Recent Magnetic Measurements of a MEBT triplet

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PIP-II meeting

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Introduction

- The first MEBT series quads were delivered to FNAL last month.
- All official handling ("travelers") of them is done using VECTOR: https://vector-onsite.fnal.gov/
- With minor adjustments the magnets were checked, assembled and accepted (Incoming Inspection).
- Thorough magnetic measurement of one triplet were performed (the same triplet was measured at BARC).
- There were two distinctive goals of the tests:
  - Verify BARC measurements and provide feedback
  - Assess a triplet
The magnets (8 QD, 4 QF, 1 DC) came with four frames and documentation – electrical, assembly and magnetic “travelers”

After assembly in IB2 the triplet went to IB1 for measurements – rotating coil, stretch/vibrating wire and Hall probe
The magnets can be individually adjusted in horizontal direction only

Enough information was provided to align the individual magnets (in X) with respect to the magnetic axes and it can still be used with beam alignment

However we never intended to measure all triplets and we want to have the alignment ready before beam tests

All the triplets were assembled with individual magnets pushed to the end of its X-axis rail and fixed at that position

In future we are to define all alignment with respect to the frame (survey points)
Usually report harmonics in a frame centered and rotated such that quad is pure positive normal quadrupole ($b_2=+10000$ units, $a_2=0$)

Since we have D quads as well as F quads, will report harmonics in the lab frame as the beam would see.

Reporting frame (lab frame) is viewing magnet from beam direction with $X$ to the right (even though from the beam direction $X$ is indicated as pointing to the left) (normal even and skew odd harmonics change sign if viewed from opposite end)
Measurements

- Magnetic center
- Integral strength (and transfer function)
- Harmonics (homogeneity)
- Relative magnet orientation, axes, effects of simultaneous operation
- Results from the survey (alignment)

Most of the magnetic measurements were done with rotating coil (1m long, 28mm diameter), where feasible compared to stretched wire measurements (e.g. for magnetic center, transfer function /TF/)

For more details: https://indico.fnal.gov/conferenceDisplay.py?confId=14484
Magnetic center, field integral, TF

- Magnetic center (X and Y) of quads was stable vs current to within **11 microns** in the worst case (BARC gave 67 microns)
  
  This is well within the required 100 microns

- Transfer functions for quads were also stable within **0.5%** though dependency vs current was different in BARC measurements
  
  (well defined pre-cycling procedure needed)
  
  At nominal current BARC measurements consistently higher by ~0.5%

- Field integral for quads was measured to be **0.850 (1.47) T . m / m** for QD (QF)
  
  at nominal current (10 A)
  
  This is within specifications which are 0.85 (1.5) T . m / m

- Field integral for DC is at ~ **1.5 mT / m**
  
  This is NOT within specifications which is 2.1  mT / m
  
  This effect is known to be caused by the proximity of quads and is now well simulated.
Generally measured harmonics are small, stable vs current and dominated by b6 (allowed term for quads)

However measurements are inconsistent with BARC in several aspects
Harmonics – inconsistencies with BARC

- BARC measurements were done with rotating wire which has at best 10 units precision whereas FNAL works with a unit and below precision
  - BARC are assembling their rotating coil system

- Both FNAL and BARC see a pole-12 component (sixth order harmonic) however skew and normal components seem to be swapped and the sign flipped in BARC measurements

- BARC sees a large a4 (up to 20 units at high current) which is not present at FNAL
  - No clear explanation

- BARC sees large contributions (up to 110 units) from some harmonics at low currents – not seen by FNAL
  - background issues, interference?
Harmonics - inhomogeneity

- A single conservative number to characterize the field quality (recently redefined)
  \[
  \text{inhomogeneity} = \left( \sum_{n=3}^{n_{\text{max}}} \sqrt{b_n^2 + a_n^2} \right) / 100
  \]

- QD showed \(~0.4\%\) inhomogeneity and QF was at \(<0.2\%\), both very stable
  This is within the required 1%

- Inhomogeneity for DC is \textbf{below 3\%} (dominated by a3 component)
  This is within the required 5%
Angles from magnetic measurements

- Measurements with the rotating coil require a reference angle – the angle measured is a random number but the relative difference between measurements is meaningful.

- The angle, in effect the relative **roll angle**, is stable with current (and separately measured for each magnet) though it changes when the polarity of DC is changed.

- At nominal current:
  - 2 mrad between QD1 and QD2 (and stable vs current)
  - Within 3 mrad from \( \pi/2 \) between QD1 and QF, stable (in the data, there is additional factor \( \pi /2 \) for technical reasons)
  - DC X and Y within 5 mrad at each current, individually – within 3 mrad

- Stretched wire measurements of the (absolute) roll angle:
  - QD1: 0.17 mrad (BARC: -1.43 mrad)
  - QF2: 0.58 mrad (BARC: -1.52 mrad)
  - QD2: 1.08 mrad (BARC: -1.91 mrad)

All this is within the required 9 mrad (0.5°).
Triplet configuration

- When all quads are powered the following effects are observed
  - A large shift in magnet center on the order of $\sim 1\text{mm} (!?)$
  - (Roll) Angle change by $\sim 15 \text{ mrad}$
  - Inconsistencies of TF at low current (SSW vs rotating coil)
  - Harmonics consistent and stable
    (harmonics and inhomogeneity can’t be directly compared with individual magnets)
  - TF value and current dependence agrees to level of meas. variation ($\sim 50$ units) with BARC meas
  - $dX$, $dY$ similarly stable at BARC vs current (microns), field angle stable vs current

- When all quads and the DC are powered the following effects are observed
  - a change of center position vs current (about $\sim 0.25\text{mm}$ over the 2-12A range)
  - the sextupole harmonic has changed, but still ok
  - all the rest is consistent (TF, strength, angles)

Most results with quads and DC powered together are relevant in direct comparisons to the Triplet configuration (three quads powered)
The survey uses a set of reference points around magnets to fix a reference system.

The axes they use are different from “ours” and they denote the rotation angle around an axis with an axes letter, Z is the vertical axis (Ry is our “roll” angle which we got with the magnetic measurements).
Angle of wire with plane
Rx = 1.090 mrad
Rz = 0.323 mrad

Angle of wire with plane
Rx = -0.719 mrad
Rz = -0.909 mrad

Angle of wire with plane
Rx = -0.040 mrad
Rz = -0.586 mrad

Those are the angles with respect to the axis denoted

Relative angles are within 2 mrad (well within requirements)
Survey – comparisons to BARC

- BARC magnet positions were not necessarily the same

- However we found the magnets almost perfectly aligned (centers to within 100 microns) and we will assume we can compare to BARC directly

- According to our survey there were few reference point (fiducials) positions that were mis-named (swapped) at BARC

- Moreover BARC didn’t measure all of the reference points

- Nevertheless with assumptions of proper renaming we see our data and BARC data is in agreement to within 200 microns (center positions)
Survey – comparisons to BARC (2)

FQF002 (the worst case)

<table>
<thead>
<tr>
<th>Name</th>
<th>X [mm]</th>
<th>Y [mm]</th>
<th>Z [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2-FQF-B-BARC-002_UP</td>
<td>0.000</td>
<td>-50.038</td>
<td>0.000</td>
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<tr>
<td>P2-FQF-B-BARC-002_F</td>
<td>177.623</td>
<td>-24.968</td>
<td>-0.056</td>
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<tr>
<td>P2-FQF-B-BARC-002_H</td>
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<td>177.724</td>
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<tr>
<td>P2-FQF-B-BARC-002_C</td>
<td>-177.623</td>
<td>25.400</td>
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Results with FLIPPED fiducials (H=B, G=A, C=D)

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Up to ~300um difference

Better fit - < 200um difference
Concerns

- Although center and angles are stable and acceptable for individual components the magnetic center (and roll angle) changes when all quad are switched ON together
  - There is a non-trivial 1 mm offset of the center!
  - Not understood, no clear instrumental effect

- In the same configuration the transfer function is not stable below 8 A

- Angles of individual elements can not be changed (by design)
  - The triplet measured show they don’t have to but...

- Higher dipole corrector currents which may be necessary will affect the quads more
Summary

- Individual magnet parameters are within specifications and stable with current

- The triplet configuration is potentially not – needs monitoring to understand the effects
  - ✓ More measurements will be necessary

- Most measurements from BARC are consistent with ours and with specifications though precision needs to be improved
  - ✓ There are few measurements which are inconsistent

- Following the results and findings, some measurement procedures in BARC need to be changed as well as reporting template

- FNAL will have to improve the traveler forms

Results and documents will be available in TC
Spare
Beam transport and dynamics - MEBT

3σ envelopes of the transmitted through MEBT bunches

MEBT requirements/features:
- Low emittance growth
- Low beam losses
- Optical Matching between RFQ and main Linac
- Wideband chopping system
- Protective system of scrapers
- Wall protecting the low-energy part of the Linac for servicing

A MEBT section installed in PIP2IT
## MEBT magnets - specifications

<table>
<thead>
<tr>
<th>Quadrupoles (two types)</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Minimum tip separation (diameter)</td>
<td>34 mm</td>
</tr>
<tr>
<td>Integrated gradient homogeneity in the good field region</td>
<td>1%</td>
</tr>
<tr>
<td>Region of the good field (diameter)</td>
<td>23 mm</td>
</tr>
</tbody>
</table>
| Maximum integrated gradient | 1.5 T  
0.85 T  for Type F  
for Type D |
| Suggested magnetic length | 10 cm  
5 cm  for Type F  
for Type D |
| Separation between centers of quadrupoles in triplets (D+F+D)- | 14.5 cm |
| in doublets (F+F) | 17 cm |

### Dipole correctors

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<td>Integral of the dipole field</td>
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<td>Region of the good field (diameter)</td>
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<td>Integrated field homogeneity in the good field region</td>
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<tr>
<td>Minimum clear aperture (diameter)</td>
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<tr>
<td>Available space between the yoke of the nearest quadrupole and a wall of a vacuum box downstream</td>
</tr>
</tbody>
</table>
MEBT magnets - fabrication

Quadrupoles (defocusing /”D”/ and focusing “F”) as well as vertical and horizontal dipole correctors are designed and fabricated by BARC (India). In total there will be 2 doublets and 10 triplets (with 12 correctors).
MEBT magnets - characterization

Geometric, electrical and magnetic measurements are performed in both BARC and FNAL (partial magnetic measurements at FNAL) and parameters compared to specifications.

A new magnetic measurement set up was commissioned in BARC with FNAL guidance.

The measurements are still being conducted and not all triplets are available at FNAL yet.

Example measurements of the field integral (for a triplet) with or w/o the dipole influence.
MEBT structure in PIP2IT

The red arrows show pictorially the (9) focusing elements

Two doublets (first two elements) + X-Y dipole corrector each
Seven triplets + the accompanying dipole correctors

Additional three triplets + correctors in PIP-II (vs PIP2IT)

Buncher installed in its place in the beam line of PIP2IT