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# An examination of the mechanical performance of the 4.5 m long MQXFA Pre-Series magnets for the Hi-Lumi LHC Upgrade

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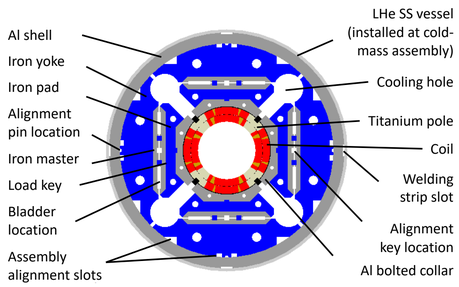
## ABSTRACT

The U.S. High-Luminosity LHC Accelerator Upgrade Project (HL-LHC AUP) team is fabricating the 4.5 m long MQXFA magnets, a 150 mm aperture high-field $Nb_3Sn$ low-β quadrupole magnet, in the context of the CERN Hi-Luminosity LHC (HL-LHC) upgrade. To date, two prototype magnets and five Pre-Series magnets have been assembled and tested. The first two prototypes did not achieve full performance requirements, but the lessons learned from them were fed back into the assembly and testing of the subsequent Pre-Series magnets, MQXFA03 thru MQXFA07. As the project is now transitioning to Series magnet production the data obtained from the as-built Pre-Series structures is instrumental to understanding the various build parameters and how they might explain or predict the mechanical performance of the structure. This paper summarizes the available strain gauge data from these structures as it relates to the FEA models and actual CMM measurements from the structural components. We also report on the fiducialization measurements performed with the warm magnetic measurements.




## INTRODUCTION

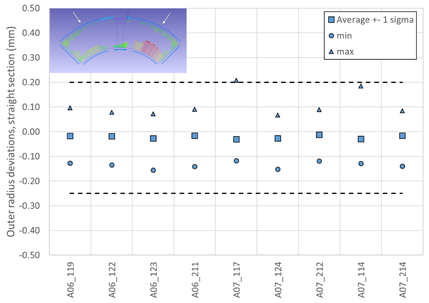
- The 4.5 m long MQXFA (AUP) and 7.2 m MQXFB (CERN) magnets share the same cross section
- Two Prototypes (AP1, AP2) and Five Pre-Series MQXFA (A03-A07) magnets have been assembled and tested
- Build data and parameters are being captured for the Pre-Series magnet assemblies, some of which are shown here
- Series magnets will be built to specifications that were developed from Pre-Series experience
- Four of the Pre-Series magnets passed vertical testing; MQXFA07 did not, and the limiting coil will be replaced

## ESSENTIAL ASSEMBLY MEASUREMENTS

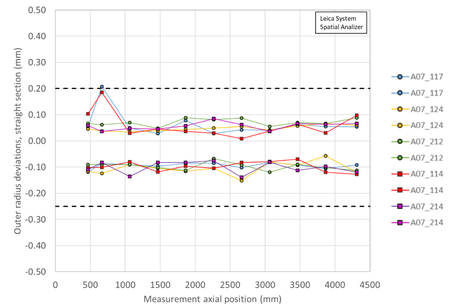
- Radius and midplane deviations of coils at 15 axial locations
- Average diameter of each shell
- Thickness of Master keys and load keys
- Coil pack sizes and collar-key gaps
- Bladder pressures during R.T. preload operations
- Strain gauges during R.T. preload
- Strain gauges during cooldown and powering
- Magnetic field measurements @R.T. and @1.9K

## COIL RADIUS AND MIDPLANE MEASUREMENT DATA

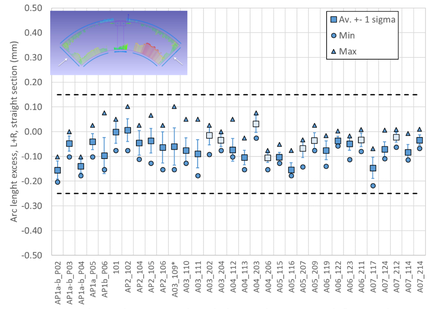
- Coil profile is measured at 15 axial locations along the length
- Coil selection and shimming is based on these measurements



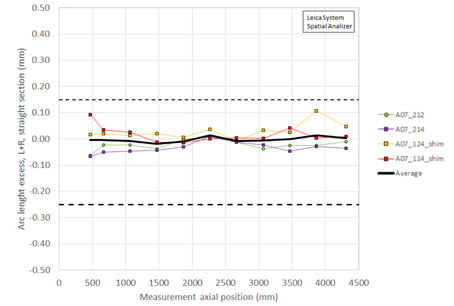

Coil outer radius deviations for magnets MQXFA06 & MQXFA07




Coil outer radius deviations min. and max. for MQXFA07 coils, vs. axial position



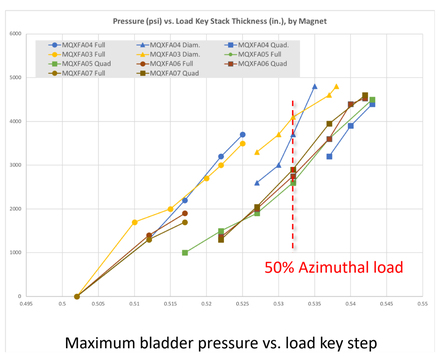

Arc length excess (midplane deviations) for coils used in magnets MQXFAP1 through MQXFA07



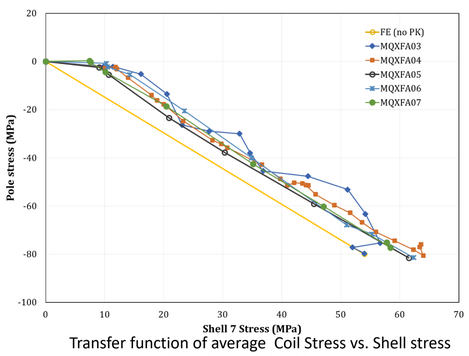

Average arc length excess in MQXFA07 coils after shimming two undersized coils vs. axial position

## ROOM TEMPERATURE MAGNET PRELOAD OPERATIONS

- Maximum bladder pressure during each load key shim step is recorded, regardless of whether all quadrants, diametrical, or quadrants are pressurized
- Transfer function of coil stress vs. shell stress is plotted for each load key shim step; the slope matches the FEA model for the magnet




Maximum bladder pressure vs. load key step



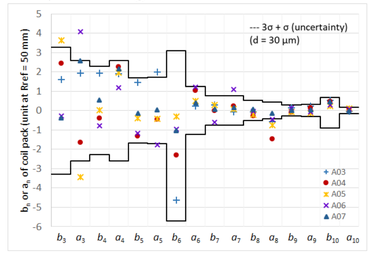

Transfer function of average Coil Stress vs. Shell stress plotted at each load key step

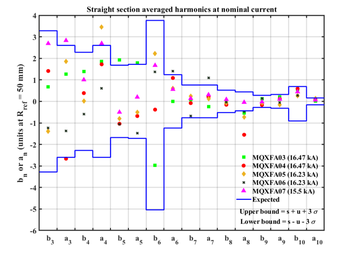
Table 1. Average R.T. preload stress achieved for Pre-Series Magnets

| | | Target | MQXFA03 | MQXFA04 | MQXFA05 | MQXFA06 | MQXFA07 |
|---|---|---|---|---|---|---|---|
| R.T. | Coil | -80 ± 8 | -79 | -76 | -82 | -81 | -75 |
| | Shell 7 | 53 ± 6 | 54 | 64 | 62 | 62 | 58 |

## MAGNETIC MEASUREMENTS

- Each magnet is measured with a rotating probe at the coil pack subassembly stage, after the preload operations, and during powering at cold

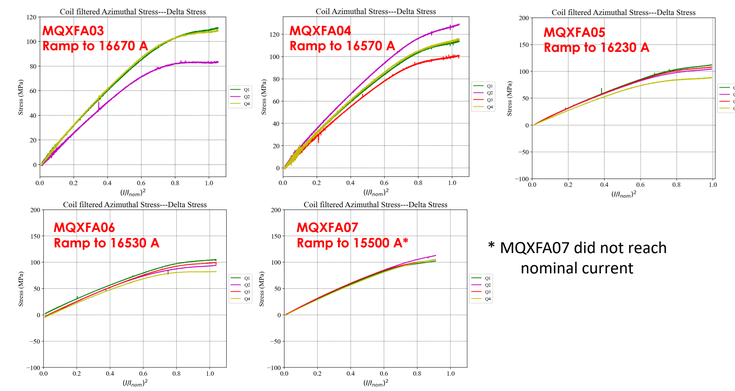



Envelope of allowed harmonics measured in the Pre-Series magnets at R.T. (left), and at nominal current (right)

## COIL PRELOAD

- The target coil pole preload is 103 MPa at 1.9 K; measured with strain gauges on the coil pole
- This is best measured using delta stress in the pole during powering
- Pre-Series magnets achieved average 100-110 MPa based on the unloading behavior observed




* MQXFA07 did not reach nominal current

## CONCLUSION

- Five MQXFA Pre-Series magnets have been assembled and tested; Series magnet production has started
- Some of the measurements taken throughout the assembly processes were described here
- The measurements will be used to both specify the Series magnet assembly parameters, and to help predict their performance