Revamp of the Epstein frame measurement system for characterising magnetic materials

Authors: Nele Reimets

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INTRODUCTION

Magnetic components are widely used in particle accelerators. In other fields like the industrial sector, magnets are often used as magnetic sweepers, sorters, and to separate impure metals during metal manufacturing or recycling. Magnets are also used in on-off applications, such as cranes sued for heavy lifting. In electronic applications, magnets are used in speakers, televisions, telephones, radios, and videotapes.

There are two types of magnets: permanent magnets and temporary magnets. Temporary magnets can be useful in applications that generate a temporary magnetic field and require a magnetic response for the duration of the field [1]. Electromagnets are temporary magnets, which means they act like magnets when current passes through the coil of the magnet. It is possible to control the magnetic properties of an electromagnet by controlling the current [1]. Electromagnets are made of soft iron or silicon steel and are used in electrical machines like motor and generator [2]. Permanent magnets are used to manufacture motors, refrigerator magnets, as well as in jewellery making [1]. Magnetism of a material can be lost at the Curie temperature. The Curie temperature is the critical point at which a material's intrinsic magnetic moments change direction. Spontaneous alignment of magnetic moments occurs below Curie temperature, which means magnetic properties get weaker on higher temperatures [3].

1. MAGNETIC MATERIALS
   1.1. Classification of Magnetic Materials

Magnetic materials are divided between diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic, and ferrimagnetic materials. Electron’s spin produces magnetic dipole moment which lets the magnetic field be either in upward or downward direction [5]. Diamagnetic materials have no net atomic or molecular moment. When subjected to an applied field, atomic currents and induced magnetic field are generated, which opposes the external field and causes a repulsive force. Diamagnetic material is for example bismuth (Bi), mercury (Hg), silver (Ag) [6].

Paramagnetic materials have a net magnetic moment at the atomic level, but the coupling between neighbouring moments is weak. The moments align with an applied field, but the degree of alignment decreases at higher temperatures due to thermal agitation [6]. A material is paramagnetic only above its Curie temperature. Paramagnetic materials are non-magnetic when a magnetic field is absent and magnetic when a magnetic field is applied [3].

Ferromagnetic materials are the strongest magnets when external magnetic field is applied. They have a net magnetic moment at the atomic level and a strong coupling between neighbouring moments [6]. Materials are only ferromagnetic below their corresponding Curie temperatures [3]. Ferromagnetic materials are for example iron (Fe), cobalt (Co), nickel (Ni) [6].
Antiferromagnetic material has oriented atomic moments with neighbouring moments antiparallel to one other. The moments are equal and cancel each other. Antiferromagnetic materials are among transition metal compounds, oxides. For example, hematite (Fe$_2$O$_3$), chromium (Cr), iron manganese (FeMn), nickel oxide (NiO). Ferrimagnetic materials are like antiferromagnetic materials, except they have a net magnetic moment due to that opposing moments are unequal. Ferrimagnetic materials can be Fe$^{2+}$, Fe$^{3+}$, magnetite (Fe$_3$O$_4$) [6].

Electromagnets can be divided in to normal conducting magnets (NC) and superconducting magnets (SC). These electromagnets are used for particle accelerators and beam transfer lines. Normal conducting magnets as well as superconductive magnets can be iron-dominated or coil-dominated. Magnets with iron yoke rely on a core made of ferromagnetic material to guide and to concentrate the magnetic flux [7]. Normal conducting magnets have high field quality because the yoke can be shaped with high precision [8]. Soft ferromagnetic materials are the materials most often used for electromagnet cores [9]. As normal conducting magnets are limited to about 1.5 T magnetic fields, superconducting dipoles, quadrupoles and correction magnets are necessary to achieve the high magnetic fields required for accelerators. Superconductivity can be used in accelerator magnets to save electrical energy or to increase the field strength or to do both [10].

1.2. Parameters of an Electromagnet’s Core

For different applications special characteristics of a material are essential to achieve the most desirable effect from the magnet. Parameters of interest when choosing the material of the core of an electromagnet are permeability, saturation, coercivity, resistivity, thickness [9].

The harder the material is the more permanent is the magnet. In detail, it is more difficult to magnetize and demagnetize the magnet in an altering current field, which result in power losses called hysteresis losses [11]. Another important aspect when taking into account the power losses is thickness. Thickness is important because it might produce undesirable effect in power loss – eddy current. Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor due to Faraday’s law of induction. Eddy currents flow in closed loops within conductors, in planes perpendicular to the magnetic field. To reduce the eddy currents the core of a magnet is made of thin laminations parallel to the field with insulation between them. Thinner the laminations are the smaller is the electrical current in eddy currents [12].

Saturation is the point where external magnetic field cannot increase the magnetization of a material. This parameter is important to determine the size of the core of an electromagnet [13]. In addition to saturation, coercivity is relevant. Coercivity is a measure of the ability of a magnetic material to withstand an external magnetic field without becoming demagnetized [14]. Coercivity, $H_c$ is measured in A/m. Besides the above mentioned parameters, one has to consider the resistivity of a material. Resistivity quantifies how strongly a material opposes the flow of electric current. Usually metals have a high conductivity and a low resistivity [15].
2. THE B-H CURVE

The B-H curves (see Error! Reference source not found.) show the behaviour of a ferromagnetic core graphically as the relationship between flux density, $B$ and magnetic field, $H$. Flux density unit is tesla (T). Having infinitely long conductor with a current $I = 1$ A perpendicular to an external flux density field, a force of 1 newton will be imparted to each meter of the conductor when $B = 1$ T. Field strength $H$ is in A/m. Having a straight, infinitely long wire carrying a current $I = 2\pi$ A, the conductor generates a tangential field strength $H = 1$ A/m at a radial distance $r = 1$ m from its centre [6].

Starting with a non-magnetized core (Figure 2) both $B$ and $H$ will be at zero. If the magnetization current is increased in a positive direction, magnetic field, $H$ and flux density, $B$ will increase. At some point flux density reaches its maximum and obtains saturation in point a [16].

After the magnetizing current in the coil is reduced to zero, the magnetic field circulating around the core also reduces to zero. However, the core flux density will not reach zero due to the residual magnetism present within the core and this is shown on the curve from point $a$ to point $b$. This ability for a core to retain some of its magnetism after the magnetization process has stopped is called retentivity or remanence, while the amount of flux density remaining in the core is called Residual Magnetism, $B_R$. Some of the tiny molecular magnets do not return to a completely random pattern and still point in the direction of the original magnetizing field giving them a sort of “memory”. Some ferromagnetic materials have a high retentivity making them excellent for producing permanent magnets [16].

To reduce the flux density at point $b$ to zero we need to reverse the current flowing through the coil. Coercivity is the magnetizing force which must be applied to null the residual flux density. It reverses the magnetic field re-arranging the molecular magnets until the core becomes unmagnetized at point $c$. If the reverse current is continuing the core will be magnetized again,
but in the opposite direction and at point \( d \), symmetrical to \( a \), it reaches its saturation. Same process will apply so that the B-H curve follows the path of \( a-b-c-d-e-f-a \) and is called Magnetic Hysteresis Loop [16].

3. MEASUREMENT METHODS

3.1. Split-Coil Permeameter / DC Measurement

The split-coil permeameter is composed by two coils wound in a toroidal shape, which can be opened allowing to wrap a toroidal specimen. One coil is to excite the field and the other one, sensing coil, to capture the flux [17]. The measurement setup is presented in Figure 3. Measurements are carried out by a split-coil permeameter, integrated with the proper acquisition system and software interface. The sample is magnetized by means of the excitation coil, which is supplied by a voltage controlled current generator. The measurements are performed by ramping the current in the excitation coil back and forth between positive and negative values. Each ramp is followed by a plateau where the current is constant and the amplitude is slightly changed after each ramp. During the excitation, the output voltages at both the measurement coil and the current sensor are continuously sampled and recorded. The signal generator for controlling the current source and the two analog-to-digital converters (ADC) for acquiring the measurement signals are embedded in a Data Acquisition System (DAQ) communicating with a Personal Computer (PC) [18].

![Figure 3. The split-coil permeameter measurement system](image)

3.1. Epstein Frame / AC Measurement

The Epstein frame is a standardised measurement device for measuring the magnetic properties of soft magnetic materials, especially used for testing of electrical steels. The Epstein frame is a 25 cm square frame, which comprises a primary and a secondary winding [13]. The measurement setup (see Figure 4) consist of a power supply (PS), a shunt resistor \( R_s \), a standard Epstein frame, a data acquisition with analog to digital converter (ADC) and digital to analog converter (DAC) devices, and a PC which controls the process and stores measurement data. For the measurement input data like the characteristics of the sample and the testing conditions are required. Based on the input data the constants, the reference waveform and the degaussing waveform are calculated. Then sample will be demagnetized by applying a powering signal with slowly decreasing amplitude to the sample. The amplitude of the sinusoidal cycles will decrease with time. Most of the cycles will be in the low current range, which is an important
feature that ensures the demagnetization of materials with a narrow hysteresis cycle. After demagnetizing the sample, the excitation cycles are applied followed by several steps of signal processing. Waveform of the excitation field has been programmed using an inverse approach. The measurement procedure has been implemented using recursive digital control. By measuring the magnetic properties of a material with sinusoidal polarization waveform at 1 Hz, a ramping rate of the polarization like the one found in the core of a particle accelerator magnet has been achieved [4].

4. EPSTEIN FRAME MEASUREMENT SYSTEM RESULTS

4.1. Metrological Characterization

To revamp the Epstein frame measurement system and measure magnetic materials, system was first reassembled and brought to the lab (CERN building 311), where it was assembled again. For understanding the system and code used to automate the magnetic measurement procedure a thesis [6] was carefully studied. To make sure the Epstein frame measurement setup is working a material was tested. Sample was tested with frequency of 0.5 Hz, 1.0 Hz, 5.0 Hz, 50.0 Hz and a B-H curve was composed. On Figure 1 B-H curve for the material tested with 0.5 Hz is presented. The obtained B-H curve was analysed and as it corresponded to expected values, Epstein frame measurement system was approved.

According to [6] and [18] an outline of measurement principle is introduced. Together with the maximum polarization level ($J_{peak}$) and frequencies for testing the material the number of sheets ($N$), mass of the samples ($m$), length ($l$) and width ($w$) of the sheets as well as density ($\rho_m$) of the material is required as input data. The average cross-section of the stack of samples along the magnetic path is calculated automatically based on the input data by the control software with the following equation [14]:

$$A = \frac{m}{4l\rho_m}$$ (1)

The specific density is required for calculating the energy losses per mass unit and the cross-sectional area of the test specimen. The cross-section of the test specimen is required for converting from flux units (Wb) to flux density units (T).
When the material is demagnetized the first excitation cycle with sinusoidal signal of 3.25 periods with the amplitude of 5 A/m is applied to the sample. To ensure no data lost three consecutive cycles are used. After magnetization acquired signals are processed. For noise filtering data series are down-sampled to 5000 samples per cycle by averaging the extra samples. Following, the values of the excitation field \( H(t) \) is calculated with equation (2) and the polarization \( J(t) \) is calculated with the equation (3) implemented with the trapeze method:

\[
H(t) = \frac{N_{c1}i_s(t)}{l_m} = \frac{N_{c2}u_s(t)}{l_mR_s},
\]

(2)

where \( N_{c1} = 700 \) and corresponds to the number of windings in the primary coil, \( i_s \) is the magnetizing current acting upon the sample \( S \), \( l_m = 0.94 \) m is the length of Epstein frame magnetic circuit, \( R_s \) is the shunt resistor connected in series with the Epstein frame with 1 \( \Omega \) and 15 \( \text{W} \), \( u_s \) is the voltage drop on \( R_s \),

\[
J(t) = J_0 + \frac{1}{N_{c2}A} \int_{t_0}^{t_1} u_2(t) \, dt,
\]

(3)

where \( J_0 \) is a constant, \( N_{c2} = 700 \) the number of windings in the secondary coil, \( A \) is the cross-sectional area of a sample under test found with (1), \( u_2 \) is the voltage induced in the secondary windings of the Epstein frame, and \( t_0 \) with \( t_1 \) indicates the time. If the convergence criteria are not verified, a new waveform for the excitation cycle is modulated and the procedure is repeated.

4.2. Experimental Results

For the measurement two non-grain-oriented samples of the same material were used (Table 1). One was from the beginning of the coil and other was the end of the coil. Samples were tested under 0.5 Hz, 1.0 Hz, and 5.0 Hz. \( J \text{ peak} \), which is a numerical input box used to specify the maximum polarization level to be achieved during measurement [14], was set to 1.8 T. According to the results of the measurement a B-H curve was composed and metrological characterization with uncertainty was studied.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality</td>
<td>M1400-100A</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>voestalpine</td>
</tr>
<tr>
<td>Coil number</td>
<td>945719</td>
</tr>
<tr>
<td>Coat</td>
<td>5( \mu )m EB548 varnish</td>
</tr>
<tr>
<td>Cutting technology</td>
<td>Guillotine</td>
</tr>
<tr>
<td>Direction of magnetizing field</td>
<td>Parallel to rolling direction</td>
</tr>
</tbody>
</table>
On Figure 5 B-H curve for the beginning of the coil and end of the coil is presented. B-H curve gives a nice and quick overview of the magnetic properties of two coils. Lines overlap when tested with 0.50 Hz or 1.00 Hz. Both coils are made out of the same material and are for that reason compatible. Some differences can be observed between the B and E coils. Saturation starts at 1.50 T for B coil and 1.42 T for E coil and reaches 1.69 T for B coil and 1.67 T for E coil. Coercivity is achieved in -51.9 A/m for B coil and -56.4 A/m for E coil. The E coil curvature is higher than the B coil’s curvature in the knee area. The biggest percent error between B and E coils is 65% and it occurs between points [300 A/m; 1.30 T] for B coil and [182 A/m; 1.31 T] for E coil.

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure5.png}
\caption{B-H curve under 0.50 Hz using Epstein frame}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.4\textwidth]{figure6.png}
\caption{Magnetization (blue) and $\mu_r$ curves (orange) for B and E coil}
\end{figure}

Magnetization curve for E coil is higher in the knee area. Percent error between magnetization is the biggest between points [164 A/m; 0.93 T] for B coil and [193 A/m; 1.08 T] for E coil with 15% error.

Relative permeability $\mu_r$ can be expressed as

$$\mu_r = \frac{B}{H_0},$$

where $\mu_0$ is the magnetic constant with value $\mu_0 = 4\pi \times 10^{-7}$ Tm/A.
Relative permeability is represented in Figure 6. Relative permeability for the B coil is steeper after the maximum compared to the line for the E coil. For the B coil maximum $\mu_r = 6257$ Tm/A and for E coil $\mu_r = 5982$ Tm/A. The biggest percent error between relative permeability for B and E coil is 23% between points [74.2 A/m; 6128 Tm/A] for B coil and [96.9 A/m; 5860 Tm/A] for E coil.

The A-type uncertainty $u_A$ or standard deviation $\sigma$ for every measured point in the B-H curve and in the magnetization curve is calculated with a following formula:

$$u_A(\bar{x}) = \sigma = \sqrt{\frac{\Sigma_{i=1}^{n}(x_i-\bar{x})^2}{n(n-1)}},$$  \hspace{1cm} (5)$$

where $x_i$ is the $i$th value of the measured point, $\bar{x}$ is the mean value of the repeated measurements for $i$th point, and $n$ is the number of repeated measurements, in this case $n = 3$.

As the uncertainty gives the range for where the actual value is, percent error was calculated for both limits, the value with “+” and value with “-” uncertainty. The measured points in the B-H curve for the E coil have relatively small uncertainties. Percent error between the mean value of the measured point and the value with $\pm$ uncertainty stays in the range of $5.3 \times 10^{-7}$% to 1.3%. For the magnetization points percent error is between $6.6 \times 10^{-3}$% to 1.6%. The measured points in the magnetization curve for the B coil vary in the range of 0.0% to 2.0%. The smallest percent error for the points in B-H curve is $9.2 \times 10^{-5}$%. The biggest percent error for the points in the y-axis, in flux density, for value minus uncertainty is 33% located around zero-point. The same value with “+” uncertainty has the percent error of 20%. In the x-axis the biggest error, 14% occurs in the knee area in the positive part of the plot between the value and the value with “+” uncertainty. Taken the same point value with “-” uncertainty, the percent error is 11%.

**CONCLUSION**

For the revamp of the Epstein frame measurement system the system was assembled and carefully studied based on [6] and [18]. The code used for automating the measurement procedure was analysed and a material was tested to determine if the system is applicable. Based on the satisfying results of the measurement, the Epstein frame system was evaluated to be precise.

Following, two samples were tested for characterizing a magnetic material with Epstein frame measurement. Samples from the beginning of the coil and end of the coil of the same kind of a steel were measured under frequencies 0.5 Hz, 1.0 Hz, and 5.0 Hz. For both coils a B-H curve, a magnetization curve and relative permeability curve were constructed. Two types of the coil had similar shaped curves, but slightly different values of saturation and coercivity. The biggest difference between two coils was percent error of uncertainty, where for the B coil the maximum error was 33% while it was only 1.6% for the E coil. That allows to conclude that a same material can have varying properties in different areas. This must be carefully considered.
when choosing a magnetic material for accelerators and similar fields where high precision of a magnet is required.

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REFERENCES


