MQXFAP1b Alignment and Field Quality


HiLumi Collaboration Meeting, Fermilab, October 16, 2019
Magnetic Measurements during Assembly

MQXFAP1b Magnet geometry and fabrication:

- Shorter magnetic length (4 m)
- Three previously used first-generation coils
- One new coil made with shorter length but incorporating many new features
  - See coil P06 review information at https://indico.fnal.gov/event/19381/
  - Mid-plane/pole shim for b6 correction still not implemented

Magnetic measurement system and plan

- Measurements performed for coil pack and after complete assembly
  - MQXFAP2: drive system was not complete for coil pack measurement, and splice box was not completed for “final” measurement
- New power supply (more stable, better controls, capability to switch polarity)
- Field harmonics as a function of longitudinal position
  - Including a detailed scan of the ends
- Magnetic axis vs. longitudinal position relative to external fiducials
- Relative change in the field orientation vs. longitudinal position
  - Including a scan step allowing to overlap the positions of the two probes mounted on the PCB
Rotating probe includes two identical PCBs from FNAL with 108.74 mm effective length and 59.5 mm radius.
Longitudinal scan: Transfer Function

- TF increases by 0.4% from coil pack to final assembly
  - Effect of loading (iron pads are already present in coil pack measurement)
- Scan length is sufficient to cover both ends – however this is a shorter magnet, may need some improvement for full length magnet
Longitudinal Scan: b6

- b6 is around -2 units in the straight section (about 5 units smaller than AP2)
- Also much more stable along the length (about +/- 1 unit)
- Change of about 1 unit (-3 to -2) from coil pack to final.
- Fine (1/4) scan of magnet ends allows to accurately capture the peaks
- Useful to compare with models and for longitudinal reference
- Will be repeated in vertical test
Comparison of MQXFAP1b and MQXFAP2

- b6 is smaller and more stable along the length
Longitudinal scan – other harmonics

- Change of 2 units of b3 from coil pack to final. All other harmonics do not change significantly.
- Comparatively large a5.
Comparison of harmonics after assembly

--- $3\sigma + \sigma$ (uncertainty) 
(d = 30 µm)
Reference axis and probe position survey

Survey performed by Chris Hernikl, Hongyan Zhu, Dan Ellis, and Federico Carrara
(Survey & Alignment Group, Engineering Division)
Magnetic Axis

- The magnetic axis will be defined as the best fit, independently for x and y.
- Variations of magnetic center relative to best fit are within +/- 0.2 mm (straight section).
- Requirement is +/- 0.5 mm.
- Additional benefit from integration length (0.5 m).
Magnetic Field Angle

Magnet angle can be adjusted for best fit
- Variations of magnetic field angle relative to best fit are within +/- 1 mrad
- Requirement is +/- 2 mrad
- Ends are excluded
- Additional benefit from integration length (0.5 m)
Magnetic Measurements System at BNL

- Top of Warm Bore Tube: 6256.57 mm [246.322 in]
- Bottom of Warm Bore Tube: 4563 mm [179.646 in]
- Top of Magnet Shell: 4753.61 mm [187.142 in]
- Bottom of Magnet Shell: 903.86 mm [35.585 in]
- Top hat to Lambda plate: 656 mm [25.827 in]
- Rotating coil in MAX UP Post: ~220 mm
- Home: 190.61 mm
- Warm Length: 331.99 mm
- Switch_UL: 4753.61 mm [187.142 in]
Magnetic Measurements during Vertical Test

MQXFAP1b Training Quenches

MQXFAP1b quench history, warm and cold magnetic field measurement time

Current [kA] | Symbol | Gradient [T/m] | Remarks
--- | --- | --- | ---
0.1 | Ires | 0.9 | Reset level for pre-cycle
0.96 | Linj | 8.5 | Injection level
6.0 | Ilim | 48.8 | Current limit (pre-training)
16.48 | Inom | 132.6 | Nominal level
17.89 | Ilult | 143.2 | Ultimate level

Stair-step measurement
Warm Measurements during Vertical Test

- Comparison between warm measurements during assembly at LBNL and prior to vertical test at BNL are generally in good agreement
- No indications of changes during shipping, small differences are mainly due to different probe length
- New identical 440 mm probes from FNAL are under fabrication for future tests
Cold Measurements during Vertical Test

Transfer function

- Decrease on the transfer function from injection to nominal by ~ 9% due to iron saturation, consistent with calculations and results from other model magnets and prototypes
Cold Measurements during Vertical Test

Similar longitudinal variations at different temperature/current, with some offset (0-2 units)
Cold Measurements during Vertical Test

MQXFAP1b Harmonics (Average Straight Section) at 16.5 kA

Upper bound: $s + u + 3\sigma$
Lower bound: $s - u - 3\sigma$
MQXFAP1b Calculated Harmonics

MQXFAP1 and MQXFAP1b included both 1<sup>st</sup> and 2<sup>nd</sup> generation coils

- One coil first generation (Quadrant 1 for the computations)
- Three coils second generation

Calculated field errors at nominal current (16.47 kA):

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<tr>
<th>MAIN FIELD (T)</th>
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<td>MAGNET STRENGTH (T/(m&lt;sup&gt;(n-1)&lt;/sup&gt;))</td>
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**NORMAL RELATIVE MULTipoles (1.D-4):**

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**SKEW RELATIVE MULTipoles (1.D-4):**

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Cold Measurements during Vertical Test

- Relative shift of magnetic vs probe axis up to ~12 mm was observed
- Calculated - assuming measured dipole stems from probe offset in pure quad field
- Significant changes in value and pattern from warm to cold measurements
- About a factor of two change from low to high current
- Addressed with additional alignment features for the warm bore between AP2 and AP1b
Additional slides
# Field Quality Reference Table

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| Magnetic length straight part | Q1/Q3 | Q2a/b | Mag. Len. Ends | 0.400 | 0.341 |

### High Field

- Systematic Uncertainty
- Random Uncertainty
- Q1/Q3
- Q2a/b
- Magnetic length straight part
- CS
- NCS
- Injection
- High Field
Reference Frame for Magnetic Measurements

- Longitudinal axis points from the return to the lead end
- \( z = 0 \) is defined as the magnetic center based on the integrated quadrupole strength
- Consider defining \( z=0 \) based on a specific geometric location/drawing
- Also need to introduce in the quadrant/coil diagram a geometric feature (e.g. main leads) to clarify angular reference
Quadrupole reference frame and powering

- Positive or negative quadrupole depending on powering
- Positive or negative depending on rotation (switches every 90 degrees)
- Positive or negative quadrupole depending on direction of travel
- Two magnets will be oriented opposite to each other in the cold mass

Next steps:
- Confirm quadrupole sign for given powering orientation at LBNL and BNL
- Some issue at LBNL comparing AP2 with AP1b: opposite quadrupole sign for nominally same powering
- But, AP2 measurement was performed with no splice box (coils connected manually)
MQXFAP1 and MQXFAP1b included both 1\textsuperscript{st} and 2\textsuperscript{nd} generation coils

- One coil first generation in Quadrant 3
- Three coils second generation

Calculated field errors at nominal current (16.47 kA):

\begin{verbatim}

\textbf{MAIN FIELD (T)} ............................................. 6.632618
\textbf{MAGNET STRENGTH (T/(m^n(n-1)))} ......................... 132.6524

\textbf{NORMAL RELATIVE MULTipoles (1.D-4)}:

\begin{tabular}{cccc}
  \textbf{b 1} & \textbf{b 2} & \textbf{b 3} & \textbf{b 4} \\
-6.75314 & 10000.000 & 2.02360 & -0.01077 \\
-3.9869 & -0.0018 & 1.87735 & -1.48728 \\
-0.06790 & -0.05544 & 0.13979 & 0.00739 \\
-0.09879 & -0.86126 & 0.00000 & -0.01071 \\
0.00000 & -0.00000 & 0.27134 & 0.00537 \\
\end{tabular}

\textbf{2G 2G 2G 2G 1G 2G}

\textbf{1G 2G 1G 2G}

\textbf{SKEW RELATIVE MULTipoles (1.D-4)}:

\begin{tabular}{cccc}
  \textbf{a 1} & \textbf{a 2} & \textbf{a 3} & \textbf{a 4} \\
-6.75314 & -0.00000 & 2.02360 & 5.90296 \\
-3.9869 & -0.00000 & 0.00000 & 1.48728 \\
-0.05104 & -0.85104 & 0.13979 & -0.00000 \\
0.00544 & 0.05544 & -0.04562 & 0.00739 \\
0.00879 & -0.00879 & 0.01071 & -0.01477 \\
\end{tabular}

\end{verbatim}
Cold Measurements during Vertical Test

MQXFAP1b Harmonics (Average Straight Section) at 16.5 kA

Upper bound: $s + u + 3\sigma$
Lower bound: $s - u - 3\sigma$