BNL-211701-2019-TECH

CBETA/035

CBETA Halbach magnet production run

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November 2018

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U.S. Department of Energy

USDOE Office of Science (SC), Nuclear Physics (NP) (SC-26)

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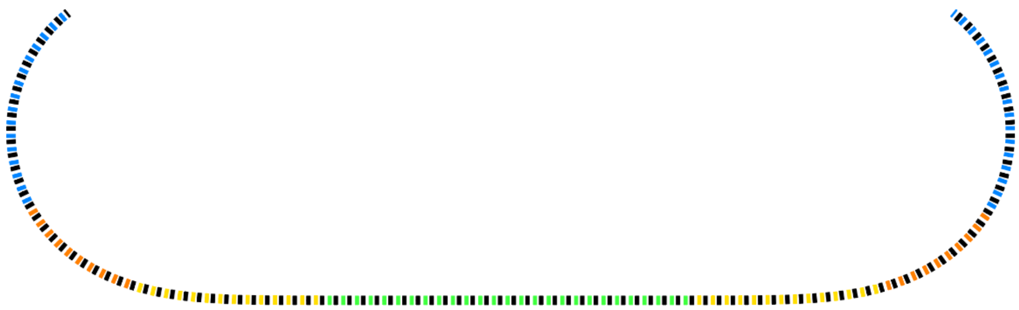
CBETA Halbach Magnet Production Run

Stephen Brooks 2018-Nov-28 CBETA machine note #35

1. Magnet Types and Counts

CBETA requires five different types of Halbach-derived permanent magnets, as colour-coded in the layout diagram below.



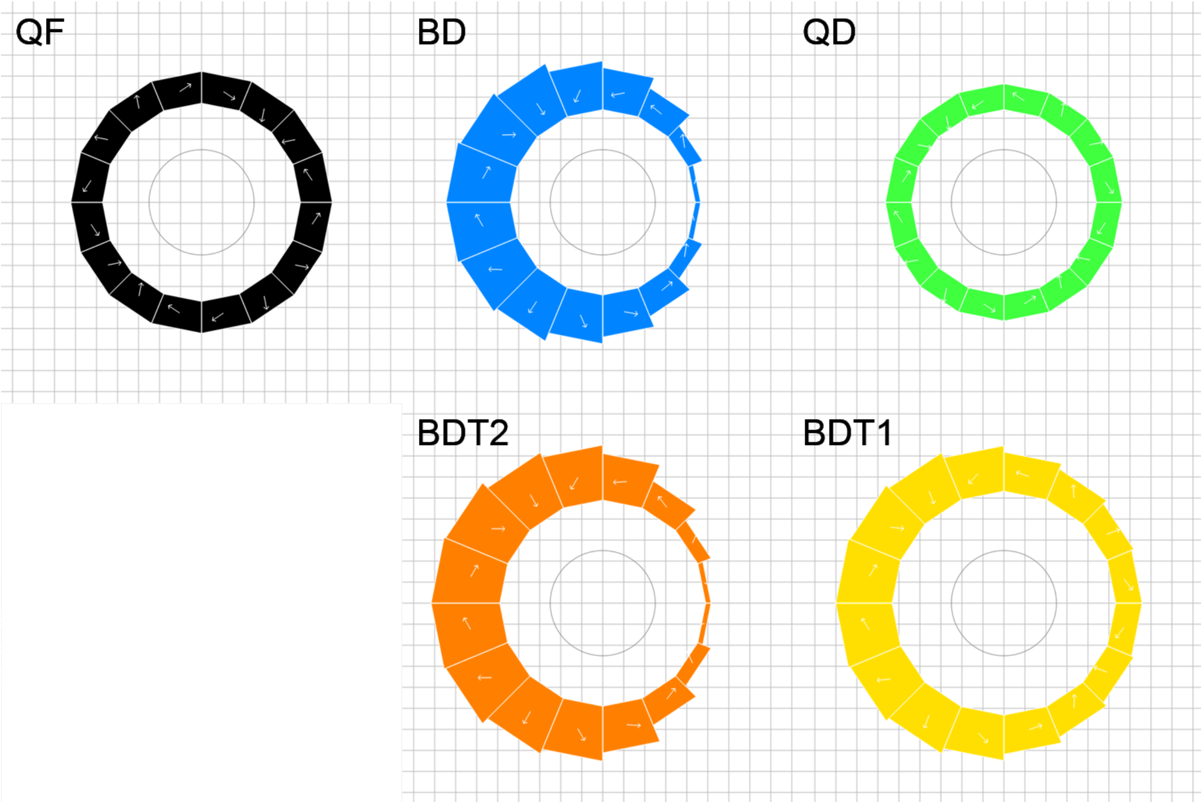
The number of each type required to build the whole return loop are:

Magnet Type	Magnet Id Range	Count	Colour in Diagram
BDT1	21nn	28	Yellow
BDT2	22nn	20	Orange
BD	23nn	32	Blue
QD	24nn	27	Green
QF	25nn, 26nn	107	Black
BDH (half length BD)	273n	1	Blue
QFH (half length QF)	275n	1	Black
Total		**214** + 2 half length	

The parameters of each main magnet type are given in the table below. Lengths are 122mm for all D-type magnets (BDT1, BDT2, BD, QD) and 133mm for QF. BDH and QFH are 61mm and 66.5mm long respectively.

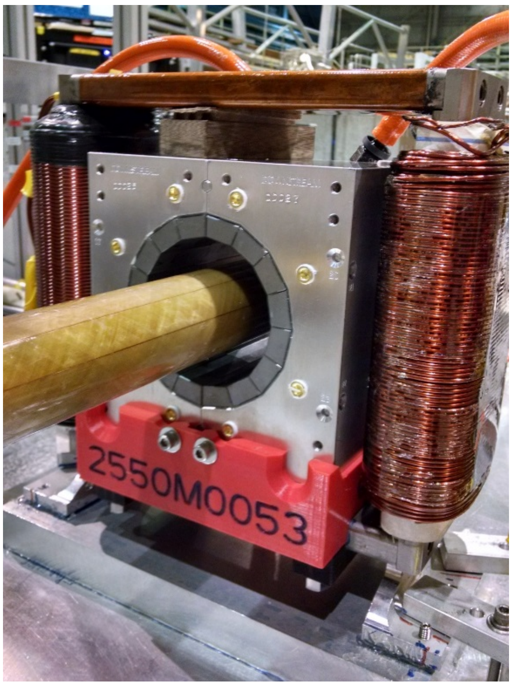
Magnet	Dipole (T)	Quad (T/m)	Good field radius (mm)	Aperture radius (mm)	Max field (T) (good region)	Max field (T) (aperture)
QF	0	-11.5624	25	43.1	0.2891	0.4983
BD	-0.3081	11.1475	25	40.1	0.5868	0.7551
BDT2	-0.2543	11.1475	25	44.938	0.5330	0.7552
BDT1	-0.1002	11.1475	25	49.085	0.3789	0.6474
QD	0	11.1434	25	40.1	0.2786	0.4469

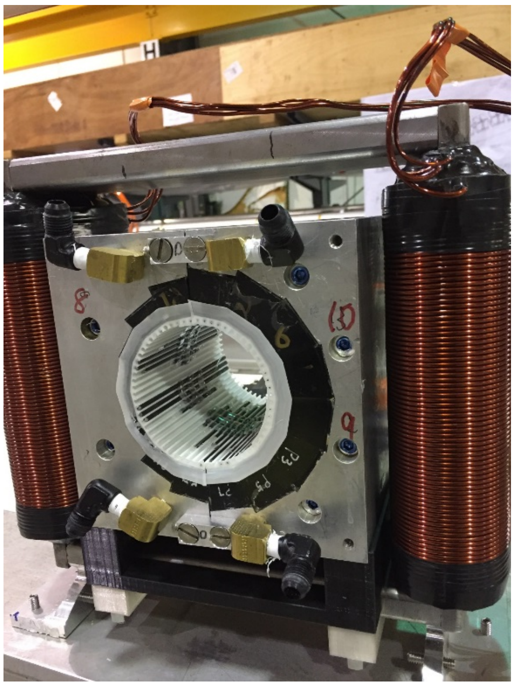
The figure below shows cross-sections of each magnet type superimposed on a 1cm grid.



2. Measurement and Tuning Process

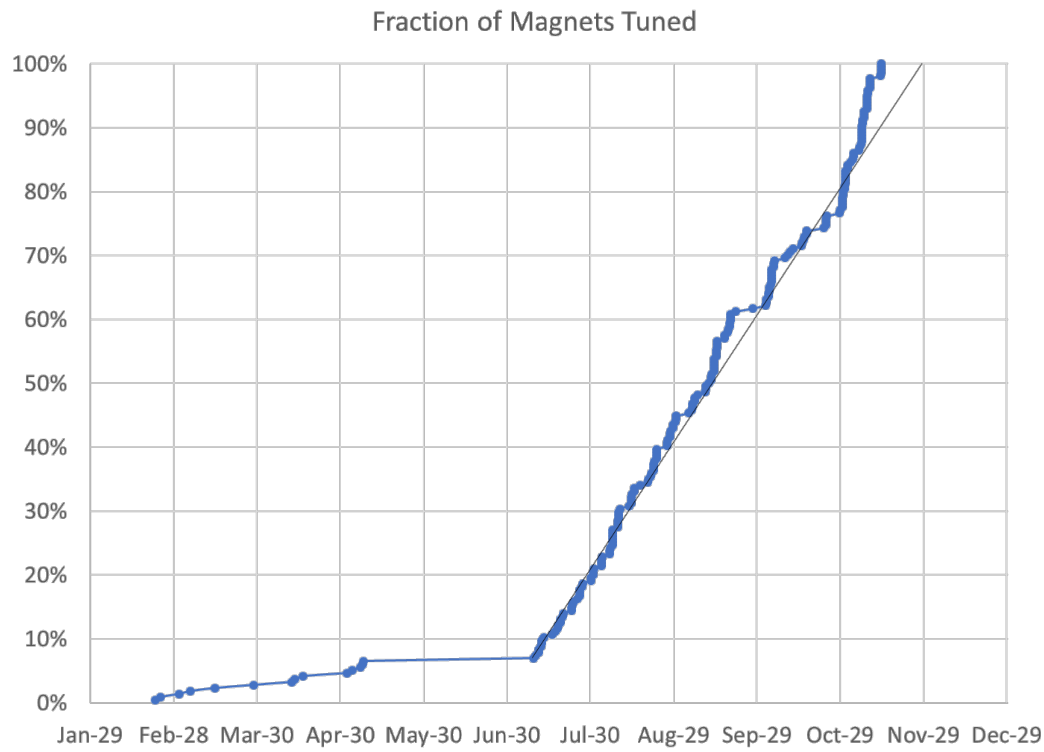
Magnets as assembled by KYMA were initially tested on BNL's rotating coil (left picture below). The harmonic errors measured were run through a program that generates a configuration of up to 64 iron wires to be inserted into the magnet in a cylindrical shim pack (right picture below). The plastic holder for the wires is made by 3D printing but is the same for each magnet type.



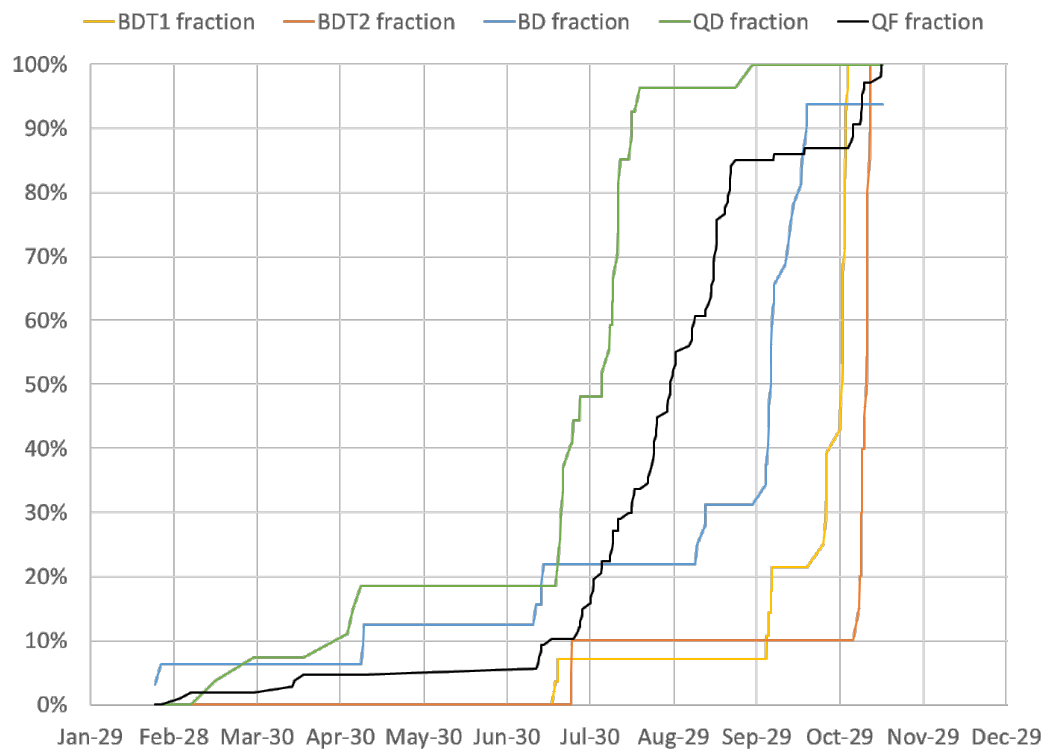


3. Schedule

The proportion of magnets tuned over time, including the early samples obtained in February through May 2018, is shown in the graph below.



The breakdown by magnet type is given in the graph below. QF made up half of the total magnets, while the other types were delivered in batches.

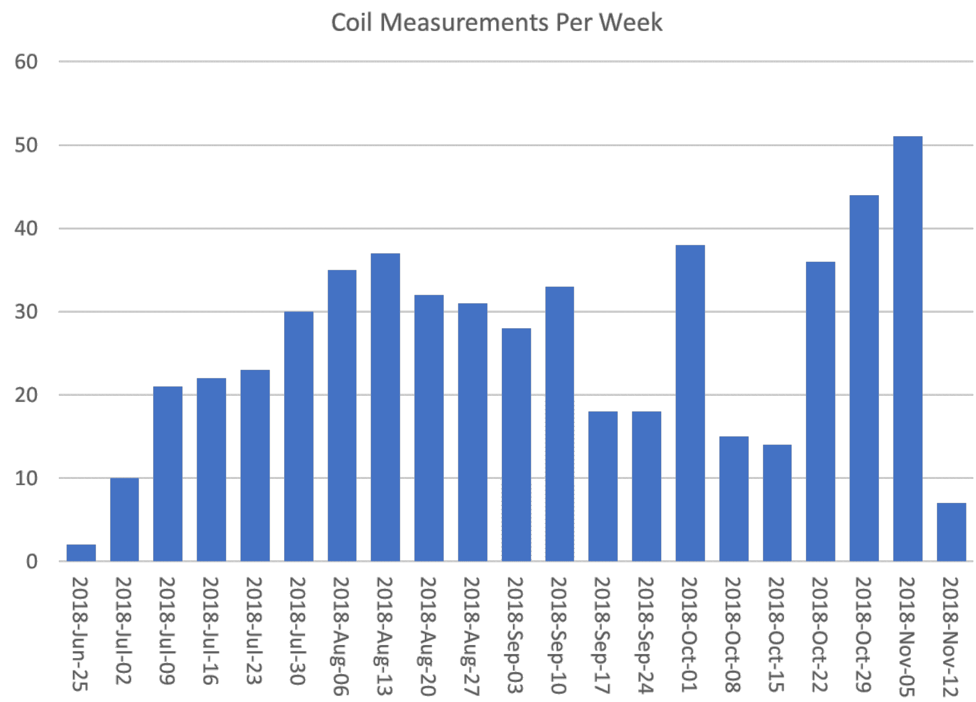


The overall statistics for the main period of the production run starting in July 2018 are given in the table below. The deadline (CBETA Technical Milestone 7) for construction of girders containing these magnets was November 30, 2018.

Main Production	
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 meas. per week (avg.)	29.88
Rotating coil meas. per magnet (avg.)	2.73

The number of rotating coil measurements per magnet is significant because in an ideal situation, there would be 2.00 measurements per magnet: one of the original magnet and one with the tuning insert. In reality, the rotating coils required additional calibration measurements each week and some magnets required more than one iteration of tuning inserts.

The rate of rotating coil measurements per week achieved by BNL Magnet Division is shown below. The goal was for a rate of ~30 per week but there were some delivery delays and equipment repairs in the latter half of production. This was ameliorated by longer shifts and more efficient measurement performance in the final weeks.



4. Field Quality Achieved

Once the rotating coil data for the magnets is obtained, the quality of the field can be defined in various ways. In CBETA, several of these were checked to be in line with expectations.

4.1. Target Field Quality Criteria

The limits for the four quality measures used for the CBETA production magnets are given below.

Quality Measure	Limit	Units
Maximum field error on midplane beam region §4.5	≤ 1.5	Gauss
Multipole figure of merit §4.2	≤ 10	Units (10^{-4} of main quadrupole field at R=25mm)
CBETA-scaled multipole figure of merit §4.3	≤ 0.375	Harmonics normalised to tracking; 0.75 preserves emittance in an otherwise perfect machine
Quadrupole strength error §4.4	≤ 0.05%	Relative to main quadrupole; only applies to QF and QD magnets

- The **multipole figure of merit** is defined as $\sqrt{\sum_{n\geq sext} b_n^2+a_n^2}$ where b and a are the normal and skew harmonics, respectively, measured in units as defined in the table.
- The **CBETA-scaled multipole figure of merit** is defined as $\sqrt{\sum_{n\geq sext}\left(\frac{b_n}{b_{lim,n}}\right)^2+\left(\frac{a_n}{a_{lim,n}}\right)^2}$,

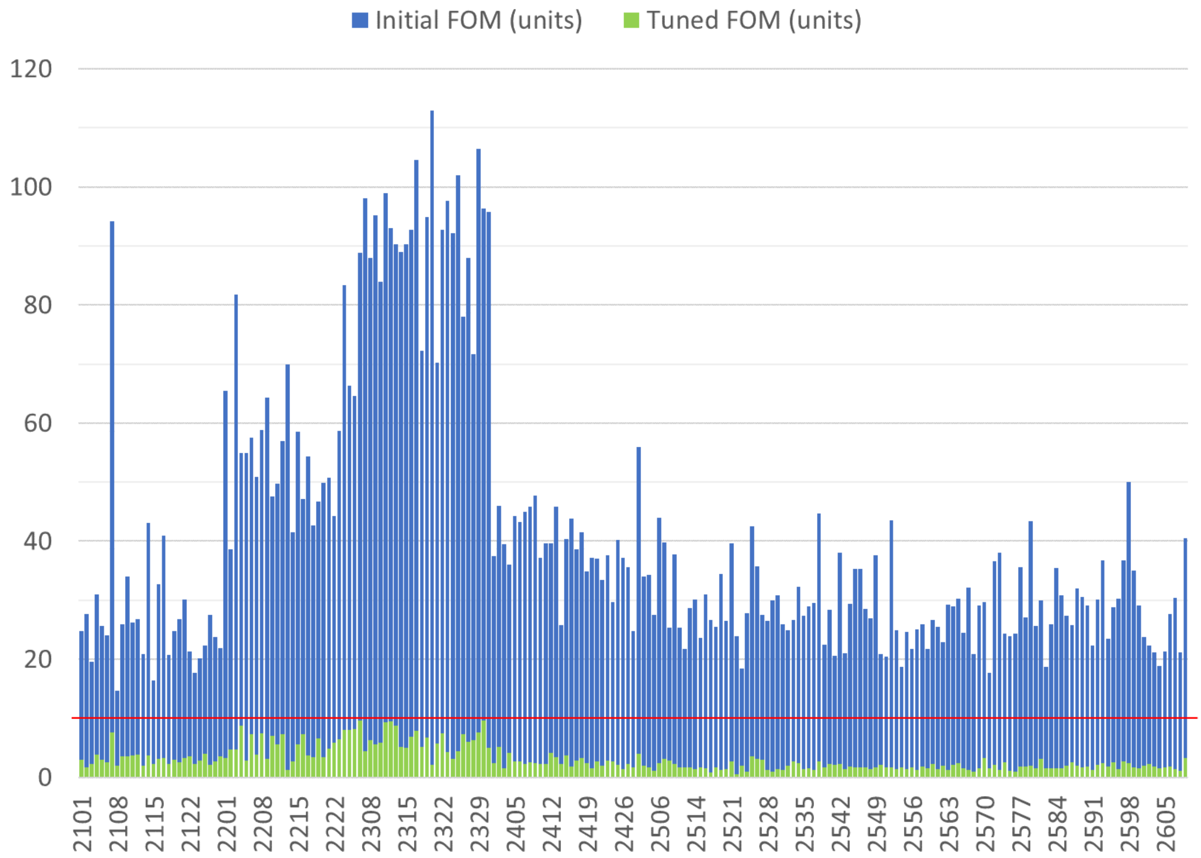
  where the limits for each individual harmonic were derived from tracking by William Lou. The combination has to be slightly less than 1 to obtain the same beam quality.

Harmonic	Normal b_{lim} (units)	Skew a_{lim} (units)
Sextupole	37	140
Octupole	30	90
Decapole	26	80
Dodecapole	21	65
14-pole	21	63
16-pole	19	58
18-pole	21	56
20-pole	18	53

- The **maximum field error on the midplane region** is max|**B**-**B**$_{goal}$| over the line from (-25,0) to (25,0)mm. NB: fields are integrated through the magnet and divided by the nominal length. Exception: for the BD magnets, the line is defined to be from (-15,0) to (25,0)mm as the beam does not enter the 1cm region at most negative X.
- The **quadrupole strength error** is (quad-quad$_{goal}$)/quad$_{goal}$, where the quadrupole is evaluated by the R=25mm rotating coil centred at (0,0). In the case of D-type magnets this is not the centre of the beam region, so this condition is not used, the maximum field error condition is assumed to be more robust.

4.2. Multipole Figure of Merit

The multipole figure of merit for all magnets, before and after tuning, is shown below. The red line indicates the limit of 10 units used for acceptance of tuned magnets.

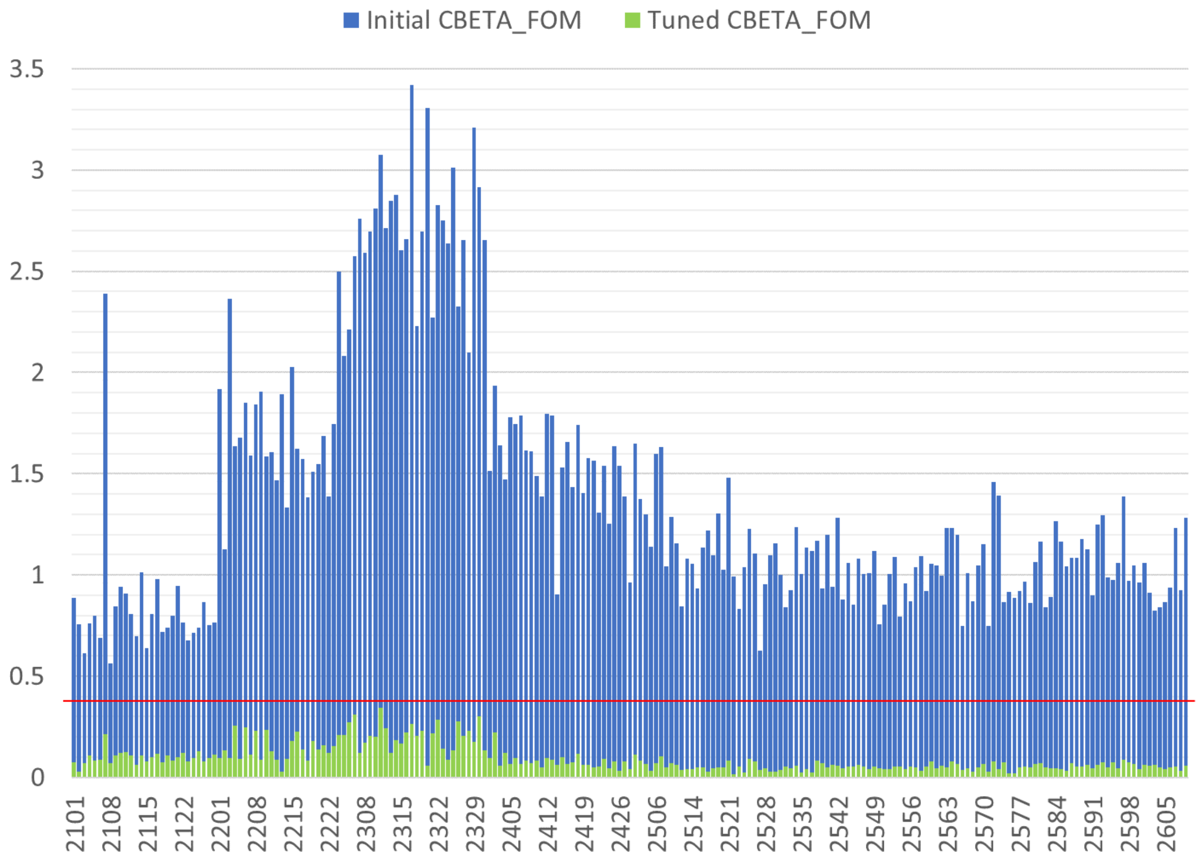


Summary statistics across all magnets are given in the table below.

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

4.3. CBETA-Scaled Multipole Figure of Merit

The CBETA-scaled multipole figure of merit for all magnets, before and after tuning, is shown below. The red line indicates the limit of 0.375 used for acceptance of tuned magnets.

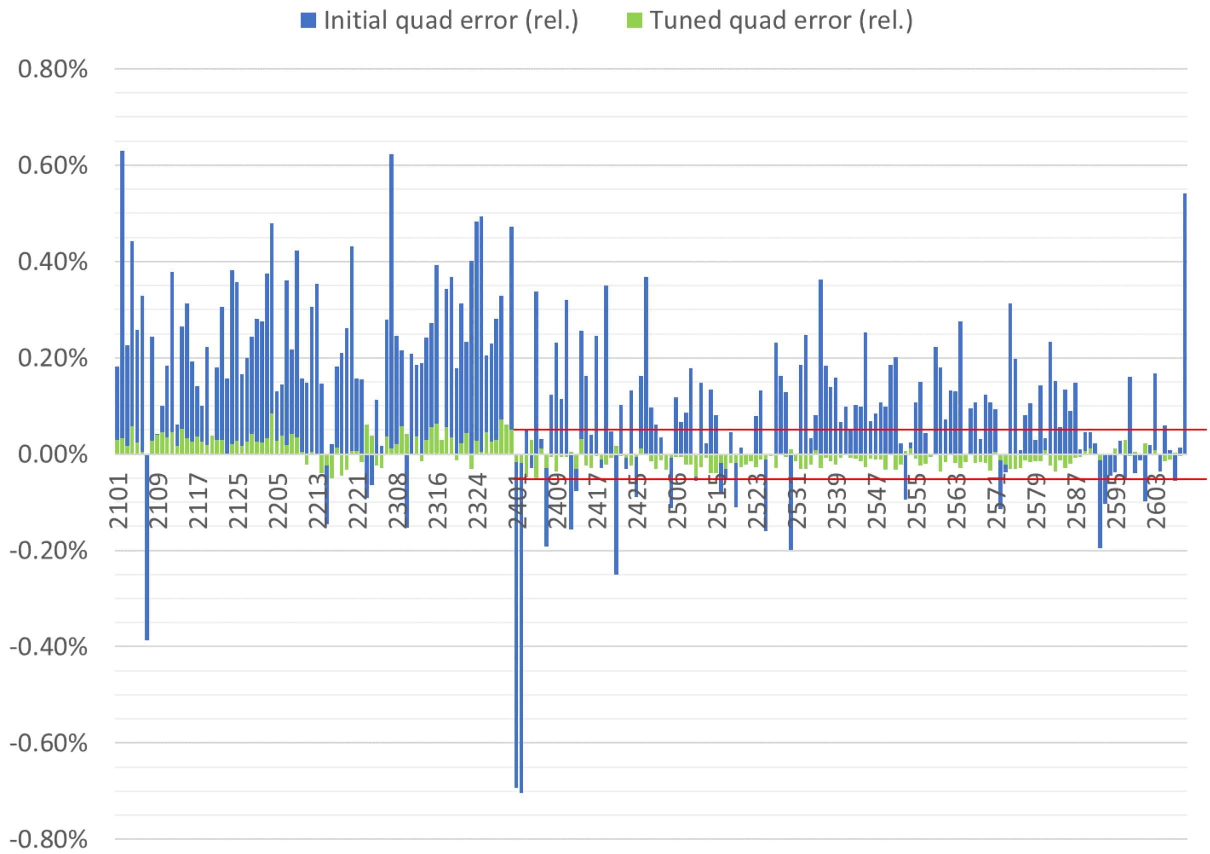


Summary statistics across all magnets are given in the table below.

CBETA FOM (units)	Initial	Tuned
Average	1.380	0.092
RMS	1.515	0.113
Max	3.422	0.343
Min	0.562	0.014
Median	1.157	0.070

4.4.Quadrupole Strength Errors

The quadrupole strength error for all magnets, before and after tuning, is shown below. The red lines indicate the limit of ±0.05% used for acceptance of F-type tuned magnets.

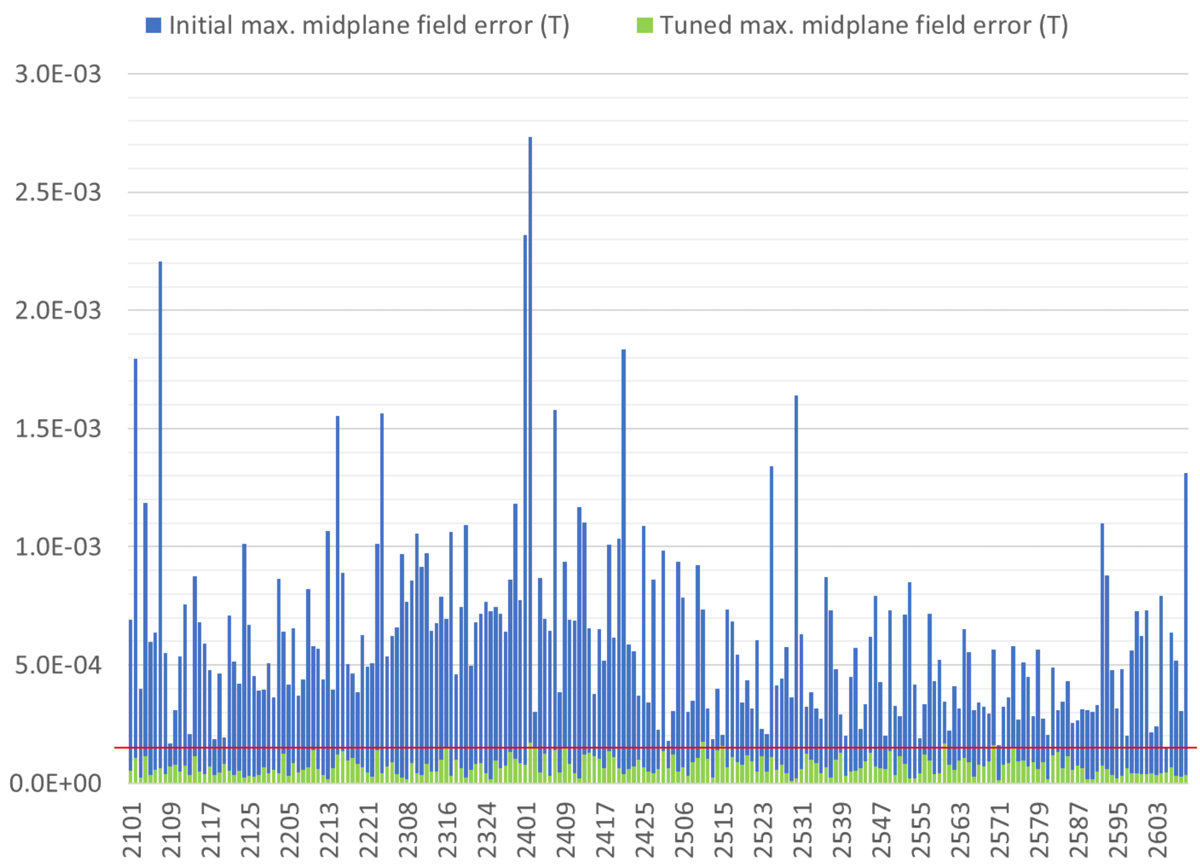


Summary statistics across all magnets, including D-types, are given in the table below. The averages are taken of the absolute value of the quadrupole error.

Quad error (relative)	Initial	Tuned
Average	0.168%	0.022%
RMS	0.217%	0.027%
Max	0.704%	0.084%
Min	0.000%	0.000%
Median	0.142%	0.019%

4.5.Maximum Field Errors on Midplane Beam Region

The maximum field error on the midplane beam region for all magnets, before and after tuning, is shown below. The red line indicates the limit of 1.5 Gauss used for acceptance of tuned magnets.

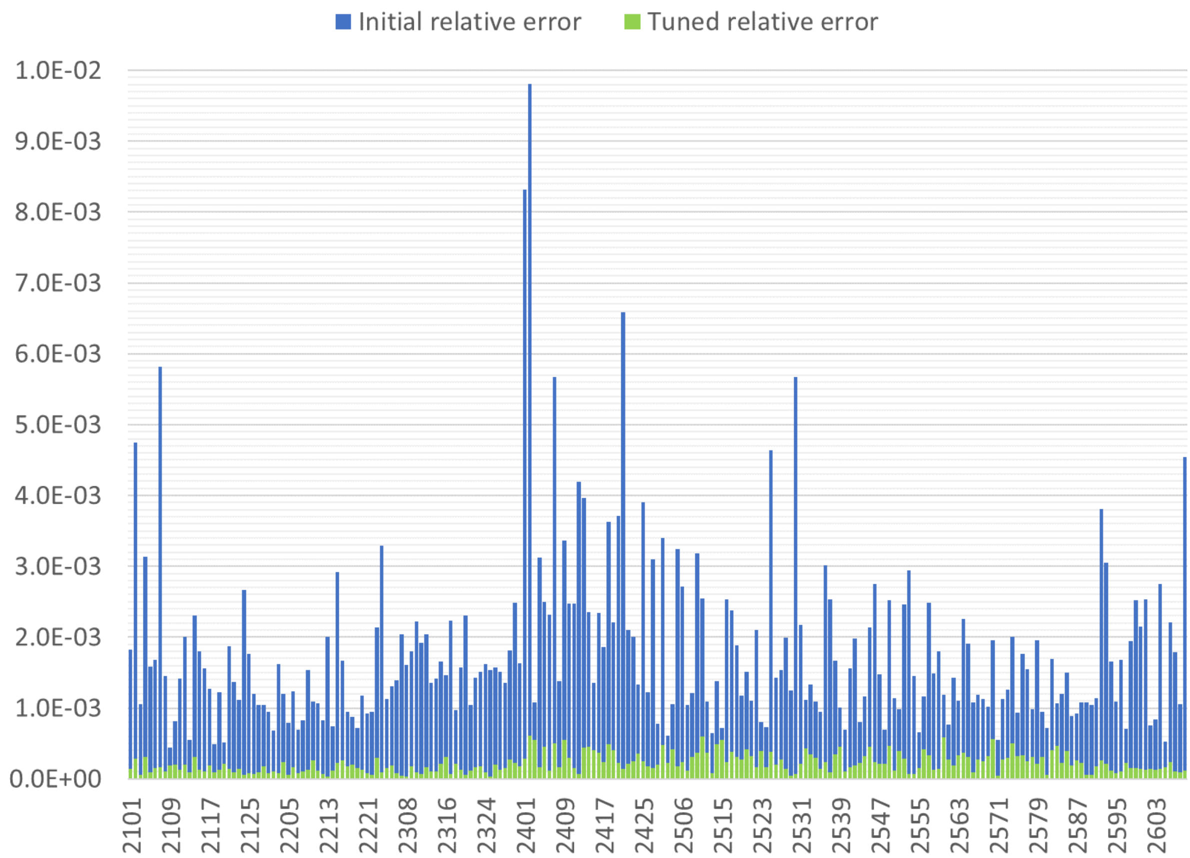


Summary statistics across all magnets are given in the table below. Some magnets had final measurements slightly above 1.5 Gauss because temperature fluctuations from the water chiller cycle change the field by a fraction of a Gauss. In these cases, previous measurements on the same tuned magnet had given error values below 1.5 Gauss.

Midplane error (G)	Initial	Tuned
Average	6.14	0.72
RMS	7.23	0.81
Max	27.32	1.74
Min	1.53	0.11
Median	5.44	0.65

4.6.Relative Field Errors on Midplane Beam Region

An intuitive measure commonly used for the quality of the magnet is the “relative field error”, which is defined as max|$\mathbf{B}$-$\mathbf{B}_{goal}$|/max|$\mathbf{B}_{goal}$| taken over a certain region of relevance. NB: fields are integrated through the magnet and divided by the nominal length. For the CBETA magnets, the region of relevance can be taken to be the same midplane beam region as used in §4.5. The resulting relative field error for all magnets, before and after tuning, is shown below.



Summary statistics across all magnets are given in the table below.

Relative field error	Initial	Tuned
Average	1.82E-03	2.19E-04
RMS	2.20E-03	2.56E-04
Max	9.81E-03	6.15E-04
Min	4.41E-04	3.05E-05
Median	1.50E-03	1.90E-04

5. Conclusion

The magnet production run was a success, producing 216 permanent magnets with good field quality within the deadline.