Standardized Testing versus Realistic Magnetization Conditions in Electrical Machines – Advanced Characterizations Methods for Rotating Magnetization, Vector Properties and Domain Structure

EUROSTEELMASTER 2024

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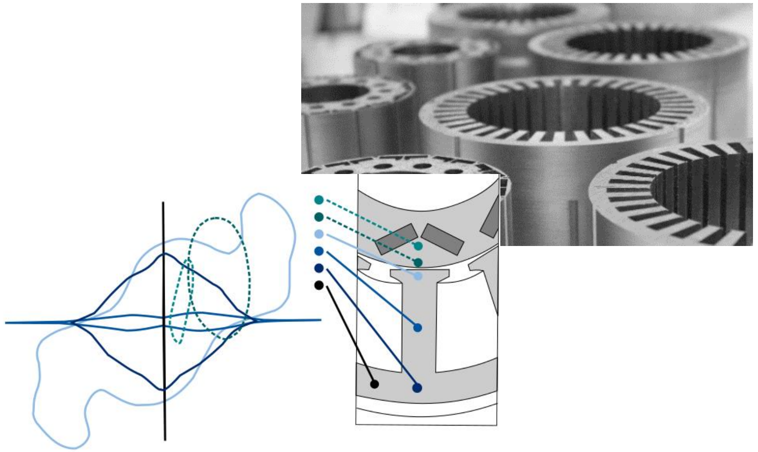

November 25th, 2024

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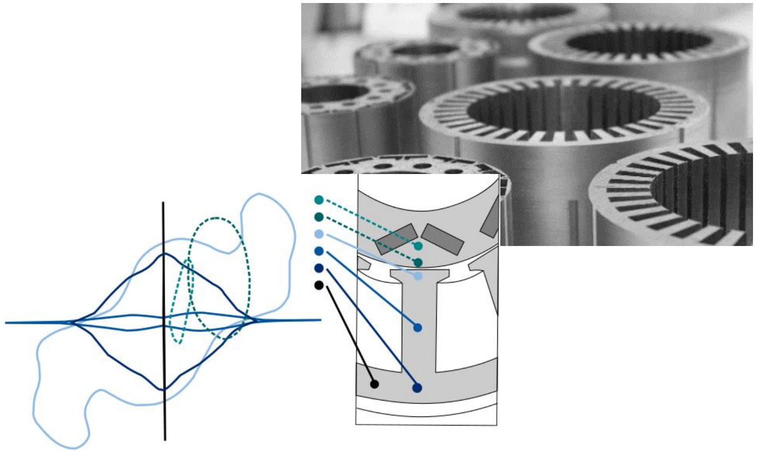
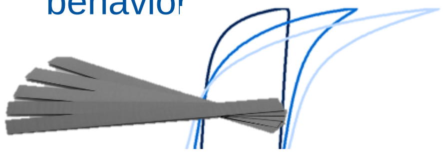


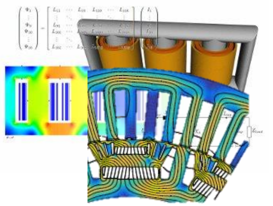
Magnetic Measurements in the Context of Electrical Drives – Why do we need them?

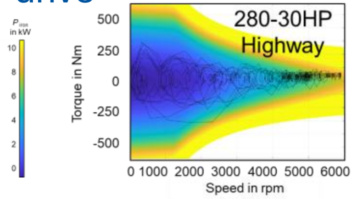
- Necessary for comparison of materials
  - Material selection
  - Targeted material design
- Needed as input for modeling
  - Calculation of electrical machines
  - Simulative comparison vs. porotypes
- In-depth study of effects
  - Increase understanding of fundamental mechanisms

From Measurements to Machine Calculation

Measurement	Modeling	Simulation
Quantification of Iron losses and Magnetization behavior	Modeling of the material behavior	Evaluation of specific parameters of the drive







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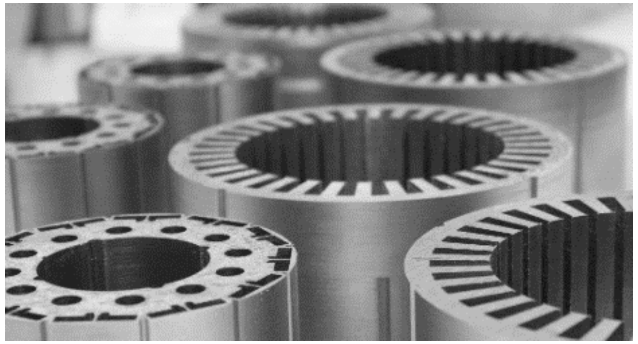
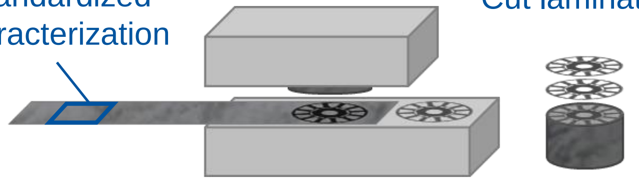
The Problem with Standardized Material Characterization

- Material characterization of electrical steel is performed on Single sheet tester (SST), Epstein frame (ER) or ring cores
- International standards (i.e. IEC60404-3) define sample geometry and demand gentle sample preparation
- Main problem:
  - Actual magnetic properties of components are simplified and effects neglected
  - No suitable possibilities to measure magnetic properties directly on components

Rotors and Stators from Electrical Steel Sheets



Standardized Characterization



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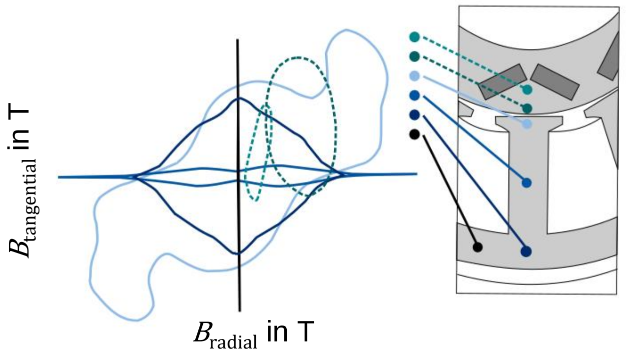
Which Effects are Typically Neglected with Standardized Measurements?

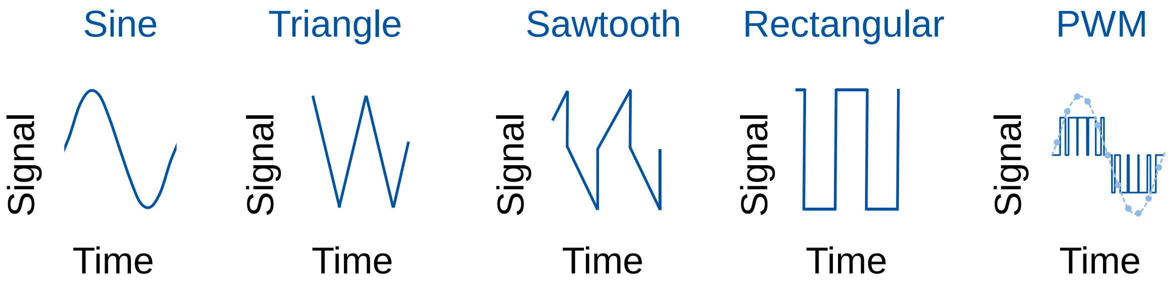
- Operation Characteristics
  - Rotating Magnetization (Local variations of B-loci)
  - Vector properties
  - Non-sinusoidal Excitation
- Detailed material characteristics
  - Homogeneity
  - Anisotropy
- Mechanical processing
  - Cutting, packaging, pressing into housing
  - Centrifugal forces
- Further operating conditions
  - Saturation
  - Temperature
  - Manufacturing Tolerances

Rotating Magnetization



Variations of actual B-loci in the stator and rotor of electrical machines

Non-sinusoidal Excitation



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  - Saturation
  - Temperature
  - Manufacturing Tolerances

Scope of Advanced Testing in the RFCS STeELS-EM Project

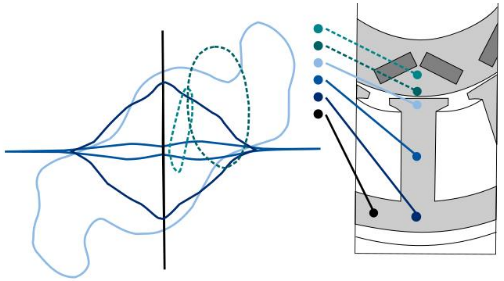
Advanced characterization methods are essential for enhancing our understanding of materials.

Utilization of advanced characterization methods in the RFCS Project,

– Effects of rotating magnetization

Neutron grating interferometry

Standardized Testing versus Realistic Magnetization Conditions in Electrical Machines



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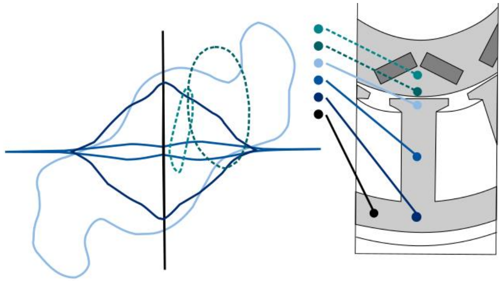


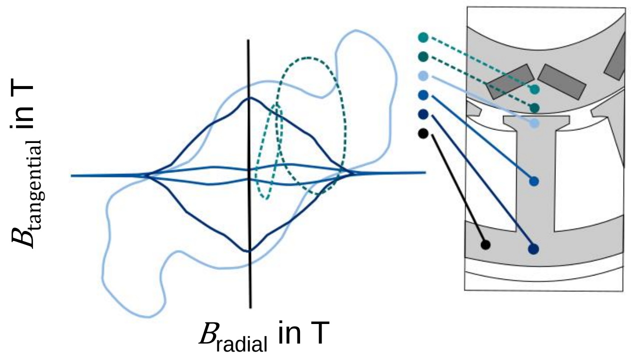
Importance of Rotating Magnetization and Vector Properties in Electrical Machines

1. Depending on the position in the magnetic circuit, different B loci appear during operation
   - Usual assumption → alternating flux density
   - Actual B-loci can have rotating magnetic flux components

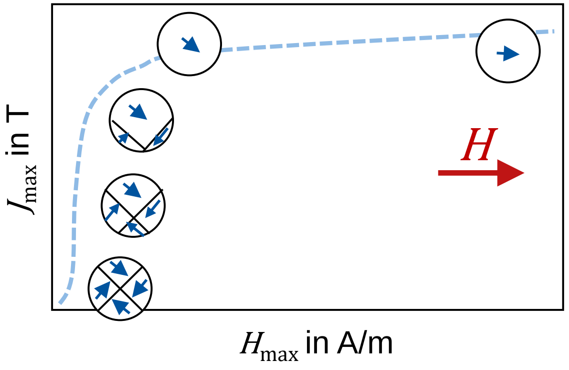
2. Interaction with anisotropic material behavior
   - Non-linear material behavior
   - Spatial orientation of field loci is important

3. Vector properties are usually neglected with standardized setups
   - Common simplification
   - Needs to be accounted for when studying certain effects

Actual B-loci in Electrical Machines



Vector Properties and Domain Structure



Resulting Polarization only aligns with external field in full saturation

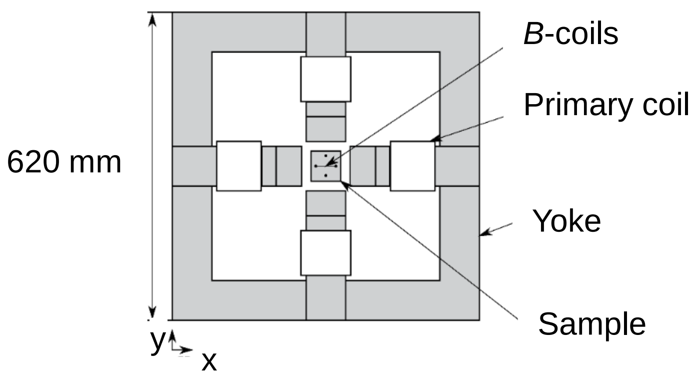
Effects - Rotating Magnetization and Vector Properties

Rotational Single-Sheet Tester (RSST)

- Rotating Magnetization
  - Four primary coils for magnetization in x- and y-direction
- Vector Properties
  - Four *H*-coils to approximate local magnetic field strength in sample area
  - Two search coils for measurement of B_x and B_y → windings applied in four drilled holes in sample
- Approximation of spatial magnetization loci in rotating electrical machines by
  - Unidirectional magnetization, elliptical magnetization, rotational magnetization

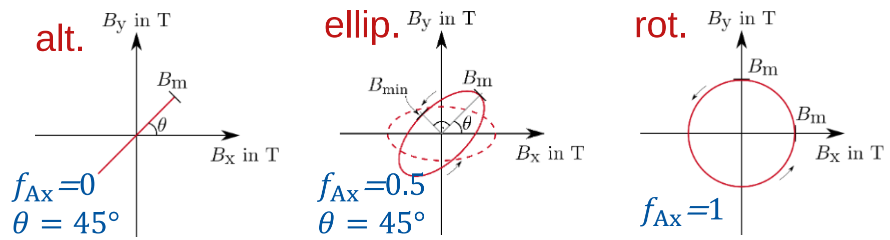
f in Hz	B_m in T	f_{Ax}	θ in °
50 - 1000	0.1 - 1.6	0.0 – 1.0	0 - 90

Schematic Drawing of RSST



Different Measurement Parameters

Axis ratio f_{Ax}
Displacement angle θ



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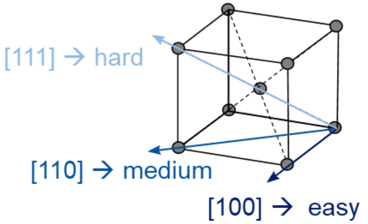
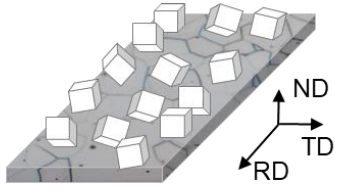
Phenomenology - Magnetization Behavior at Rotating Magnetization

- Controlled rotating J-Loci at 50 Hz for exemplary axis ratio f_{Ax} of 1.0 (rotating)
- At rotating magnetization, magnetic anisotropy leads to different required magnetic fields H in different directions of the sheet plane
  - Effect is pronounced at medium to high polarization where crystallographic texture effect is dominant
  - At medium to lower polarizations required H is more elliptical/square due to mechanical stress effect

Anisotropy of Unit Cell

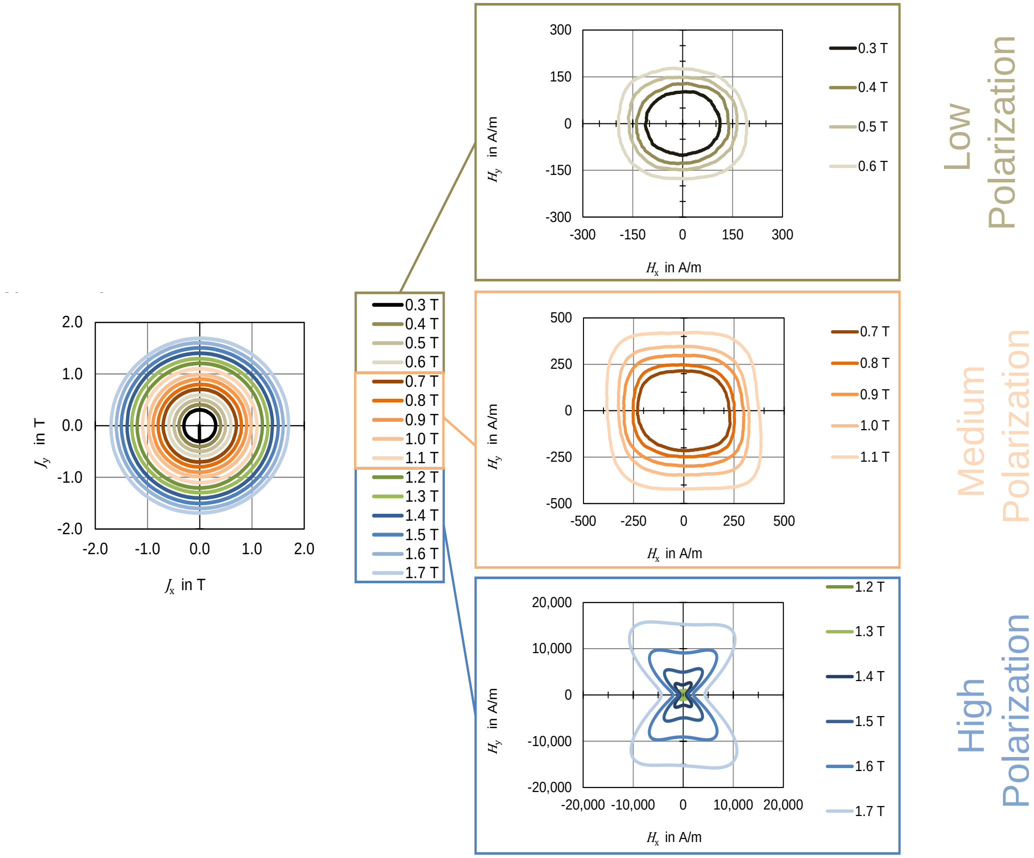


Crystallographic Texture



ND: normal direction

J-loci at $f = 50\ \mathrm{Hz}$ for Exemplary Sample K426F



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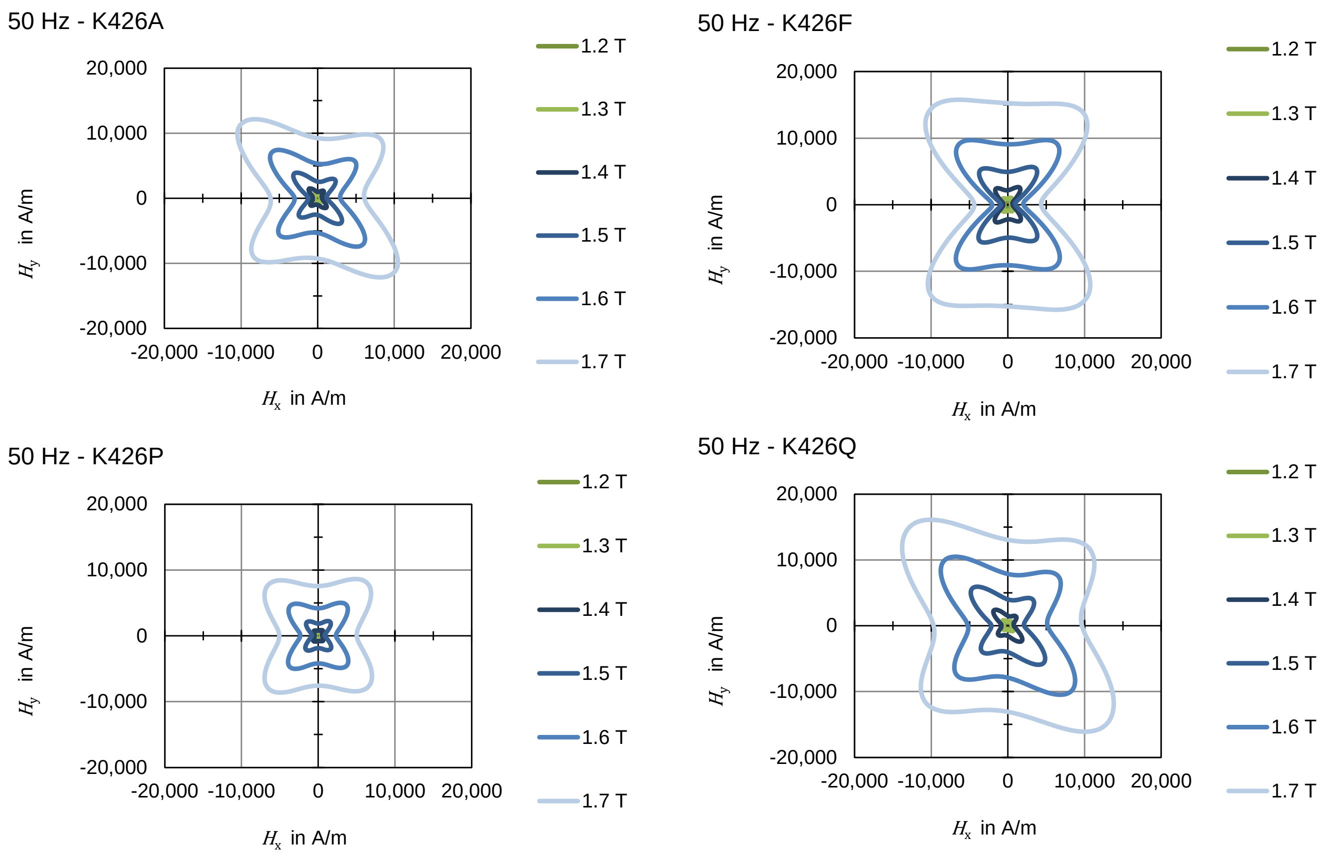
Effects - Rotating Magnetization and Vector Properties

Results of Studied Materials

Name	Si-Content	Ti-added	Hot Rolling	Cooling	Hot Band Annealing	Interm. Annealing	Final Annealing
K426A	high Si	no	RT1250	CT700	NOHBA	1050	1000
K426F	high Si	no	RT1050	CT700	NOHBA	1050	1000
K426P	high Si	added Ti	RT1050	CT700	HBA	1125	1070
K426Q	low Si	added Ti	RT1250	WQ	NOHBA	1100	1080
K426X	high Si	added Ti	RT1250	CT700	HBA	1125	1080

- Anisotropy and vector properties are distinctly different
- K426P hast the best magnetic properties, i.e. lowest magnetic field and less anisotropy
- K426Q has the worst magnetic properties, i.e. highest magnetic field

***J*-loci at $f = 50$ Hz for Exemplary Sample K426F**



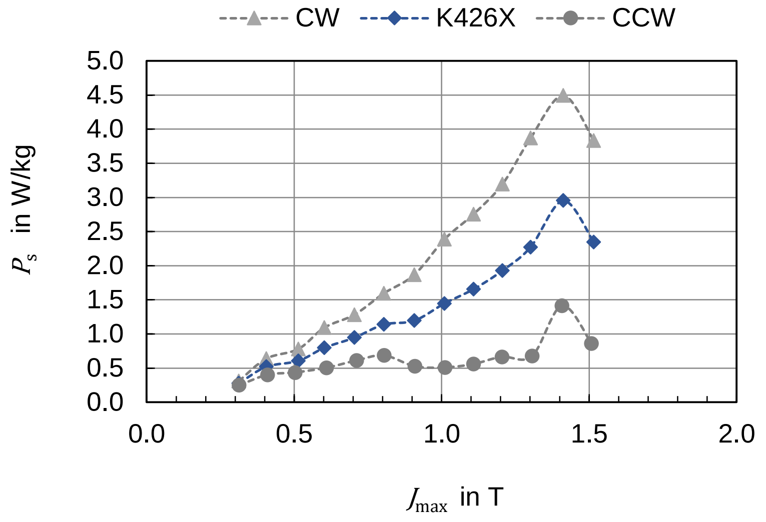
Effects - Rotating Magnetization and Vector Properties

Phenomenology - Iron Loss at Rotating Magnetization

- For rotating magnetization, resulting iron loss strongly differs from unidirectional magnetizations
- Increased general movement of domain walls for low and medium saturation states of materials
- Near saturation Polarization J_S → magnetic moments overcome anisotropy energy and start to rotate following the applied magnetic field → decrease of loss
- Measurements performed clockwise and anti-clockwise

Hysteresis loss declines for high rotating magnetizations → smooth transition with respect to J_m

Iron Loss at Rotating Magnetization



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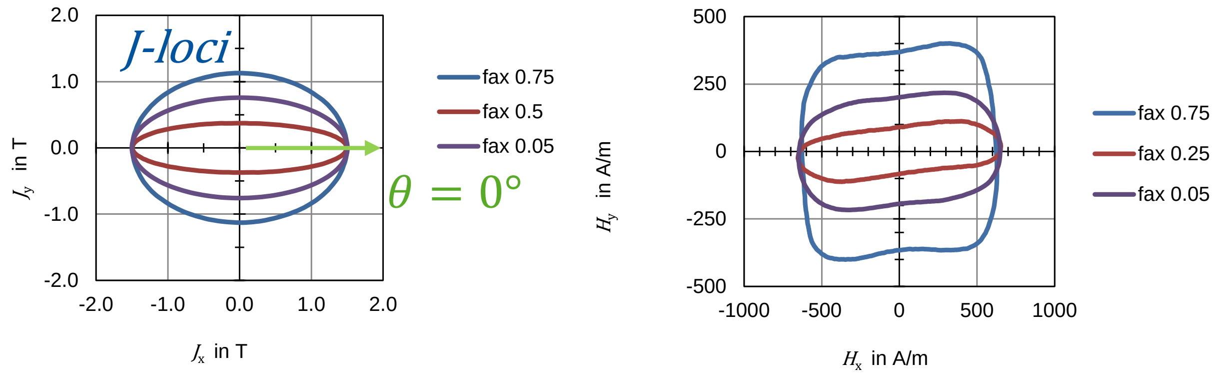
Effects - Rotating Magnetization and Vector Properties

Elliptical B-loci

- Elliptical Loci results in more distorted required magnetic fields to magnetization
- It is important to account for effects of rotating magnetization and vector properties in the deeper analysis of electrical steel and their applications

J-loci and resp. Magnetic Field at $f = 50$ Hz, 1.5 T with displacement angle $\theta = 0°$



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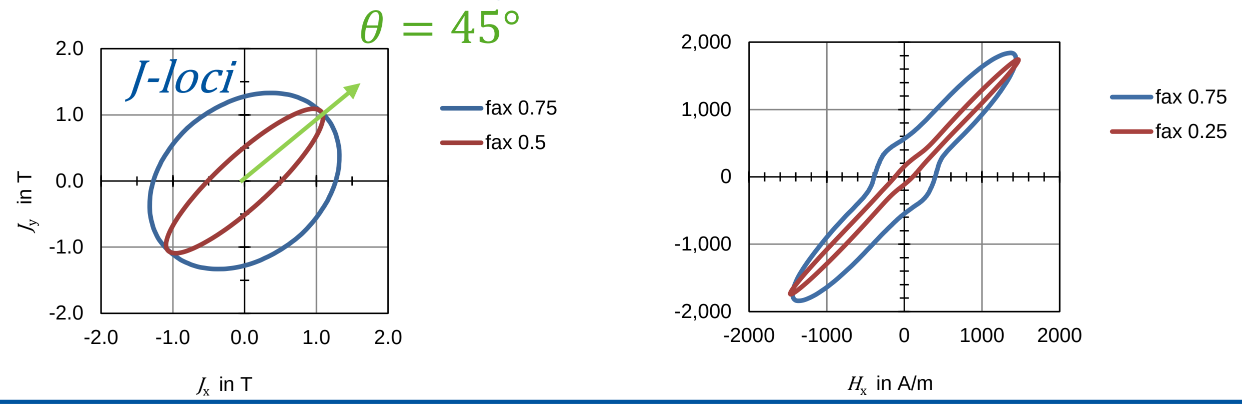

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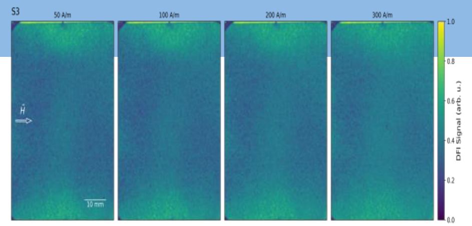
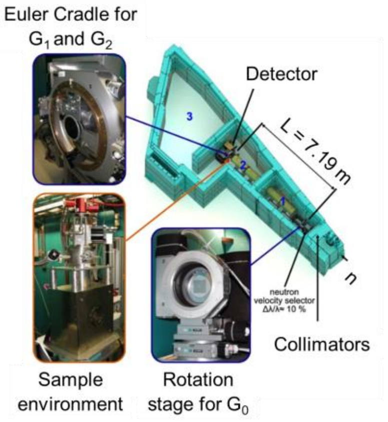


Neutron Grating Interferometry (nGI) for Electrical Steel

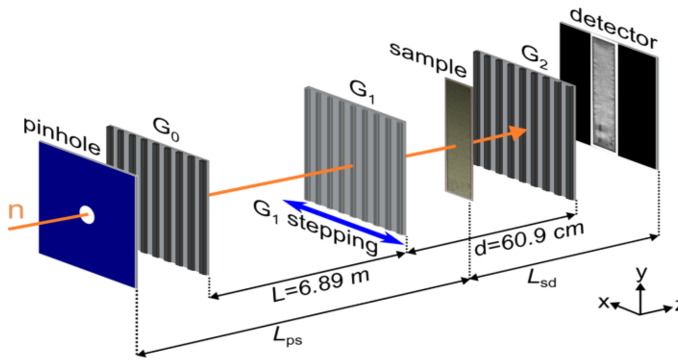
- Neutron-based imaging technique that utilizes the principles of grating interferometry to probe the internal structure and properties of materials
  - nGI modulates neutron beams using periodic gratings
  - Gratings create interference patterns for sample analysis
- Gratings in nGI Setup:
  - Beam Splitter Grating (G_0): Splits the beam into coherent parts
  - Phase Grating (G_1): Induces phase shift in the neutron wavefront
  - Analyzer Grating (G_2) : Transforms phase modulation into intensity modulation
- Sample placed between G_1 and G_2, neutron beam interacts with sample and domain walls. Resulting interference pattern recorded by a detector.

Antares Beamline

Experiments conducted at PSI, Villigen, Switzerland but performed by MLZ staff from TU Munich



Gratings in the Measurement Beamline



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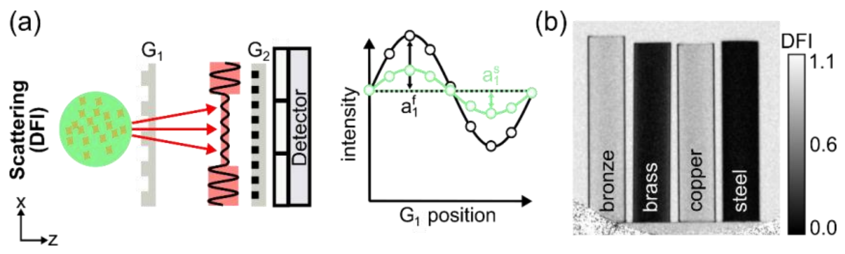
Neutron Grating Interferometry

- General Imaging Techniques
  - Transmission Image (TI)
  - Differential Phase Contrast Image (DPC)
  - Dark Field Image (DFI)

- DFI used to study domain structures in electrical steel
  - Scattering of neutrons occurs at domain walls, altering the beam's phase and amplitude
  - Changes in domain structure due to magnetization are captured with high contrast in DFI
  - Highlights domain wall movement and reorientation under an applied magnetic field

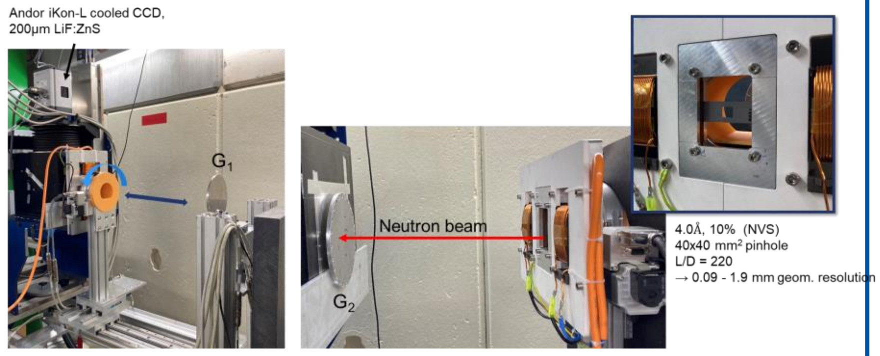
- Magnetizing Yoke added to nGI setup to study magnetization of electrical steel.
  - Sample dimensions: 60mm × 60mm (same as RWTH Aachen’s Single-Sheet-Tester)

DFI Imaging Principle



Vortex matter beyond SANS,
T. Reimann, Thesis, 2017

Magnetizing Yoke in nGI Seupt



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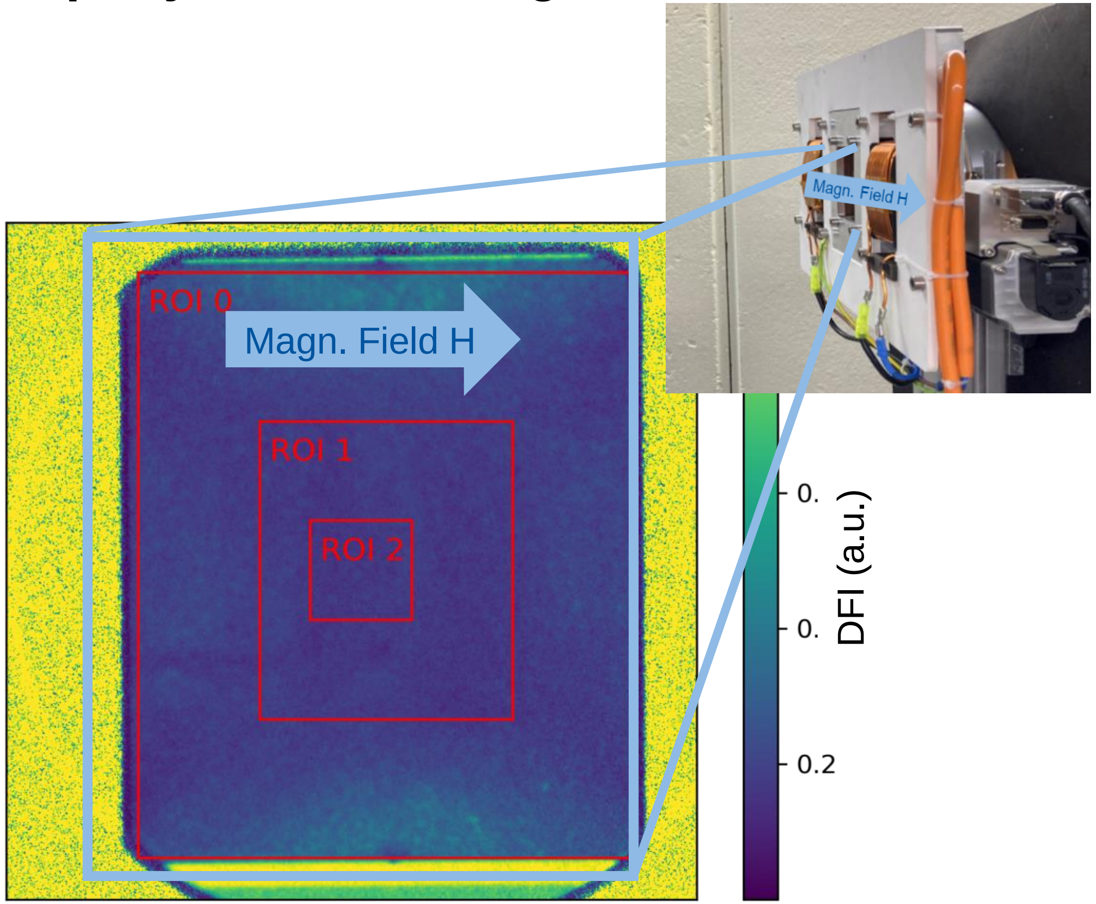
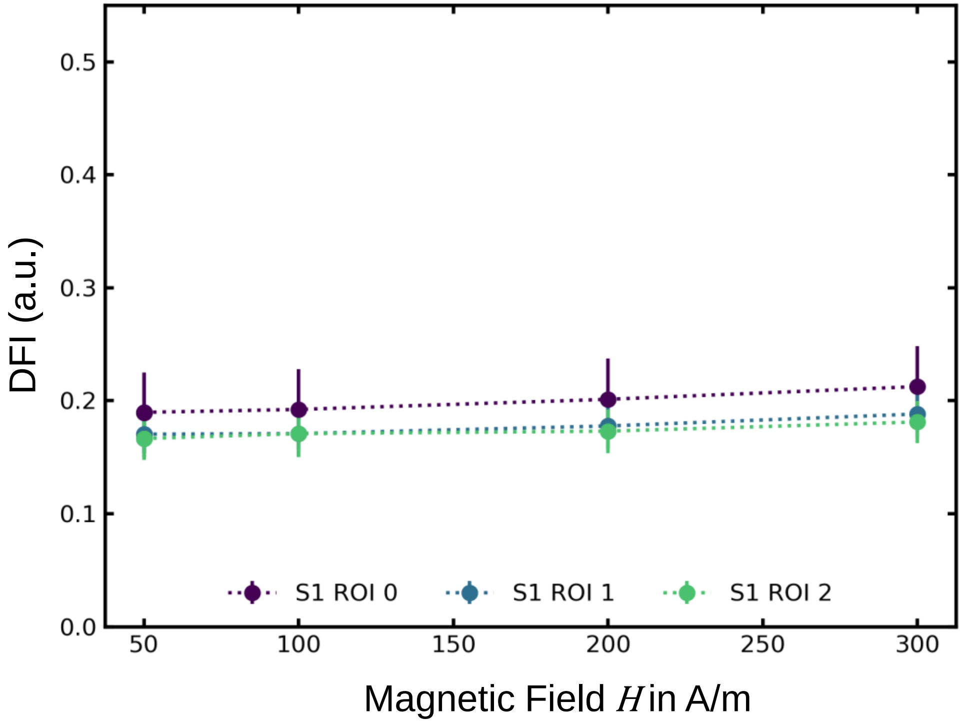
Exemplary Results – Region of Interest



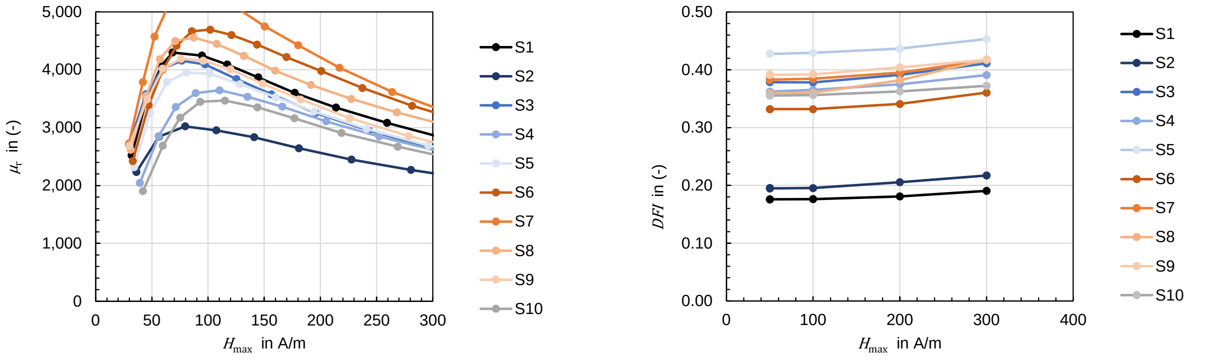


Effects – Neutron Grating Interferometry

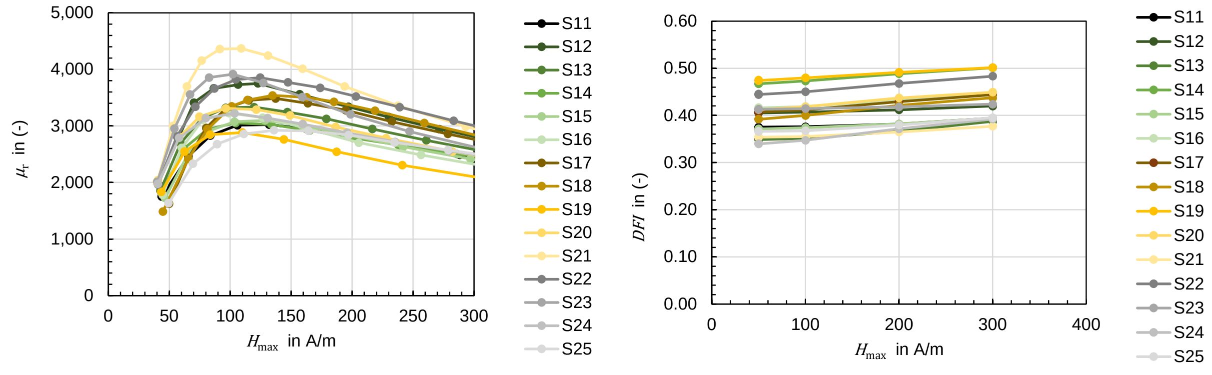
Results

- In total 25 material samples have been tested at four different magnetic field strength
- DFI signal increase as the scattering is expected to be less due to domain growing
- Two waves
  - Without Ti (top)
  - With Ti (bottom)
- Variations of Si-content, hot band annealing, cooling, intermediate and final annealing

Without Ti



With Ti

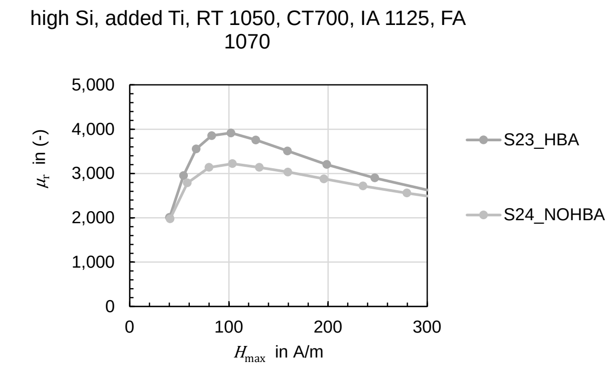


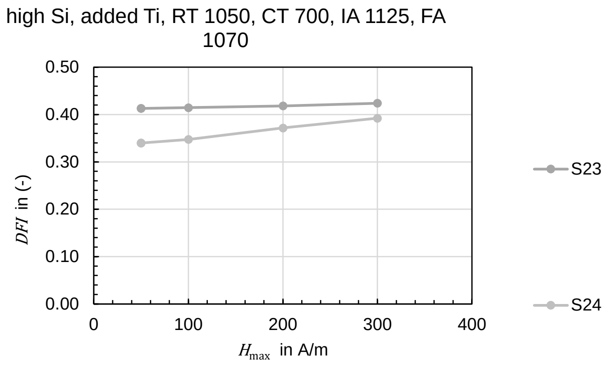
Effects – Neutron Grating Interferometry

Exemplary Results

- When samples are compared which differ only in one parameter, the DFI signals correlates with the permeability
  - Higher permeability means easier domain mobility during magnetization and thus less scattering
  - Grain size and precipitations can impede domain wall moving
  - Mechanical stress is another factor influencing domain mobility

Only Difference Hot Band Annealing





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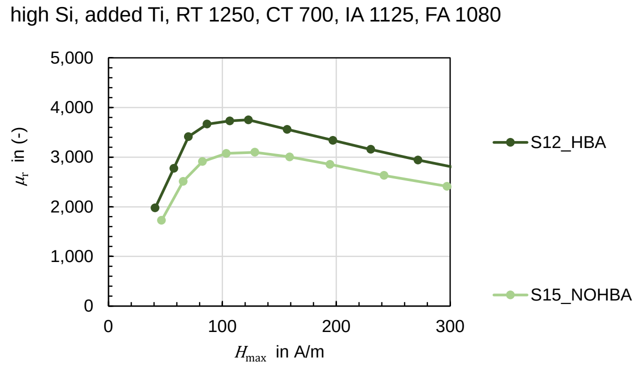

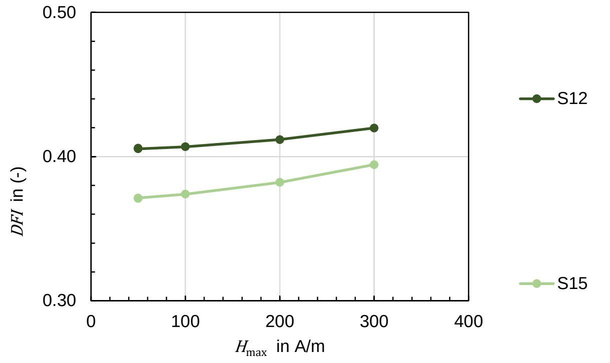

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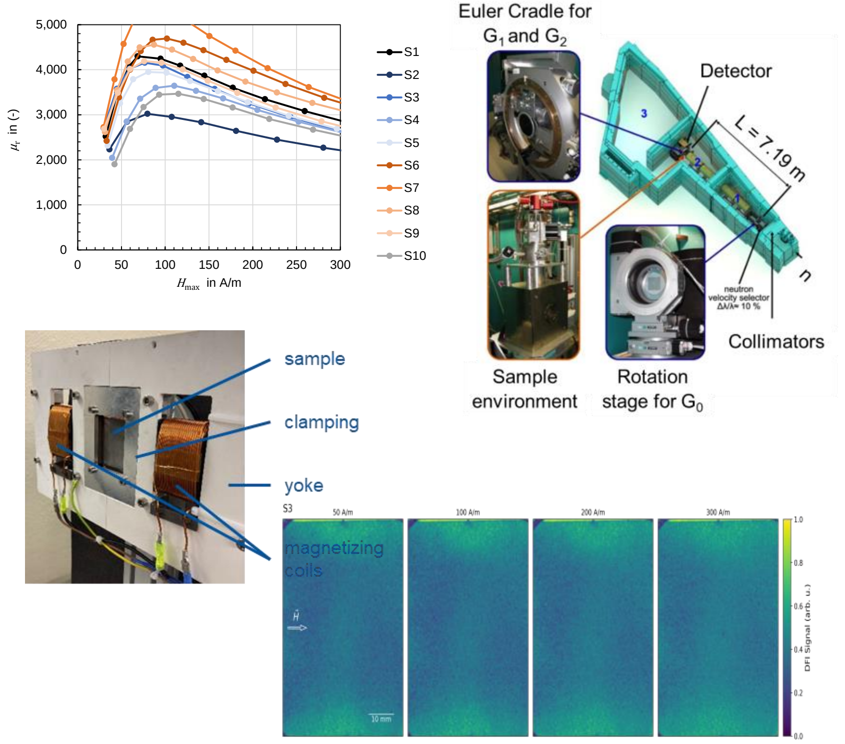
Conclusion for nGI Study

- For the majority of the samples, the DFI signal and magnetic measurements fulfill the expectations.
  - A high permeability is generally accompanied by a high DFI signal. This is observed when comparing the grades with and without Ti-added separately.
  - In general, grades without Ti-added exhibit higher peak permeabilities, but slightly smaller DFI signals which indicates an impact of additional material parameters.
- Some samples exhibited behavior deviating from the expectation. Further analysis on microstructural properties will be conducted to establish correlations between the nGI measurements, magnetic performance and the processing conditions.

nGI as an Advanced Characterization Technique for Electrical Steel



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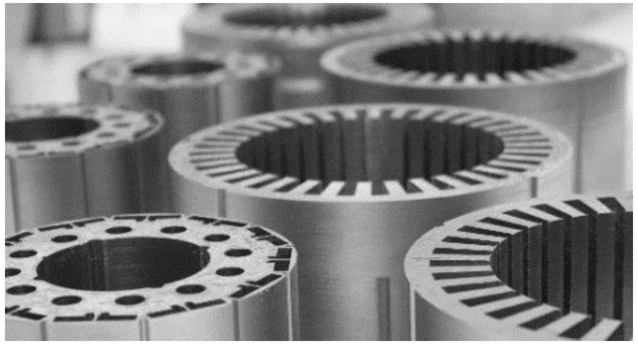
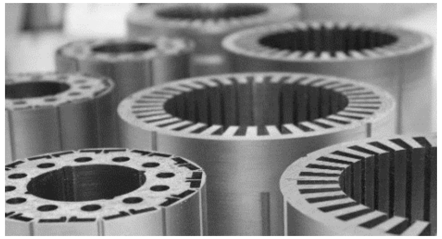
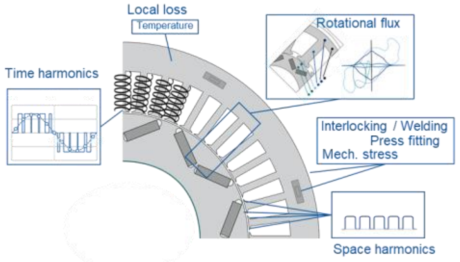


Summary & Outlook

- Compared to standardized measurements, the magnetization in electrical machines is subject to many nonidealities, e.g.
  - Rotational magnetization
  - Local variations of magnetic properties
  - Mechanical stress
- Advanced measurement setups are needed to understand the effects on a material level
- In the RFCS Project the advanced methods of RSST and nGI have been utilized to study selected samples to further the understanding of the impact of processing variations on the properties of electrical steel
- Outlook
  - Use results to develop, improve and validate material models

Nonidealities in Electrical Machines





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