

# NONLINEAR NUMERICAL SIMULATION OF PERMANENT MAGNETS

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## Abstract

Rare earth permanent magnet models are commonly used in the design of undulators and wigglers. Normally the operating point of the magnet in the B vs. H diagram corresponds to a linear reversible characteristic. The region of linearity is strongly dependent on the temperature. The operation of part of the magnet blocks in the region of non-linearity is responsible for the so-called irreversible losses. A non-linear model for permanent magnets has been introduced in the 3D magnetostatic computer code RADIA. The model handles the complete demagnetization curve B(H) including the temperature dependence of the remanent field and intrinsic coercivity of the material. It allows careful analysis of local demagnetization in a permanent magnet structure as a function of temperature. The result of the simulation is in good agreement with the measured demagnetization of an assembly of Sm2Co17 and NdFeB magnets following a baking at several different temperatures. Such numerical simulations are of major importance in the selection of magnetic material for in-vacuum undulators which requires a baking at temperatures of 100-150 deg. C. They also allow the proper selection of NdFeB material for any application where the highest field in a selected range of temperature is desired.

## 1 INTRODUCTION

The magnetization curve parallel to the easy axis of anisotropic high performance permanent magnet materials (SmCo, NdFeB) can be separated into two distinct regions (figure 1):

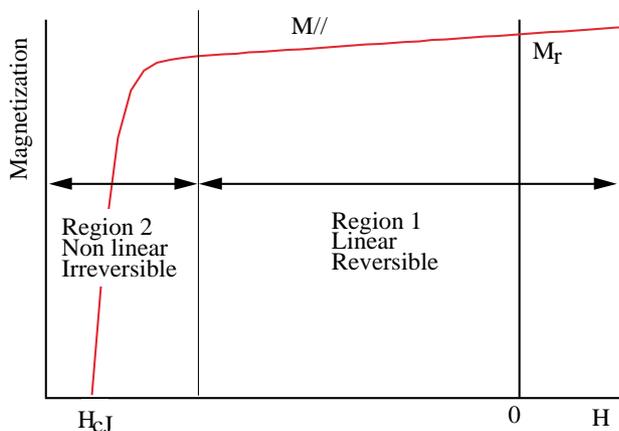


Figure 1: generic magnetization curve of high performance anisotropic permanent magnets

A linear reversible part (region 1) where the magnetization is described with:

$$M_{//}(H_{//}) = M_r + \chi_{//} H_{//} \quad (1)$$

$M_r$  is the remanent magnetization and  $\chi_{//}$  the magnetic susceptibility of the material parallel to the easy axis. Perpendicular to the easy axis, the magnetization is also represented according to a linear model:

$$M_{\perp}(H_{\perp}) = \chi_{\perp} H_{\perp} \quad (2)$$

$\chi_{\perp}$  is the susceptibility perpendicular to the easy axis.

Both equations (1) and (2) are generally used to compute permanent magnet field structures with various numerical methods.

The region 2 of figure 1 corresponds to non linear irreversible behaviour where partial undesirable demagnetization occurs at some locations in a permanent magnet structure. The intrinsic coercivity  $H_{cJ}$  defines the field H where the magnetization is cancelled. Within linear models, the resulting working points in the M(H) or B(H) diagram have to be carefully checked in such a way that they remain in the region of validity of the model (region 1). Materials with "sufficient" coercivity are therefore selected from suppliers' datasheets.

It is nevertheless difficult to combine high coercivity and high remanence, as observed for NdFeB materials: high remanence is detrimental to high coercivity and vice versa. The optimum choice of a material can be delicate. The material properties of permanent magnets are, in addition, strongly dependent of temperature, in particular the coercivity can be significantly reduced with a temperature elevation of a few tens of degrees Celcius. Accidental or intentional temperature elevations have to be anticipated to avoid any irreversible losses in the magnetic structure. An optimum design requires a non-linear permanent magnet model.

## 2 NON LINEAR MODEL

### 2.1 Temperature coefficients

Both quantities  $M_r$  and  $H_{cJ}$  are dependent on temperature T and can be represented using second order polynomial models:

$$\begin{aligned} M_r(T) &= M_r(T_0) \left( 1 + a_1(T - T_0) + a_2(T - T_0)^2 \right) \\ &= M_r(T_0) P(T - T_0) \end{aligned} \quad (3)$$

$$H_{cJ}(T) = H_{cJ}(T_0) \left( 1 + b_1(T - T_0) + b_2(T - T_0)^2 \right) \quad (4)$$

$$= H_{cJ}(T_0) Q(T - T_0)$$

$T_0$  is a reference temperature, and  $a_1$ ,  $a_2$ ,  $b_1$  and  $b_2$  are coefficients derived from suppliers datasheets.

## 2.2 Magnetization curves

The description of the M(H) curve up to the intrinsic coercivity  $H_{cJ}$  at temperature T requires a dedicated model under the form:

$$M(H, T) = \alpha(T) \sum_{i=1}^3 M_{si} \text{Tanh} \left( \frac{\chi_i}{M_{si}} (H + H_{cJ}(T)) \right) \quad (5)$$

At room temperature  $T_0$ ,  $\alpha(T_0) = 1$  and all coefficients  $\chi_i$  and  $M_{si}$  are determined with a non-linear fit of the relevant magnetic data. At any temperature T in the domain of validity of equations (3) and (4) the coefficient  $\alpha(T)$  is determined using:

$$M(H = 0, T) = M_r(T) \quad (6)$$

Once the model is built at temperature  $T_0$ , any magnetization curve at temperature T can be dynamically reconstructed. This is illustrated in figure 2 for a Sm2Co17 type material.

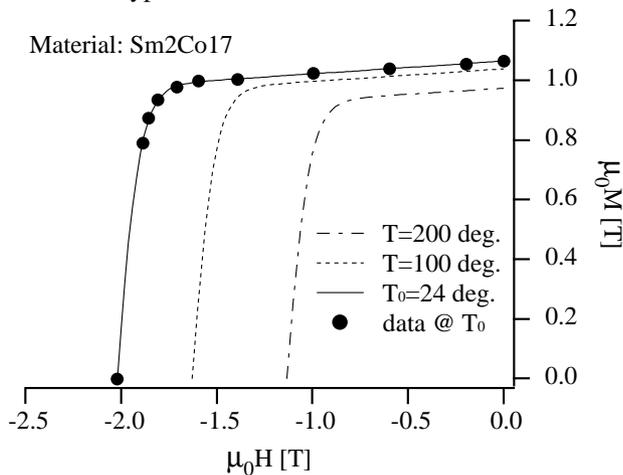


Figure 2: Magnetization curves at different temperatures for a Sm2Co17 material. The data at temperature  $T_0$  are fitted according to equation 5. The curves at other temperatures are directly reconstructed from the fit at  $T_0$ .

Perpendicular to the easy axis of the magnet, a similar formulation of equation 2 is used:

$$M_{\perp}(H_{\perp}, T) = \chi_{\perp}(T) H_{\perp} \quad (7)$$

The dependence upon the temperature of  $\chi_{\perp}$  is assumed to be similar as for the remanence (equation 3):

$$\chi_{\perp}(T) = \chi_{\perp}(T_0) \left( 1 + a_1(T - T_0) + a_2(T - T_0)^2 \right) \quad (8)$$

The linear behaviour at constant temperature perpendicular to the easy axis is only valid for anisotropic magnet material with very narrow distribution of the easy axis within the material texture. This is a good approximation for NdFeB and SmCo anisotropic materials.

## 3 EXPERIMENTAL RESULTS

### 3.1 Test structures

The non-linear model has been inserted in the magnetostatic code RADIA [1]. The required parameters used in the model have been obtained from manufacturers' datasheet (mostly using digitization of magnetization curves with scaling). The test structures consisted in two identical sub assemblies of ESRF U42 undulators (modules of 5 magnet blocks): one with NdFeB material, the second one using Sm2Co17 magnet blocks (figure 3).

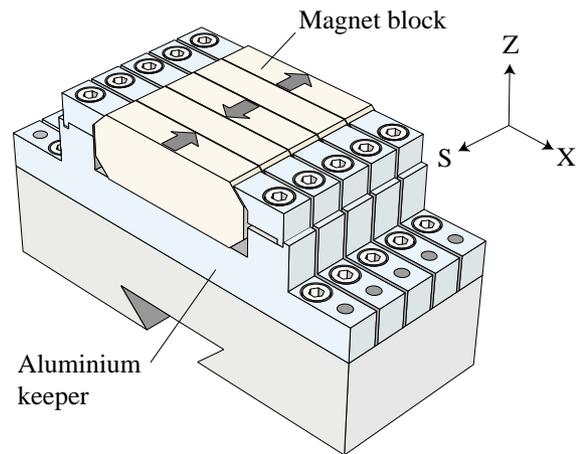


Figure 3: Permanent magnet structure used for experimental tests of the model. The size of the magnet block is: 55 mm (X), 21 mm (Z) and 10.4 mm (S).

### 3.1 Magnetic measurements

As a key parameter, the vertical peak field at several horizontal positions ( $x=0, \pm 10$  and  $\pm 20$  mm) has been determined using hall probe scans at a distance Z of 8 mm from the magnet blocks. The test structure have been submitted to successive (increasing) temperature stages using a laboratory oven, each stage being followed by cooling at room temperature and a magnetic measurement sequence. The measured irreversible losses of the peak field are defined as:

$$\beta_m^x(T) = \frac{(B_m^x(T) - B_m^x(T_0))}{B_m^x(T_0)} \quad (9)$$

where the subscript m refers to measured values (all performed at temperature  $T_0$ ) and the variable T being the temperature stage preceding the magnetic measurements, x is the transverse horizontal position. In order to illustrate

the non uniform demagnetization within the magnetic structures, the transverse field roll off written as:

$$r^x(T) = \frac{(B_{T_0}^x(T) - B_{T_0}^0(T))}{B_{T_0}^0(T)} \quad (10)$$

has also been quantified in all cases.

Within the numerical simulations, the peak field  $B_c^x(T)$  is computed at temperature T. The irreversible losses are deduced using:

$$\beta_c^x(T) = \frac{B_c^x(T) - B_c^x(T_0)P(T - T_0)}{B_c^x(T_0)P(T - T_0)} \quad (11)$$

With the legitimate assumption that no additional losses take place during the cooling from T to  $T_0$ ,  $\beta_m^x(T)$  should represent the same quantity as  $\beta_c^x(T)$ . Since the actual coercivity of the materials is not accurately known, the nominal and minimum values from data sheet for  $H_{c_j}$  have been used instead. Calculated and measured irreversible losses on the peak field at median position ( $x=0$ ) are compared in figures 4 and 5 for the NdFeB and Sm2Co17 structures respectively with a good agreement

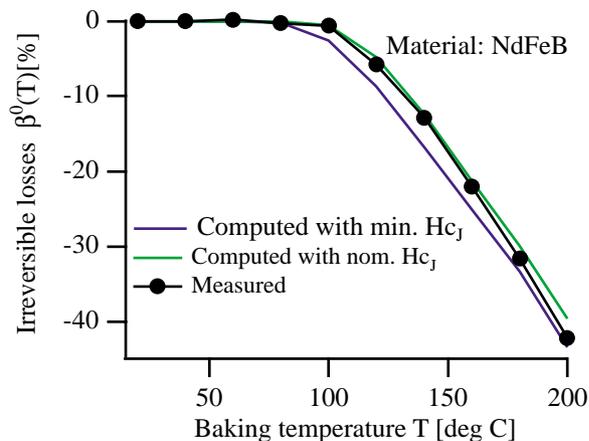


Figure 4: Irreversible losses on peak field at  $x=0$  (beam axis) for the NdFeB structure as a function of temperature

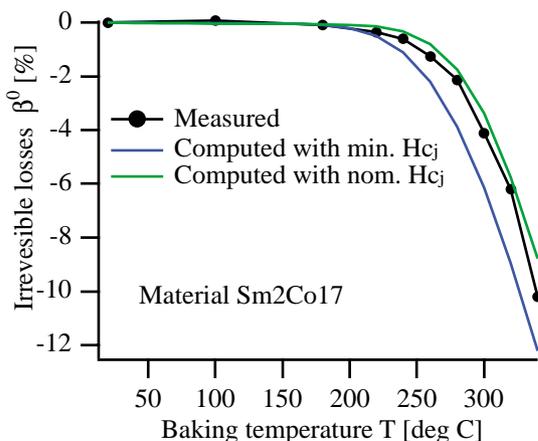


Figure 5: Irreversible losses on peak field at  $x=0$  (beam axis) for the Sm2Co17 structure as a function of temperature

Both calculated and measured peak field roll offs also show a good agreement as presented in figure 6.

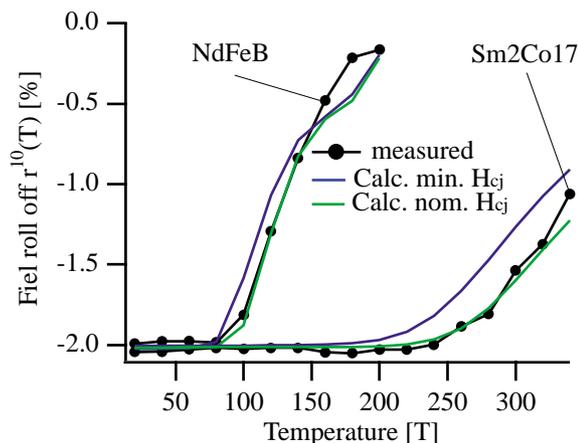


Figure 6: Peak field roll off at  $x=10$  mm off-axis for both NdFeB and Sm2Co17 structures

## 4 CONCLUSION

The non linear simulation of a permanent magnet material based structure can be handled using the described model. The main interest being to improve predictions on potential local partial demagnetization within the structure. This is of practical interest for in vacuum insertion devices where initial baking of the permanent magnet structure is required for ultra high vacuum compatibility. In particular, it allows the optimum choice of the permanent magnet material (highest peak field) compatible with a required baking temperature (no irreversible losses). A tutorial example using this model is available from the RADIA WEB site [2].

## REFERENCES

- [1] O. Chubar, P. Elleaume, J. Chavanne, "A 3D Magnetostatics Computer Code for Insertion devices", SRI97 Conference August 1997, J. Synchrotron Rad. (1998). 5, 481-484
- [2] A tutorial example can be downloaded at: <http://www.esrf.fr/machine/support/ids/Public/Codes/Radia/Examples/List.html>