Measurement of dynamic effects in normal-conducting magnets

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- Measurement systems
- Measurement analysis
- Ongoing research on dynamics characterization

Introduction

Dynamics of normal-conductive magnets

Introduction

Normal-conducting magnets are widely adopted in CERN accelerator complex.

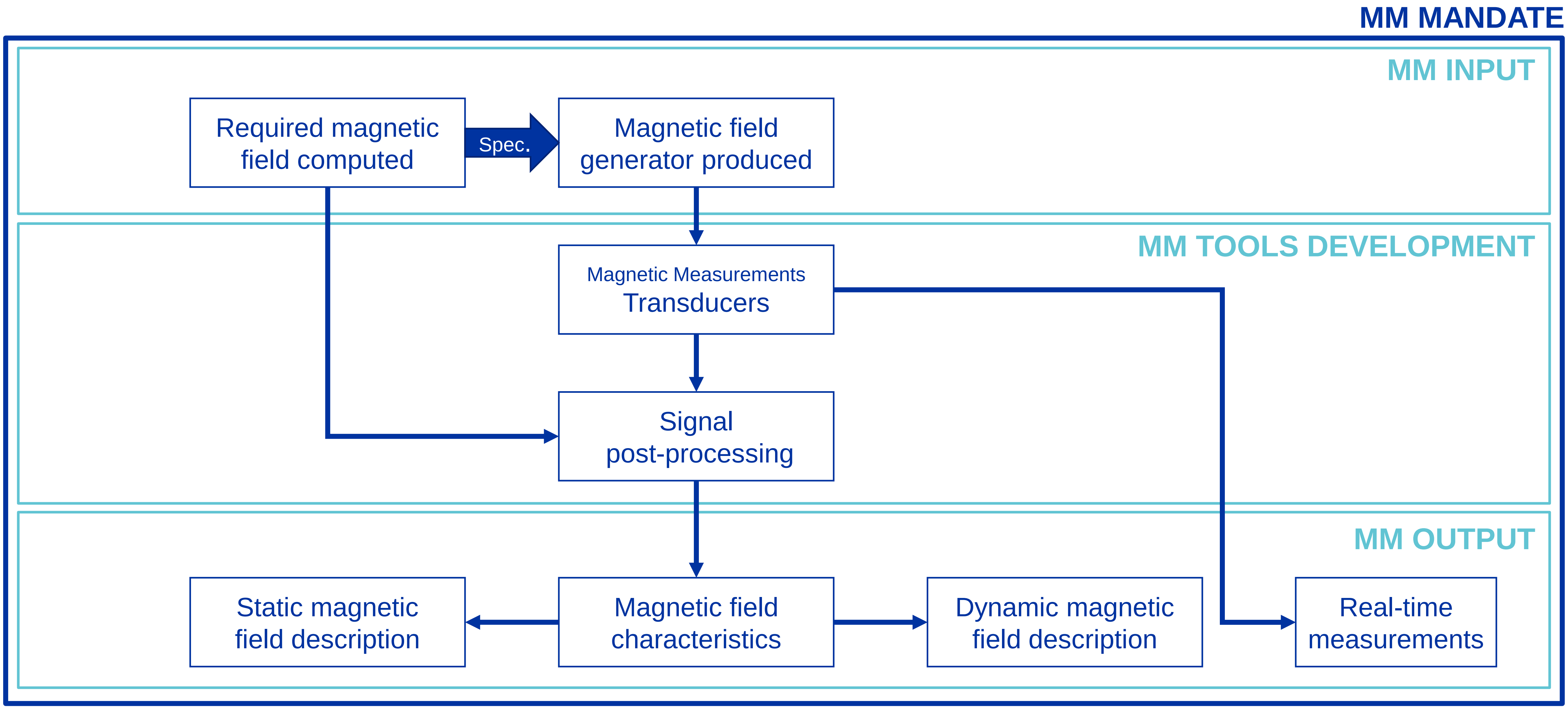
- More than 4800 normal-conducting magnets are installed in the CERN machines [1].
- Injection, extraction, beam dump and switch magnets operated in *pulsed mode*.
- Nowadays, pulsed magnets are introduced also for energy saving, following CERN strategy [2].
- Pulsed magnets are being implemented also in existing infrastructures (i.e. East Area, 81% energy saving [3])
- This often requires an assessment of the electromagnetic dynamics of the magnet.
- Strongly nonlinear phenomenon, hardly predictable with 10^{-4} accuracy.

[1] T.Zickler, Normal-conducting & Permanent Magnets, CERN Accelerator School, ESI Archamps, France, 25 June 2018

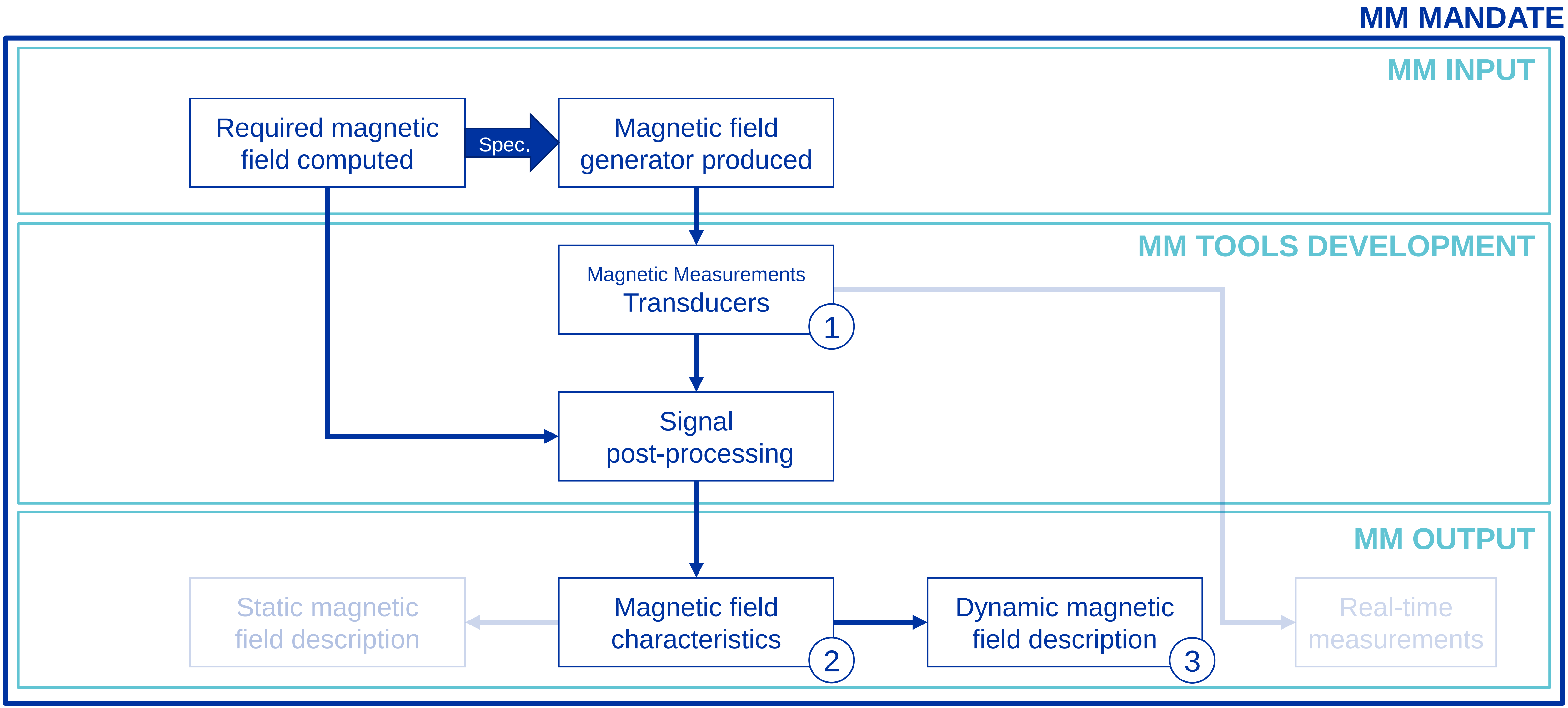
[2] E. Jensen, Energy Efficiency of HEP Infrastructures, CERN Open Symposium on the Update of European Strategy for Particle Physics, Granada, Spain, 13-16 May 2019

[3] B. LM. Lamaille et al, Study of the energy savings resulting from the east area renovation, IPAC2019, Melbourne, Australia, 19–24 May 2019

Introduction



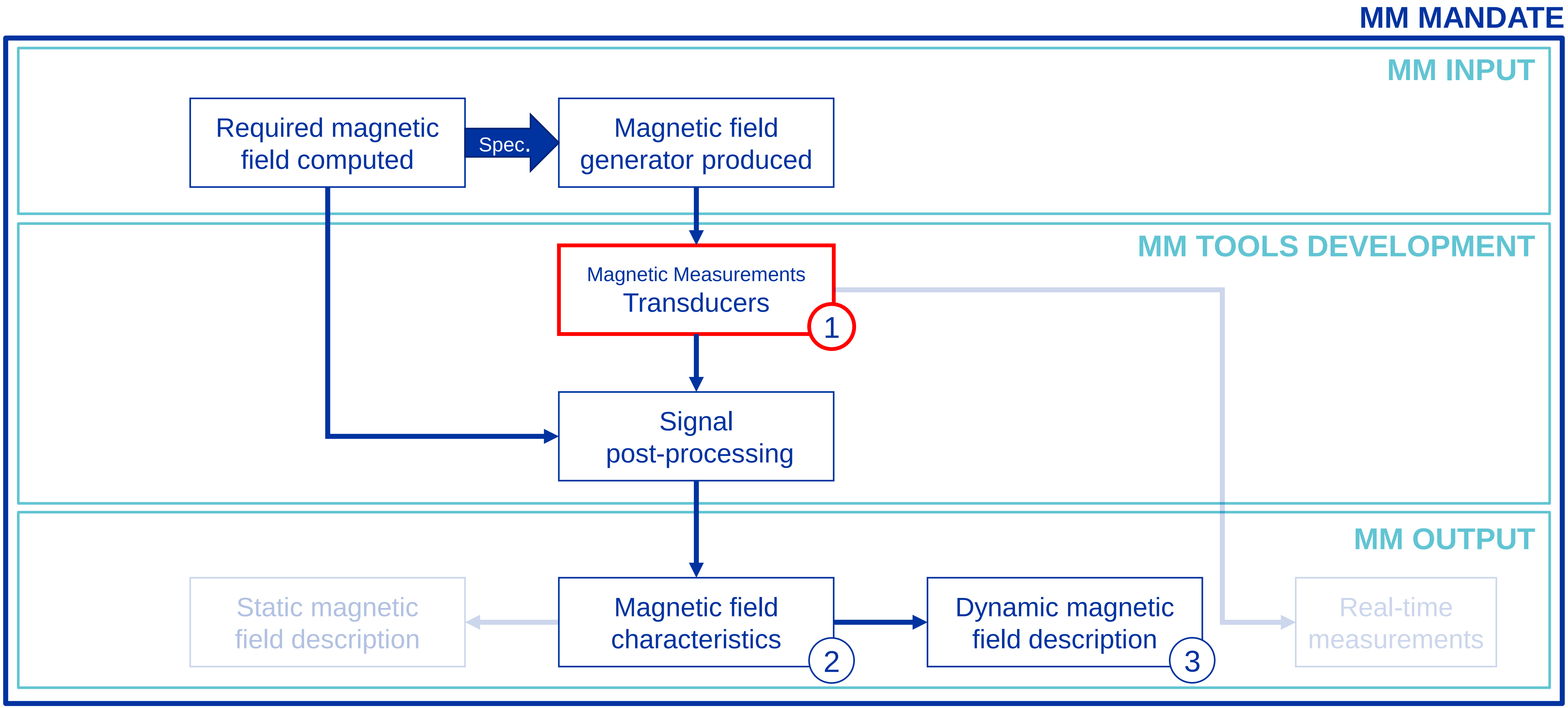
Introduction



Measurements systems

Development of magnetic measurement devices and tool

Measurements systems



Measurements systems

Different techniques available to characterize magnet dynamics:

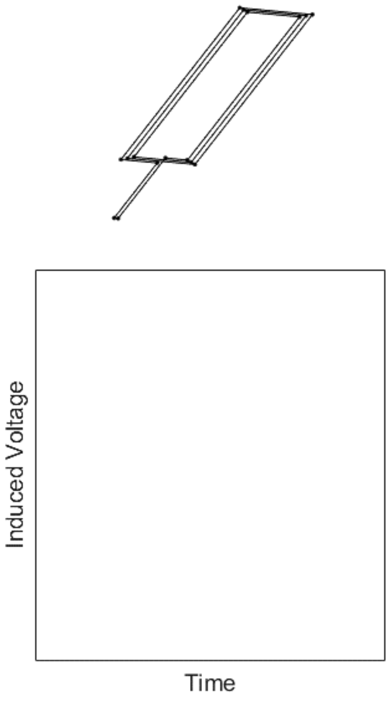
(1) Field components
(2) uncertainty
(3) Bandwidth
(4) Transversal sensor size
(5) Sensor size along the beam direction

Technique	Dim[1]	Range [T]	σ [-] [2]	BW [Hz] [3]	Size [mm][5]	Length [6]	Notes
Local							
NMR	|B|	10^{-2}~10	10^{-6}	DC~10^{0}	10	10 mm	Reference for local field
Hall effect sensors	1/3D	10^{-5}~10^{2}	10^{-3}	DC~10^{4}	<1	<1 mm	Accuracy requires calibration
Local and integral (induction coils based)							
Fixed coil(s)	1D-2D	>10^{-5}	10^{-4}	10^{-2}~10^{6}	5~500	1 mm ~ 10 m	Sensitivity increases with BW - fast cycles
Rotating coil(s)	2D	>10^{-5}	10^{-5}	DC~10^{1}	∅ 8-400	1 mm ~ 2 m	2D information (multipoles)
Translating coil(s)	1D-3D	>10^{-5}	10^{-5}	DC~10^{1}	5~500	1 mm ~ 5 m	Positioning important for accuracy
Integral (stretched wires based)							
Translating wire	2D	>10^{-3}	10^{-4}	DC	∅ 0.1	~< 25 m	Reference for integral field
Vibrating wire	2D	>10^{-5}	10^{-4}	DC	∅ 0.1	~< 25 m	Particularly sensitive
Oscillating wire	2D	>10^{-5}	10^{-4}	DC	∅ 0.1	~< 25 m	Particularly flexible

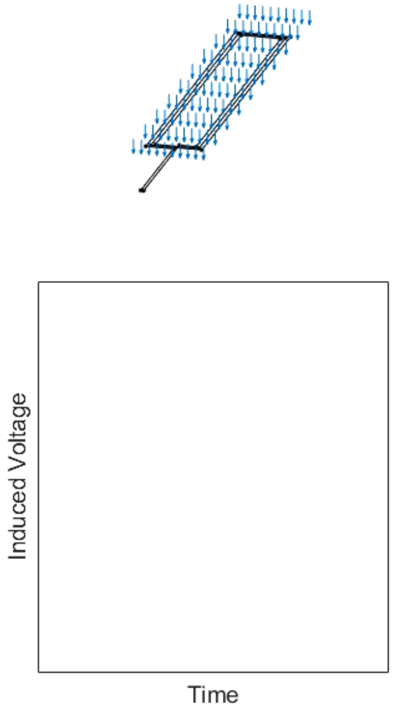
Measurements systems

Induction Coils

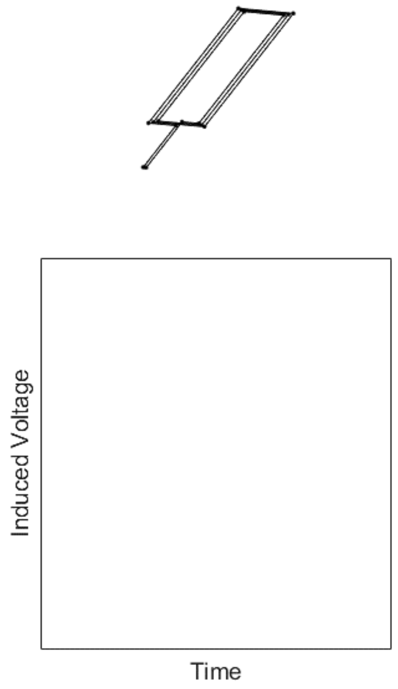
FIXED COIL



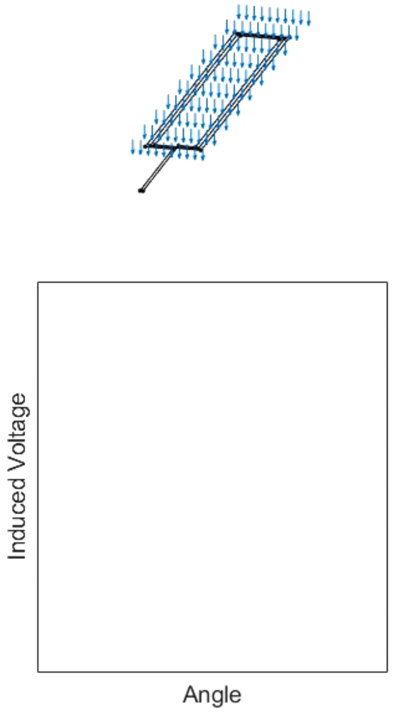
FLIP COIL



AC MOLE



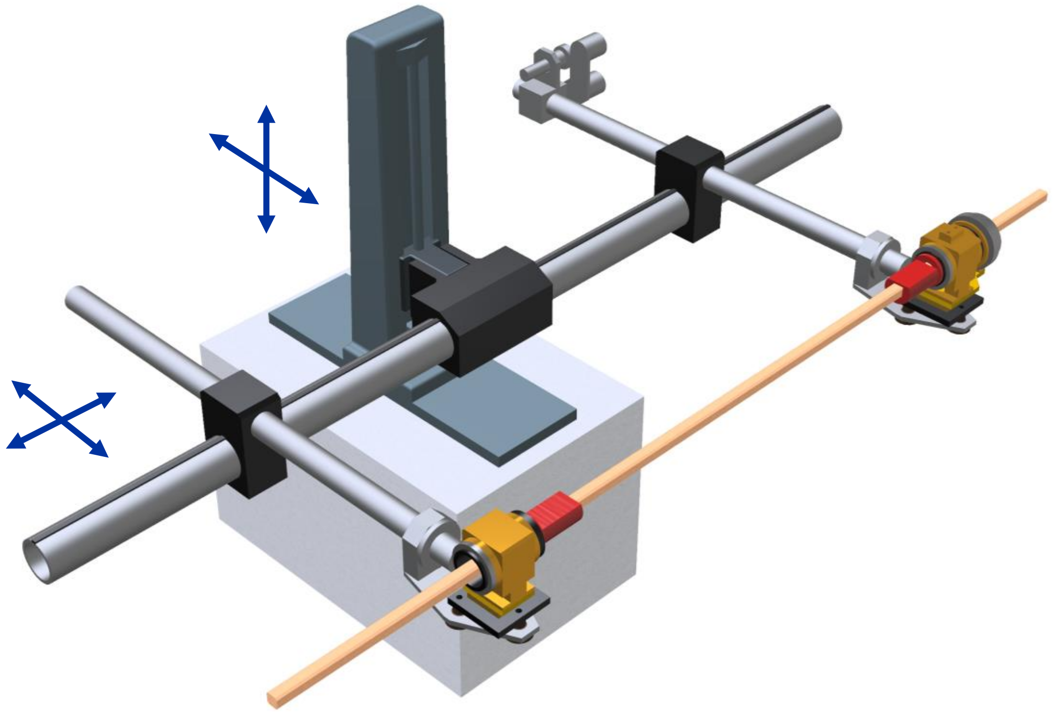
ROTATING COIL



Measurements systems

The historical instrument: PS Huron

- Flip coil for pulsed magnets, located in 867 – MM laboratory.
- Travel range : 300 mm × 400 mm.
- Arms extension: 1200 mm × 2400 mm.
- +30 years of service (with 4 main updates), measuring for Linac4 [4], PSB [5], PS [6], SPS [7].

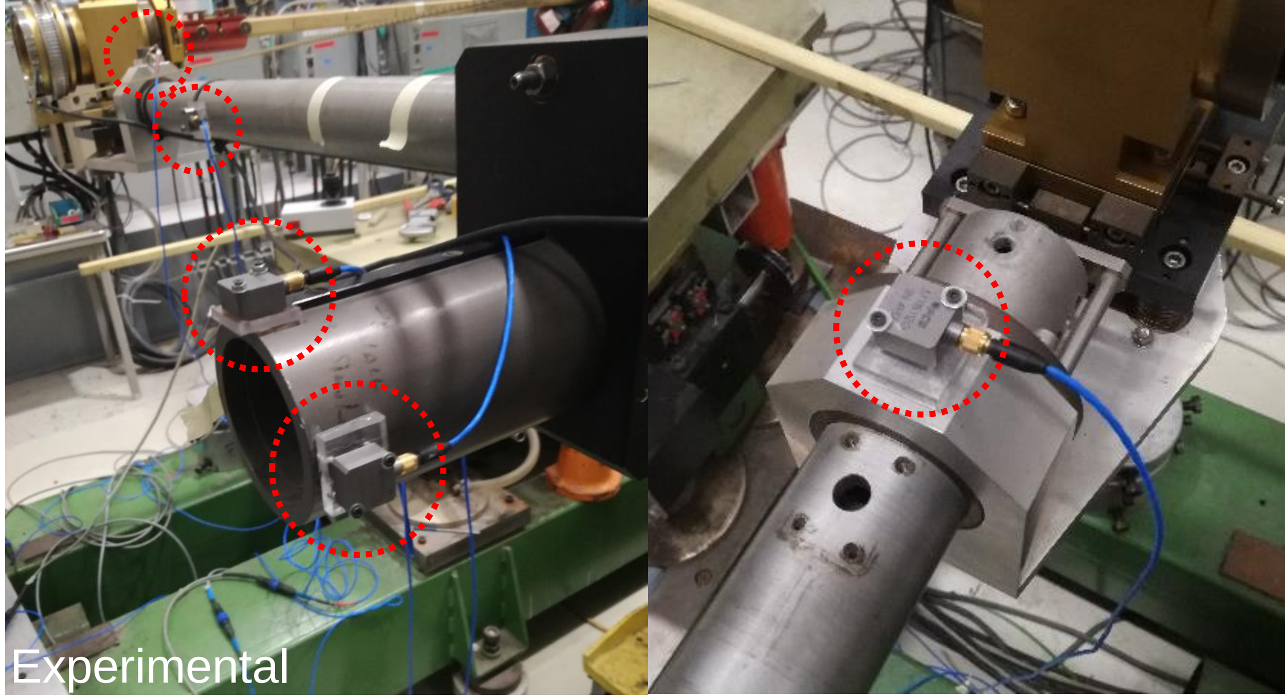


[4] M. Buzio, R. Chritin, Mesures magnétiques de dipôles pour ligne de transfert LINAC 4, 2015
[5] M. Buzio, R. Chritin, Mesures magnétiques sur un quadrupôle du Booster de type QFO, 2016
[6] R. Chritin, Mesure magnétique d'un dipôle bumper horizontal, 2007
[7] R. Chritin, Mesures magnétiques d'un dipôle vertical, 2016

Measurements systems

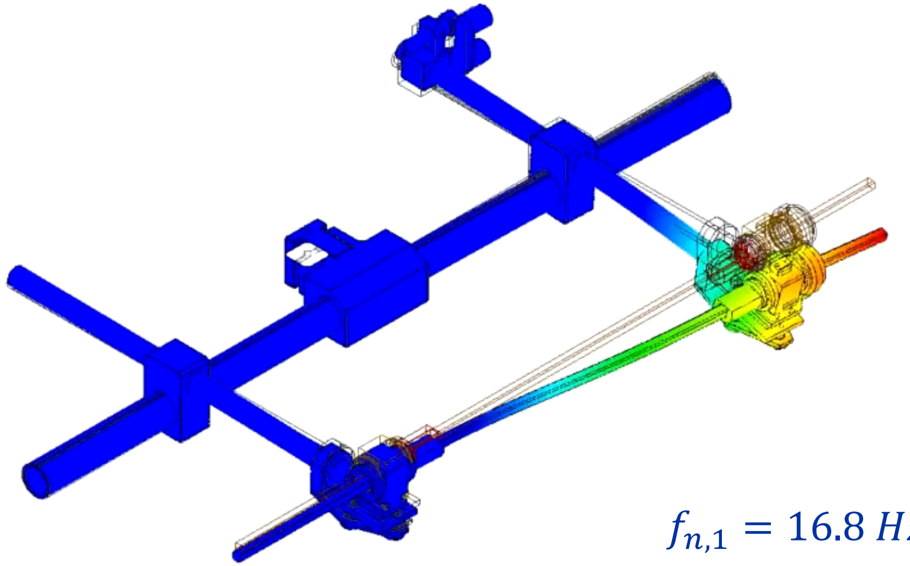
Analysis of PS Huron

- Great Flexibility for flip-coil measurements, but can we achieve more?
- Numerical and experimental analysis was performed to assess it.
- Results: inconvenient to upgrade it
  - Arm adjustment system is unpractical;
  - Too low natural frequency of the structure.
- It motivates the need for a new bench.



Experimental

Numeric

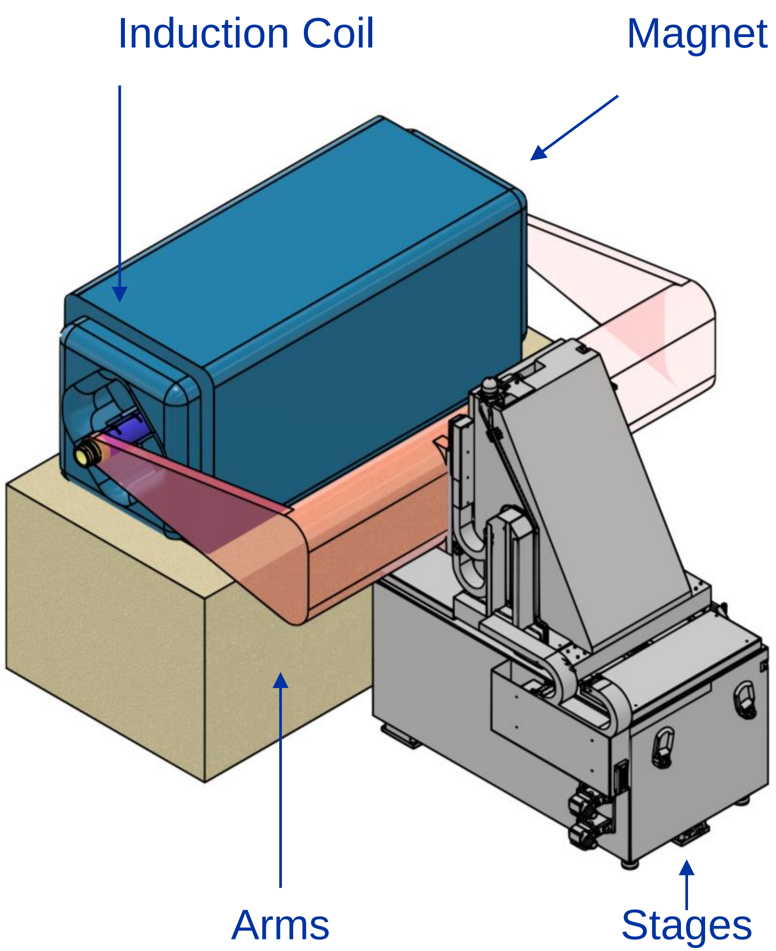


$f_{n,1} = 16.8\ Hz$

Measurements systems

A new PS Huron bench, the Rotating Coil Mapper

- Preserve Huron capabilities.
- Cover all the induction-coil techniques.
- Possibility to mount different structures.
- Possibility to perform virtually any measurement:
  a “mother of all benches”.



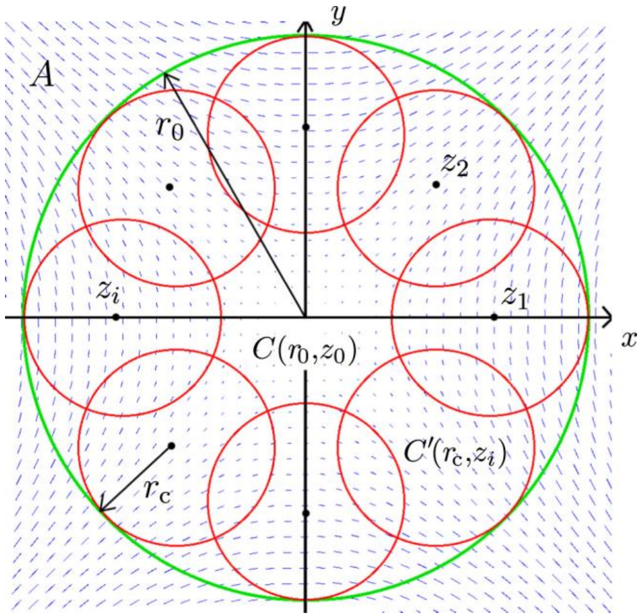
Measurements systems

Rotating Coil Mapper as a multi-purpose bench

Among all the possible measurement techniques available on the system, some of them are of relevant interest also for DC measurements. In particular:

- Calibration of quadrupole coils
  Given the high accuracy in the measurement of the displacement, the system is a possible tool for calibrating coils for quadrupole field.

- Oversampling of large apertures [8]
  Integrated magnetic field is measured in different positions inside the aperture. Combining the measurements, it is possible to reduce the uncertainty on the field harmonics, but it relies on very precise displacements.



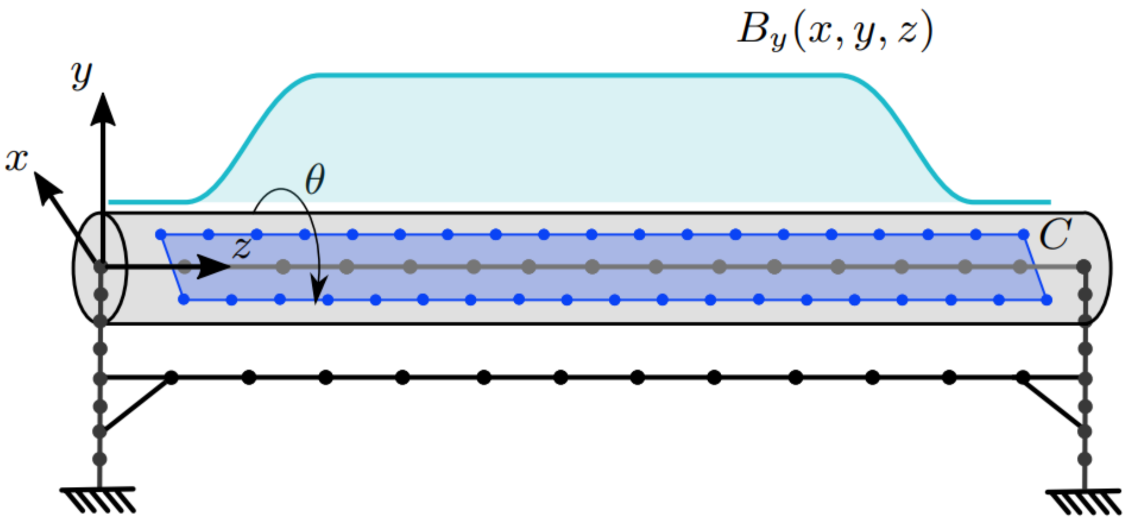
Oversampling, reprinted from [5]

[8] Oliver Köster, Lucio Fiscarelli, Stephan Russenschuck, A procedure for combining rotating-coil measurements of large-aperture accelerator magnets, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 2016

Measurements systems

Rotating Coil Mapper, induction coils and supports

- Having cantilever supports on moving stages is a critical condition for mechanics.
- It motivates a deeper analysis, extended to the more general problem of a coil and its supports.
- Goal: assess sensitivity of measurement result to the mechanics of the instrument.
- Outcome: a magneto-mechanical model for induction coils.



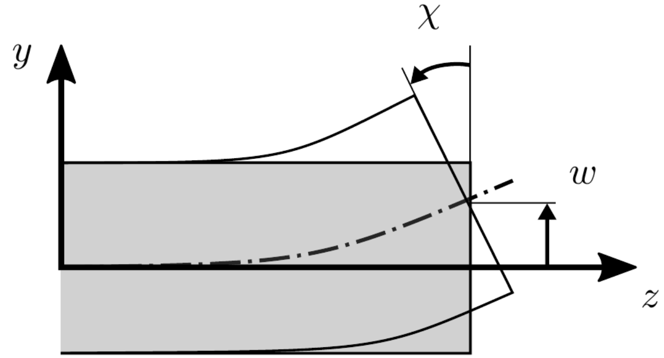
Measurements systems

Induction coils and supports, mechanical model

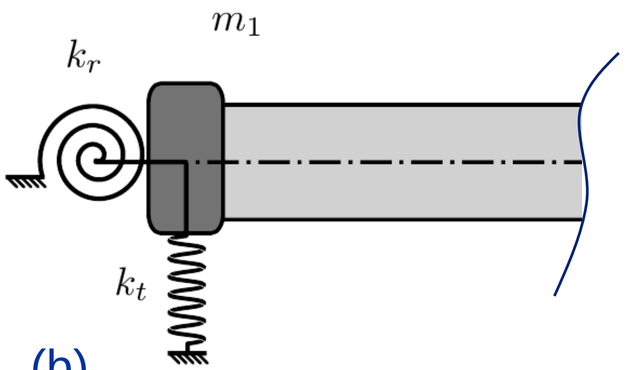
- Timoshenko theory is firstly adopted for both shafts and supporting frame.
- Degrees of freedoms are cross-sections linear and angular displacements (a).
- Possibility to include lumped masses, springs and dampers (b).
- Both analytical and numerical methods have been developed, resulting in a system of equations as:

$$M\frac{\partial^2 \boldsymbol{v}}{\partial t^2}(z,t) + R\frac{\partial \boldsymbol{v}}{\partial t}(z,t) + K\boldsymbol{v}(z,t) = \boldsymbol{f}(z,t)$$

Mass matrix — Damping matrix — Stiffness matrix — Cross-sections displacements — External forces



(a)

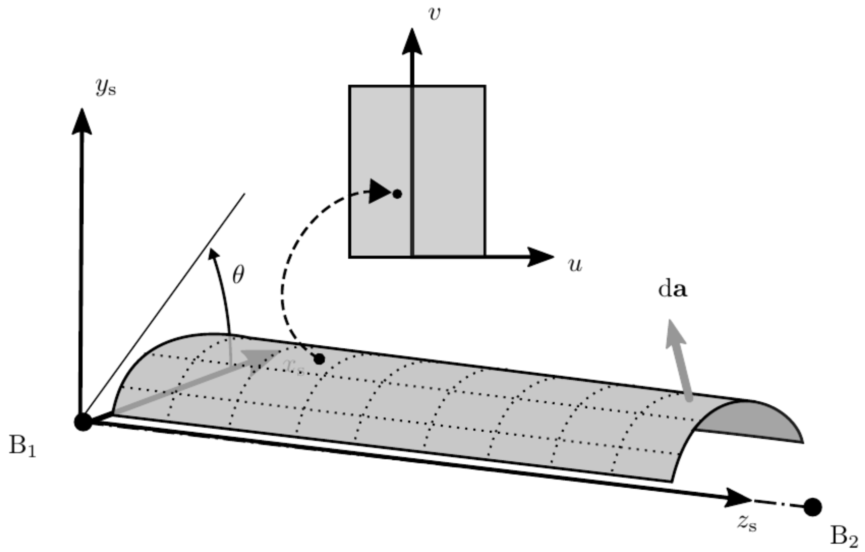


(b)

Measurements systems

Induction coils and supports, coupled model

- The deformation field resulting from mechanics is applied to a simulated coil inside a prescribed magnetic field.
- Any field distribution can be included, as 3D series or maps
- A simulated measurement process is performed:



$$\Phi = \int_A \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{a} \quad \rightarrow \quad \Psi_n = \sum_{m=0}^{M-1} \Phi_m \cdot e^{\frac{-i2\pi mn}{M}} \quad \rightarrow \quad C_n^{\mathrm{a}}(r_0) = {r_0}^{n-1} \frac{\Psi_n}{k_n}$$

Flux

Field Density

Deformed coil

Angular FFT

Multipoles

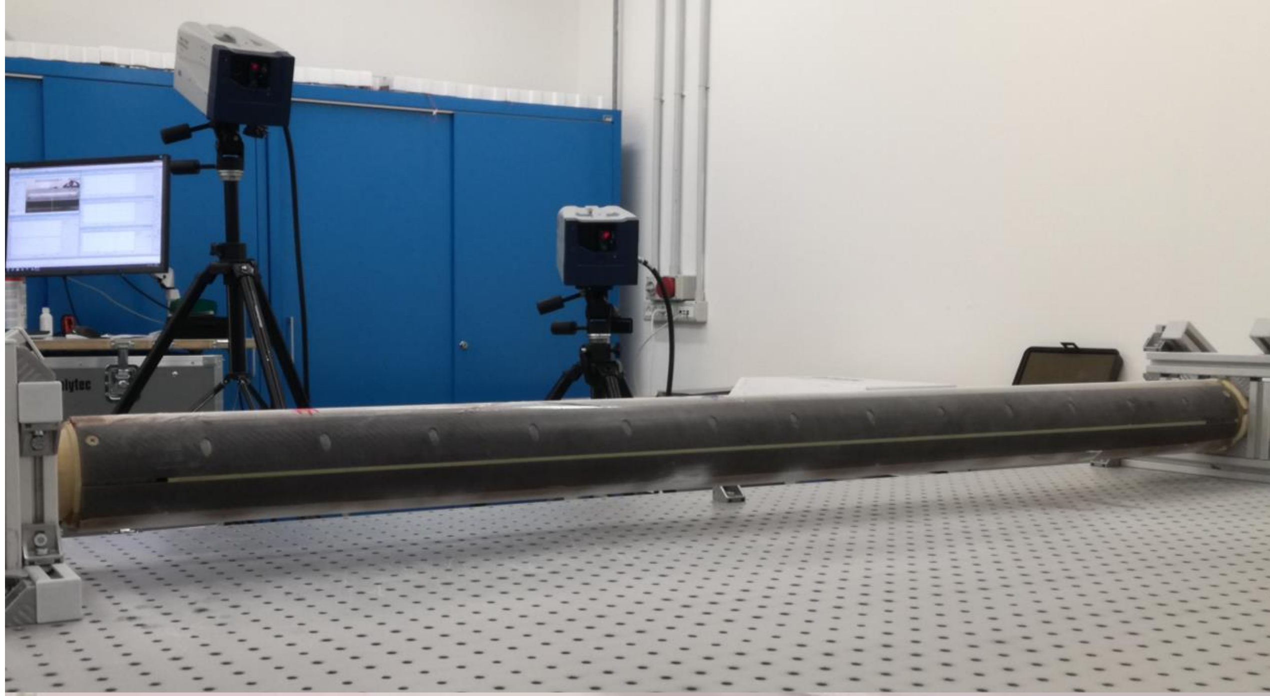
Reference radius

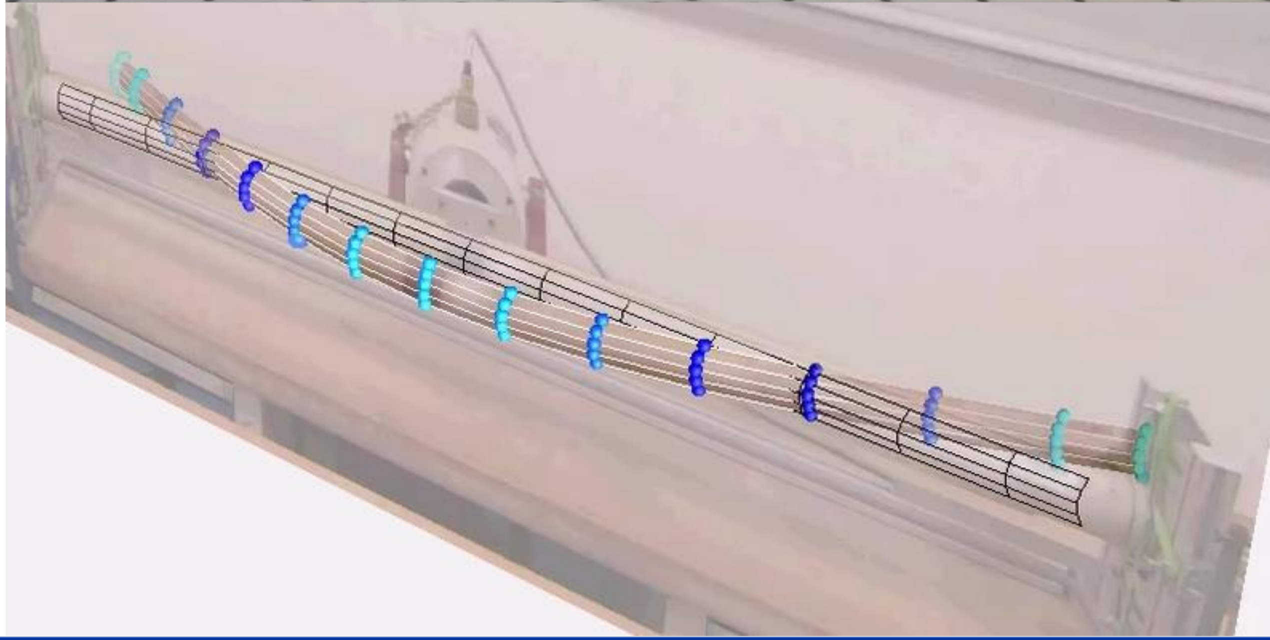
Nominal calibration factors

Measurements systems

Induction coils and supports, validation

- Mechanics was experimentally validated at POLIMI (Milan, Italy), where a 3D laser-scanning vibrometer scanner was available.
- Scan of 3D deformation fields validating mechanical modes.
- Numerical validation by a 3D FEM model (useful also as final design validation).





Measurements systems

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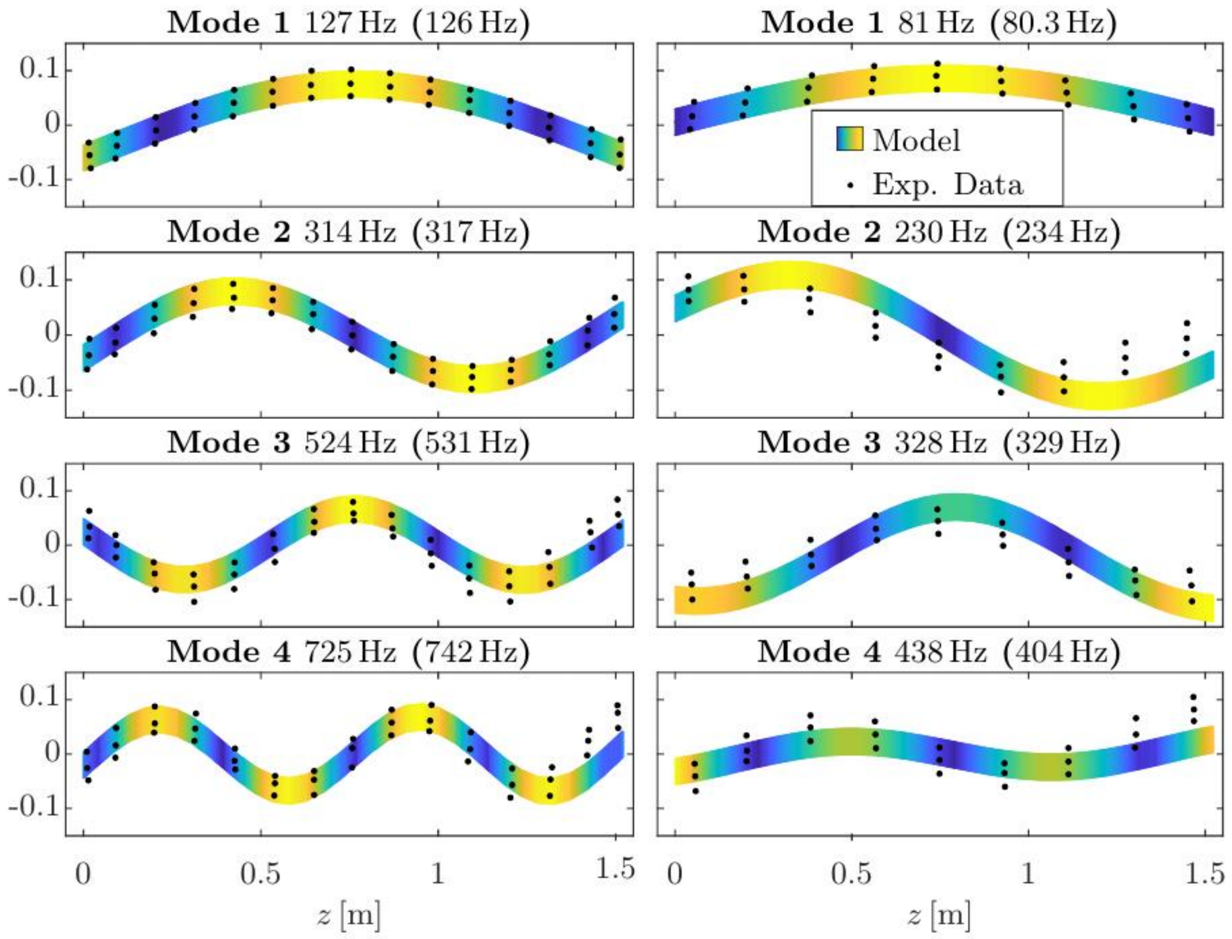
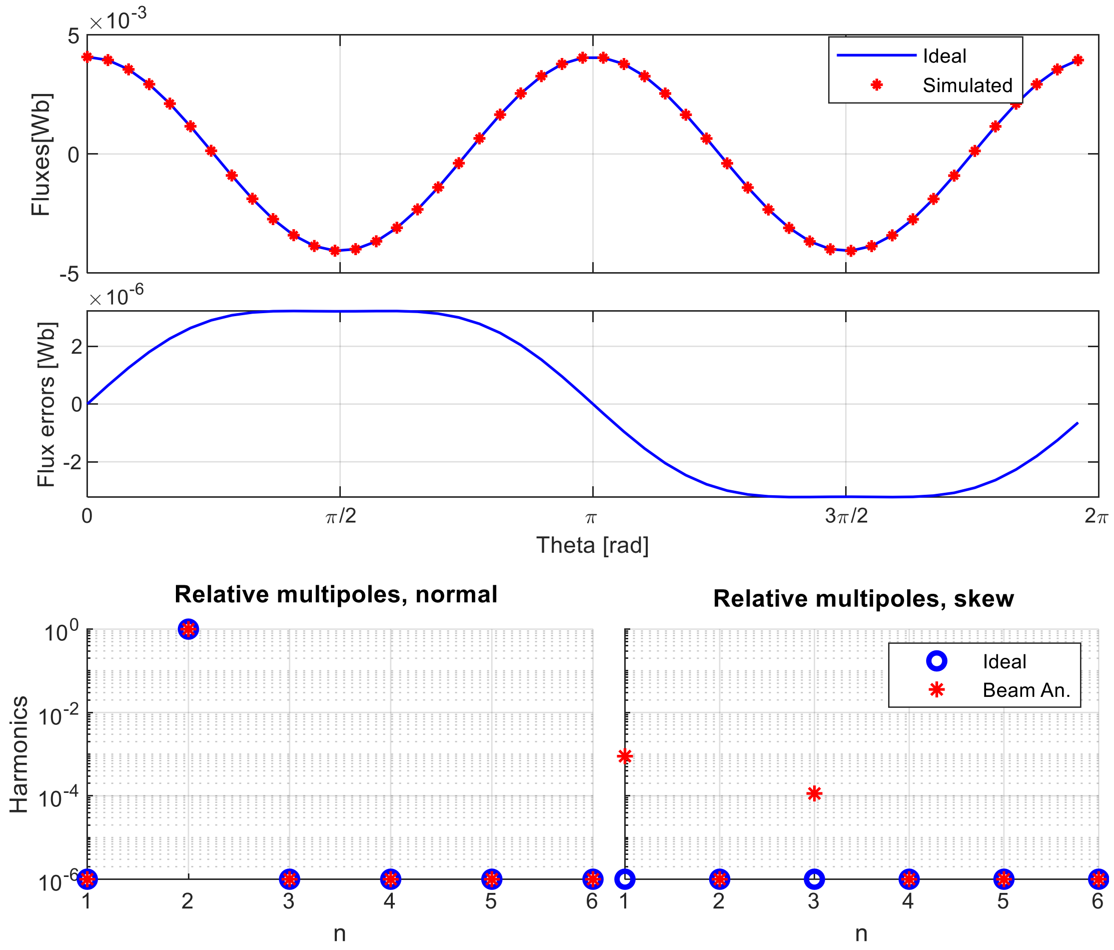


Measurements systems

Induction coils and supports, simulations

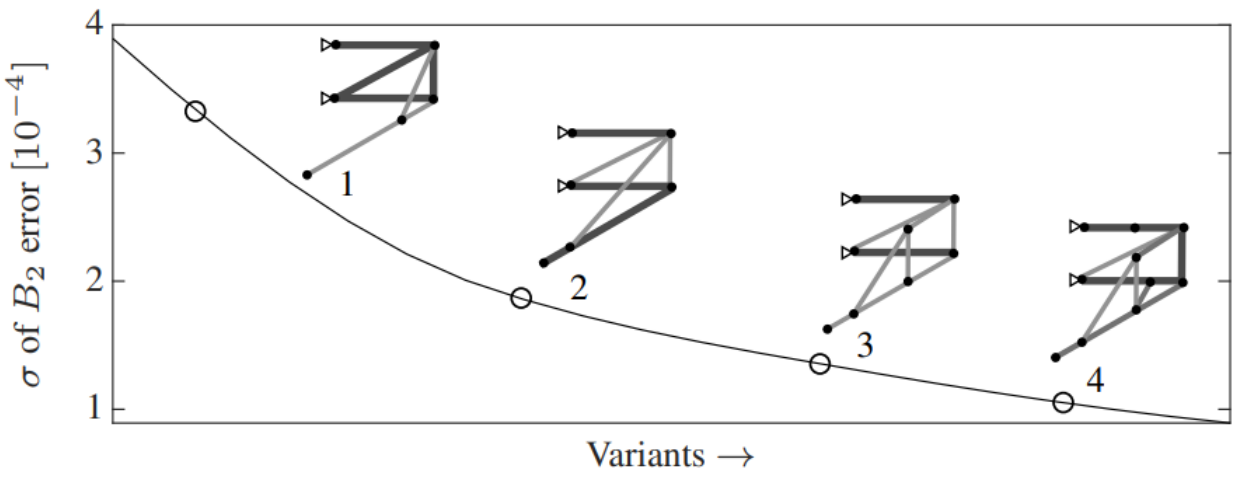
- The model is adopted to design the induction coils for the system.
- Gravity and support vibrations are introduced, testing different load combinations.
- The model confirms the relevance of a good compensation scheme (bucking) and of properly designed supports.

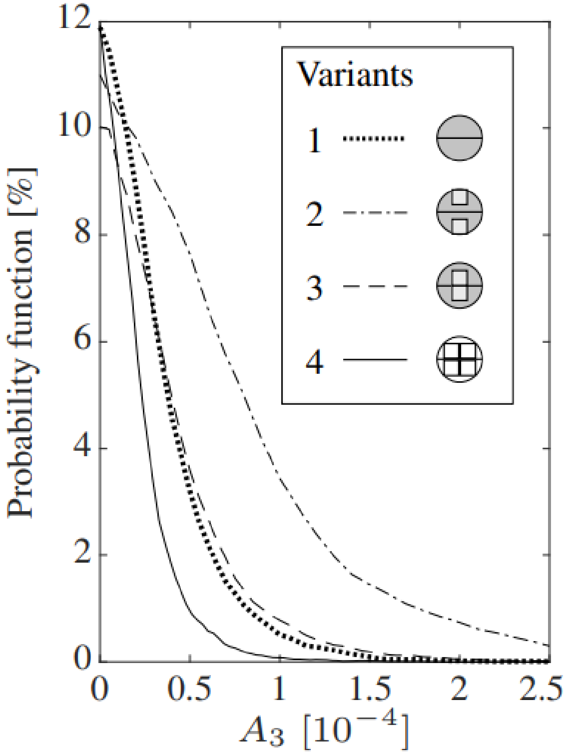


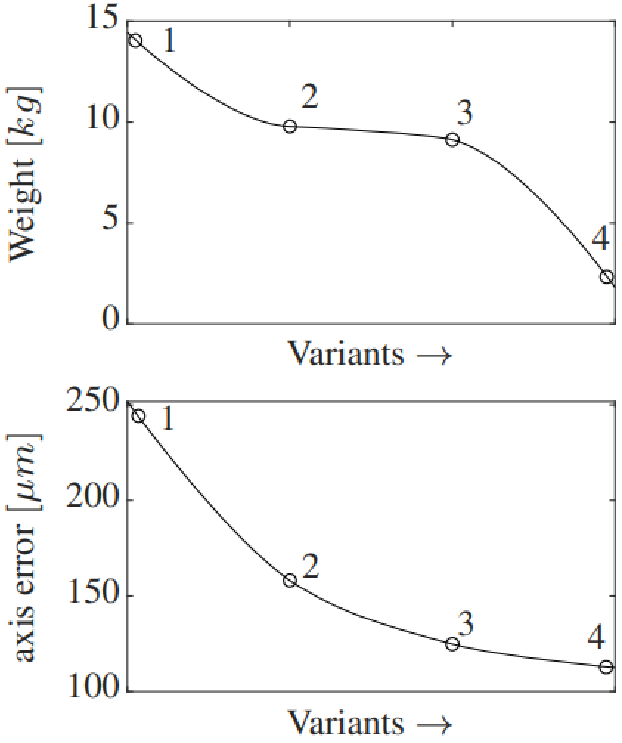
Measurements systems

Induction coils and supports, design

- Aiming at better performances than standard design.
- Saving costs adopting commercial parts.

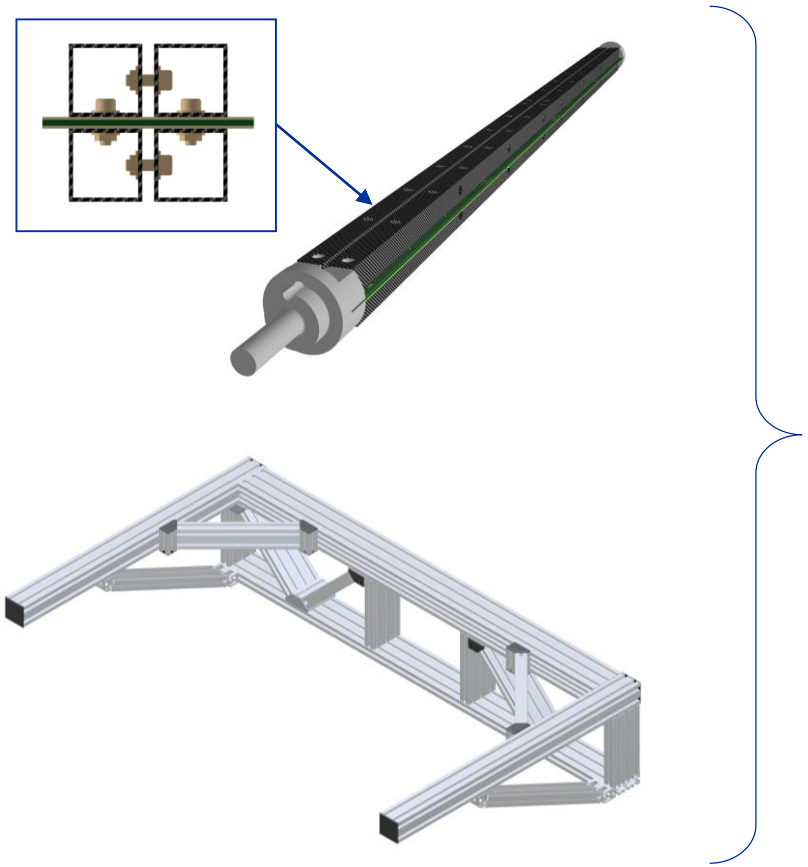






Measurements systems

Induction coils and supports, design



Measurements systems

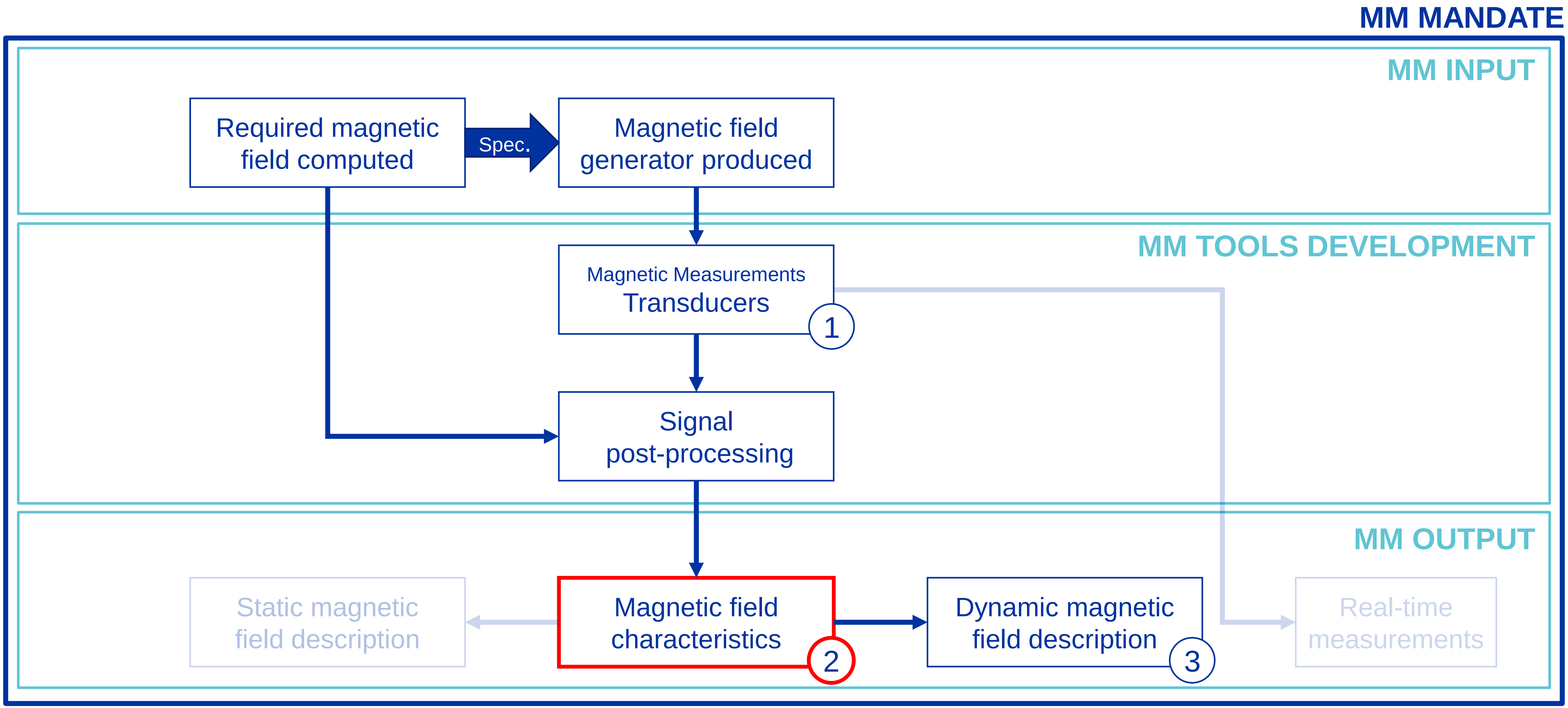
Rotating Coil Mapper, stages

- Displacements measurements accuracy of 1 μm per 1 cm.
- Travel range of 500 mm per 300 mm.
- Maximum load for this accuracy of 100 kg and 400 Nm.
- Fully programmable with standard frameworks (FFMM).
- Already commissioned, manufactured and delivered.

Measurement analysis

Collecting and summarizing measurements

Measurement analysis



Measurement analysis

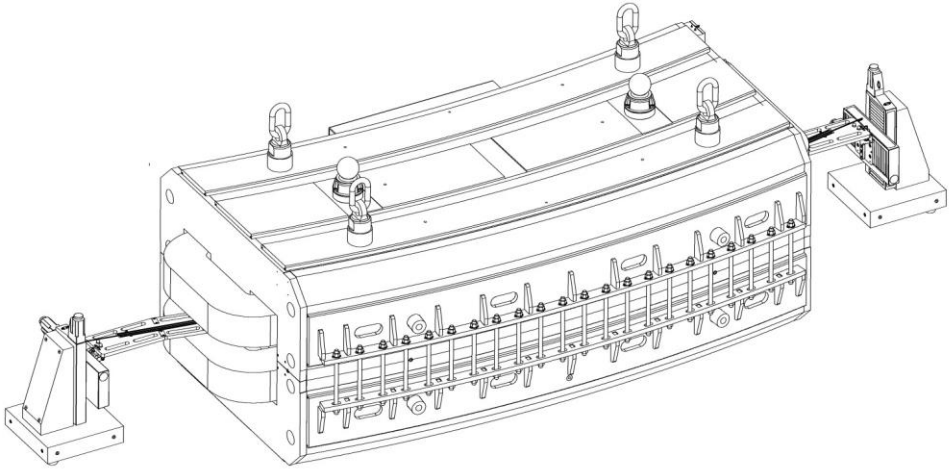
Different tools are available to describe magnet dynamics.

- The following slides present some of them, applied to recent measurements campaigns.
- Most of the concepts are not brand-new and rely on previous measurements experience [5],[6].
- Nevertheless, there is still room for improving the way they are performed and implemented for magnet operation. This motivates the ongoing researches on dynamics characterization.

Measurement analysis

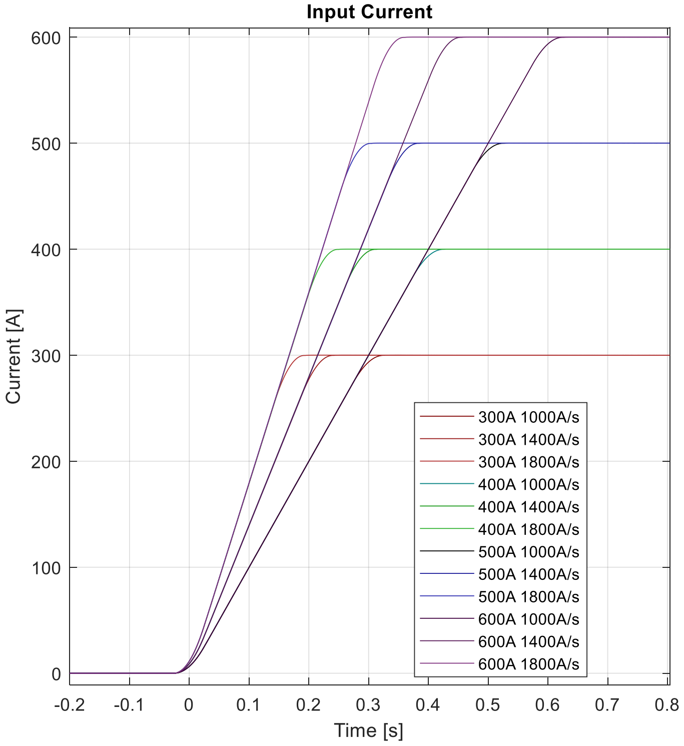
PXMBXGECWP: a first sight to magnet dynamics

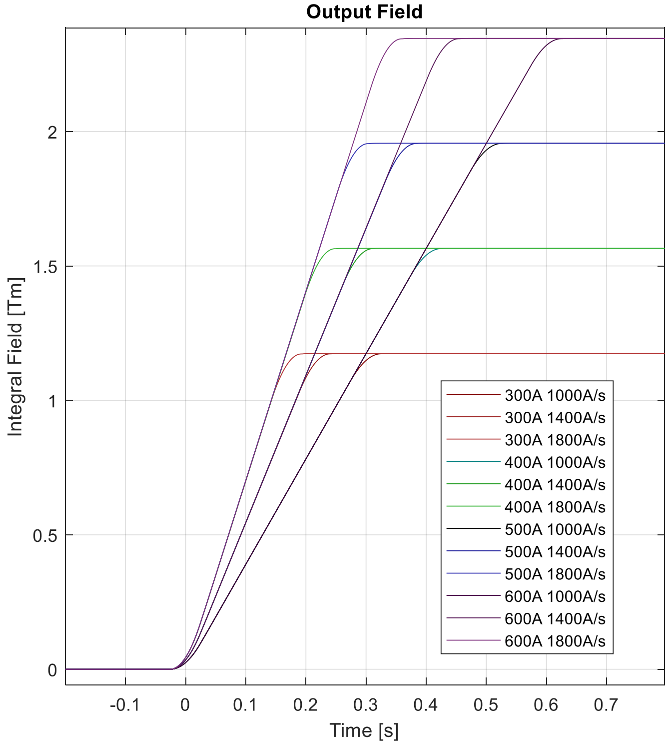
- Measurement campaign to assess a new magnet in BTM.BHZ10 slot.
- It included dynamic characterization.
- Custom multi-instrument system adopted.

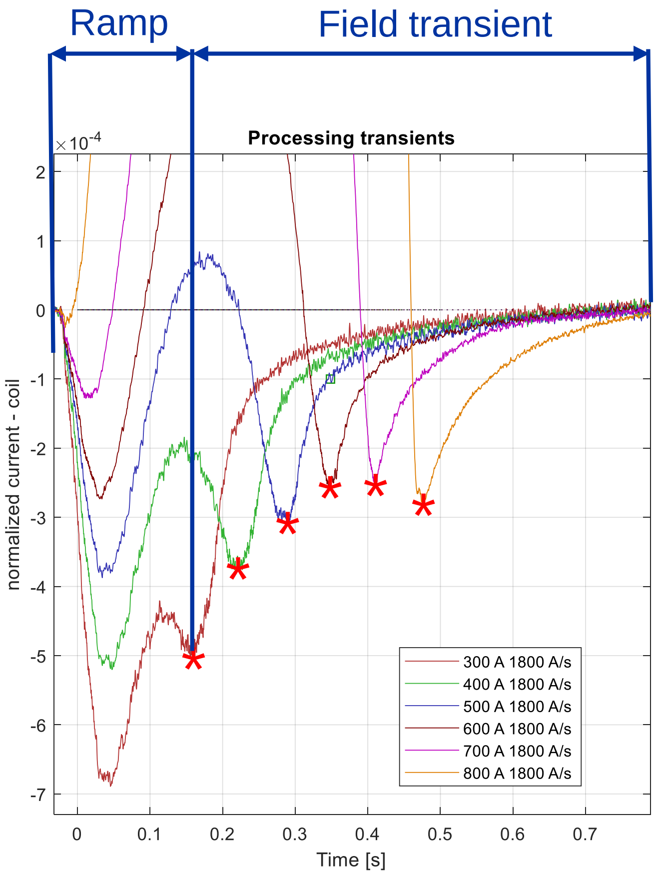


Measurement analysis

PXMBXGECWP: a first sight to magnet dynamics [9],[10]





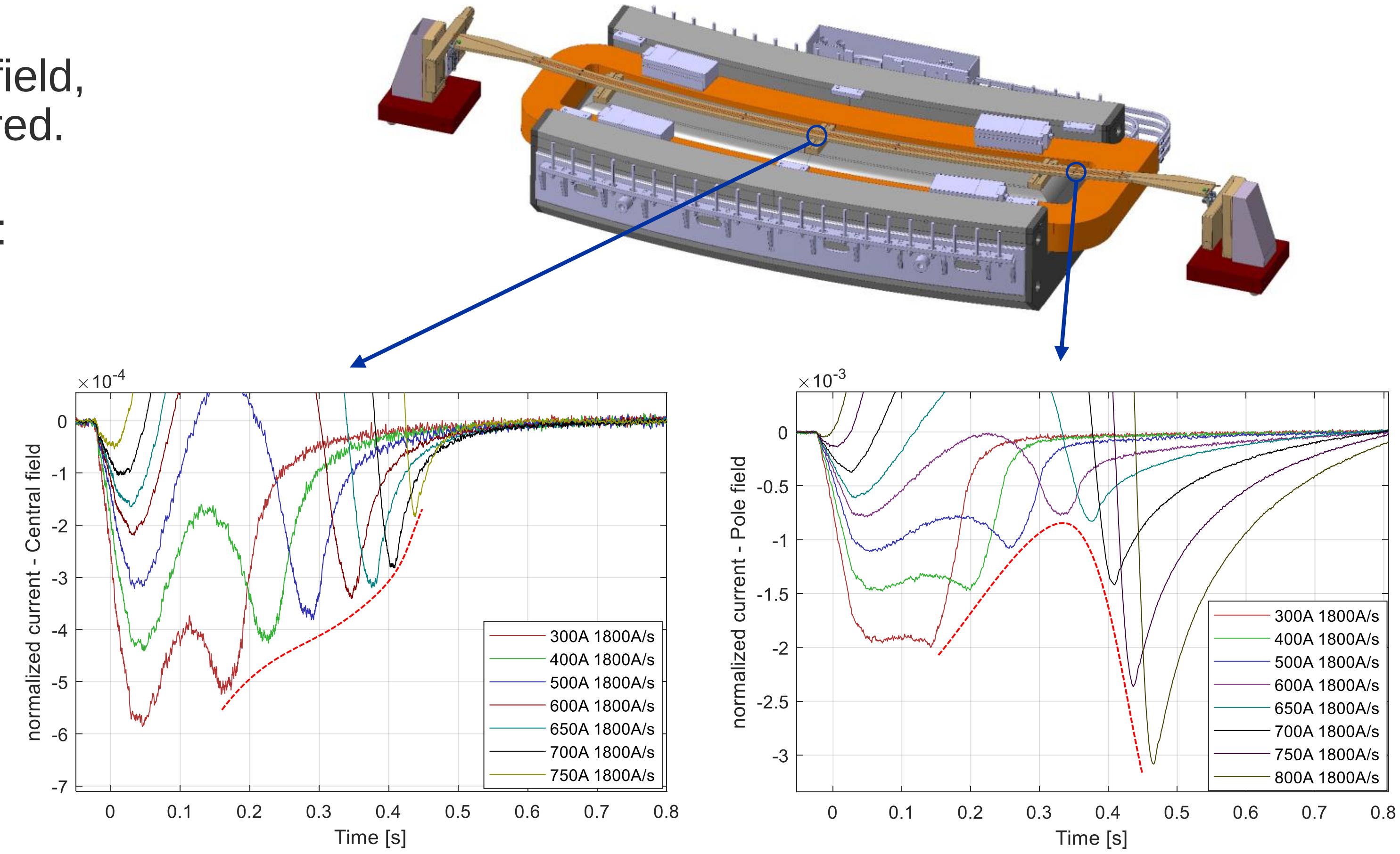


[9] S. Sorti, C, Petrone, Magnetic measurements of the curved dipole BTM.BHZ10 (PXMBXGEHWP-SP000001). EDMS Nr: 2226412
[10] Eddy currents in accelerator magnets, G. Moritz GSI, Darmstadt, Germany

Measurement analysis

PXMBXGECWP: Pole and center

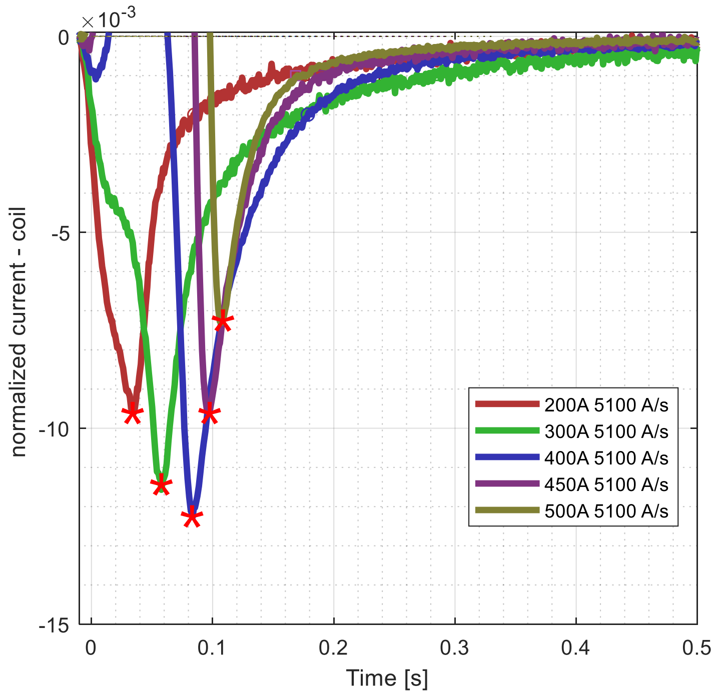
- Given the possibility of measuring local field, transients at center and poles are acquired.
- First comparison regards the magnitude: poles are slower.
- Second comparison regards trend: pole not monotonic.



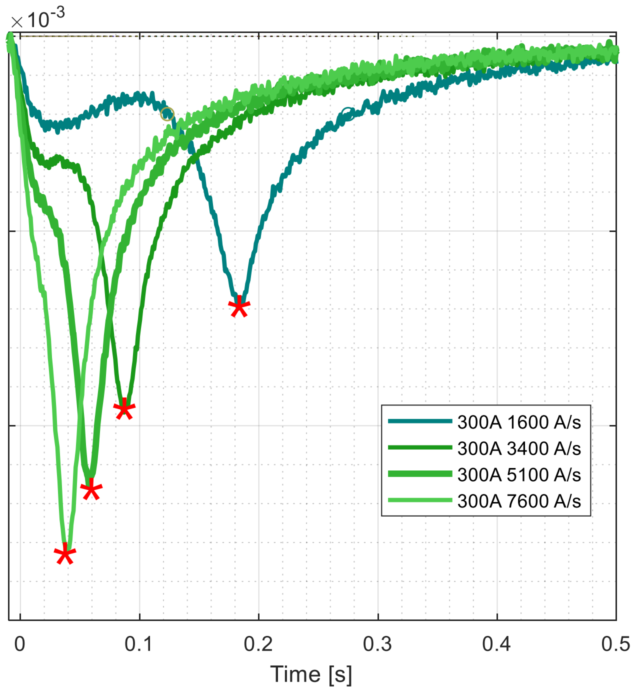
Measurement analysis

PXMQNDCTWP 11: a systematic overview of transients

Non-linear, non-monotonic behavior of the relative difference between integral field and current.



(constant ramp-rate)

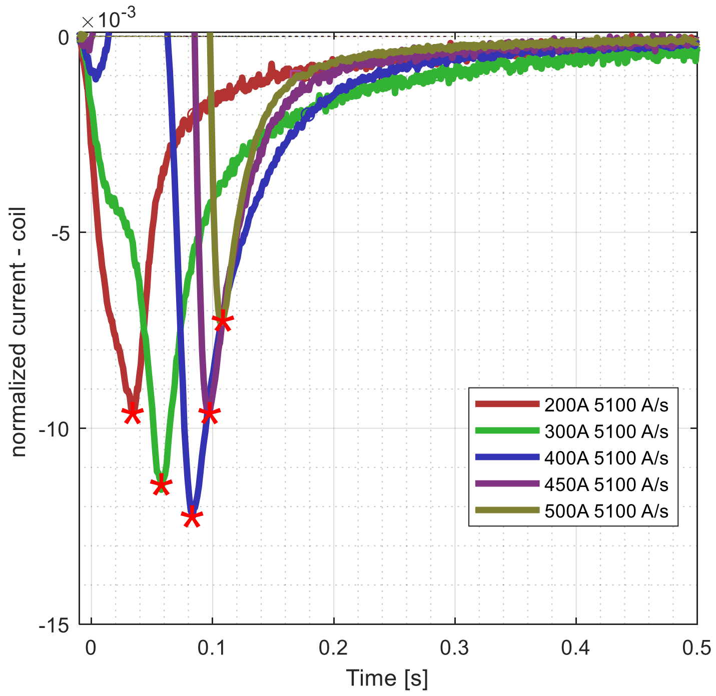


(constant current level)

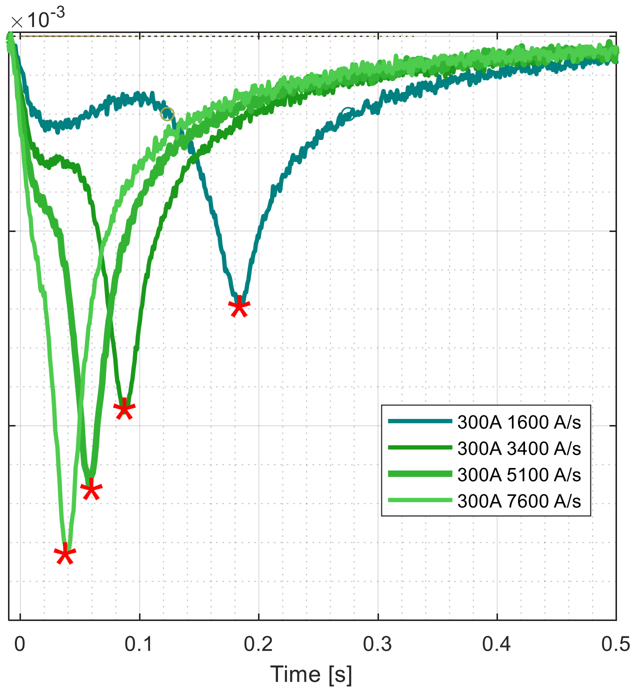
Measurement analysis

PXMQNDCTWP 11: a systematic overview of transients

Non-linear, non-monotonic behavior of the relative difference between integral field and current.

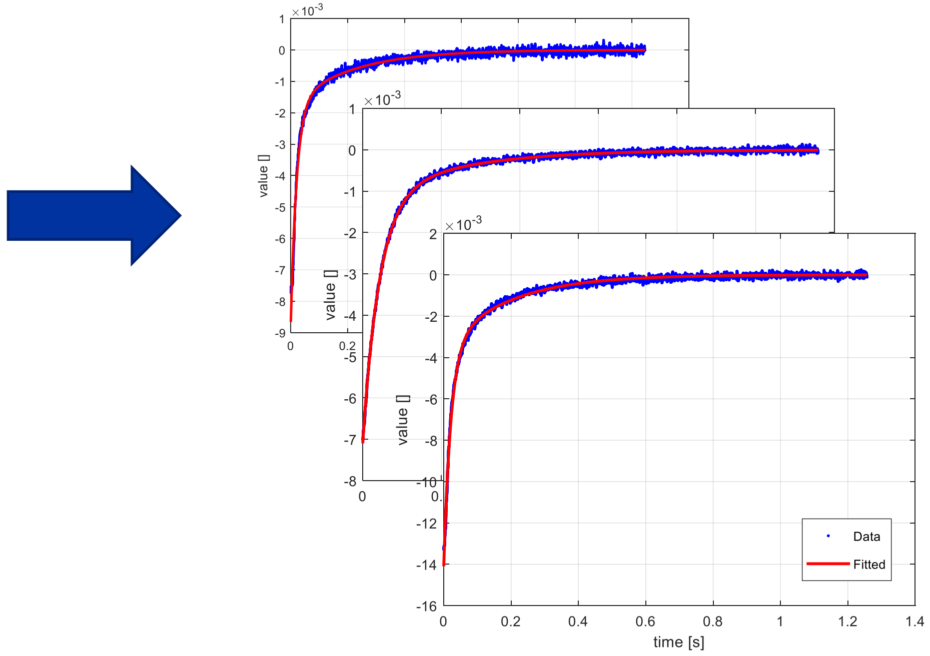


(constant ramp-rate)



(constant current level)

$$I_{\mathrm{rel}}(t) = A_1 e^{\frac{t}{\tau_1}} + A_2 e^{\frac{t}{\tau_2}}$$

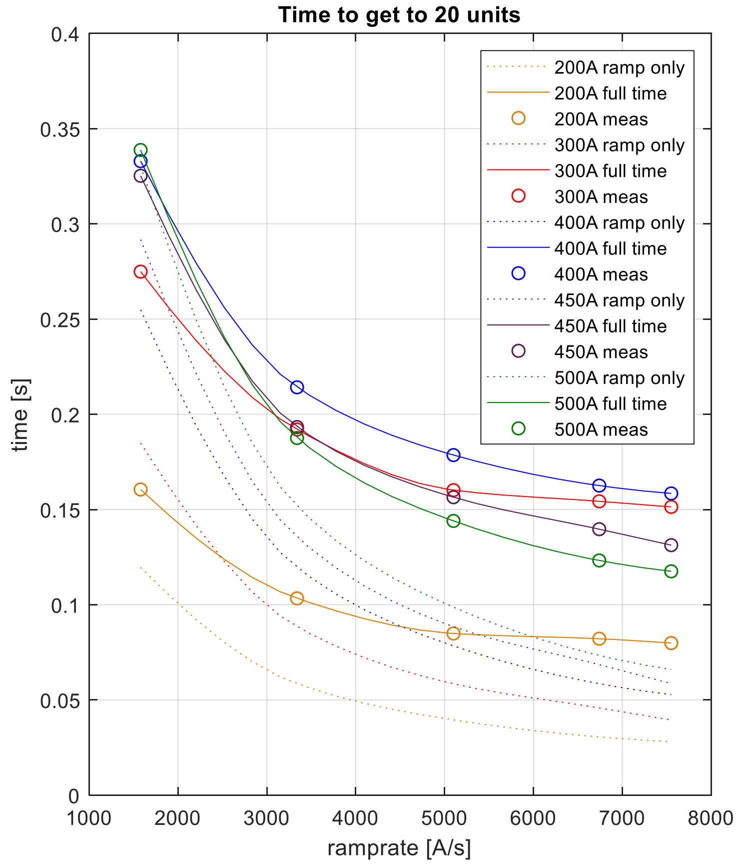


Measurement analysis

PXMQNDCTWP 11: Dynamics summarized in tables and time maps [11]

Time constant of first exponential [ms]					
Ramp-rate [A/s] \ Current [A]	200	300	400	450	500
1600	23.4	32.9	42.4	29.5	30.5
3400	20.9	26.6	41.1	29.9	22.4
5100	16.6	23.8	39.9	29.4	22.8
6800	15.7	22.3	38.1	30.0	22.5
7600	15.4	21.5	37.4	30.3	22.5

Amplitude of first exponential, relative to maximum field []					
Ramp-rate [A/s] \ Current [A]	200	300	400	450	500
1600	-0.00399	-0.00452	-0.00589	-0.00332	-0.00135
3400	-0.00693	-0.00706	-0.00915	-0.00708	-0.00460
5100	-0.00856	-0.00867	-0.01096	-0.00902	-0.00709
6800	-0.00998	-0.00993	-0.01209	-0.01039	-0.00834
7600	-0.01070	-0.01056	-0.01235	-0.01108	-0.00894

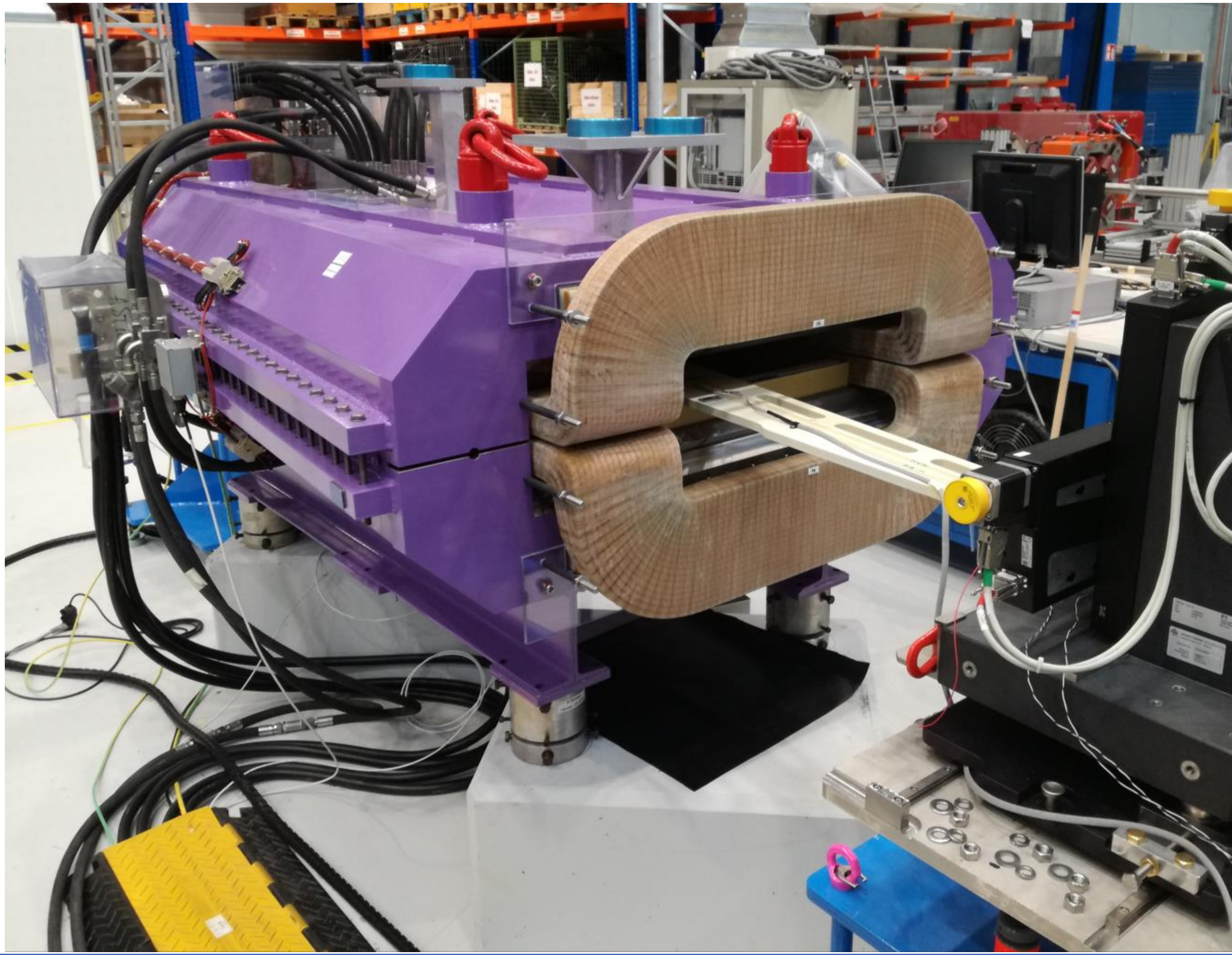


[11] S. Sorti, C, Petrone, J. R. Anglada. Magnetic measurement of quadrupole PXMQNDCTWP-B2000011 (QDS11). EDMS Nr: 2226385

Measurement analysis

PXMBHGAWWP: testing the pre-emphasis correction

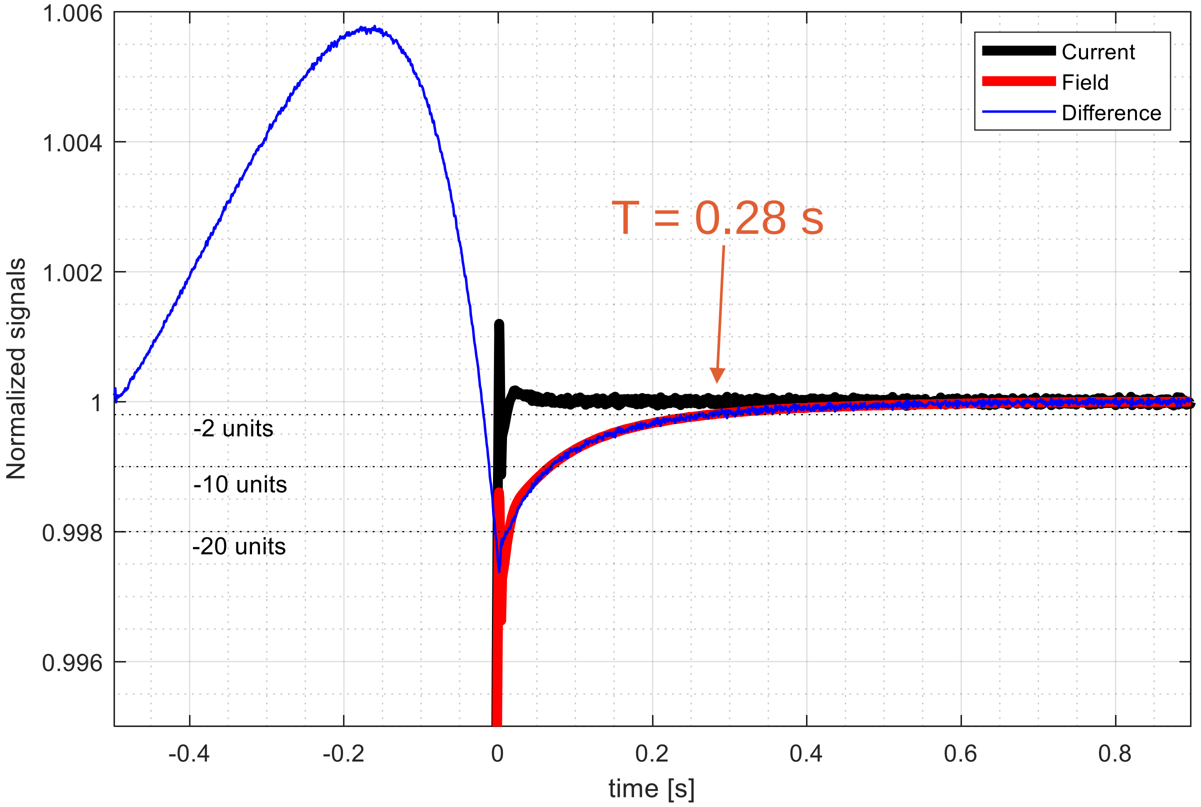
- Pre-emphasis correction consists in compensating the transient compensating the eddy-currents field.
- Widely adopted in MRI [12] and even for some magnets (Linac).
- Finely tuned for the nominal cycle.

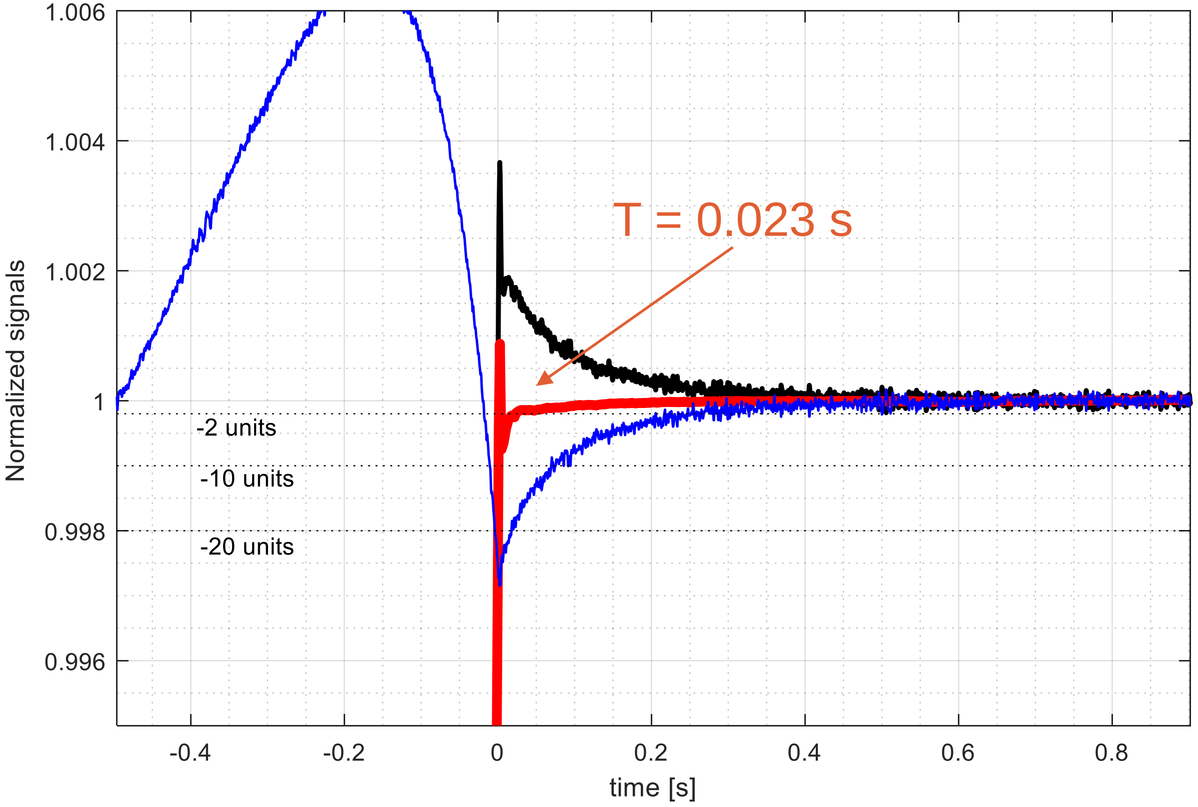


[12] Ahn CB, Cho ZH. Analysis of the eddy-current induced artefacts and the temporal compensation in nuclear magnetic resonance imaging. IEEE Trans Med Imaging. 1991

Measurement analysis

PXMBHGAWWP: testing the pre-emphasis correction, results [13]





[13] S. Sorti, C, Petrone, J. R. Anglada. Magnetic measurements of the LIU-PSB transfer-line switching magnet BT.BHZ10 (PXMBHGAWWP-000001), EDMS Nr: 2158606

Measurement analysis

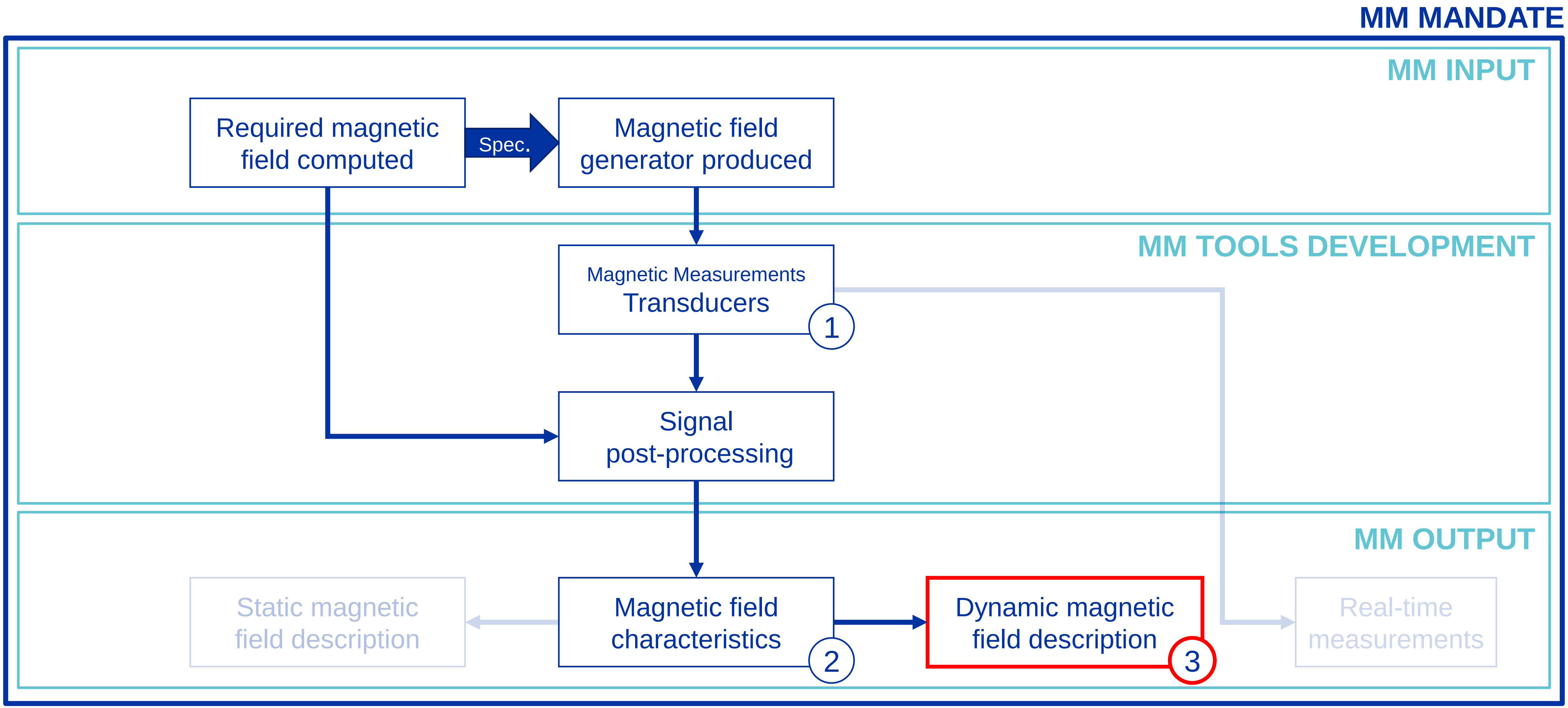
A possible dynamics characterization may be the combination of all the steps

- Measuring local transients in poles and center as a general feedback on eddy-current sources.
- Collecting a set of transients and introducing exponential fitting.
- Constructing tables and graphs summarizing the results.
- Actively applying the characterization in operation, like pre-emphasis correction.

Research

Pursuing a better synthesis

Research


MM MANDATE
MM INPUT
Required magnetic field computed
Spec.
Magnetic field generator produced
MM TOOLS DEVELOPMENT
Magnetic Measurements Transducers
1
Signal post-processing
MM OUTPUT
Static magnetic field description
Magnetic field characteristics
2
Dynamic magnetic field description
3
Real-time measurements

Research

Motivations

- Non-linear non-monotonic trends $\rightarrow$ interpolating may be inaccurate, extrapolating is a leap of faith.
- One should describe also jumps between current levels $\rightarrow$ huge amount of data to present.
- Overshoots should be tested if applied for new cycles $\rightarrow$ How can we do this for magnets not in MM lab?

Requirements

- Interpolation and extrapolation with a certain degree of reliability.
- Acceptable characterization by partial sets of data.

Research

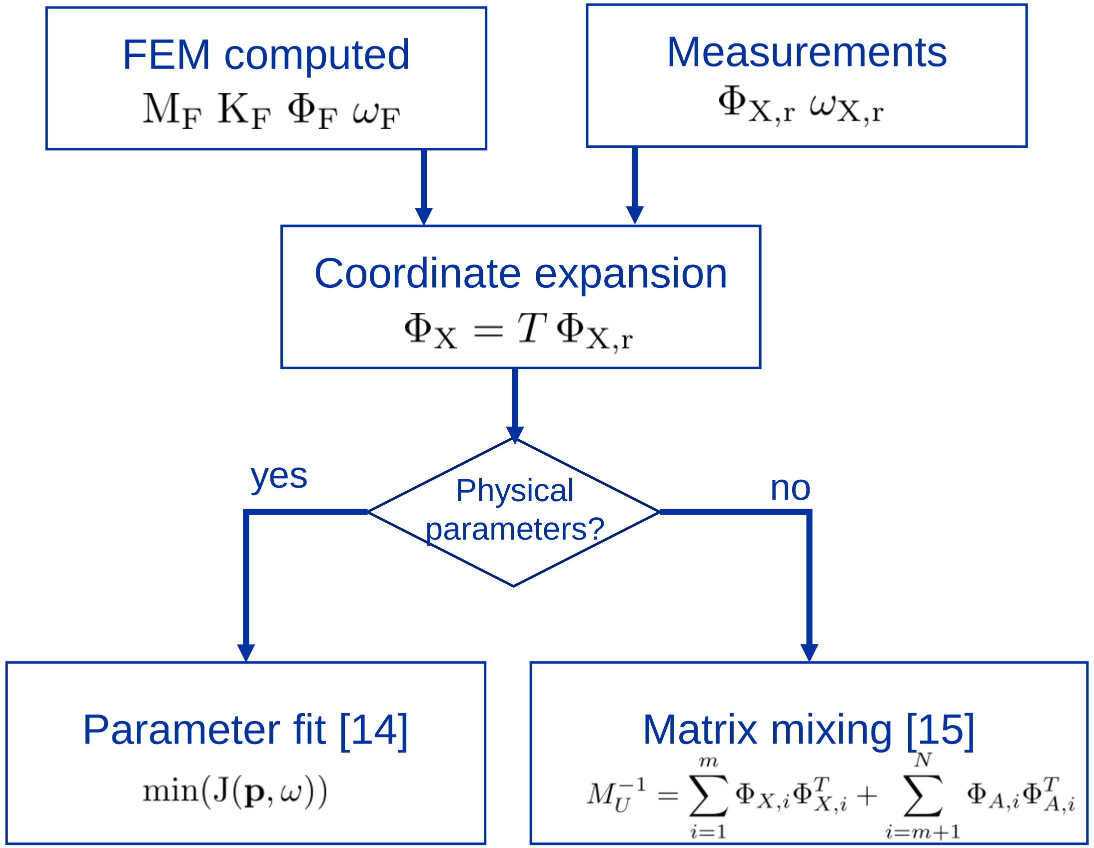
Proposal: a measurement-driven dynamic model

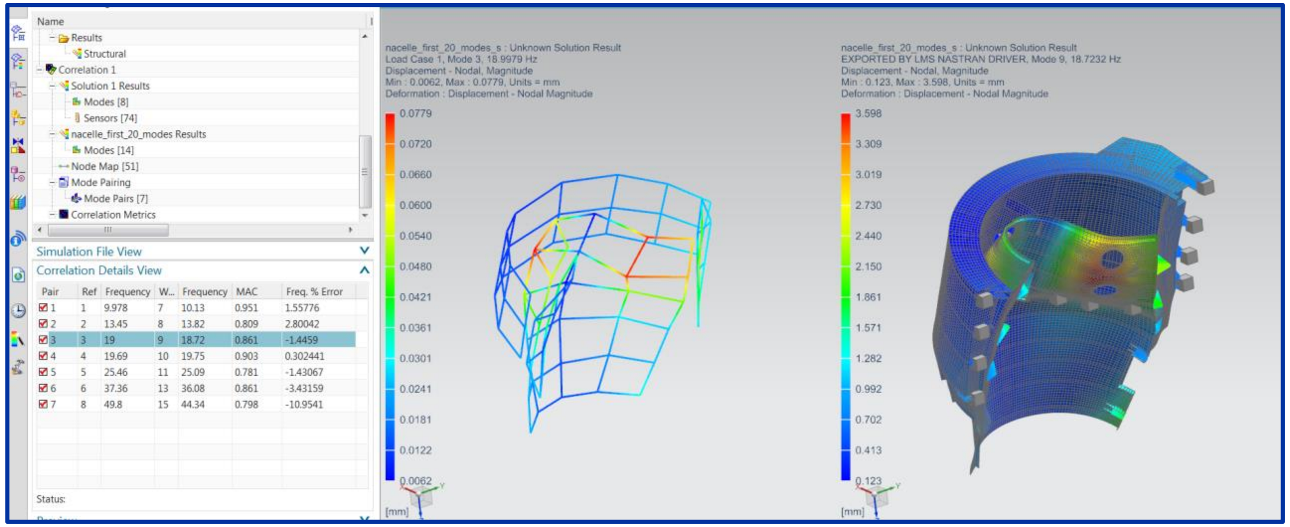
- A “prior” is constructed by numerical models, as FEM, BEM or VIM.
- The most relevant “modes” of the model are identified.
- Measurements look for actual modes in the real magnet.
- Modelled modes are corrected to match the experimental ones.
- The resulting model interpolates and extrapolates measurements through physics equations.
- The final goal of this research would be the construction of a “digital twin” of the magnet.

Research

Model Updating is a common techniques in mechanics

F = FEM
$\mathrm{X,r}$ = experimental (reduced set of d.o.f.)
X = experimental (final, typically expanded)
$\mathrm{M,K}$ = mass and stiffness matrices
Φ, ω = modal shapes and natural frequencies





Siemens Simcenter™ 3D FE Model Updating, applied to an aircraft engine nacelle (reprinted from https://www.mayahtt.com/)

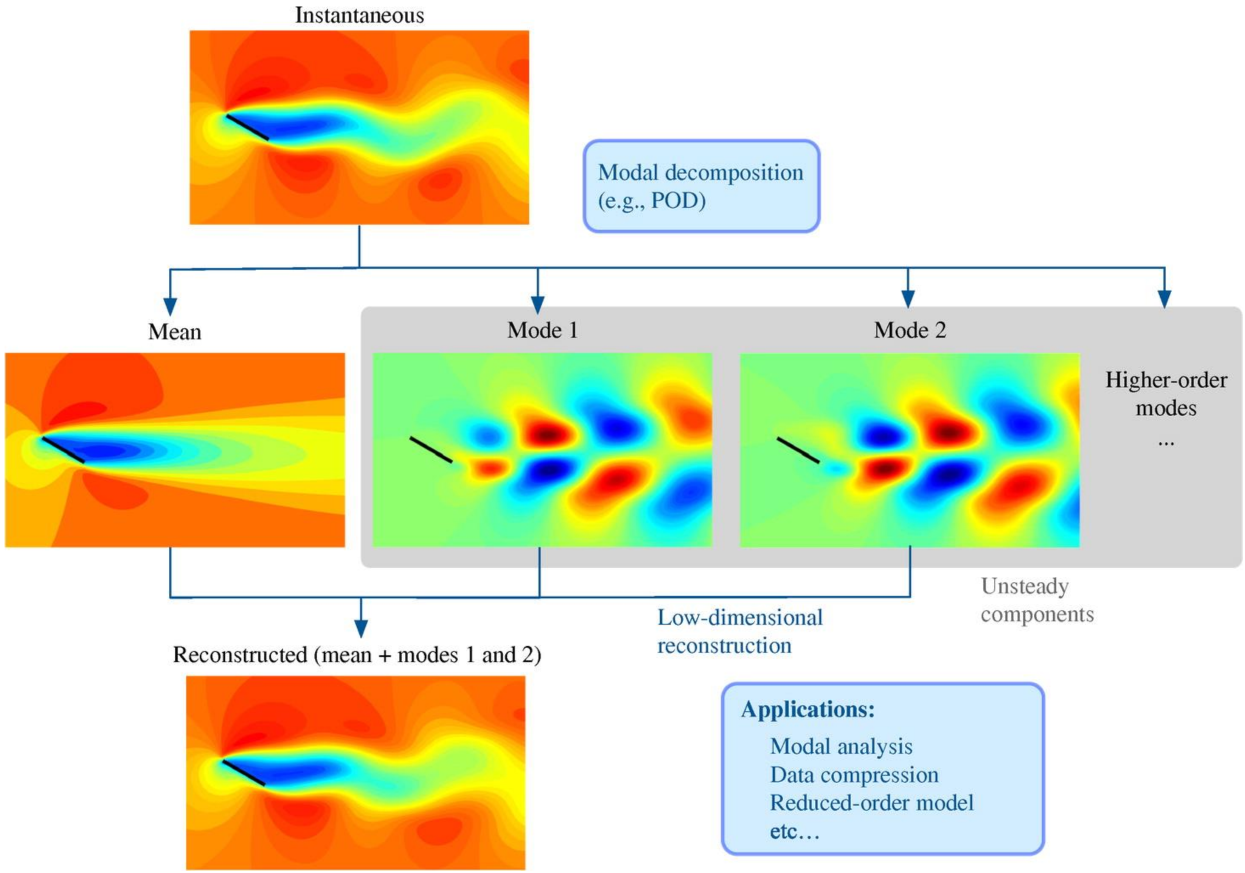
[14] A.J. García-Palencia, and E. Santini-Bell, A Two-Step Model Updating Algorithm for Parameter Identification of Linear Elastic Damped Structures. Computer-Aided Civil and Infrastructure Engineering, 2013

[15] B. Caesar and J. Peter, Direct update of dynamic mathematical models from modal test data, American Institute of Aeronautics and Astronautics Journal, 1987

Research

Introducing nonlinearity

- The concepts can be extended to nonlinear systems.
- "Modes" need to be extended. Different possibilities:
  - Modes of the linearized system,
  - Snapshots of the NL system on nominal trajectories,
  - Proper nonlinear modes.
- Snapshots can come directly from measurements.
- "Modes" are not orthogonal, thus equations are not reduced by orders of magnitude.

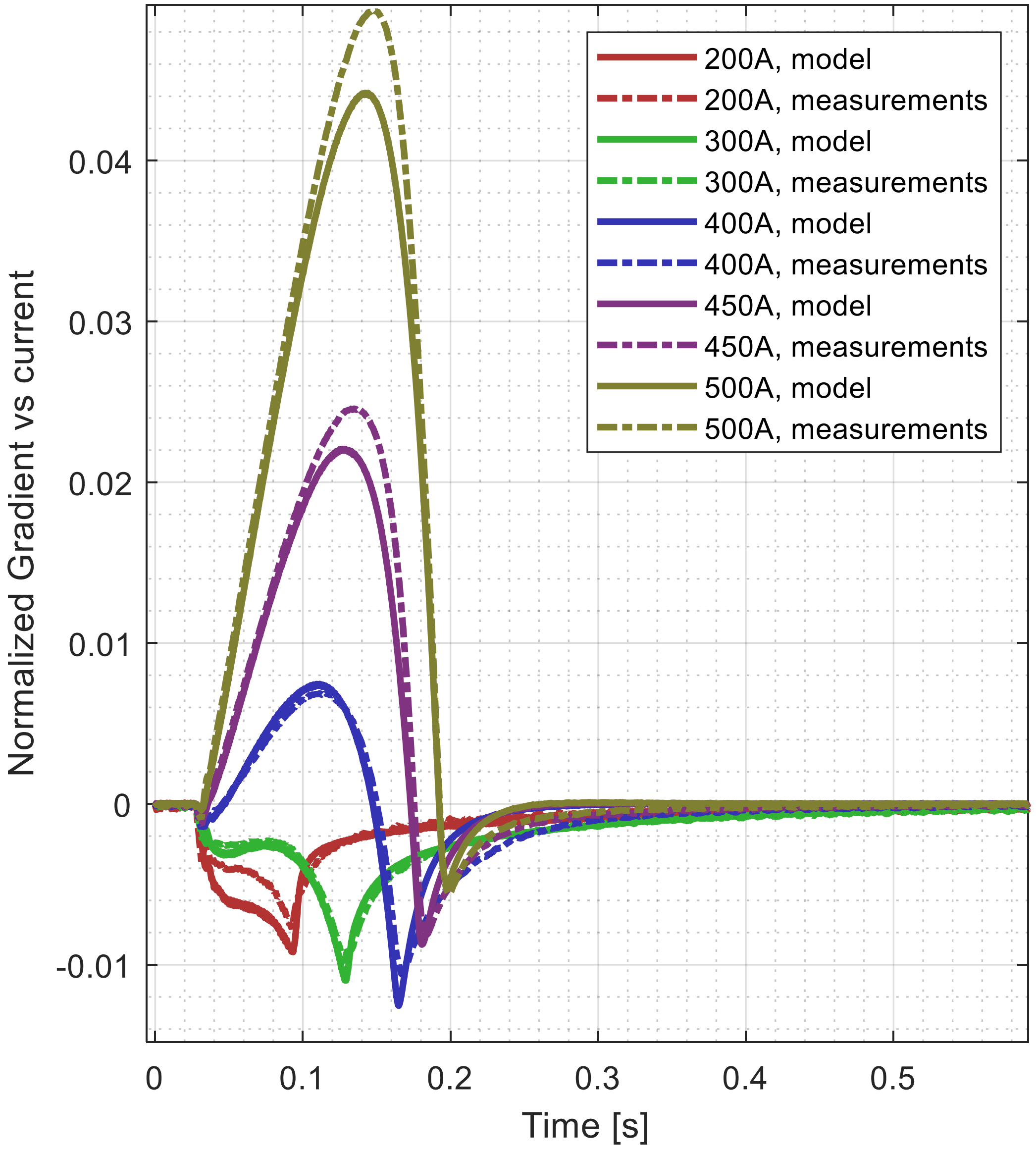


Reprint from [16] K. Taira et al., Modal Analysis of Fluid Flows: An Overview, AIAA Journal , Feb. 2017

Research

Lumped parameter model for QDS11

- 18 X 4 point measurements (supposing symmetry).
- Fitting a lumped parameter model, made by 6 X 12 main flux tubes plus couplings.
- Imposing soft constraints to return physical numbers to cost function to approximate local field.
- Validation against integral field reconstruction.
- Not accurate enough. Not enough physically correct.

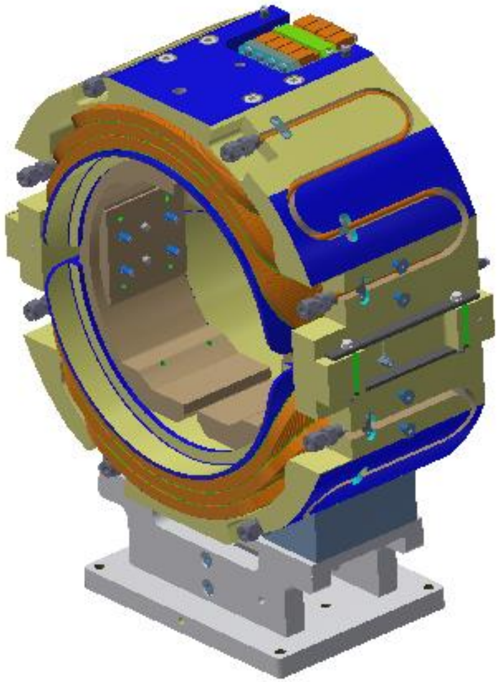


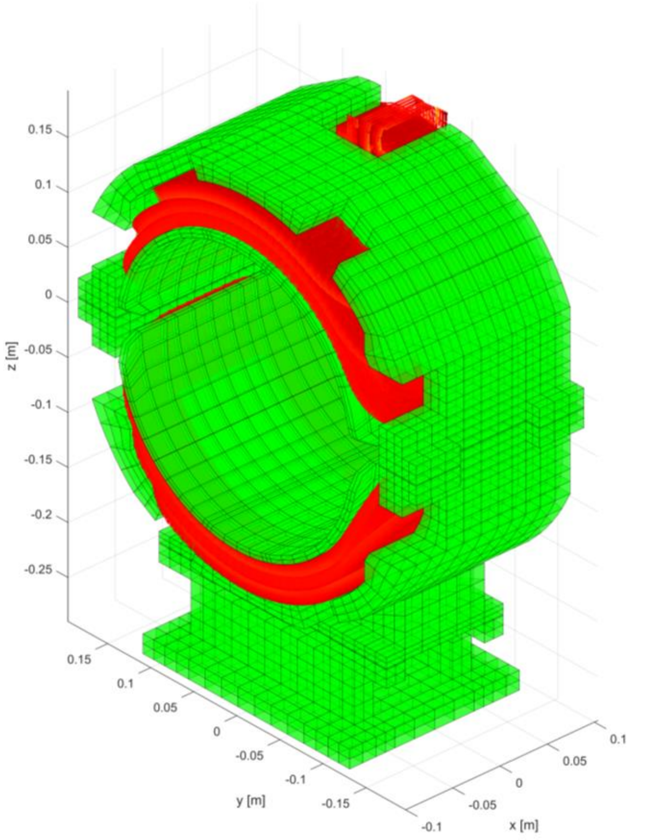
Research

[17] R. Albanese and G. Rubinacci, Integral formulation for 3D eddy-current computation using edge elements IEE Proceedings A - Physical Science, Measurement and Instrumentation, Management and Education, 1988

Distributed parameters, an example

- Non-magnetic materials → not a complete example.
- Volume Integral Formulation [17].
- Winding discretized in 3D as filament currents.
- Yoke discretized in 3D as hexahedra.
- Tricks to reduce full matrix operations complexity.





$$\underline{\eta} \cdot \boldsymbol{J}(\boldsymbol{r},t) + \frac{\mu_0}{4\pi}\int_\Omega \frac{1}{|\boldsymbol{r}-\boldsymbol{r}'|} \cdot \frac{\partial \boldsymbol{J}(\boldsymbol{r}',t)}{\partial t} d\tau' = -\frac{\partial \boldsymbol{A}_e(\boldsymbol{r},t)}{\partial t} - \nabla\phi(\boldsymbol{r},t),$$

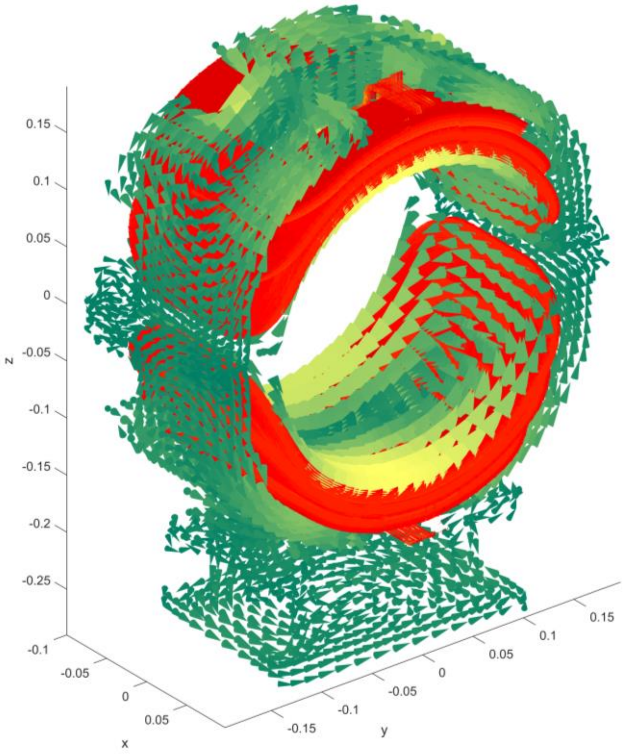
Resistivity tensor

(Resistance) (Inductance) (External field) (Scalar electric potential)

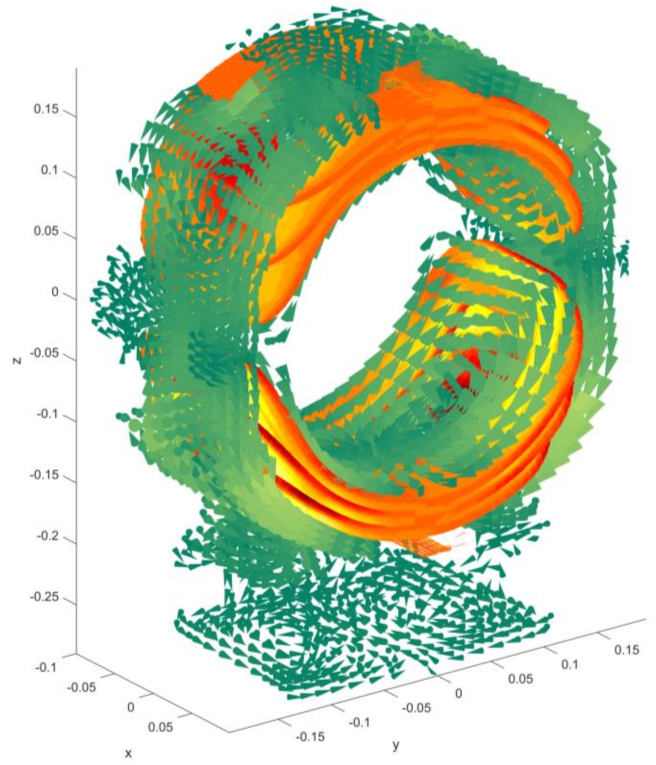
Research

Modes of the dipole corrector, an effective way to discern dynamic contributions

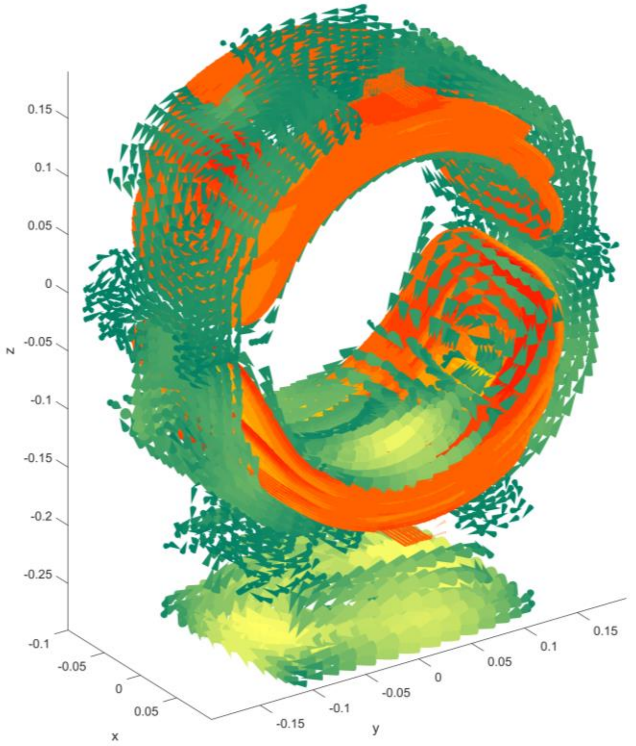
1st mode: inner plates



2nd mode: coils

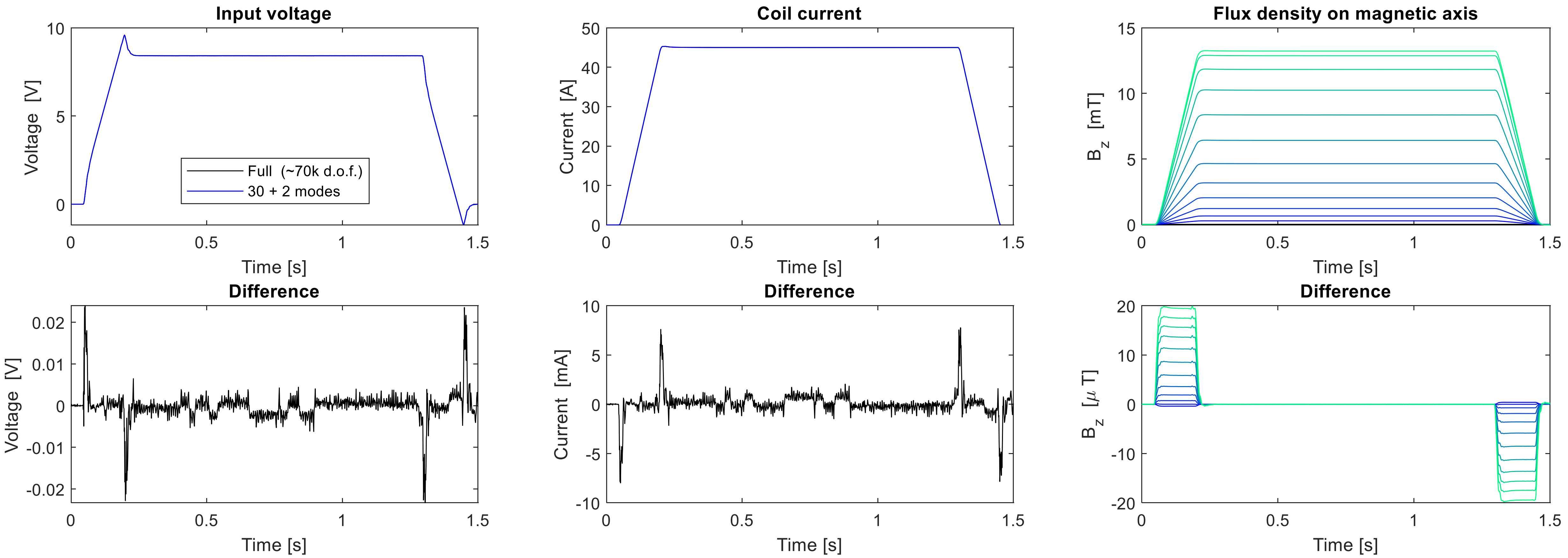


3rd mode: baseplate



Research

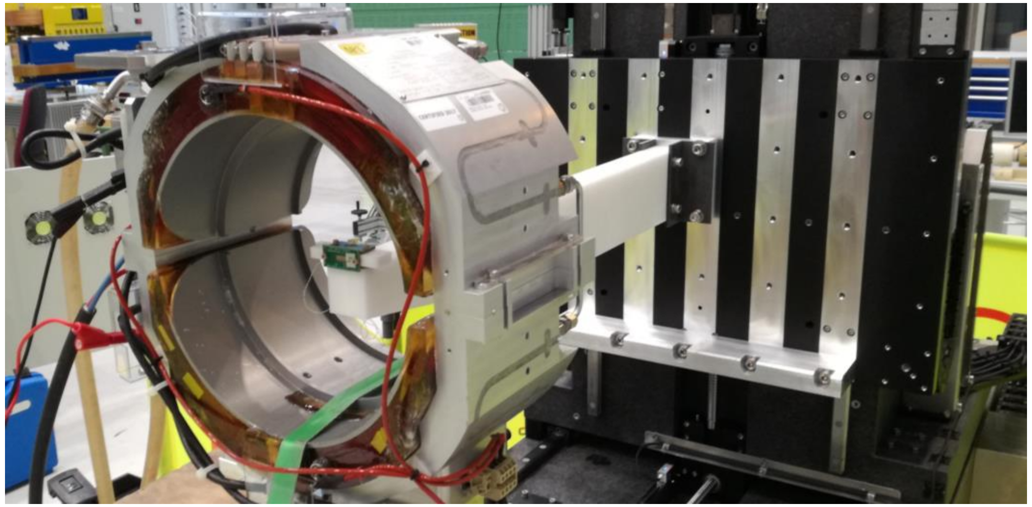
MOR of the dipole corrector numerical model

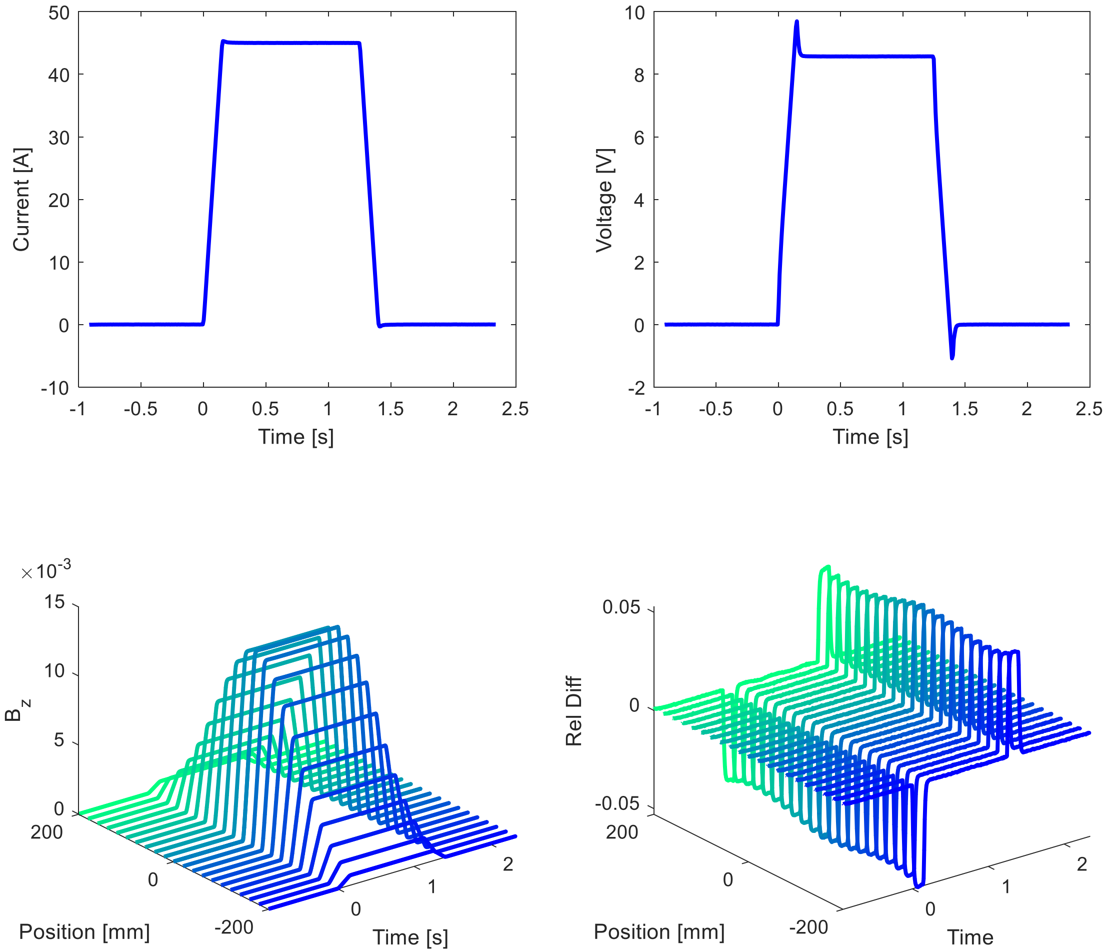


Research

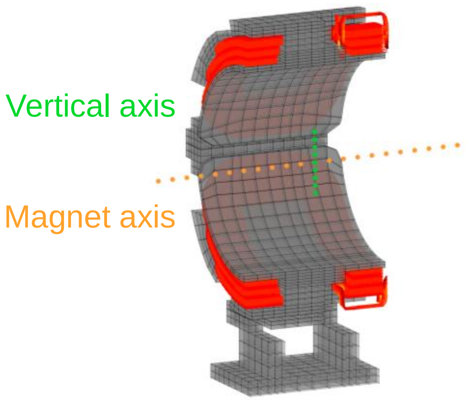
Dipole corrector, ongoing campaign

- A single, plastic arm is mounted on the stages.
- Static coil measurement by PCB on the tip.
- Magnet ramped, different positions evaluated.



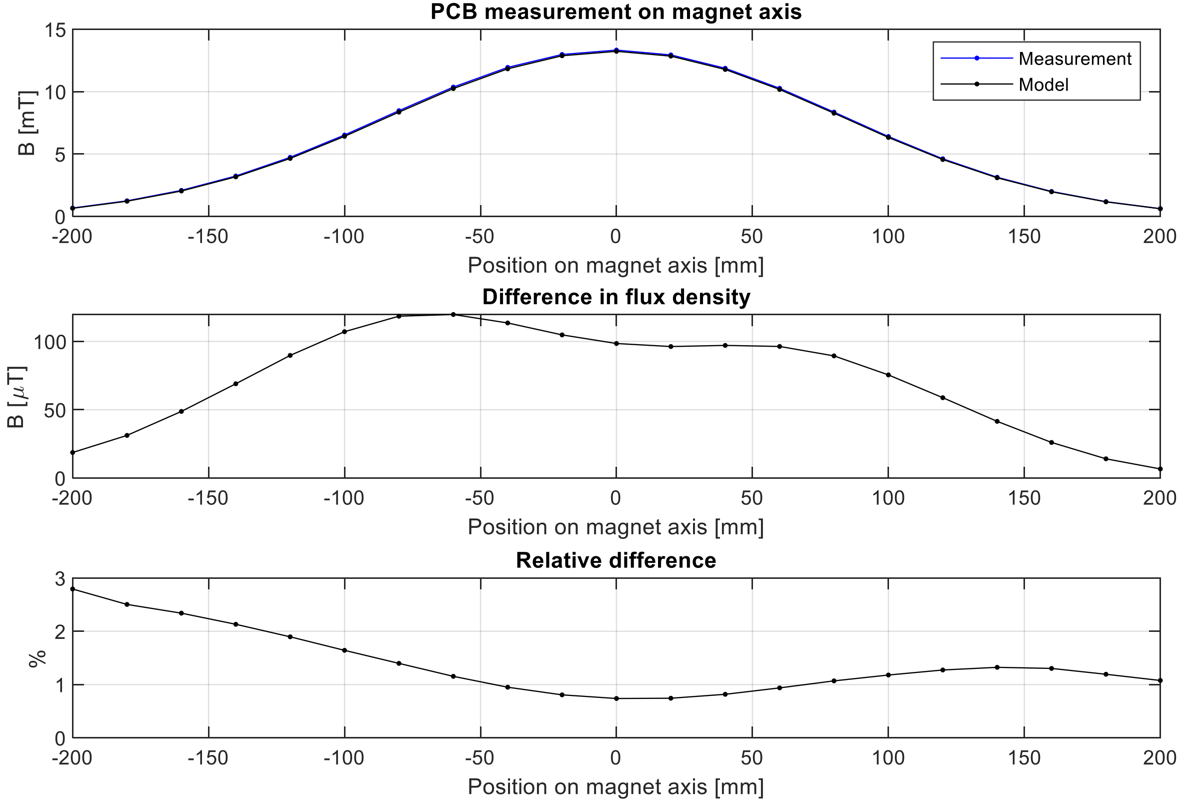


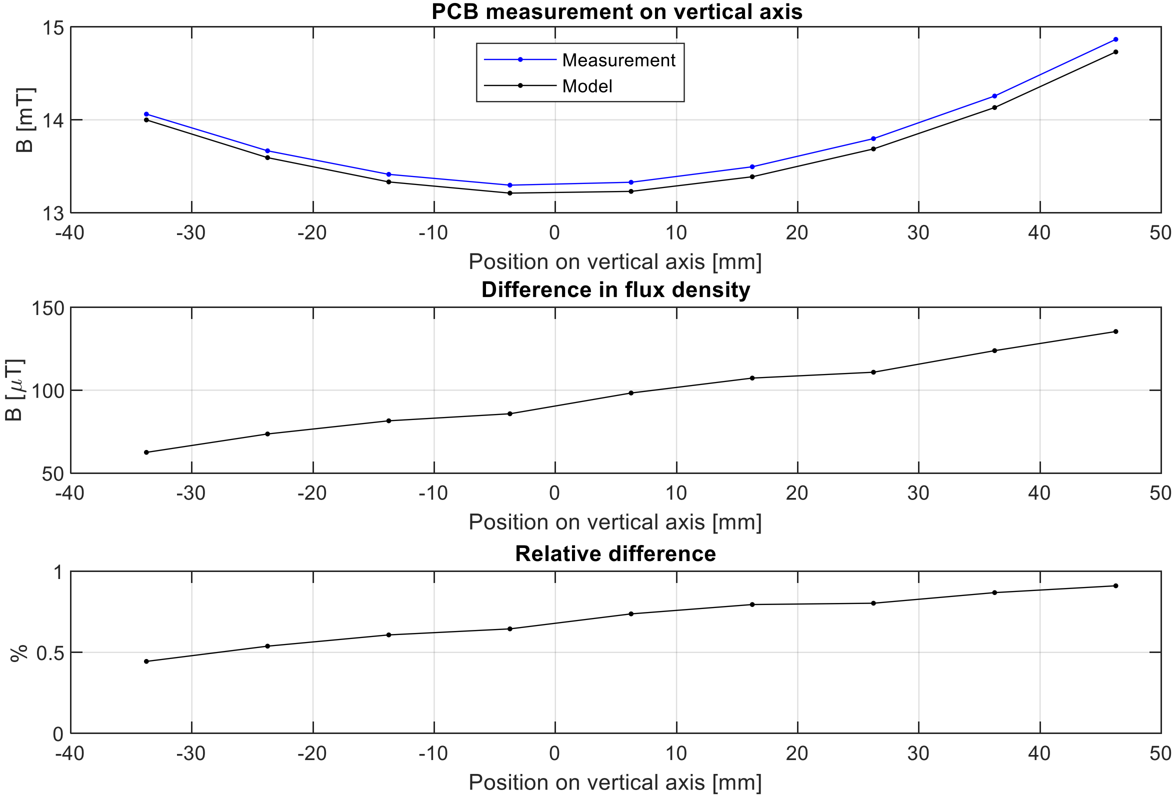
Research



Dipole corrector, model static check

- The model could be corrected also statically, but for the moment it is accepted as it is.

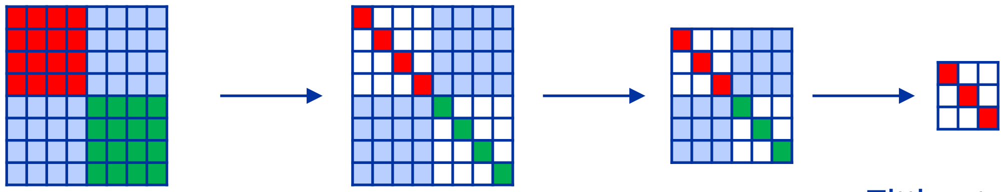


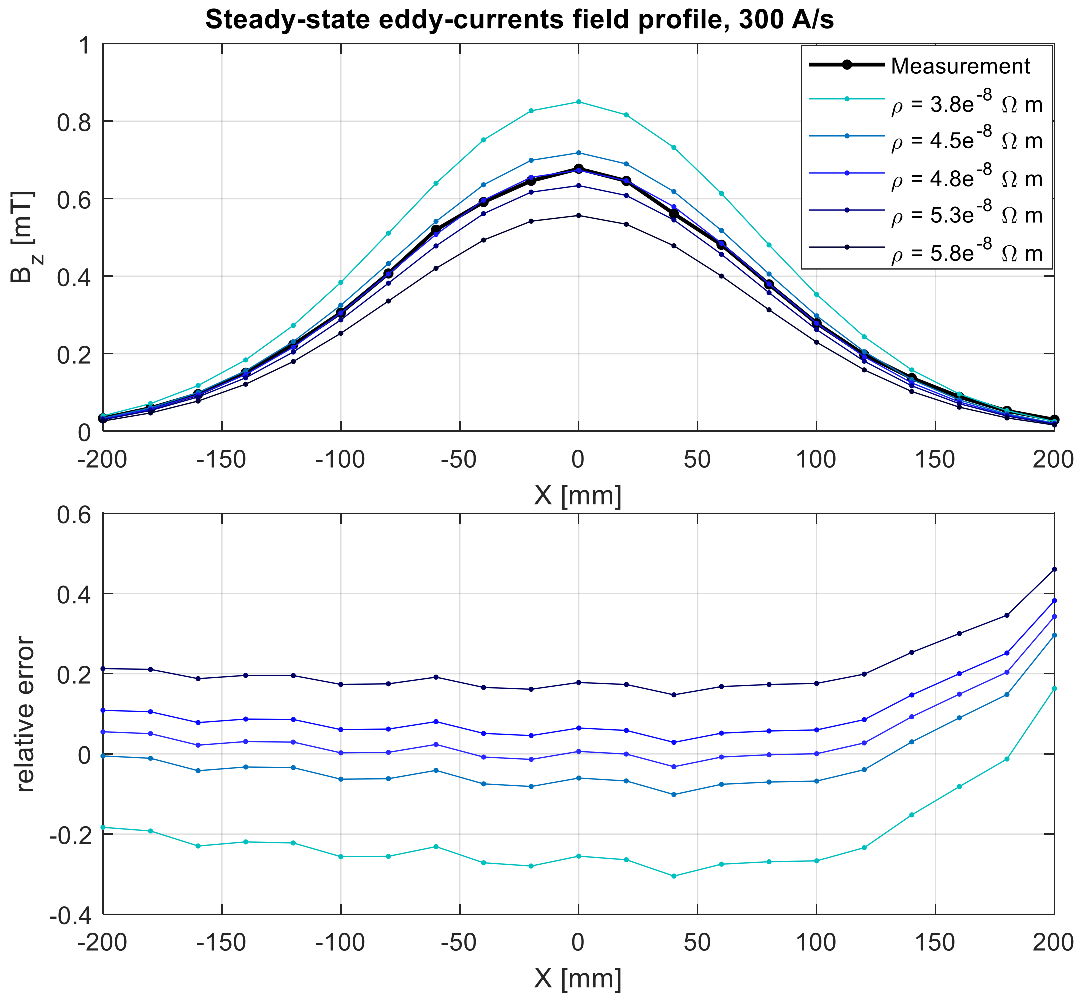


Research

Dipole corrector, option I: parameter fitting

- The chosen integral formulation is well suitable for Dynamic Substructuring.
- Modal transformation and MOR before final coupling and fitting.
- For linear elements, modal shapes are preserved if matrix is scaled $\rightarrow$ must fit only the frequencies of the reduced substructure.



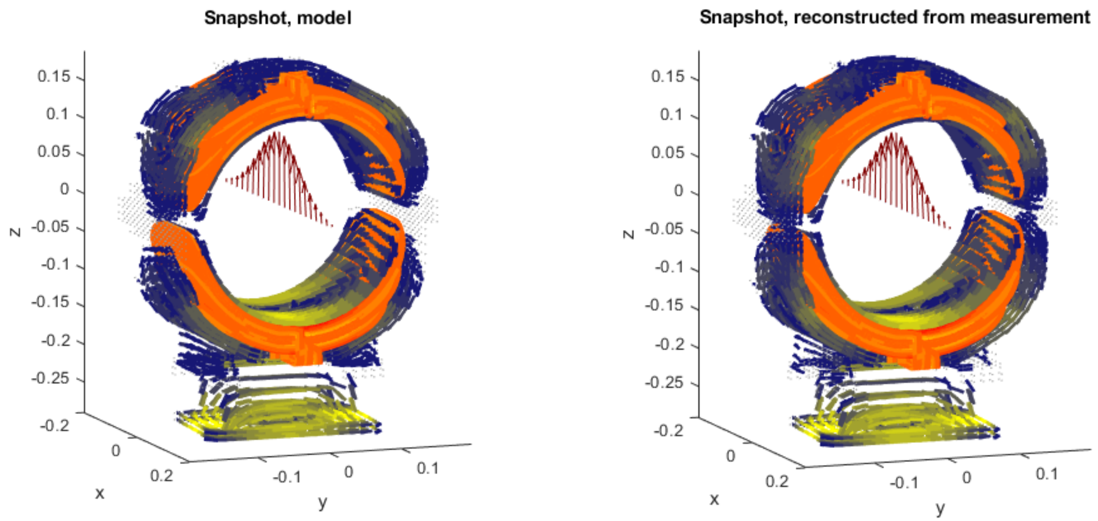


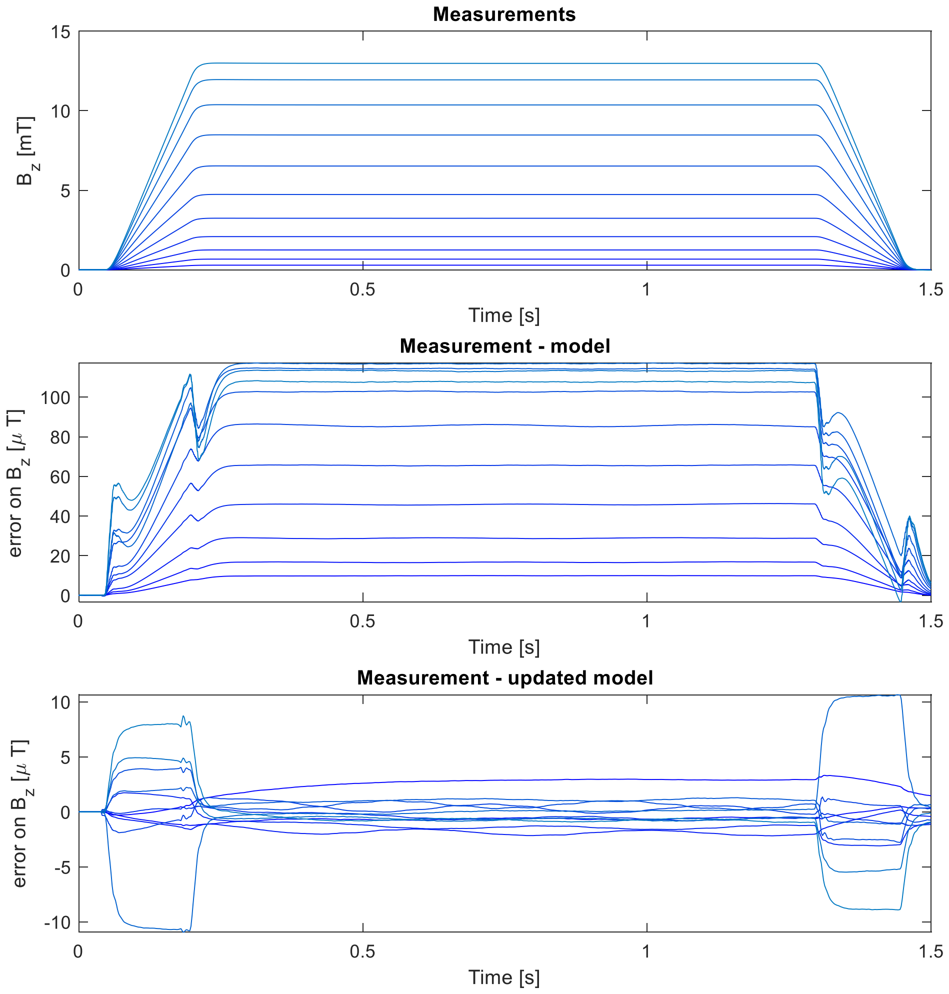
Research

Dipole corrector, option II: experimental snapshots

- “modes” as eigenvectors of state matrix may require ad-hoc measurements campaigns

- “Snapshots” from time histories are a fast replacement. It is required to provide the full state, which is estimated by a Kalman Filter.





Summarizing

The measurements of normal-conductive magnets dynamics

- Normal-conductive magnets dynamics involve complex nonlinear phenomena.
- Ad-hoc measurement instruments are adopted, under continuous development.
- A new flexible bench is being made operative. It involved novel studies for instrument mechanics.
- Typical measurement outcomes are transients of normalized field minus normalized current. Exponential functions can be fitted to them and pre-emphasis adopted.
- Ongoing researches are evaluating model reduction and updating techniques to have a physical based method to interpolate and extrapolate measurements. The next step regards the implementation of nonlinear materials.

These activities greatly benefitted from the efforts of Carlo Petrone, Stephan Russenschuck, Dmitry Akhmedyanov, Regis Chritin, Matthias Bonora, Alberto Bellelli and all the other colleagues of Magnetic Measurements section.

Questions?

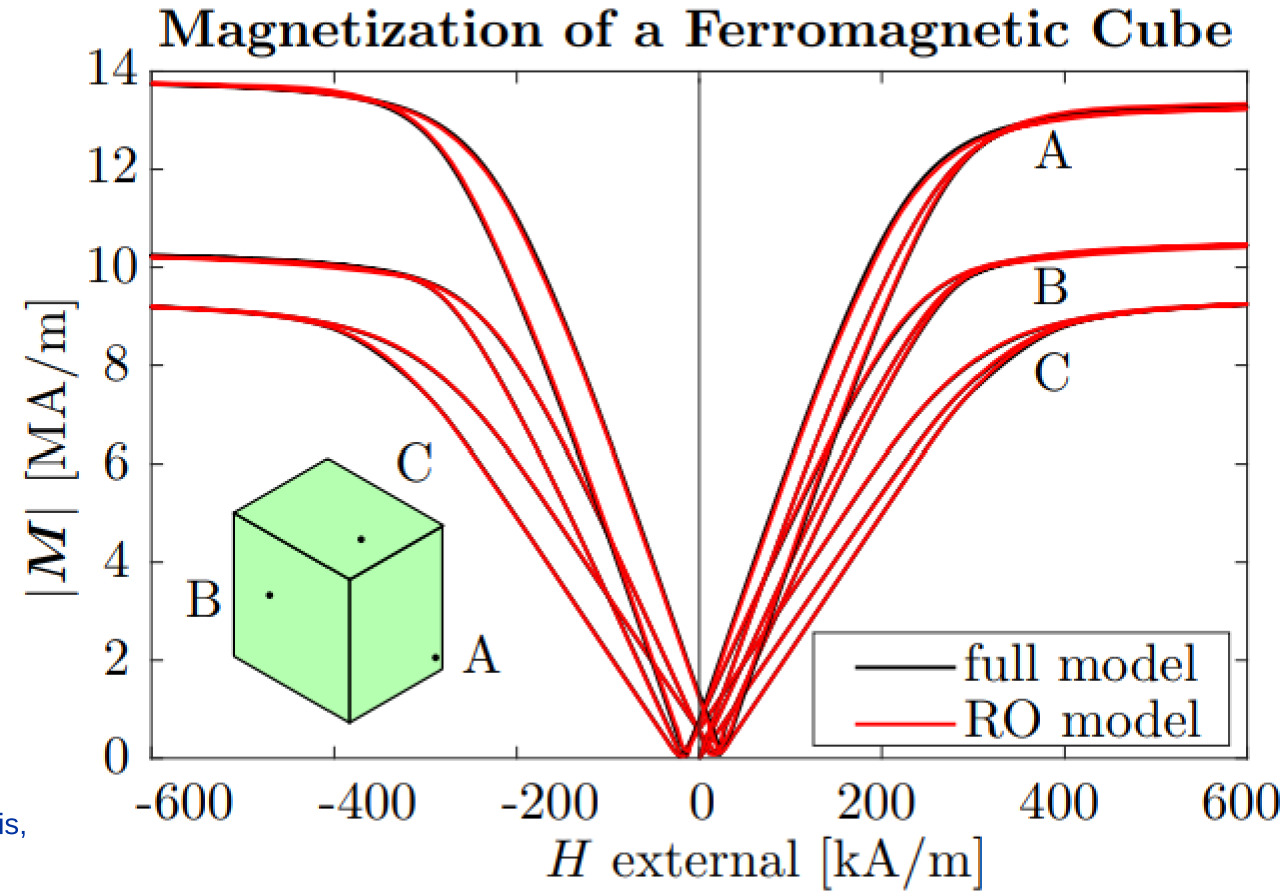
Thanks a lot for your attention!

home.cern

Appendix: MOR for magnetic hysteresis

Preliminary tests

- Vector Jiles-Atherton model [15] is applied to a 2-cm-side cube, inside a uniform dipole field. The full model is 1008 d.o.f.
- Five equally spaced samples are taken between virgin curve and stabilizing cycle.
- Proper Orthogonal Decomposition is applied to obtain a 10 d.o.f. model (5 for anhysteretic curve and 5 for the hysteresis)

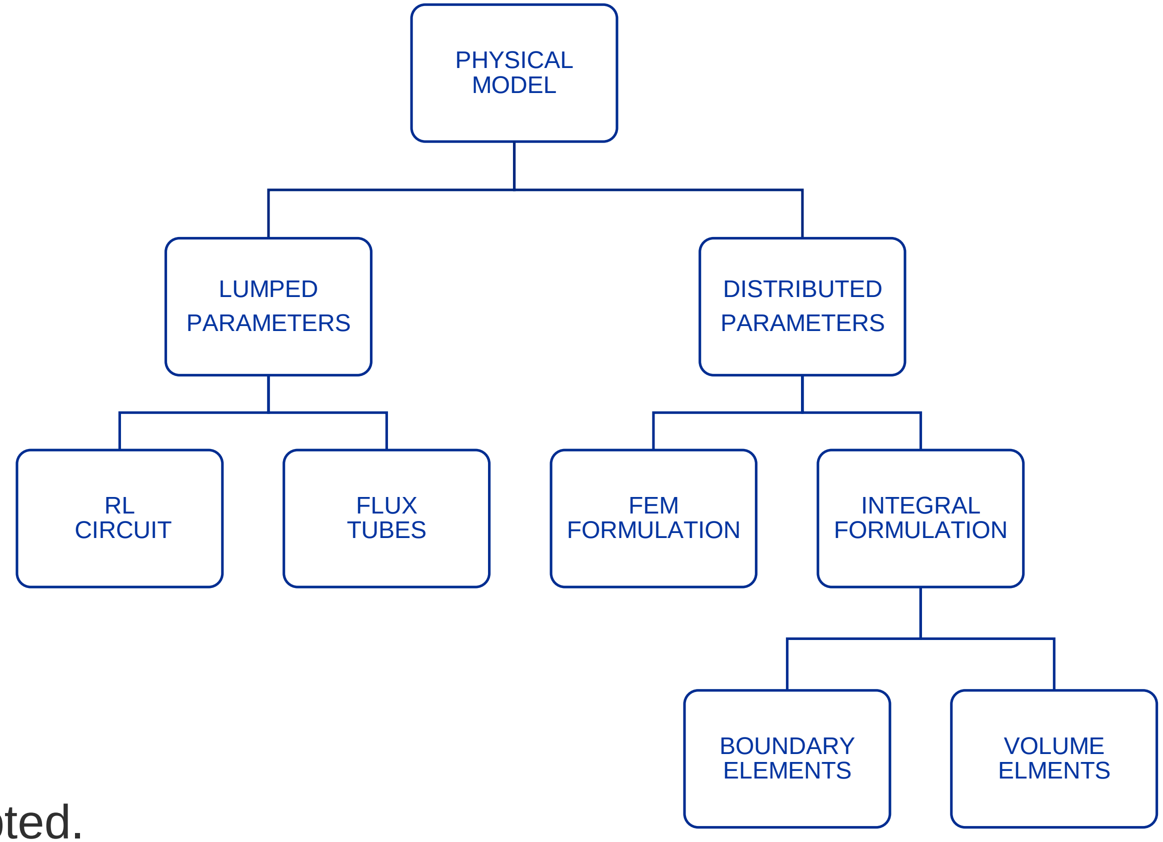


[15] A. J. Bergqvist, A Simple Vector Generalization of the Jiles-Atherton Model of Hysteresis, IEEE Transactions On Magnetics, Vol. 32, No. 5, September 1996

Appendix: Research

Formulating the E.M. problem

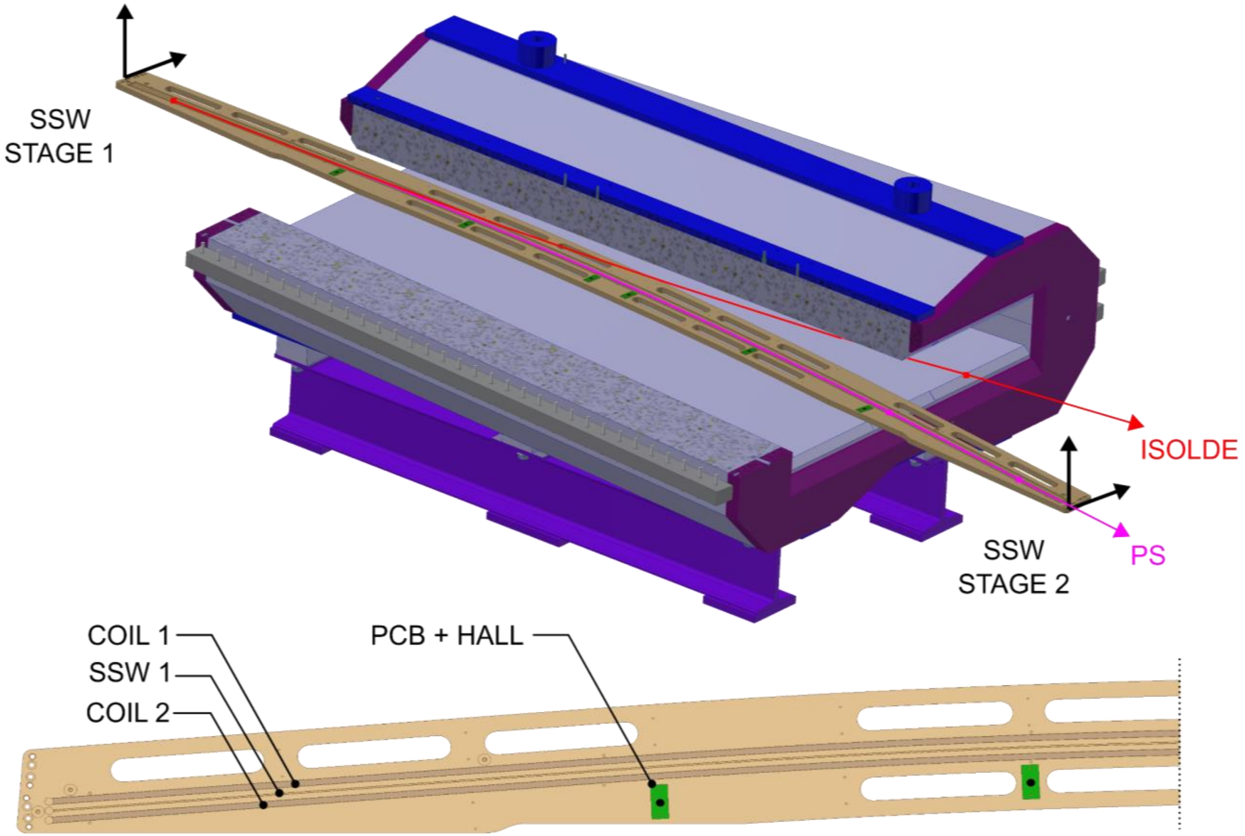
- The model should include:
  - 3D magnet geometry
  - Eddy-currents
  - Nonlinear hysteretic magnetic materials
  - Expansion possibilities (i.e. to include temperature)
- The model must be suitable for MOR. Preferably:
  - Lowest d.o.f. possible (high-order shape functions)
  - Lowest “unnecessary” d.o.f. possible (avoid meshing air)
- For preliminary investigations, a VIM formulation is adopted.



Appendix: Measurements systems

Other instruments:
Multi-instrument systems

- Combining all the main techniques for local and integral field.
- Regarding dynamics, static coils and Hall probes.
- Possibility to displace the system inside the aperture.;
- In future, can take advantage of the Rotating Coil Mapper.

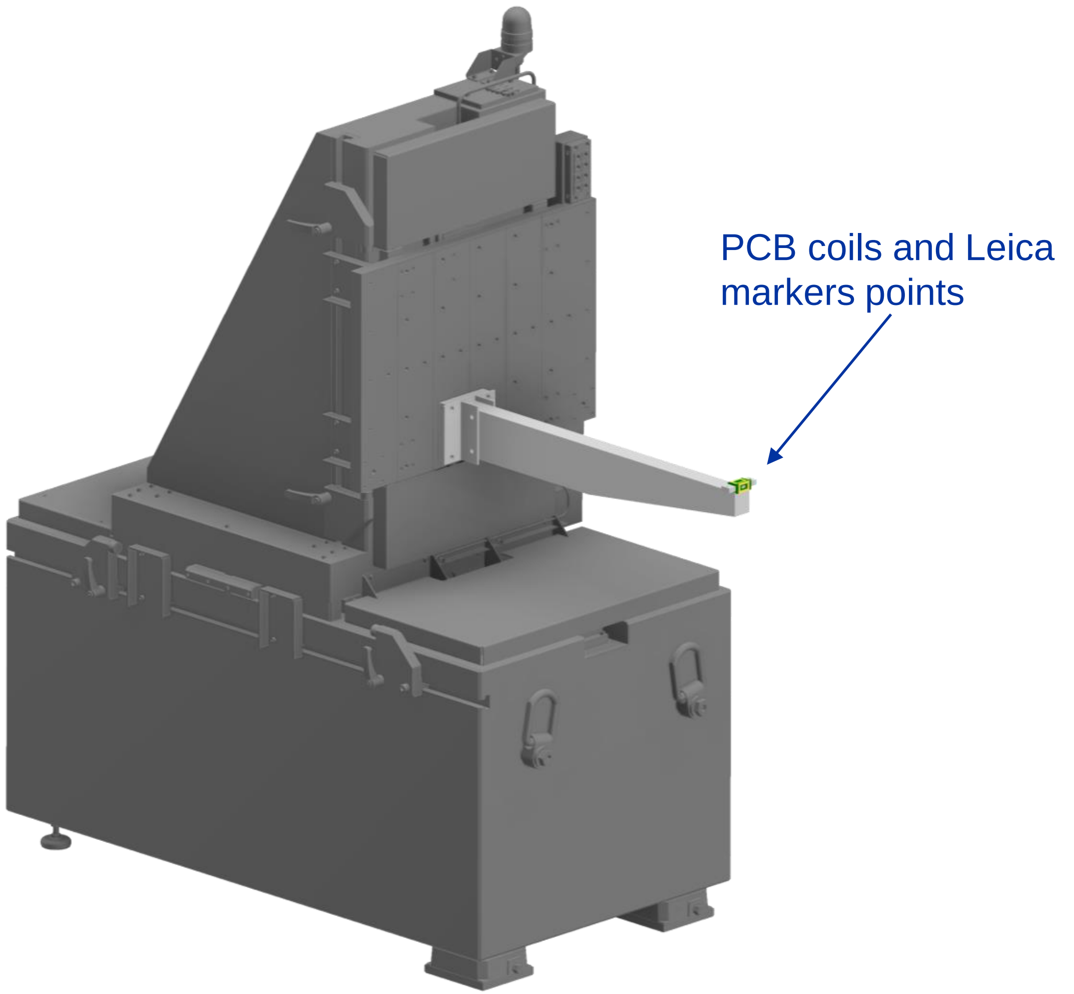


Curved fluxmeter for the LIU-PSB transfer-line switching magnet

Appendix: Measurements systems

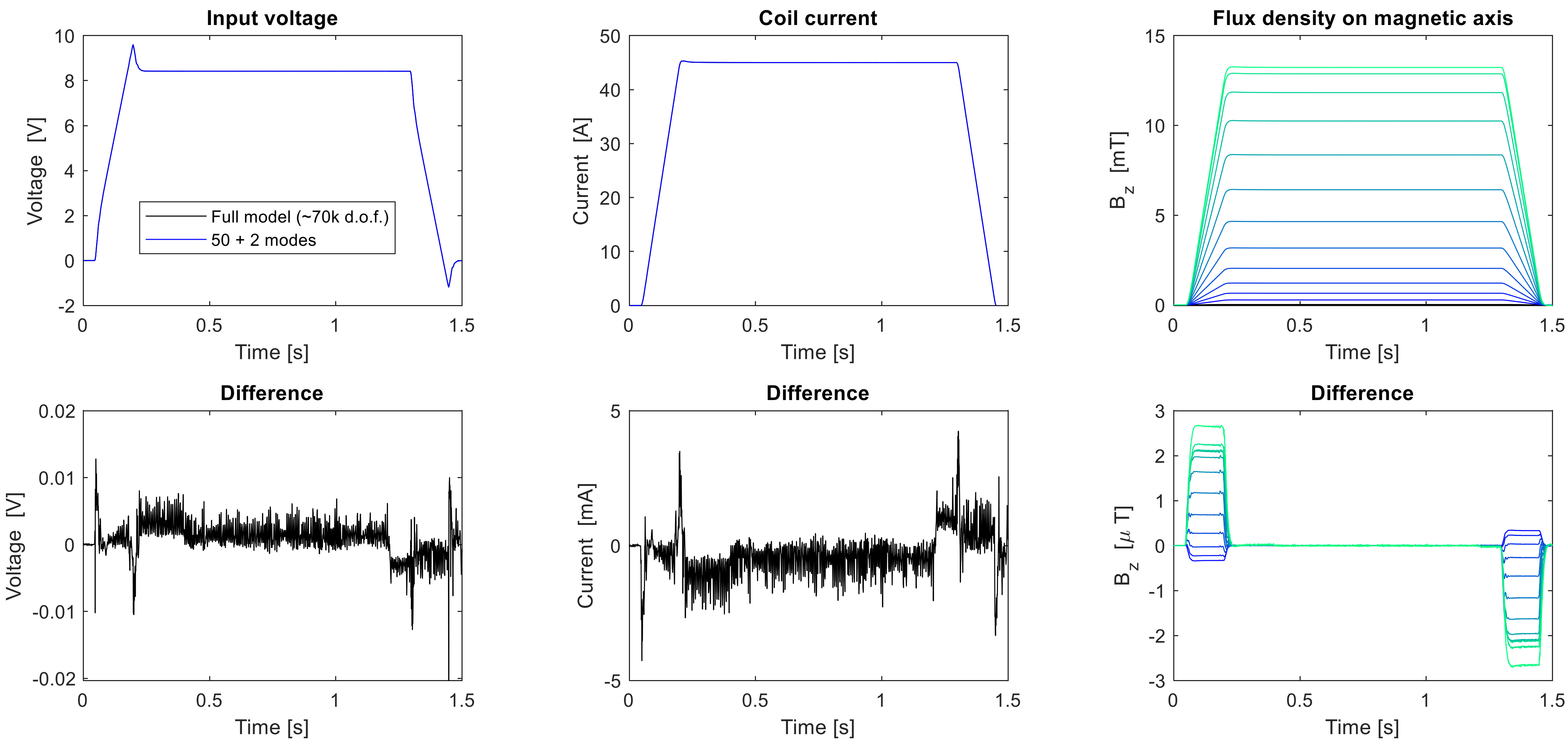
Other instruments:
Moving Fluxmeter

- Fixed or moving coil.
- Field profiles along lines.
- Dynamic maps of cloud of points.
- First application of the new bench, adopted also for ongoing researches in magnets dynamics.



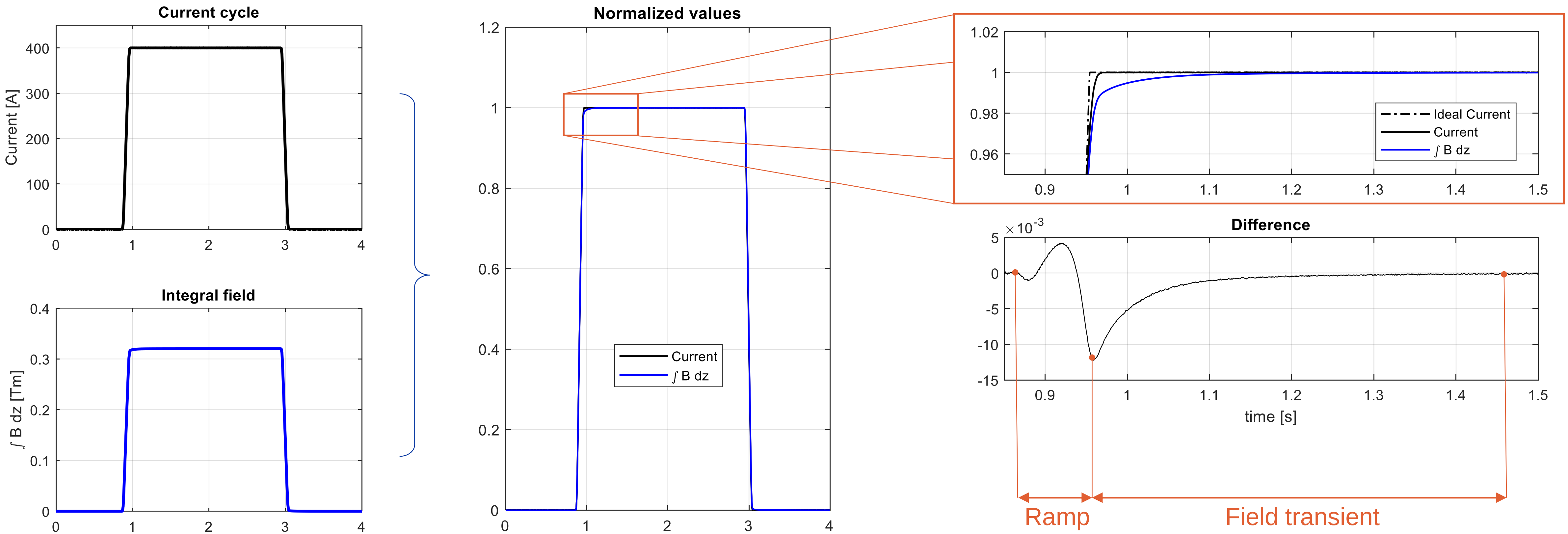
Moving fluxmeter for local measurements (profiles and transients)

Appendix: MOR, example 2



Introduction

Dynamic effects arise as delay between current and magnetic field



Appendix: Eddy-currents theory

Eddy-currents in normal conductive magnets are not a new topic [10].

- Magnets are made by mainly conductive materials (iron, aluminum, copper).
- Faraday's law: a voltage is induced in a conductor loop, if it is subjected to a time-varying magnetic flux.
- It can be well summarized through the diffusion equation:

$$\nabla^2 \mathbf{H} = \sigma \mu \frac{\partial \mathbf{H}}{\partial t}$$

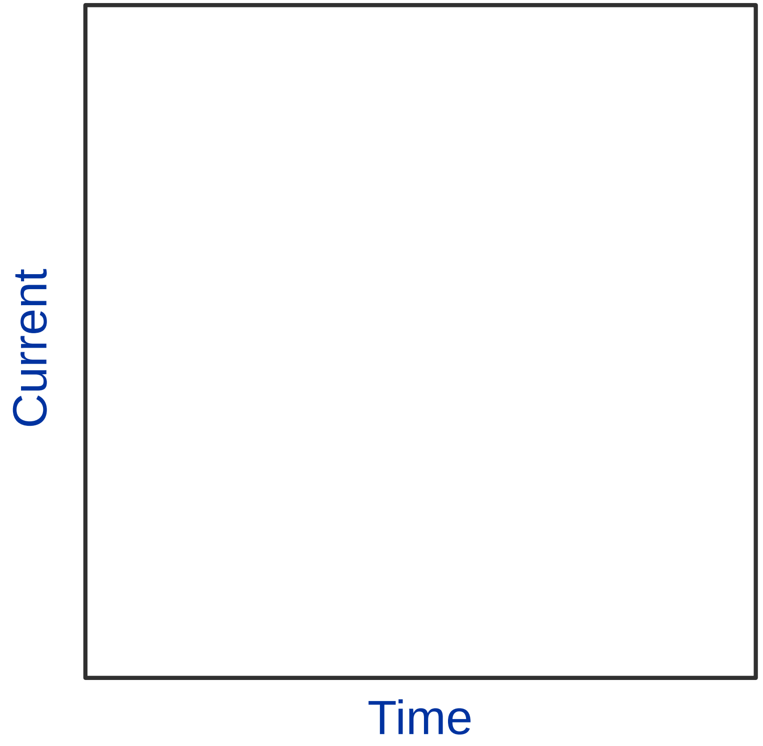
Magnetic Field

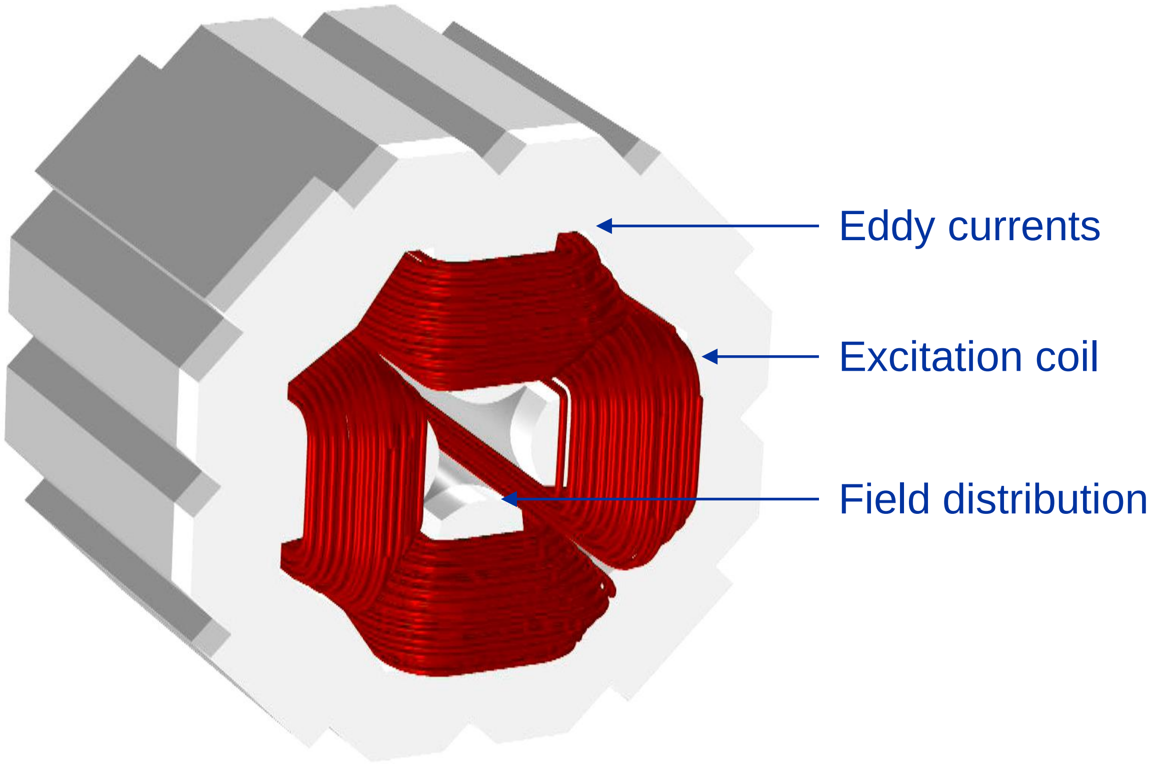
Electrical conductivity

Magnetic permeability

Appendix: Eddy-currents theory

Dynamic effects are mainly due to eddy currents arising





Appendix: Eddy-currents theory

- Eddy-currents distribution in magnets is not trivial.
- Non-linear hysteretic magnetic materials result in non-linear eddy currents.
- Yoke lamination gives shorter loops of currents, but material anisotropy.
- Fringe field at magnet ends results in a complex 3D distribution of flux density and currents.
- Eddy-currents produce heat (Joule heating) and mechanical forces.

→ Need for Magnetic Measurements