EXPERIENCE WITH A NdFeB BASED 1 Tm DIPOLE*

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Abstract

A 30° Green Magnet based on permanent NdFeB magnets has been developed and installed in the injection line at the ASTRID2 synchrotron light source. The cost efficient design is optimized for a 1 T field at a length of 1 m using shaped iron poles to surpass the required field homogeneity. The inherent temperature dependence of NdFeB has been passively compensated to below 30 ppm/°C. A study of potential demagnetization effects has been performed by irradiation of NdFeB samples placed directly in a 100 MeV e-beam. A high permanent magnet work point was found to result in enhanced robustness, and the risk of demagnetization was found to be negligible for typical synchrotron applications. The magnet has successfully been in operation at ASTRID2 since autumn 2013.

INTRODUCTION

Permanent magnet based Green Magnets with fixed field seem to be an ideal solution for use in applications such as synchrotron light sources. A compact optical design is feasible without the need for large coils while saving most of the power needed to operate the accelerator. Without the need for water cooling, thick power cables and large power supplies, the installation process is simplified, the maintenance task is decreased and the risk of an operation failure is reduced. To demonstrate the above arguments, a 1 Tm strong 30° bending dipole has been developed and installed in the beam injection line of the ASTRID2 synchrotron light facility at Aarhus University (see Fig. 1). The design is based on experience from our first Green Magnet with a smaller field integral of 0.17 Tm successfully tested at ETH in Zurich [1].

Permanent magnet solutions have recently attracted increased attention [2, 3] for use in synchrotron light facilities. A concern is the potential risk of radiation damage to the permanent magnets especially for NdFeB magnets. Based on previous radiation resistance (RR) studies [4, 5] we expected permanent magnets in iron dominated circuits to show enhanced RR as compared to the typical studies performed on free samples with large demagnetizing fields. The effect of RR has been studied, see below, and the results are used to evaluate the robustness of the Green Magnets. Results from the installation and operation at ASTRID2 will be presented with focus on the long-term stability.

DESIGN AND PERFORMANCE

The magnet is built as a C-type magnet to demonstrate the technology readiness for use in a synchrotron, where access for vacuum pumps and beam lines is needed. The magnetic field can be adjusted ±3% with air-cooled trim coils powered by a small air-cooled 20 A power supply rather than a normal large water-cooled supply. Cooling water is thus avoided completely while saving at least 99% of the 4 kW needed to operate the equivalent electromagnet. The overall mechanical length of 1 m is equal to the effective magnetic length and 15% shorter than the typical electromagnet due to the smaller coils. Thermal drift of the NdFeB magnets have been passively compensated [1] better than 30 ppm/°C.

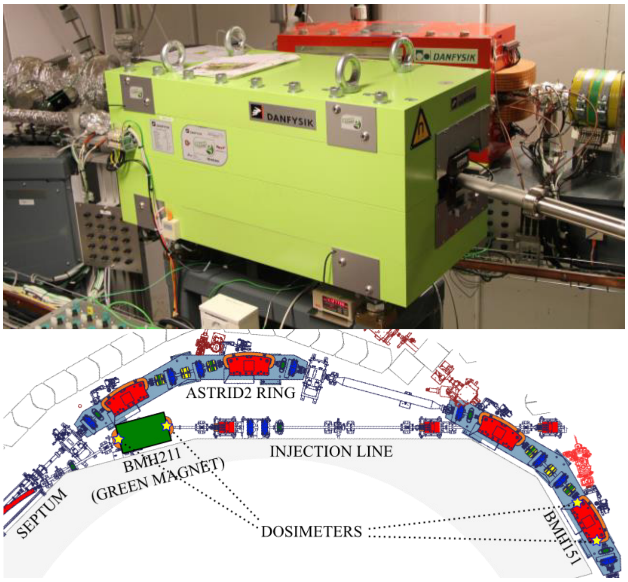

Figure 1: A photo of the ASTRID2 Green Magnet in the beam injection line (top) and a top-view of part of ASTRID2 and its injection line, where the original resistive magnet with coil ends are visible (bottom).

Based on our previous experience [1], the design concept has been further optimized by developing a flexible design which minimizes the needed amount of permanent magnet materiel, allows for easy fine-tuning of the center field and thermal stability while still reducing the machining costs. The design uses only one size of high remanence permanent NdFeB blocks (N48M grade). A new efficient tooling concept has been developed for handling of the magnetic forces and mounting of the permanent magnets. This allows one person to mount the

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*Work supported by The Danish National Advanced Technology Foundation nearly 500 permanent magnets within one week. The iron poles homogenize the small unavoidable imperfections and remanence variations of the NdFeB. For this hybrid iron-dominated design, the pole shape will determine the field homogeneity. Higher field homogeneity for synchrotron ring applications or a combined function design with a built-in gradient can therefore be obtained through the pole design, as for traditional electromagnets. The magnetic shim angle of the effective magnetic field boundary was determined from Hall probe mapping of the fringe fields. The obtained shim angles were within 0.05° of the target value and thus within the stringent specification, as was also the case for all other requirements (see Table 1).

Table 1: ASTRID2 Green Magnet Design Parameters

Parameter	Specification	Obtained
Deflection angle	30°	30°
Pole gap	30 mm	30 mm
Radius of curvature	1.9099 m	1.9099 m
Magnetic length	1000 mm	1002.6 mm
Center field base value	1.015 T	1.015 T
Operating range	(100±2) %	(100±3) %
Field homogeneity	$< 1 \cdot 10^{-3}$	$< 0.6 \cdot 10^{-3}$
Fringe field shim angle	15.0 ± 0.5°	15.01°
Thermal stability, 15-35°C	< 50 ppm/°C	< 30 ppm/°C

INSTALLATION AT ASTRID2

The ASTRID2 Green Magnet was installed in September 2013 in the beam injection line leading into the ASTRID2 synchrotron at Aarhus University, cf. Fig. 1. The installation was quick and easy without need for cooling water installations and allowed for a considerable reduction in cable cross section due to a power need of less than 20 A for the correction coils.

For the installation of the vacuum chamber, the top and bottom half of the magnet has to be separated due to the small rose shims added on the side of the poles. A magnetic force of 90 kN had to be overcome to perform this separation using four assembly bolts that can be mounted on the sides of the magnet. This tooling is removable so that it can be reused for other similar magnets and is needed for any later replacement of components, such as the coil.

OPERATIONAL EXPERIENCE

After the magnet exchange, from the original resistive magnet to the new Green Magnet, practically no adjustments of any of the magnet elements along the injection line were necessary to reach the same injection efficiency. Specifically, powering the trim coils of the ASTRID2 Green Magnet have never been needed for standard beam operation.

Radiation damage and ageing effects of the NdFeB magnets are common concerns about the use of Green Magnets in accelerators and both the short and long-term stability of the Green Magnet is therefore being evaluated. A precise measurement of the field is possible using a precision Group3 Hall probe in fixed bracket supports. The field was initially measured in three reference points (entrance, center, and exit of the magnet) after installation but prior to commissioning with beam. Over a period of 7 months, the field was regularly checked, cf. Fig. 2. It should be noted that while we are aware of systematic measurement errors (e.g. a -80 ppm/K probe temperature-dependence), these have not been compensated for. A synchrotron dipole is also located immediately adjacent to the Green Magnet, and this was powered in all but the first measurement. This may affect field measurements through stray field and local heating. A weighted mean of the final deviation is 212 ± 12 ppm, well below the experimental uncertainty and comparable to the required stability of the magnet.

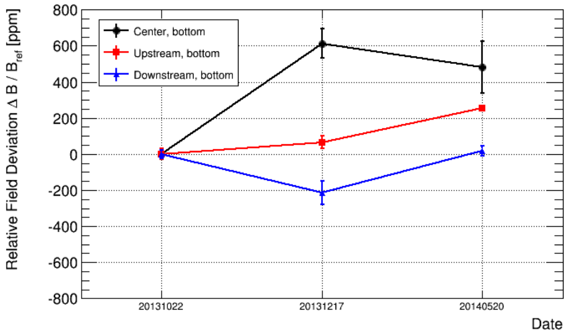

Figure 2: Teslameter measurements at 3 reference points. The data points are relative to the first measurement.

Over a period of 45 days of general accelerator commissioning, i.e. not necessarily having nominal beam optics, the radiation levels were monitored using a combination of TLDs and CR-39 dosimeters. Such pairs were located at the up- and downstream end of the Green Magnet and for comparison also around a ring dipole (BMH151), see Fig. 1, bottom panel. The dosimeters were placed on the yoke in the height relevant for the permanent magnets. In general, the accumulated doses are small with maximum 73 mSv (TLD) on the upstream end of BMH151 and about a factor 5 less at the Green Magnet. Also, at the downstream end of either magnet, the doses are reduced by 1-2 orders of magnitude, i.e. the 1 m long magnet yoke provides considerable radiation shielding. During the dosimeter measurements, a total of 7.5 µC beam was extracted from the ASTRID booster, through the injection line.

BEAM-INDUCED DEMAGNETIZATION

A demagnetizing temperature can be estimated for each permanent magnet material as the temperature at which the magnet will be demagnetized. Temnykh observed [4]

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an exponential correlation between the demagnetizing temperature and radiation-induced demagnetization. This demagnetizing temperature increases with increasing intrinsic coercivity H_{ci} and with decreasing demagnetizing field H_d. The shape dependent demagnetizing field decreases with increasing permeance, i.e. operating point. Radiation resistance (RR) has been known to similarly depend on the intrinsic coercivity and local H_d [5]. Most experiments concerning RR have been performed on oblate shaped (thin in direction of magnetization) free magnet samples, i.e. driving an air-circuit, although many practical applications involve magnetic circuits of lower reluctance. Especially such free oblate samples have a wide distribution in H_d, with larger values near the central part. These weaker spots are expected to have a reduced RR, and the apparent RR would thus be pessimistically low compared to a sample driving a realistic, well-designed circuit, where the H_d-distribution is far narrower.

A more careful RR experiment has been conducted, cf. Fig. 3. Samples of NdFeB (or SmCo) can be placed between soft iron poles of an electromagnetic dipole providing up to ±0.9 T bias field across the sample. Applying a reverse bias field, a very narrow (~1%) distribution of H_d can be maintained across the sample volume while irradiating this with an intense uniform beam of 100 MeV electrons from a microtron operating at 8 Hz, a current of 5 mA and a pulse length of 0.5 µs. The resulting demagnetization is measured using a precision teslameter for several similar N35 and N35M samples. N35 has H_{ci} of 1243 kA/m and N35M a higher value of 1443 kA/m that is similar to the N48M grade. The accumulated beam fluence necessary to demagnetize the samples by 1%, $RR_{1\%}$ was found for several settings of the H_d bias field. Preliminary results are shown in Fig. 4 and reveal clear exponential correlations between $RR_{1\%}$ fluence and $(H_{ci} - H_d)/H_{ci}$, the relative distance between H_{ci} and the operating point. For the weakest N35 sample $RR_{1\%} \sim 30\ \mu C/cm^2$ is found at the maximum reverse bias field. Comparing even the full previously mentioned 7.5 µC injection line beam charge over a period of 45 days to the cross section of permanent magnets in the Green Magnet, 1700 cm^2, the $RR_{1\%}$ is comfortingly low. A localized demagnetization could be induced by unintentionally steering the full beam at the same spot for months. Monte Carlo simulations reveal that a pencil beam of 580 MeV (max. energy in ASTRID2) generates a shower where 90% is contained within Ø0.8 x 10 cm^2, i.e. only $3 \cdot 10^{-4}$ of the 17000 cm^3 of NdFeB would be affected. The homogenizing iron yoke and poles would thus reduce the level of the localized demagnetization by more than a factor 3400 at the magnet gap. On top of this, the demagnetizing field in the NdFeB of the Green Magnet is designed to be low, cf. Fig. 4, which increases the RR exponentially. The risk of radiation damage is thus not a concern at all. For larger beam energies the shower depth increases only logarithmically and the conclusion therefore hardly changes for the 3 GeV used in many synchrotron light sources.

The radiation resistance can be improved by about three orders of magnitude by using Sm_2Co_{17} based permanent magnets. This option is mostly relevant for low field magnets as it comes at the expense of about 25% lower remanence and about a factor of two higher permanent magnet mass.

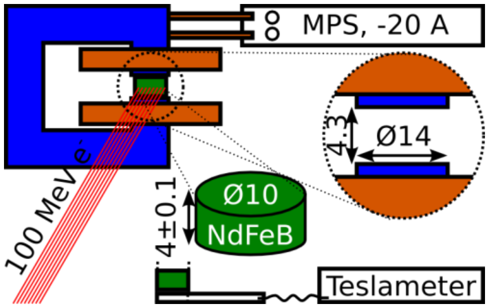

Figure 3: Setup for demagnetizing small samples of permanent magnets subjected to an intense uniform beam of electrons, while a reverse magnetic bias field is applied. Dimensions are listed in mm and are not to scale.

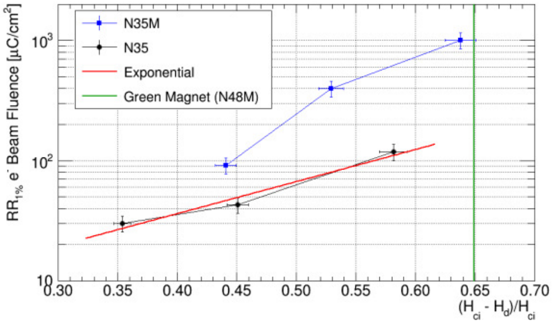

Figure 4: The experimental RR results. The Green Magnet work point is marked by a green line.

CONCLUSION

A permanent magnet based 1 Tm bending dipole has been designed and built to the requirements of the injection line at the ASTRID2. The magnet has exhibited impeccable performance during 8 months of operation with no detectable field variations. The permanent magnet work point was found to be important for the radiation resistance of NdFeB magnets and this can improve the stability of Green Magnets. The radiation resistance of the Green Magnets is also large simply due to the large volume of permanent magnets, all nested behind pole and yoke material. Green Magnet technology is therefore found to be well suited for use in synchrotron light facilities.

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