FEM Simulation Tool for Electromagnetic NDT System in Different Inspection Situation and Visualization Platform

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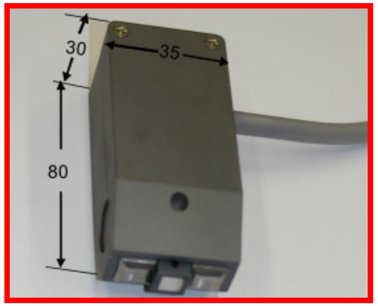
Fraunhofer
IZFP

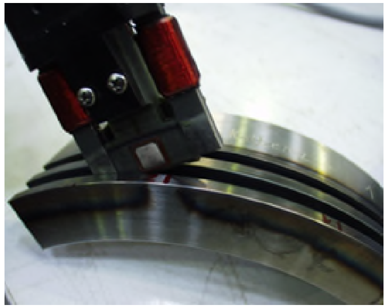
Structure

1. Introduction
2. Modeling of the magnetic material
   - General procedure
   - Characterization
3. FEM simulation
   - 3MA principal and challenges
   - Impact of hysteresis
   - Low frequency eddy current
   - Incremental permeability
4. Validation on a homogeneous case
5. Correlation between mechanical properties and 3MA outputs

Introduction: 3MA probes

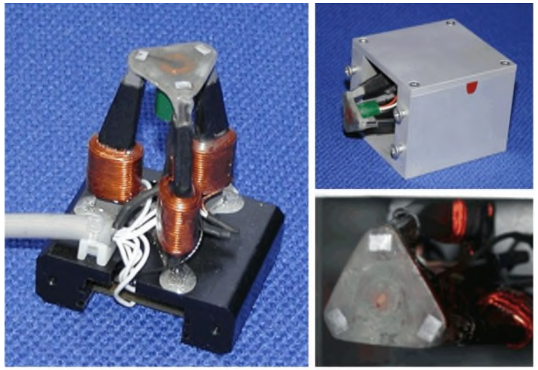


Type E1030-B
Spherical pole shoes Max. measuring depth≤ 4 mm



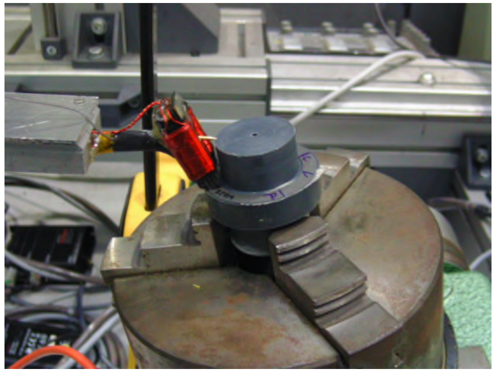
Special Probe Head for Piston Grooves

For large gear wheels



Rotating field probes allows directional determination of stress, elongation,grain orientation

Automated Strip Steel Inspection Systems

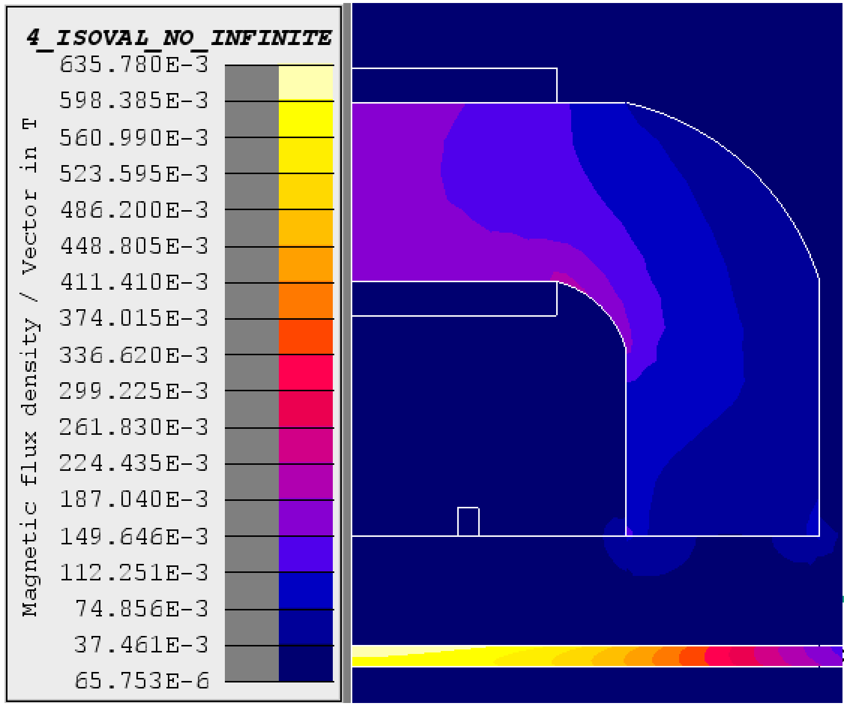


Rotating sample

New: Magnus probe (3MA +ultrasound)

Magnus

Specificity:
- -Eddy current
- -Harmonic analysis
- -Barkhausen noise
- -Incremental permeability
- -Ultrasound

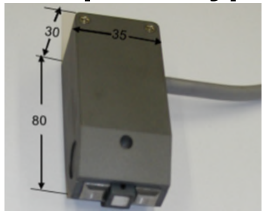


For the incremental permeability
The magnetization coil send
superimposed signals
LF+HF

Simulation & visualization

Preparation → Parametric model → Simulation → Evaluation, visualization → Validation

3MA probe type



Specimen data

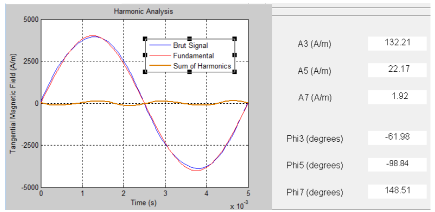
3MA method
(HA, IP or EC)

Settings
(Excitation magnitude, frequency, etc.)

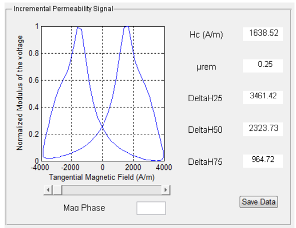
Parametric model of the inspection situation

FEM Solver

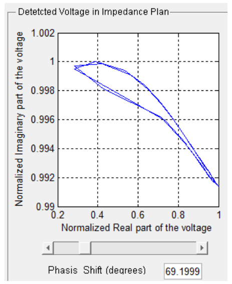
Post processing



HA



IP

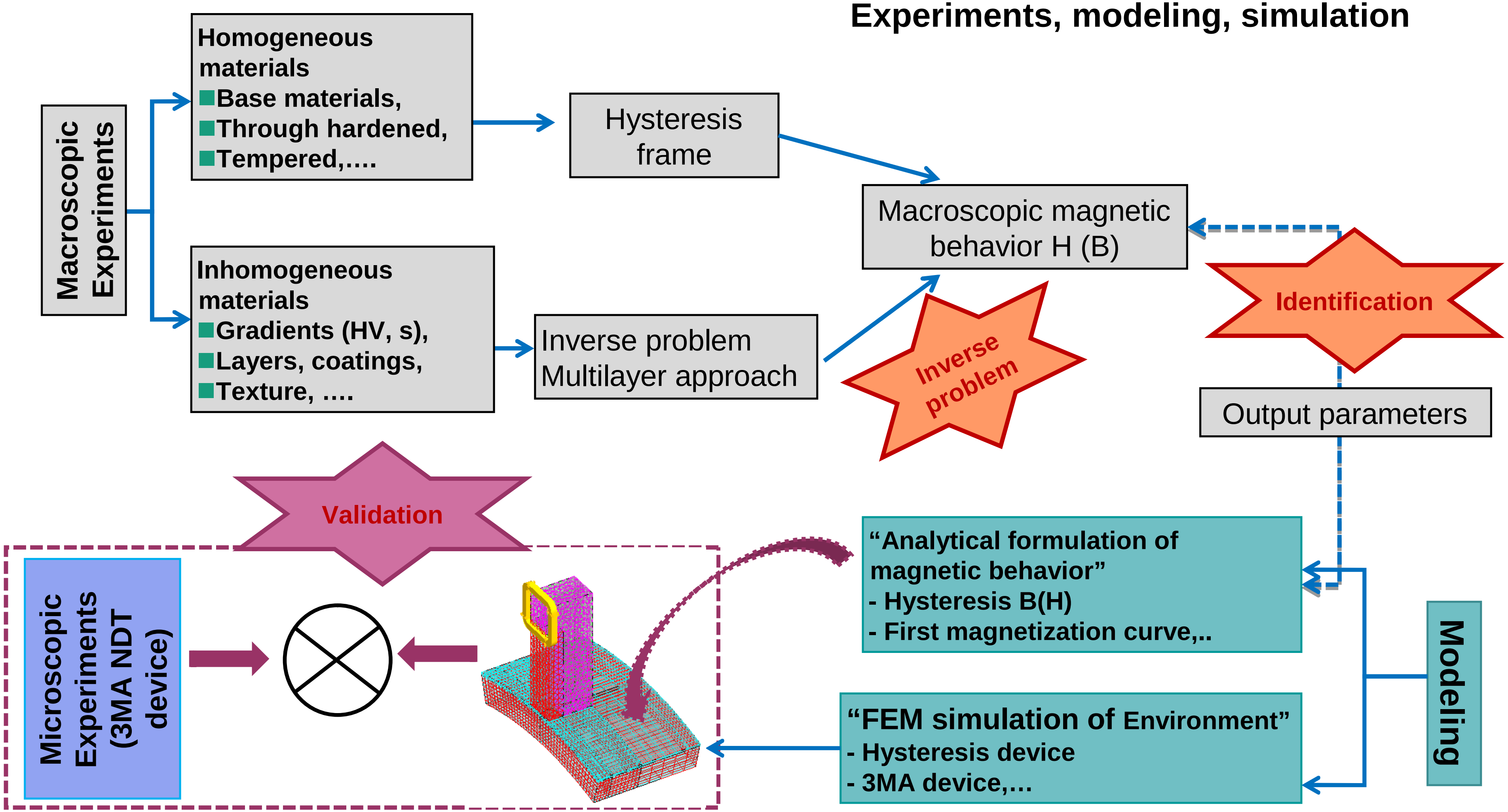


EC

Structure

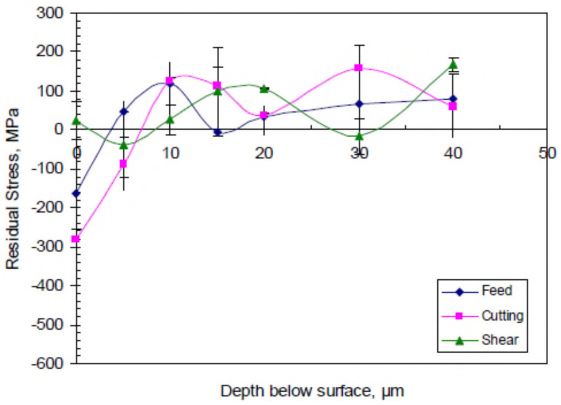
Material modeling: General procedure

Experiments, modeling, simulation

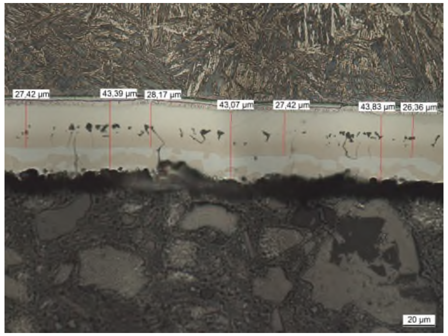


Multi layer approach

Mechanical Profiles (literature example)

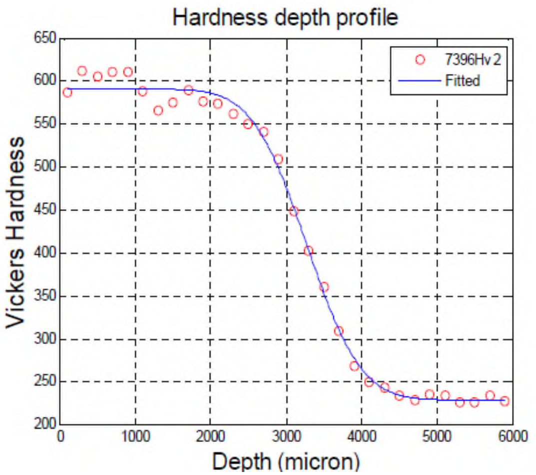


Hardening profile (literature example)



Microstructure

Multi layer approach



Inverse problem

-Combination of 3MA

-Analytical formulation of linear eddy current

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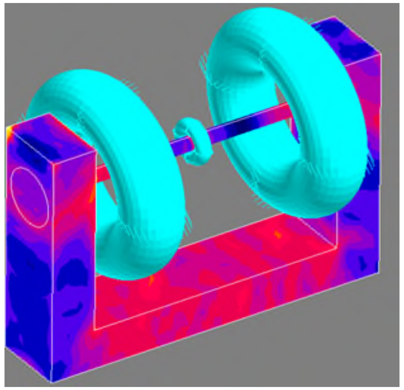
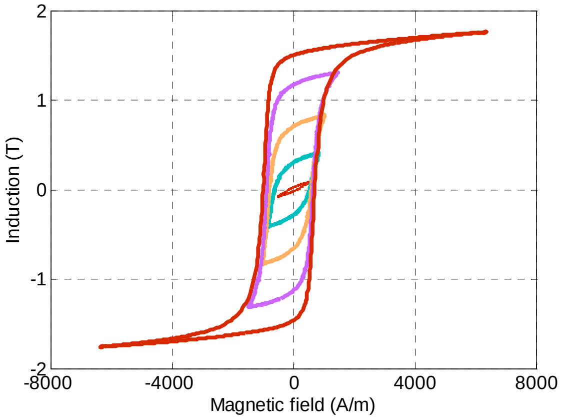
Material modeling: Global and local characterization

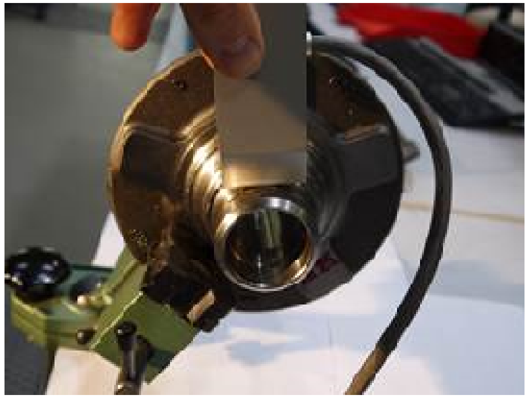


Hysteresis frame measurements

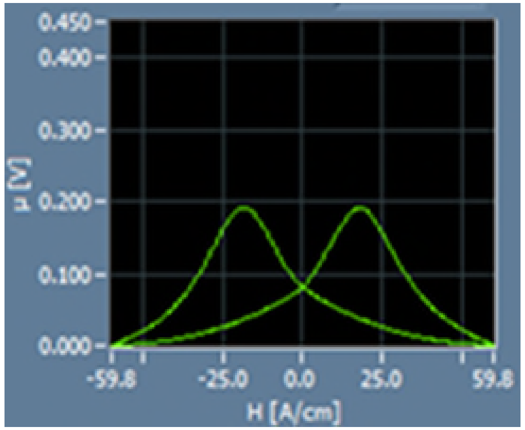


Results:
-Js = 2T
-µr = 419,
-Hc = 708 A/m
-Br =1.5T

3MA measurements



Results:
-Hcµ = 18,1 A/cm
-µmax = 0.2 V
-DH25µ = 54.9 A/cm
-DH50µ = 35.3 A/cm
-DH75µ = 18 A/cm



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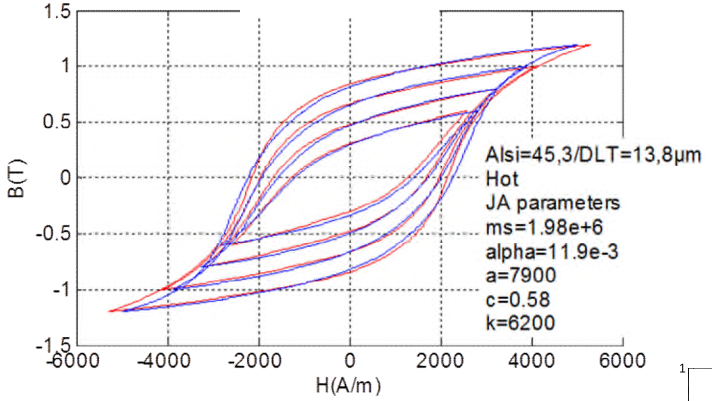
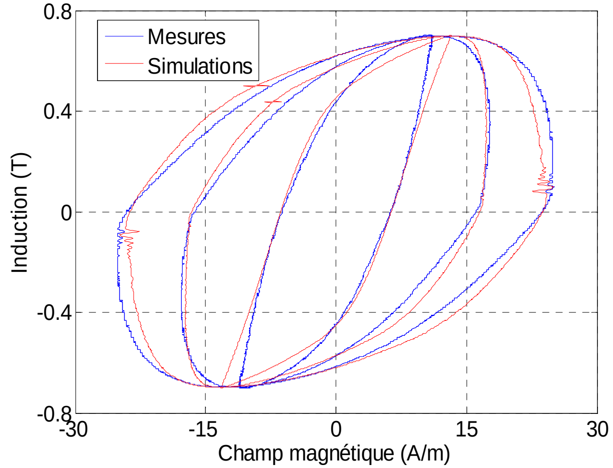
Material modeling: Calculation and experiment

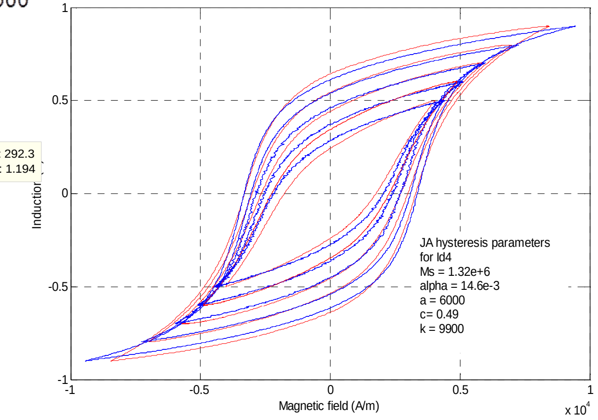
22MnB5



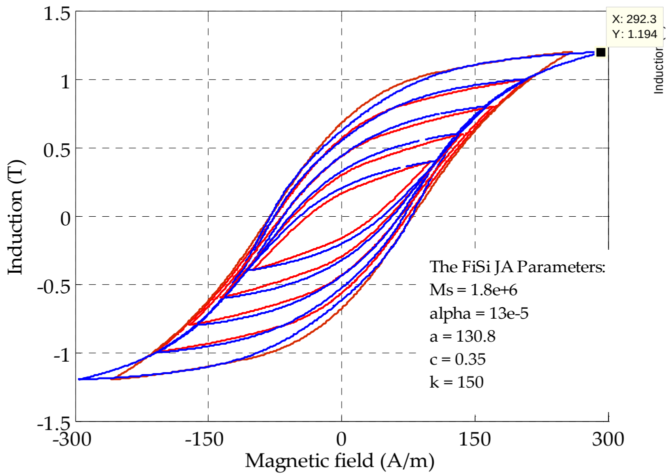
Dynamic: Jiles Atherton+ Berttoti
f =50Hz, 100Hz, 200Hz

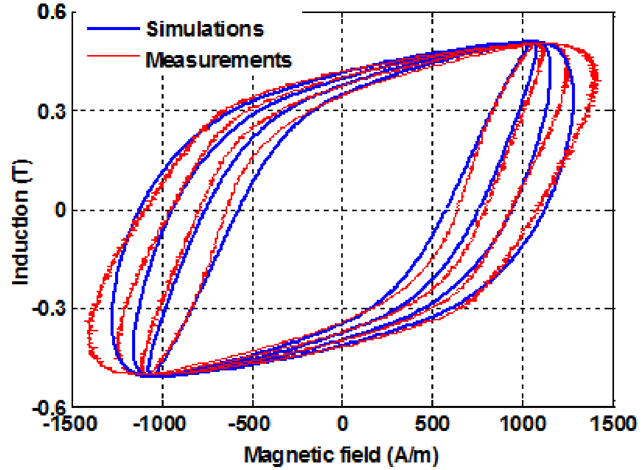


50CrMo4



FeSi 3%





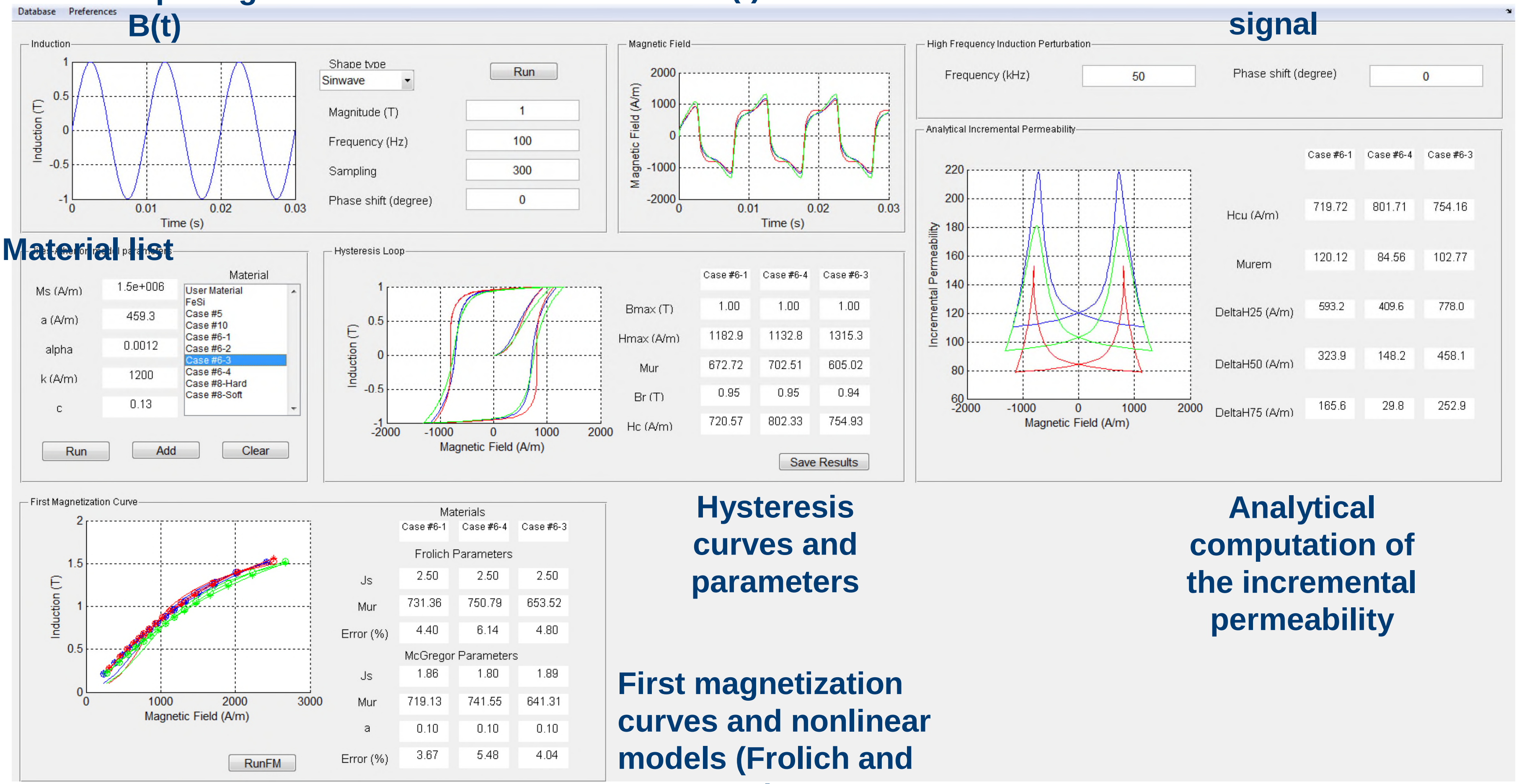
Material modeling: Material data base in the platform

Input signal B(t)

H(t)

Perturbation signal

Material list



Hysteresis curves and parameters

Analytical computation of the incremental permeability

First magnetization curves and nonlinear models (Frolich and McGregor)

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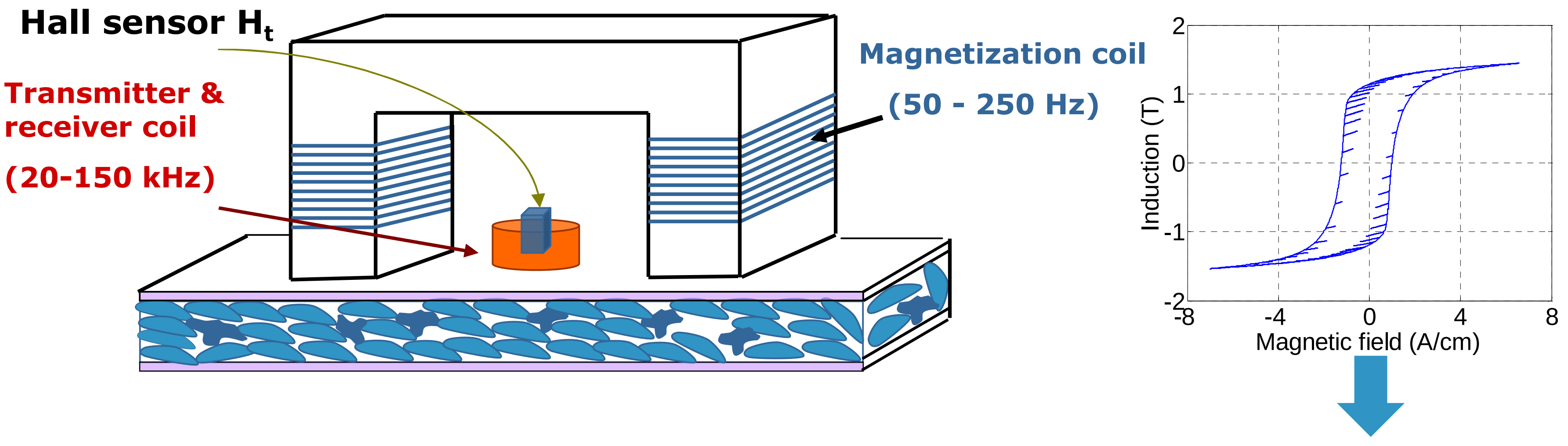
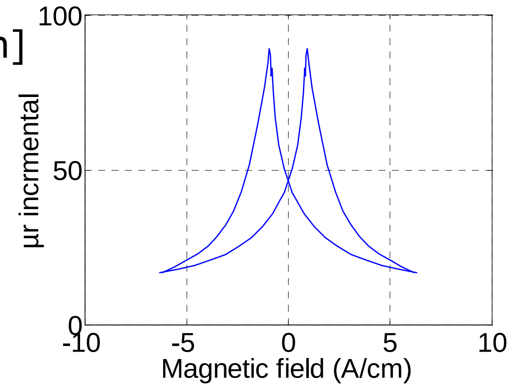
FEM simulation: Modeling of the 3MA inspection situation

3MA: **M**icromagnetic **M**ulti-parametric **M**icrostructure & Stress **A**nalysis



1. **Harmonic analysis:** F_{LF} = [50-200] Hz, H_{tmax} = [5 A/cm-80 A/cm]
2. **Eddy current:** F_{HF} = [20-200]kHz, H_{tmax} = µT
3. **Incremental permeability:** combination of both methods



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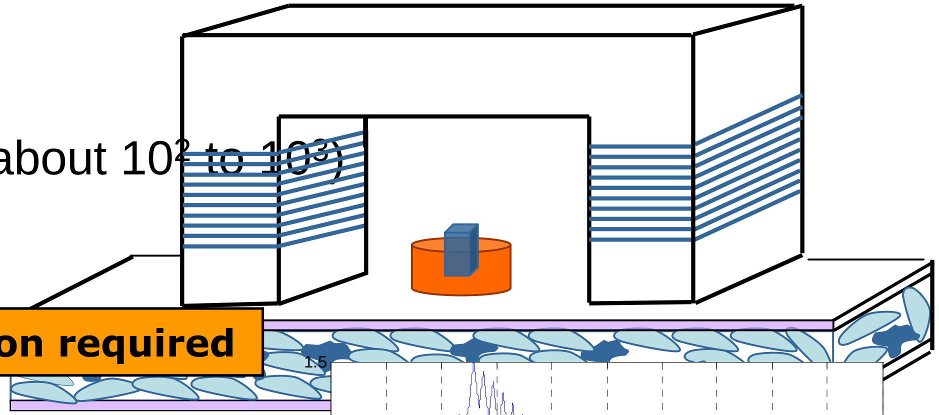
FEM simulation: Challenges

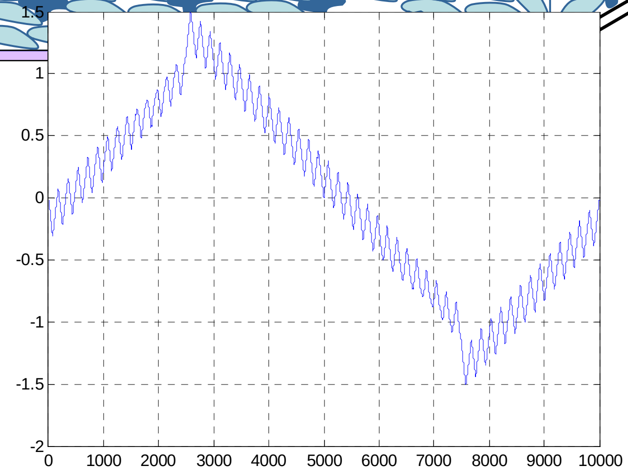
- Multiscale geometry system (scale factor of about 10^4)
  - System size # 100 x 100 mm²
  - multilayer specimen: 1mm thick sheet, 10µm thick for surface layers

➡ **Adapted mesh required**

- Multiscale time signal (scale factor of about 10^2 to 10^3)
  - Low Frequency LF: 50 Hz – 250 Hz
  - High Frequency HF: 20 kHz – 150 kHz

➡ **Adapted time stepping resolution required**



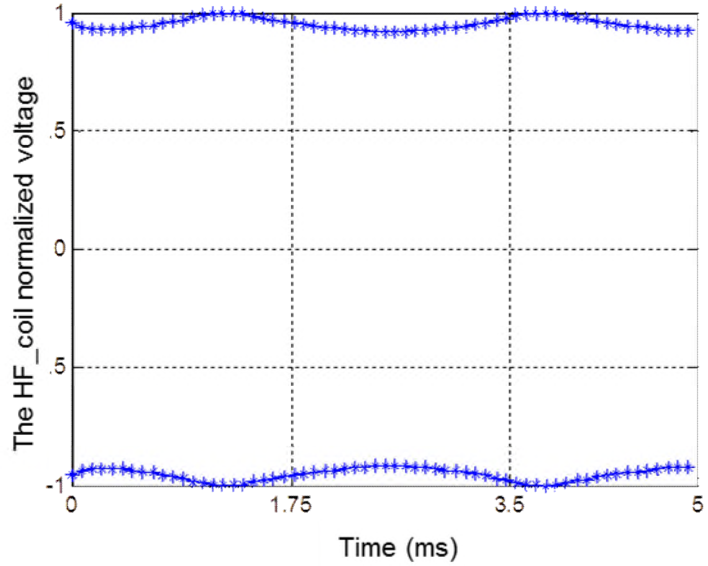


- Different layers magnetic properties :
  - Anhysteretic behavior in the first step
  - Hysteresis behavior consideration : convergence, Resolution time, Memory space.

- Eddy current at LF & HF excitations

FEM simulation: IP signal - Combination of LF & HF

- **The computation is performed in transient, step by step in time considering:**
  - 1 LF period (fLF =200 Hz)
  - 50 pts on HF period (fHF = 20 kHz)
  - dt = 1.66µs



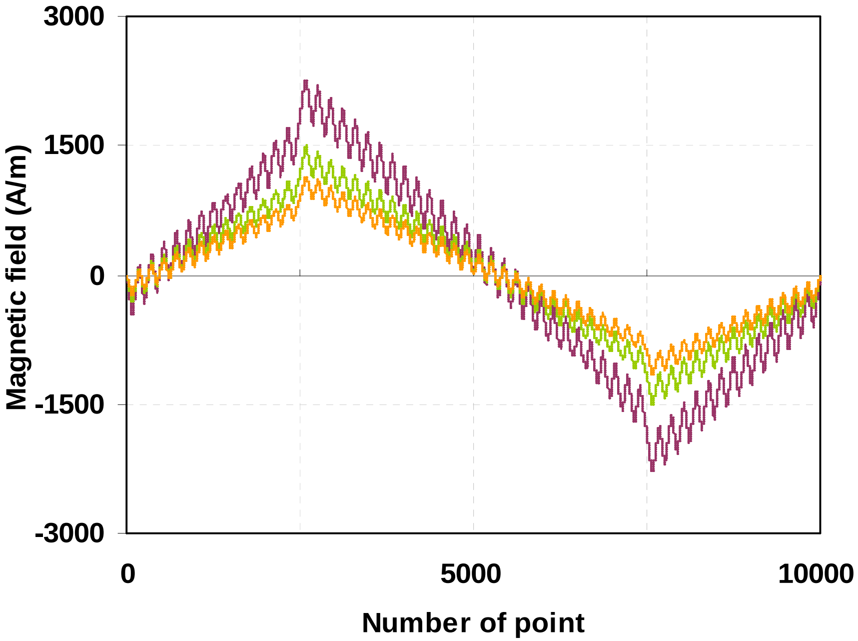
- **Problems:**
  - Time computation exceed 3h (PC standard
  - « intel ® core ™ 2CPU with 2.13 GHz,
3Gb RAM)
  - Space memory (35000 surface elements)

- **Go to more efficient computation**
  - To separate the two excitations
  - The second computation (HF) is seen as a disturbance around an operating point which is imposed with LF excitation.

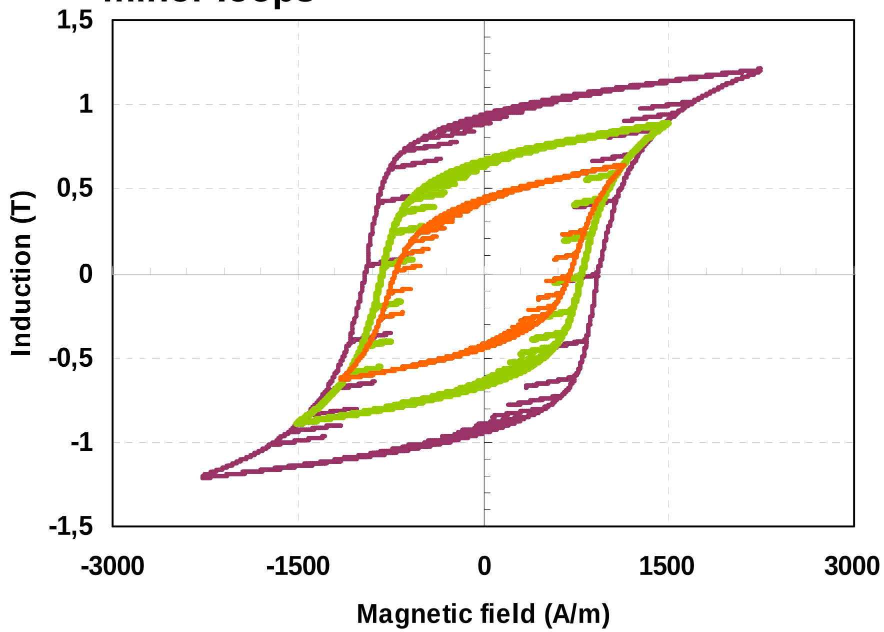
FEM simulation: IP signal - Combination of LF & HF

What means disturbance around the signal?

Low frequency signal disturbed by HF signal



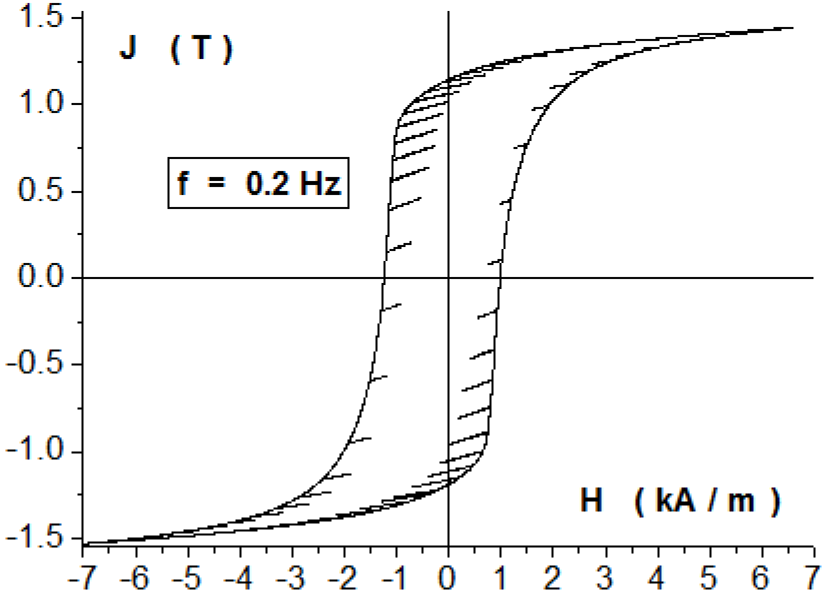
Symmetric and asymmetric hysteresis minor loops

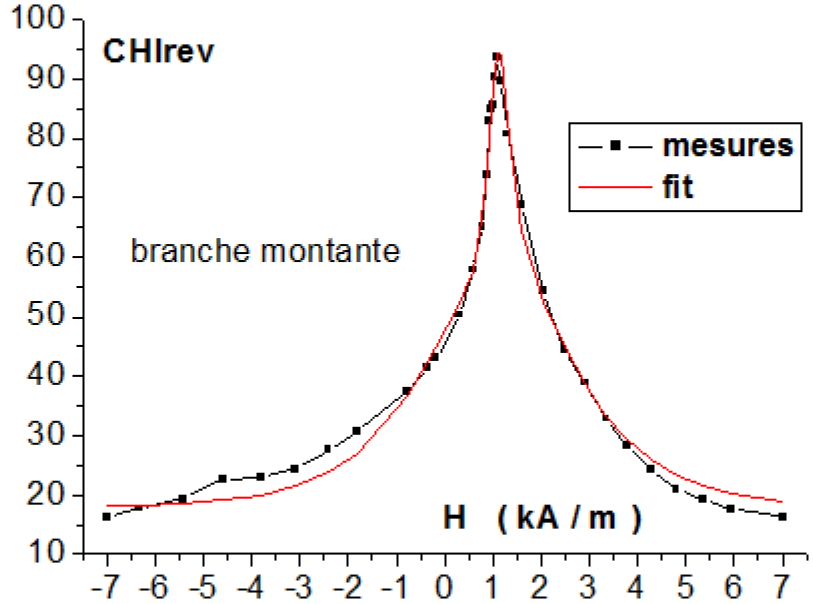


The magnetic “answer” of the sample: Minor symmetric and asymmetric curves
→ Slope of asymmetric curves is the incremental permeability

FEM simulation: Validation of analytical formulation

IP calculation: Epstein and analytical formulation

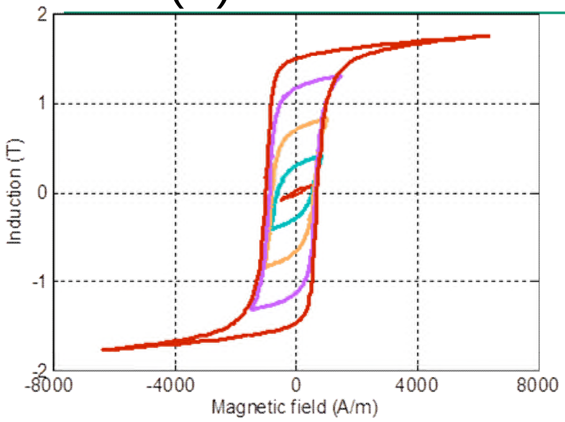


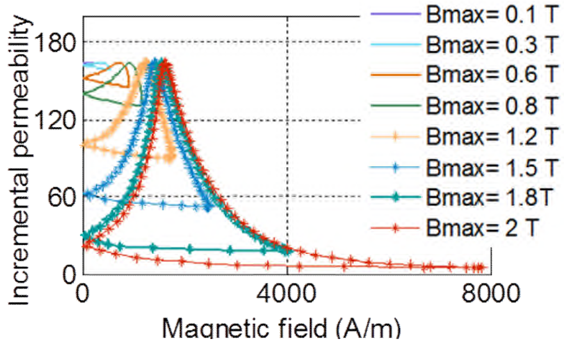


The results from the model fit correctly the measurements

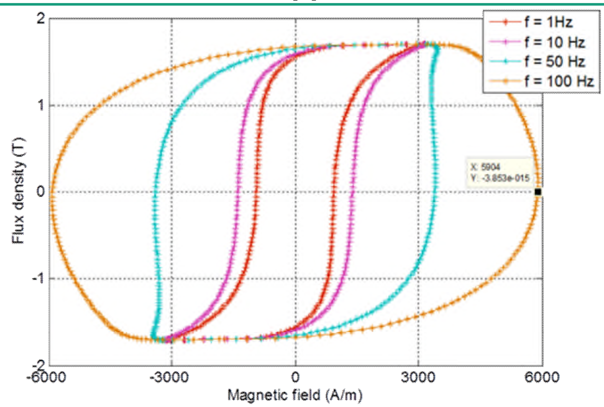
FEM simulation: Accuracy of the analytical IP algorithm

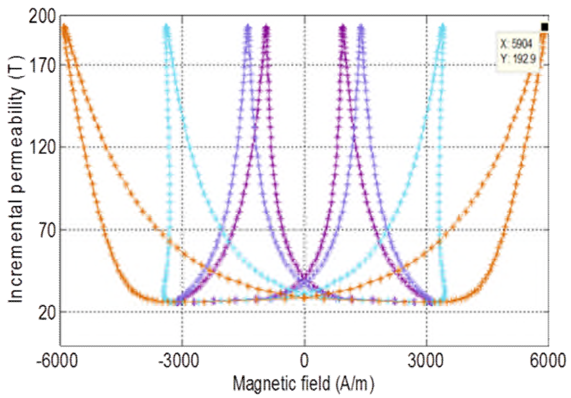
IP (B)



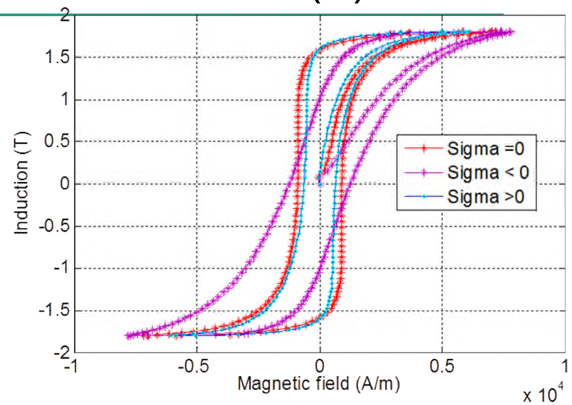


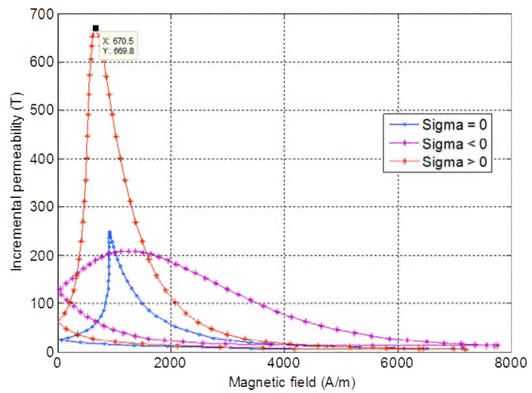
IP (f)





IP (σ)





FEM simulation: Modelling of 3MA IP method in FEM code

How to model 3MA IP method in FEM code?

The permeability tensor:

$$[\mu_r] = [\begin{bmatrix} \mu r_x & 0 \\ 0 & \mu r_y \end{bmatrix}]$$

The IP tensor:

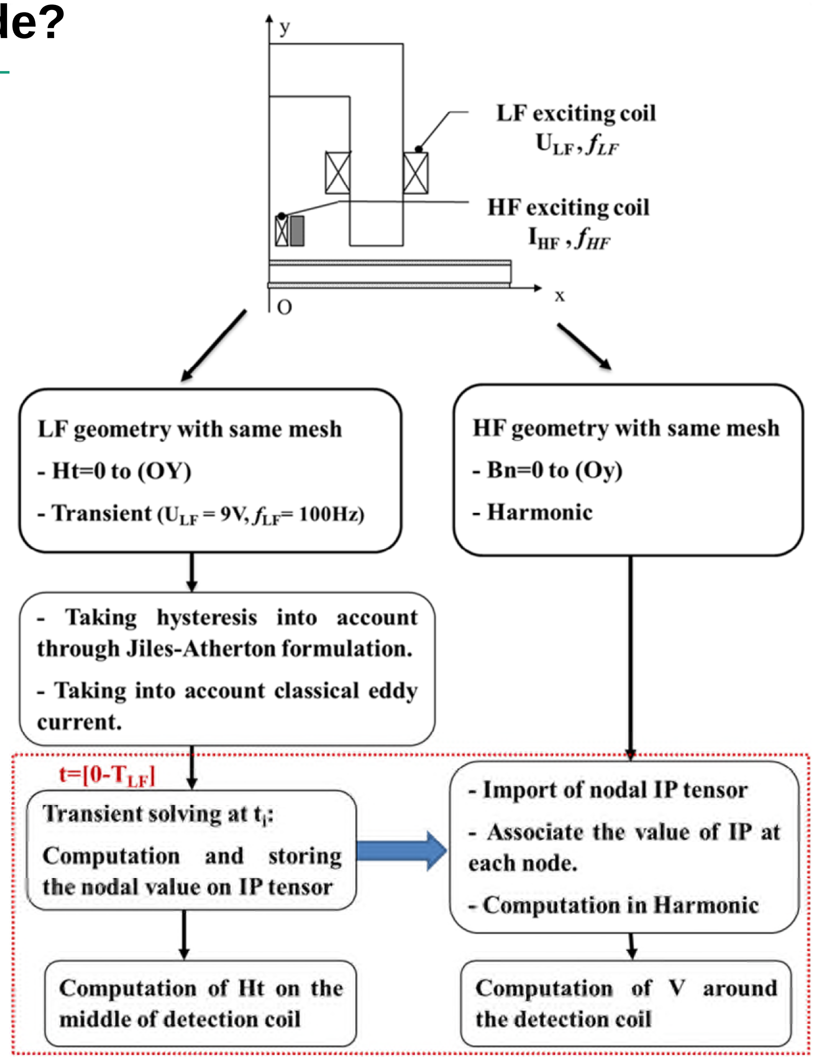
$$\left[\frac{\partial B}{\partial H}\right] = \begin{bmatrix} \mu + 2.H_x^2.\dfrac{\partial \mu}{\partial H^2} & 2.H_x.H_y\dfrac{\partial \mu}{\partial H^2} \\ 2.H_x.H_y\dfrac{\partial \mu}{\partial H^2} & \mu + 2.H_y^2.\dfrac{\partial \mu}{\partial H^2} \end{bmatrix}$$

If the material is isotropic:

$\mu r_x = \mu r_y$

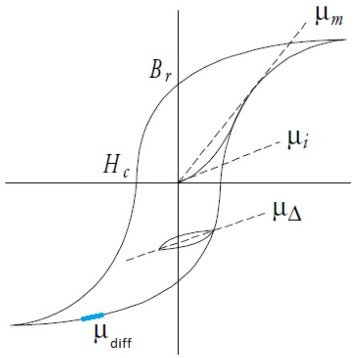
$\mu rIncx \neq \mu rIncy$

Incremental permeability signal depends on the magnetization direction



Simulation steps: Impact of hysteresis

Via FEM simulation using big 3MA probe

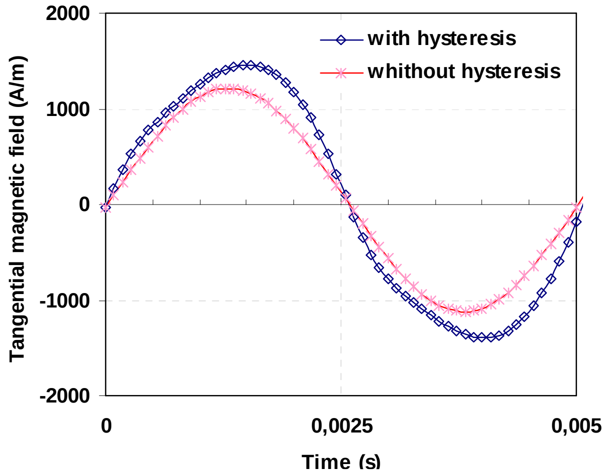


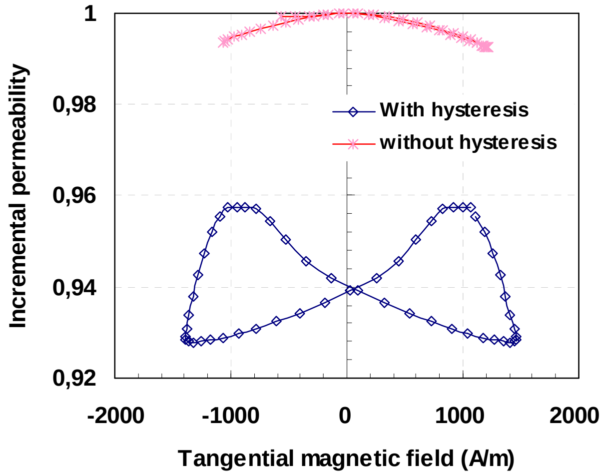
Non-linear anhysteretic

Non-linear hysteretic

μΔ= μdiff

μΔ= slope asymmetric curves

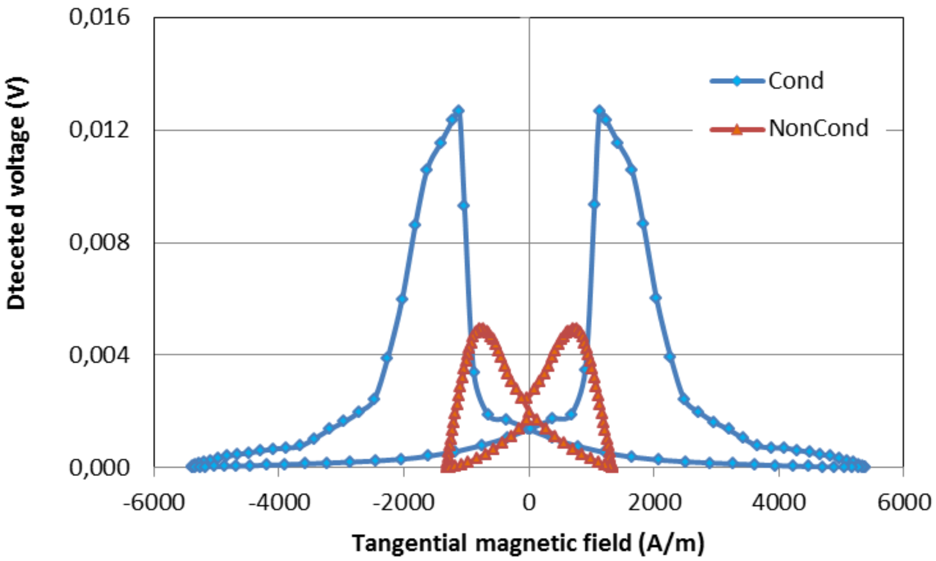




Simulation steps: Impact of low frequency eddy current

Simulation condition:
No lift-off!
Vmax = 20V
f_{LF} = 200 Hz
f_{HF} = 20 kHz

σ = 28.1μΩ.m



- Not conductive→ No eddy current effect

$$Htot = \mathrm{Hhyst(B)}$$

- Conductive→ Classical eddy-current

$$Htot = \mathrm{Hhyst(B)} + \sigma \frac{d^2}{12} \frac{dB}{dt}$$

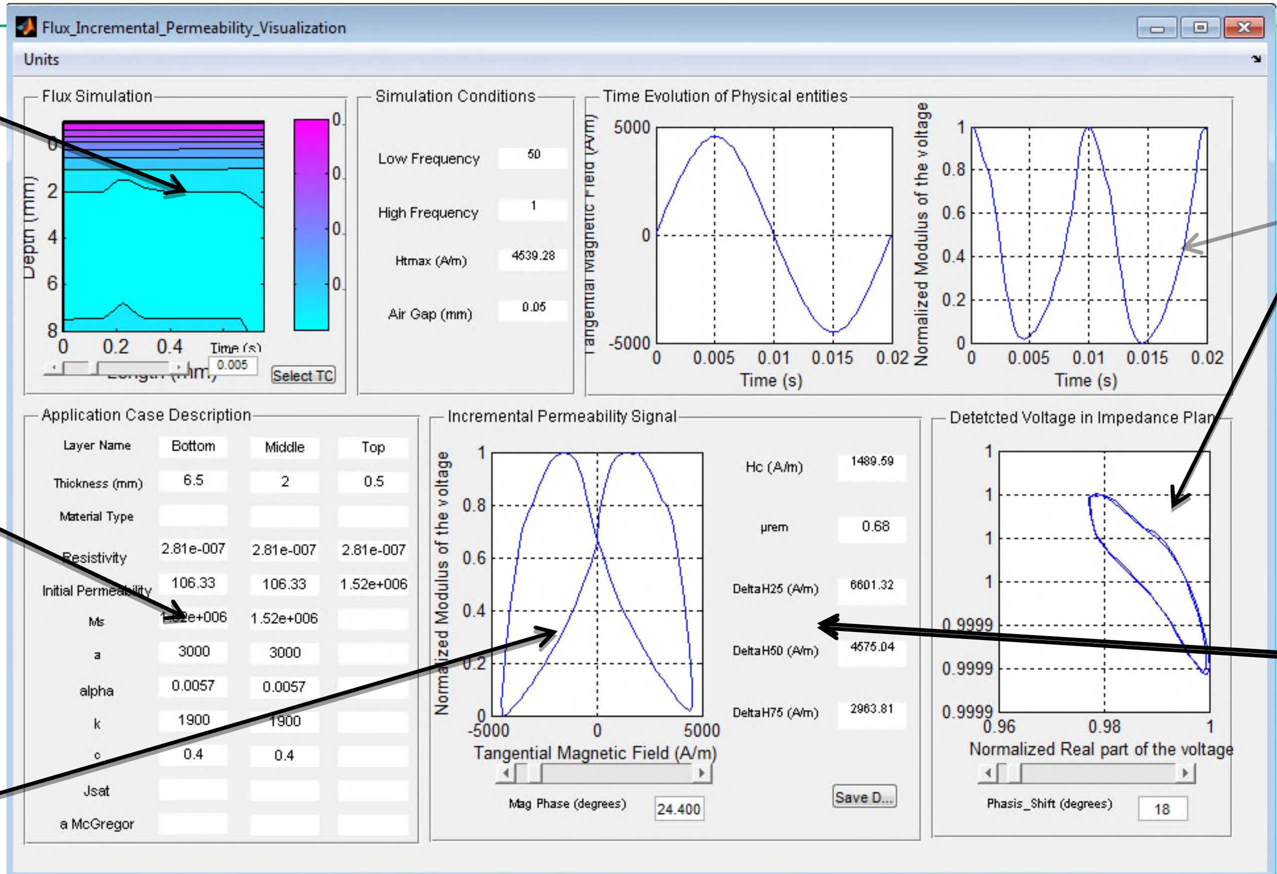
If H increases → Variation of IP increases significantly!

3MA visualization

Simulated flux distribution

Specimen data

Simulated signals



Simulated signals

Simulated signal parameters

3MA simulation user interface is similar to 3MA NDT user interface

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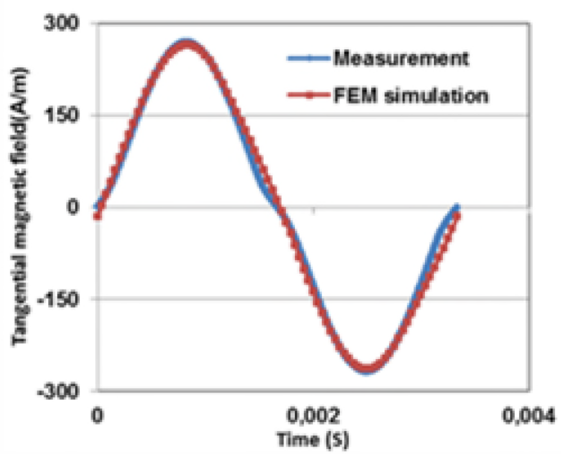
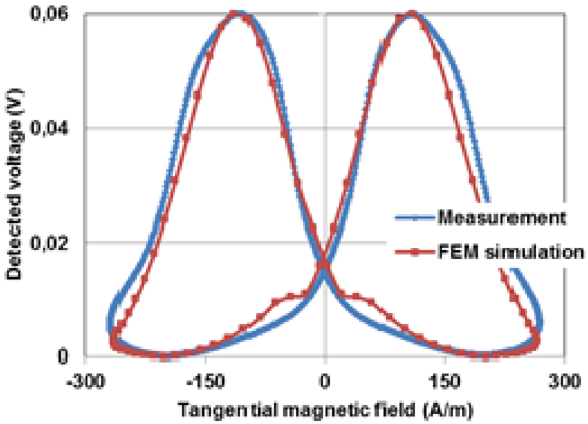
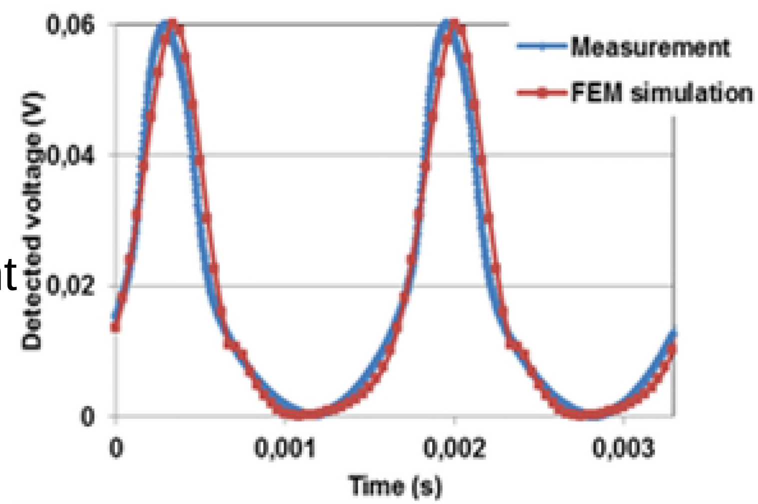
Validation: Soft FeSi material





Good agreement between measurement and simulation!



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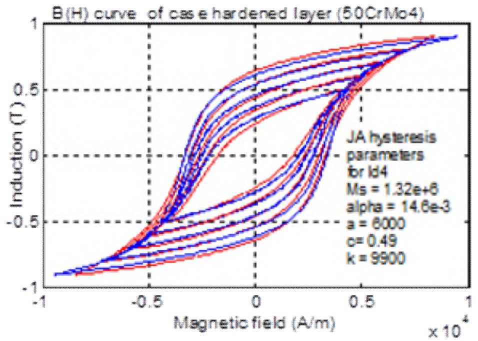
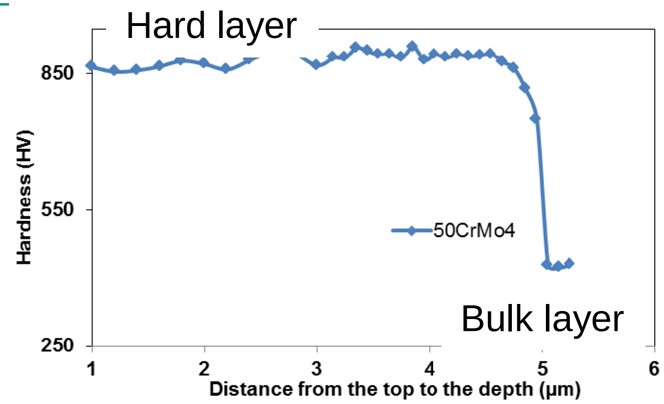
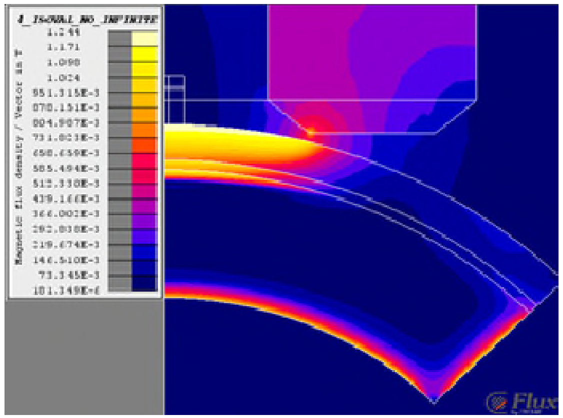
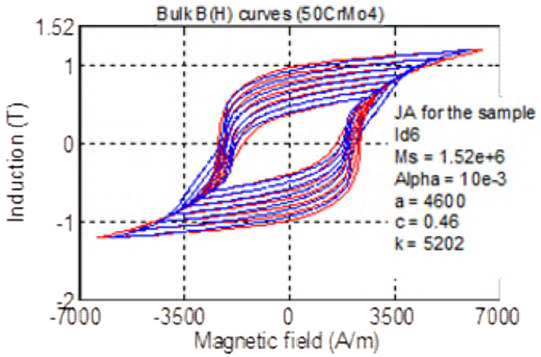
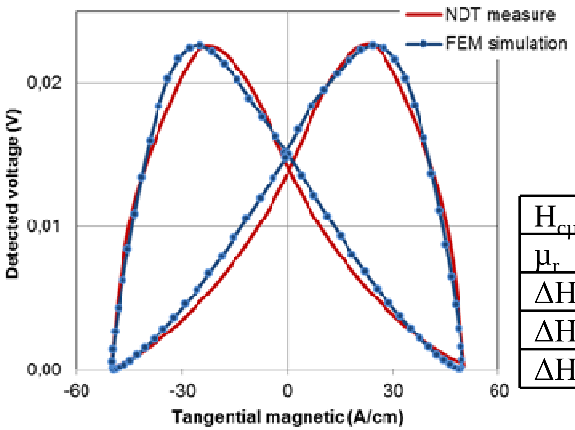
Validation: hardened material









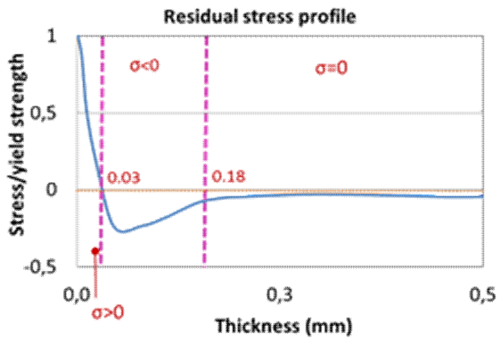


	Experiment	Simulation	Relative error (%)
$H_{c\mu}$ (A/cm)	23.10	22.60	2.16
μ_r	9.21e-3	1.48e-2	0.37
$\Delta H_{25\mu}$ (A/cm)	70.30	72	23
$\Delta H_{50\mu}$ (A/cm)	49.70	52	4.42
$\Delta H_{75\mu}$ (A/cm)	31.50	33.09	7.07

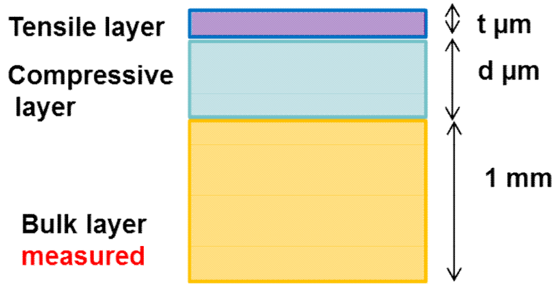
Results published in ECNDT 10/10/2014 at Prague
Y. Gabi, B. wolter, O. martins, A. Gerbershagen
'Examination of Hardened Depth of Steel Using 2D Nonlinear Hysteresis FEM Analysis'

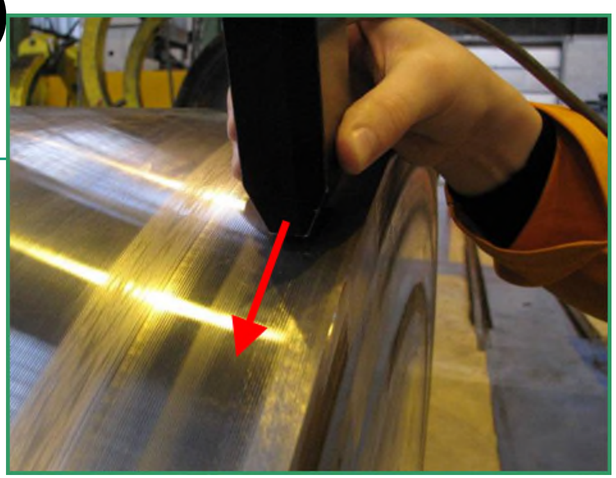
Validation: forged shafts (residual stress)

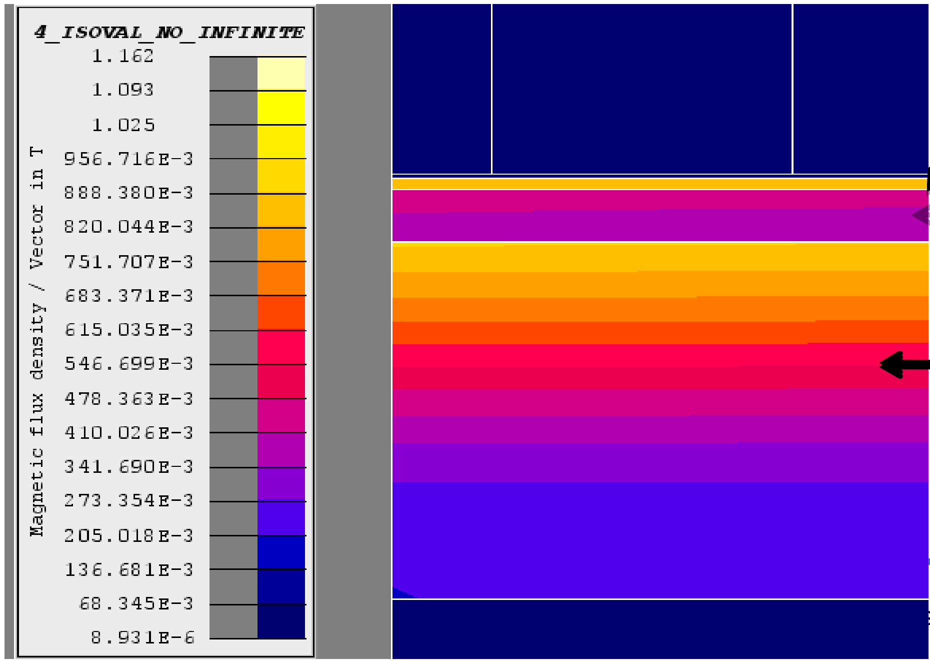
(Residual stress)



Material modeling





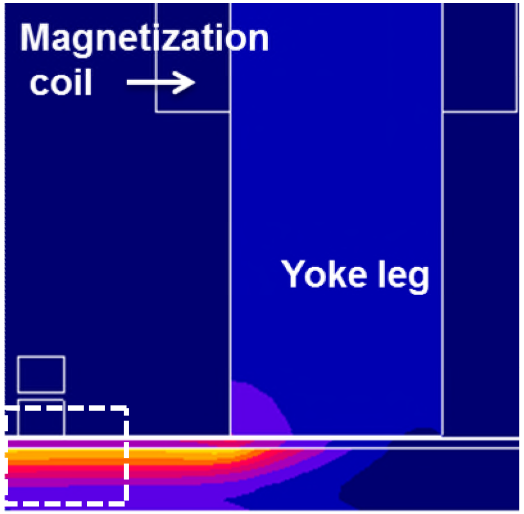


Tensile layer

Compressive layer

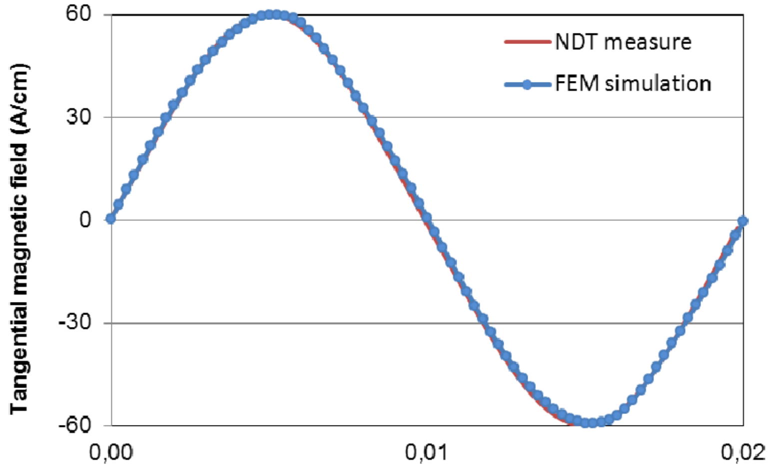
Bulk

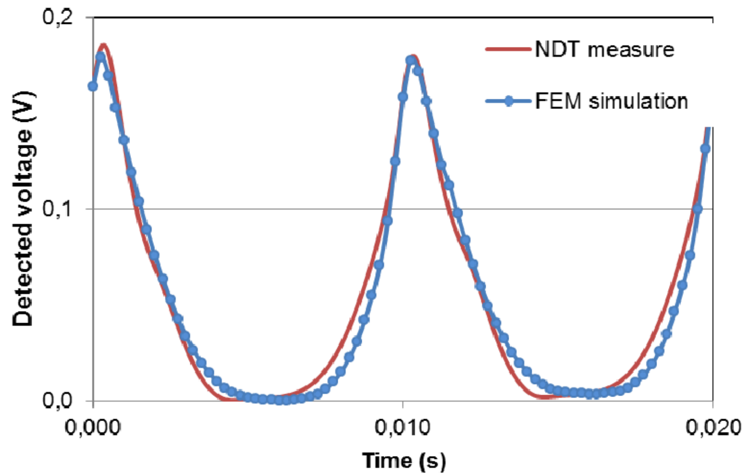
Zoom



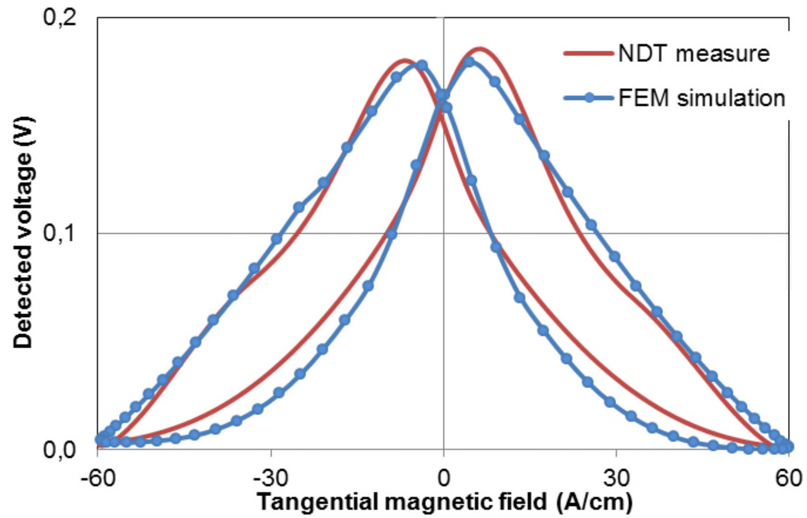
Validation:

In axial direction





	Measurements	Simulation	Relative Error
H_c (A/m)	645	550	13 %
μ_r (V)	0.169	0.175	3.42 %
ΔH_{25} (A/m)	6819	6474	5.05 %
ΔH_{50} (A/m)	3862	3850	0.31 %
ΔH_{75} (A/m)	2029	1800	11.28 %

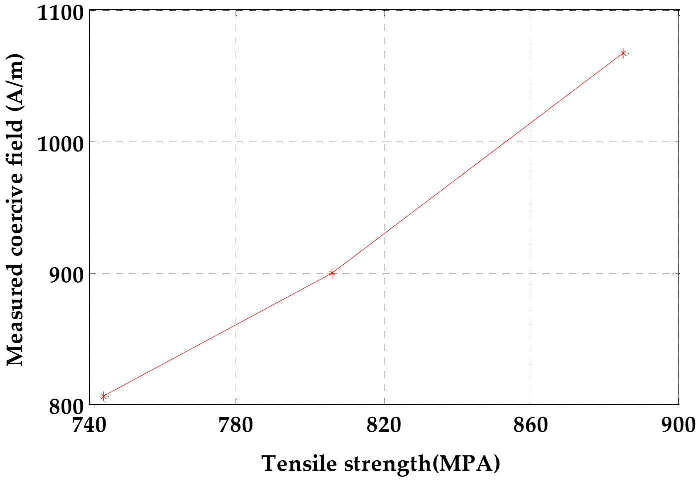


Results published in IMF conference in China,
Paper awarded: M. Ewen, P. Braun, Y. Gabi, B. Wolter
“Development of Nondestructive Determination of Mechanical Properties of Open-Die Forgings and Potentials for Full Implementation in Production Process Chain“

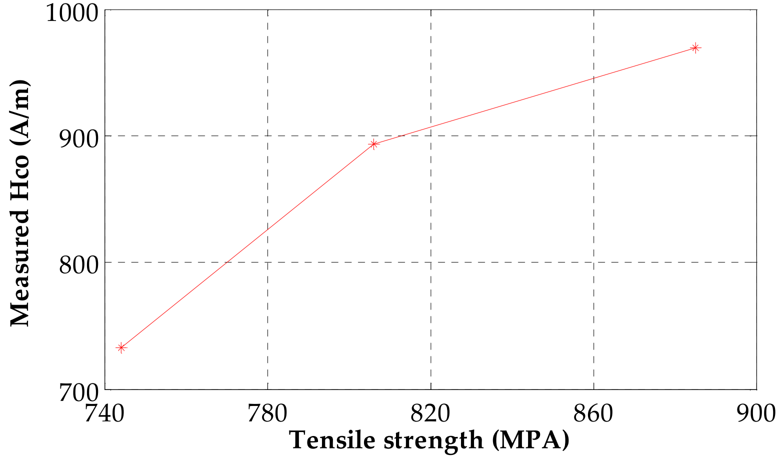
Correlation

Evolution of the coercive field with the tensile strength : f_{LF} = 100 Hz, Ht = 30 A/cm

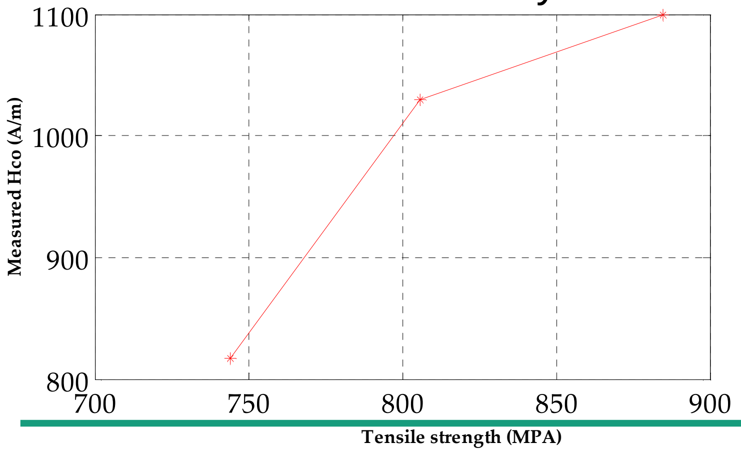
Hysteresis measurements



Harmonic Analysis Simulation



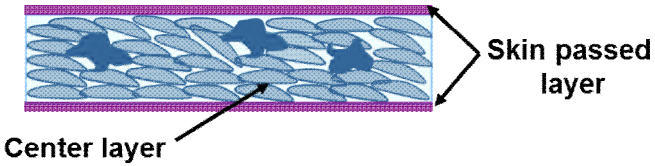
Incremental Permeability

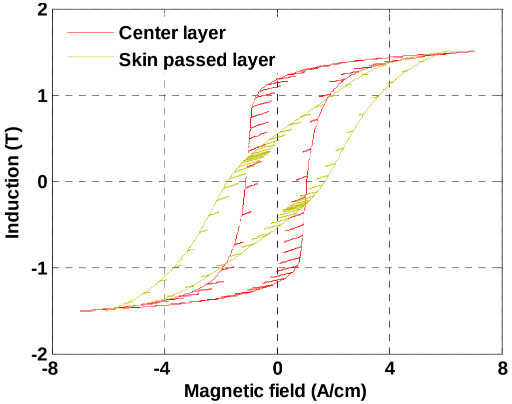


Measured and simulated parameters

Applied Strength (MPa)	Measure-ment	Harmonic Analysis		Incremental Permeability
	Hc (A/m)	Hco (A/m)	K (%)	Hcµ (A/m)
744	791	733	10.31	817.34
806	908	893	9.83	1030
885	1065	970	9.6	1100

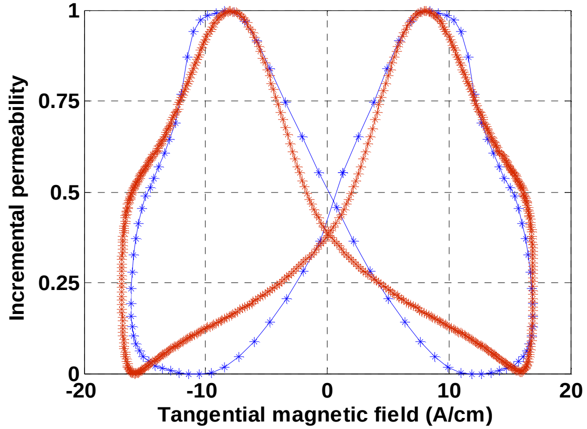
Validation on dual phase steel

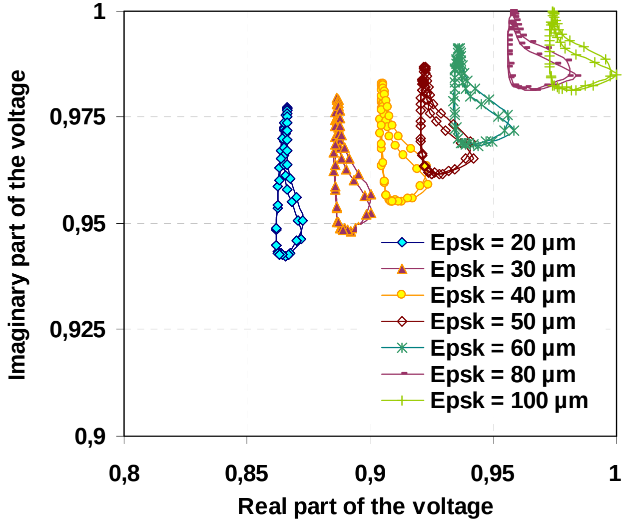




Output 3MA parameters directly correlated to Thickness of skin passed layer !

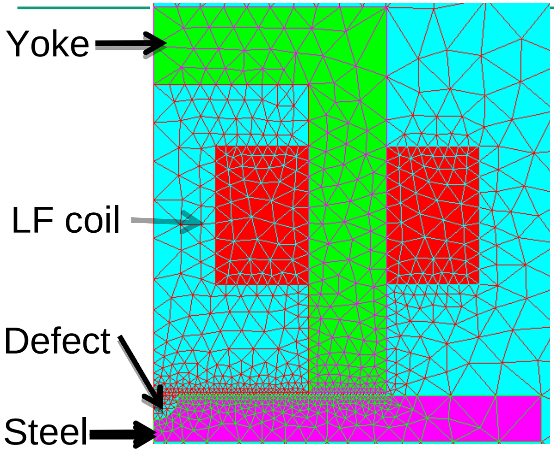
IP : Ht=17A/cm, f_{LF}=200 Hz & F_{HF}=20 kHz



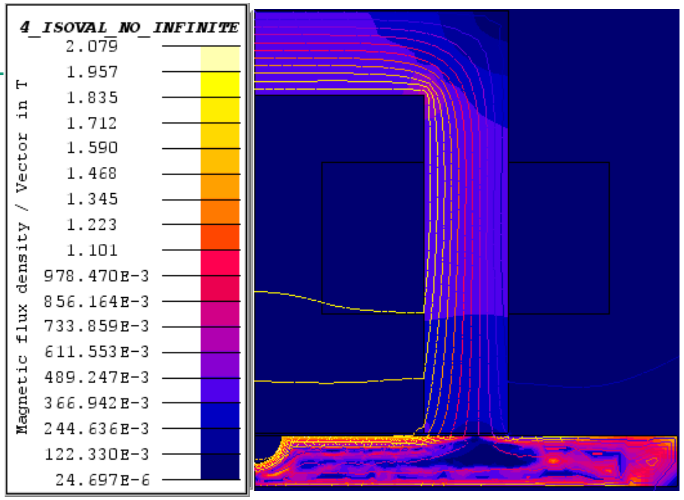


PHD Y. GABI : Dr. A.Lebouc, Dr. G.Meunier, Dr.Ol.Geoffroy, from G2Elab
Dr. P. Meilland , Arcelormittal
Dr. B.Wolter, IZFP Saarbrucken
Dr. C. Guerin and P. Labie from Cedrat

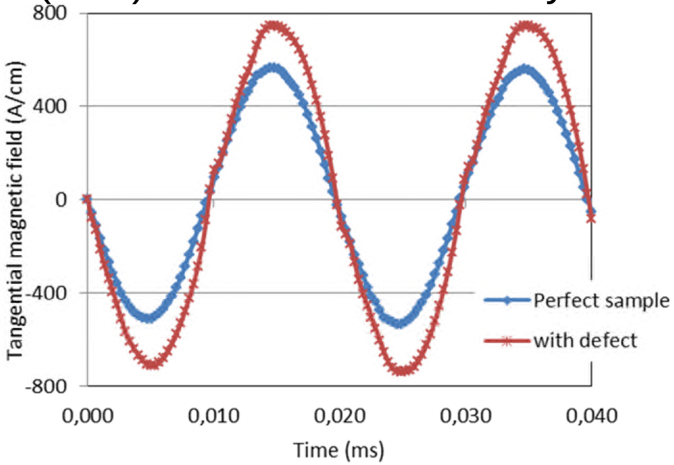
Defect on steel



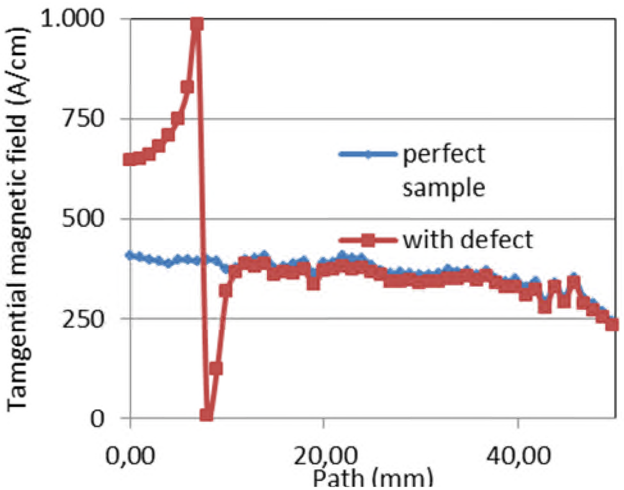
Radius=16 mm
Sample thickness=16 mm



H(time) on the middle of the yoke



H(path) from the middle to the yoke leg



Summary & conclusions

- **3MA FEM modelling**
  - **Modeling of the magnetic material (Hysteresis, eddy current, excess, stress,,..)**
  - **FEM simulation (strategy computation,..)**
  - **Modeling of the 3MA Signature and the output parameters is completed!**
- **Advantage of the used code:**
  - **Complex geometry can be simulated**
  - **Automatic meshing**
  - **Time computation: 3 periods, 30mn**
  - **Convergence: Newton Raphson, 7 iterations**
- **IZFP interest:**
  - **Succeed to reproduce 3MA experiment signals and outputs**
  - **Link the NDT output parameter to mechanical properties**
  - **Support calibration process**
  - **Indirect manner to characterize surface layers using the combination of models + experiments**

Summary & conclusions

- **3D modeling of 3MA**
  - especially for complex yoke and rotating magnetic field
  - Manage the convergence and stability

- **Combine electromagnetic code and mechanical l code**
  - So far, residual stress was represented by multi layer approach
  - It is necessary to calculate the local value of residual stress
  - Found B(Hσ,) formulae
  - Multi physic calculation
- **Main interest:**
  - Multi scale modeling, ex press hardened steel→ complex soft phase
  - Inverse problem taking into account non linear hysteretic behavior
  - Built an intelligent calibration process!

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- Funding Scheme: Collaborative Project
- Homepage: www.simposium.eu

Many thanks for your attention!

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