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CBETA PERMANENT MAGNET PRODUCTION RUN

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Abstract

214 neodymium permanent magnets have been manufactured for the return loop of the CBETA [1] multi-turn ERL being built at Cornell University. There are 5 types of quadrupole and combined-function gradient magnets using a variant of the circular Halbach design. These are made out of NdFeB material and glued into an aluminium housing with water channels for temperature stabilisation. The NdFeB wedges and magnet construction were done by outside companies, while the final "tuning" using inserts containing 64 iron wires per magnet was done at BNL over a period of about 6 months. Average relative field errors of $2.3{\times}10^{-4}$ were achieved on the beam region. The magnet strengths vary by type but are of order 10 T/m for quadrupole component and up to 0.3 T for the dipole. This paper reports on the field quality and timeline achieved in this production process.

MAGNET TYPES AND QUANTITIES

The different magnet types required for the CBETA fixed-field return loop are specified in Table 1.

The BDH and QFH magnets are half-length versions of BD and QF, used once each at the ends of the accelerator for better matching. That leaves five distinct magnet cross-sections as shown in Fig. 1.

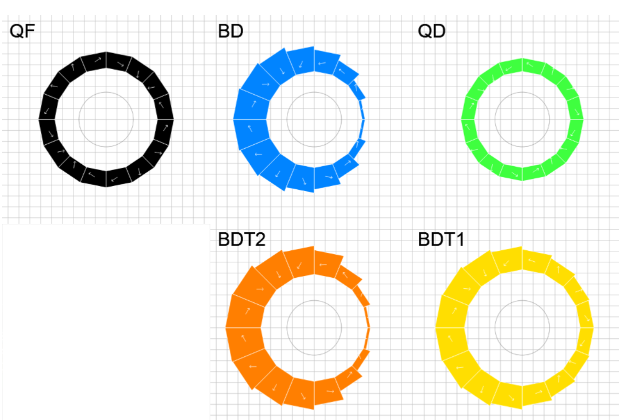

Figure 1: Permanent magnet cross-sections with 1 cm grid.

Q-type magnets are quadrupoles, while BD-type include both bending and a horizontally-defocussing gradient. The sequence BD, BDT2, BDT1, QD gradually decreases the bending component to zero to allow the adiabatic transition from curved arc to straight as shown in Fig. 2.

The transitional magnets have larger aperture so that further intermediate values of the dipole, on a continuous range, may be obtained by displacing them horizontally.

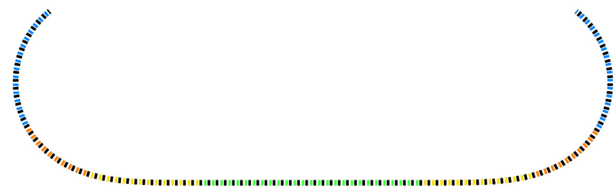

Figure 2: The fixed-field return loop for the CBETA ERL.

PRODUCTION METHOD

Each full-length magnet contains 32 permanent magnet wedges: two layers of the designs shown in Fig. 1. The BD-types require 16 distinct types of wedge when magnetisation angles are also considered, whereas the Q-type magnets can be built from four types of wedge, some inserted backwards. In total there are 56 different wedge types and 7648 wedges (including spares), which were ordered from Allstar Magnetics [2] and produced in China. RMS magnetisation accuracies of 1% strength and 1° angle were achieved for most wedges, with larger angle tolerances allowed for the smallest two BD-type wedges, which are more difficult to manufacture and contribute less to the total field. Quality control was achieved with the testing process in Fig. 3.

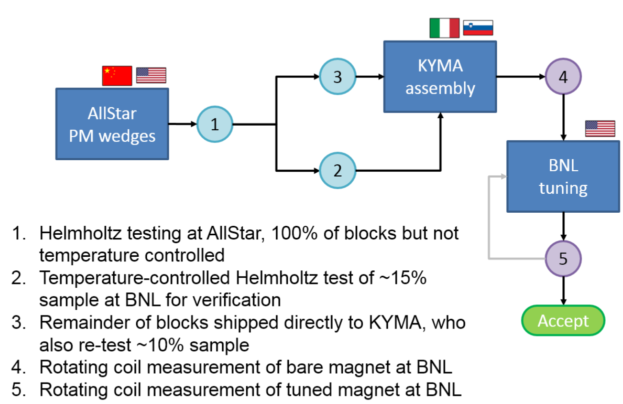

Figure 3: Production and testing flow.

Manufacture of the aluminium frames and gluing the magnet wedges into them was done by KYMA [3], who had previous experience with making undulator magnets and the strong forces between permanent magnet blocks. Wedges had to be positioned within ±0.25 mm to ensure field quality and this was achieved. Field strength could be re-tuned during production by changing the thickness of brass shims inserted between the wedges, which was done successfully for the QD magnets. The frames were made in left-right halves with pins to accurately align them with each other when assembled onto the vacuum chamber. Threaded rods

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Table 1: Magnet Specifications

Magnet type	Count	Dipole (T)	Gradient (T/m)	Length (mm)	Aperture radius (mm)	Good field radius (mm)
QF	107	0	-11.5624	133	43.1	25
BD	32	-0.3081	11.1475	122	40.1	25
BDT2	20	-0.2543	11.1475	122	44.938	25
BDT1	28	-0.1002	11.1475	122	49.085	25
QD	27	0	11.1434	122	40.1	25
QFH	1	0	-11.5624	66.5	43.1	25
BDH	1	-0.3081	11.1475	61	40.1	25

had to be used to overcome repulsive and attractive forces during this assembly.

Magnet Tuning

Once the magnets reached BNL, they were tuned using the method in [4], where 3D printed plastic tuning packs [5] containing iron wires were inserted to cancel the multipole errors measured in the magnet by a rotating coil. Figure 4 shows two steps in this process.

As the NdFeB material has a temperature coefficient of -1.1×10^{-3}/K, chillers were used to circulate water through the magnets during this process, with a temperature of 85 °F maintained to within ±0.2 K.

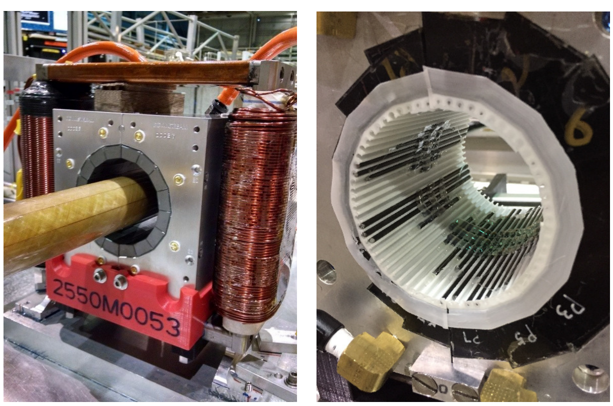

Figure 4: (a) QD magnet being measured with a rotating coil at BNL magnet division. (b) BD magnet with tuning wire pack inserted.

Schedule Achieved

Up to five prototypes of each magnet type were received and tested before approving final production, as shown in the early part of Fig. 5. There was then typically several weeks lead time before full production of the aluminium frames and magnets could occur, leading to the various magnet types being made in turns, as shown in Fig. 6.

The start of full production was defined by the first large batch of 27 magnets arriving at BNL and the statistics until completion are given in Table 2. Two rotating coils were used in parallel for much of this time.

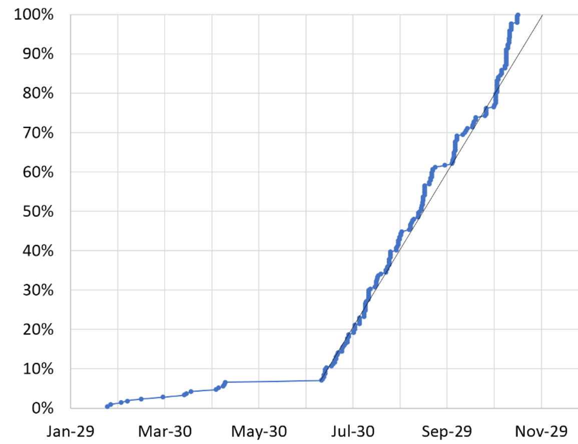

Figure 5: Fraction of magnets completed over time.

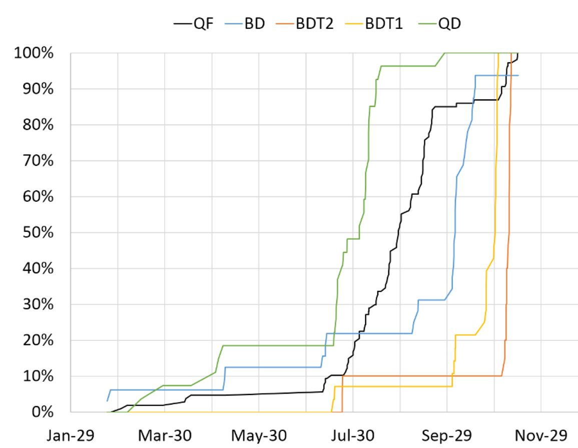

Figure 6: Fraction of each magnet type completed over time.

The diagonal line in Fig. 5 shows a linear interpolation from the production start until the project milestone deadline of November 30th.

FIELD QUALITY RESULTS

Several field quality metrics were calculated for each magnet from rotating coil data and compared to the acceptance thresholds given in Table 3.

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Table 2: Main Production Run Statistics

Magnets tuned	200 (excl. early samples)
Rotating coil measurements	545
Start date	July 9, 2018
End date	November 14, 2018
Total weeks	18.2
Magnets tuned per week (avg.)	10.96
Rotating coil measurements per week (avg.)	29.88
Rotating coil measurements per magnet (avg.)	2.73

Table 3: Quality Measures Used for Magnet Acceptance

Quality measure	Limit	Units
Maximum field error on midplane	≤ 1.5	Gauss
Multipole FOM	≤ 10	units
CBETA-scaled multipole FOM	≤ 0.375	
Quadrupole strength error	≤ 0.05	%

The maximum field error is measured on the $y = 0$ midplane good field region, which is ± 25 mm in x. All field values are averages derived by dividing the integrated field measured by the rotating coil by the nominal magnet length.

The multipole figure of merit (FOM) is defined as $\sqrt{\sum_{n \geq \text{sext}} b_n^2 + a_n^2}$ where b_n and a_n are the normal and skew harmonics, respectively, measured in "units" defined as 10^{-4} of the main quadrupole field at $R = 25$ mm.

The CBETA-scaled multipole FOM is defined as $\sqrt{\sum_{n \geq \text{sext}} \left(\frac{b_n}{b_{\text{lim},n}}\right)^2 + \left(\frac{a_n}{a_{\text{lim},n}}\right)^2}$, where the limits for each individual harmonic are derived from tracking studies with errors [6]. It was found the FOM had to be less than 0.75 to preserve beam quality under the assumption that the magnets were the only source of error, so half this value was used as the production limit.

Figure 7 shows how the multipole FOM of magnets decreased during the tuning process to be uniformly better than the limit. Similar results were obtained for the CBETA-scaled FOM (see [7] for more detail).

Table 4 gives summary statistics for the multipole FOM of all CBETA magnets.

Table 4: Multipole Figure of Merit Statistics

Multipole FOM (units)	Initial	Tuned
Average	41.09	3.09
RMS	46.92	3.70
Maximum	112.87	9.63
Minimum	14.64	0.52
Median	32.76	2.33

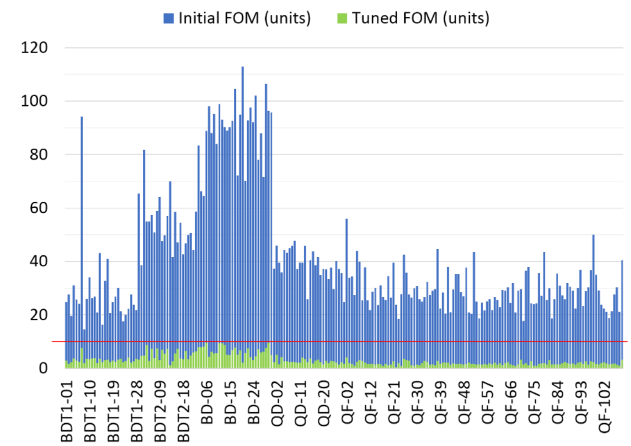

Figure 7: Multipole FOM of magnets before and after tuning.

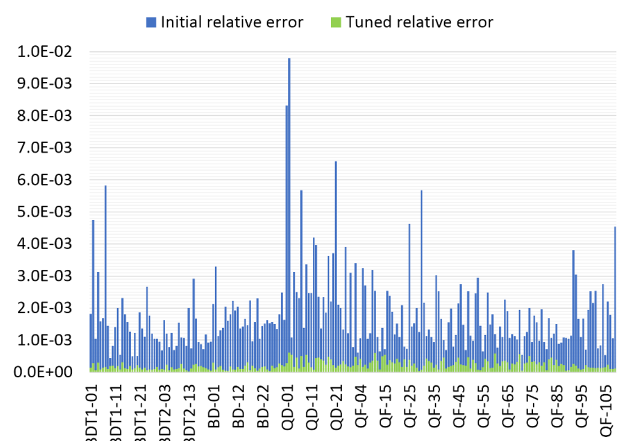

Figure 8: Relative field errors before and after tuning.

Figure 8 expresses the field quality as a relative error $\max |\mathbf{B} - \mathbf{B}_{\text{goal}}| / \max |\mathbf{B}_{\text{goal}}|$ taken over the midplane good field region.

Table 5 gives summary statistics for the relative field error.

Table 5: Relative Field Error Statistics

Relative field error	Initial	Tuned
Average	1.82×10^{-3}	2.19×10^{-4}
RMS	2.20×10^{-3}	2.56×10^{-4}
Maximum	9.81×10^{-3}	6.15×10^{-4}
Minimum	4.41×10^{-4}	3.05×10^{-5}
Median	1.50×10^{-3}	1.90×10^{-4}

CONCLUSION

The magnet production run was a success, producing all magnets with good field quality within the deadline.

The cost per magnet for NdFeB material was $3303 and the total cost fit within the planned CBETA budget. Note, however, that the cost of rare earth materials can vary substantially with fluctuations in global market supply.

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