

# PERMANENT MAGNETS IN ACCELERATORS CAN SAVE ENERGY, SPACE AND COST\*

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## Abstract

Green Magnet® technology with close to zero electrical power consumption without the need for cooling water saves costs, space and natural resources. A compact dipole based on permanent magnets has been developed at Danfysik in collaboration with Sintex and Aarhus University. Our first Green Magnet has been delivered to ETH Zurich for testing in a compact accelerator mass spectrometer facility. Permanent NdFeB magnets generate a fixed magnetic field without using electrical power in the 90° bending magnet. Thermal drift of the permanent magnets is passively compensated. Small air cooled trim coils permit fine tuning of the magnetic field. Magnetic field measurements and thermal stability tests show that the Green Magnet fully meets the magnetic requirements of the previously used electromagnet. A permanent 30° bending dipole is currently being development to demonstrate the use of Green Magnet technology in other accelerator systems like synchrotron light sources and transfer beamlines.

## INTRODUCTION

Permanent magnet systems are ideally suited for fixed field applications or cases that only require small field variations. Here we present a permanent magnet based dipole magnet designed and built for use in the commercially available MICADAS accelerator mass spectrometer (AMS) developed at ETH in Zürich [1]. The facility layout is shown in Fig. 1 and Fig. 2 shows a photo of the magnet.

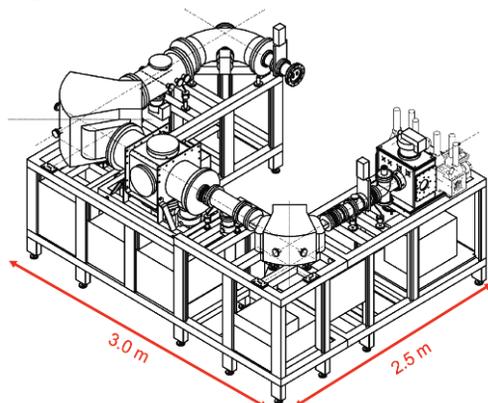


Figure 1: Layout of the ETH MICADAS AMS system.

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The Green Magnet fulfils all the requirements while being more compact and saving most of the power cost of the electromagnet which it replaces. A permanent magnet based system has the additional advantage of not needing cooling water which reduces both installation and operational costs. Additionally, the originally water-cooled power supplies can be replaced with smaller and cheaper air cooled supplies for minor field adjustments. A Green Magnet based AMS system can therefore be more compact with reduced installation and operation costs.



Figure 2: Photo showing our first AMS magnet based on Green Magnet technology.

## MAGNETIC DESIGN

The magnet presented here is the smaller of the two 90° AMS bending magnets as it is to be used on the low energy side (LE). The larger high energy (HE) magnet with a center field of 1.0 T is currently being designed in a Green version. The main design requirements for the LE magnet are given in Table 1 and Fig. 3 shows the magnet as modeled in Opera-3D [2].

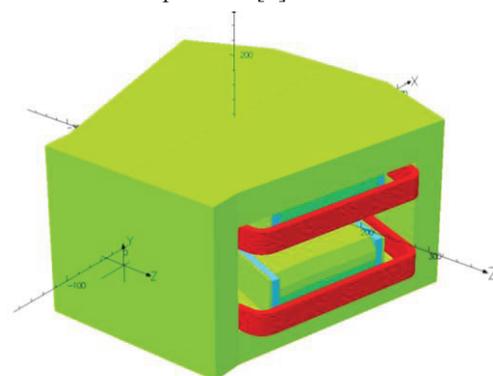


Figure 3: Layout of the AMS magnet in Opera-3D with the permanent magnets shown in dark green.

With a modest center field requirement of 0.43 T, the magnet can be made using a design where the permanent magnets are placed between the iron poles and the yoke with a width similar to that of the poles. To minimize the permanent magnet cost, the available space has been filled as much as possible using only two different permanent magnet block sizes. This was possible using a high remanence NdFeB grade with a typical remanence of 1.42 T.

The large 90° deflection angle and the 28.52° magnetic fringe field edge rotation angle (shim angle) are significant design challenges. The magnet could have been made in a simple straight version but that would have increased the pole width by 30 % and thus increased the amount of relatively expensive permanent magnet material and the overall magnet size. A design with a bent pole has thus been selected. The top and bottom half of the magnet can be separated for insertion of the vacuum chamber using four bolts (see Fig. 5).

The electromagnet used until now in the AMS facility is made with adjustable field clamps at the ends due to stringent requirements on the magnetic shim angle and on minimum transverse fringe field curvature. The AMS magnet has been designed in full 3D using the Opera simulation code [2] to meet specifications without use of field clamps.

Air-cooled trim coils are included to allow the field to be increased by 3% from a base value of 0.4267 T using a small simple unipolar 10 A power supply with air cooling.

Table 1: Magnet Design Parameters

Parameter	Specification	Obtained
Deflection angle	90°	90°
Pole gap	38.5 mm	38.51 mm
Radius of curvature	250 mm	250 mm
Magnetic length	393 mm ±1 %	394 mm
Center field base value	0.4267 T	0.42673 T
Operating range	0 - 2 %	0 - 3 %
Field homogeneity	$< 1 \cdot 10^{-3}$	$< 0.8 \cdot 10^{-3}$
Fringe field shim angle	$28.52 \pm 0.1^\circ$	$28.42^\circ/28.47^\circ$
Thermal stability, 15-35°C	$< 50 \text{ ppm}/^\circ\text{C}$	$< 20 \text{ ppm}/^\circ\text{C}$

## THERMAL STABILIZATION

The AMS magnet is required to have a field stability of better than 50 ppm/°C, a typical stability requirement level for accelerator deflection magnets. If strong and compact magnets are desired, high-remanence NdFeB is the permanent material of choice. The remanent field strength of NdFeB magnets is strongly temperature dependent as it decreases with a gradient of about 1000 ppm/°C. Thermal field variation was previously minimized by using flux shunting [3,4]. A similar scheme

was used for the AMS magnet and optimized by Opera-3D. The temperature compensation works well as observed from the measured temperature variation of the center field shown in Fig. 4 for the case without current in the trim coils. Increasing the center field by up to 3% resulted in a slightly increased thermal drift of 18 ppm/°C which is still well within the specification.

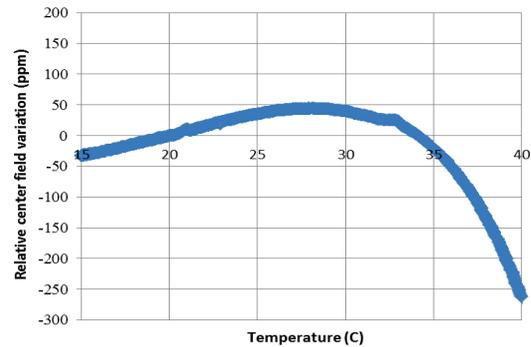


Figure 4: Relative center field variation as measured with an NMR probe during cool down for the case without current in the trim coils.

## MAGNETIC PERFORMANCE

The magnetic field strength of the as-built magnet can deviate a few percent from the nominal design value as the average strength of the permanent magnets of a given NdFeB grade typically varies a few percent between different production batches. This effect has been included in the design such that the center field can be adjusted to the required value using iron shims for magnetic flux shunting. Using this method the target field value was obtained within 0.01% which minimized the needed field adjustment strength of the electromagnetic trim coil. The transverse field homogeneity was measured with a “Hall probe field mapper” showing the relative variation of the center field with transverse position to agree with the 3D model calculations within  $2 \cdot 10^{-4}$  and well within the requirements.

The shim angle of the effective magnetic field boundaries was determined from Hall probe mapping of the fringe fields. The entrance and exit angles were 28.42° and 28.47°, respectively, and thus within the stringent specification. The transverse variation of the effective field boundary was found to be straight within  $\pm 0.1$  mm and this result is about a factor of three better than the original AMS electromagnet.

## INSTALLATION AND TEST AT ETH

The Green Magnet was installed in an AMS facility at ETH, as shown in Fig. 5. The installation of the Green Magnet was straight forward with the possibility of using thin and flexible power supply cabling for the trim coils and the advantage of not needing any water cooling connections. The magnet performed well during the test and we could not observe any difference to the normal measurement conditions with a conventional electromagnet.



Figure 5: Test installation at ETH. The water cooling tubing and thick power cable were used for the original electromagnet.

### USE IN OTHER FACILITIES

A larger permanent magnet based  $30^\circ$  bending dipole with a total length of 1 m and a center field of 1.0 T has been designed (see Fig. 6) and is currently in production for use in the transport line of the newly upgraded ASTRID2 synchrotron light facility at Aarhus University, Denmark. The risk of radiation damage has been evaluated but not found to be of concern. This magnet is made as a C-type magnet to demonstrate that the technology is ready for use also in a synchrotron where access for vacuum pumping and beam lines is needed.

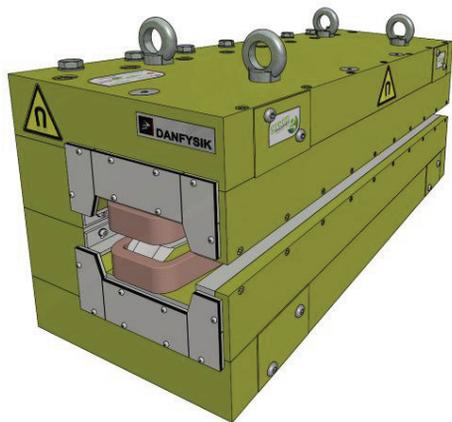


Figure 6: The permanent magnet based  $30^\circ$  bending dipole designed for use in the ASTRID2 transport line.

Another Green Magnet application is using a small permanent field gradient quadrupole magnet designed and built using SmCo magnets. It has a total length of 160 mm, an internal diameter of 25 mm and an integrated gradient of 3.3 Tm/m. It is made with soft iron poles with adjustable pole strength using a principle conceptually similar to that used for the LINAC4 quadrupoles [5]. The overall design concept is shown in Fig. 7. In our case the magnet was thermally stabilized to better than 20 ppm/ $^\circ$ C at room temperature. After a simple optimization the higher harmonic field error terms were all well below 0.01% (1unit) of the main gradient with the exception of the allowed 12- and 20-poles which can be minimized by adjustment of the chamfer depth at ends of the four iron poles. This result shows that high performance permanent

quadrupole magnets can be made as the field profile is determined by the soft iron poles.

The next step could be to make most of the bending dipole and quadrupole magnets using this type of permanent magnet technology for synchrotron light facilities like the ASTRID2 ring or even a 3 GeV facility. With Green Magnets, there is no need for high duty power cables, large water cooled power supplies and magnet cooling-water connections, and additionally the installation will be simpler and more compact. Such a facility is also expected to require less service and thus also provide higher reliability. With negligible power consumption for the magnets and reduced need for water cooling such a facility can be made with a clear green technology image.

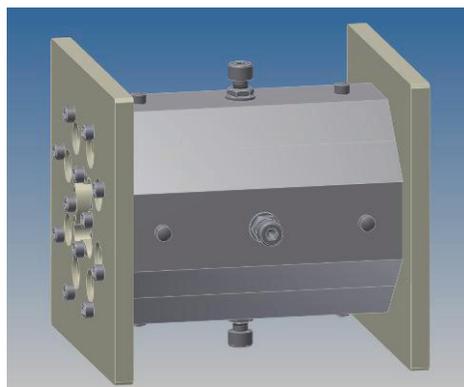


Figure 7: Mechanical design illustration of a temperature stabilized permanent quadrupole built for use as a calibration magnet.

### CONCLUSION

A permanent magnet based Green Magnet was designed and built to the specification of the original electromagnet for an AMS facility at ETH. The magnet performed well on all accounts in the acceptance tests and in terms of temperature stabilization even better. It was easy to install and the AMS facility showed excellent performance with the Green magnet as we could not observe any difference to the normal AMS operation. A high performance temperature-stable quadrupole has been made using permanent magnets and a dipole for use in the ASTRID2 transport line is in production. Green Magnet technology is found to be a safe and mature technology ready for use in a wide range of demanding applications.

### REFERENCES

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