CONSTRUCTION OF PERMANENT MAGNET ARRAYS WITHOUT CUSTOM MATERIALS

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Abstract

Permanent magnet Halbach arrays can be used for beam steering and focusing for synchrotron light sources, Fixed Field Accelerators, and plasma accelerators. Conventional implementations require many custom wedge-shaped magnets with tailored geometries and magnetisation angles, preventing material reuse. We present a method for constructing Halbach arrays from many identical rectangular magnets, each rotated in the transverse plane to approximate the optimal configuration. Although this introduces gaps and reduces magnetic efficiency compared with custom-wedge designs, it simplifies fabrication, lowers costs, and enables the magnets to be redeployed for future applications. A prototype array based on this approach has been built for Project TURBO at the University of Melbourne, and measurements confirm that the magnetic field quality meets the requirements of the planned beamline. Construction of the full arrays for TURBO will soon commence, and the reusability of the magnets is expected to provide long term flexibility for subsequent accelerator projects.

INTRODUCTION

Permanent magnets for particle accelerators offer potential advantages over conventional electromagnets in cases where the magnetic field does not need to vary over time. The design of these magnet arrays was proposed by Halbach, taking advantage of the high fields achievable by oriented rare earth materials, in excess of 1.3 T [1]. An ideal ‘Halbach array’ uses material with a continuously varying magnetisation axis, however realistic constraints instead require many individual pieces, each with a singular orientation. To reduce costs and improve prospects of material reuse, we propose to use magnets arrays comprising many identical bar magnets, which do not necessarily approximate the Halbach solution. This has proven successful in the context of compact NMR machines [2], where the requirements on field uniformity are more stringent than for particle accelerators, and has also been proposed for accelerator facilities [3]. At The University of Melbourne, we are working towards the construction of permanent magnet arrays with large nonlinear multipolar components. The first-order design of these magnets, which will be used in a large momentum acceptance closed-dispersion arc for ‘Project TURBO’, has already been completed [4]. As a first step towards the construction of these arrays, we have built a prototype dipole magnet and measured the magnetic field it produces, finding that magnetisation errors degrade the field quality, and that the results can be accurately replicated by our simulations.

MAGNET DESIGN AND OPTIMISATION

To demonstrate the viability of TURBO’s magnet arrays, a prototype dipole has been designed. To facilitate the design of the magnet array, a wrapper for the Python library Magpylib [5] has been developed. This wrapper provides convenience classes for the definition of accelerator magnets, the calculation of multipole coefficients, and visualisation of the arrays and B-fields produced. It also provides tools to automate the production of the magnet mounts, using CadQuery [6] to build the geometry. The Python wrapper also enables optimisation of the multipole content of a given magnet array. Each magnet block has three degrees of freedom: its position in the transverse plane (x, y), and its rotation angle about the longitudinal axis (θ_y), measured relative to the y-axis. The symmetry requirements of accelerator multipole magnets simplifies the optimisation problem, as the position and orientation of magnets beneath the horizontal midplane can be inferred by mirroring and flipping the sign on the rotation of magnets above the midplane, via the transformation $(x, y, \theta_y) \rightarrow (x, -y, -\theta_y)$. If we also constrain magnets on the midplane such that they must remain on the midplane and are not rotated during optimisation, this reduces the number of degrees of freedom for an n-magnet array from $3n$ to $(3n-2)/2$. For the purpose of magnet prototyping, 35 identical permanent magnet blocks have been procured from Chinese supplier Kingsun Magnetics. Each individual magnet is $10 \times 10 \times 100$ mm^3, magnetised along one of the short axes. They are made of NdFeB material, nominally N42H grade with a remanent field of 1.3 T. In practice, the large length/diameter ratio of these magnets will reduce the actual magnetic polarisation, requiring experimental determination of the field strength. It was decided that eight magnet blocks would be used to create the first prototype array. Using a small number of magnets allowed us to ensure that our magnet construction techniques were safe with a reduced risk of injury from the magnets, at the expense of reduced field uniformity and a lower maximum field strength. Beginning with the Halbach solution, Nelder-Mead simplex optimisation was performed to improve the field quality at the magnet centre and increase the field strength in the magnet bore, without changing the number of magnets. The good field radius was set to 15 mm, however a totally uniform field could not be achieved out to this distance due

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to the low magnet packing factor. The difference between the original and optimised arrays is given in Fig. 1, indicating a 17.8 % increase in the field strength, and a small improvement in the field uniformity.

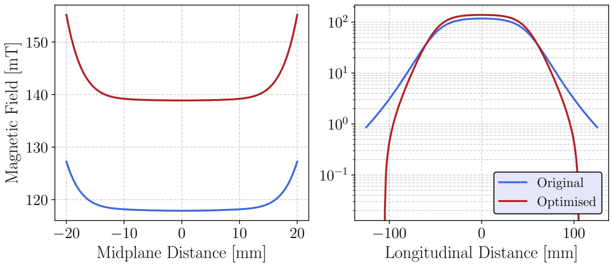

Figure 1: Vertical B-field strength before and after optimisation. Note the different scales. Left: Horizontal midplane ($y = z = 0$). Right: Longitudinal axis ($x = y = 0$).

The source of the increased field becomes more clear from the distribution of magnets around the bore, shown in Fig. 2. The optimised array has a higher concentration of magnets near the top and bottom of the array than the Halbach result, giving a higher field and reducing the symmetry that contributes to unwanted multipoles. The fringe field extent is also reduced by the optimisation, an unintended side-effect that indicates how sensitive the fringe field is to the magnet positioning. Notably, the optimisation is not constrained to enforce mirror-symmetry about the y-axis, so the fact that the result exhibits this expected property indicates that the solution is globally optimal.

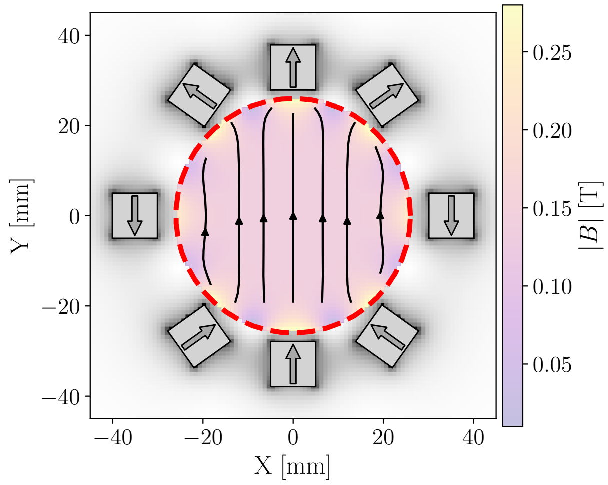

Figure 2: Transverse fieldmap for the optimised magnet array, measured at the magnet centre ($z = 0$). Shading in the exterior region indicates field strength in the mount.

One concern with these magnet arrays is that the strong magnetic forces could make the array construction difficult. Using Magpylib, we find that the strongest resultant force is exerted on the 'corner' magnets, with a magnitude of 37 N. This motivates the introduction of mitigations to reduce the likelihood of injury during array construction.

ARRAY CONSTRUCTION

For safety reasons, each magnet is housed in a 3D printed (PLA) 'shell' with 1 mm thick walls: this dramatically reduces the risk of injury and makes it much easier to pull magnets apart when they come into contact, at the expense of a reduced magnetic fill factor in the final array. The lid of each shell has an arrow to indicate the magnetisation axis, and narrow slits are included to facilitate magnet removal if necessary. A magnet housed in a shell is shown in Fig. 3. As part of this prototyping process, we wanted to test whether a fully 3D printed mount would be suitable. We chose ASA filament for its strength and resistance to warping over time, with an infill of 15 % and multiple wall loops to reinforce the structure. For assembly, PLA spacers were used to insert the magnets, and a 'blank' was positioned above the actual mount to increase the distance between magnets and reduce the likelihood of magnets being pulled out. Once all the magnets were inserted, an ASA cap was fixed to the front face of the mount, keeping all magnets rigidly in place. The constructed array, prior to the addition of the cap, is shown in Fig. 3.

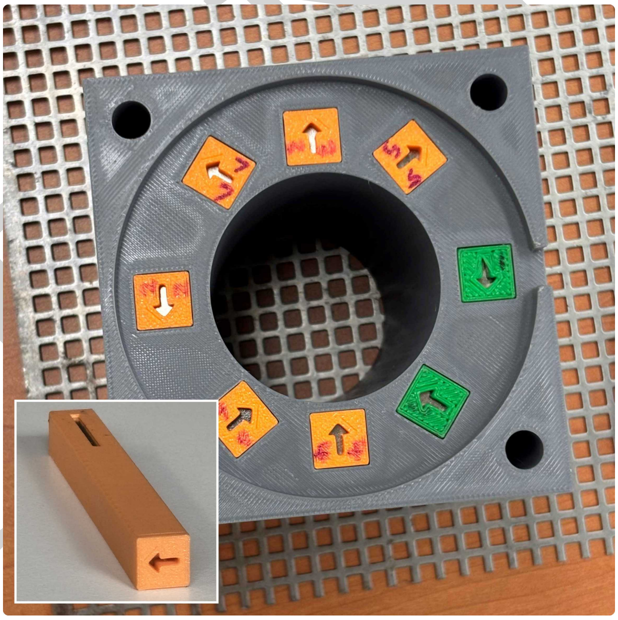

Figure 3: Mount with all eight magnets inserted. The inner bore radius is 25 mm, and the exterior has sides 100 mm long. **Inset:** A single magnet in its 3D printed shell.

The arrays must be held at a constant temperature, as the strength of NdFeB magnets varies by approximately 0.15 %/K [7]. To achieve this, water cooling channels were included near the corners of the magnet mount, as can be seen in Fig. 3. Each channel has an 8 mm inner diameter, matching the outer diameter of PTFE tubes carrying cooled water from a 1.7 kW SMC chiller. It had been hoped that this would be sufficient to keep the temperature variation of the magnet array below 0.5 °C, which is necessary as the space where these magnets will be used experiences fluctuations of several °C. Unfortunately, this plan proved to be overly optimistic: the low thermal conductivity of the plastic mount, coupled with the large exterior surface area and relatively small area in contact with the cooling tubes, means that these cooling channels are insufficient in practice. We are currently investigating the feasibility of housing each plastic mount in an aluminium casing, which can be more readily held at constant temperature.

FIELD MEASUREMENTS

Measurements of the field produced by the magnet array were performed to determine the effectiveness of the model, and to begin to characterise the errors present in real magnets. As the fringe fields are expected to be a major factor in the application of these magnet arrays, a measurement of the integrated field would not be sufficient. Instead, the magnetic field was measured with a Hirst Magnetics GM08 Gaussmeter with a single axis transverse probe, requiring rotation to measure the magnetic field in both the horizontal and vertical planes. Measurements of the longitudinal field have not been performed. The field directly on the exterior surface of the ASA mount peaks at 35 mT and falls below 1 mT at 3 cm, making the magnet safe to handle and transport with reasonable precautions. Measurements of the vertical magnetic field along the horizontal midplane and longitudinal axis are presented in Fig. 4. Each data point is the average of four measurements, and the error bars represent one standard deviation. Longitudinal measurements at $z > 60$ mm were not possible, due to geometric constraints. We see that, after renormalisation to represent the reduced remanent field, the Magpylib model shown in Fig.2 reproduces the essential features: in particular, there is excellent agreement in the rate of fringe field fall-off, indicating that the model provides a good description for the magnet array.

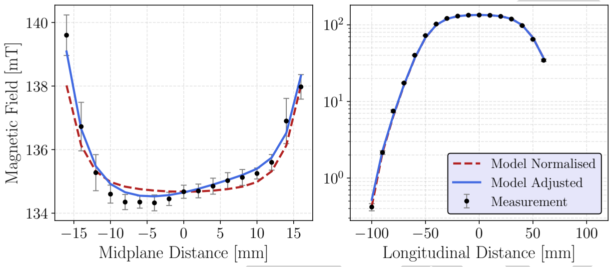

Figure 4: Measured and simulated vertical B-field. The normalised model is the same as Fig. 1, with B_r =1.261 T. The adjusted model varies magnetisation angles and strengths.

However, the renormalised model is not able to account for the asymmetry observed along the horizontal axis. The field asymmetry can be explained by assuming all magnets in the array have small manufacturing errors, shifting the magnetisation axis and remanent field: this provides three degrees of freedom per magnet. With this limited set of measurements, there is insufficient data to uniquely determine the magnetisation of all eight magnets, however it is enough for now to estimate the magnitude of the errors. In Fig. 4, we see that this adjusted model reproduces the magnetic field profile, with all remanent fields between 1.2-1.32 T, and both off-axis magnetisations below 0.25°. Even viewed as a best-case scenario, this is an encouraging indication that the magnetisation errors are small.

There are significant sources of uncertainty in these measurements. As these measurements were performed manually with a 3D printed mount, the error on the probe position is as much as ±0.5 mm, and the probe angle ±5°. In addition, the temperature of the room rose by approximately 1 °C over the course of the measurements. For these reasons, these measurements should be taken as indicative of the broad performance of the magnet array, but should not be interpreted as an exact field map.

DISCUSSION

Permanent magnet arrays are potentially advantageous over electromagnets for accelerators in cases where the magnetic field does not need to vary over time. Often, these permanent magnets must be custom-manufactured for a given application, which raises costs and prevents reuse of magnetic materials. At The University of Melbourne, we are developing permanent magnet arrays to produce highly nonlinear magnetic fields as part of Project TURBO, using many identical permanent magnet blocks for each array. We have designed, constructed, and measured the field of a prototype dipole magnet, as a first step towards the production of the more complex arrays. Using eight NdFeB magnet blocks, we have found that the classic Halbach magnet solution can be improved by optimisation, giving a better field quality and increasing the maximum magnetic field. Using a commercial 3D printer, we produced individual shells for each magnet, as well as a mount and lid to construct the array. After assembly, we measured the actual magnetic field in the magnet bore, finding that it has some asymmetry that can only be explained by magnetisation errors. Though it is not possible to uniquely constrain these errors with our current set of measurements, we found that our model was able to reproduce the key features with reasonable assumptions about the magnitude of the errors. The production of this prototype dipole has led to several insights to consider for the full-scale arrays. It will be necessary to include a set of fiducials on the surface of the magnet mount, as locating measurements precisely proved challenging without them. This should be coupled to an automated rig for future magnet measurements, providing greater accuracy and reproducibility. Techniques to compensate for field errors in the constructed array must be investigated further, extending existing methods [8]. Finally, each magnet in the array should be individually characterised, and methods should be considered to optimise their positions in the full array to minimise the impact of their errors. Overall, the prototype dipole has provided confidence in the effectiveness of our magnet array design and construction methods, guiding our plans for the production of larger arrays. We can now proceed with the work towards the arrays for TURBO, as well as investigating the uses of permanent magnet arrays for other cases.

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