CBETA Permanent Magnet Production Run

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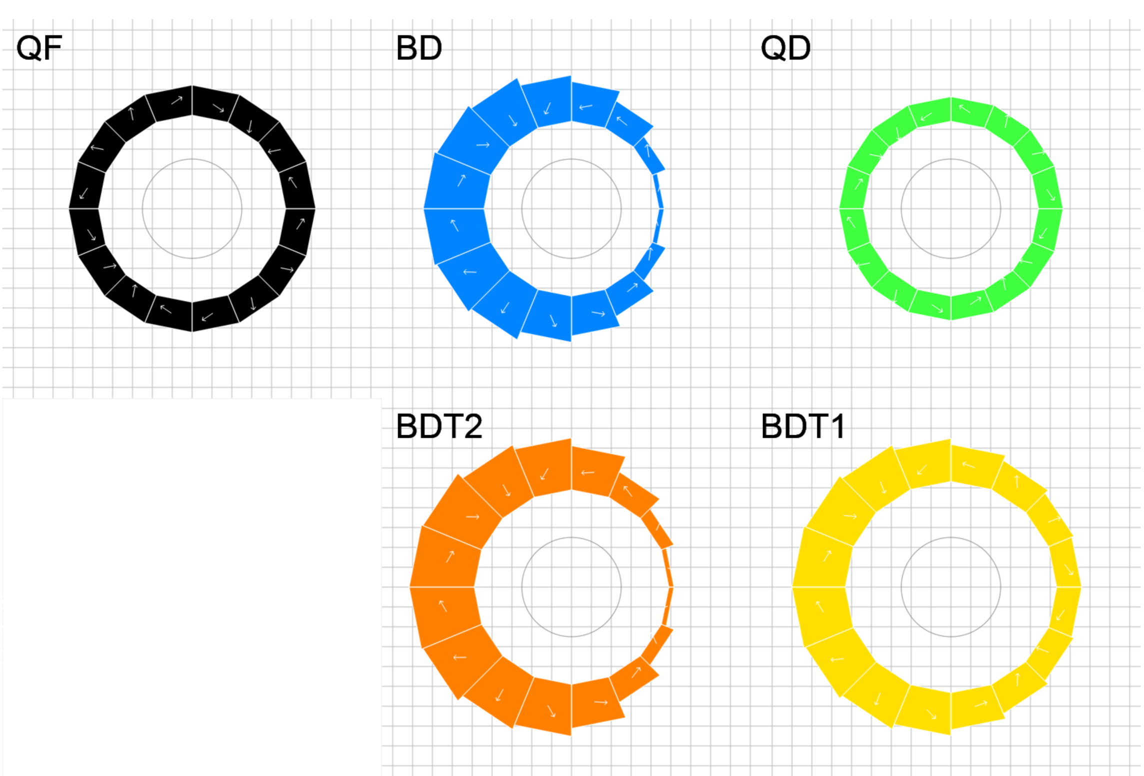
Abstract

214 neodymium permanent magnets have been manufactured for the return loop of the CBETA 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 2.3×10^{-4} were achieved on the beam region. The magnet strengths vary by type but are of order 10T/m for quadrupole component and up to 0.3T for the dipole. This paper reports on the field quality and timeline achieved in this production process.

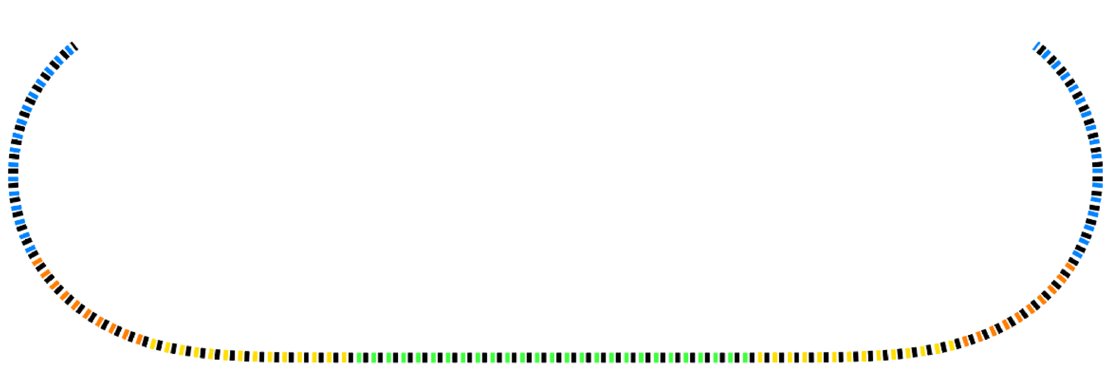
Magnet Types and Quantities

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



Different magnet cross-sections (above) are used in different parts of the CBETA return loop (below) to vary the curvature.



Schedule Achieved

All the magnets were accepted by the November 30th 2018 deadline, as shown in the graph below.

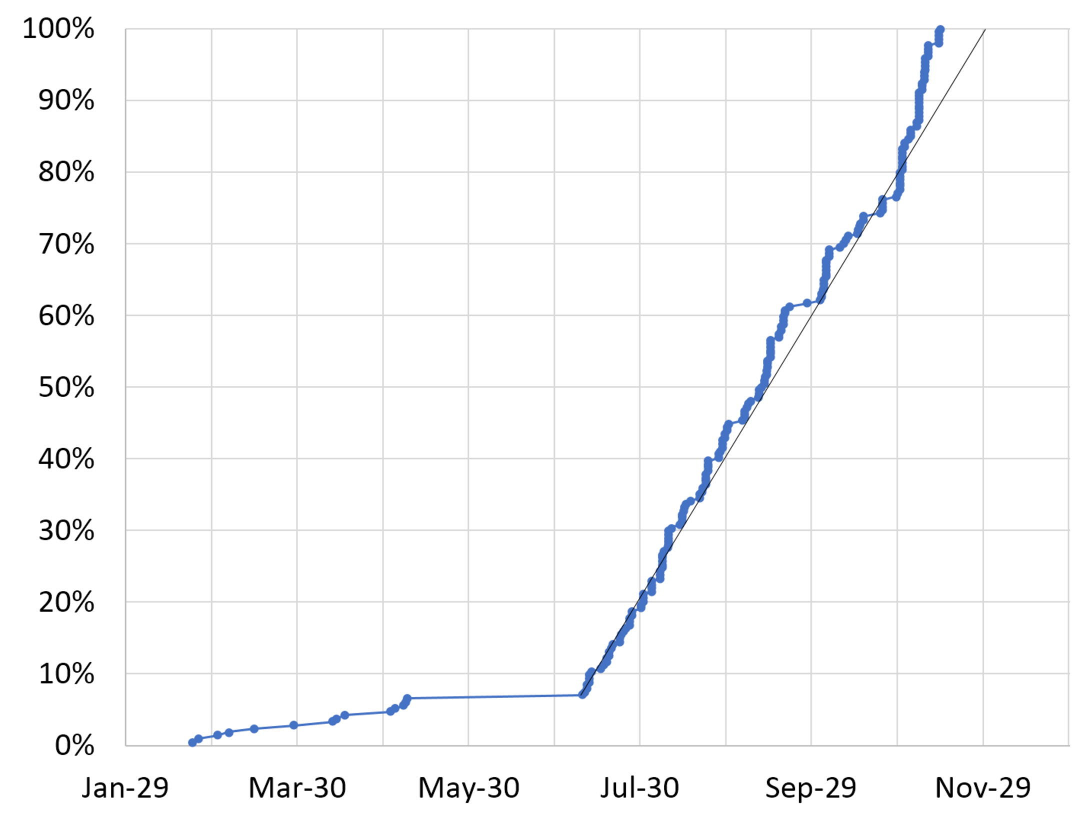
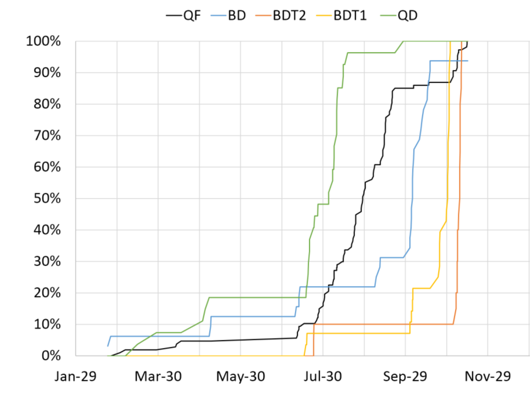


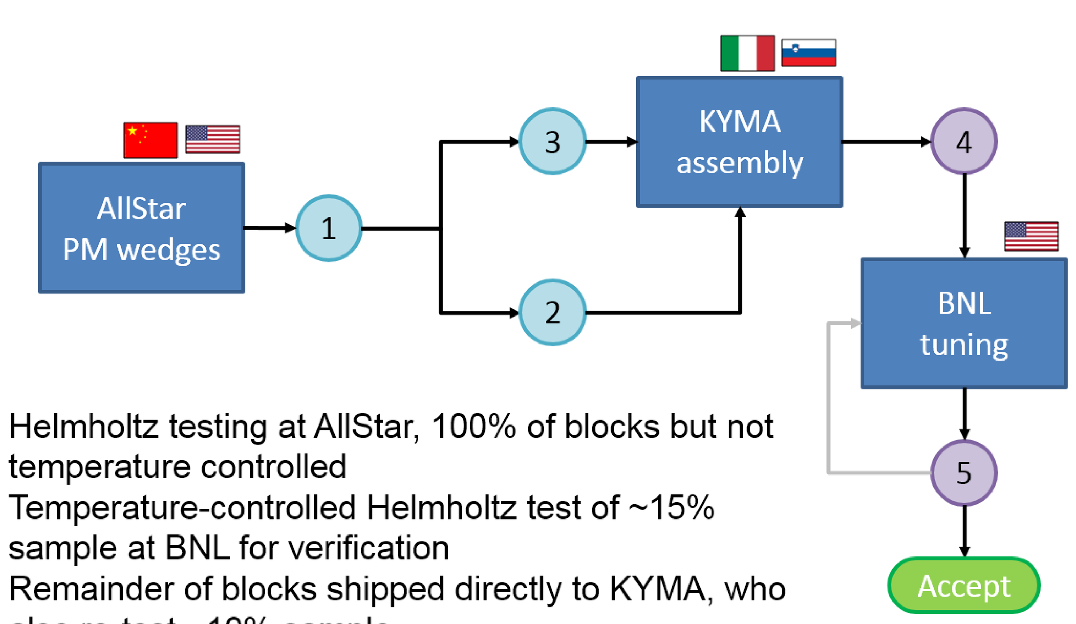
Table 2: Main Production Run Statistics

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



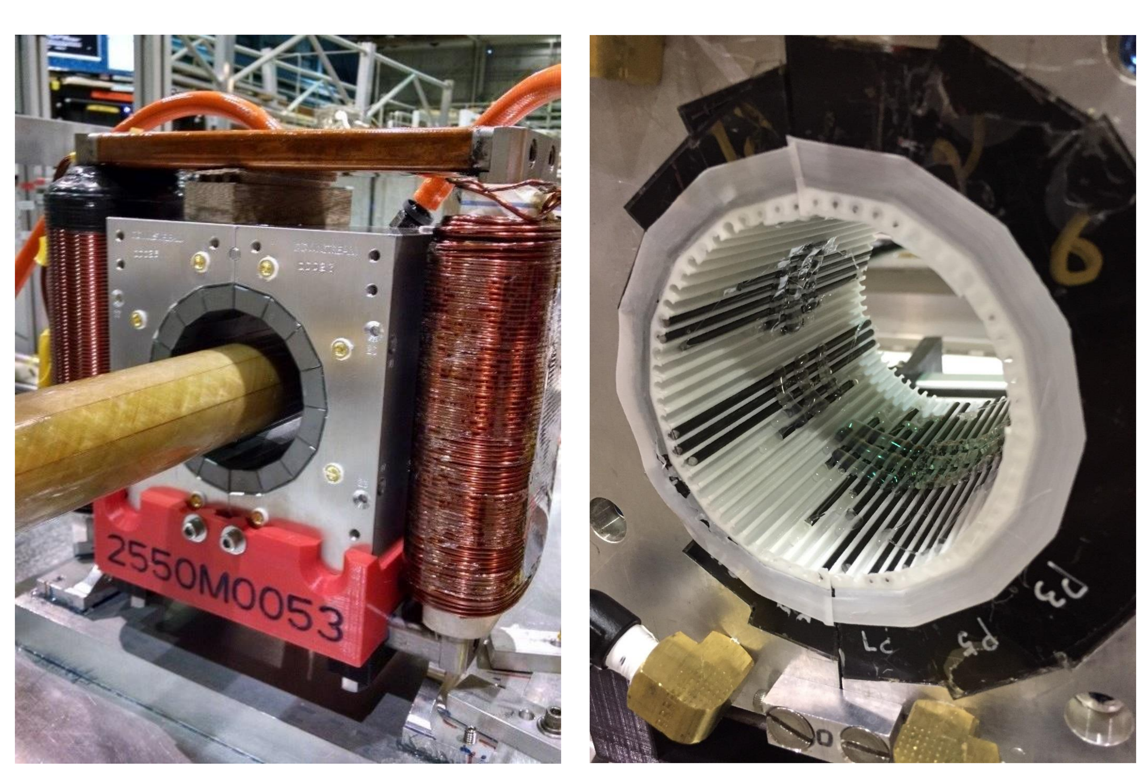
Production Method

Permanent magnet wedges with 1°, 1% RMS magnetisation accuracy were produced by Allstar Magnetics using a manufacturer in China. The assembly was done by KYMA, who made the aluminium housings and glued the magnets into place to within ±0.25mm. The diagram below shows the quality control and acceptance process.



1. Helmholtz testing at AllStar, 100% of blocks but not temperature controlled
2. Temperature-controlled Helmholtz test of ~15% sample at BNL for verification
3. Remainder of blocks shipped directly to KYMA, who also re-test ~10% sample
4. Rotating coil measurement of bare magnet at BNL
5. Rotating coil measurement of tuned magnet at BNL

Magnet Tuning



(above left) QD magnet being measured with a rotating coil at BNL magnet division. The harmonic errors were used to determine an arrangement of iron wires to be inserted into the magnet bore: (above right) shows a BD magnet.

Field Quality Results

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	%

Achieved distributions of "multipole FOM" and relative field error are shown below.

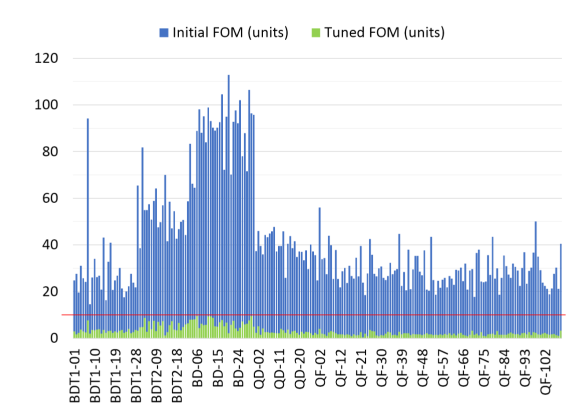


Table 4: Multipole Figure of Merit Statistics

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

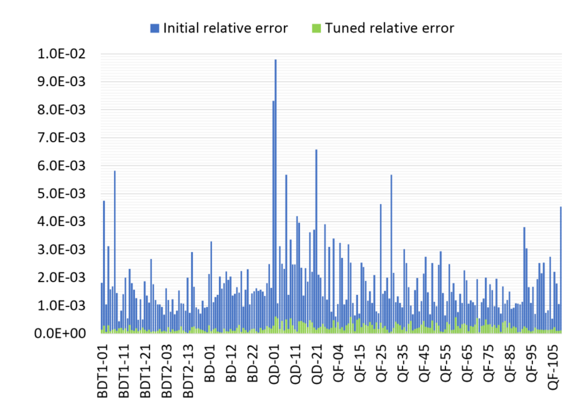


Table 5: Relative Field Error Statistics

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}

The multipole FOM is defined as $\sqrt{\sum_{n\geq\text{sext}} b_n^2 + a_n^2}$ where a_n and b_n are multipole field amplitudes at R=25mm, scaled so that the main quadrupole is 10000 units.

Relative field error equals $\max|\mathbf{B}-\mathbf{B}_{\text{goal}}|/\max|\mathbf{B}_{\text{goal}}|$ taken over the y=0, x=±25mm beam midplane.

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 limits are derived from tracking studies.

Cost and 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. (NB: the cost of rare earth materials varies substantially with global supply fluctuations.)