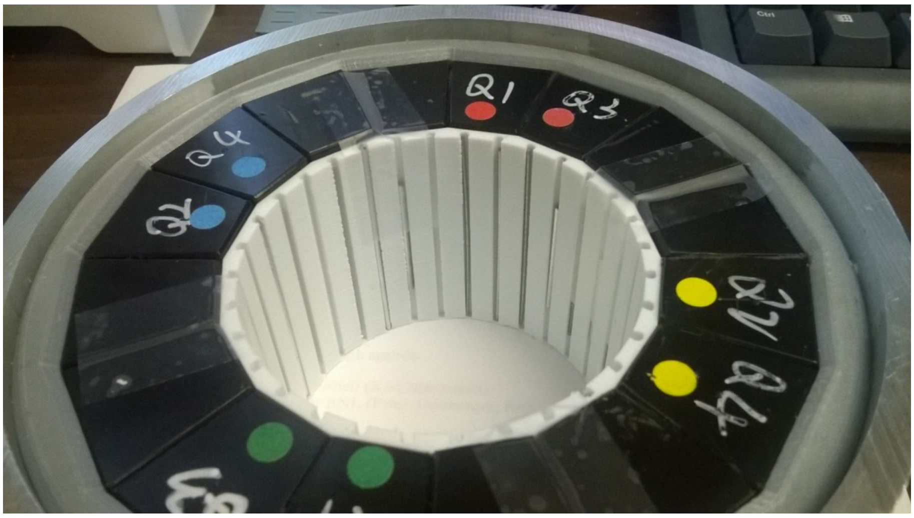
Halbach Magnets Risks and Challenges

Stephen Brooks 2016-Dec-15 CBETA machine note #2

1. Technological principles and challenges

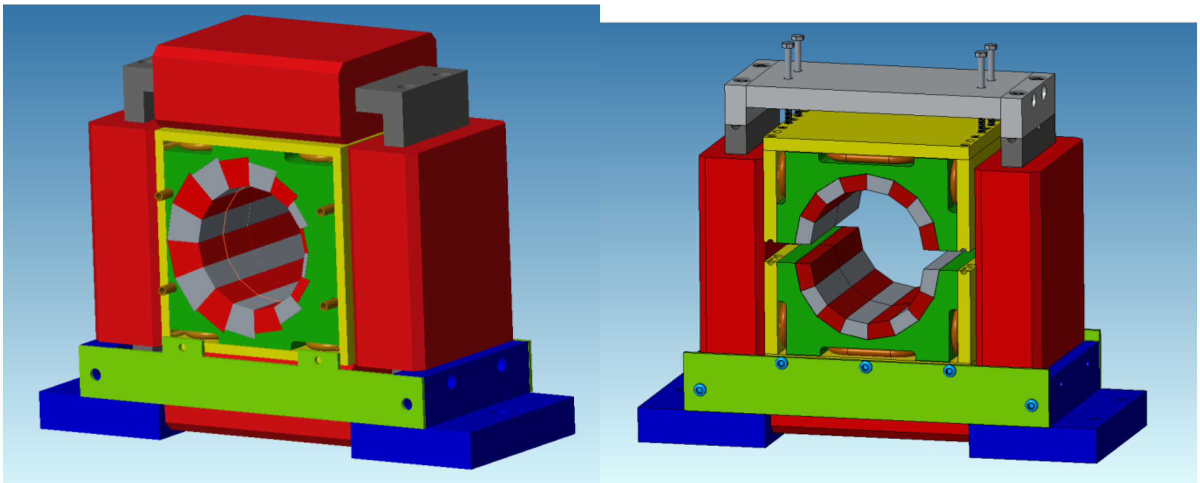
The Halbach magnet design produces magnetic field directly from magnetised blocks, without intervening iron to shape the field. This traditionally has made it difficult to get good field quality, as the field will be directly sensitive to the blocks' positions, angles and magnetisation strength, the last of which can vary by of the order of 1% from the factory.

The shimmed Halbach design proposed here circumvents these difficulties by producing the field in two stages. The permanent magnets are placed (without sorting) and produce a field with errors of the order of 1%, but the errors are repeatable provided the blocks are fixed in place. This unshimmed magnet is then measured on a rotating coil to determine the error harmonics. A combination of iron wires of various sizes placed around the inner bore has been found to cancel any combination of multipoles provided they are weak enough. The picture below shows 32 such wires confined in channels in a 3D printed plastic shim holder.



The above magnet is part of a prototype series of 6 quadrupole and 6 combined-function magnets, which have been shimmed to field quality required for CBETA, as described in other documents.

For CBETA, an additional online correction is needed to compensate for the material's temperature coefficient and also to provide correction to beam steering and corrections for misalignments errors of the magnet placement. A "window-frame" electromagnetic corrector is placed surrounding the magnet to provide this. The permanent magnet assembly within has $\mu_r \sim 1$, so the correction field adds linearly onto the main field. A design with these elements is shown in the two pictures below.



The left-hand magnet is the "BD" combined function magnet, where the asymmetrical choice of permanent magnet thicknesses generates both a dipole and a quadrupole (and the magnetisation angles have been chosen to cancel all other harmonics in the ideal case). The right-hand picture shows the "QF" pure quadrupole magnet in the process of being split with screws. This procedure is needed to assemble the magnets around the CBETA vacuum chamber.

2. Risk drivers

2.1. Variability of magnetisation from factory

a) Random errors of block magnetisation strength and direction.

Mitigation: these can be corrected by the shimming wires if small enough. For instance +/-1% errors in magnetisation strength and +/-0.01rad (+/-0.57deg) errors in direction can always be shimmed with 32 wires of up to 63mil thickness. For larger errors it is possible to use more or thicker wires for a proportionate gain in strength, but the above error sizes are consistent with what was seen in prototyping. There is some averaging, so the "1%" level block errors produce 25-50 units of total multipole error at the beam radius (shimmable to almost always less than 1 unit in simulation).

b) Overall average magnetisation strength of blocks is too small by a few percent. This was observed in measurements of blocks received for the iron-poled magnet: the block-to-block variability was very good but the average was too low.

Mitigation: this can be corrected by designing the magnet for the low end of the strength range. If blocks are then received with a higher average strength, the magnet can be weakened by placing the blocks slightly further away from the centre (they may be separated for example by aluminium shimming pieces).

2.2. Temperature coefficient

a) The NdFeB material has a temperature coefficient of -1.1e-3/K, meaning the magnet will weaken in higher temperatures (by about 1% for a 9K increase in temperature). There is no obvious way to include temperature compensation material (such as NiFe) into the Halbach magnet due to its geometry with field lines not parallel to the magnetisation vectors.

Mitigation: the Halbach magnets will be surrounded by window-frame correctors that can provide at least +/-2% of the overall field in quadrupole and dipole. This range would be able to compensate a 20C (68F) room swinging from 2C to 38C (36F to 100F). The corrections will be calculated from the low-frequency orbit feedback system in the same way that other slow orbit drifts are compensated. This method has been approved by Chris Mayes (L2 for accelerator physics).

b) It is possible that parts of the magnet will heat up non-uniformly and produce field errors that are not a simple scaling of the dipole+quad field.

Mitigation: the largest source of heat near the magnet is the window-frame corrector coil. A chilled aluminium plate with water cooling channels has been placed surrounding the NdFeB blocks and inside the window-frame, so that the heat has a much lower resistance path into the cooling water than to the blocks. This will also provide some additional temperature stabilisation to the blocks due to the water's regulated temperature.

2.3. Top/bottom alignment after reassembly

In order to be able to assemble the magnets around the vacuum chamber pipe (which has protrusions), they must be able to be split into top and bottom halves. Lateral offsets caused by reassembly produce a unit of skew quadrupole at the beam maximum radius for each 5 micron (0.2 mil) displacement and a unit of skew sextupole for each 18 micron (0.7 mil) displacement.

Mitigation: after initial assembly and measurement, holes will be drilled into the centre line between the top and bottom halves, and metal pins fitted tightly into these holes. This is a standard procedure used in e.g. quadrupoles for reliable reassembly.

2.4. Radiation damage

This design puts the permanent magnet blocks very near the vacuum chamber (within a few mm) and they surround it on all sides including the midplane where beam losses are most probable. NdFeB is not particularly radiation hard although this varies with material grade.

Mitigation: firstly, quotes have been obtained for the material grades N35SH and N35UH, which have enhanced resistance to demagnetisation ("high temperature" grades) and are also not the strongest possible grade (which also tends to be more fragile). CBETA operates at a lower energy than light sources, so synchrotron radiation should be smaller. Beam loss is more concerning: although the strong focussing in the FFAG makes this a less likely place for loss, it will have to be monitored carefully. Permanent magnet wigglers have operated for long periods of time in light sources although these have open midplanes and some in the literature have shown small amounts of field degradation. A further mitigation is possible by adopting a magnet design where some of the midplane is "open" (filled with aluminium rather than NdFeB) so radiation on this plane does not directly hit a magnet block. Advice should be sought from wiggler experts.

2.5. Construction issues

a) The magnet blocks have large forces between each other during assembly (~100lbf).

Mitigation: the technique used on the prototypes was to have "dummy" plastic blocks (although they could equally well be non-magnetic metal) initially filling the space, which were replaced one-by-one by magnets. There was also a filler piece for the magnet bore. Once all the pieces had been inserted, the 16 wedges of the circular aperture were self-supporting like an arch. However, there were still large forces during assembly: the magnets could be assembled by hand but only just. Some extra tooling might help streamline this, or just buy from a company with experience handling permanent magnets (or wigglers, which are similar).

b) The arrangement of blocks as a whole is an odd shape.

Mitigation: in the prototypes, a 3D printed plastic mould proved strong enough to surround the magnets provided that it was confined inside an aluminium tube to strengthen against the easiest deformation mode. ABS plastic has survived on the RHIC beam dump to ~700Gy of irradiation so could be used in production too. Alternatively a custom aluminium extrusion may be affordable when building larger quantities.

3. Drivers for the schedule

3.1. Permanent magnet blocks initial lead time

Quotes for the full quantity of wedge-shaped NdFeB blocks from one vendor show an 80 day lead time. We may want to take delivery of a smaller batch first, however.

3.2. Measurement/shimming cycle

For each magnet, the main stages are:

- Assembly of Halbach magnet part and bolt it to window-frame corrector;
- Initial rotating coil field measurement;
- Calculate, cut and insert shims using shim holder;
- Second rotating coil measurement;
- [Finish if multipoles are low enough or do another iteration if necessary].

The prototype magnets were removed from the rotating coil in order to insert the shims, so these stages were done on batches of magnets in parallel. It may(?) be faster to shim a single magnet while still on the coil, but this requires the shim wires to be immobilised in their holders so they do not fall out of place when inserted into the magnet, plus ~32 shim wires to be rapidly cut to different lengths.

4. Drivers of the cost

Some estimates of the cost for the Halbach magnets (including hardware and labour at BNL rates) have been obtained, using actual quotes from companies for hardware where possible.

Radiabeam quoted either assembling just the window-frame correctors or also the Halbach assemblies plus supporting stands. They would also include an initial 1e-3-level rotating coil measurement to check for errors, although this is not accurate enough to do shimming. There were also two options for the correctors: water-cooled giving +/-4% quadrupole adjustment, or air-cooled giving +/-2% quadrupole adjustment (and more than sufficient dipole adjustment in both cases). The air-cooled is believed to be sufficient, particularly given the mitigation in 2.1(b) is available.

Danfysik provided a quote for the Halbach and window-frame parts, not including the stands, so Radiabeam's estimate was included for that option.

The permanent magnet blocks themselves are not a major cost driver, being 8-12% of the total cost. This makes it easier to specify a high temperature resistance grade and purchase spare pieces.

The window-frame correctors (insulated coils and iron) are the most expensive subsystem with 29% of the total cost when air-cooled and 46% when water-cooled.

The assembly of the Halbach enclosure from the magnet blocks is the 2nd largest item, from 20-22% of the total cost.

The kinematic stands seem to be a large cost but Radiabeam may have slightly overspecified them pending the final drawings, still they will be significant.

The labour for rotating coil measurements is large enough to appear at ~5% of the total. Significant increases in time required for this and shimming may therefore be noticeable.