercondutores
Laboratory for Applied Superconductors

Universidade Federal do Rio de Janeiro
Federal University of Rio de Janeiro