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CBETA/023

Measurement of first magnet made with production material

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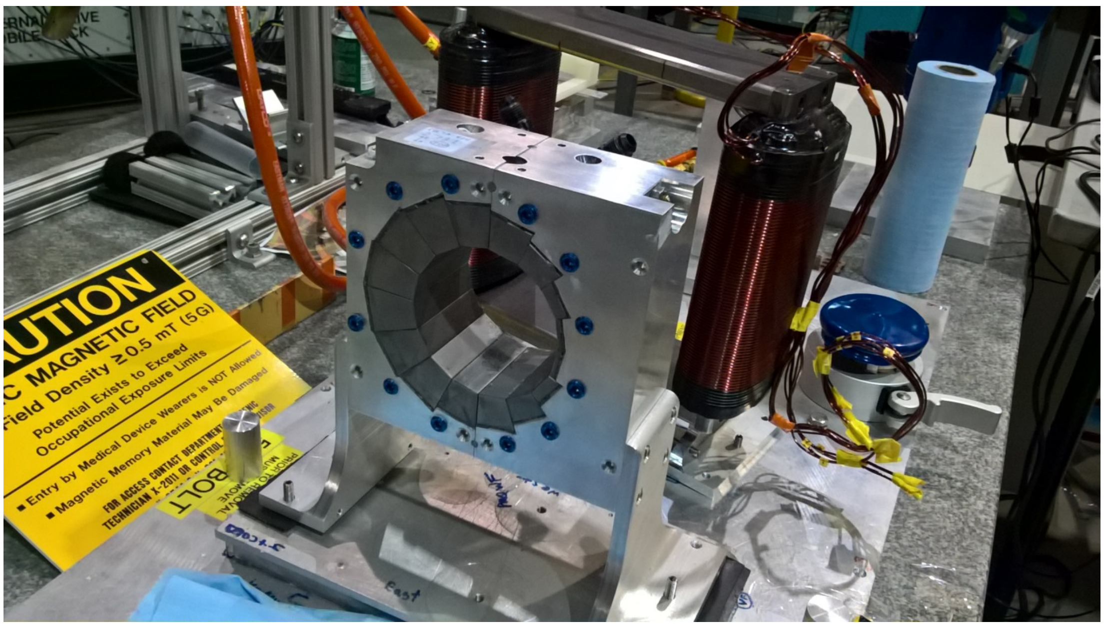
1. Introduction

The first CBETA magnet to be made using the production run of permanent magnet wedges is the BDH magnet, a "half length BD" to be placed at the start of the first girder of the FFAG return loop. This magnet has identifier number 2731 and is shown in the picture below while being prepared for measurement.

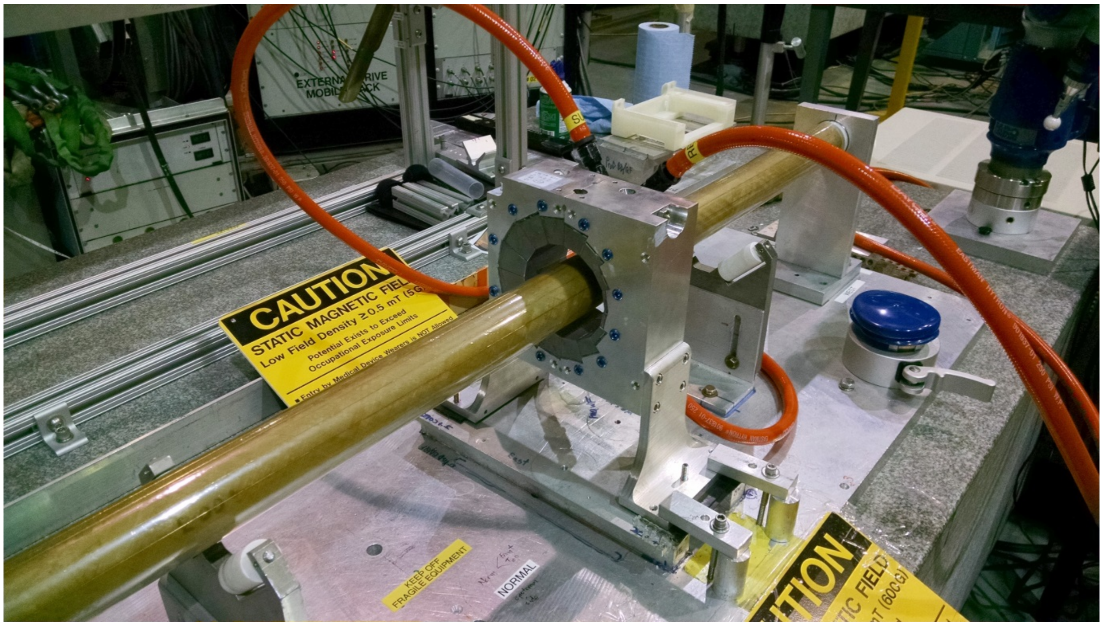


The parameters of this magnet are highlighted in the table below in comparison to the other types of permanent magnet in the CBETA return loop.

Magnet type	Identifier range	Length (m)	Dipole (T)	Gradient (T/m)
BD	2301-2399	0.122	-0.308115	11.1475
QF	2501-2699	0.133	0	-11.5624
BDT1	2101-2199	0.122	-0.100246	11.1475
BDT2	2201-2299	0.122	-0.254262	11.1475
QD	2401-2499	0.122	0	11.1434
QFH	2751-2759	0.0665	0	-11.5669
BDH	2731-2739	0.061	0.308361	-11.1541

2. Magnet Tuning Iteration

The integrated magnetic field was measured by placing the BDH magnet onto the BNL Magnet Division rotating coil as shown in the picture below.



The measurements were conducted with the magnet's water channels connected to a chiller loop run at 85F (the nominal operating temperature for these magnets), so that the temperature coefficient of the permanent magnet material would not give incorrect results.

After initial measurement of the untuned magnet, plastic cartridges populated with iron wires of various length were prepared in order to correct the observed multipole and strength errors. This procedure is described in more detail in [1], for a previous run of R&D magnets. The magnet was measured again and more tuning cartridges prepared as necessary, until the field converged to the correct strength and quality after a number of iterations.

The field quality observed on each run is shown in the table below.

Iteration number	Maximum field error on midplane (Gauss)	Central gradient error (relative)	Multipole figure of merit (units)	CBETA figure of merit
0 (bare magnet)	17.46	+1.154%	82.93	2.638
1	8.66	+0.458%	16.15	0.531
2	2.76	+0.121%	7.11	0.134
3	0.28	-0.001%	5.58	0.162

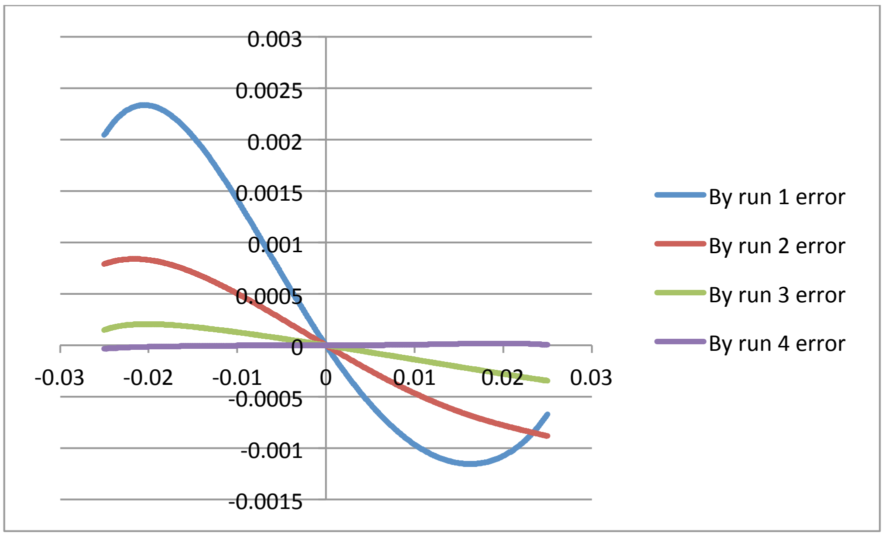
The maximum field on the midplane is calculated on the beam-relevant portion of the magnet midplane (X=-15mm to +25mm here), with optimised magnet placement (transverse displacements and roll rotation). It should be compared to the quadrupole field at R=25mm, which is 2788.5 Gauss.

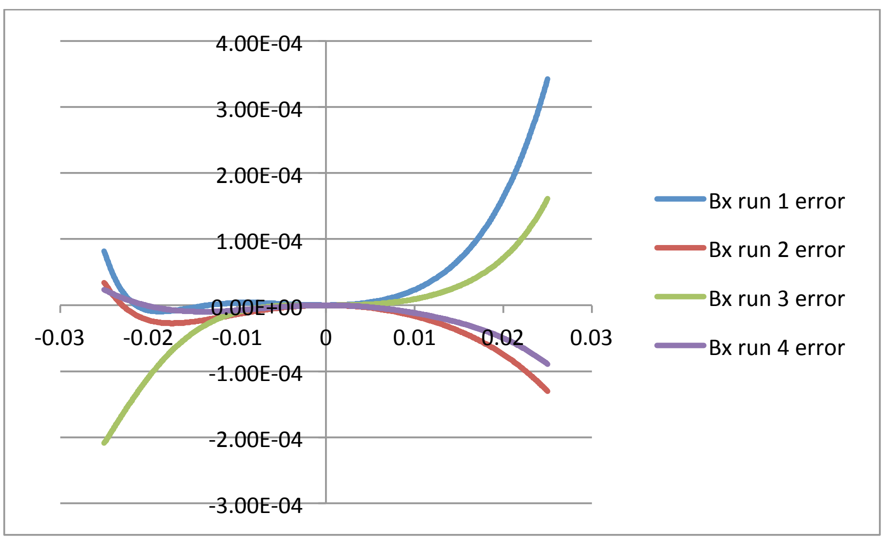
The "multipole figure of merit" is taking the square root of the sum of the squares of all the nonlinear multipole components (normal and skew). This figure of merit is also described in [1]. The "units" for magnet purposes are 10^{-4} of the strength of the quadrupole field component.

The “CBETA figure of merit” is a similar sum where the various multipoles have been scaled according to their effect on the beam tracked through CBETA in simulations. A value of 0.75 or less is predicted to give acceptable beam quality in the absence of other errors, so the preferred value is substantially less than 0.75.

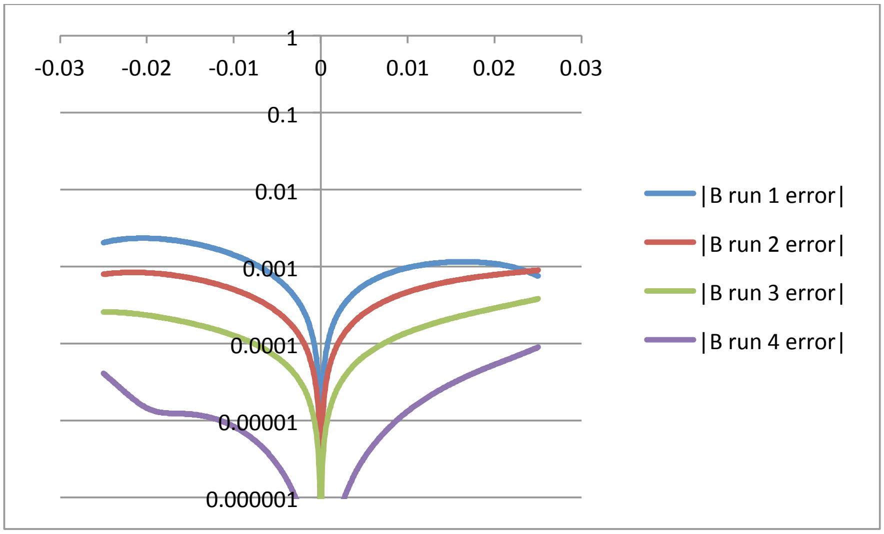
In the case of the BDH magnet, the aperture diameter is larger than its length, giving loss of field at the fringes of the magnet, an effect that is not yet taken into account in the model. This meant the wire tuning procedure took more iterations than usual to converge: usually CBETA magnets are expected to converge in 1 or 2 iterations. The 2nd iteration here was at the edge of 10^{-3} field quality so it was decided to try and improve further.

The graphs below show the field error components across the midplane from X=-25mm to +25mm. Run 1 is the bare magnet and runs 2,3,4 are the three iterations. Y axis is in Tesla.





The graph below shows the modulus of the field error on the midplane in Tesla, on a log scale. Note that this is plotted before the detailed magnet placement optimisation, so the maximum of the final magnet error is 0.89 Gauss rather than 0.28 Gauss.



3. Final Field Result

The multipole harmonics of the magnet, with main field quadrupole scaled to 10000, are given in the table below.

Pole	Normal	Skew
Dipole	-11058.34	0.00
Quad	10000.00	0.00
Sext	-0.24	2.55
Oct	-2.16	0.86
Deca	-0.74	-2.44
Dodeca	2.33	1.77
14-pole	1.16	0.84
16-pole	-0.81	-0.86
18-pole	0.38	0.58
20-pole	0.12	0.13
22-pole	0.13	-0.21
24-pole	-0.04	0.13
26-pole	-0.11	-0.16
28-pole	-0.05	0.00
30-pole	-0.01	0.04
32-pole	0.00	0.01
34-pole	-0.09	-0.02
36-pole	0.06	-0.01
38-pole	0.05	0.01
40-pole	0.00	-0.02

These harmonics, like the field error graphs in the previous section, are stated in the frame of reference where the central dipole is perfect and the central quadrupole is upright (that is, before position optimisation of the magnet over the beam excursion).

In this frame, the magnet's integrated quadrupole is -0.680392 T, or an average of -11.1540 T/m over its nominal length.

When placement optimised, the magnet's maximum field error on the beam-relevant region of the midplane is 0.28 Gauss, compared with a primary quadrupole at the maximum beam radius of 2788.5 Gauss, meaning this magnet has a relative field error of 10^{-4}.

References

[1] *Production of Low Cost, High Field Quality Halbach Magnets*, S.J. Brooks, J. Cintorino, A.K. Jain, and G.J. Mahler, in *Proc. IPAC2017*, pp. 4118--4120, Copenhagen, Denmark, May 2017, paper THPIK007, available from http://jacow.org/ipac2017/papers/thpik007.pdf or https://doi.org/10.18429/JACoW-IPAC2017-THPIK007 (2017).