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Outline

• A service for the CERN community
• A bit of physics
• Classification of magnetic materials
• Measurement principles
• A zoo of test benches
• Summary
• …a bit more. Digital twins.
• Future plans
A service for the CERN community - 1

- Materials have to display - thermal, electrical, mechanical, magnetic - properties compatible with the target application

- Assessing how a material behaves under the effect of a magnetic field is crucial for a vast range of applications at CERN

- At the TE-MSC-TM section we do this for you!

Superconducting magnets

Collars, vacuum chambers, etc.

Normal conducting magnets

Magnetic shields
Where most of the requests come from?

Reference period: 2015 - 2020

About 230 specimens in the last 5 years!
• Generally the single request may take into account multiple specimens. The time scale can be from 30 min up to an entire week for a single measurement.
A bit of physics

Maxwell’s equations in the local form

\[ \nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t} \]

\( \mathbf{H} \), magnetic field

\[ \nabla \cdot \mathbf{B} = 0 \]

\( \mathbf{B} \), magnetic flux density

\[ \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \]

\( \mathbf{E} \), electric field

\[ \nabla \cdot \mathbf{D} = \rho \]

\( \mathbf{D} \), electric displacement field

\( \rho \), free charge density

\[ \nabla \cdot \mathbf{D} = \rho \]

Constitutive laws

\[ \mathbf{E} = f(\mathbf{D}) \]

\[ \mathbf{B} = f(\mathbf{H}) \]

Characterizing magnetically a material means determining this law, typically non-linear and past-history dependent (hysteresis)

\[ B = \mu_0 \mu_r (H) H \]

\( B \), magnetic flux density

\( \mu_r \), magnetic relative permeability

\[ \mu_r = 1 + \chi_m \]

\( \chi_m \), magnetic susceptibility

\( \mu_0 \), magnetic permeability of the free space
Classification of magnetic materials

Diamagnetic materials (copper, mercury, silver, etc.)

\[ \mu_r < 1 \]

\[ \chi_m \approx -10^{-5} \]

Paramagnetic materials (aluminium, brass, bronze, etc.)

\[ \mu_r \geq 1 \]

\[ \chi_m \approx 10^{-5} \]

Soft ferromagnetic materials

\[ H_c < 1000 \text{ A/m} \]

Stainless steels

Pure irons, low-carbon steels

Silicon steels

\[ B_{\text{sat}} \approx 1.5 \text{ T} \]

\[ \mu_{r_{\text{max}}} > 1000 \]

\[ B_{\text{sat}} \approx 2 \text{ T} \]

\[ \mu_{r_{\text{max}}} > 1000 \]

Mild-, high-carbon steels

Iron-cobalt alloys

\[ B_{\text{sat}} \approx 2.3 \text{ T} \]

\[ \mu_{r_{\text{max}}} > 1000 \]

\[ B_{\text{sat}} < 1.2 \text{ T} \]

Permanent magnets (ferrites, AlNiCo, NdFeB, SmCo)

Strong domain wall interactions

\[ H_c > 1000 \text{ A/m} \]

Ferrimagnetic and anti-ferromagnetic materials

Ferromagnetic materials

Weak domain wall interaction

Ferrimagnetic

Antiferromagnetic

Hard ferromagnetic materials

\[ B_{\text{sat}} \approx 2.3 \text{ T} \]

\[ \mu_{r_{\text{max}}} > 20000 \]
The measurement methods can be grouped in three macro-areas:

- **Fluxmetric methods**: the sensing element, generally a pick-up coil, detects flux variations. The cause of the flux variations determines a sub-classification:

  - **Transformer principle**: Application of a time-varying magnetic field $H$.
  - **Generator principle**: The specimen is moved in a constant magnetic field $H$.
The measurement methods can be grouped in three macro-areas:

- **Flux distortion methods**: the application of a magnetic field $H$ on a test specimen having $\mu_r \neq 1$ determines a local distortion of the field lines. This distortion can be mapped by a sensor and the permeability can be evaluated by inverse-problem solving.

A vast choice of sensor technologies can be used for this approach: fluxgate magnetometers, Hall probes, NMR
Measurement principles - 3

The measurement methods can be grouped in three macro-areas:

- **Force detection techniques (Gouy balance):** the force on a test specimen under the effect of an applied magnetic field can be detected by a change in the apparent mass. This apparent change of mass is proportional to the magnetic permeability of the object.

![Schematic representation of a Gouy balance](image1)

![A commercial Gouy balance from Holmarc Ltd.](image2)
## A zoo of test benches - 1

### Magnetic measurements of materials

**Method**
- Fluxmetric methods
- Flux distortion methods

**Specimen shape**
- Toroidal samples
- Strips/Laminations
- Single sheets
- Cylindrical needles/small bricks
- Permanent magnets
- Arbitrary shape
- Arbitrary shape/cylinder recommended

**Bench**
- Split-coil permeameter
- Custom-winding permeameter
- Cryogenic permeameter
- Superconducting permeameter
- Epstein frame
- Single sheet tester/coercimeter
- Vibrating sample magnetometer
- Mini-permeameter
- Rotating sample magnetometer
- Static-sample magnetometer
- Foerster magnetoscope

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**MSC Seminar – 29/04/2021**  
The lower the permeability, the higher must be the applied test field.

- **MSC Seminar – 29/04/2021**
A zoo of test benches - 3

- **Split-coil permeameter**

- **Old** (first version dated 1967) but **gold**
- Based on the **fluxmetric method** principle
- **Fast characterization** at RT. Results in 30 min.
- $H$ analytically determined from the current reading.
- $\frac{u(\mu_r)}{\mu_r} \approx \frac{u(B)}{B} \approx 0.1\%$ for most of ferromagnetic steels
- Static and dynamic determination of the magnetic properties. Up to 10 Hz with laminated specimens.
- Measurements compliant with IEC norm
- Non-optimized for high-permeability alloys (up to 10 % uncertainty)
- Non-optimized for low-permeability materials (up to 5 % uncertainty)
A zoo of test benches - 3

- Split-coil permeameter – some measurements worth mentioning

Selection of ARMCO’s annealing sequence for HL-LHC magnet yokes

Assessing the effect of cold work for HL-LHC magnet yokes

Selection of steels for FCC-ee magnet prototypes
A zoo of test benches - 4

• Custom-winding permeameter
  • Manual winding of the coils allows to cover what the split-coil permeameter can’t do
    • Very-high permeability materials (i.e. mu-metals)
    • Fewer excitation turns can be used to measure low magnetic fields (<10 A/m) by using conveniently high currents.
  • Dynamic characterization possible up to 1 kHz for some materials
• Non-standard sized toroids
  • Maximum field limited to 6 kA/m at RT for thermal reasons and to limit the coil resistance.
  • It works at cryogenic temperatures!
A zoo of test benches - 4

- Custom-winding permeameter – some measurements worth mentioning

Characterization of Mu-Metal for CLIC beamline shielding

Characterization of Vitroperm500F for current derivative sensors

Warm characterization of CRYOPHY for HL-LHC crab cavities
A zoo of test benches - 5

• Cryogenic and superconducting permeameter
  • Measurements of ferromagnetic steels at 77 K (LN) and 4.2 K (LHe).
  • Holder made of 3D printed bluestone to avoid mechanical stress on the specimen (0.01%/K thermal coefficient) and preserve the sensing coil area (thanks to G. Kirby, MSC-SMT, for the tip).
  • With a 3200-turns of excitation coil in NbTi, we reached an internal record measured field in a toroidal specimen of about 2.8 T!

Data related to an ARMCO specimen for HL-LHC. The hysteresis shape is mainly due to eddy-current effects when ramping up and down the material.
A zoo of test benches - 6

- Epstein frame
  - **Introduced** in late 2018 in our equipment
  - Working on the **fluxmetric method** principle
  - Magnetic characterization of strips, arranged in a squared magnetic circuit having 250 mm side. $H$ semi-empirically determined from the current reading.
  - Not as accurate as the toroidal solutions (1 %), although comparable with industry standards
  - **Grain-oriented silicon steels** measurable

Source: IEC 60404-2 norm

M1200-100A silicon steels tested in DC and at 50 Hz for the East Area Renovation Project
A zoo of test benches - 7

- Foerster magnetoskop
  - **Only** portable instrument available
  - Based on the *flux distortion detection* principle
  - Two probes, one of which with 10x sensitivity
  - Measurements of permeabilities from 1.00001 up to 2 at 80 kA/m (about 0.1 T) on a minimum volume of about 35 mm x 35 mm x 25 mm.
  - **Only 5% accuracy** (source: datasheet)
  - Excellent for in-situ inspections of material batches

HGCAL plate (Type 304L) inspection for CMS
A zoo of test benches - 8

- Static-sample magnetometer (SSM)

Test bench layout

Post-processing flowchart

\[ \mu_r = 1.00268 \]

Example of output of the problem
A zoo of test benches - 8

• Static-sample magnetometer (SSM) – main features

  - Working on the **flux distortion detection** principle
  - High-repeatability ($< 10^{-5}$) and high accuracy ($\approx 10^{-4}$)
  - Specimen having arbitrary shape. Dimensions must be compatible with the available air-gap.
  - Measurements only possible for fields $\geq 0.1$ T in a high homogeneity dipole magnet
  - Measurements at cryogenic temperatures not yet possible (cryogenic NMR difficult to be manufactured and difficulties in making a moving cryogenic system)

• Fully-working from end 2019

MSC Seminar – 29/04/2021

A zoo of test benches - 8

- Static-sample magnetometer – some worth mentioning results

![Image of test bench]

**Characterization of 10RM18 for HL-LHC collars**

**Magnetic permeability measured on a bellows of 1.4441 (316L)**

![Graph showing magnetic permeability measurement](image)

Lowest ever measured permeability values (tungsten alloy) – validated by Univ. of Zaragoza

![Graph showing permeability values](image)

Triple cross-check with three different methods

![Graph showing permeability comparison](image)
A zoo of test benches - 9

- **Mini-permeameter**

- Introduced at the end of 2020 in our equipment
- Based on the **fluxmetric method** principle. This time, given the low permeabilities, the field source is a high-field dipole magnet.
- Smallest test specimen (4x4x10 mm3) among our internal solutions
- Good resolution ($10^{-4}$) and accuracy ($10^{-3}$)
- Tests at fields below 0.1 T possible. This allows to locate the peak permeability (wide test field range).
- Possible tests permeabilities up to 10. Above, this level, the demagnetizing factor cannot be neglected and toroidal specimens are recommended.
A zoo of test benches - 10

- Vibrating sample magnetometer

- Reference system in many standard institutes. It belongs to the group but not to our section. We outsource the measurement to MSC-SCD when possible, especially for cold tests (thanks to D. Richter for the precious help).

- Based on the **fluxmetric method** principle in generator configuration.

- Possible tests field up to 10 T in a wide range of temperatures (1.9 K up to 200 K), with very high accuracies (< 10^-5).

- Possible tests permeabilities up to 10. Above this level, the demagnetizing factor cannot be neglected and toroidal specimens are recommended.

Characterization of AISI 310S at different fields and temperatures
A zoo of test benches - 11

- Rotating sample magnetometer

- Reference system for hard magnetic materials (permanent magnets), **based on the fluxmetric method**
- Recently **fully automatized** for long series measurements. 5 min – 30 repetitions per single PM block.
- The giant area of the coils ($> 100 \, m^2$) determines high sensitivity and good accuracy (up to 0.1 % of the magnetic moment, 0.15° of angle accuracy).
- **No hysteresis. It just detects the remanence** $B_r$ **of the blocks.**
A zoo of test benches - 11

- Rotating sample magnetometer – some results worth mentioning

\[
\begin{align*}
\sigma(m) &= 0.6 \%, \text{ max dev. } 2 \% \\
\sigma(\bar{a}b - AVG) &= 0.39^\circ, \text{ max dev. } 1.44^\circ \\
\sigma(\bar{ac}) &= 0.49^\circ, \text{ max dev. } 1.9^\circ.
\end{align*}
\]
Summary

- A wide range of test methods is available at CERN TE-MSC to characterize magnetic materials. Complementary methods are necessary to cover a wide spectrum of requirements.

<table>
<thead>
<tr>
<th>Test bench</th>
<th>H-field range</th>
<th>Permeability range</th>
<th>Accuracy</th>
<th>Sample shape</th>
<th>Sample dimensions</th>
<th>Test temperature</th>
<th>Dynamic range</th>
<th>Test duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Split-coil permeameter</td>
<td>20 – 24,000 A/m</td>
<td>1.1-15,000</td>
<td>≤1% Ferromagn. Steels and very high permeability materials</td>
<td>Toroids</td>
<td>114 mm De 105 mm Di up to 19 mm H (15 mm preferred)</td>
<td>RT</td>
<td>DC-10 Hz Up to 50 Hz for H&lt;10k A/m</td>
<td>30 min for initial magnetization curve and continuous recorded hysteresis</td>
</tr>
<tr>
<td>Custom-winding permeameter</td>
<td>0.01 – 6,000 A/m - depending on number of excitation turns</td>
<td>1.1-500,000</td>
<td>1%</td>
<td>Toroids</td>
<td>Minimum 70 mm Di De &lt; 1.1 Di Minimum 5 mm H</td>
<td>RT</td>
<td>DC-10 Hz Up to 50 Hz for H&lt;10k A/m</td>
<td>30 min for initial magnetization curve and continuous recorded hysteresis</td>
</tr>
<tr>
<td>Cryogenic permeameter</td>
<td>0.01 – 24,000 A/m - depending on number of excitation turns</td>
<td>1.1-500,000 (cryog. Perm.) 10 - 10,000 (supercond. Perm.)</td>
<td>1%</td>
<td>Toroids</td>
<td>Minimum 70 mm Di De &lt; 1.1 Di Minimum 5 mm H</td>
<td>77K - 4K (cryog. perm.) 4 K (supercond. perm.)</td>
<td>DC-10 Hz</td>
<td>30 min for initial magnetization curve and continuous recorded hysteresis</td>
</tr>
<tr>
<td>Epstein frame</td>
<td>20 – 10,000 A/m</td>
<td>1.1-15,000</td>
<td>1%</td>
<td>Strips (min 4.)</td>
<td>Width 30 mm Length min. 280 mm - max. 320 mm</td>
<td>RT</td>
<td>DC-50 Hz</td>
<td>30 min for initial magnetization curve and continuous recorded hysteresis</td>
</tr>
<tr>
<td>Foerster Magnetoscope</td>
<td>80 kA/m</td>
<td>1.0001-2</td>
<td>5%</td>
<td>Arbitrary - cyl. preferred</td>
<td>Min. 30 mm x 30 mm x 25 mm</td>
<td>RT</td>
<td>DC</td>
<td>Few seconds</td>
</tr>
<tr>
<td>Static-sample magnetometer</td>
<td>80 - 800 kA/m</td>
<td>1.00001-1.1</td>
<td>about 5x10(-5) - regular geometries (cube, cylinder) 5x10(-4) - complex geometries</td>
<td>Arbitrary</td>
<td>CAD drawing required for complex geometries (.stp)</td>
<td>Max 60 mm heigth</td>
<td>RT</td>
<td>DC</td>
</tr>
<tr>
<td>Mini-permeameter</td>
<td>0-800 kA/m</td>
<td>1.001-10</td>
<td>10^(-3)</td>
<td>Bricks</td>
<td>4 mm x 4 mm x 10 mm</td>
<td>RT</td>
<td>DC</td>
<td>1 day with simple geometries 2 days for complex geometries</td>
</tr>
<tr>
<td>Vibrating sample magnetometer</td>
<td>0-8 MA/m</td>
<td>1.00001-10</td>
<td>10^(-5)</td>
<td>Bricks Needles</td>
<td>Max. 6 mm x 1 mm x 1.6 mm</td>
<td>1.9 k up to 200 k RT possible but risky for the integrity of the setup</td>
<td>DC</td>
<td>1 day with simple geometries 2 days for complex geometries</td>
</tr>
<tr>
<td>Rotating sample magnetometer</td>
<td>0</td>
<td>-</td>
<td>0.1% of the magnetic moment 0.15° angle accuracy</td>
<td>Cube Prismatic Bricks</td>
<td>Max. 150 mm x 150 mm x 150 mm</td>
<td>RT</td>
<td>DC</td>
<td>5 min</td>
</tr>
</tbody>
</table>
Summary

• Fluxmetric methods vs flux distortion detection methods? Which approach is better?

Fluxmetric methods are less accurate in the transformer configuration and the measurement duration should be kept short to limit the integrator drifts. However, the linearity of the coils determines extremely wide ranges of test fields.

Flux distortion methods can be more accurate but the range of test fields and the performance highly depend on the sensor technology (i.e. NMR, fluxgates).
• Whether you need a standard IEC/ASTM test or something customized, please feel free to contact us! Even if we don’t have a ready-to-use solution, we like challenges and we can develop something that fits your specifications!
...a bit more. Digital twins

- Neural networks for hysteresis modeling

- Hysteresis modeling is an extremely challenging problem because of intrinsic non-linearity and irreversibility

- We developed a model based on the combination of Preisach operators and a Recurrent Neural Network, capable of reaching good accuracy on unseen data.

- There are margin of improvements. At the moment

The model is limited to only waveforms similar to the ones used for the training.

The implementation in a model (i.e. FEM) would require a 3D vector model.

Hysteresis modeling is an extremely challenging problem because of intrinsic non-linearity and irreversibility
Future plans

- As many applications are at **cryogenic temperatures**, we want to improve the existing test methods and introduce new ones, especially for **low-permeability** materials. A cryogenic version of the **Static-Sample Magnetometer** is currently under development.
Future plans

• For the post-LHC era many systems would need to be **revamped** or even **re-designed**. Our oldest piece of equipment, the split-coil permeameter, is from the late ‘60s and we had to convert it from being water-cooled to air-cooled for problems of integrity.
Future plans

- We are evaluating the introduction of techniques based on quantum SI standards to improve the accuracy. SQUIDs seem to be a very attractive solution because based on the flux quantum constant, \( \Phi_0 \). SQUIDs can also bring benefits to other magnetic measurement systems (i.e. switching from \( B \) to \( \Phi \) as the basis for calibrations).

3D LTS SQUID sensor kit from Supracon AG

SQUID installation layout (no electronics)

Quantum SI units definition
Thanks for the attention

Any questions?