IMPROVEMENTS IN PRODUCTION OF PERMANENT MAGNETS AND POLE-PIECES FOR UNDULATORS

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Abstract

Undulators built with rare-earth permanent magnets and soft-magnetic pole-pieces are a well-established technology for radiators in synchrotrons and FEL's. The optimisation of the quality of the light produced by these radiators still needs intense labour on fine-tuning and balancing of the magnet structures. The reported improvements in the minimization of residual errors of the permanent magnets and the high quality of pole-pieces shift the goal of the tuning process from the first order errors towards compensation of higher order deviations.

INTRODUCTION

Applications using permanent magnets to control charged particle trajectories require a high degree of homogeneity of all Cartesian components of the magnetic moment in order to achieve optimal performance. Vacuumschmelze GmbH & Co KG (VAC) has taken significant steps forward in the production of permanent magnets of high homogeneity in the last years. So magnets with typically less than +/-1% remanence distribution and less than +/-1° angular error even for large scale undulator projects can be provided.

For such homogeneous magnets with already small remaining errors in the dipole moment, the higher order effects or near field effects come closer into focus as they contribute to the horizontal and vertical field integrals.

FIRST-ORDER (DIPOLE) EFFECTS

A first classical characterisation of the permanent magnets for use in undulators is the measurement of the three Cartesian components of the magnetic dipole moment in a Helmholtz-coil setup. Those results – expressed as main magnetic moment in the preferred direction and angular deviations alpha and beta from this direction – dominantly represent the dipole error contribution to imperfections of the field trajectory in the undulator.

Magnetic Moment

The main contribution for the field in the air gap on the undulator is gained from the magnetic moment of the permanent magnet in its preferred direction. The distribution of magnetic moment from magnet to magnet contributes to variations of the gap induction and thus is intended to show small scatter. Typical specifications (Figure 1) allow for errors in the range of 1%. In most cases, this range is easily met or even smaller (+/- 0.7% or better). For mass production of undulator magnets like those for FEL-projects as EXFEL at Hamburg, the distribution of moments within a single undulator could be kept below +/- 0.5% and below +/- 1% for the whole set of more the 35000 magnets (several tons of material, produced over more than one year).

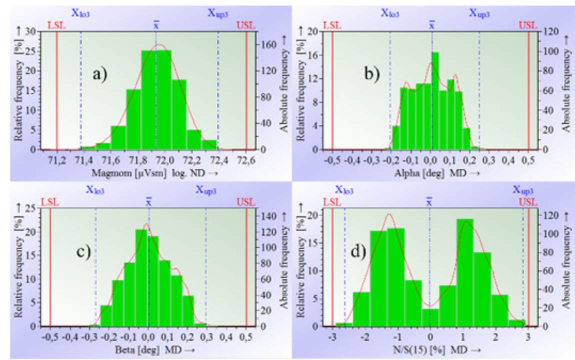

Figure 1: distribution of a) magnetic moment, angles b) Alpha, c) Beta and d) N/S-effect

Angular Deviations of the Magnetic Moment

From the measurements of the three components of the magnetic moment, also the angular misalignment of the dipole moment from the preferred direction (z) can be characterised as angle alpha = $\arctan(M_x/M_z)$ and beta = $\arctan(M_y/M_z)$. Up to now, typical specifications request those angles to be below +/- 1 degree. For a lot of geometries produced in larger series, a much smaller distribution with all magnets within +/- 0.5° and rms-values of less than 0.2° could be achieved.

HIGHER ORDER EFFECTS

N/S- or Hot/Cold - Side Effect (1 point)

Another characteristic, which is recorded for most of the undulator magnets is the co-called N/S- or hot-/cold-side effect. This characteristic resembles the relative difference of pole-strength measured by a Hall-probe in a defined distance over the centre of the pole face on as well the N-pole- as the S-pole-face. It is expressed as the difference (in percent) of N-pole- and S-pole-signal divided by the average of both signals. The value is dependent on the measuring distance – the larger the distance, the more the pure dipole-effects contribute. Therefore, a specification for an individual magnet should be attributed with the target measuring distance, e.g. N/S(15mm). The latter is a typical distance used for the relative large magnets for hybrid undulators for example at some projects at DESY, EXFEL and currently LBNL SXR for LCLS-II. For these projects, the limits of N/S-effects were in the range of +/-4% and currently may be reduced to +/-3% or even lower values.

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ISBN 978-3-95450-182-3

Although we still find a systematic split in the distribution of N/S-records of about 1%, the whole distribution is pretty symmetric and thus can be controlled as additional variable in the sorting process. Typical measuring distances are in the range of the gap width of an undulator. Induction differences are directly meaningful for V-magnets, whilst for H-magnets they describe the pole strength as collected by the pole-pieces. Local deviations from the ideal preferred direction will contribute to the N/S-effect and may also contribute directly to field errors in the gap.

SIMULATION OF N/S CONTRIBUTIONS

Local Deviations from Ideal Orientation

In order to understand influences of local orientation errors inside a magnet, a magnet of size 75 mm x 60 mm x 12 mm with known dipole properties was cut into smaller blocks of equal size (5 x 5 over the cross-section and 3 slices along the preferred (12 mm) direction) and the dipole properties (magnetic moment and angles) of each partial block was measured individually. In a reconstruction, the stray field of the whole block can be calculated from a superposition of the individual contributions. Analytical models for the calculation of the stray field of parallelepipeds are available in literature [1]. The ideal magnet can be reconstructed from ideal individual sub-blocks.

As long as the subdivision is done in a symmetric manner (as well for the split of geometries as the global compensation of errors in magnitude of magnetization and of direction of magnetization, an integral view from large distance (like the dipole approximation in Helmholtz measurements) would still show a perfectly aligned dipole. A closer view at the typical measuring distance for N/S-effects shows deviations in the field profile.

The individual parallelepipeds are more or less ideally oriented in the central sheet, but inclined by up to 3 degrees (upward resp. downward) in the outer upper or lower parts.

The induction profile B_z at 10 mm distance from the surface is shown in (Figure 2).

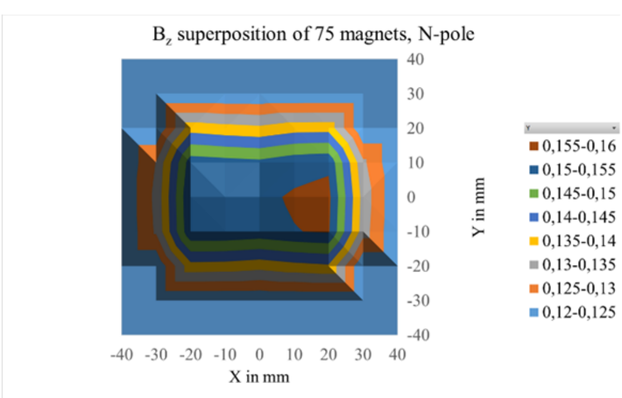

Figure 2: Simulation of the field profile for the undulator magnet recombined from measured results on 75 small pieces.

Field Scans

A typical field scan (at 10 mm distance from the pole face) for a magnet intended for use in a hybrid undulator is shown in Figure 3.

The induction level measured at a central position resembles the (small) difference in N-pole- and S-pole-induction readings resulting in a small N/S-percentage.

The variation of induction across the surface, however, indicates that there are still slight variations for different locations along the cross-section, which may have an impact of induction transfer to the pole piece.

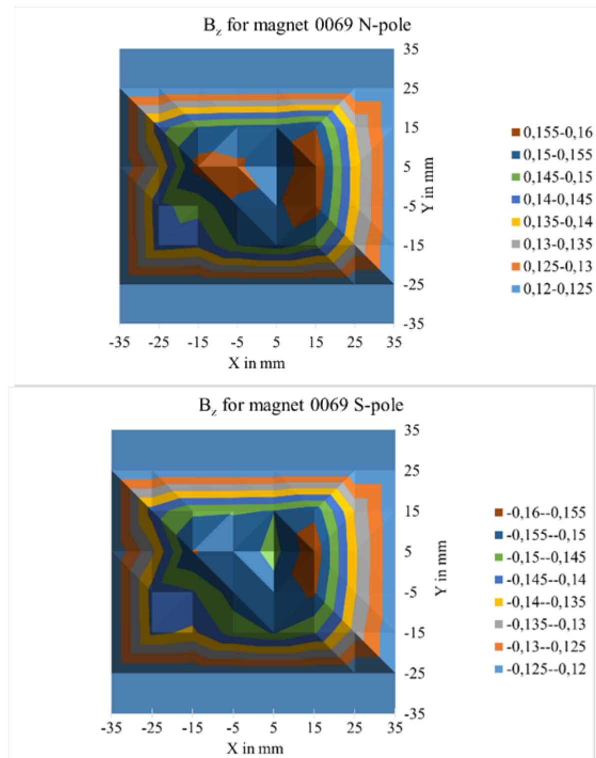

Figure 3: Field scan of B_z in T for a hybrid undulator magnet at 10 mm distance (N-pole and S-pole).

Multi-Point-N/S-Effect

There are various options to implement additional characterizations for an individual magnet and to look for higher order deviations, once the basic (first order) effects have come to a reasonably small influence. These start from measuring the local N/S-effect at a few additional positions (as actually performed for LBNL's SXR-undulator magnets for LCLS-II) or multiple point scans with a Hall-probe array (performed for DESY's latest PETRA-III-undulators) up to stretched wire scan methods.

Whilst the wire scans include an integration of the signal over a line and is oriented more functional to the application of the undulator, the local scans may help in understanding the source of residual errors inside the permanent magnets used.

EFFECT OF POLE PIECES

Influence of CoFe-Material Properties

Typical pole pieces for hybrid undulators are built from solid CoFe-alloys, which combine controlled magnetic properties with a high saturability. Vacuumschmelze offers not only the well-known standard grade VACOFLUX®50 with composition of about 50% Co and 50% iron and a saturation polarisation of about 2.35 T, but also newer CoFe-grades like VACOFLUX®17 and VACOFLUX®27. Especially the latter is optimized to achieve still higher saturation levels in the range of 2.4 T. Moreover, these new alloys contain less Cobalt and thus are less expensive.

Typical J-H-characteristics of these grades are shown in Figure 4. Due to the difference in anisotropy constants between the different grades, VACOFLUX®50 shows a higher initial permeability compared to the other grades, where rotation processes of the polarisation shift the approach to saturation to higher field levels.

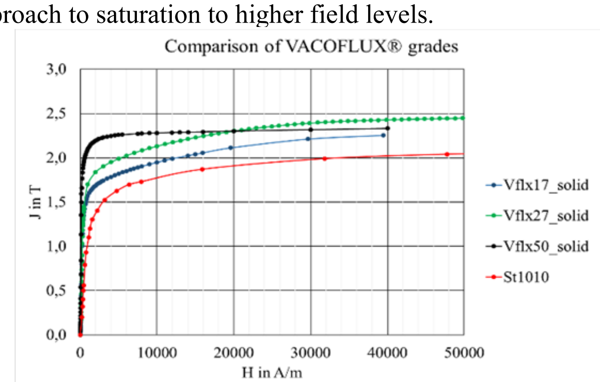

Figure 4: J-H-characteristics for various VACOFLUX®-grades.

NonlinearSimulations

Starting from a typical setup of a typical hybrid undulator structure, the thickness of the magnet and pole-piece thicknesses was varied in order to evaluate the impact of various levels of CoFe-grades in a finite element simulation with gap induction as target value (Figure 5).

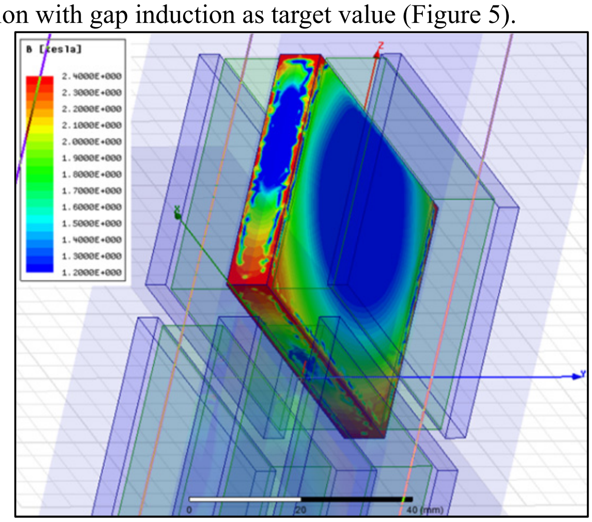

Figure 5: Model calculation of a hybrid undulator with saturation level in pole piece.

A clear indication of the higher saturation of VACOFLUX®27 could not be identified for the range of magnet and pole thicknesses taken into account. This is attributed to the necessity of higher exciting fields (delivered by the permanent magnets) to achieve higher saturation levels. Even VACOFLUX®17 seems to be able to get comparable gap inductions whilst low carbon steels still suffer from too low saturation at relevant H-field levels as shown in Fig. 6.

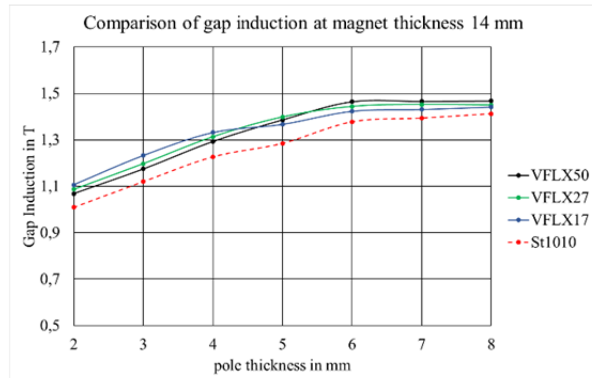

Figure 6: Comparison of gap induction for various CoFe-materials.

CONCLUSION

The quality of permanent magnets used for undulators has been significantly increased for the leading dipole components of the magnetic moment. At this point, the remaining local imperfections inside a magnet get a major role in further optimization of undulator magnets. The local deviations inside a magnet can be seen from moment measurements on subdivided blocks. These results can be taken to reconstruct the real stray field behaviour by superposition. Real multi-point-measurements of the stray-field show still more information of local differences and the evaluation of multi-point N/S-effects reveal options for further analysis and further improvements in the sorting process of undulators.

The optimization of undulator designs with respect to the pole-pieces may take into account the options of new CoFe-alloy grades, will not necessarily lead to significant increases in the gap-induction achieved, but still may be interesting from cost-aspects.

REFERENCES

[1] G. Akoun, J-P. Yonnet, "3D analytical calculation of the forces exerted between two cuboidal magnets", *IEEE Trans. Magn.,* MAG 20, n° 5, p. 1962-1, Sept. 1984.

ISBN 978-3-95450-182-3