

A hybrid modeling environment to describe aggregates of cells heterogeneous for genotype and behavior with possible phenotypic transitions

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# On the importance of magnetic material characterization for the design of particle accelerator magnets

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**Abstract.** In this paper, the importance of magnetic material measurements in the framework of the design of magnets for particle accelerator is discussed. In particular, five samples of different ferromagnetic materials are analyzed experimentally and compared with literature results. These materials have been (or will be) used for producing yokes for several normal-conductor magnets at CERN, such as REX-ISOLDE main dipole, ELENA dipole and quadrupole, and SESAME dipole. The comparison with literature shows several disagreements. The main one of them is analyzed in detail in a case study based on finite elements simulation of a quadrupole magnet installed in CERN. This analysis shows that a good knowledge of the yoke initial magnetization curve is important to guarantee a given level of magnet performance, especially concerning its field quality.

## 1. Introduction

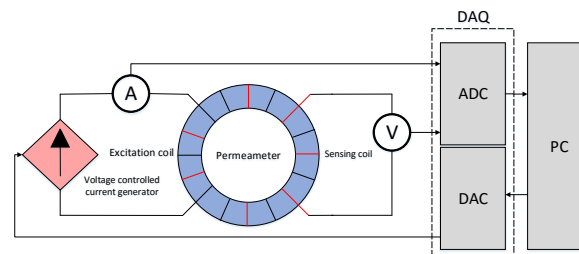
Magnetic materials are key pieces of a complex technology puzzle fundamental in satisfying basic demands such as generation, distribution, and conversion of energy, the storage and retrieval of information, and even in media and telecommunications [1]. Also in particle accelerators, all the involved magnetic materials have to be characterized by measuring mainly the initial magnetization curve ( $B$ - $H$  curve) and the relative magnetic permeability curve ( $\mu_r$ - $H$  curve). Several methods can be used, depending on the expected magnetic material behavior. At CERN, for feebly magnetic materials (with a relative magnetic permeability  $\mu_r$  less than 1.05), a measurement system based on a novel perturbative method, recently developed and described in [2], is available. For materials with  $\mu_r$  between 1.1 and 6.0, the standard measurement method is an adapted-to-low-permeability DC flux-metric method, described in [3]. Finally, for materials with  $\mu_r > 6.0$ , the method presented in the IEC Standard 60404-4 [4] was implemented by means of a unique device built at CERN. It allows to test the magnetic properties of material at room temperature, without the use of winding coils on a sample, the main drawback of the flux-metric approach. In this paper, the importance of magnetic material measurements in



the framework of the design of magnets for particle accelerator is discussed by referring to the recent CERN experience.

## 2. Measurement system

The measurement system architecture is shown in Fig.1. Two coils wound around a specimen are necessary: an excitation coil, carrying the current that generates the magnetic field of excitation, and a sensing coil, at whose terminals the induced voltage is measured. Both the current and the voltage signals are simultaneously acquired. The current is measured by a closed-loop current transducer providing at its secondary terminals a voltage proportional to the current. A computer stores all the acquisitions and controls a digital-to-analog converter (DAC) that sets a voltage which in turn defines the power supply current. All the computer operations are performed by means of a FFMM [5] package, a suite of interactive programs that allows to control the data-acquisition-system (DAQ). The measurements are performed according to the procedure and recommendations of the IEC standard 60404-4 [4].

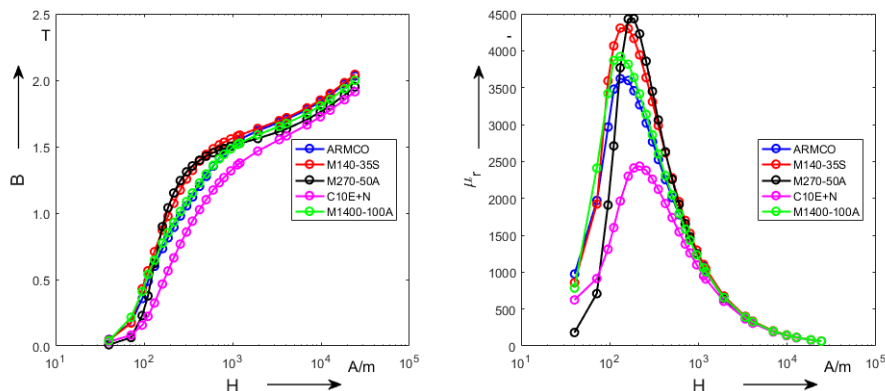


**Figure 1.** Architecture of the measurement system.

## 3. Characterization of ferromagnetic materials

This section shows the results of the magnetic characterization of five different ferromagnetic materials. The materials have been (or will be used) for the production of yokes of several normal conductor magnets at CERN.

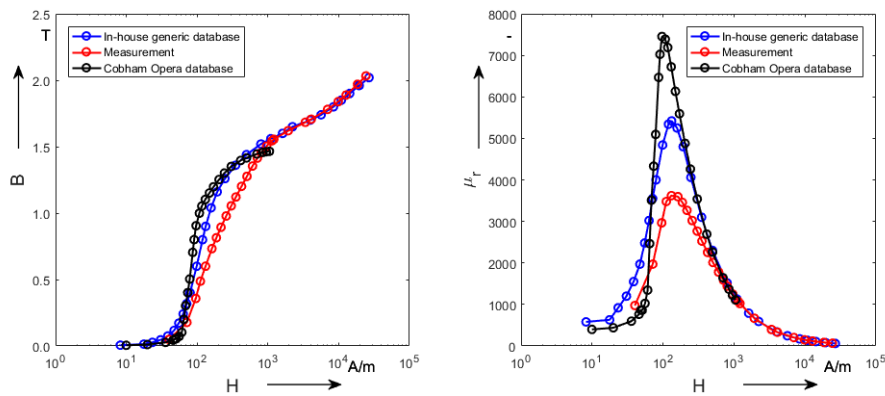
Fig. 2 shows the initial magnetization profiles (left) and the relative permeability curves of the materials (right).



**Figure 2.** Comparison among the initial magnetization curves (left) and relative permeability curves (right) of the five samples.

In Fig.3, the ARMCO curves stored in a CERN database and in OPERA [6] are compared with the curves obtained experimentally from its magnetic characterization. The OPERA trends are quite different from the other two, showing higher permeability peak and lower saturation level. The other two initial magnetization trends are quite similar (the logarithmic scale on  $x$ -axis amplifies the difference). This means they could refer to the same material and that the differences are probably caused by some post-production treatments or different annealing. Discrepancies are stronger in the first part of the magnetization curve, up to 1000 A/m. After this threshold, both curves have same shape, showing that the saturation region is less sensitive to annealing and other treatments. On the other side, the relative permeability curve and, specially, the permeability peaks show significantly different behaviors.

This comparison clearly raises the problem of checking how big is the impact of using a wrong  $B$ - $H$  curve during the magnet design phase. This problem is addressed in the following section for a case study.



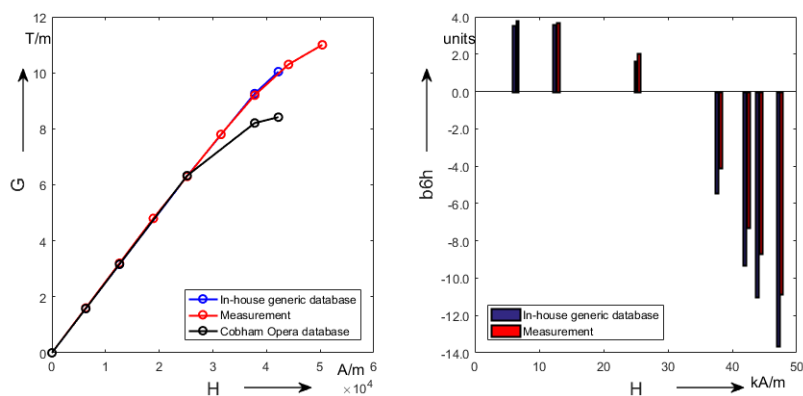
**Figure 3.** Comparison among initial magnetization (left) and permeability curves (right) of ARMCO obtained from CERN database (blue), OPERA software (black) and experimentally measured (red).

#### 4. Case Study: Q200 quadrupole magnet

This section shows how the magnetic properties of a magnet yoke can affect the performance of the whole magnet. A case study based on the normal-conducting quadrupole magnet Q200 [7, 8] and Finite Element Analysis (FEA) is presented. The magnet has a rated current,  $I_n = 750$  A, and 63 turns per pole to achieve a nominal gradient of  $G = 11.0$  T/m and integrated gradient of  $int_G = 22.05$  T. Fig.3 shows the three  $B$ - $H$  curves used for the simulation: (1) Cobham OPERA database[8], (2) in-house CERN database, and (3) measured from a steel sample.

In Fig.4 (left), the gradient at the center of the magnet for all cases is compared with the gradient found by means of magnetic measurements on the magnet [9]. It can be seen that the simulation results of case (1) are very different compared with the results from the magnetic measurements. Therefore, it can be concluded that this  $B$ - $H$  curve does not accurately represent the properties of the steel used for this magnet. On the other hand, the results of case (2) are consistent with the magnetic measurements.

In addition to the magnitude of the gradient it is important to guarantee also a good field quality. The field quality can be measured from the amplitude of the magnetic field harmonics. Fig.4 (right) shows the normalized sixth harmonic  $b_6$  as a function of the magnetic field. It can be seen that, as the magnetic field increases, there is a difference between the sixth harmonic for case (2) and the measurements (3). This is due to the fact that the  $b_6$  is highly sensitive



**Figure 4.** Flux density gradients inside the Q200 quadrupoles for the three cases under study (left) and 6<sup>th</sup> harmonic values as function of the magnetomotive force (right).

towards the saturation of the pole profile. This case study confirms the importance of having a reliable  $B$ - $H$  curve during the design process to minimize the risk of designing a magnet that doesn't respect the field quality requirements.

## 5. Conclusion

In this paper we discussed the importance of assessing the magnetic measurements of materials used for the construction of particle accelerator magnets. First, it was shown that ferromagnetic materials used in the construction of yokes of several CERN magnets show different magnetic properties. Then, for a specific material, ARMCO, a comparison between measurements and data from both in-house and OPERA's database highlighted several discrepancies in terms of  $B$ - $H$  and relative permeability curves. This led to investigating how these different  $B$ - $H$  curves can affect the results during the design of a magnet. This was assessed by means of OPERA's simulation of a quadrupole magnet installed in the CERN North Area. The case study showed that even similar  $B$ - $H$  curves can cause significant differences in the magnet's field quality. In conclusion, the lesson learned from this experience is that the characterization of magnetic materials is important, not only for the quality control during the production phase of a magnet, but also during its design phase.

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