SIMULATION OF NdFeB PERMANENT MAGNETS AT LOW TEMPERATURE

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Abstract

Cryogenic Permanent Magnet Undulators (CPMU) are currently being developed in some Synchrotron Light Sources. Low temperature magnetization hysteresis curves cannot be obtained by a simple transformation of ambient temperature curves; this requires a specific simulation tool. A Monte-Carlo based Permanent Magnet Simulator has been developed at the ESRF. In this simulator, the magnets can be described as a set of several magnetic grains. The model inputs are physical parameters such as anisotropy constants, easy-axis distribution and coercive field. The orientations of magnetic moments are calculated for each grain according to an analytical model and optimization methods are used for fast computations. Magnetization versus external field curves is calculated in a few seconds. The result fits with low temperature NdFeB magnetization measurements. These curves have been efficiently used to obtain Radia material parameters for the CPMU design.

INTRODUCTION

Cryogenic Permanent Magnet Undulators have appeared over the last few years [1, 2, 3, 4, and 5]. In these insertion devices, low temperature NdFeB permanent magnets are used to achieve both a high remanence and a high coercive field.

When the temperature decreases, the remanent magnetization passes through a maximum. At low temperatures, magnetization is reduced by the Spin Reorientation Transition phenomenon (SRT) [6, 7]: SRT must be taken into account for CPMU designs. Magnetization measurements have been taken at several temperatures and optimum performances were observed for T~150 K. Yet, for a more efficient CPMU design it should be worthwhile to develop numerical models for low temperature NdFeB magnets.

Modern permanent magnets are made with sintered powders. In these powders each grain has well-known magnetic properties, governed by crystal orientation, anisotropy constants, defaults, etc. However, there are no numerical models at a magnet level (*i.e.* for a set of magnetic grains). The aim of this paper is to develop such a model.

The classic phenomenological model for magnets and magnetic grains is first recalled. Then, a Monte-Carlo based simulator is built. Few physical parameters, such as easy-axis dispersion, anisotropy constants or coercive field are used for magnetization calculations. This model has applied to the CPMU design.

NdFeB MAGNET MODEL

Phenomenological Model

Powder metallurgy processes are used for high performance permanent magnet manufacturing. Bulk magnetic materials are reduced to monocrystalline magnetic grains. These grains are aligned under a magnetic field during powder compaction. The magnet is then sintered at a temperature of around 1100°C to provide an optimal remanence. A further annealing process ($\sim 650°C$) enables the development of the coercivity. The magnetic field alignment stage of this process defines the so-called *easy-axis*; the magnetization of the magnet is parallel to this direction. The standard deviation of the grain symmetry axis (so-called c-axis) angular dispersion is about 15 degrees around the easy-axis.

The orientations of the grain's magnetic moments are governed by the magnetic anisotropy energy, which tends to align the magnetization and the easy-axis, and by the Zeeman energy which aligns the magnetization and the external magnetic field. The energy of one magnetic moment should be expressed as

$$E = -\mu_0 \mathbf{M} \cdot \mathbf{H} + K_1 \sin^2 \theta + K_2 \sin^4 \theta , \qquad (1)$$

where μ_0 is the vacuum permeability, $\mathbf{M}$ the magnetization, $\mathbf{H}$ the applied magnetic field strength, K_1 and K_2 the anisotropy constants and θ the angle between the magnetization and the c-axis.

The coercive field should be derived from equation (1). However, the coercive field calculated with this equation is one order of magnitude higher than the measured coercive field. This is due to anisotropy defaults in the magnetic materials [8, 9, and 10]. In our model, we will use the coercive field as a phenomenological parameter. A linear variation of the coercive field is observed when the temperature decreases.

The evolution of NdFeB anisotropy constants with temperature is given in Fig. 1. It appears that K_1 constant passes trough zero and is negative for $T < 130$ K. The Spin Reorientation Transition is due to this inversion. If there is no external field, the angle between the magnetization and the c-axis can be easily calculated. For reasons of symmetry, magnetic moments are distributed on a cone. This results in a reduction of the remanent magnetization.
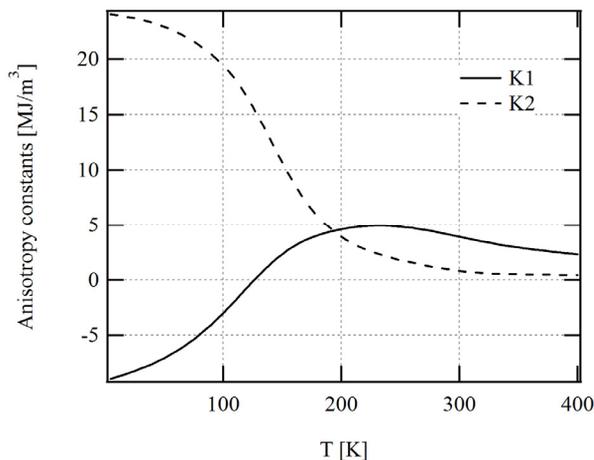
Figure 1: Evolution of NdFeB anisotropy constants with temperature [7].

In a permanent magnet, the overall magnetization should be computed as the sum of all the magnetic moments. This can be written as

$$\mathbf{M} = M_S \iint p(\theta, \varphi)\, \mathbf{u}(\theta, \varphi, \mathbf{H})\, d\theta\, d\varphi, \qquad (2)$$

where M_S is the saturation magnetization, θ and φ give the orientation of a c-axis, $p(\theta, \varphi)$ is the probability density of finding grains with c-axis oriented by θ and φ, $\mathbf{u}(\theta, \varphi)$ is a unit vector which gives the orientation of the magnetic moment of a grain with c-axis oriented by θ and φ in an external field strength $\mathbf{H}$.

Magnet Simulator

A magnet simulator has been developed. Inputs are physical parameters such as anisotropy constants, easy-axis distribution and coercive field.

At initialization, c-axis are randomly distributed around the easy-axis. The angle between c-axis and easy-axis follows a Gaussian law with a typical standard deviation $\sigma = 15°$. Then, an external magnetic field is applied to each grain and the magnetic energy (Eq. 1) is minimized. The macroscopic magnetization is calculated as the sum of the grain magnetizations (Eq. 2).

The simulator has been written in object-oriented language (C++). The Gradient and Newton methods were implemented for fast energy minimization. Downloads are available on the ESRF website [11].

Simulation results are shown in Fig. 2 for an external magnetic field parallel to the easy-axis. The results correspond well to the magnetic measurements. On the simulated curves, one can observe an angular point around the coercive field. The measured curves are smoother: this difference is due to the non-homogeneous demagnetizing field in the magnet sample.

Figure 3 shows the magnetization versus temperature curves at several operating points. In a cryogenic permanent magnet undulator, the reverse magnetic field strength is in the range $1\ \text{T} < \mu_0 H < 1.5\ \text{T}$: the operating temperature should be in the range $140\ \text{K} < T < 180\ \text{K}$.
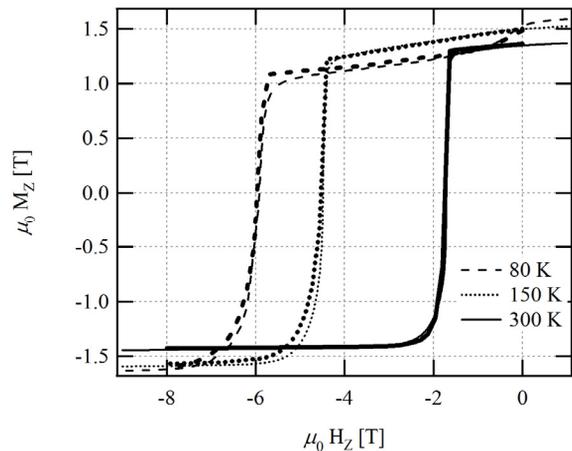

Figure 2: Parallel magnetic field: simulation results (thick line) and measurements (thin line) for a Vacuumschmelze Vacodym 764 NdFeB Magnet [4, 12].
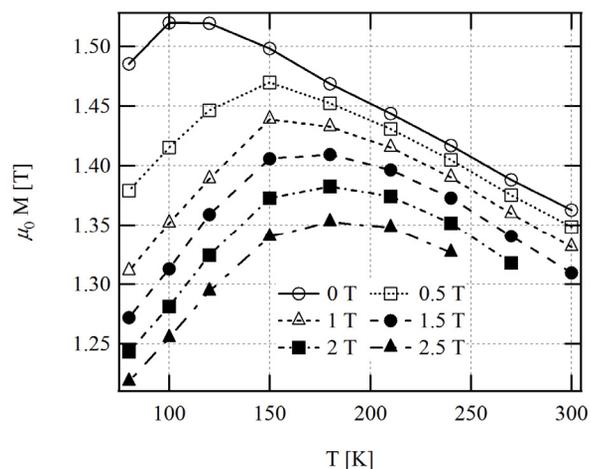

Figure 3: Simulated magnetization vs. temperature curves for different values of reverse magnetic field $\mu_0 H$ (for Vacuumschmelze Vacodym 764 NdFeB magnet).

Linear Model

For a relatively weak external field strength (*i.e.* below the coercive field) and for small field variations, the magnetization should be modelized by a linear model:

$$\mathbf{M}(H) = \mathbf{M_R} + \chi \mathbf{H}, \qquad (3)$$

where $\mathbf{M_R}$ is the remanent magnetization and χ is the magnetic susceptibility tensor. At a first approximation, this tensor reduces to a diagonal matrix with eigenvalues $\chi_{//}$ and $\chi_{\perp}$.

The temperature variation of magnetic susceptibilities is shown on Fig. 4. A Mathematica linear model has been built from the simulated magnetization and susceptibilities. This model gives approximate results very quickly but is valid for relatively low fields only.
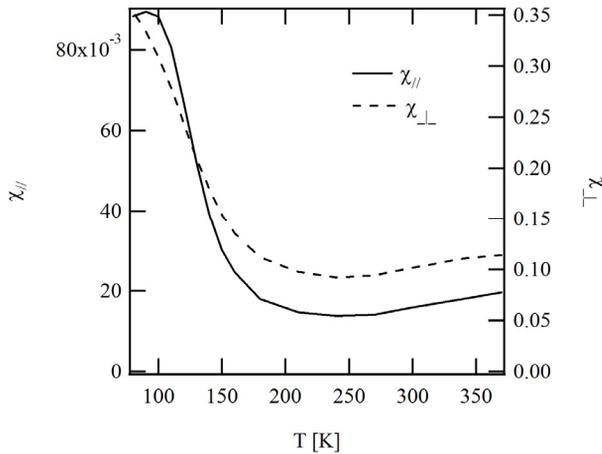
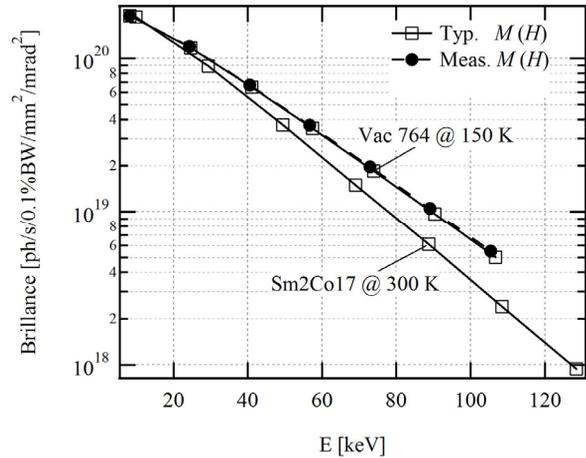Figure 4: Simulated susceptibilities for Neorem 595 NdFeB Magnet [13].

Figure 5: SRW simulations for an ESRF low-beta section with $E = 6$ GeV, $I = 200$ mA, $\varepsilon_H = 4$ nm, $\varepsilon_V = 30$ pm, $\beta_H = 0.5$ m and $\beta_V = 2.73$ m.

CMPU DESIGN

The numerical model described in the above section has been used for CPMU simulations. The simulation process includes:

- Computation of parallel and transverse $M(H)$ curves at various temperatures, starting for NdFeB datasheets.
- Fitting a Non-Linear Radia model [14, 15] on the $M(H)$ curves.
- Calculation of the peak magnetic field for a given undulator geometry, using the Radia software.
- Computation of the radiation spectrum with the SRW software [16].

The undulator geometrical parameters are given in Table 1. The peak field and the defection parameter have been computed for a commercial NdFeB magnet at 150 K and for a reference Sm2Co17 material (Table 2). The calculated brilliance is shown in Fig. 5.

Table 1: Undulator Geometrical Parameters

Period	18	mm
Magnetic Gap	6	mm
Length	2	m
Magnets	6.2x50x30	mm^3
Poles	2.8x32x24	mm^3

Table 2: Peak magnetic field and deflection. Typ. values are computed from a material datasheet and Meas. values are computed from measured $M(H)$ curves.

Material		**T [K]**	**B$_{MAX}$ [T]**	**K**
Vacodym 764	Typ.	150	0.97	1.64
	Meas.		0.98	1.66
Sm2Co17 ($B_R = 1.1$ T)	Typ.	300	0.82	1.38

CONCLUSION

A Monte-Carlo magnet simulator has been developed. This model uses physical properties of the magnets. To model a grade of NdFeB magnets, one needs few parameters: easy-axis dispersion, saturation magnetization, coercive field and temperature coefficient. This low temperature NdFeB model has been used to simulate a cryogenic permanent magnet undulator. The magnetic field and the brilliance obtained with this model match those computed from measured magnetization curves.

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