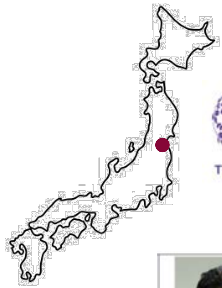
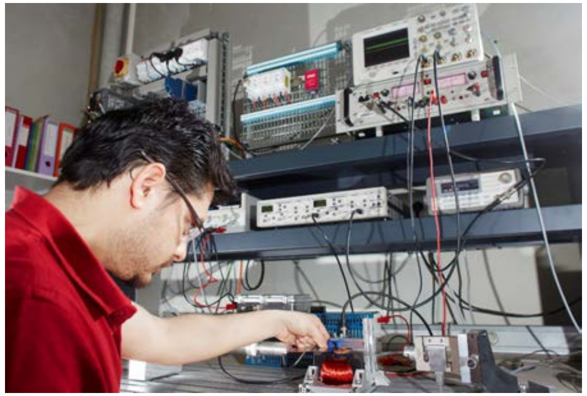
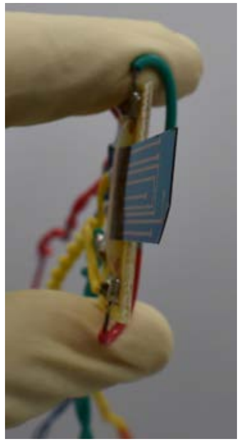
International Symposium: Risk–based Management of Energy Infrastructure

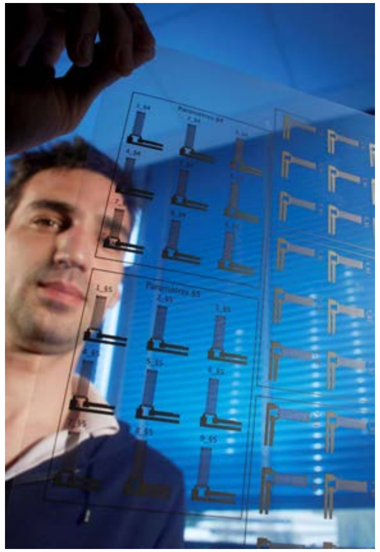
Magnetic Non-destructive testing, based on the magnetization mechanisms

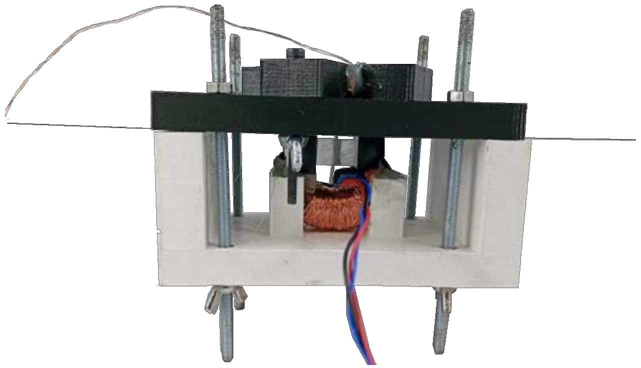
B. Ducharne











Magnetic NDT in ELyTMaX:

- ≈ 2.5 permanent researchers
- ≈ 4 Ph. D. students
- > 100 k€ annual industrial collaborations
- > 10 annual publications

Industrials/academics collaborators:

Upcoming:

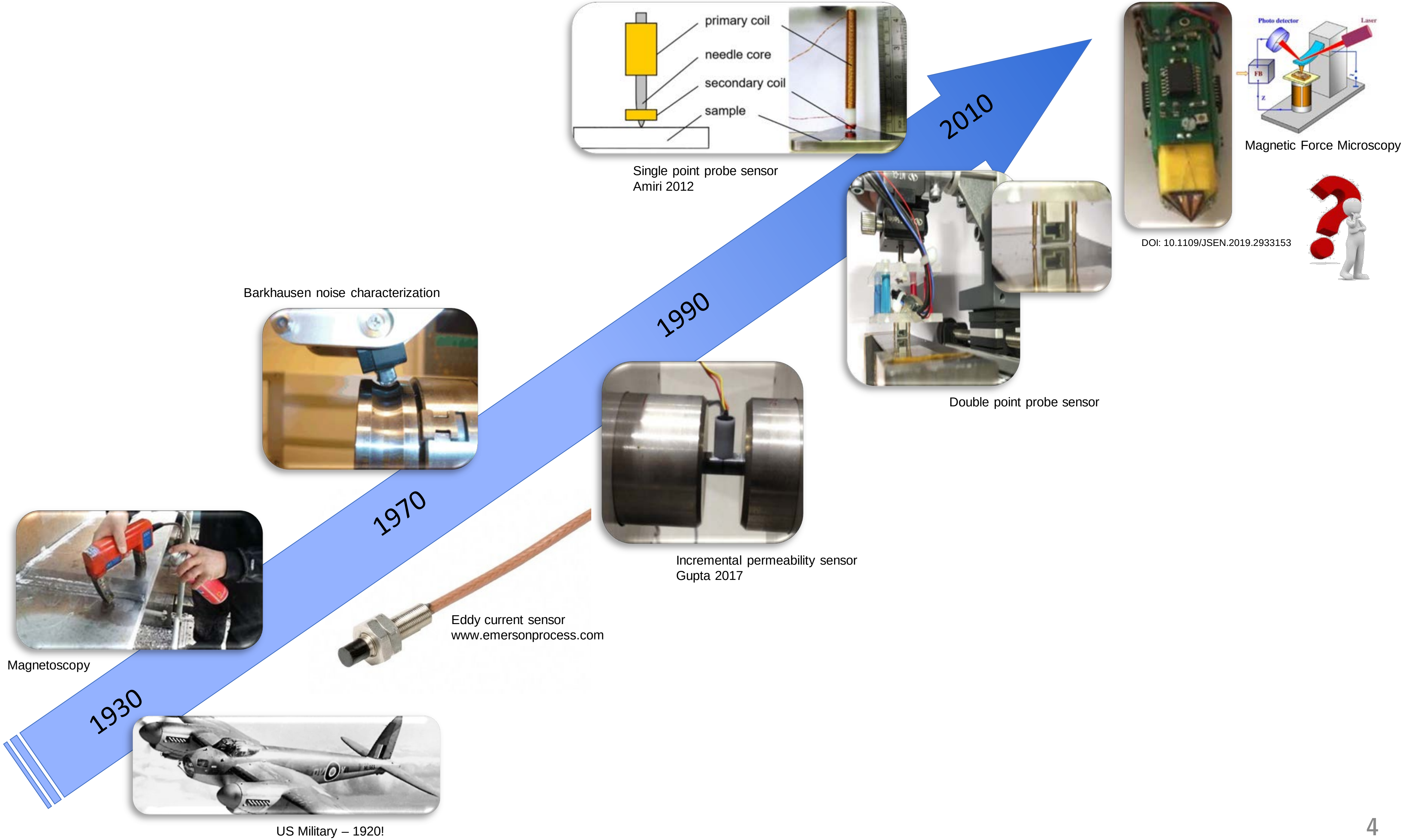
Magnetism in NDT

Eddy current testing
Magnetism -> Energy conversion quantity

Magnetoscopy
Magnetism -> mechanical support

Magnetic memory
Magnetism -> distortion of a natural phenomena

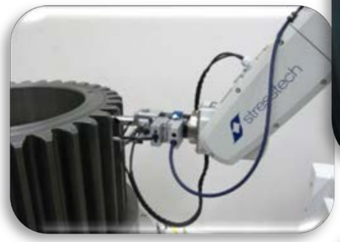
Magnetization mechanisms NDT, magnetization processes (Incremental permeability, Barkhausen noise…)


primary coil
needle core
secondary coil
sample
Single point probe sensor
Amiri 2012
2010
Magnetic Force Microscopy
Photo detector
Laser
FB
DOI: 10.1109/JSEN.2019.2933153
Double point probe sensor
1990
Barkhausen noise characterization
1970
Incremental permeability sensor
Gupta 2017
Eddy current sensor
www.emersonprocess.com
Magnetoscopy
1930
US Military – 1920!

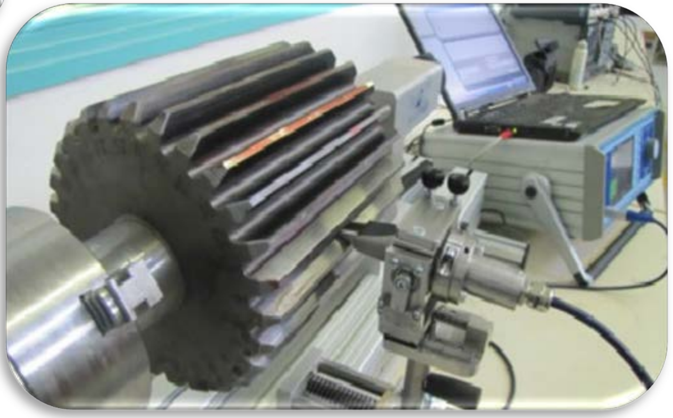
Motivations

- Quality control, an increasing demand

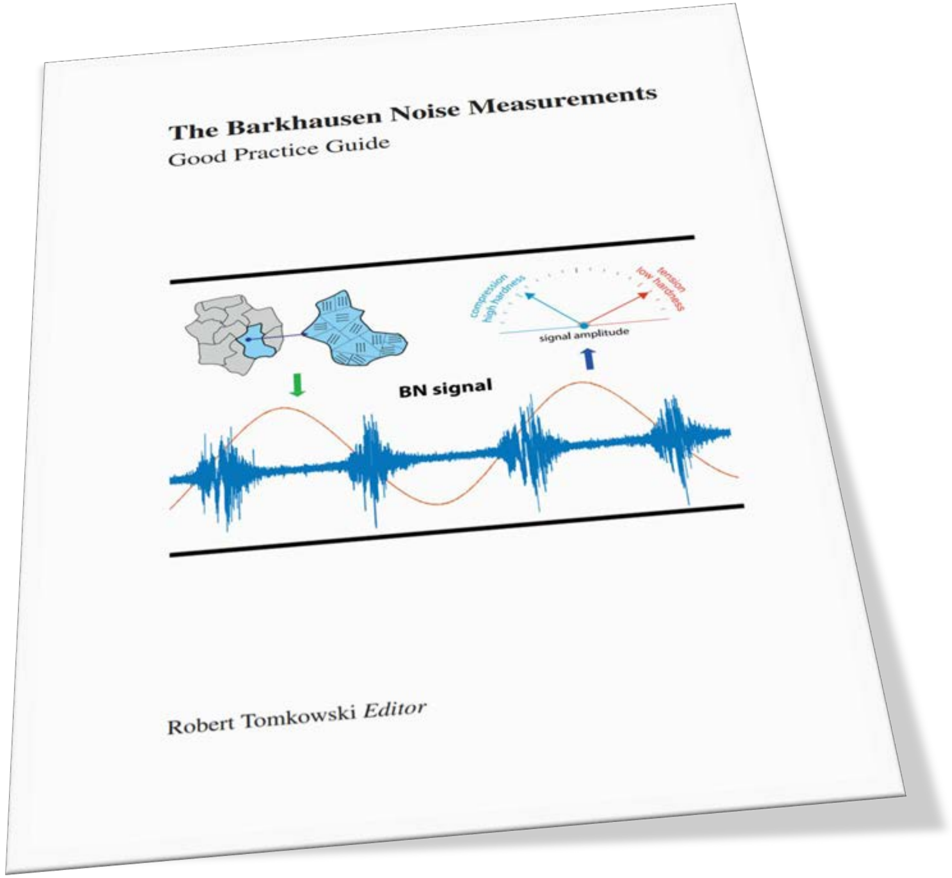
http://www.izfp.fraunhofer.de



http://ast.stresstechgroup.com



http://www.lmdindustrie.com



- Steel and mechanical industries (bearings, gear boxes, boilers…)

Research problematic

http://ast.stresstechgroup.com

Gerd Dobmann
Universität des Saarlandes

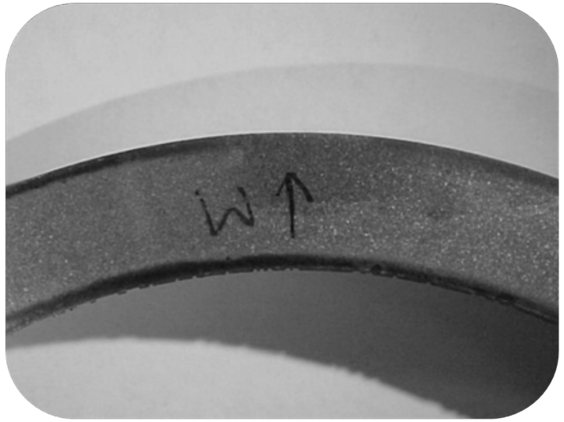
3MA is a matured technology and a wide field of applications is given. However, besides the success story we also can find critical remarks from industrial users. These are mainly to <u>the calibration efforts and problems of recalibration</u> if a sensor has to be changed because of damage by wear. Therefore, actual emphasis of R&D is <u>to generalize calibration procedures</u>.

Good news! Magnetic NDT based on the magnetization mechanisms works!!!

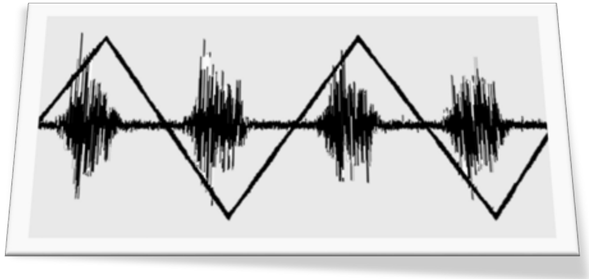
Philip John Withers
University of Manchester

NDT magnetic controllers are "mature, but a unified theory <u>relating magnetic signals</u> to <u>basic magnetic parameters</u> is <u>lacking</u>. At present signals are equipment supplier-specific".

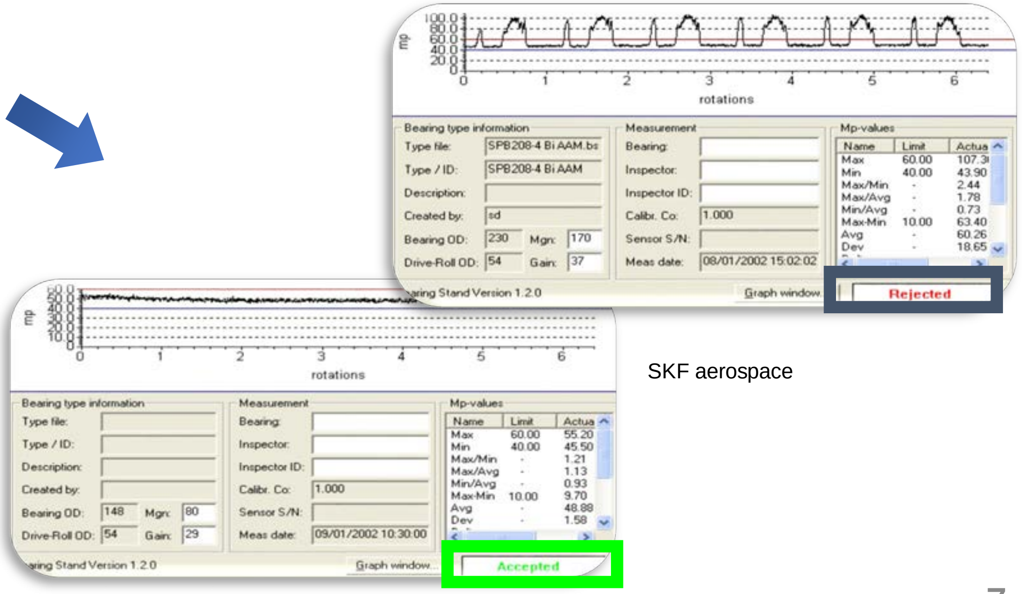
Research problematic



1) Well known specimen



2) Time consuming experimental process



SKF aerospace

Settings are not transposable

A small change might end in unconsistent results

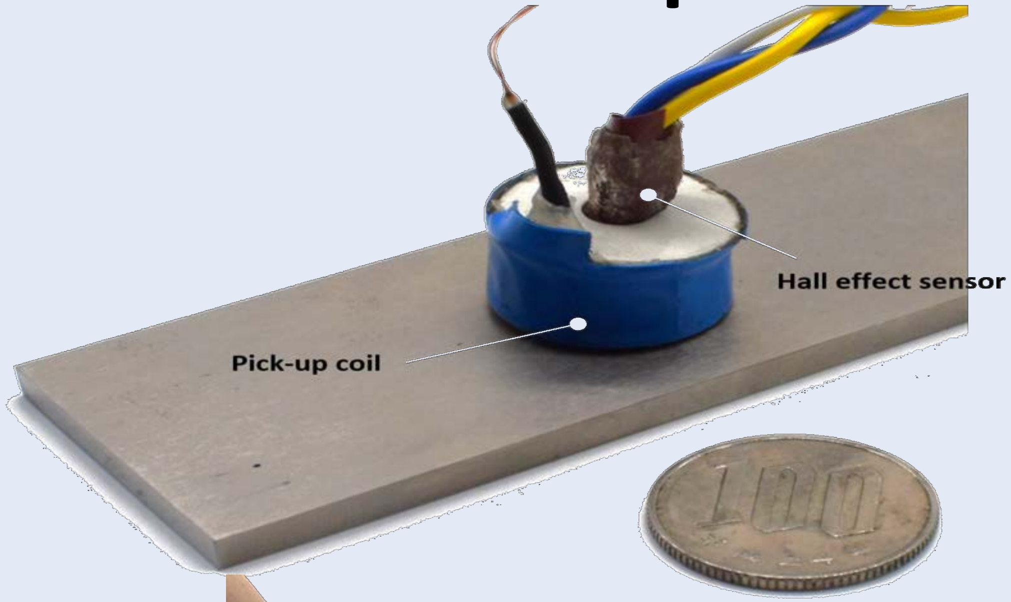
3) Rejection threshold

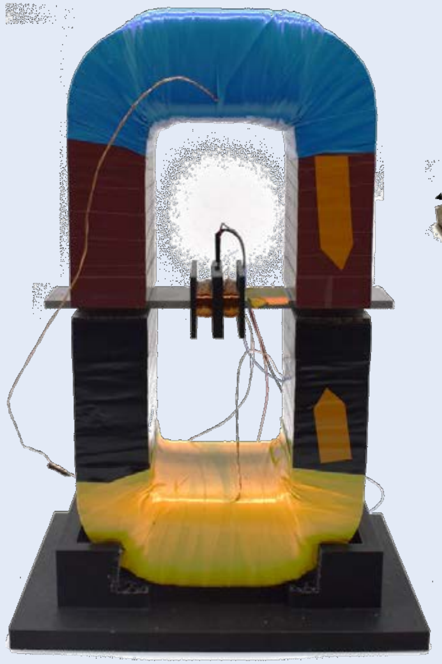
Surface treatments:

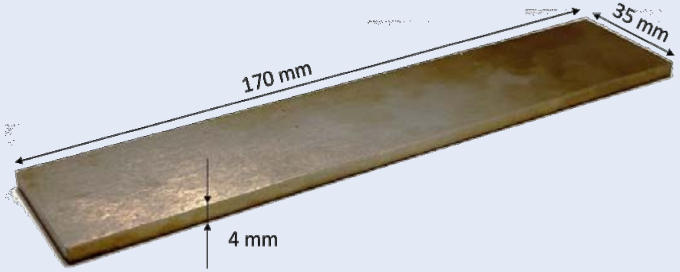
Desired: shot peening, carburization, residual stress, etc.

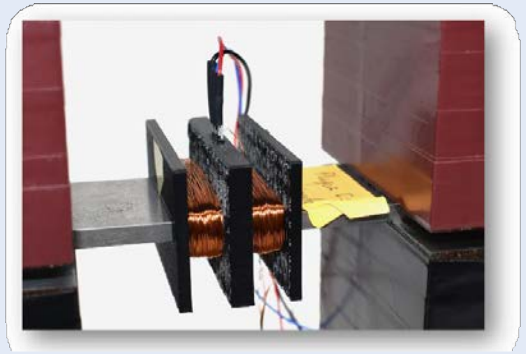
Undesired: corrosion, residual stress, etc.

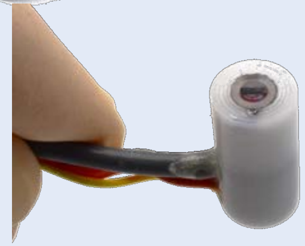
Instrumentation development:

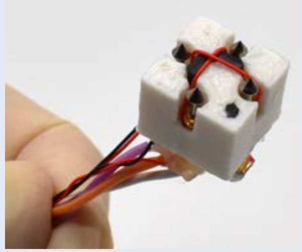


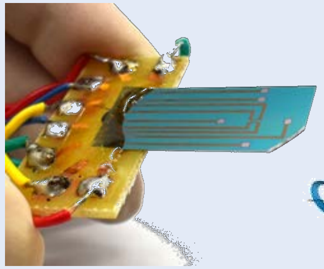




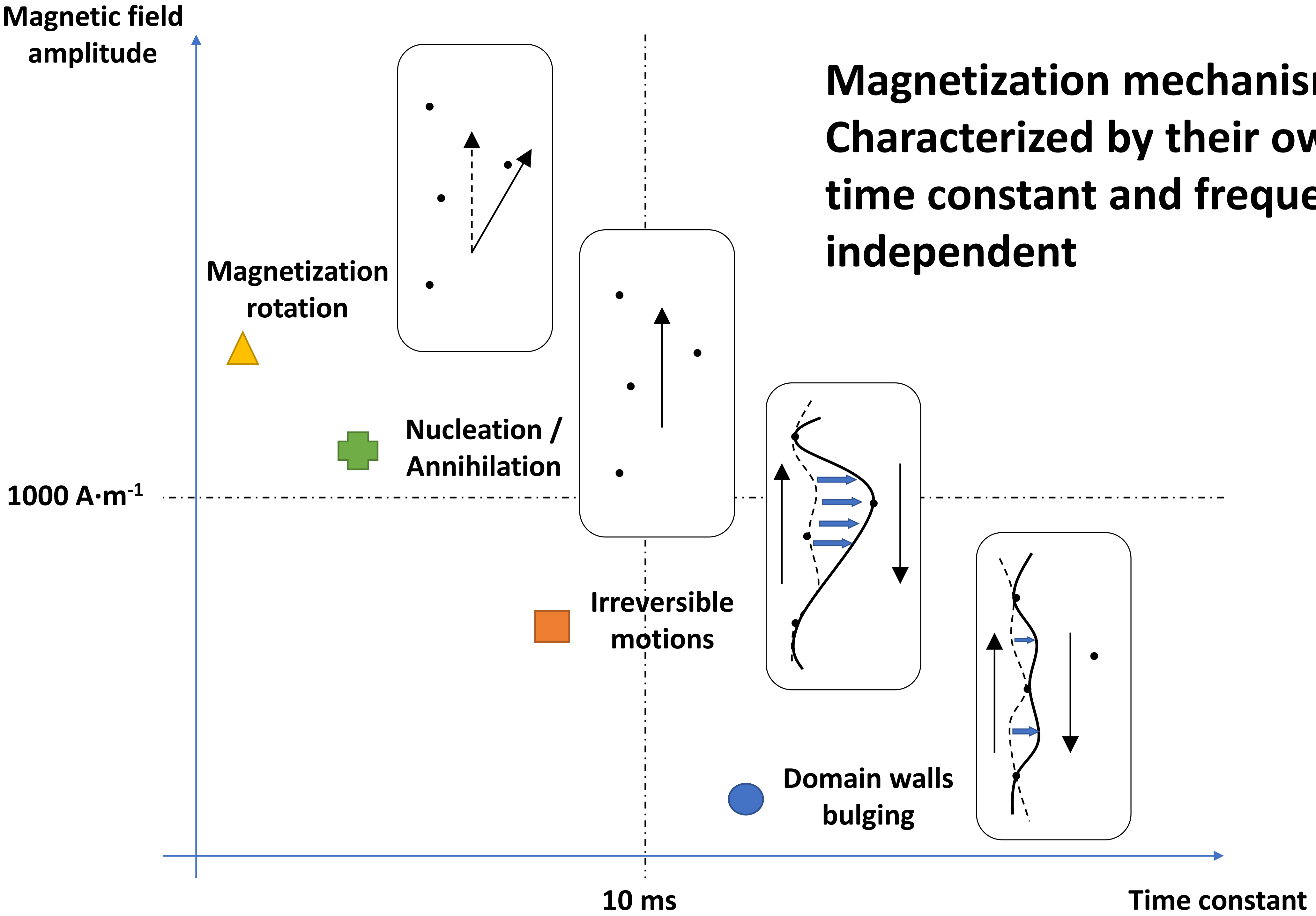




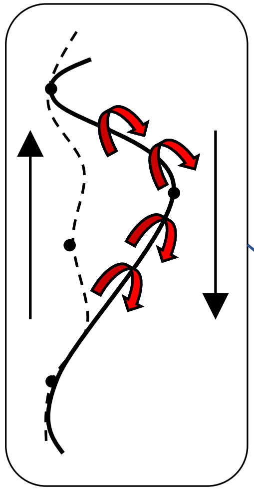




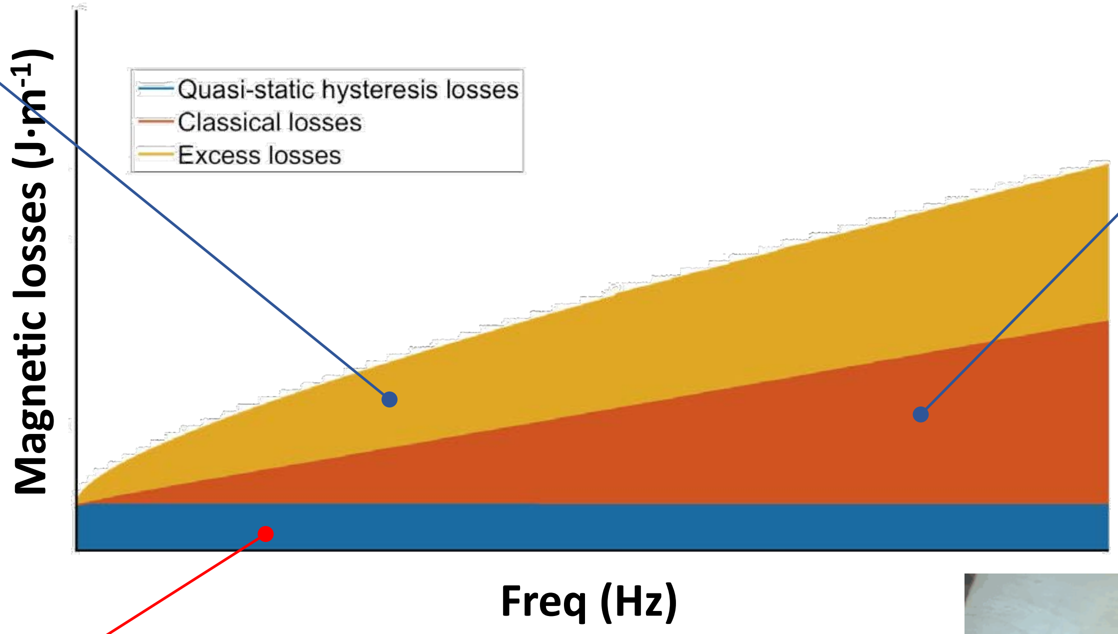
Magnetization mechanisms Characterized by their own time constant and frequency independent



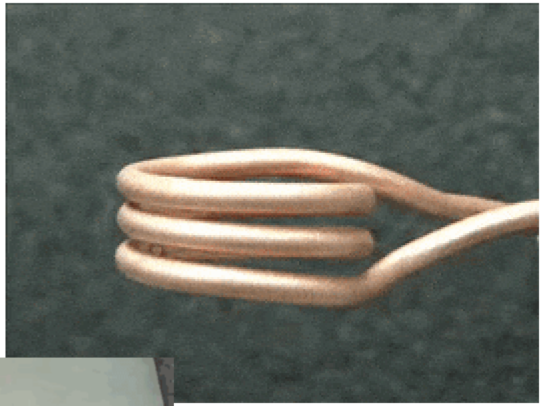
Frequency dependent magnetization mechanisms

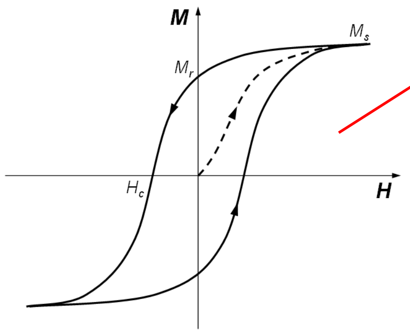


Microscopic eddy currents

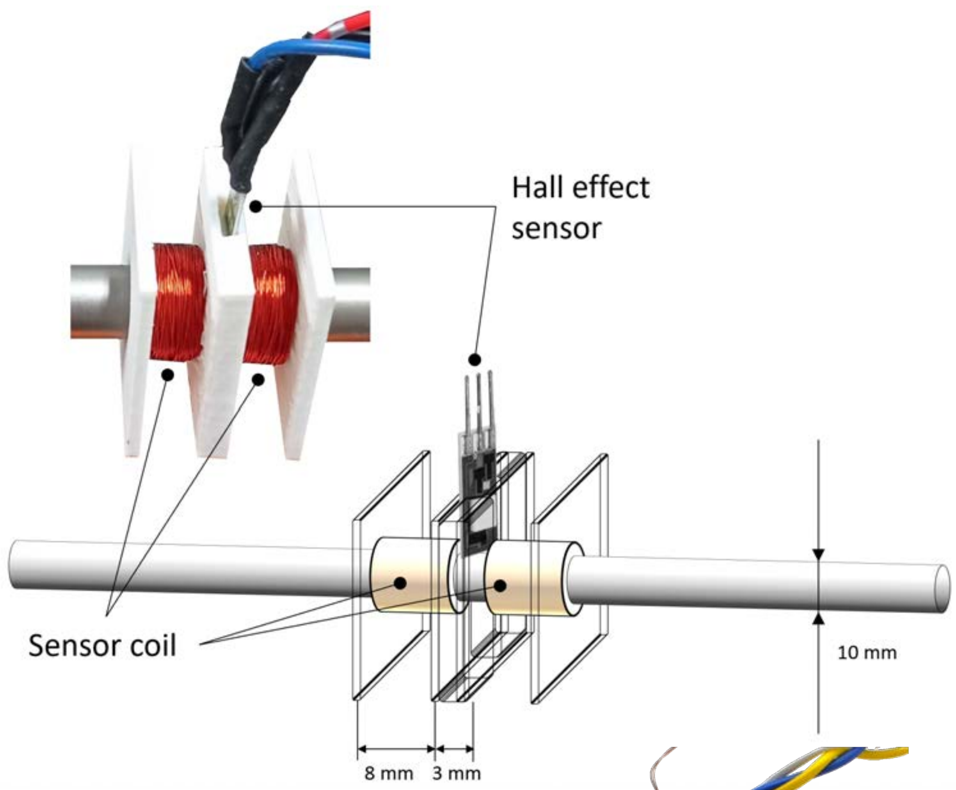


Macroscopic eddy currents

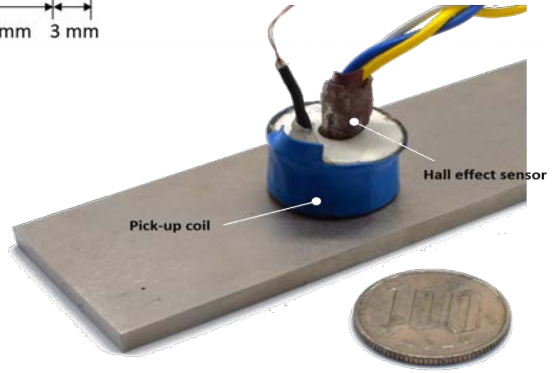


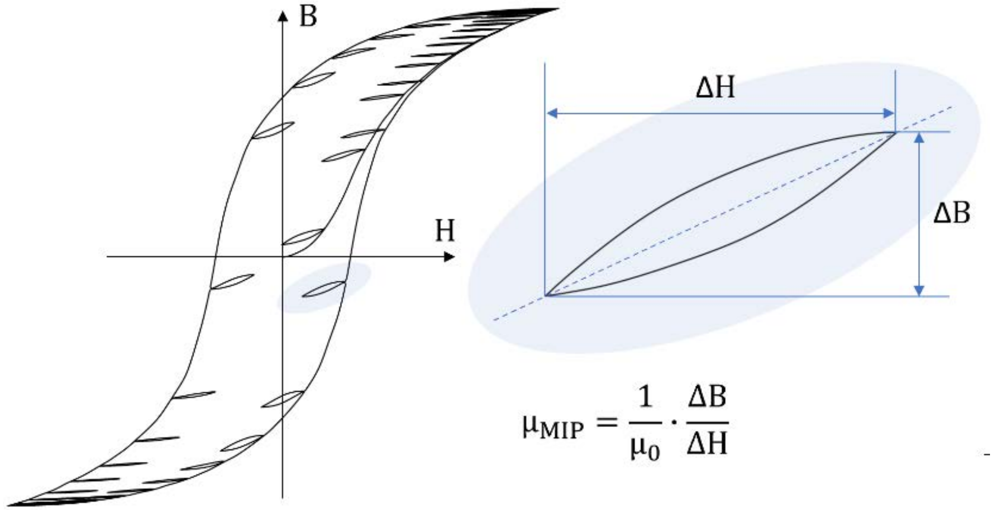


Magnetic field amplitude

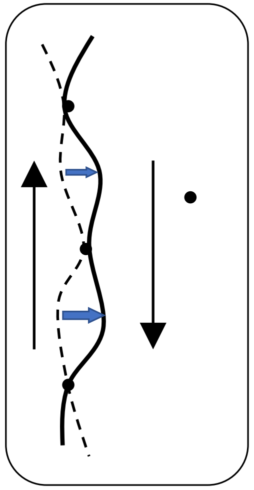


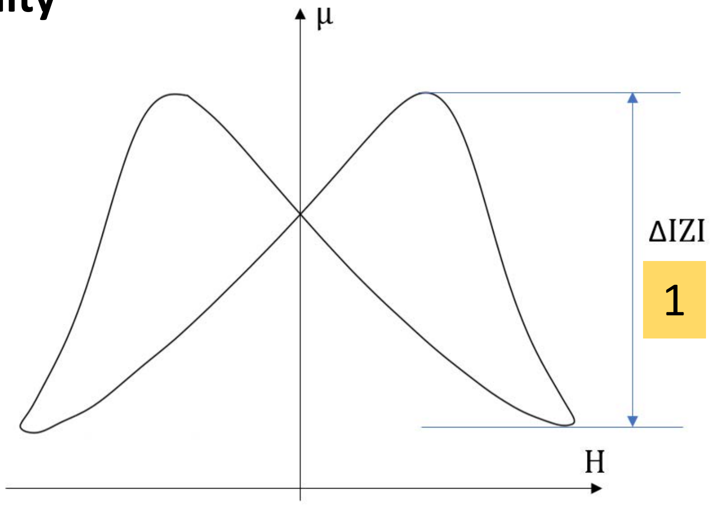
1000 A·m^{-1}





Magnetic Incremental Permeability



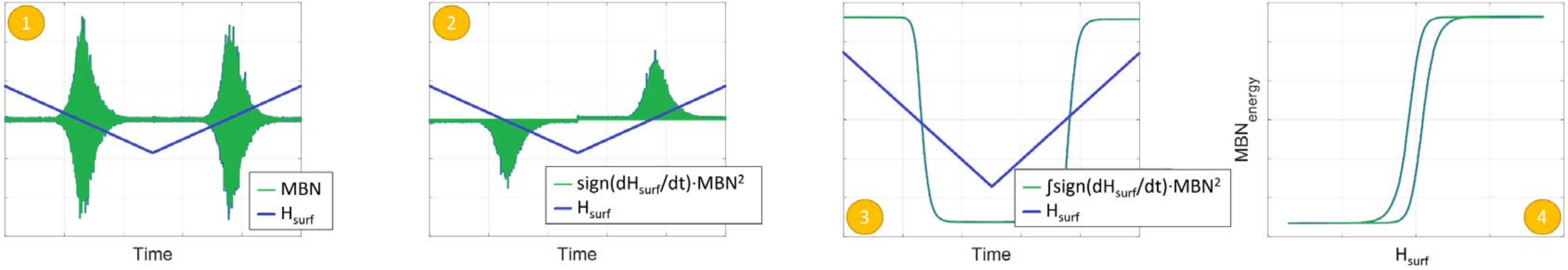


Domain walls bulging

10 ms

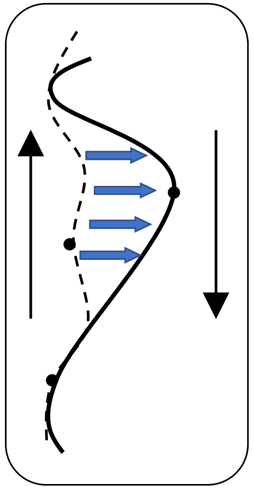
Time constant

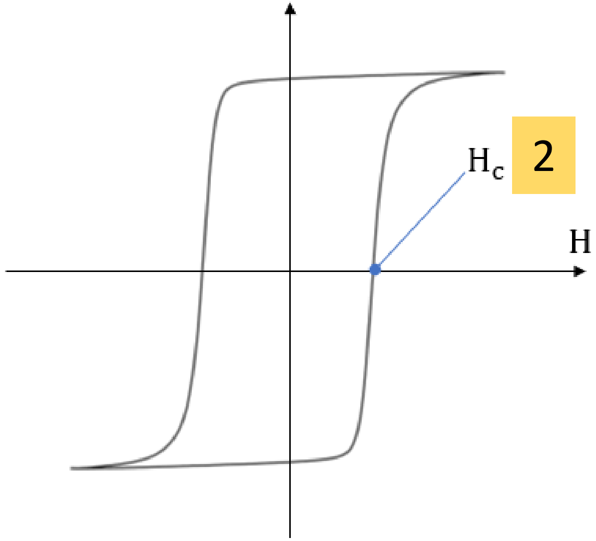
Magnetic field amplitude

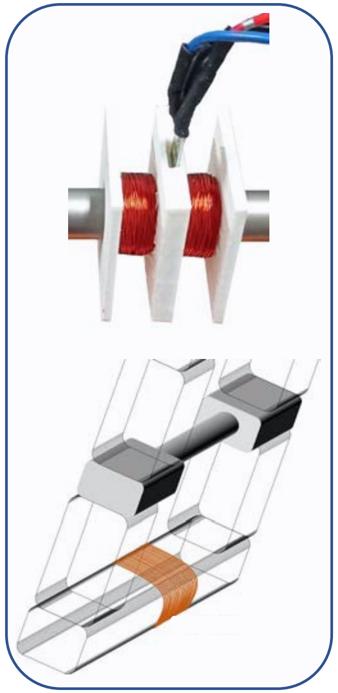


1000 A·m^{-1}

Magnetic Barkhausen noise



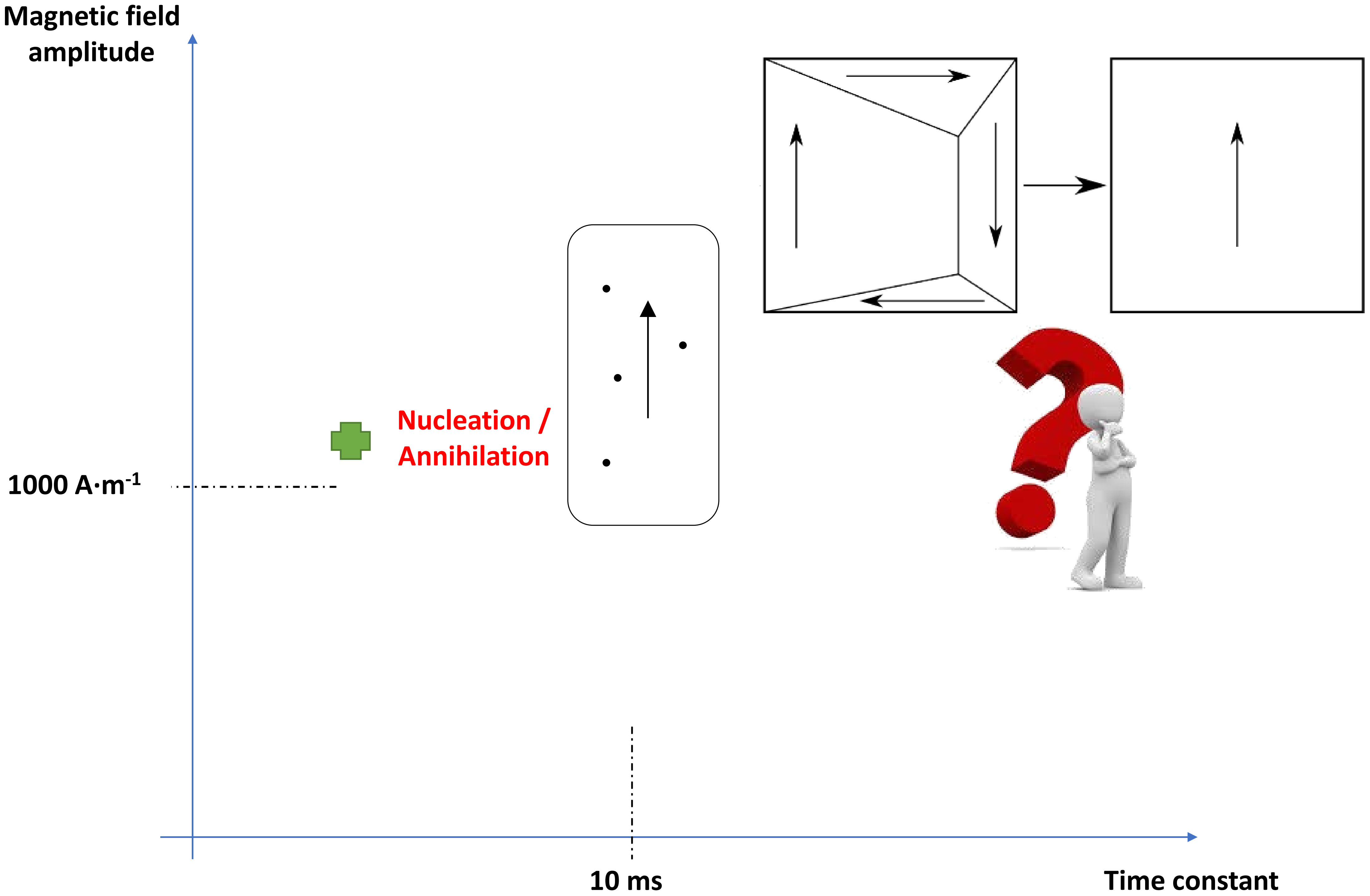


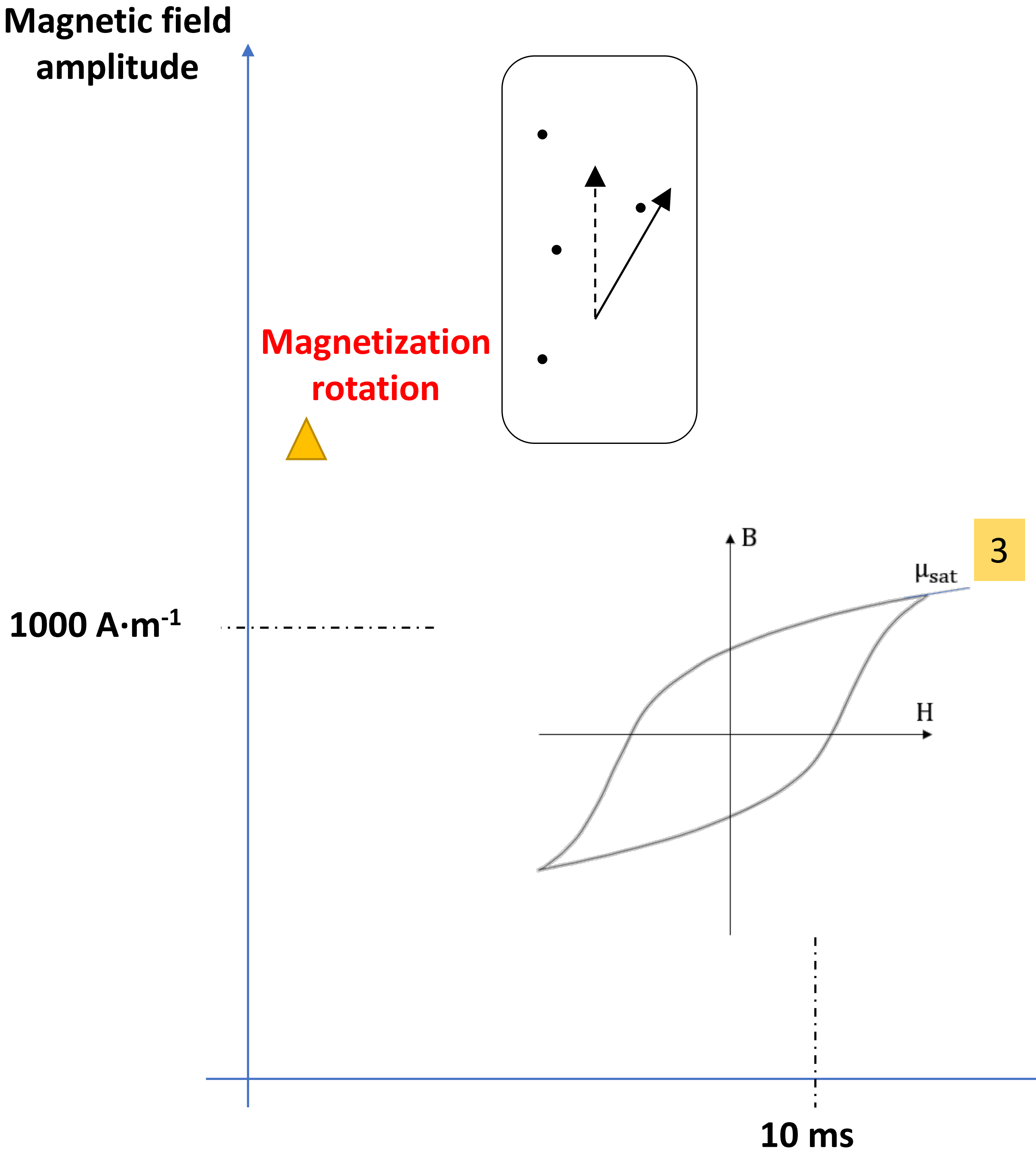


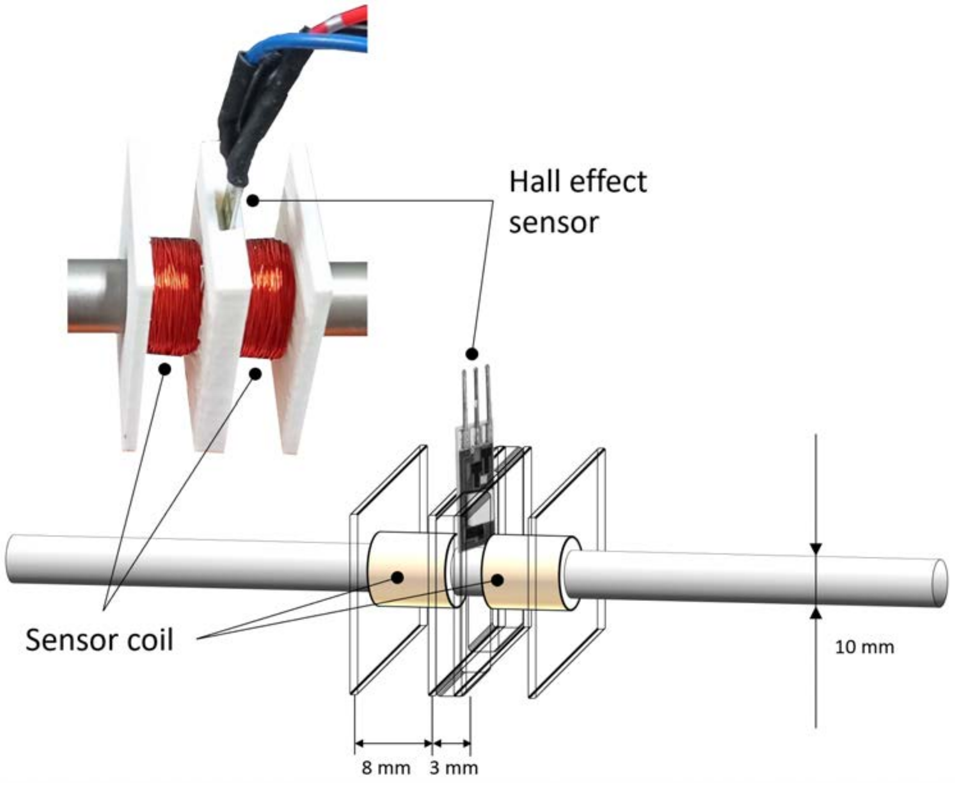
Irreversible motions

10 ms

Time constant

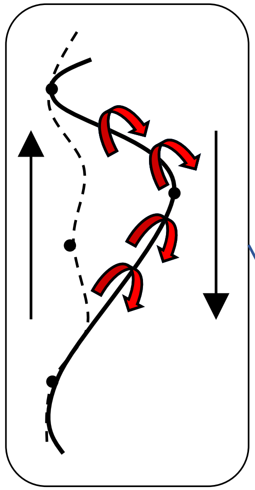

Magnetic field amplitude
1000 A·m-1
Nucleation / Annihilation
10 ms
Time constant



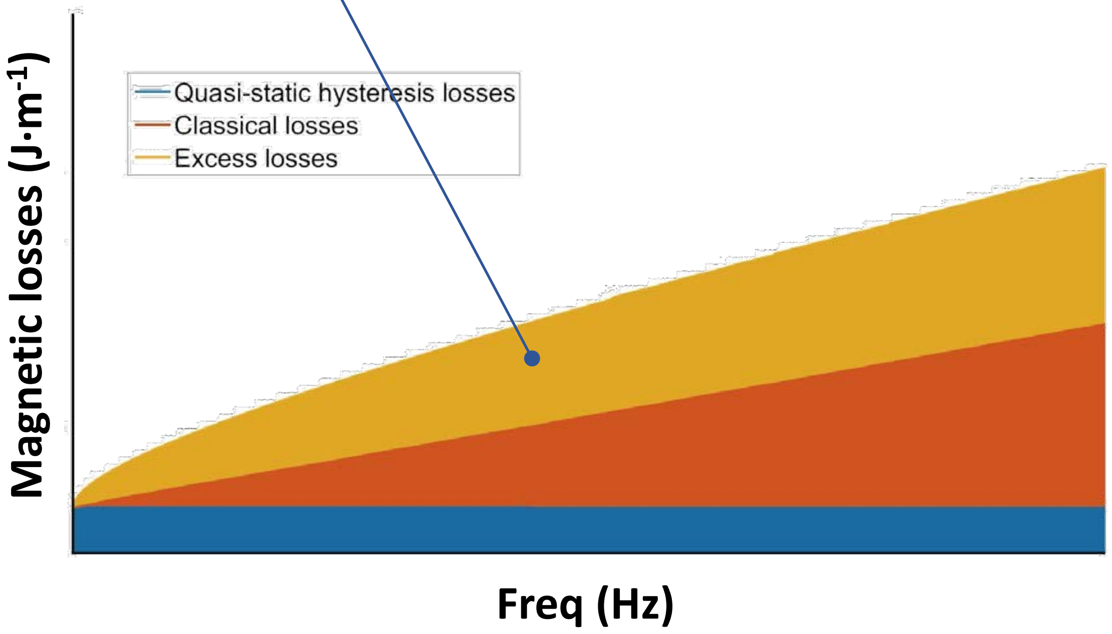


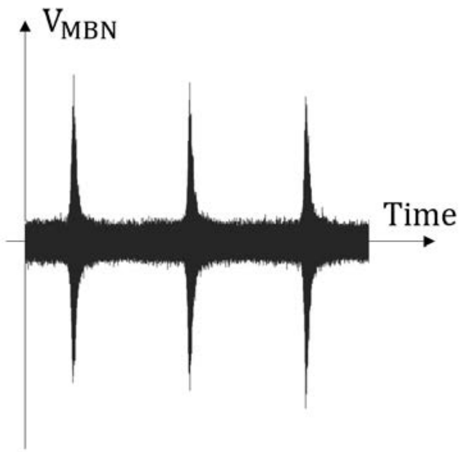
$$B(t) = -\frac{1}{2n \cdot S}\int_{0}^{t} e(x)dx$$

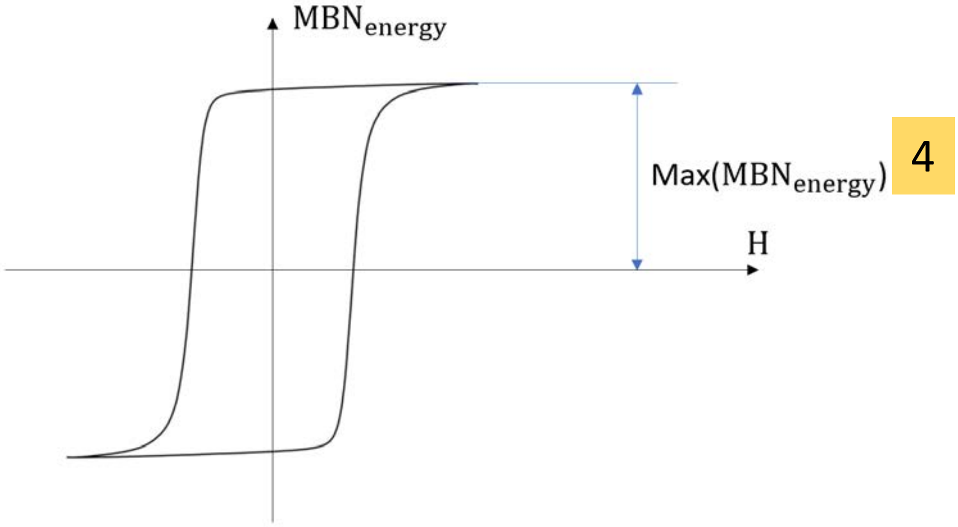
Magnetization properties frequency dependent

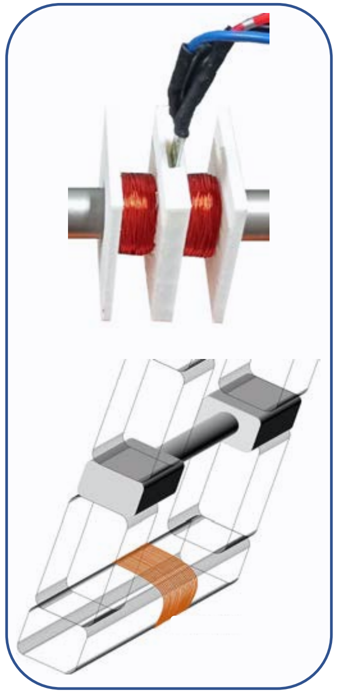


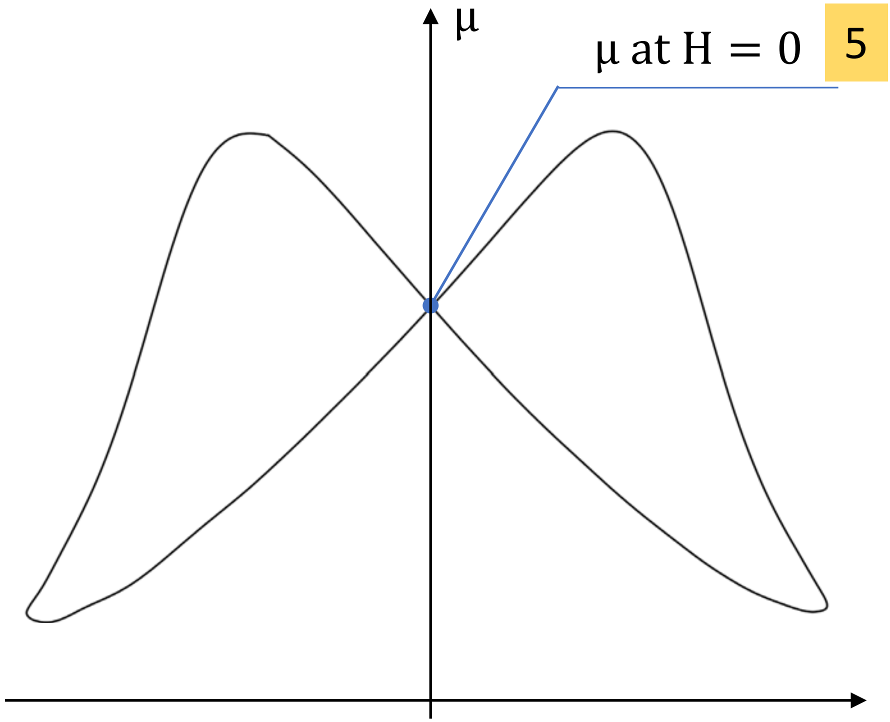
Microscopic eddy currents



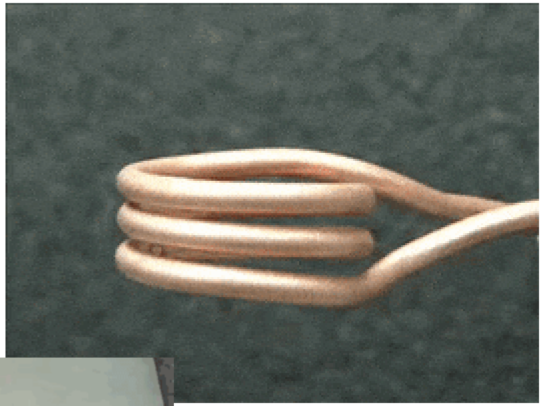




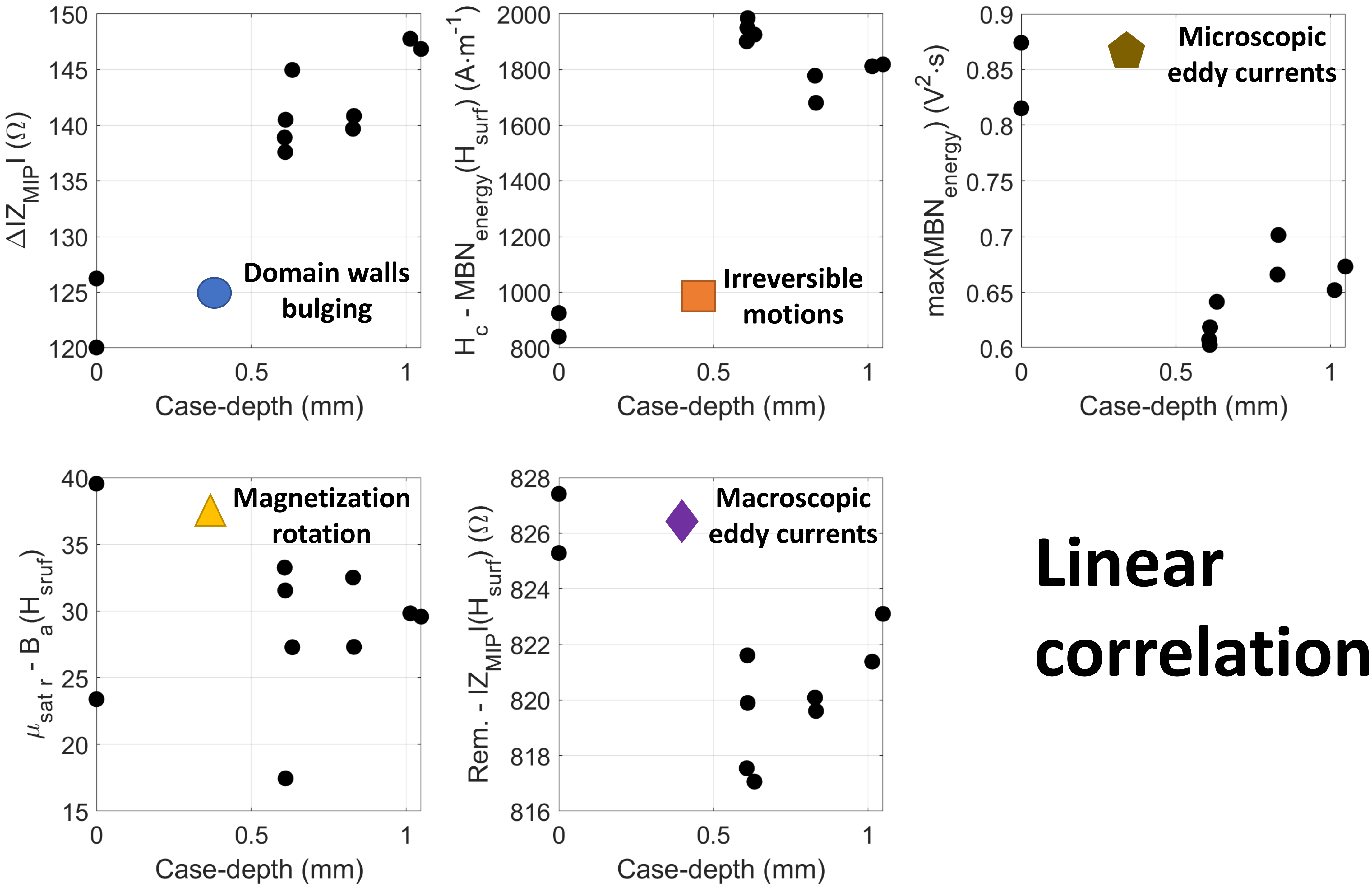




Macroscopic eddy currents

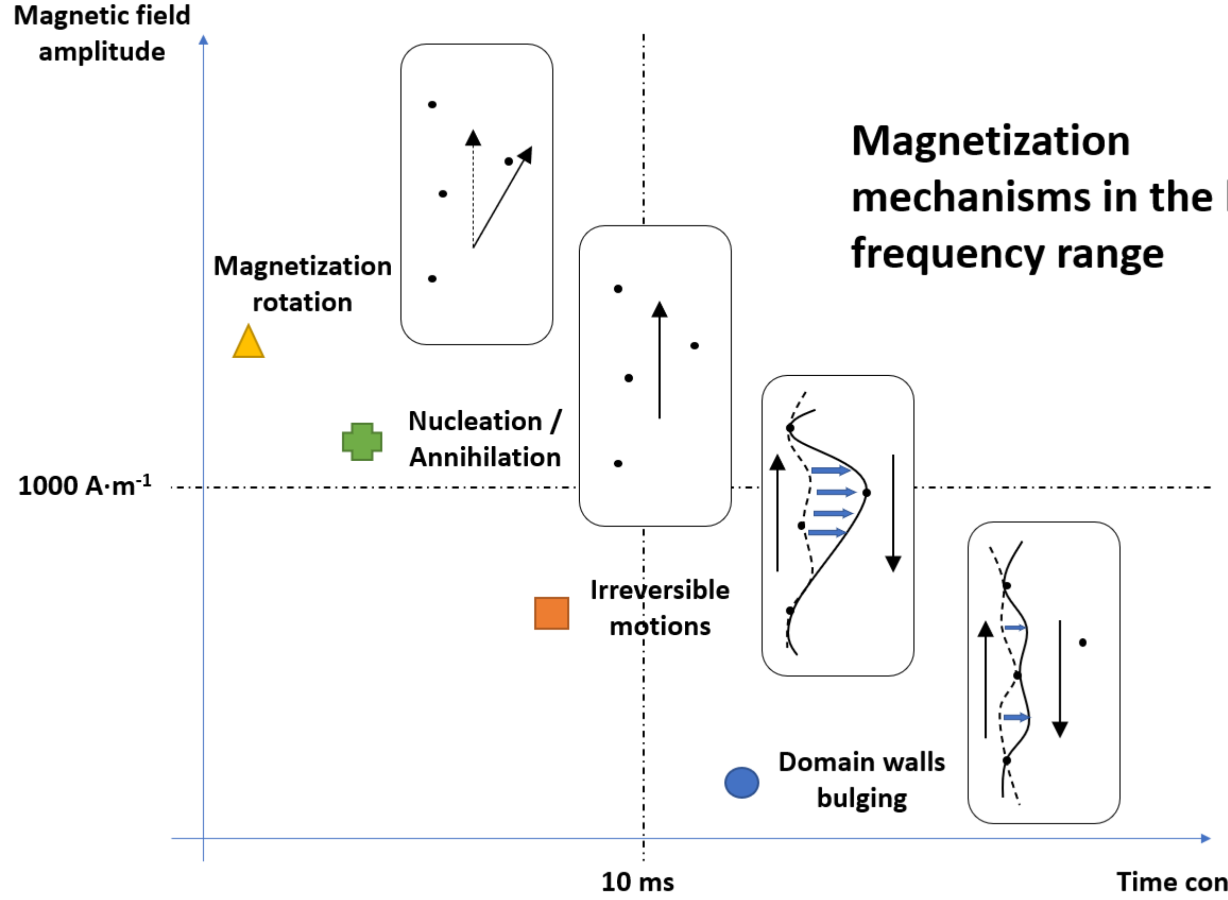


magnetization mechanism	magnetic indicator
Domain wall Bulging	ΔZ - (MIP)
Domain wall irreversible motions	Coercivity - (MBN)
Nucleation and Fusion	-
Microscopic eddy currents	$\max(MBN_{energy})$ - (MBN)
Magnetization rotation	μ_{sat} - ($B_a(H)$)
Macroscopic eddy currents	Remanence - (MIP)

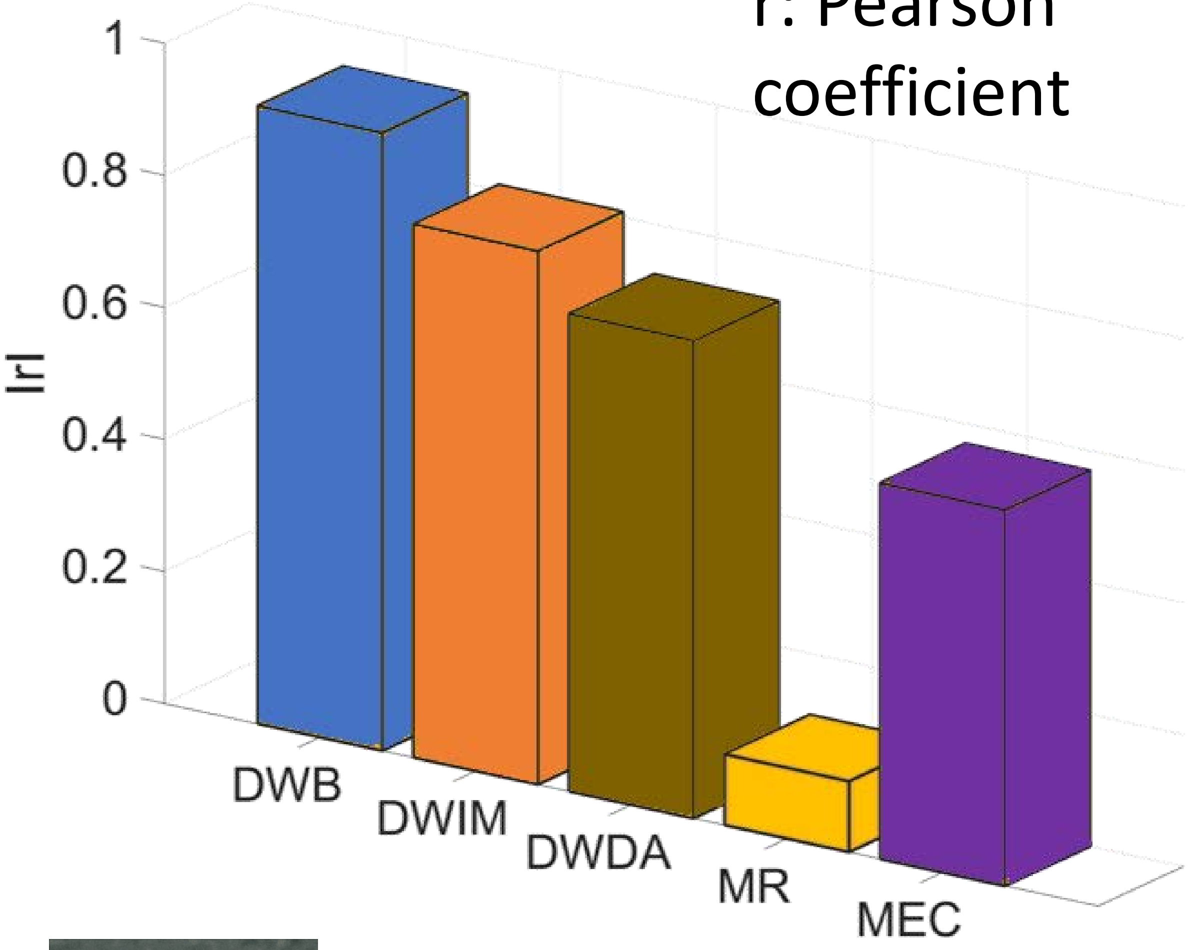


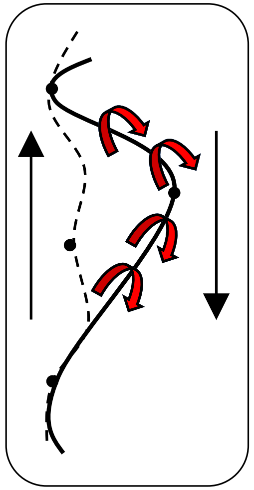
Linear correlations

Magnetization mechanisms in the low frequency range



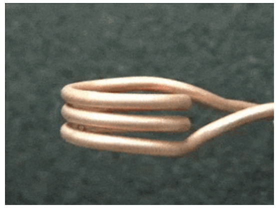
r: Pearson coefficient





Microscopic eddy currents

Macroscopic eddy currents



Recent papers on this topic (2022-2023):

Ducharne, B., 2024. Non-destructive testing of ferromagnetic steel components based on their magnetic response. In *Non-Destructive Material Characterization Methods* (pp. 707-725). Elsevier.

Ducharne, B., Deffo, Y.A.T., Zhang, S., Sebald, G., Lallart, M., Uchimoto, T., Gallais, C. and Ghibaudo, O., 2023. Carburization depth evaluation from magnetic nondestructive testing. *NDT & E International*, *137*, p.102864.

Ducharne, B., Sebald, G., Petitpré, H., Lberni, H., Wasniewski, E. and Zhang, F., 2023. Magnetic Signatures and Magnetization Mechanisms for Grinding Burns Detection and Evaluation. *Sensors*, *23*(10), p.4955.

Zhang, S., Ducharne, B., Sebald, G., Takeda, S. and Uchimoto, T., 2023. Magnetic indicators for evaluating plastic strains in electrical steel: Toward non-destructive assessment of the magnetic losses. *NDT & E International*, *134*, p.102780.

Saoudi, R., Morel, L., Raulet, M.A. and Ducharne, B., 2022. Magnetic properties and Barkhausen noise evolution during FeSiCuNbB nanocrystalline material aging. *Journal of Magnetism and Magnetic Materials*, *563*, p.169986.

Fagan, P., Ducharne, B., Zurek, S., Domenjoud, M., Skarlatos, A., Daniel, L. and Reboud, C., 2022. Iterative methods for waveform control in magnetic measurement systems. *IEEE Transactions on Instrumentation and Measurement*, *71*, pp.1-13.

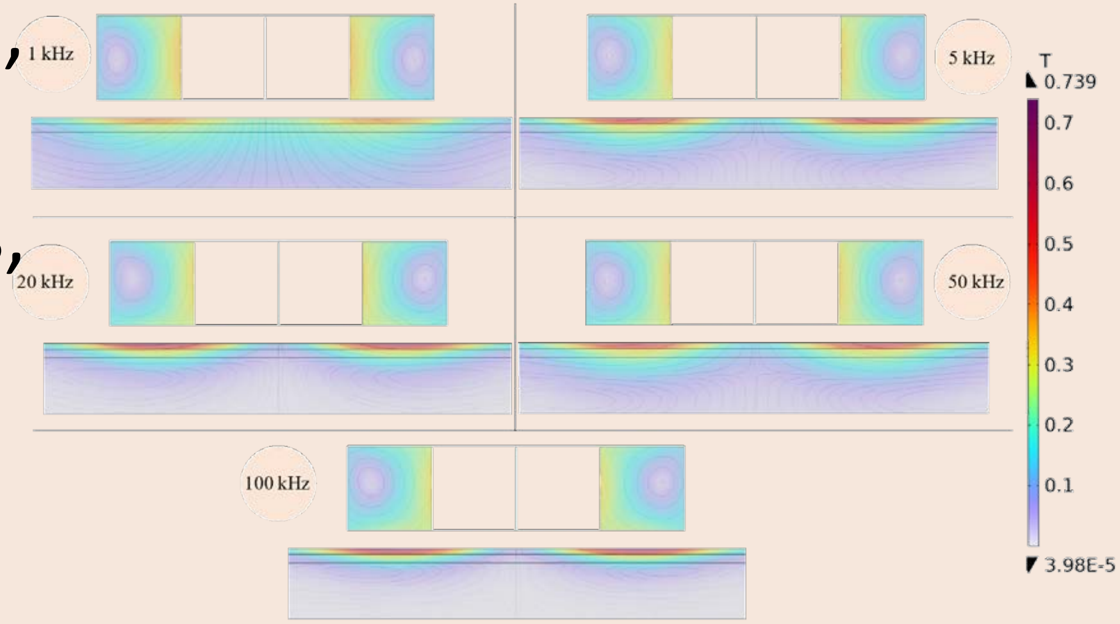
Toutsop, B., Ducharne, B., Lallart, M., Morel, L. and Tsafack, P., 2022. Characterization of Tensile Stress-Dependent Directional Magnetic Incremental Permeability in Iron-Cobalt Magnetic Sheet: Towards Internal Stress Estimation through Non-Destructive Testing. *Sensors*, *22*(16), p.6296.

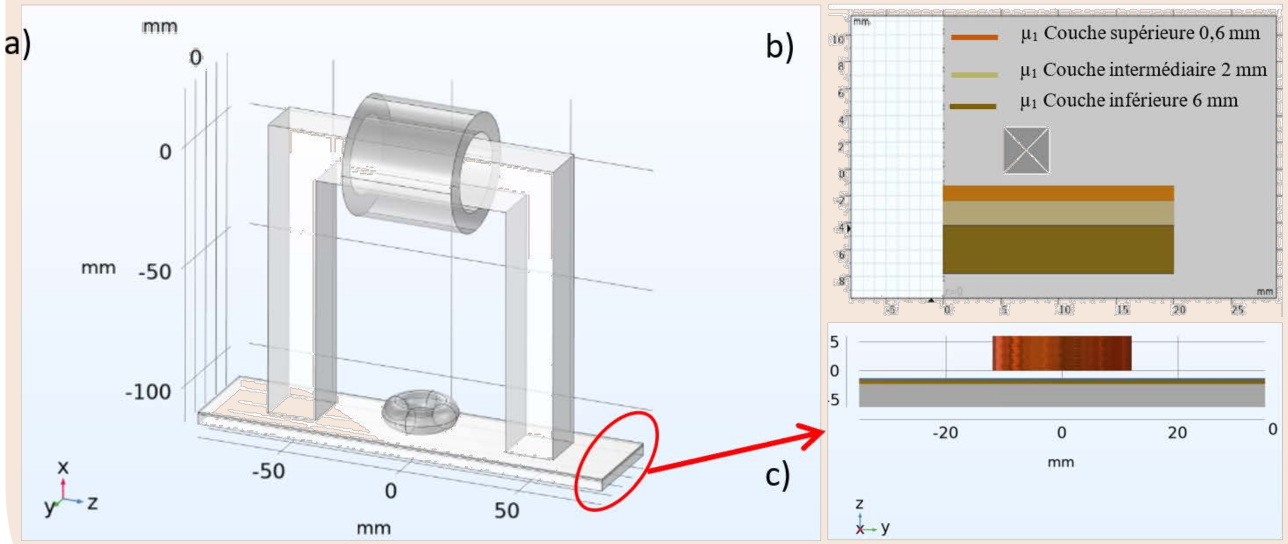
Surface treatments:

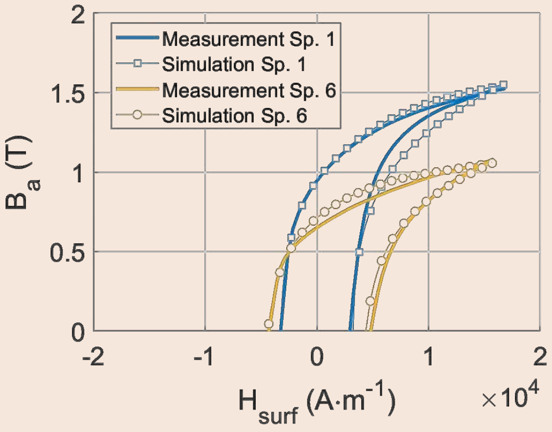
Desired: shot peening, carburization, residual stress, etc.

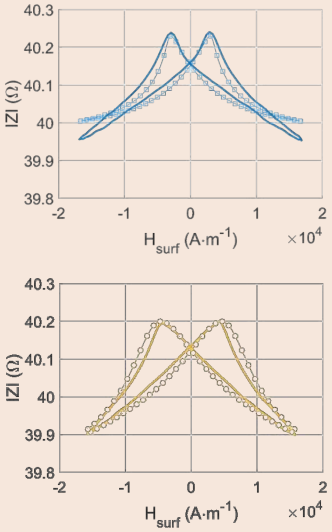
Undesired: corrosion, residual stress, etc.

Numerical methods development:







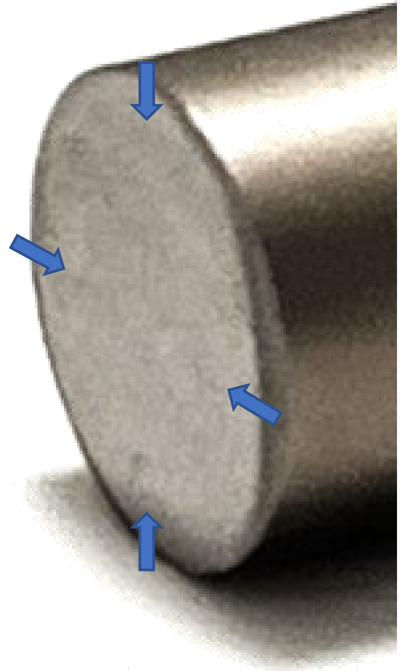


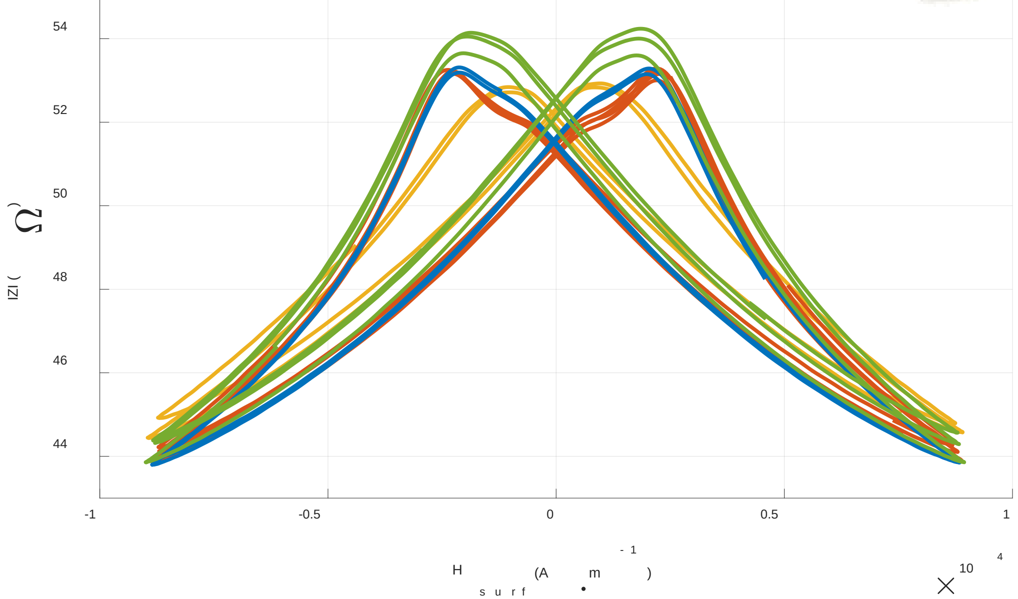
SAFRAN

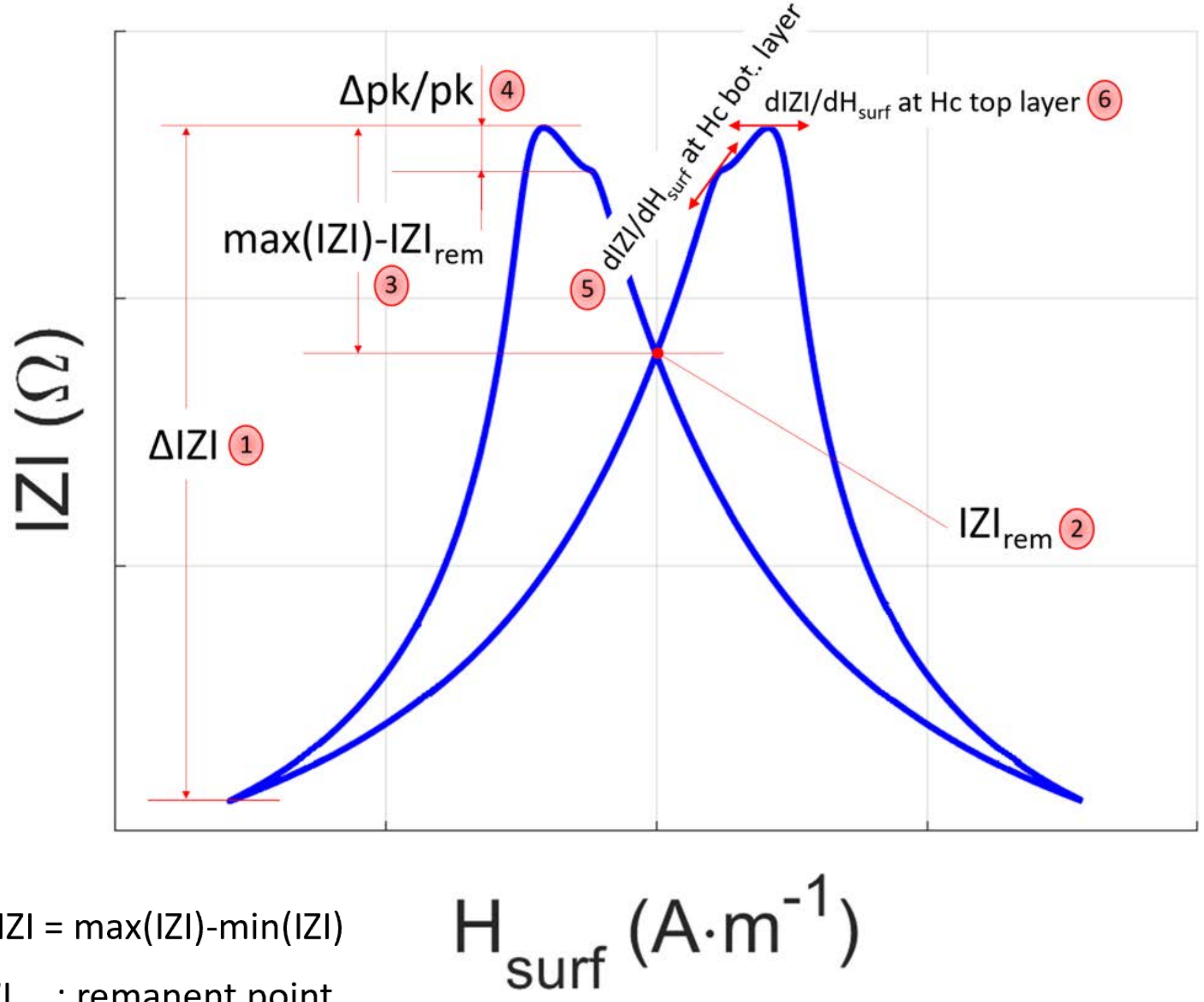
CETIM

cea

Low frequency MIP

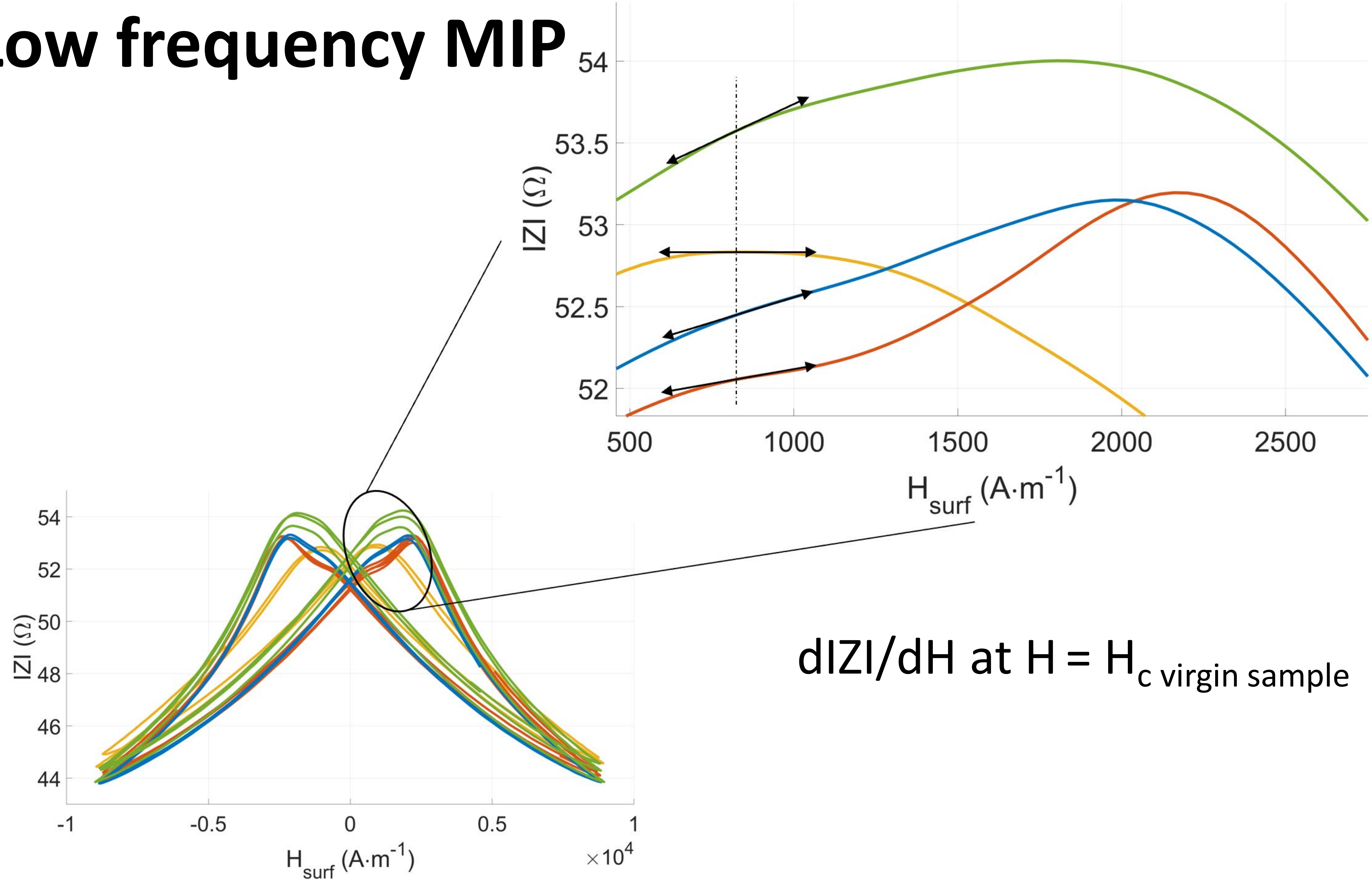






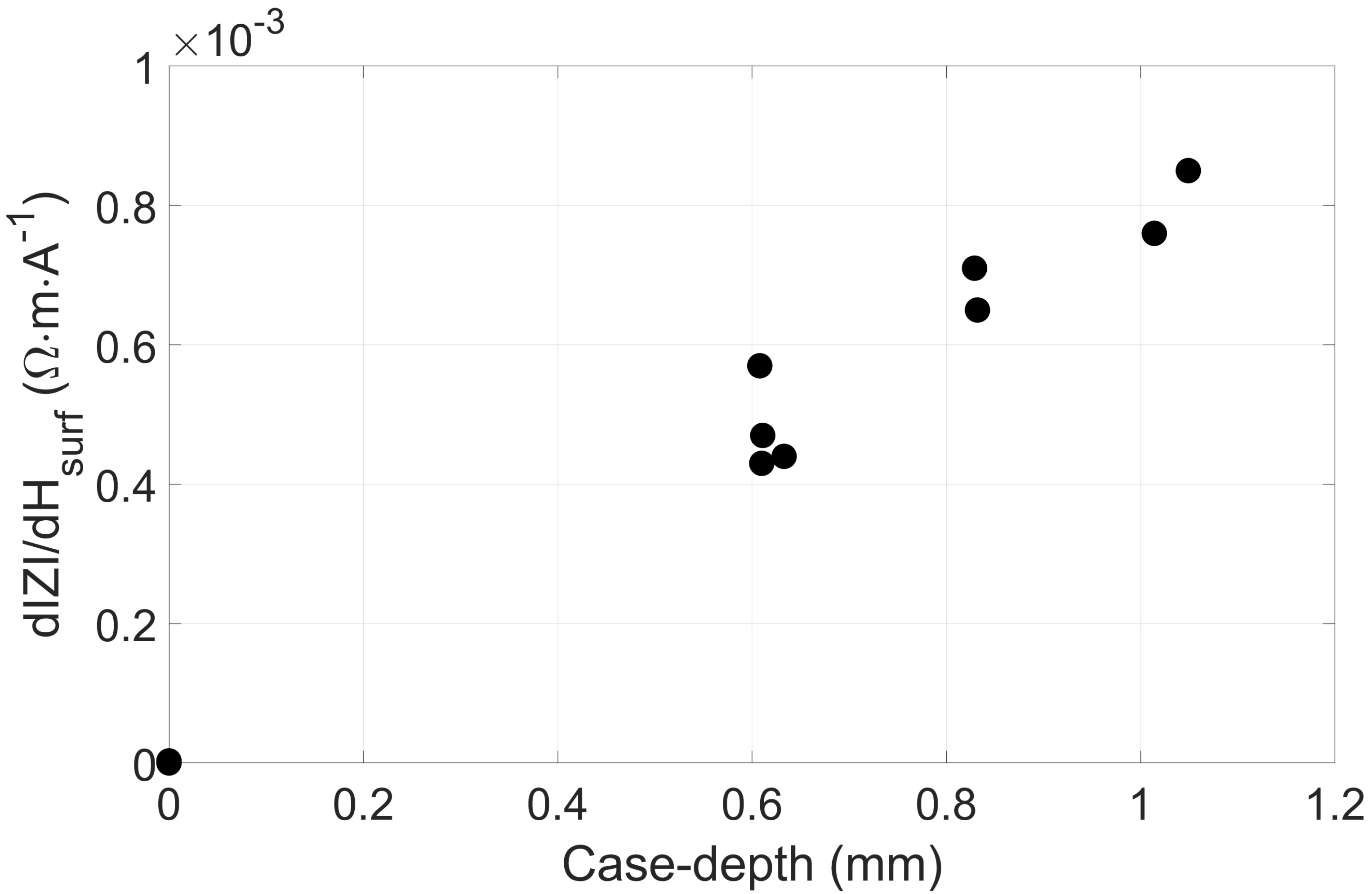
1. - ΔIZI = max(IZI)-min(IZI)
2. - IZI_{rem}: remanent point
3. - max(IZI)-IZI_{rem}
4. - Δpeak/peak
5. - $dIZI/dH_{surf}$ at Hc bot. layer
6. - $dIZI/dH_{surf}$ at Hc top layer

Low frequency MIP



dIZI/dH at $H = H_{c\ virgin\ sample}$

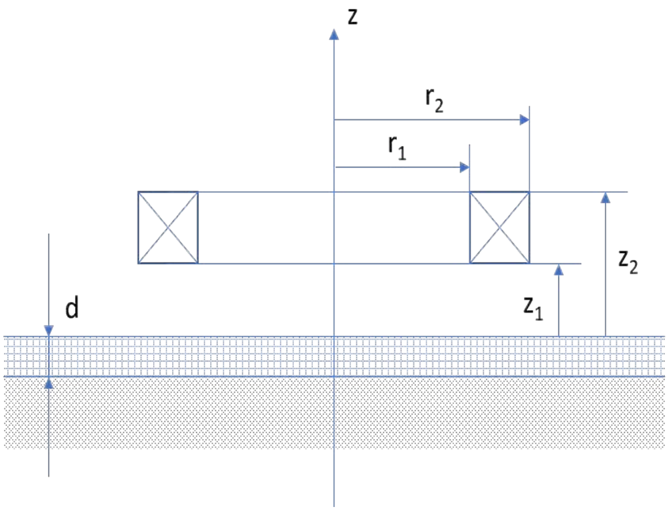
dIZI/dH at H = $H_{c\ virgin\ sample}$



r = 0.987

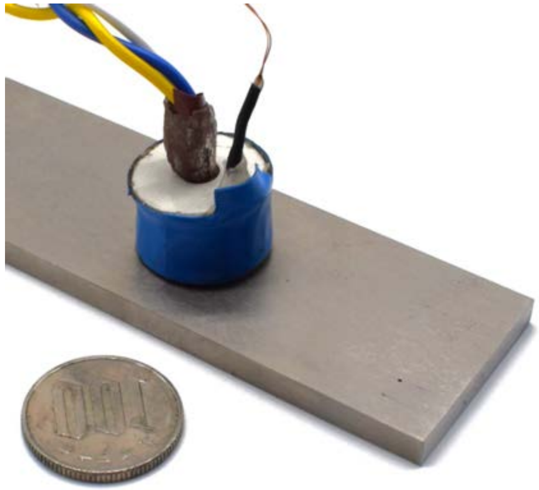
Ducharne, B., Deffo, Y.A.T., Zhang, S., Sebald, G., Lallart, M., Uchimoto, T., Gallais, C. and Ghibaudo, O., 2023. **Carburization depth evaluation from magnetic non-destructive testing**. *NDT & E International*, p.102864.

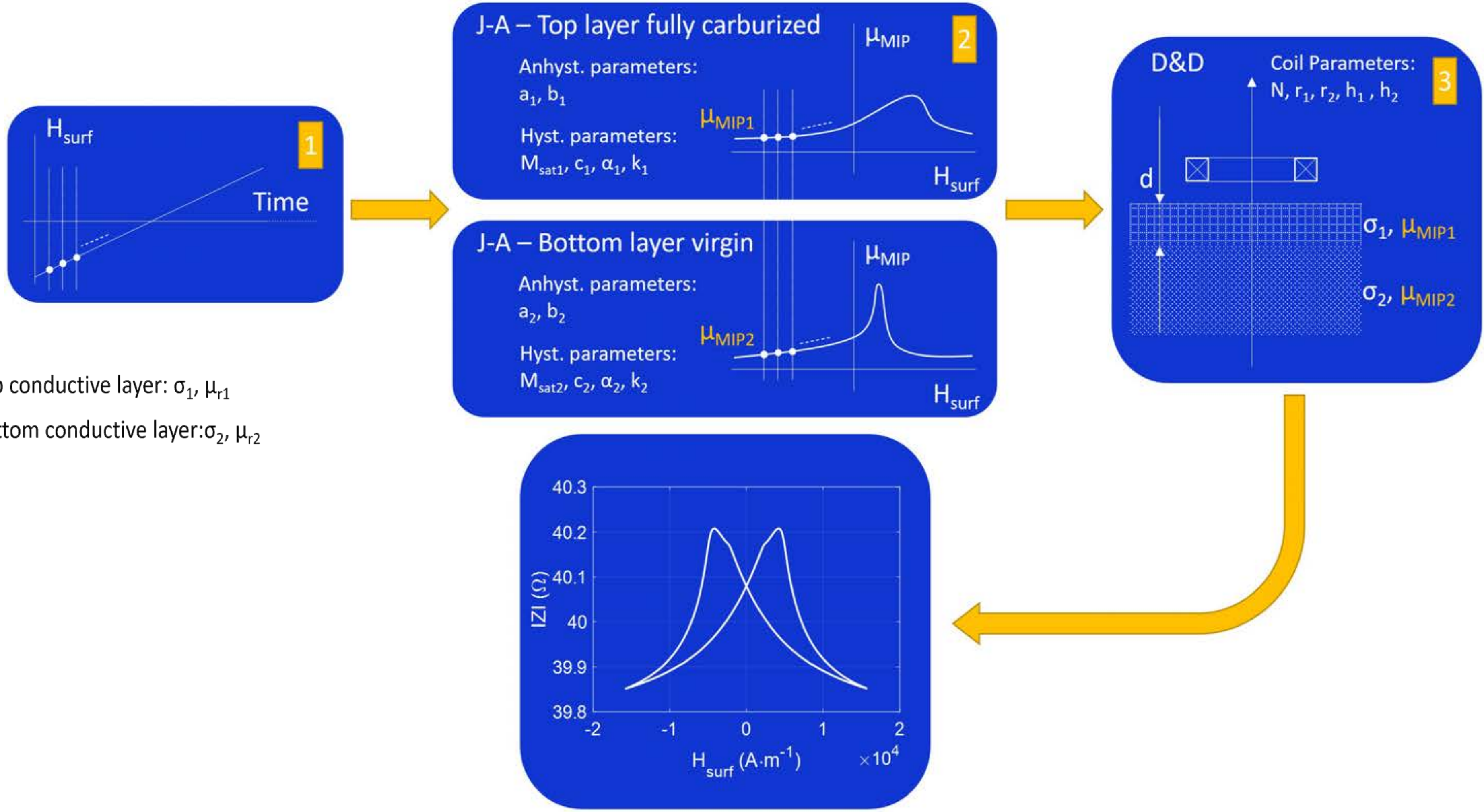
The Dodd & Deeds analytical expression for a coil above a two-layer conductor



Top conductive layer: σ_1, μ_{r1}

Bottom conductive layer: σ_2, μ_{r2}

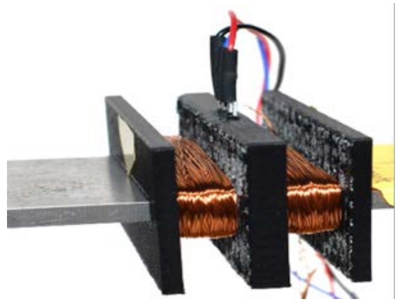


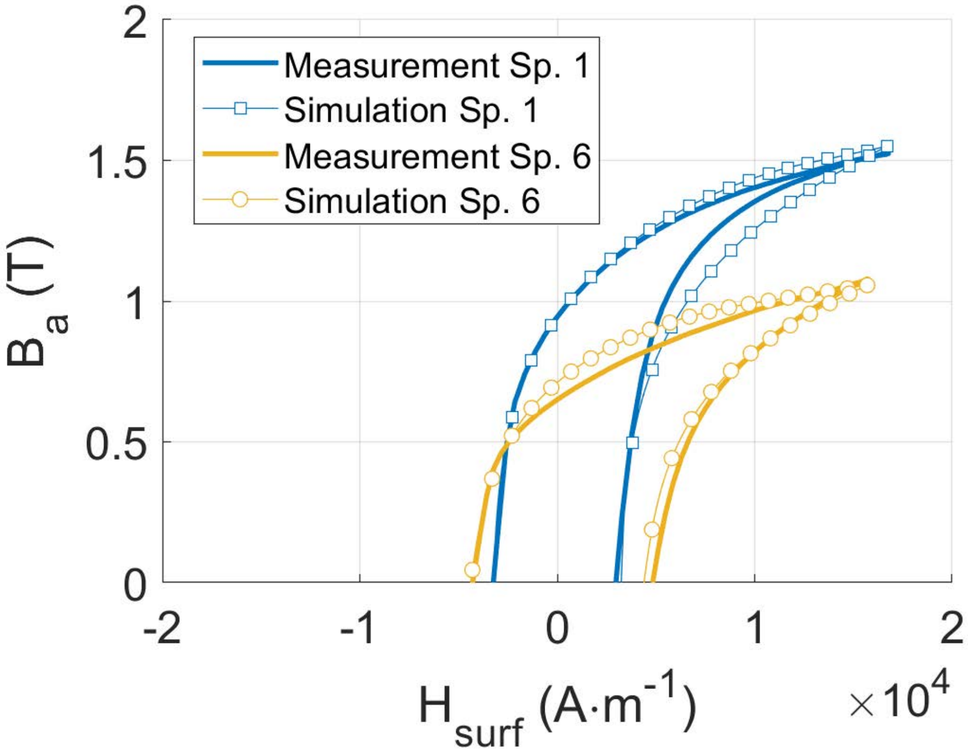


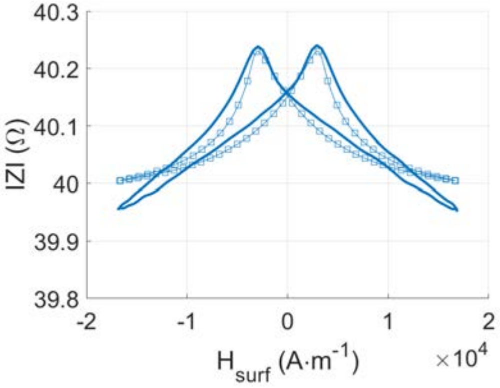
Simulation parameters adjustment

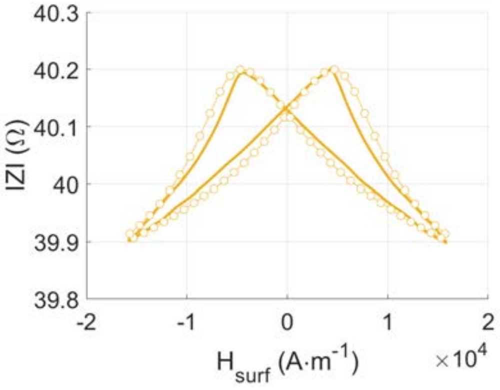
optimization process based on the minimization of the relative discrete Euclidean difference (Eq. 17) error function

$$RED_{discrete}\,(\%) = 100 \cdot \sqrt{\frac{\sum_{i=1}^{m}\left|x_i^{sim} - x_i^{meas}\right|^2}{\sum_{i=1}^{m}\left|x_i^{sim}\right|^2}} \qquad (17)$$









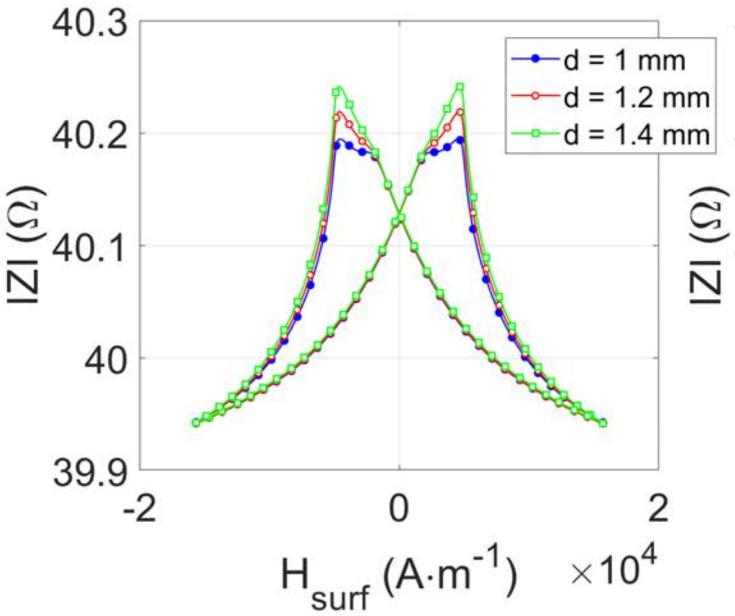
J-A Parameters Top layer (Sp. 6)	Typical value
a ($A \cdot m^{-1}$)	11000
b	6.8
Ms ($A \cdot m^{-1}$)	900000
k ($A \cdot m^{-1}$)	6500
c	0.074
α	0.023

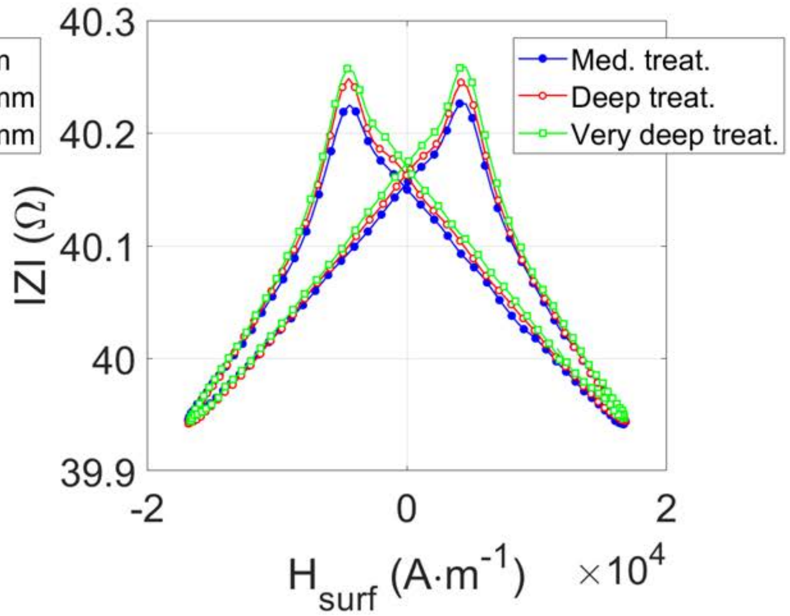
J-A Parameters Bottom layer (Sp. 1)	Typical value
a ($A \cdot m^{-1}$)	8300
b	10
Ms ($A \cdot m^{-1}$)	1110000
k ($A \cdot m^{-1}$)	3500
c	0.04
α	0.017

Tab. 4 – J-A model top (Sp. 6) and bottom (Sp. 1) layers parameters.

Simulation predictions

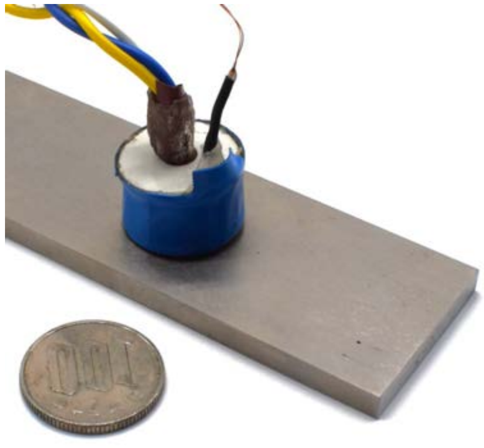
- Numerical method exploitation and practical validation

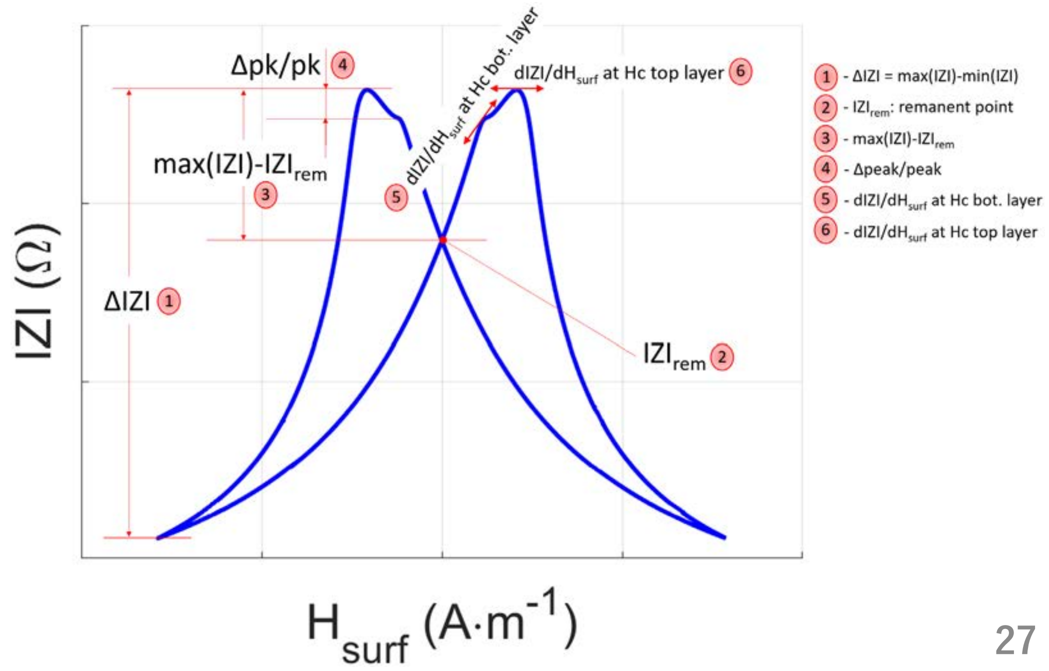




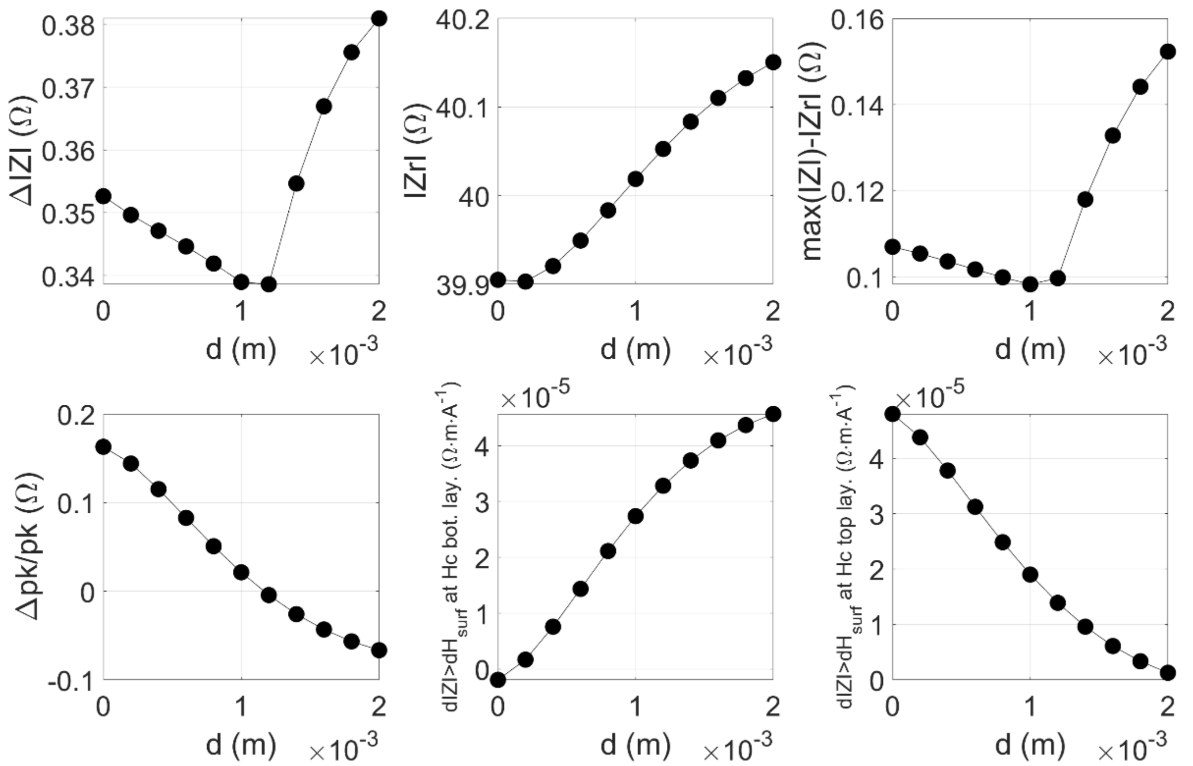
- Model prediction

d ∈ [0 – 2] mm
f ∈ [500 – 20] kHz





Simulation predictions



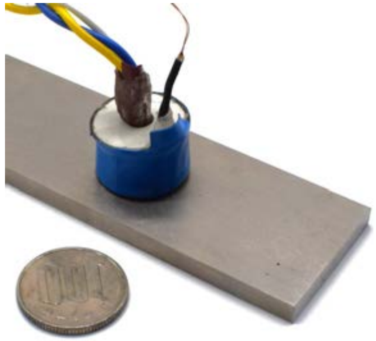
Model predictions for all indicators vs. at *f* = 1 kHz.

Pearson correlation coefficients: magnetic indicators vs. CD.

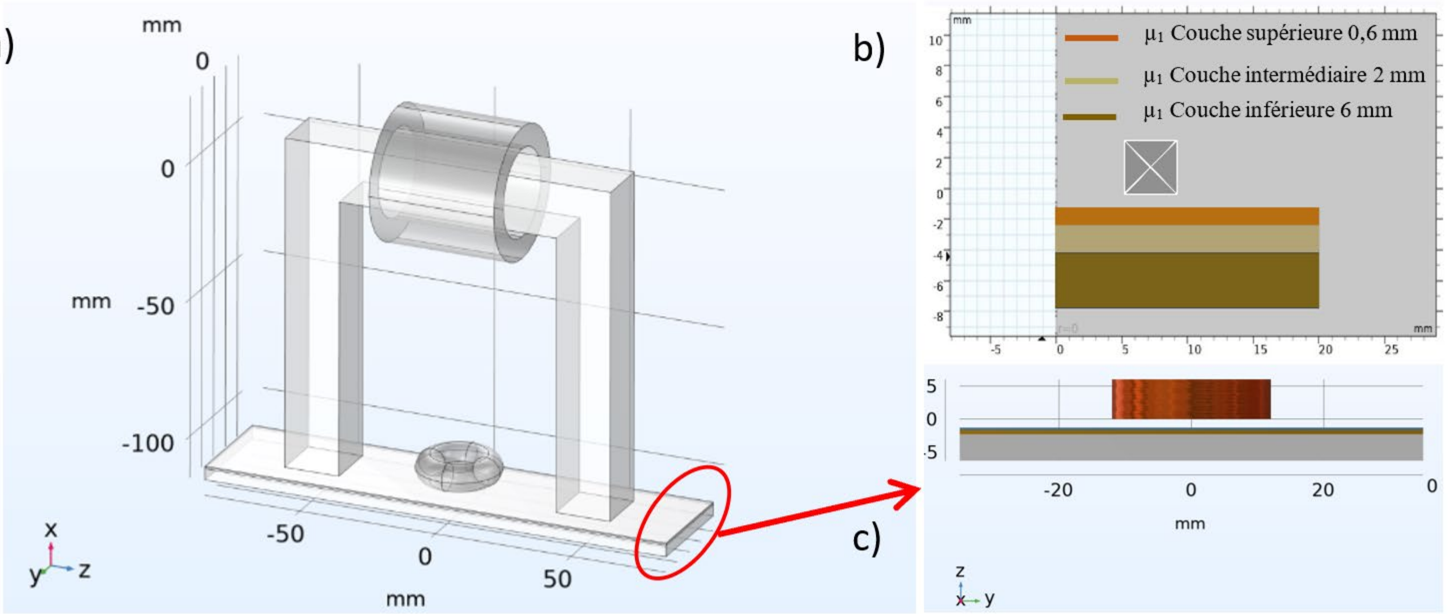
freq (kHz)	0.5	1	2	5	10	20
Magnetic indicators						
ΔIZI = max(IZI)-min(IZI)	0.544	0.665	0.838	0.58	0.479	0.452
IZI_{rem}: remanent point	0.043	0.978	0.958	0.8	0.66	0.556
max(IZI)-IZI_{rem}	0.86	0.779	0.925	0.769	0.617	0.523
Δpeak/peak	0.974	0.99	0.932	0.765	0.637	0.543
dIZI/dH_{surf} at Hc bot. layer	0.972	0.99	0.928	0.755	0.629	0.538
dIZI/dH_{surf} at Hc top layer	0.979	0.99	0.935	0.773	0.642	0.546

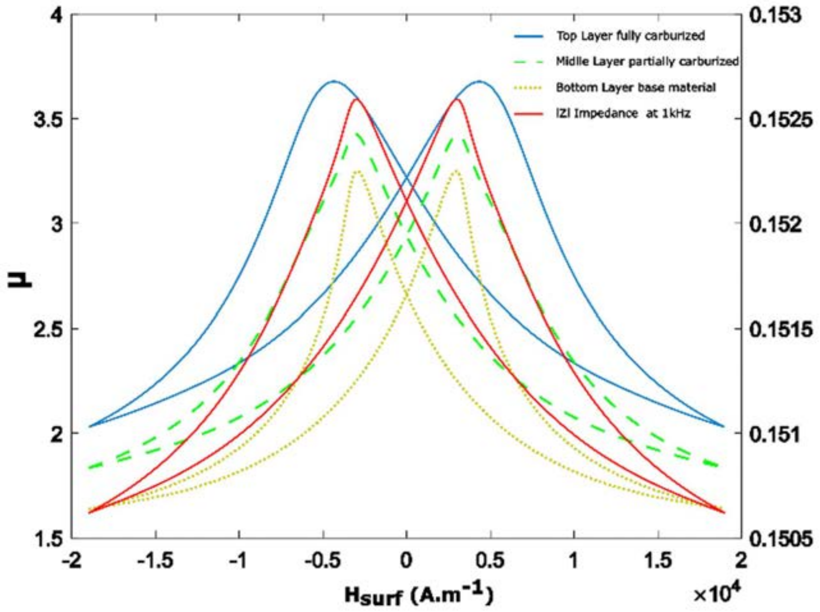
r : Pearson correlation coefficient

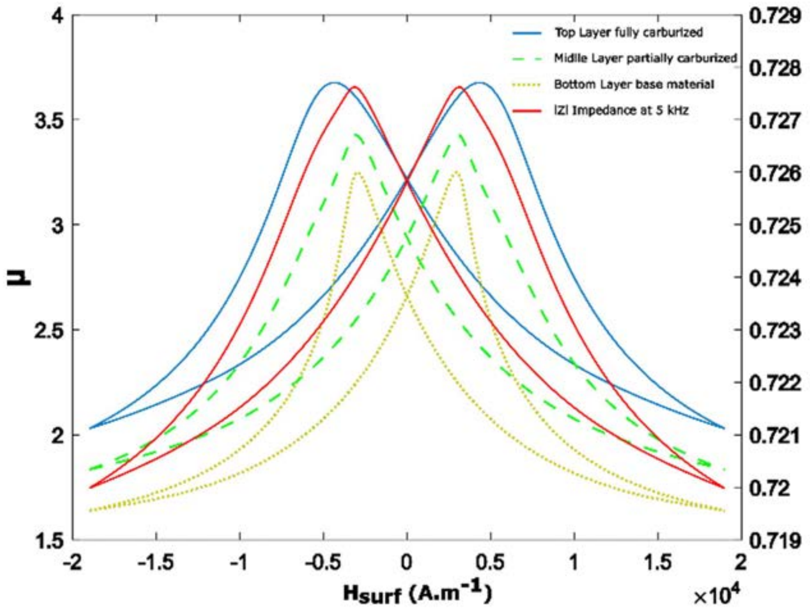
- **r** > 0.95
- 0.95 ≥ **r** > 0.9
- 0.9 ≥ **r** > 0.8
- 0.8 ≥ **r** > 0.7
- **r** ≤ 0.7

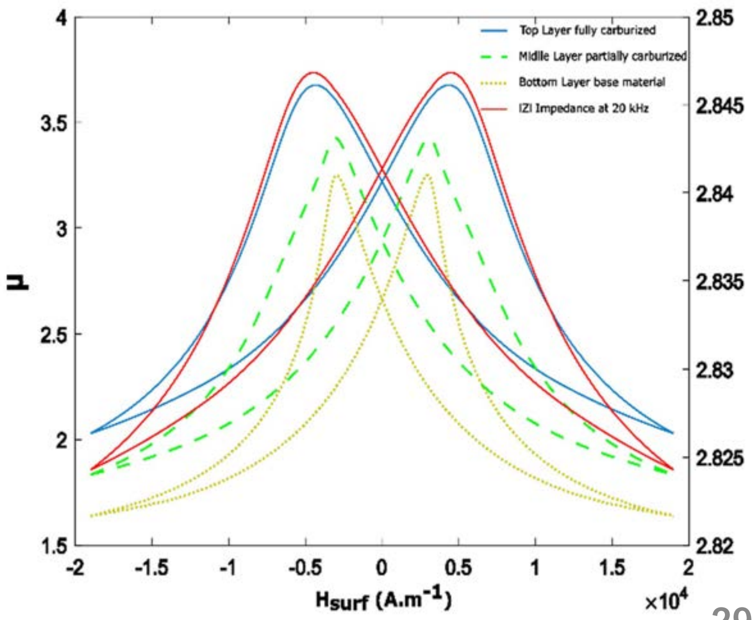


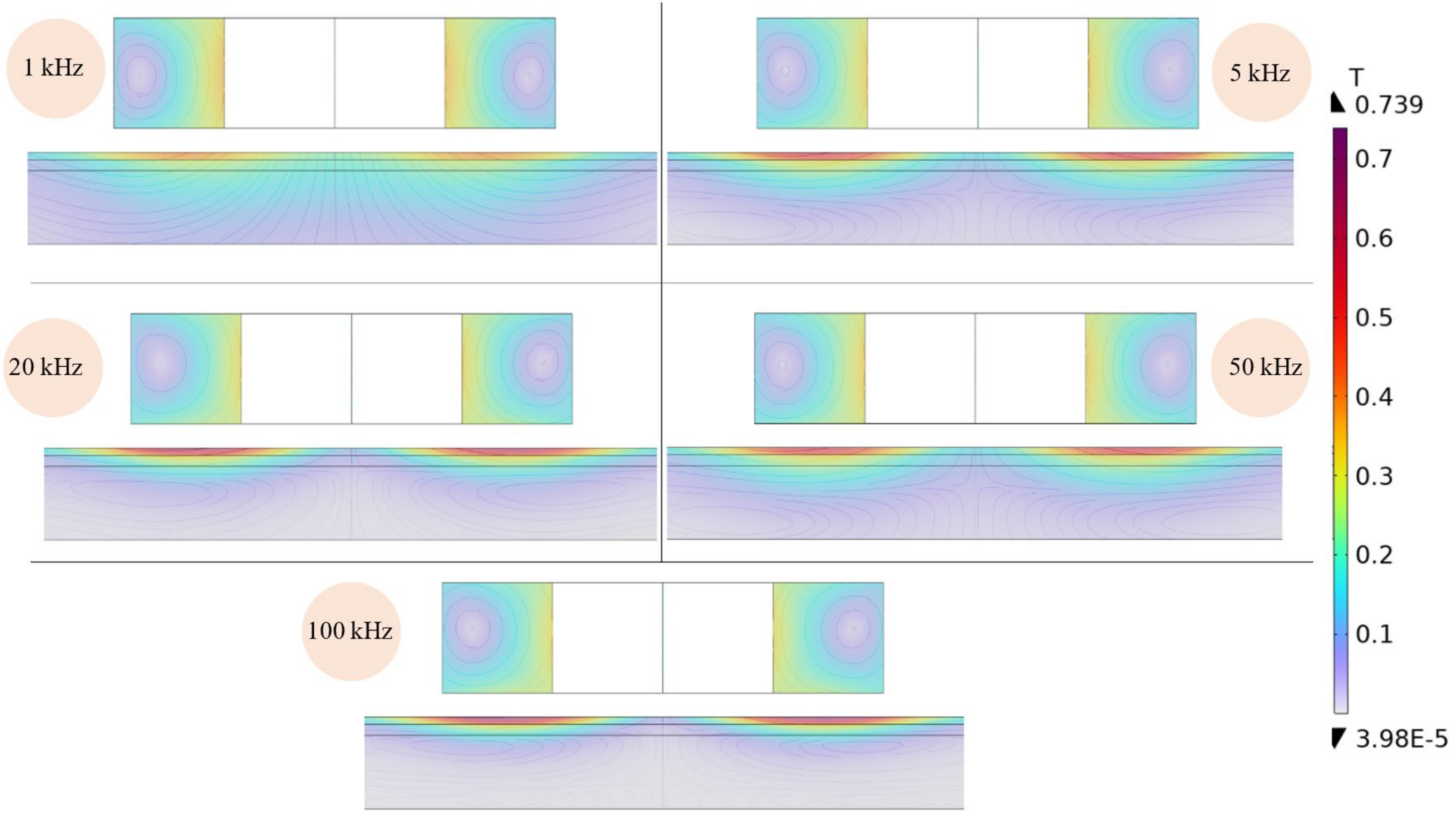
COMSOL MULTIPHYSICS










1 kHz
5 kHz
20 kHz
50 kHz
100 kHz
T
0.739
0.7
0.6
0.5
0.4
0.3
0.2
0.1
3.98E-5

Recent papers on this topic (2022-2023):

Ducharne, B., Deffo, Y.A.T., Sebald, G., Uchimoto, T., Gallais, C. and Ghibaudo, O., 2023. Low-frequency incremental permeability for the evaluation of deep carburization treatments: Theoretical understanding. *Journal of Magnetism and Magnetic Materials*, p.171236.

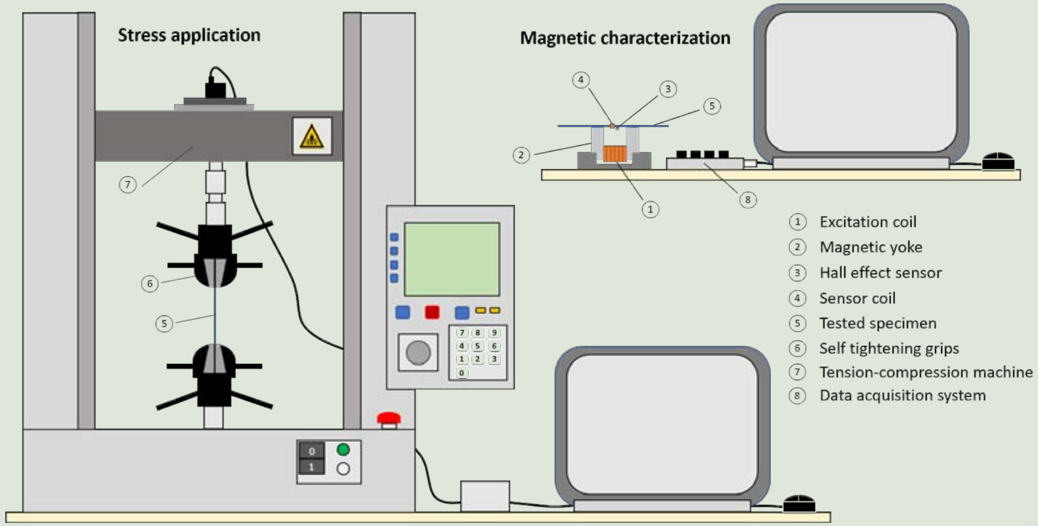
Fagan, P., Zhang, S., Sebald, G., Uchimoto, T. and Ducharne, B., 2023. Barkhausen noise hysteresis cycle: Theoretical and experimental understanding. *Journal of Magnetism and Magnetic Materials*, *578*, p.170810.

Ducharne, B., Zhang, S., Sebald, G., Takeda, S. and Uchimoto, T., 2022. Electrical steel dynamic behavior quantitated by inductance spectroscopy: Toward prediction of magnetic losses. *Journal of Magnetism and Magnetic Materials*, *560*, p.169672.

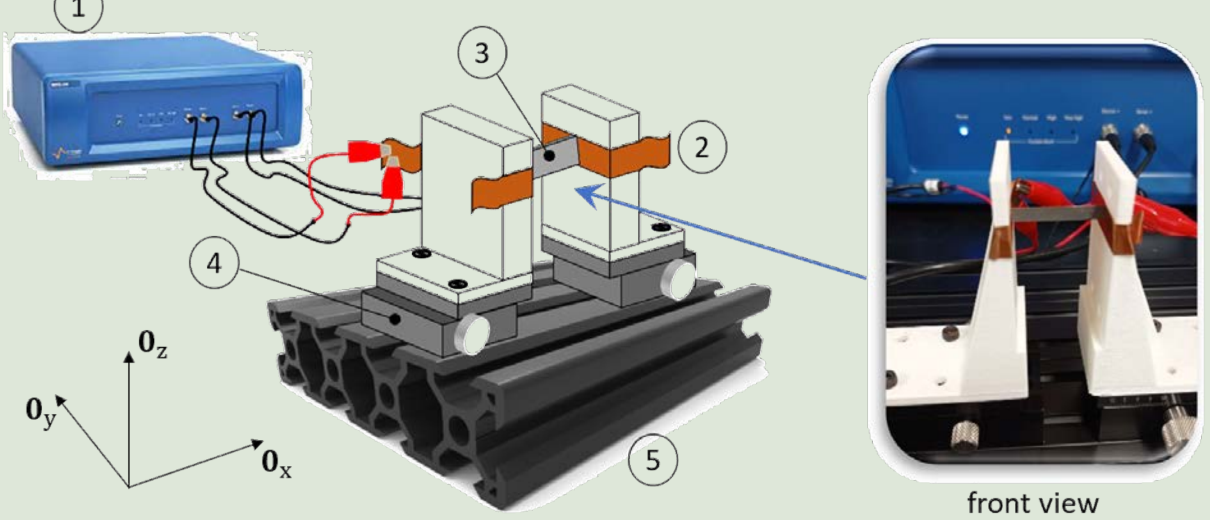
Fagan, P., Ducharne, B., Daniel, L., Skarlatos, A., Domenjoud, M. and Reboud, C., 2022. Effect of stress on the magnetic Barkhausen noise energy cycles: A route for stress evaluation in ferromagnetic materials. *Materials Science and Engineering: B*, *278*, p.115650.

Material laws:

_ Magnetostriction
_ Frequency dependency
_ Magnetic losses

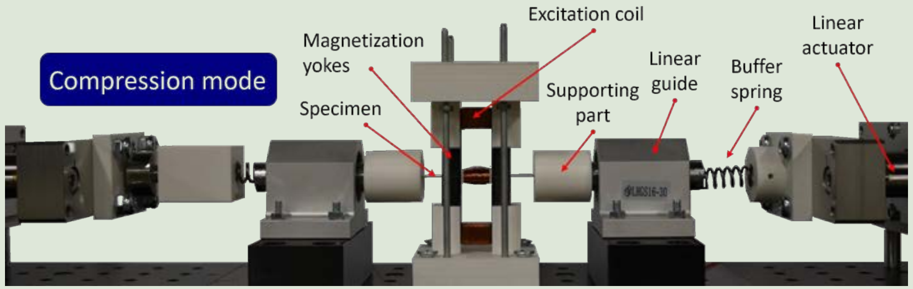


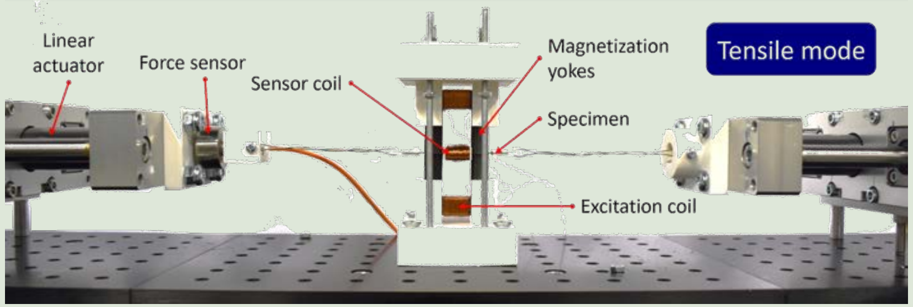
Magnetic instrumentation:



1 Impedance analyzer
2 Copper tape
3 GO FeSi specimen
4 Linear actuator
5 Aluminum rail

Fig. 1 – Picture and overall 3D view of the experimental setup.





thyssenkrupp
CETIM
GeePS Group of electrical engineering - Paris

Recent papers on this topic (2022-2023):

Daniel, L., Ducharne, B., Liu, Y. and Sebald, G., 2023. Choosing the best magnetostrictive material for energy harvesting applications: A simple criterion based on Ericsson cycles. *Journal of Magnetism and Magnetic Materials*, p.171281.

Diguet, G., Ducharne, B., El Hog, S., Kato, F., Koibuchi, H., Uchimoto, T. and Diep, H.T., 2023. Monte Carlo studies of skyrmion stabilization under geometric confinement and uniaxial strain. *Journal of Magnetism and Magnetic Materials*, *579*, p.170819.

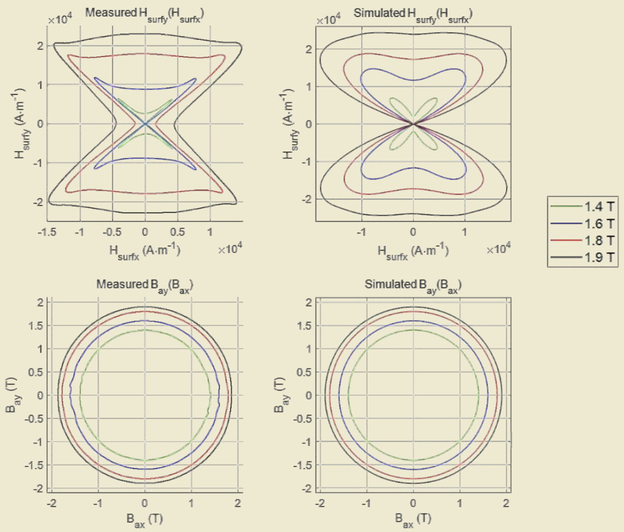
Liu, Y., Ducharne, B., Sebald, G., Makihara, K. and Lallart, M., 2023. Investigation of Energy Harvesting Capabilities of Metglas 2605SA1. *Applied Sciences*, *13*(6), p.3477.

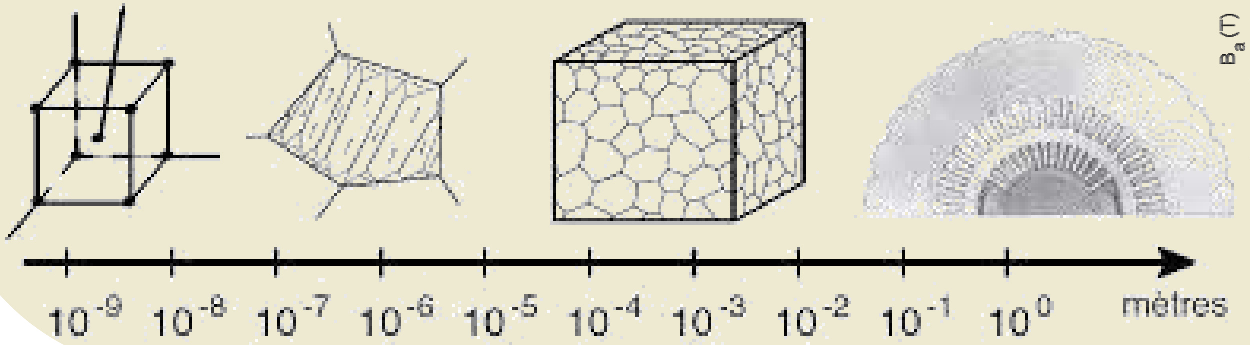
Ducharne, B., Zhang, S., Sebald, G., Takeda, S. and Uchimoto, T., 2022. Electrical steel dynamic behavior quantitated by inductance spectroscopy: Toward prediction of magnetic losses. *Journal of Magnetism and Magnetic Materials*, *560*, p.169672.

Kouakeuo, S.H.N., Solignac, A., Sabariego, R.V., Morel, L., Raulet, M.A., Toutsop, B., Tsafack, P. and Ducharne, B., 2022. Internal characterization of magnetic cores, comparison to finite element simulations: A route for dimensioning and condition monitoring. *IEEE Transactions on Instrumentation and Measurement*, *71*, pp.1-10.

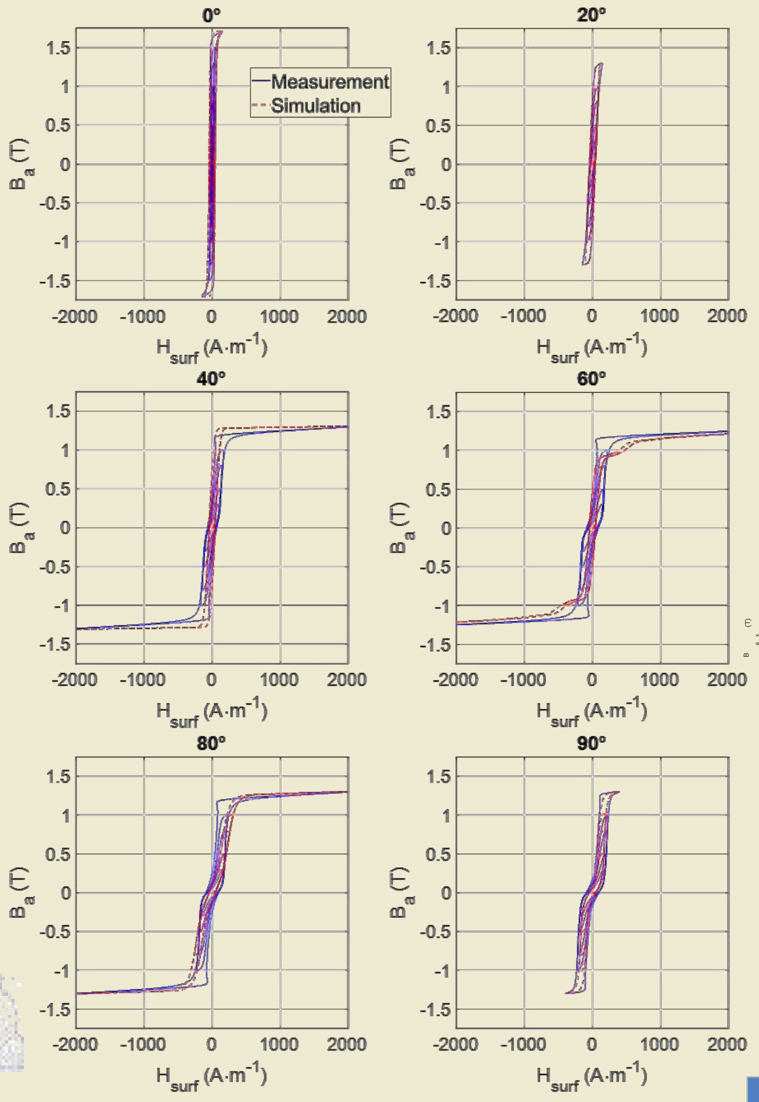
Material laws:

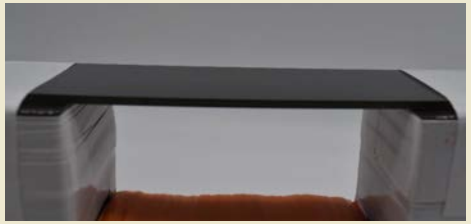
- _ Magnetostriction
- _ Frequency dependency
- _ Magnetic losses

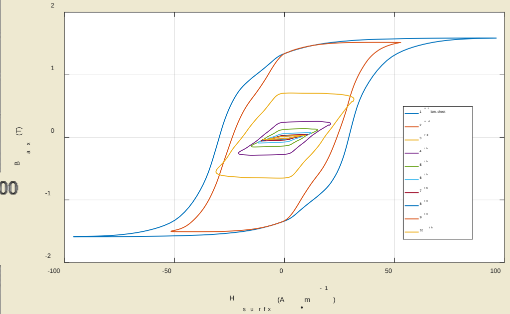




Magnetic simulation:







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cetim

GeePS
Group of electrical engineering - Paris

Recent papers on this topic (2022-2023):

Ducharne, B., Zurek, S., Daniel, L. and Sebald, G., 2022. An anisotropic vector hysteresis model of ferromagnetic behavior under alternating and rotational magnetic field. *Journal of Magnetism and Magnetic Materials*, *549*, p.169045.

Ducharne, B., Zurek, S. and Sebald, G., 2022. A universal method based on fractional derivatives for modeling magnetic losses under alternating and rotational magnetization conditions. *Journal of Magnetism and Magnetic Materials*, *550*, p.169071.

Ducharne, B. and Sebald, G., 2022. Fractional derivatives for the core losses prediction: State of the art and beyond. *Journal of Magnetism and Magnetic Materials*, p.169961.

Ducharne, B. and Sebald, G., 2022. Combining a fractional diffusion equation and a fractional viscosity-based magneto dynamic model to simulate the ferromagnetic hysteresis losses. *AIP Advances*, *12*(3).

Magnetic Non-destructive testing, based on the magnetization mechanisms - Perspectives

WAINVAM-E

CETIM CARNOT GeePS Group of electrical engineering - Paris MaX

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OCEA

SERPRO TRONICS services et solutions électroniques

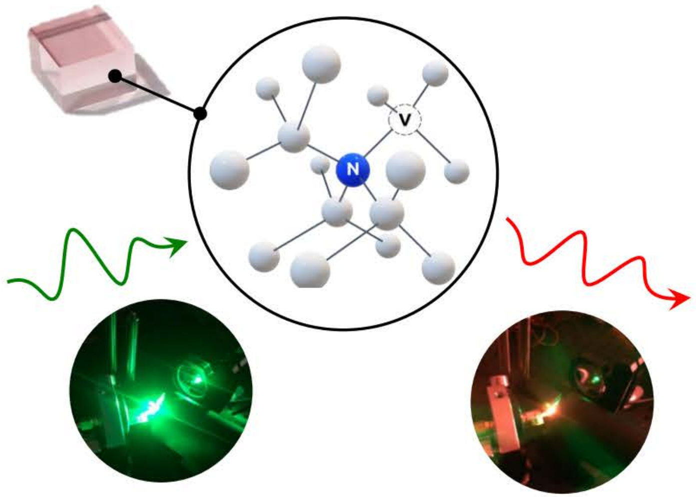
CMPhy MESURES PHYSIQUES

MaX

WAINVAM-E

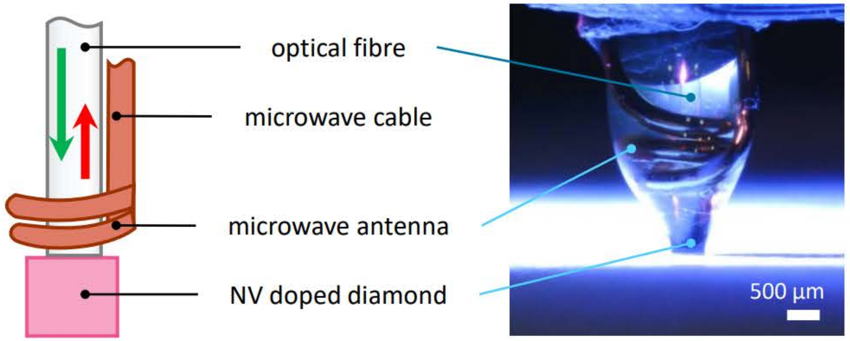
NV magnetometry

The NV centre is a defect of diamond, which can be used as an optically-adressed quantum (atomic) sensor.



With a microwave close to 3 GHz, the NV centre can be used as an excellent magnetometer.

At WAINVAM-E, we functionalize optical fibres with macroscopic diamonds enriched in NV centers to fabricate NV endoscopes.



These endoscopes display multiple advantages for the measurement of the magnetic field:

- High resolution (~100 µm)
- Vectorial
- Quantitative and absolute (no calibration)
- Sensitive (nT $\rightarrow$ pT)
- Robust, easy to integrate

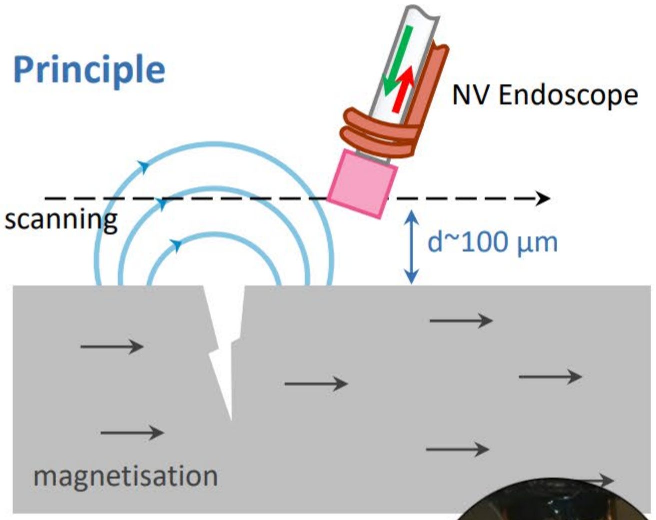
WAINVAM-E

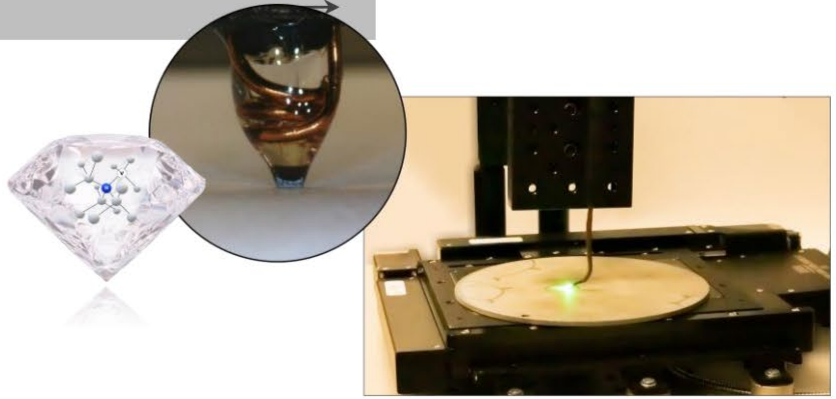
First step, the stray field imager prototype

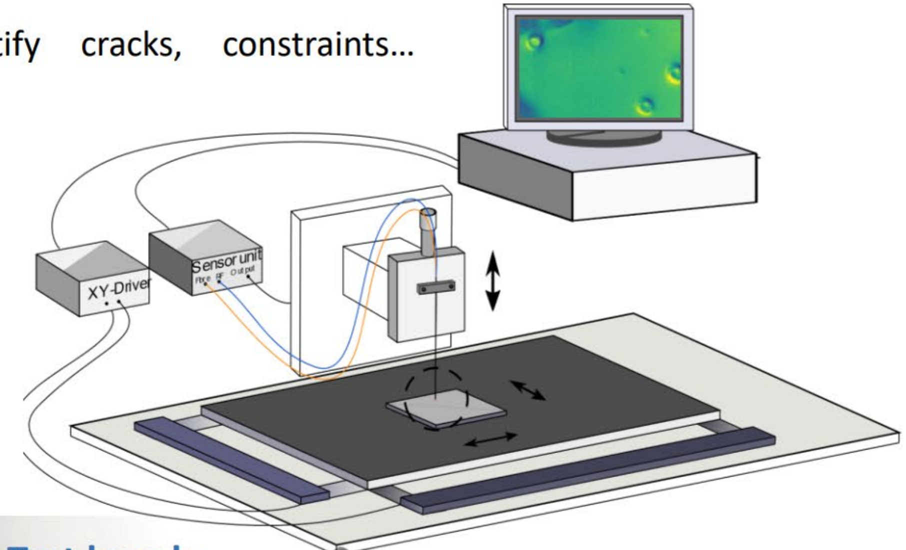
The test bench consists of a control unit, a remote endoscope with a NV centres diamond head.

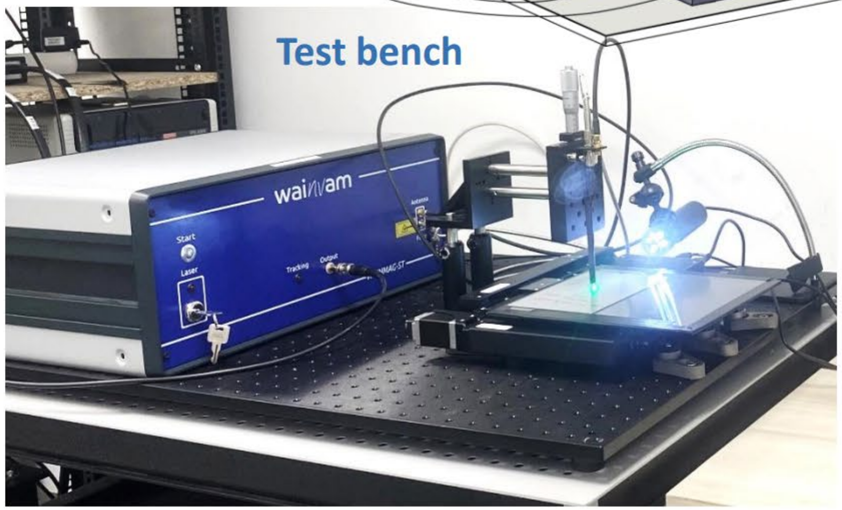
The endoscope scans metallic parts to measure stray fields and then identify cracks, constraints… which are rendered as images on the computer.

Principle









WAINVAM-E

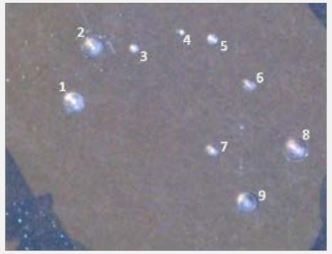
Applicable techniques: all (stray field, low and high frequency AC sensing)

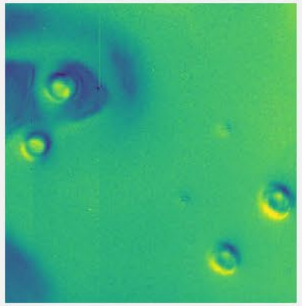
Added value of NV:

- ✓ High resolution & sensitive
- ✓ Quantitative (discriminate big defects)

E.g. pitting

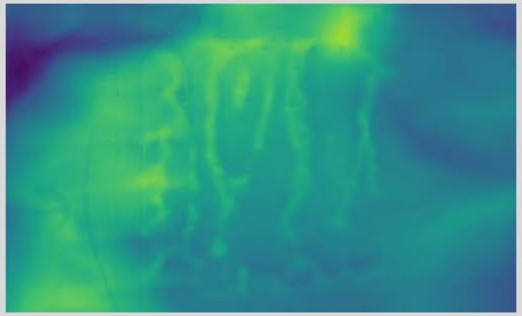
Photograph of the scanned area





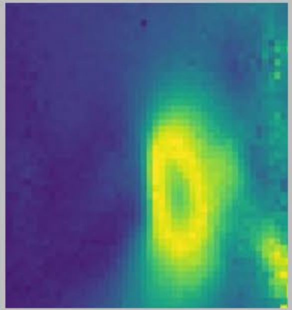
- ✓ Works through coatings and paints
- ✓ No preparation of the surface

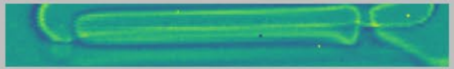
E.g. crevice corrosion under paint



- ✓ Access to difficult geometries

Hole in Steel Tube





Damage on Gear

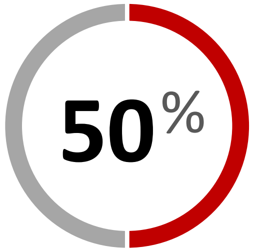
Labcom: CETIM GeePS Max

Electromagnetic NDT

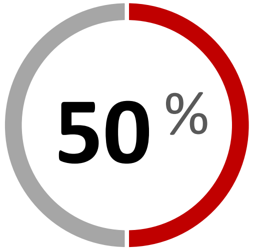
Technological Institute of Mechanics

steered by mechanical engineering industrialists under French State supervision

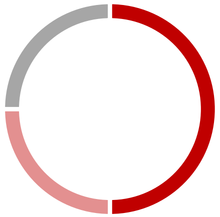
Governed by Articles
L521.1 to L521.13
of the French Code of Research



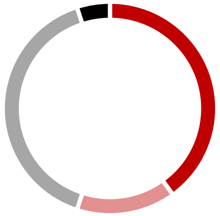
€173
million
Overall business volume



A JOINT ACTION



A COMMERCIAL OFFER



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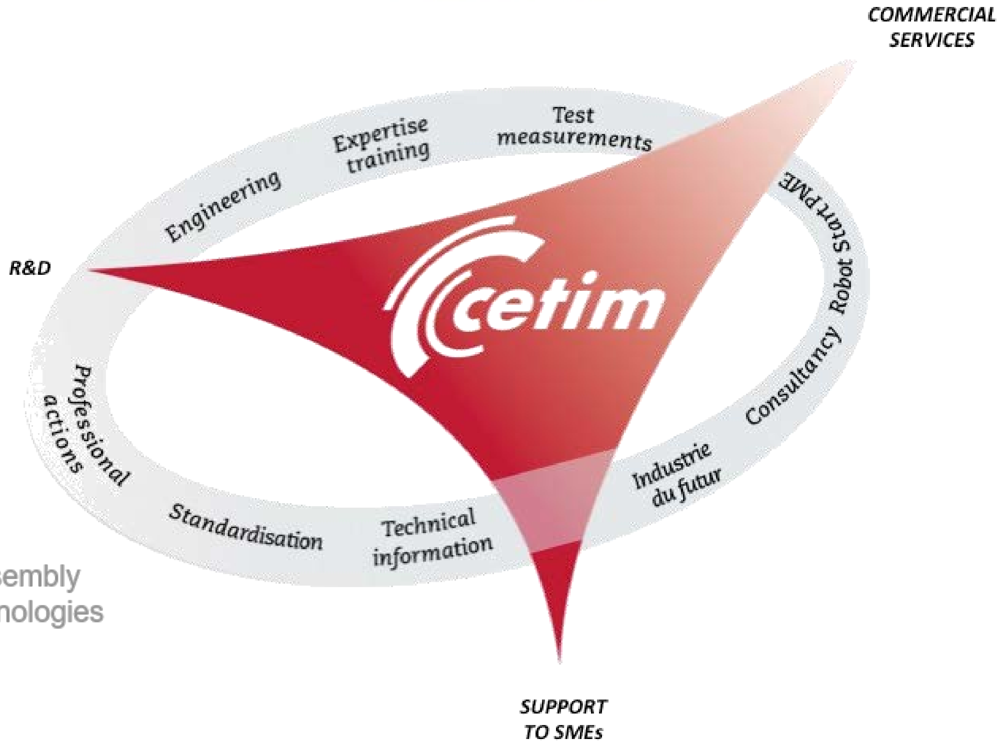
Electromagnetic NDT



Fatigue Optimisation Durability	Monitoring non-destructive testing & connected objects	Power transmission	Simulation	Sustainable Industrial performance	Assembly Technologies
Metallic materials and surfaces	Polymers and composite engineering	Fluid and sealing technologies	Metrology and calibration expertise	Integrated production systems	Advanced Additive Manufacturing

Strategic and technological intelligence	Failure analysis and expertise	Training and skills management	Software

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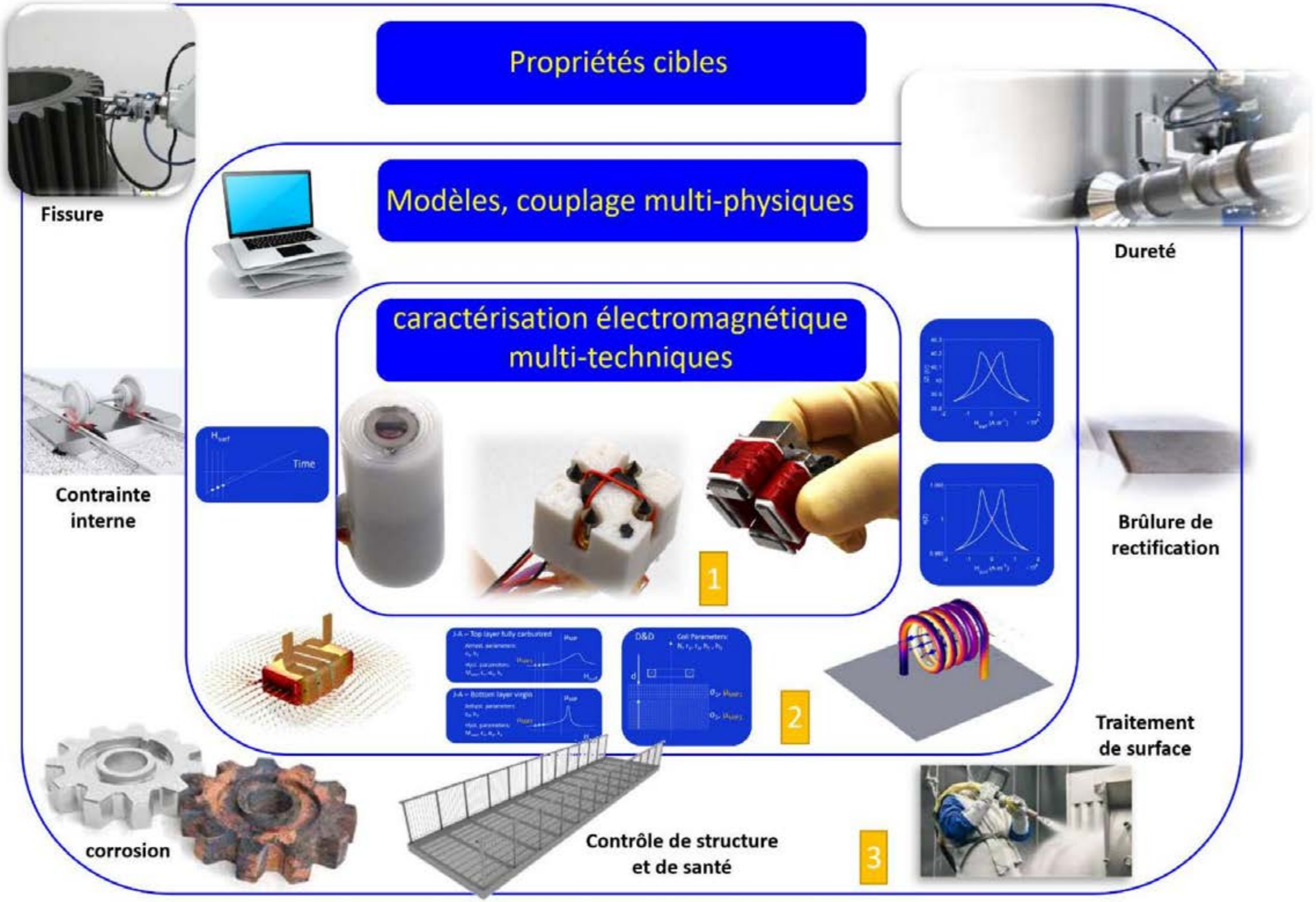
OCEA

SERPROTRONICS
services et solutions électroniques

CMPhy
MESURES PHYSIQUES

ElyTMaX



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OCEA

SERPRO TRONICS
services et solutions électroniques

CMPhy
MESURES PHYSIQUES

ELyTMaX

Key numbers:

_ **2.2** M€

_ **5** people (hired, 1 Ph.D + Post-doc for ELyTMaX)

_ **5** years

_ **1** commercialized equipment

Magnetic Non-destructive testing, based on the magnetization mechanisms

B. Ducharne