Results of the US triplet Pre-Series magnet tests and measurements

Giorgio Ambrosio, Joe DiMarco, Sandor Feher, Joe Muratore, GianLuca Sabbi, Peter Wanderer, and the whole MQXFA team

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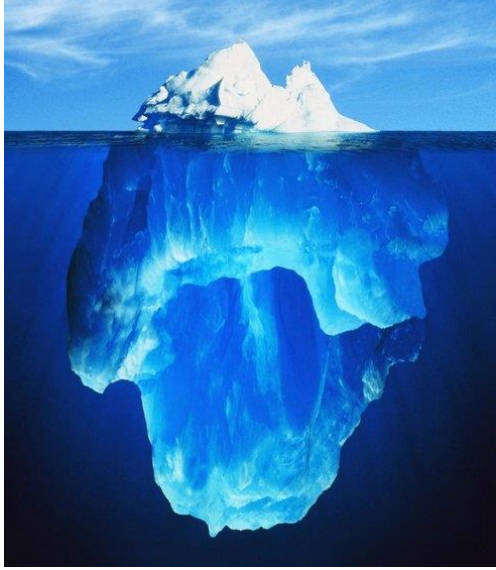
Outline

- MQXFA Pre-Series Magnets status
- Measurements before cooldown: MQXFA03/4/5
  - Field Quality
  - Alignment
- Cold Powering Test Results: MQXFA03/4
  - Quench History & Memory
  - Quench location
  - Ramp rate dependence & splice resistance
  - Magnetic measurements
  - Electrical tests
- Schedule and next steps
- Conclusions

Below the Surface…

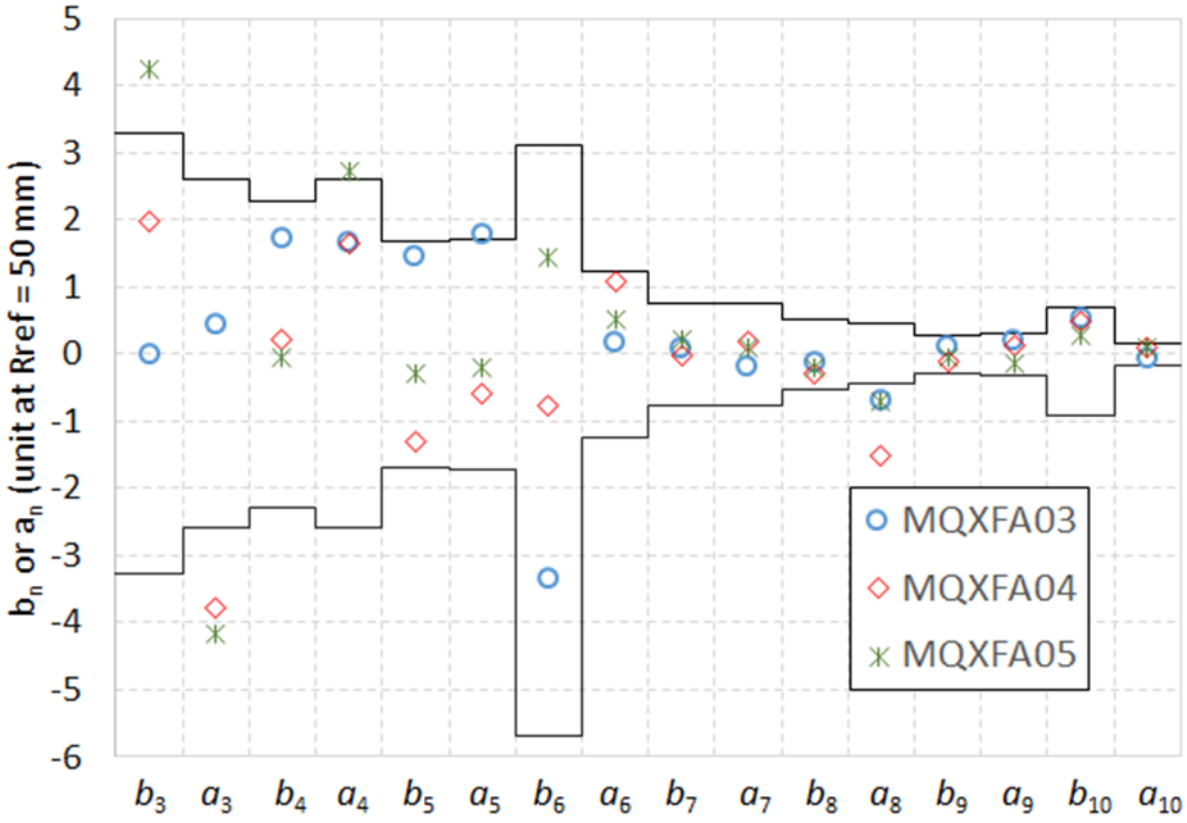


- Before MQXFA Pre-Series Magnets:
  - Several Nb_3Sn quadrupoles magnets with bladder & Key structure by the LHC Accelerator Research Program (LARP)
  - One MQXF short coil and one long coil tested in “mirror magnet” by LARP
  - Five MQXFS short models, many re-assemblies and many tests by LARP/CERN/AUP (S1a/b/c/d/e) and CERN (S3a/b/c, S4a/b/c, S5, S6a/b/c)
  - Two MQXFA prototypes and one re-assembly by LARP/AUP
  - One MQXFB prototype by CERN

MQXFA Pre-Series Magnet Status

- **MQXFA03**:
  1st pre-series magnet
  1st magnet completely fabricated by AUP
  Status: cold test is complete, magnet is at FNAL
  accepted for use in 1st Cold-Mass
- **MQXFA04:**
  Status: 1st thermal cycle is complete
- **MQXFA05:**
  Status: assembly is complete, magnet is at BNL
- **MQXFA06:**
  Status: assembly is in progress at LBNL

Warm Magnetic Measurements @ LBNL



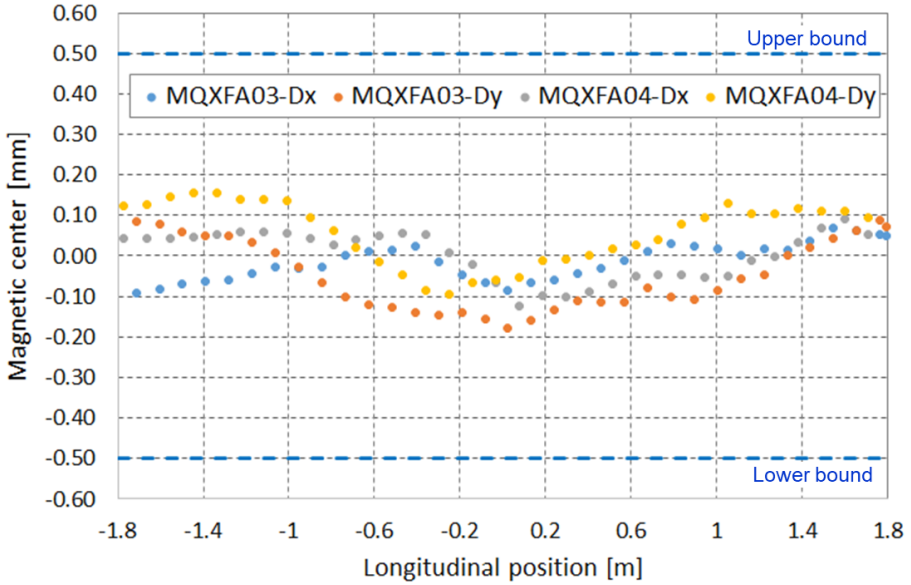
Use of **magnetic shims** decided to correct b_3 and a_3 in MQXFA05

Boundary is based on the harmonic table: [Sy-U-3S; Sy+U+3S] (Sy=Systematic, U=Uncertainty, S=Sigma)
Systematic is for the original design, without b_6 correction
b_6 correction: no coils in MQXFA03; 1 coil in MQXFA04; 4 coils in MQXFA05

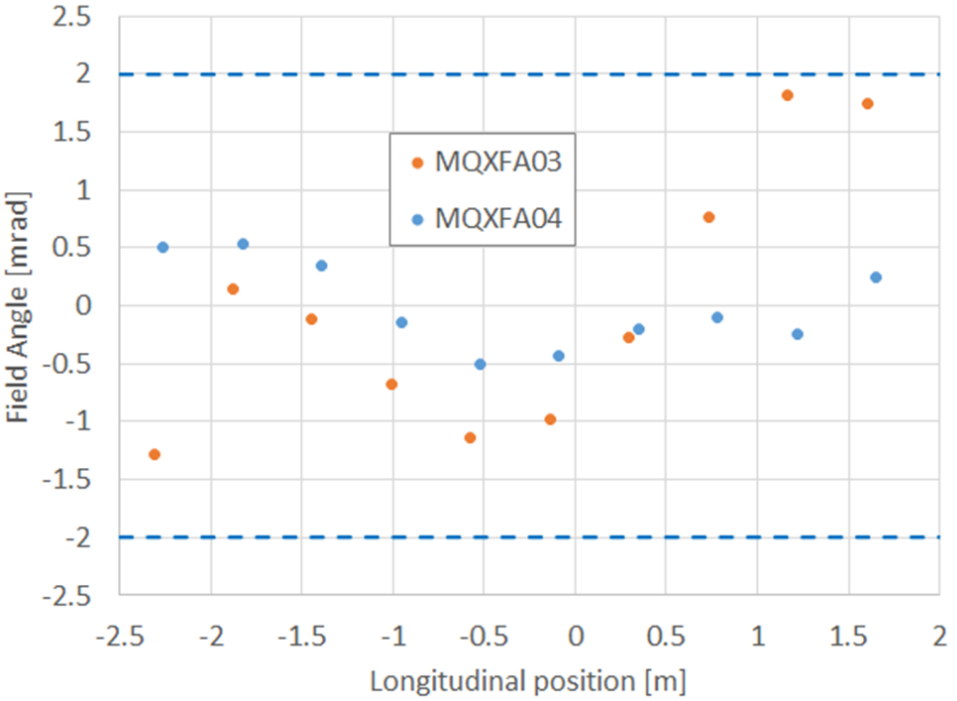
Alignment Measurements @ LBNL

- MQXFA03 and A04 met specs after assembly

Magnetic Center



Field Angle

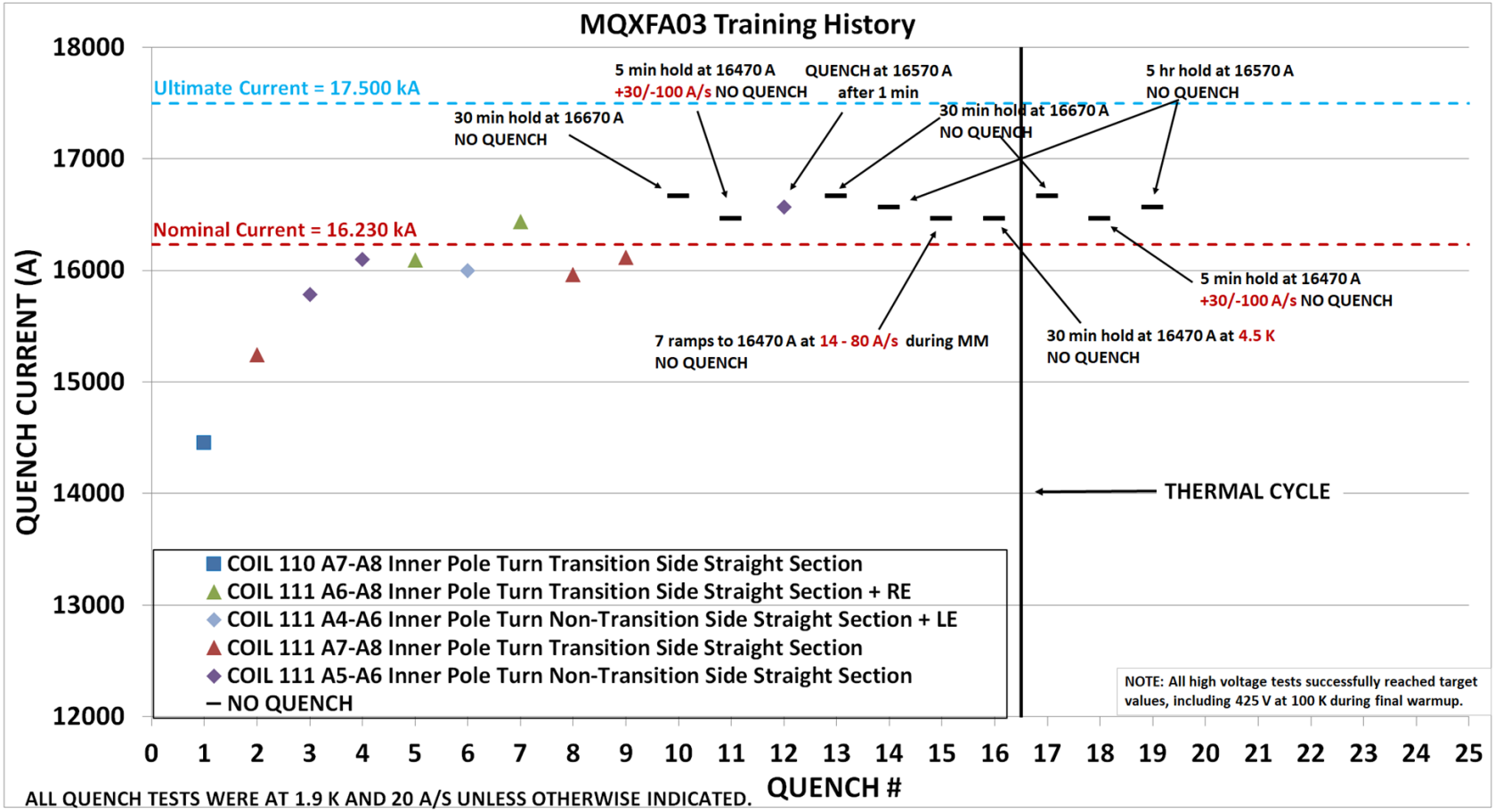


Field angle over 434 mm segments relative to average over entire magnet

MQXFA03 Quench History @ BNL

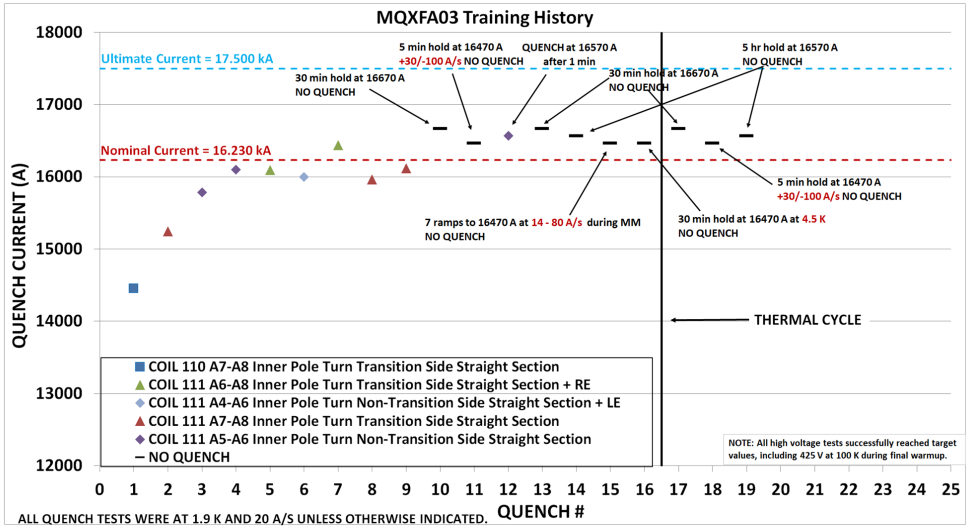
Requirement MQXFA-R-T-03: The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 556.9 T in superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K. ➔ 16230* A + 300 A (margin) = **16530 A for 300 minutes**

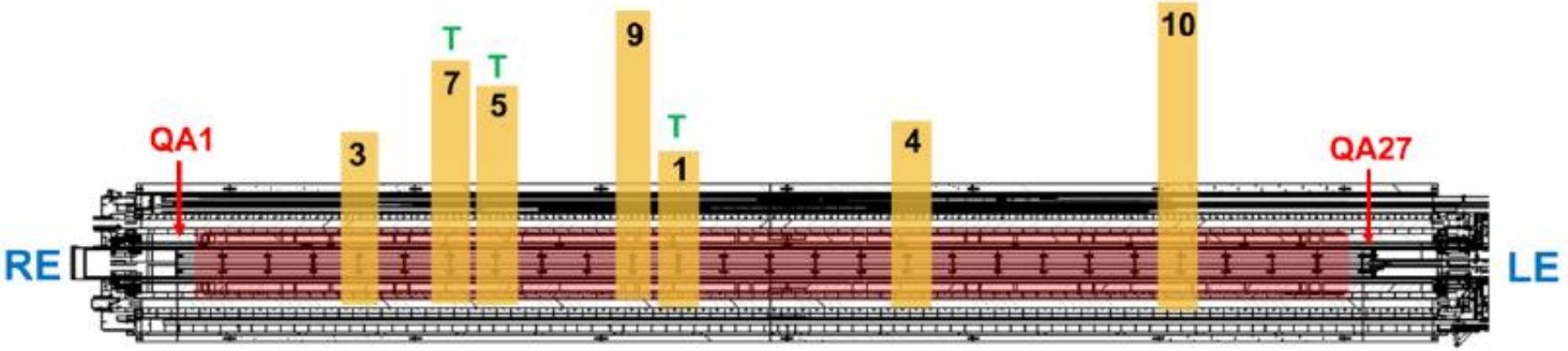
Requirement MQXFA-R-T-17: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with **no more than 3 quenches.**



** Nominal and ultimate currents of WP3 magnets* EDMS 2114564

MQXFA03 Quench Locations



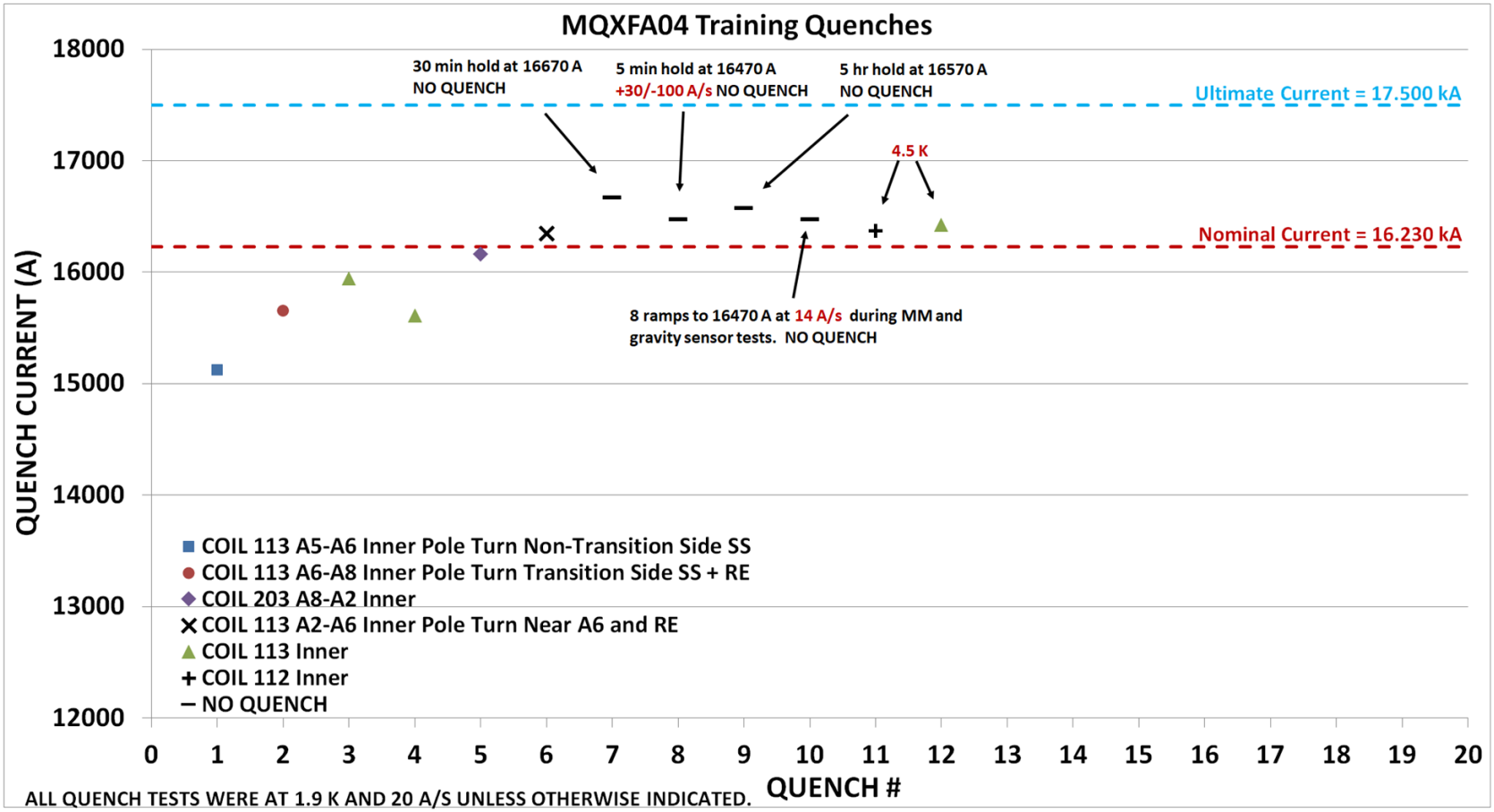


- Most quenches in one coil (111), with one exception
- Location moved from one coil side to the other side, and along coil length

MQXFA04 Quench History @ BNL

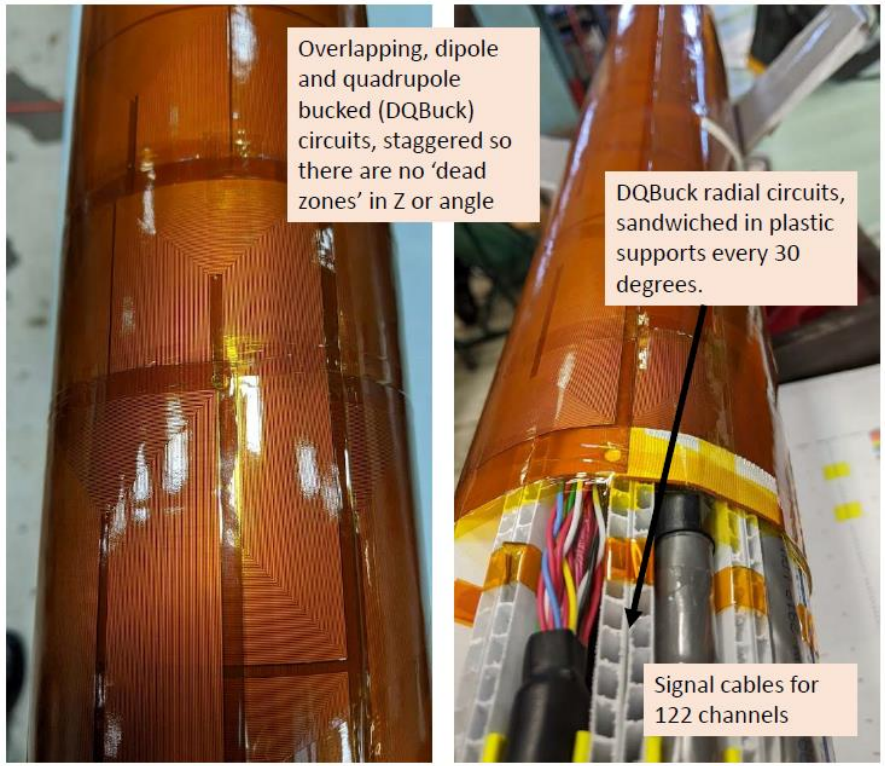
Requirement MQXFA-R-T-03: The MQXFA magnet must be capable of operating at steady state providing an integrated gradient of 556.9 T in superfluid helium (HeII) bath at 1.3 bar and at a temperature of 1.9 K. ➔ 16230* A + 300 A (margin) **= 16530 A for 300 minutes**

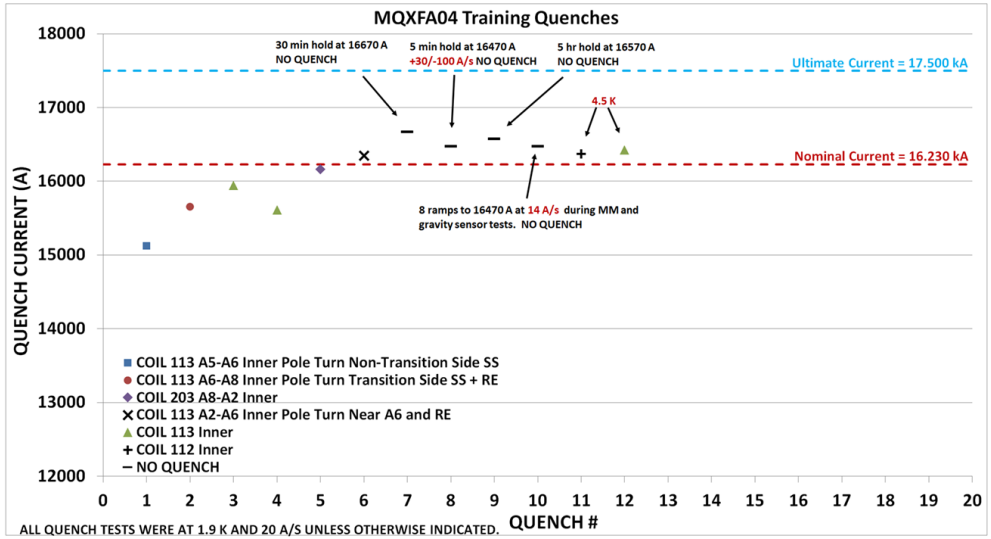
Requirement MQXFA-R-T-17: After a thermal cycle to room temperature, MQXFA magnets shall attain the nominal operating current with **no more than 3 quenches**.



* *Nominal and ultimate currents of WP3 magnets* EDMS 2114564

MQXFA04 Quench Locations





- Most quenches in one coil (113), with 2 exceptions
- New QA: quench location moved along coil length
  - further analysis is in progress

Ramp-Rate Dependence & Splice Req.

- **Requirement MQXFA-R-T-11:** The MQXFA magnets shall be capable of operating at any ramp rate within ±30 A/s.
- **Requirement MQXFA-R-T-18**: MQXFA magnets shall not quench while ramping down at 150 A/s from the nominal operating current.
- **MQXFA03 & MQXFA04:** no quench in ramp to nominal current up to 30 A/s and down at -100 A/s
  - Note: 100 A/s is the max ramp rate at BNL Vertical Test Facility
  - **Plan:** demonstrate ramp down at -150 A/s with no quench in LMQXFA cold masses
- **Requirement MQXFA-R-T-29:** Splice resistance must be less than 1.0 nΩ at 1.9 K
- **MQXFA03:** All splice resistances less than 1.0 nΩ at 1.9 K**.**
- **MQXFA04:** Splice resistance to be measured during Thermal Cycle 2

Magnetic Measurements: Field Quality

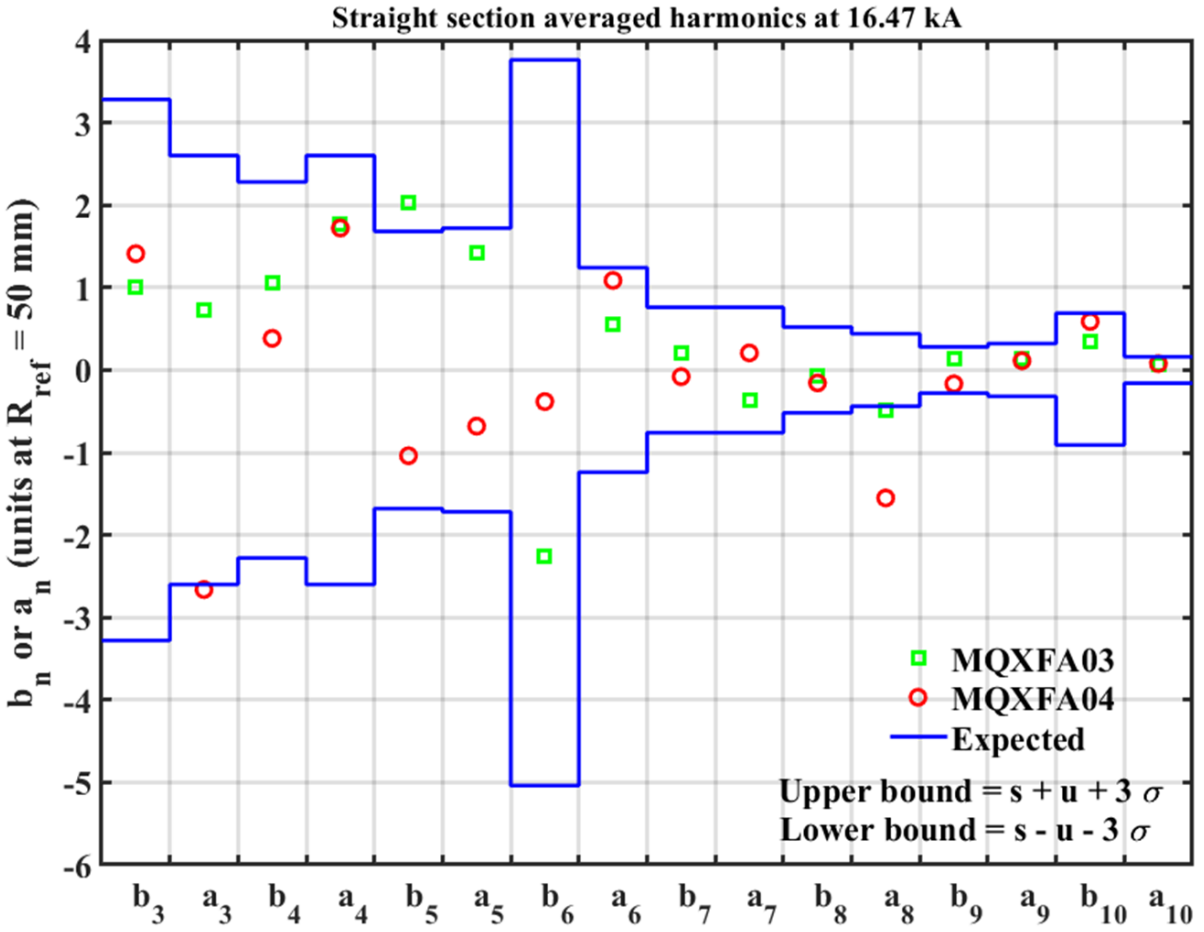
- **Requirement MQXFA-R-O-02:** The MQXFA field harmonics shall be optimized at nominal current. Table 1 from the MQXFA Functional Requirements Specification [EDMS 1535430] provides expected values for integral field harmonics at a reference radius of 50 mm.

MQXFA03 has 4 coils w/o b6 correction

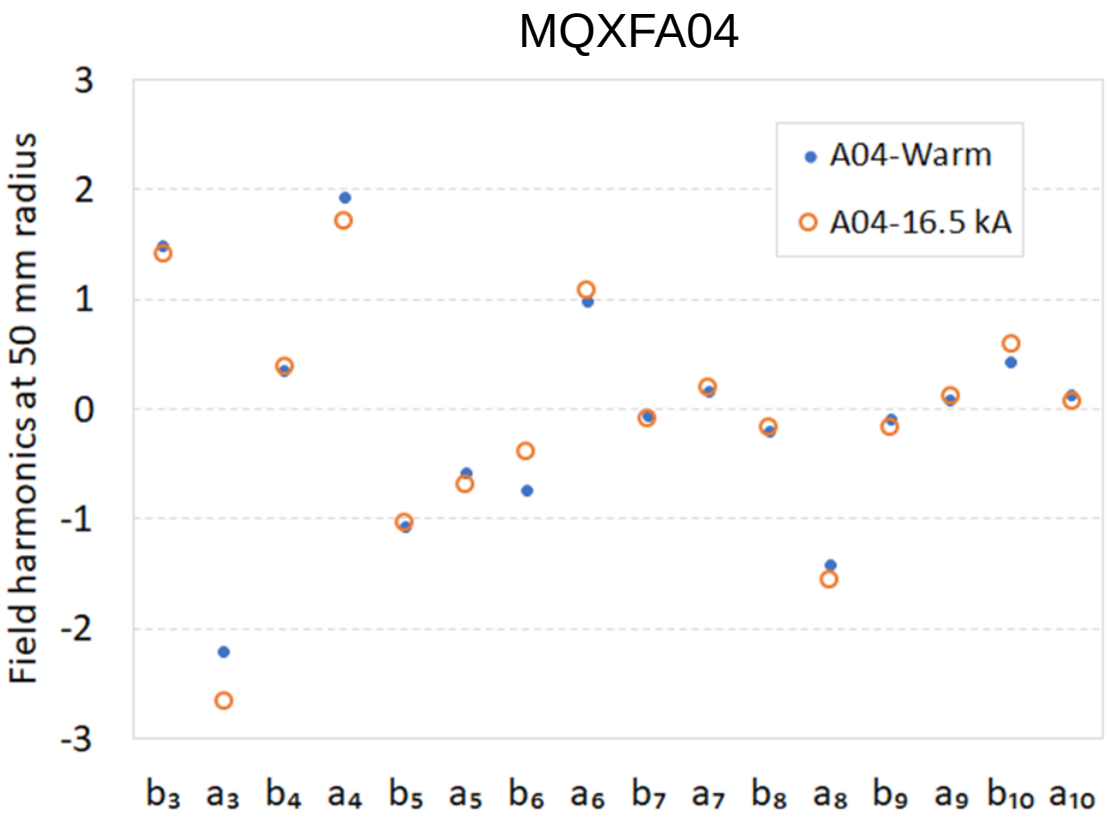
MQXFA04 has 1 coil with b6 correction: *125 um shift toward midplane*

If there is an issue with FQ, it will be addressed during assembly at LBNL (**MIP Hold Point**)

Integral harmonics to be measured in Coldmass



Magnetic Measurements: Warm – Cold @ BNL



- Warm and cold measurements from vertical test at BNL
- Data from z scan, 220 mm probe, averaged over the magnet straight section

- **Good Warm – Cold correlation**
- During MM at high current the probe appears to be significantly off center. Analysis of this issue is in progress

Electrical tests

Requirement MQXFA-R-T-16: The MQXFA magnet coils and quench protection heaters shall pass the hi-pot test specified in Table 2 of MQXFA Functional Requirements Specification, EDMS 1535430

Table 2: Required hi-pot test voltages and leakage current
Based on Electrical Design Criteria for HL-LHC Inner Triplet Magnets [8]

Circuit Element	Expected Vmax [V]	V hi-pot	I hi-pot [µA]***	Minimum time duration [s]
Coil to Ground at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Quench Heater at RT before helium exposure *	n.a.	3.68 kV	10	30
Coil to Ground at cold **	353	1.84 kV	10	30
Coil to Quench Heater at cold **	900	2.3 kV	10	30
Coil to Ground at RT after helium exposure *	n.a.	368 V	10	30
Coil to Quench Heater at RT after helium exposure *	n.a.	460 V	10	30
Coil to Ground at 100±20K and 1.2±0.2 bar	n.a.	425 V	10	30
Coil to Quench Heater at 100±20K and 1.2±0.2 bar	n.a.	425 V	10	30

* Room Temperature conditions refer to air at 20±3 °C and relative humidity lower than 60%

** Cold conditions refer to nominal cryogenic conditions (superfluid helium)

*** Maximum leakage current does not include leakage of the test station.

MQXFA03 & A04 Test Summary

- Requirements & Test Goals:

	A03	A04
Hold current at nominal current + 300 A (T-3)	✓	✓
Ramp to/from I_nom at ±30 A/s (T-11)	✓	✓
150 A/s ramp down w/o quench (T-18)	✓	✓
Temperature margin	✓	✓
Magnetic measurement (O-2)	✓	✓
Splice resistance < 1 nΩ (T-29)	✓	
Training memory (T-17)	✓	
All other requirements	✓	

- MQXFA03 was accepted for use in 1st LMQXFA Cold Mass

Schedule & Next Steps

- Complete test of MQXFA04 by end of the month

- MQXFA05 is at BNL
- Start testing MQXFA05 in December 2020

- Complete MQXFA06 assembly in December 2020
- Start testing MQXFA06 in February 2021

- Complete MQXFA07 assembly in February 2021
- Start testing MQXFA07 in April 2021

- Peak production rate: 2 coils every 18 days
  1 magnet every 6 weeks

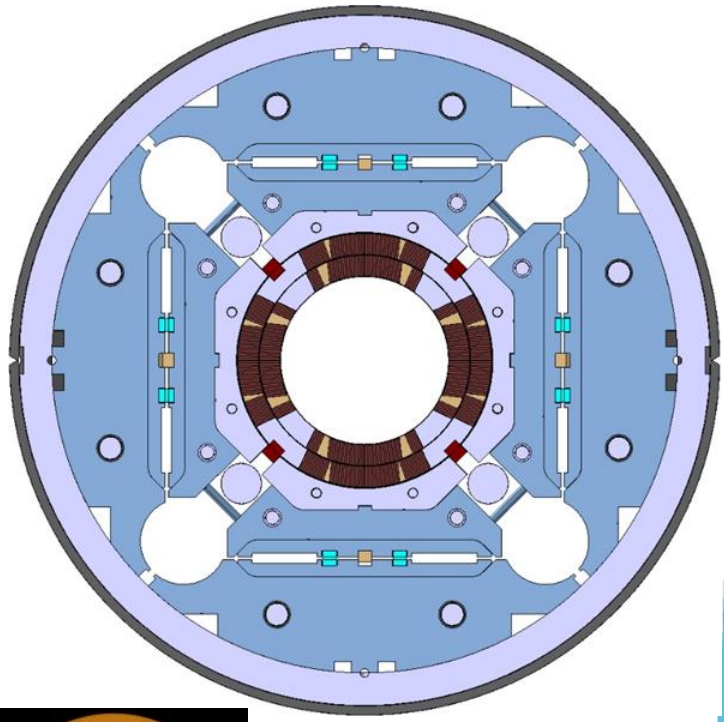
Conclusions

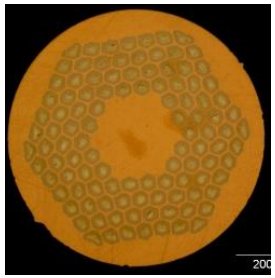
- MQXFA03 met all requirements, which could be tested at LBNL and at BNL Vertical Test Facility
  - Fast ramp down demonstrated at 100 A/s
- Test of MQXFA04 is in progress and it met all requirements up to this point
- Starting from MQXFA05 we plan to complete assembly and test a magnet every two months

Back up Slides

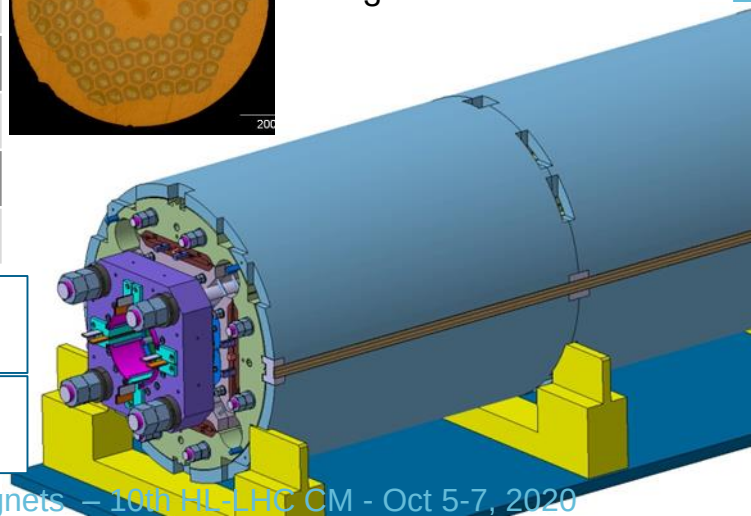
FDR: MQXFA Design

Parameter	Unit	MQXFA
Coil aperture	mm	150
Magnetic length	m	4.2
N. of layers		2
N. of turns Inner-Outer layer		22-28
Operation temperature	K	1.9
Nominal gradient	T/m	132.2
Nominal current	kA	16.23
Peak field at nom. current	T	11.3
Stored energy at nom. curr.	MJ/m	1.15
Diff. inductance	mH/m	8.26
Strand diameter	mm	0.85
Strand number		40
Cable width	mm	18.15
Cable mid thickness	mm	1.525
Keystone angle		0.4





Nb_3Sn Conductor



P. Ferracin et al., "Development of MQXF, the Nb_3Sn Low-β Quadrupole for the HiLumi LHC " IEEE Trans App. Supercond. Vol. 26, no. 4, 4000207

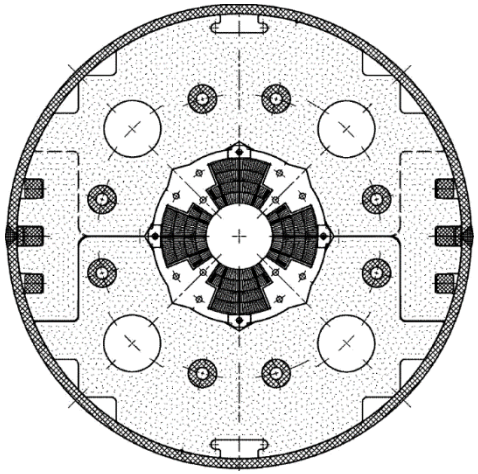
G. Ambrosio et al., "First Test Results of the 150 mm Aperture IR Quadrupole Models for the High Luminosity LHC" NAPAC16, FERMILAB-CONF-16-440-TD

Low-β quadrupole magnets from LHC to HL-LHC

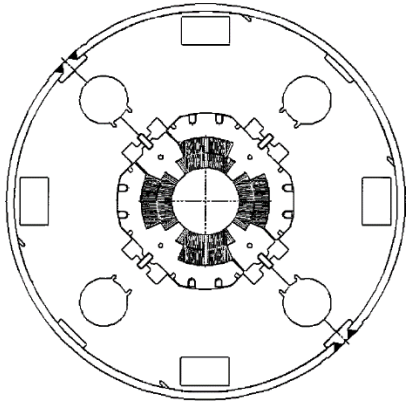
- Cold mass OD from 490/420 to **630 mm**
- More than double the aperture: from 70 to **150 mm**
- ~4 times the e.m. forces in straight section
- ~6 times the e.m. forces in the ends

State of the art quadrupoles at the time of LHC construction

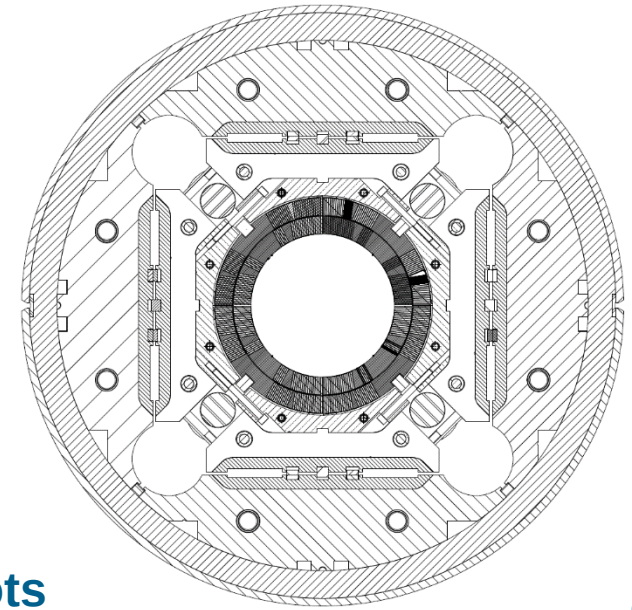
MQXA



MQXB

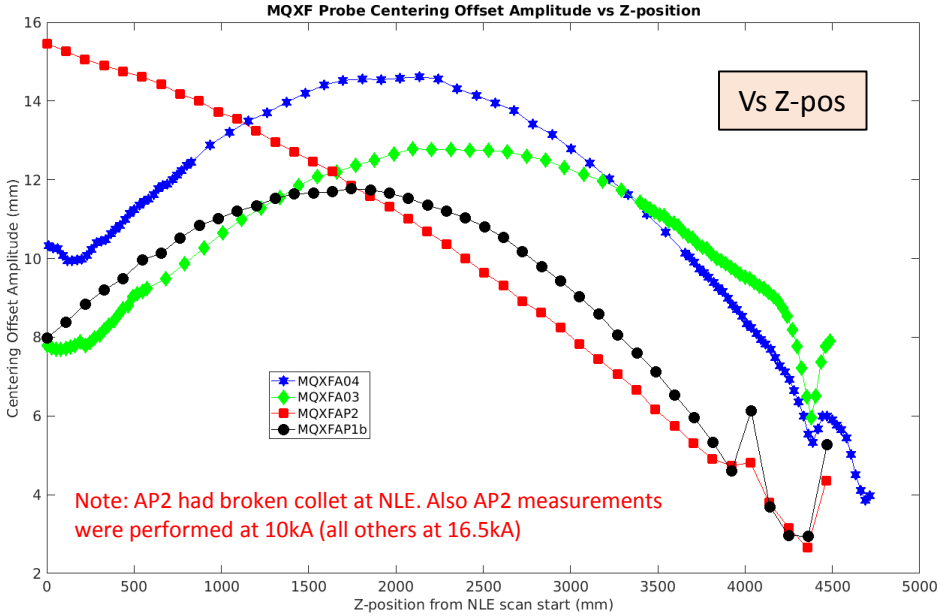


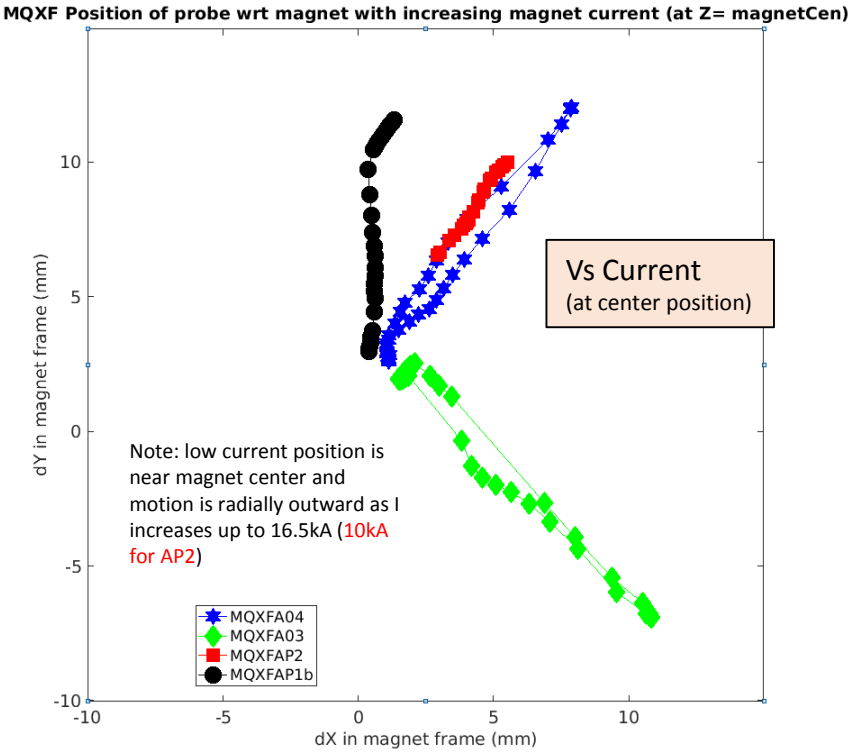
MQXF



Same scale for all 3 plots

Probe Offset from Field Center





- The probe offset is observed to change as a function of current and axial position during measurements
- Effect of magnetic Warm Bore Tube?!