Experimental verification and comparison of analytical and FE models for calculation of a bitter solenoid

Part II: Numerical simulation

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I²FG Workshop on Impulse Forming

Gent, 7 May 2013

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Content

- introduction

- study of coil system by 3D BEM analysis
- study of coil system by 2D FEM analysis
- parametric study of coil system by 3D FEM analysis

- conclusions and outlook

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Appropriate and available Software

LS-DYNA v980a
MPP alpha

- 980 alpha version contains em-modul in test stage
- first tests show capability for highly nonlinear mechanical problems (contact, material)
- mag. materials (nonlinear B-H dependency → ferromag-netic materials) are non-implemented

ANSYS 14.0 ✓

- circuit coupled and multiphysics capability
- nonlinear magnetic capability for modeling B-H curves
- coupling method between magnetic and electric degrees of freedom (low-frequency formulation)

ANSOFT Maxwell (2D/3D FEM) (*now part of ANSYS*)

FEMM (2D FEM)

QuickField* (2D FEM)

COMSOL* (2D/3D FEM)

FastHenry (3D BEM)

**multiphysics capability*

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Our Research Profile

- Design of microsystems (sensors and actuators) and their application in a device environment
- **Modeling, simulation and experimental** validation of the behavior of microsystems
- **Development of design tools and methods**
- Characterization of MEMS and precision engineered structures
- Measurement and test technology for microsystems

Hardware

Workstation
Intel® Core™ i7-3930K CPU @3.20GHz
64.0GB RAM

Software

- **ANSYS Academic Associate product**
- ANSYS Academic Research product

- ANSYS Simplorer
- MathCad
- MATLAB

http://www.tu-chemnitz.de/etit/microsys

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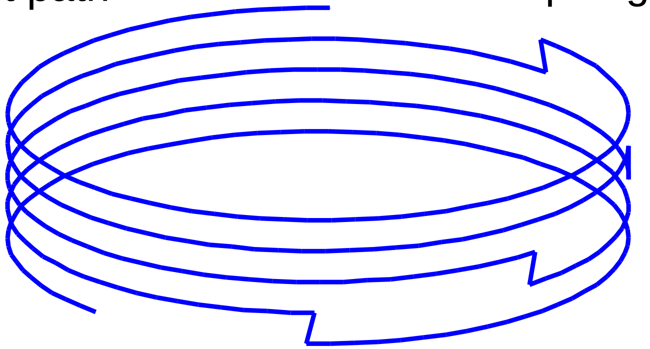
3D BEM

output: Impedance matrix **Z**=**R**+j**L**

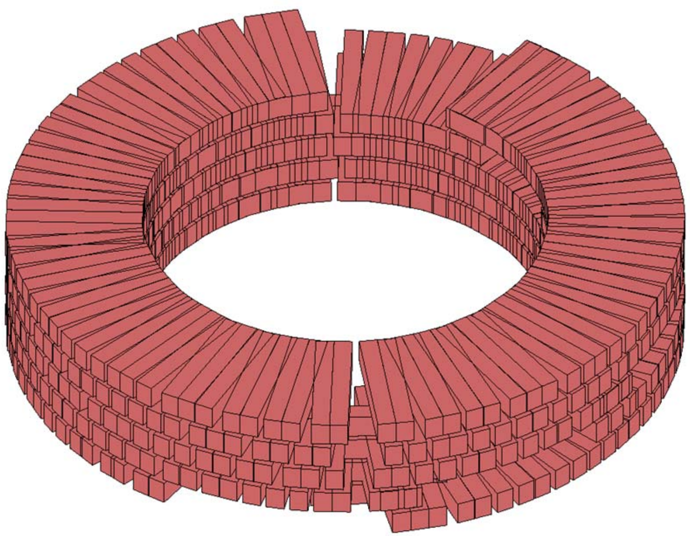
"Current path"

Topology of coil

input



3D model



FastHenry from MIT

http://www.rle.mit.edu/cpg/research_codes.htm

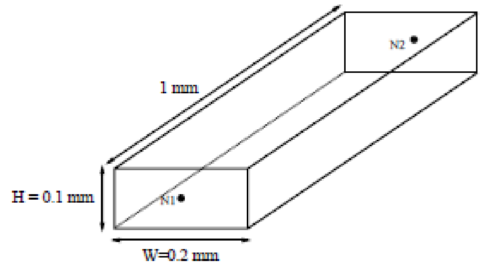


Figure 1: Example Segment for Sample Input File

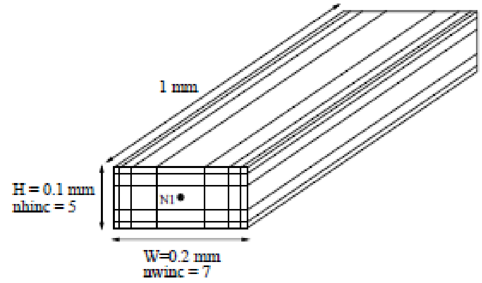
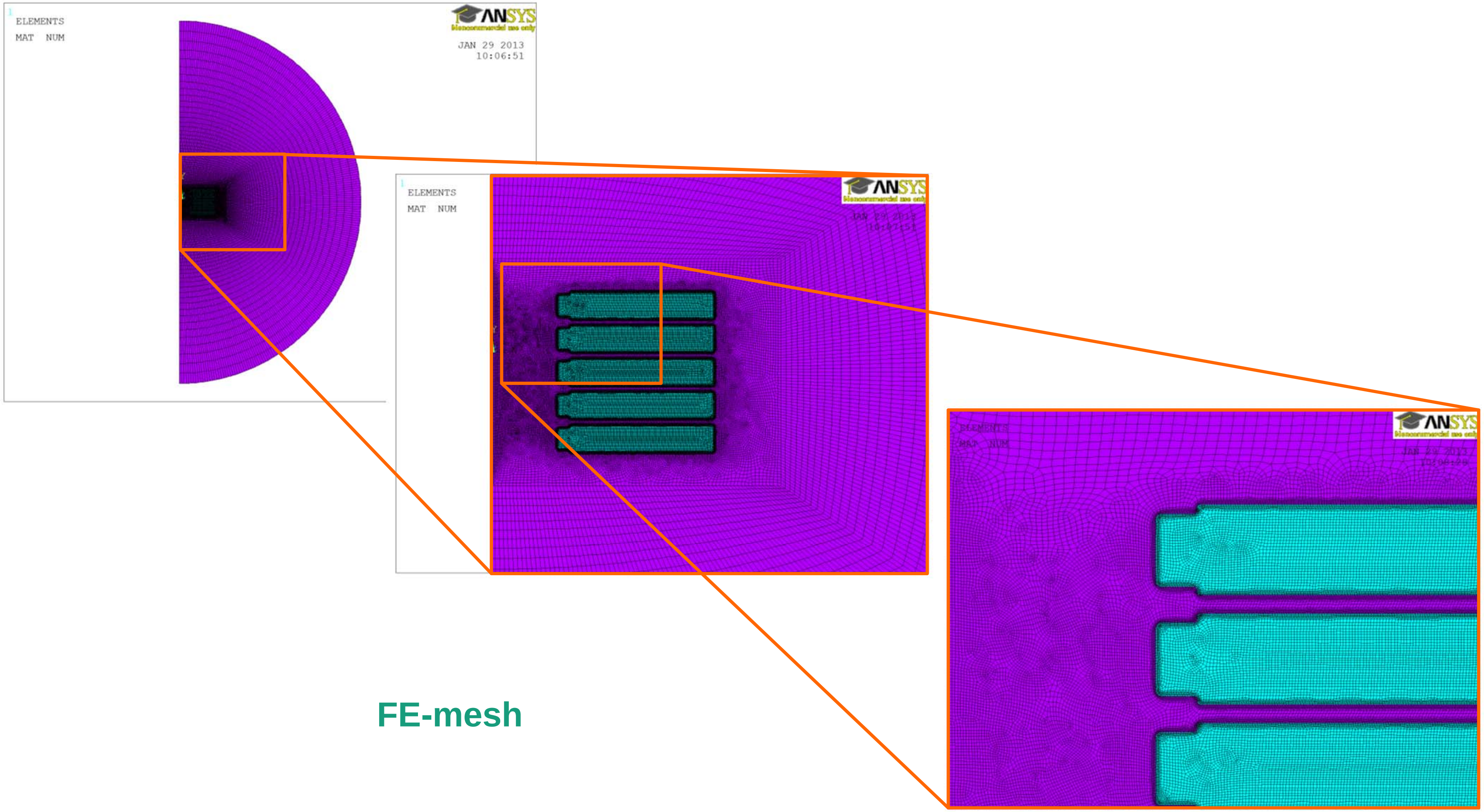


Figure 2: Segment discretized into 35 filaments

file.inp

```
N1   x=1.50e+01 y=0.00e+00 z=0.00e+00
N2   x=1.80e+01 y=0.00e+00 z=0.00e+00

E1   N1   N2 w=9.0 h=4.0
```


ELEMENTS
MAT NUM
ANSYS
JAN 29 2013
10:06:51
ELEMENTS
MAT NUM
ANSYS

FE-mesh

2D axisymmetric MVP FE analysis in ANSYS

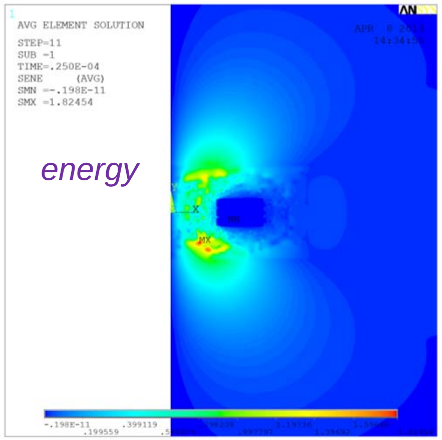
PLANE53 (quadratic) element

ρ = 4.0E-8 Ohm·m

$$L = \frac{2W_{mag}}{I^2}$$

$$R = \frac{P_{rms}}{I^2_{rms}}$$

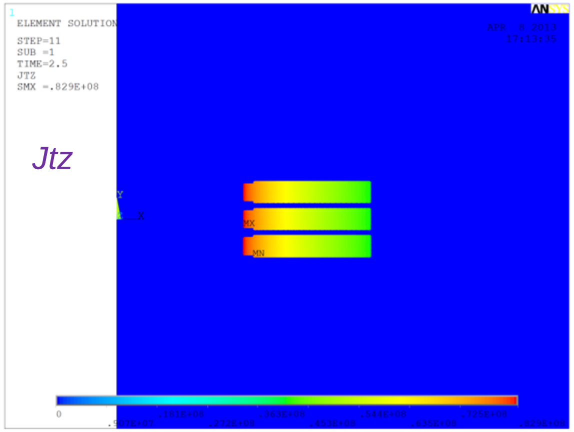
f=10kHz, I=75kA



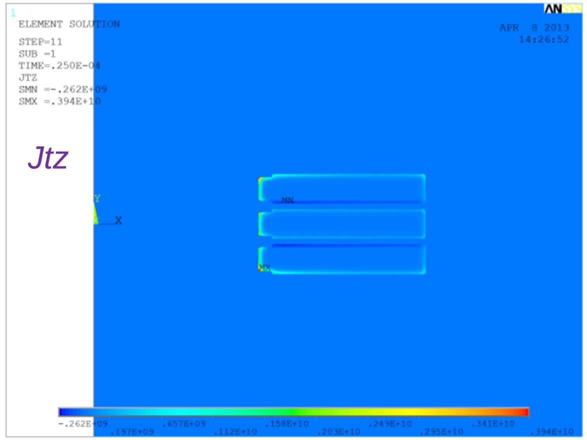
N_turn=3

transient analysis

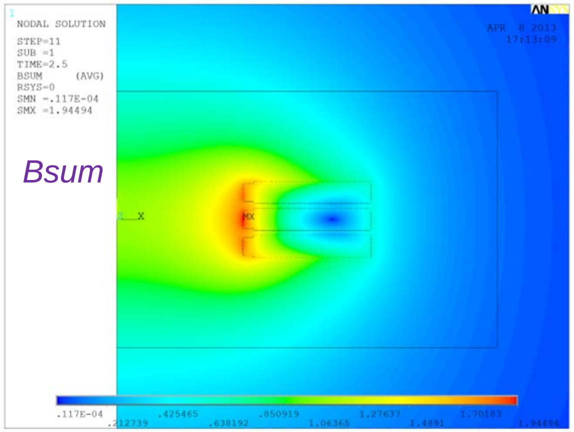
f=0.1 Hz, I=75kA

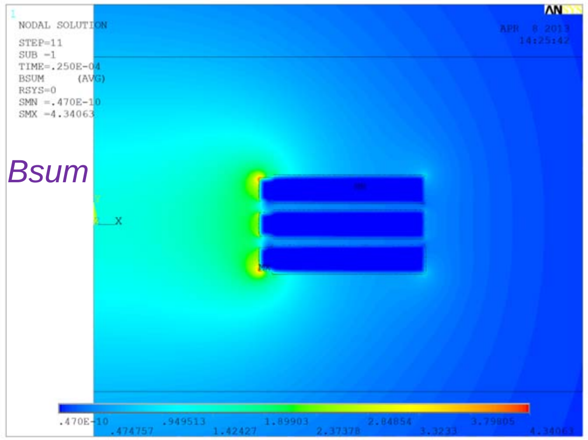


f=10kHz, I=75kA



ET,1,PLANE53,1,,1





$R_{coil}(0.1)$ = 71.232 μOhm
$L_{coil}(0.1)$ = 2.131 μH

$R_{coil}(f)$ = 994.251 μOhm
$L_{coil}(f)$ = 1.608 μH ✓

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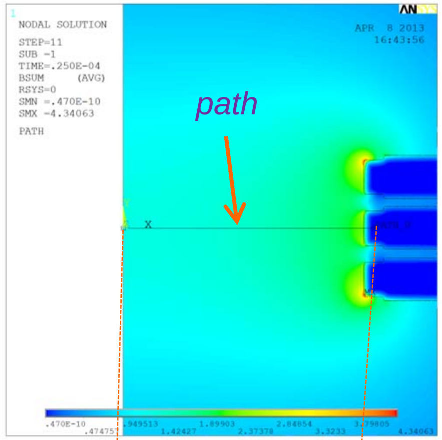
2D axisymmetric MVP FE analysis in ANSYS

PLANE53 (quadratic) element

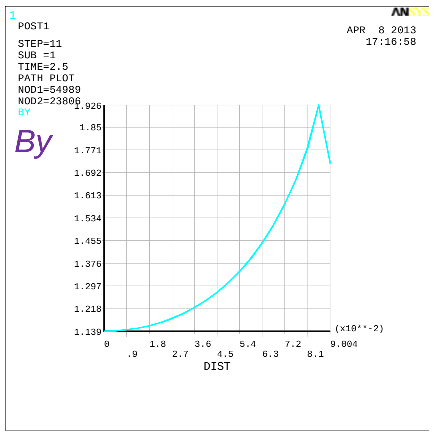
ρ = 4.0E-8 Ohm·m

transient analysis

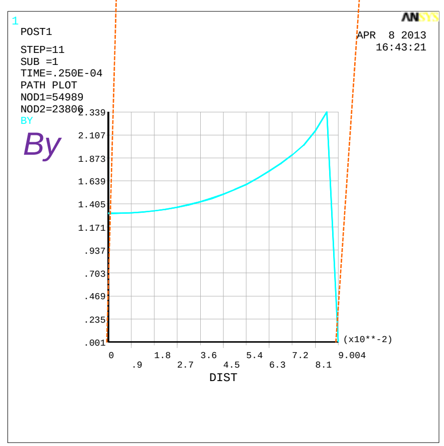
f=10kHz, I=75kA



f=0.1 Hz, I=75kA



By=1.4…1.9 T



By=1.3…2.3 T ✓

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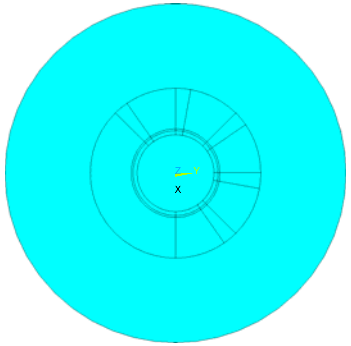
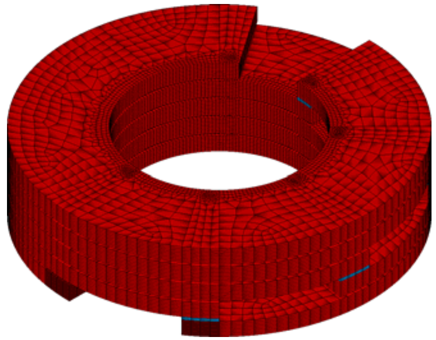
3D edge-flux formulation FE analysis in ANSYS

2D model



3D model



Generates volumes by dragging an area pattern along a path

Solid236

3D edge-flux formulation

Model status:

number of nodes = 5 775 365
number of elements = 1 438 560
number of edge-flux DoF = 4 325 372
number of equations = 3 253 926

solution time: 6:44 h

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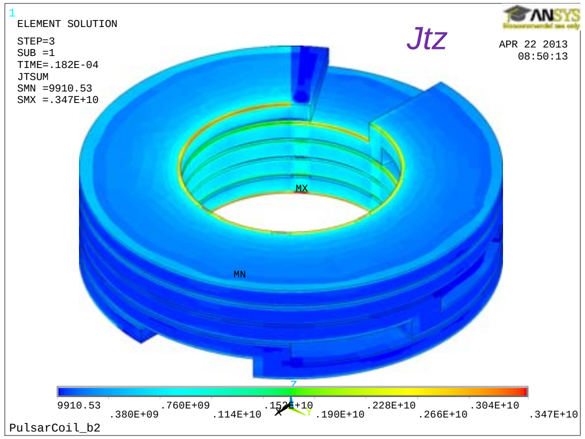
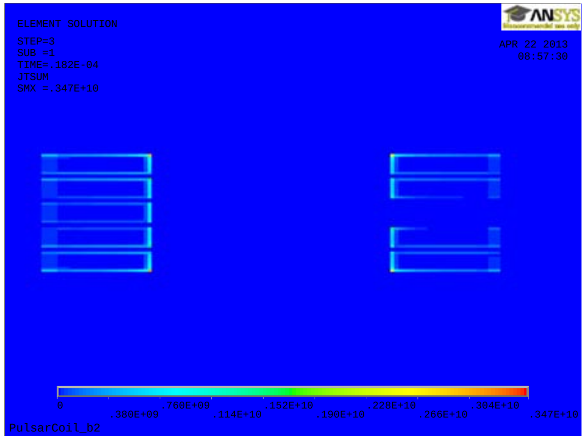
3D edge-flux formulation FE analysis in ANSYS





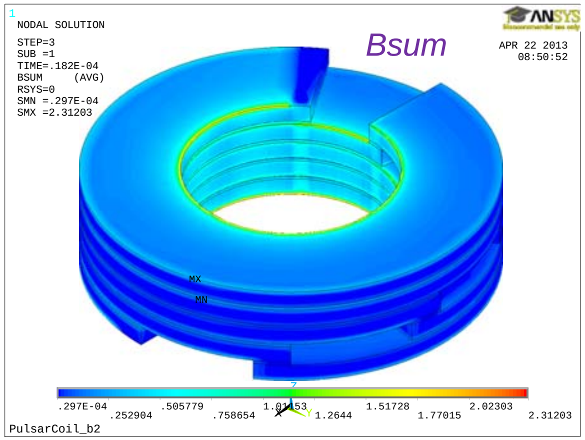
ρ = 4.0E-8 Ohm·m

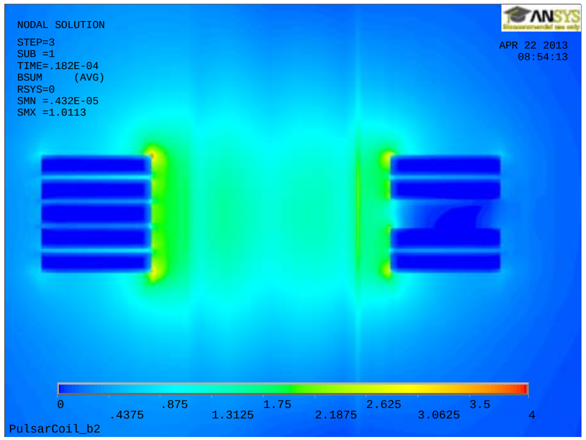
f=10kHz, I=75kA

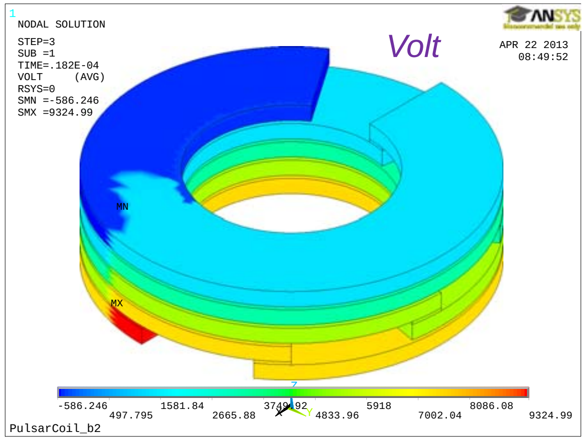
transient analysis

$R_{coil}(f) = 1.943$ mOhm

$L_{coil}(f) = 2.446$ μH







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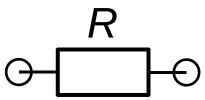
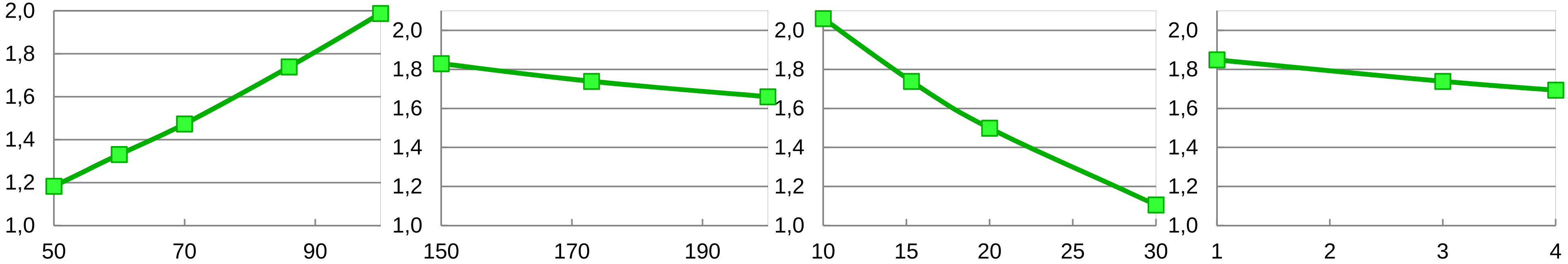
Parametric study

R, mOhm

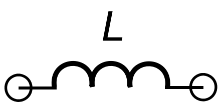


$$R_{\mathrm{dc}} = \rho \frac{L}{A}$$

R, mOhm

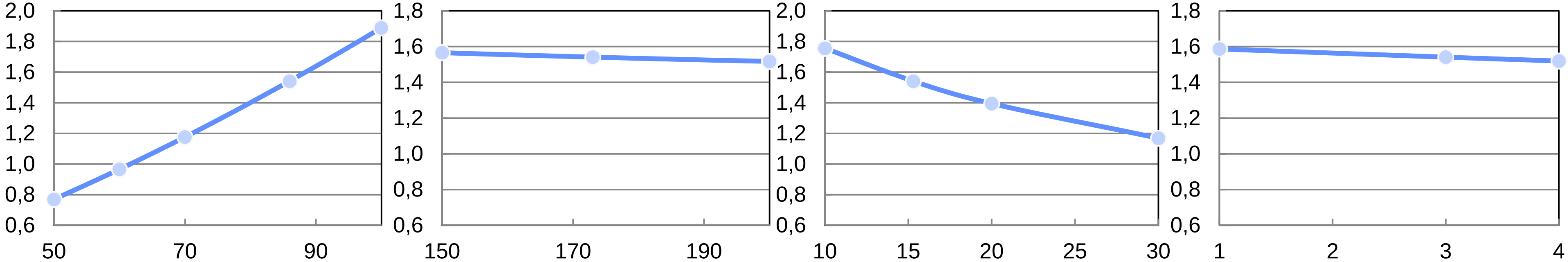


L, µH



$$L = \eta^2 \frac{\mu_0 r_1 \Lambda(\alpha, \beta)}{4\pi}$$

L, µH



Inner radius, mm

Outer radius, mm

Turn thickness, mm

Connection thickness, mm

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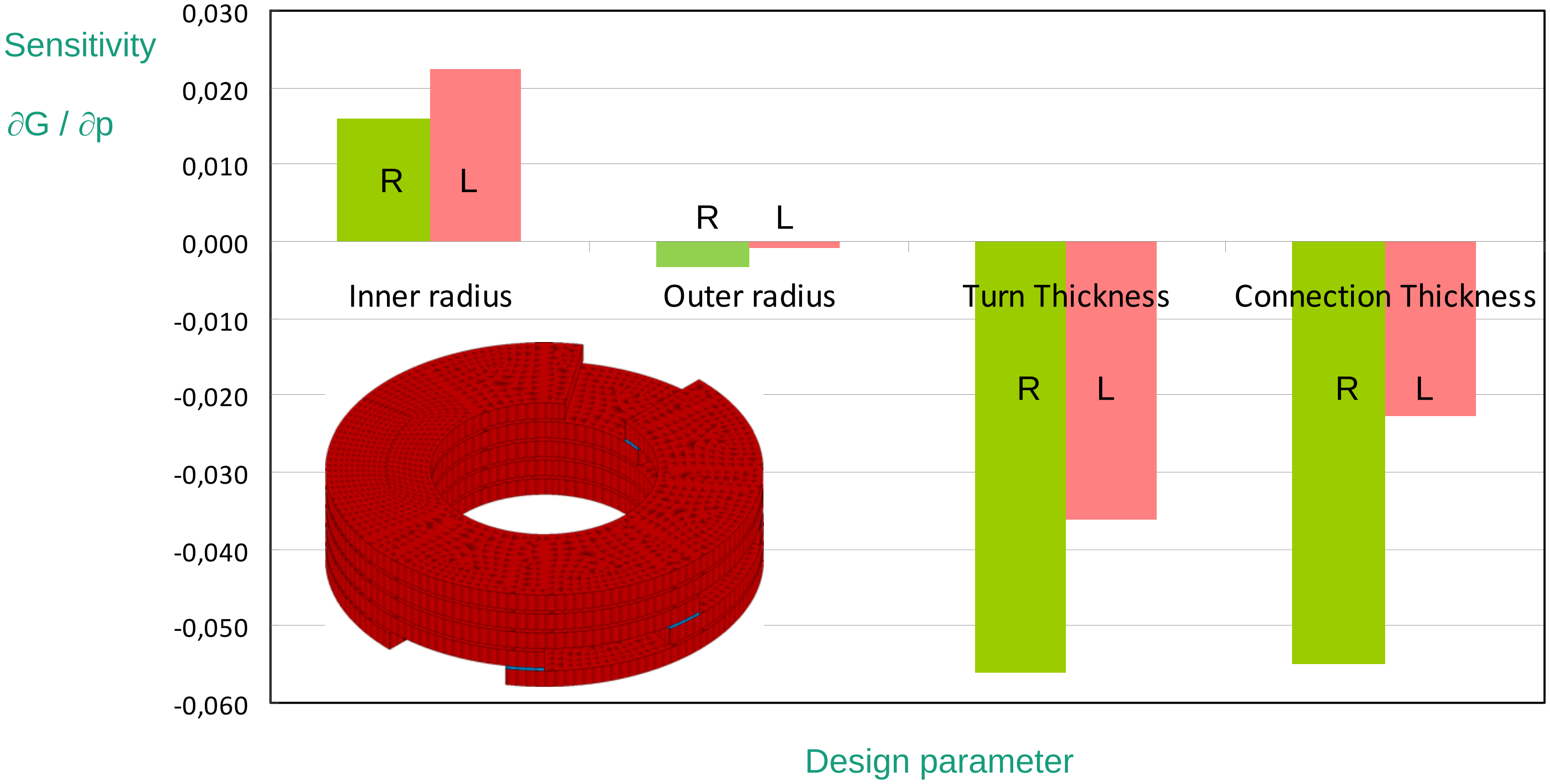
Sensitivity analysis



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Results

Software	Analysis type	R, mOhm	L, µH	B, T
FastHenry 3D	dc	0.152	6.914	n.a.
	ac 10kHz	3.616	6.013	n.a.
ANSYS 3D electro-conductivity	dc	0.109	n.a.	n.a.
ANSYS 2D emag	0.1 Hz 3 turn*	0.071	2.131	1.4…1.9
	10kHz 3 turn*	0.994	1.608	1.3…2.3
FEMM 2D	10kHz 3 turn*	-	-	1.4…2.4
ANSYS 3D emag	dc	0.110	4.093	-
	ac 0.1 Hz	0.110	2.047	1.30…2.23
	ac 10kHz	3.478	1.541	1.45…2.17
Analytical	10kHz	6.588	1.838	1.2
Experimental	10kHz	7.441	1.504	0.76…1.9

Conclusions and Outlook

A short conclusion is given in the following:

- parametric study of coil system by 3D BEM and FEM analyses has been presented

Further work will be focused on:

- iterative verification and validation of presented models
- application of efficient algorithm (e.g. Variational Technology method within ANSYS)

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Thank You for Your Attention!

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