Field Quality Measurement of a Nb_3Sn Quadrupole Magnet during the Assembly Stage for HL-LHC

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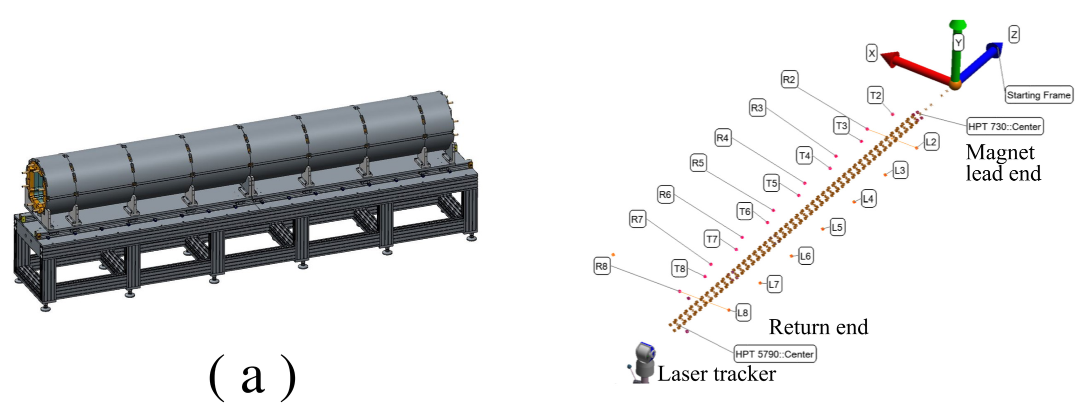
1. Motivation

- In collaboration with CERN, the U.S. High-Luminosity LHC Upgrade Project is developing 20 Nb_3Sn low-β quadrupole magnets.
- Magnetic measurements during the magnet assembly stage can help correct geometric field errors through magnetic shims, provide first data on magnetic axis and main field twist angle.
- We expect the measurements of MQXFA magnets can provide useful feedback for the Nb_3Sn magnet technology for future circular colliders.

2. MQXFA magnets, measurement system and protocol

- Three MQXFA magnets were measured: AP1b, AP2 and A03. Each has a 4.2 m magnetic length.
- Present the results from the latest A03 magnet and compare results from three magnets.

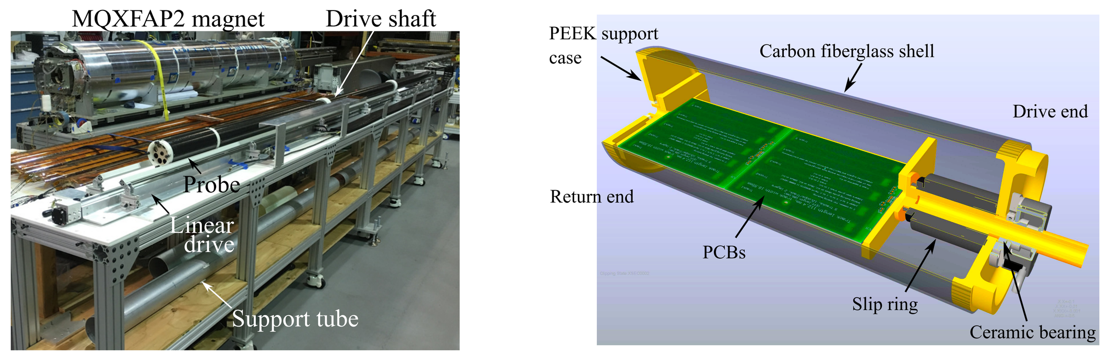


(a) (b)

Figure 1: *(a) Coordinate system viewed from the magnet lead end. (b) Reference frame for the survey with 7 groups of fiducial points.*

Three goals for the measurement system:

1. Geometric field errors
2. Magnetic center with respect to magnet fiducials
3. Relative change in the field orientation



(a) (b)

Figure 2: *(a) The measurement system. (b) Probe assembly using PCB rotating coil.*

- Probe scanned along the magnet with steps of 110 mm. Measurement with ± 10 A.
- The magnetic field in the aperture of the magnet straight section can be expressed as $B_y + i\,B_x = \sum_{n=1}^{\infty}(b_n + ia_n)10^{-4}B_2\left(\frac{z}{R_{\rm ref}}\right)^{n-1}$, with $b_n + ia_n$ the harmonics in units at $R_{\rm ref} = 50$ mm.

3. Test results

3.1 A03: TF and low-order harmonics

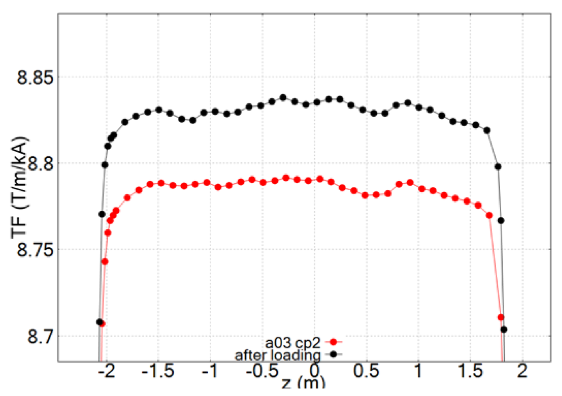
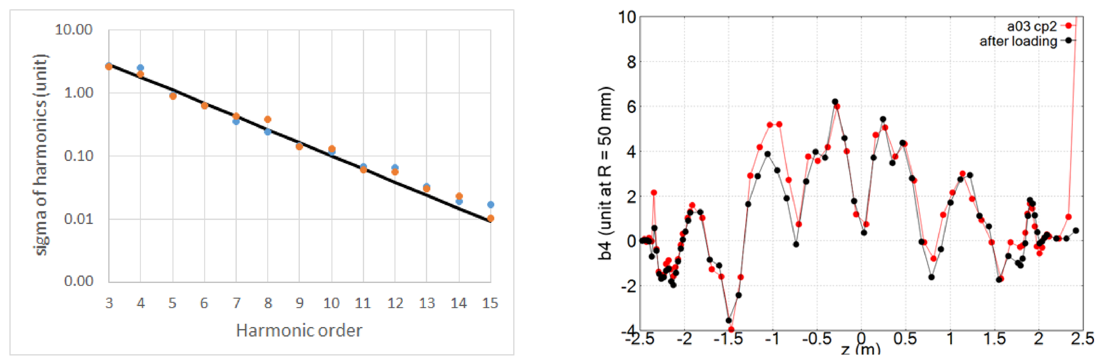


Figure 3: *The TF of A03 magnet increased by 0.19% compared to the coil pack.*

- Observed a 0.1% step in the TF in the magnet center (Fig. 3).
- The standard deviation of the harmonics indicate a block positioning error of 80 μm. It reduced to 70 μm after loading (Fig. 4), consistent with earlier LARP HQ and short models of MQXF magnets.
- Periodic pattern on harmonics is not due to the segmented structure. It appears already on the coil pack before loading (Fig. 3 and 4).



(a) (b)

Figure 4: *The low-order harmonics of A03: a_3 and b_4 along the magnet aperture.*

- Field errors in the magnet straight part improves over magnets. The latest magnet A03 has the best performance so far (Fig. 5).

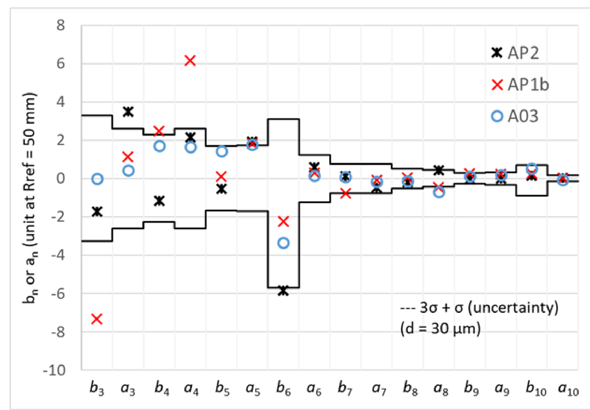
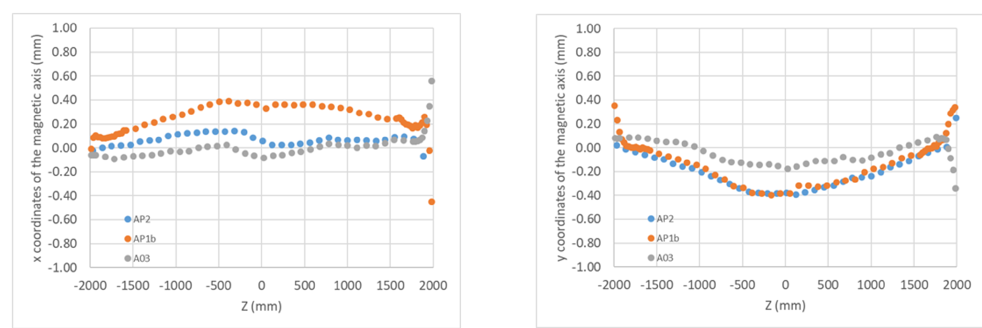


Figure 5: *Comparison of the field errors of three magnets with the allowed ranges.*

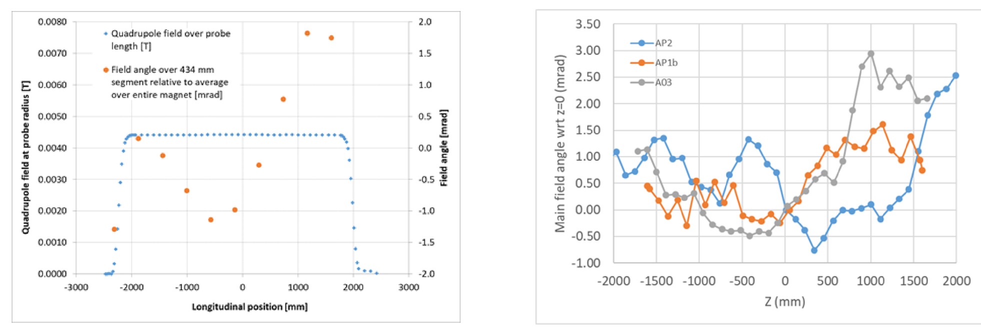
3.2 Magnetic centers and main field twist angles

- Magnetic centers of all three magnets meet the acceptance criterion (Fig. 6): within the ± 0.5 mm of the mechanical axis.
- The twist angle was within the ± 2 mrad acceptance criterion (Fig. 7).



(a) (b)

Figure 6: *Coordinates of the magnetic center along the magnet aperture: (a) x coordinate; (b) y coordinate.*



(a) (b)

Figure 7: *Main field twist angle. (a) A03 integrated over 440 mm length. (b) comparison between three magnets.*

4. Conclusion and next steps

- Successfully measured three AUP magnets during the assembly stage. Field errors are within the target range. Magnetic center and twist angle meet the acceptance criterion.
- The variation of the harmonics along the magnet aperture remain to be understood and correlated to the coil fabrication to deliver lower field errors.
- We plan to switch from 110 to 440 mm long measurement probe to provide more relevant data for the AUP project.
- The measurements will provide valuable data and statistics for the first application of Nb_3Sn accelerator magnet applications with a strong impact for future large-scale applications in high-energy circular colliders.

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