MODELIZATION OF INHOMOGENEITIES IN PERMANENT MAGNET BLOCKS

V. Massana, J. Marcos, J. Campmany
CELLS, ctra. BP 1413, Km 3.3, 08290 Cerdanyola del Vallès, Catalonia, Spain

Abstract

Nowadays one of the main objectives for insertion devices manufacturers is to reduce the gap of undulators as much as possible while keeping the features of the generated magnetic field. Because of that, the effects of inhomogeneities of magnetic blocks are playing an increasing role in the quality of the whole device. In this paper we present a modelization of the inhomogeneities of permanent magnet blocks used to build wigglers and undulators. The model is based in splitting individual magnet blocks in different parts which are considered magnetically homogeneous. The model takes into account the relative orientation of magnet blocks assembled into their holders as well as local magnetic properties.

We have applied the model to fit magnetic field integrals measured with a fixed stretched wire bench and magnetization data obtained from Helmholtz coils measurements for both single blocks and groups of blocks mounted on a common holder.

The results of the model fit with experimental data within an rms error of 0.6 μT·m for individual blocks and 1.7 μT·m in the case of magnet groups.

INTRODUCTION

Influence of Insertion Devices (IDs) on electron beam is determined, at first order, by first and second field integrals. In the case of undulators, performance in terms of flux of emitted light at high harmonics is determined by the phase error. Current techniques of sorting and shimming magnetic arrays achieve low integrals and phase errors. In the case of pure permanent magnets devices, these techniques are based on two steps. First, individual magnetic blocks are characterized through Helmholtz coil measurements, to obtain their magnetization. Second, blocks are grouped in order to compensate main magnetic component, and then each group is characterized in terms of field integral through Fixed Stretched Wire (FSW) measurements.

Unfortunately, the field integrals of each group of blocks, even in the case of a single magnet, cannot be deduced from magnetization data. This is because geometrical errors associated to holder assembly, as well as inhomogeneities, play a big role in the field integral for minor components. In this paper we present a simple model than can explain the signatures obtained in the field integral measurements. Using this model, we can reproduce with the usual computation codes (OPERA [1], RADIA [2], etc.) the profile of the field integral measurements both for single blocks (singlets) and for groups of three blocks (triplets) assembled on their holders, and thus it can be used to model a realistic device. This is relevant to understand the behaviour of magnet array during shimming process.

As a case of study we have selected a set of blocks intended to build a short section of undulator with a period of $\lambda_0 = 21.3$ mm. Nominal dimensions of the blocks are 50×5×16 mm, with a chamfer of 3 mm in each corner. Real dimensions have been measured with a non-magnetic dial comparator. Magnet blocks are made of sintered NdFeB powder material. A high degree of magnetic moments alignment and thus a higher remanence is obtained by the manufacturer (*Neorem*) using transverse die-pressing technique [3]. Depending on the direction of the main magnetization component we have horizontal (**H**) or vertical (**V**) magnetic blocks. Therefore, according to the reference system defined in Fig. 1, the main magnetization component of blocks can point in $\pm Z$ directions in the case of **V** blocks and $\pm Y$ for horizontal ones. We call them, **VN**, **VS**, **HN** and **HS** blocks, respectively.

In the case presented in this study, magnets are arranged in two sorts of modules: groups of three blocks mounted into a common holder (*triplet*) and single horizontal magnets **HN** mounted into single holders (*singlet*). Triplets consist of a **HS** horizontal magnet between a **VN** and a **VS** vertical magnet.

The presented model doesn't handle the complete demagnetization curve, and it is assumed that magnets are in the reversible linear part of the magnetization curve [4]. Results are computed using the RADIA toolkit running under Mathematica [5].

EXPERIMENTAL DETAILS

The average magnetization vector of the magnet blocks has been measured using a system of Helmholtz coils, and the field integrals generated by the modules have been measured using a FSW [6].

The used FSW provides the transverse dependence of the magnetic field integrated along the longitudinal axis. The measuring wire has 10 turns and is placed vertically position to avoid undesired sag. Kinematic parameters of the motion of the bench have been optimized to minimize the signal/noise ratio. We measure 104 points along *ca.* 250 mm, that is, a measurement every 2.45 mm.

In order to minimize positioning errors modules have been measured laying on two opposite faces (180° rotation around Z axis) and the obtained field integral signatures have been averaged.

Temperature of the laboratory was stable in a range of 22 ± 0.5°C for all measurements, guaranteeing that susceptibility, and other magnetic properties of the material, do not change significantly [7].

MODEL DESCRIPTION

We have evaluated two sources of errors: angular errors and magnetic inhomogeneities inside the blocks.

Misalignment between the reference systems of magnet blocks and the Helmholtz coils can be slightly different to the misalignment between the reference systems of the FSW bench and the holder faces, yielding angular errors in the field integral measurements.

In order to determine the geometrical errors, we modelled homogeneous blocks rotated according to "pitch" and "roll" angles as defined in Fig. 1. Magnetization of block at this stage is considered to be that deduced from Helmholtz coil measurements. Using Simplex algorithm we have determined the angles that minimize the rms difference between the simulated and measured field integrals. "Yaw" angle causes a projection of one minor component onto the other one and can be neglected.

The rms error between simulated and measured field integrals is presented by blue square dots in Fig. 3 and 4. As it can be seen, even allowing the modules to rotate freely we don't fully reduce to zero the rms error. This is because inhomogeneities as we'll see bellow.

Mean value of "pitch" and "roll" angles are (-1.13 ± 4.38) mrad and (0.8 ± 2.08) mrad, respectively, in the case of singlets, and (-0.70 ± 6.15) mrad and (0.96 ± 6.02) mrad for triplets. These errors are well within the error associated to mounting tool, used to assemble blocks on holders.

Simulated model incorporates real dimensions of the blocks in its code, and also takes care about the real boundary conditions that each block has inside the holders: all magnets must touch the bottom of the holders when they are slightly rotated and overlapping part of the neighbour magnets is not allowed. Geometrical issues have been treated to give a realistic behaviour to the model.

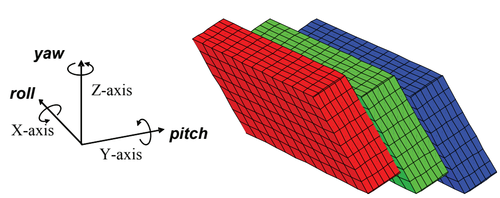

Figure 1: Used system of coordinates and definition of rotation angles (*left*). Effect of rotation on a triplet (*right*).

Once the angles of each module are determined we characterize the magnetic inhomogeneities, which are relevant even at large gaps. We consider that they are concentrated mainly in the edges of the magnet blocks because this part has suffered more mechanical interventions. Our model takes care of this fact dividing the horizontal magnets **HN** and **HS** in one central part (80% of the whole width) and two edge zones with equal length (see Fig. 2). A 5.3 mm small gap is selected in order to evaluate the model in the worst case.

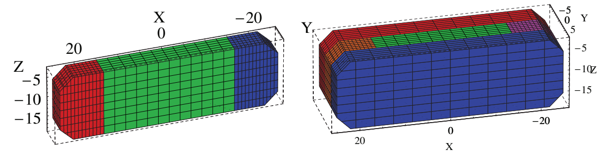

Figure 2: Model of singlet horizontal magnet divided in three parts (*left*), and model of triplet with the horizontal magnet split in three parts (*right*). The set of modules consist in 20 singlets and 19 triplets.

Rotation angles are set according to the values obtained in previous calculation and Simplex algorithm is set up to find the values of M_x and M_z, transversal and vertical components of the magnetization, in each one of the three parts in which the magnets are split. Function to be minimized is again the rms difference between the simulated and the experimental vertical field integrals.

In the case of triplets, the two vertical blocks inside the triplets have their main magnetization components pointing in opposite directions. This particular configuration doesn't allow to find a single-valued major component, M_y, using the Simplex code, and these blocks are not suitable to be split as in the case of singlets. So, we model them considering that they are homogeneous.

RESULTS

Figures 3 and 4 show the rms difference between calculated and measured field integrals in two cases: (1) considering only free rotation of magnets in the holders, and (2) angular rotation plus inhomogeneities.

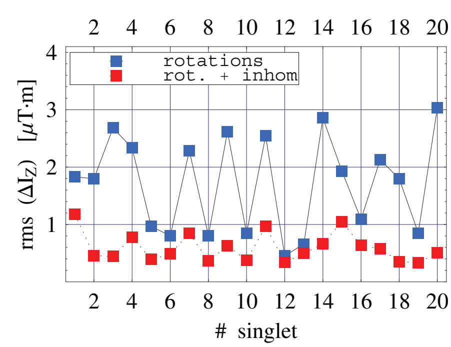

Figure 3: Rms error of the simulated signature for the whole set of singlets.

Mean value of the rms error for the evaluated models in Fig. 3 and 4 are: 1.7 μT·m and 0.6 μT·m, in the case of singlets, and 3.4 μT·m and 1.4 μT·m for triplets. If we consider homogeneous and non-rotated blocks, and take the magnetization values measured with Helmholtz coils,

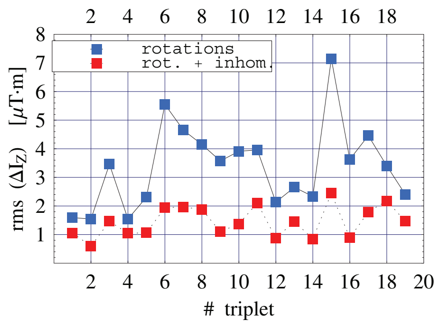

Figure 4: Rms error of the simulated signature for the whole set of triplets.

rms differences are 2.9 µT·m for singlets and 5.4 µT·m for triplets.

As an example, Fig. 5 shows together the measured field integral and the simulated one in the case of a triplet.

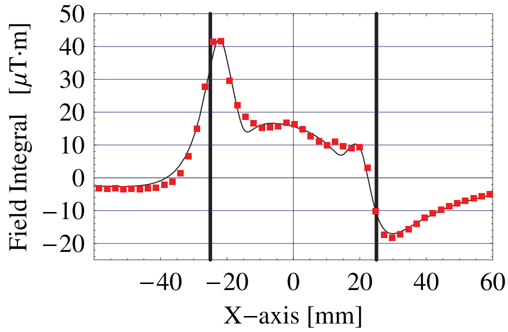

Figure 5: Vertical field integral signature measured using a FSW bench (red points) and simulated curve generated with the model corresponding to a triplet. Vertical black lines indicate the transversal dimensions of the blocks.

Minor components of the magnetization measured with Helmholtz coils and the average magnetization of modelled blocks agree within a 1% of accuracy as Fig. 6 shows, where M_x and M_z components magnets **HN** are presented together with their respective linear regressions.

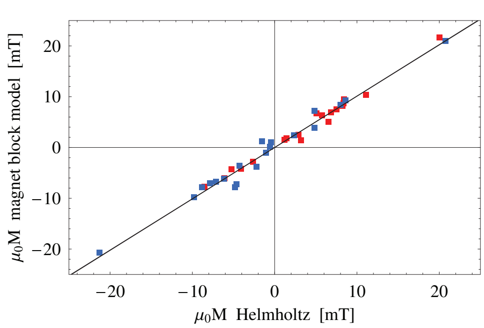

Figure 6: Correlation between M_x (red) and M_z (blue) measured experimentally and the ones determined using our split block model.

Previous results allow us to simulate whole arrays of magnets with realistic blocks assembled on holders and to make predictions of total demagnetizing fields by adding blocks during the assembling process.

At Magnetic Measurement Laboratory at Alba we have tested successfully this method for the assembly of an array of magnets with 19 periods. Predictions of the magnetic effects of a group of modules on its neighbours fit with the horizontal and vertical field integrals measured with a flipping coil bench. The agreement between modelled and experimental data is < 10 µT·m in the good field region ±10 mm (see Fig. 7).

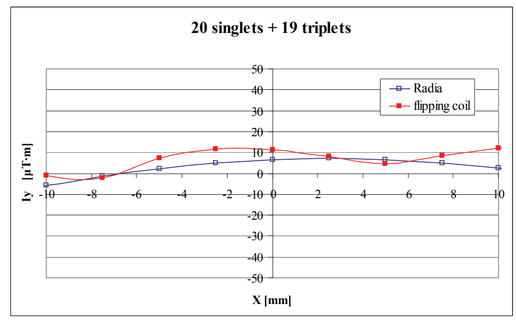

Figure 7: Vertical field integral in the good field region of the whole set of modules assembled. Red dots correspond to the measurement with a flipping coil bench; blue dots are simulated with our model of inhomogeneities plus rotation.

CONCLUSIONS

Inhomogeneities present in magnet blocks show up in the generated field integrals and give rise to high order multipoles. We have shown that the particular signature of a module can be understood and reconstructed with a model in which the magnets are built as a sum of several parts.

REFERENCES

[1] OPERA, Vector Fields Limited, see `http://cobham.vectorfields.com`.

[2] J. Chavanne, O. Chubar, P. Elleaume, "A 3D Magnetostatics Computer Code for Insertion Devices", SRI97 Conference August 1997, J. Synchrotron Rad. (1998). 5, 481–484.

[3] J. Bahrdt, "Permanent Magnets Including Wigglers and Undulators", CAS on "Magnets", June 20th-22nd, 2009, Bruges.

[4] J. Chavanne, O. Chubar, P. Elleaume, P.Van Vaerenbergh,"Nonlinear Numerical Simulation of Permanent Magnets", Proceedings of EPAC 2000, Viena, 2316–2318.

[5] Mathematica, Wolfram Research Incorporation, see `http://www.wolfram.com`.

[6] J. Marcos, J. Campmany, D. Einfeld, "The Study of Errors of Alba Fixed Stretched Wire Bench", Proceedings of EPAC 2006, Edinburgh, Scotland.

[7] G. Le Bec, J. Chavanne, "Simulation of NdFeB Permanent Magnets at Low Temperature", Proceedings of EPAC 2009, Vancouver.