Feed-back from Mini-Workshop on MQXF Assembly, Pre-load & Simulations

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H. Pan, S. Prestemon, E. Takala and G. Vallone

on behalf of the MQXF collaboration

9th HL-LHC Collaboration Meeting
14-16 October 2019
Fermilab, Batavia, USA
Goals of the workshop

• Review of
  • Assemblies and loading procedures
  • Shimming plans and pre-load levels
  • Finite element mechanical models

• In order to
  • Define a plan for MQXFA03 assembly and loading
  • Identify possible issues linked to the performance of MQXFAP1b
    • In particular re-assembly, change of coils, re-loading
Mini-Workshop on MQXF Assembly, Pre-load & Simulations

MQXFA Mini-Workshop
chaired by Giorgio Ambrosio (FNAL TD/MSD), Paolo Ferracin (CERN), Soren Prestemon (Lawrence Berkeley National Laboratory)
Monday, July 1, 2019 from 10:00 to 11:30 (US/Central)

Description: Meeting by Zoom. Info for the connection are provided by email.
Material: Summary and Action Items

Monday, July 1, 2019

10:00 - 10:40  MQXFA FEM Analyses 40'
   Speakers: Heng Pan (LBNL), Giorgio Vallone (CERN), Paolo Ferracin (CERN), Eels Tapani Takala (CERN)
   Material: Slides

10:40 - 11:10  Data analyses 30'
   Speakers: Paolo Ferracin (CERN), Heng Pan (LBNL), Daniel Cheng (LBNL), Giorgio Vallone (CERN)
   Material: Slides

11:10 - 11:25  AOB 15'
   Speakers: Dr. Soren Prestemon (Lawrence Berkeley National Laboratory), Heng Pan (LBNL), Paolo Ferracci
   (CERN), Giorgio Vallone (CERN)
   Material: Slides

Participants:
- Giorgio Ambrosio
- Daniel Cheng
- Paolo Ferracin
- Heng Pan
- Soren Prestemon
- Eels Tapani Takala
- Giorgio Vallone

Date and Time:
July 1-2, 2019

Location/Connection:
LBNL, Video conference room
Video link by Zoom, info by email.

Link to agenda with talks and other documents:
https://indico.fnal.gov/event/21164/

And with the participation of:
- Jose Ferradas Troitino (remotely)
- Shlomo Caspi
- Gianluca Sabbi

Paolo Ferracin
Outline

• MQXFA03
  • Coil shimming plan
  • Pole key clearance
  • Pre-load levels
  • Pre-load sequence

• MQXFAP1b finite element investigation
  • Effect of loading sequence in end region
  • Wedge strain
  • Coil replacement

• Conclusions
Nominal Shim Plan

Collar Radius: 114 mm

Impreg. Radius: 113.376 mm

GPI, Kapton: 125 μm

Kapton Shims: 125 μm
Just a quick reminder…

- **Transfer function**…

![Graph showing TF - PK Gap with lines for different total gaps (L+R): 760 - PK, 760 - nPK, 760 - PK - 100 um, 760 - PK - 200 um, 760 - PK - 300 um, 730 - PK + 50 um, 730 - PK + 100 um.](image_url)

![Diagram showing different components like Iron Yoke, Iron Pad, Iron Master, Alignment Pin, Load Key, Bladder Slot, Pole Key, Pole Strain Gauge, Gauge Stations, Shell Strain Gauge, LHe SS Vessel, Al Shell, Coil, Alignment Key, Al Collar, Titanium Pole, Cooling Hole.](image_url)
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MQXFA03 shimming plan

- For field quality purposes → bring all the coils to the same inner radius (high field region...).
- Starting with MQXFS3 → shims only on the mid-plane.

Before shimming

After shimming

Paolo Ferracin
MQXFA03 shimming plan

- Not really an issue for MQXFA coils
  - coils very close to nominal size $\rightarrow$ no need to shim in recent coils
- Instead, always implemented in MQXFS/B coils
MQXFA03 shimming plan

• What about radial shims?
  • So far, the plan has been to remove 0.125 mm of radial shim with respect to nominal shim plan
  • This has always been done since LQ to improve coil to collar contact based on
  • Fuji paper and strain gauge data during bolting of collar pack

<table>
<thead>
<tr>
<th></th>
<th>MQXFS3a/b</th>
<th>MQXFS5</th>
<th>MQXFS3c</th>
<th>MQXFS4</th>
<th>MQXFS6a</th>
<th>MQXFS6b</th>
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<tbody>
<tr>
<td>Coil pack (um) (exp. shimming)</td>
<td>-105</td>
<td>-112</td>
<td>-187</td>
<td>-263</td>
<td>-118</td>
<td>-118</td>
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<td>Polekey clearance (um)</td>
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<td>50</td>
<td>200</td>
<td>100</td>
<td>300</td>
<td>npk</td>
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<td>Shell stress (MPa)</td>
<td>84</td>
<td>104</td>
<td>101</td>
<td>59</td>
<td>67</td>
<td>64</td>
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<td>Pole stress (MPa)</td>
<td>-75</td>
<td>-101</td>
<td>-116</td>
<td>-76</td>
<td>-83</td>
<td>-93</td>
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<td>Axial force (MN)</td>
<td>0.7/1.15</td>
<td>1.2</td>
<td>1.05</td>
<td>1.2</td>
<td>1.23</td>
<td>1.23</td>
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<td>Shell slope (MPa/mm)</td>
<td>124</td>
<td>128</td>
<td>122</td>
<td>123</td>
<td>112</td>
<td>128</td>
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<tr>
<td>Pole slope (MPa/mm)</td>
<td>-99</td>
<td>-152</td>
<td>-163</td>
<td>-205</td>
<td>-134</td>
<td>-209</td>
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<td>TF slope (MPa/MPa)</td>
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<td>-1.2</td>
<td>-1.3</td>
<td>-1.7</td>
<td>-1.2</td>
<td>-1.6</td>
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<td>Shell contact key (mm)</td>
<td>13.15</td>
<td>13.22</td>
<td>13.3</td>
<td>13.38</td>
<td>13.11</td>
<td>13.34</td>
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<tr>
<td>Pole contact key (mm)</td>
<td>13.25</td>
<td>13.25</td>
<td>13.36</td>
<td>13.41</td>
<td>13.11</td>
<td>13.38</td>
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<td>Contact key offset (um)</td>
<td>-100</td>
<td>-30</td>
<td>-60</td>
<td>-30</td>
<td>0.7</td>
<td>-40</td>
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<tr>
<td>Pole stress offset (MPa)</td>
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<td>5</td>
<td>10</td>
<td>6</td>
<td>0.7</td>
<td>8</td>
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<td>Coil pack (um) (cont.key meas.)</td>
<td>-150</td>
<td>-220</td>
<td>-300</td>
<td>-380</td>
<td>-110</td>
<td>-340</td>
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</table>

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• Study of the LQ effect

![Graph and diagrams showing stress distributions for m125, Nominal, and p125 models.](image)
“Dent”

QXFA109 CMM

Section #5 at -1140 mm from LE scale x100 (1box=.1mm)
Alignment is to this cross section only + OD and sides

Section #7 at -1940 mm from LE scale x100 (1box=.1mm)
Alignment is to this cross section only + OD and sides

Section #9 at -2740 mm from LE scale x100 (1box=.1mm)
Alignment is to this cross section only + OD and sides

Section #11 at -3540 mm from LE scale x100 (1box=.1mm)
Alignment is to this cross section only + OD and sides
MQXFA03 shimming plan
Workshop action items

✔ Investigating LQ effect
  • 2D model
    • Coil with changing radius (larger on pole, smaller on the mid-plane)
    • Miss-match between coil radius and collar radius
      • This could either create the LQ effect or compensate it

✔ Continue to apply to MQXFA03 the “reduced radial shim” option
Outline

• MQXFA03
  • Coil shimming plan
  • Pole key clearance
  • Pre-load levels
  • Pre-load sequence

• MQXFAP1b finite element investigation
  • Effect of loading sequence in end region
  • Wedge strain
  • Coil replacement

• Conclusions
MQXFA03 pole key clearance
Workshop action items

• Reproduce MQXFS4 case → large clearance
  • Pole key with fiber in the azimuthal direction → low thermal contraction and high modulus
  • Key machined to have ~8 mils of pole key gap per side
    • In MQXFS4 we have 4 mils of pole key gap per side
• As a result, pole key in contact with the collar only after cool-down
MQXFA03 pole key clearance
Workshop action items

✓ Extract the pole keys (fiber in the azimuthal directions) from MQXFA03 coils
✓ and machine them in order to have ~8 mils of pole key gap
✓ In parallel, continue with shell-yoke sub-assembly
✓ Once keys are machined, proceed with coil-pack assembly (no Fuji test)
MQXFA03 pole key clearance

- Transfer function
  - Measurements data on no-pole key line
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MQXFA03 pre-load levels

• **Azimuthal pre-load**
  • The target is MQXFS4, with a reduction of 10 MPa to account for possible larger spread due to the longer length

• **Axial pre-load:**
  • The target is MQXFS4, with a reduction of 0.2 MN to limit the rod stress at room temperature and meet the design criteria
MQXFA03 pre-load levels

**Shell 04 Azimuthal Strain**
- **Target:** 760 με @RT

**Coil Azimuthal Strain**
- **Target:** -580 με @RT

**Rod Strain**
- **Target:** 960 με @RT

Axial Preload
Azimuthal Preload
Outline

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• Conclusions
MQXFA03 pre-load sequence

• The plan is to adopt the MQXFS4 sequence
  1. Coil pack centering (13.1-13.2 mm interference keys)
  2. Pre-load axial rods with ~50-100 microstrain
  3. 50% azimuthal pre-load (0.250 mm added shim)
  4. 50% axial pre-load (about 300 micro-strain)
  5. 100% azimuthal pre-load
  6. 100% axial pre-load

• FEM computations indicate lower axial strain in the coil pole during pre-load with this sequence with respect to “100% azimuthal then 100% axial” pre-load
  • Further investigation with FE model is in progress
MQXFA03 pre-load sequence

**Shell 04 Azimuthal Strain**
- **Target:** 760 με @RT

**Coil Azimuthal Strain**
- **Target:** -580 με @RT

**Rod Strain**
- **Target:** 960 με @RT

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Outline

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• Conclusions
Effect of loading sequence in end region

50%_Azi.  50%_Axial  100%_Azi.  100%_Axial

-3.15E+07 -2.60E+07 -2.05E+07
-1.50E+07 -950000 -400000
150000 700000 .125E+07 .180E+07

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Effect of loading sequence in end region

- Some effect on the coil axial strain
Outline

• MQXFA03
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  • Wedge strain
  • Coil replacement

• Conclusions
Wedge strain

Wedge 1 --- bond after cooldown

- Cooldown with sequence
- 16.47 kA with sequence

Wedge 2 --- bond after cooldown

- Cooldown with sequence
- 16.47 kA with sequence

Wedge 1 --- float (Baseline) after cooldown

- Cooldown with sequence
- 16.47 kA with sequence

Wedge 2 --- float (Baseline) after cooldown

- Cooldown with sequence
- 16.47 kA with sequence
Outline

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• Conclusions
**Full Size 2D model**

- Coil Q1 is the virgin coil, Q2 – Q4 are the used coils.
- Virgin coil has the original modulus of 20 GPa;
- Used coil has higher modulus of 40 GPa.
- Preload is set as MQXFAP1b load level.
Impact with Used Coils

All virgin coils

Q1 --- virgin coil; Q2 – Q4 ---- used coils

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Outline

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• Conclusions
Conclusions

• MQXFA03 assembly/loading procedures defined
  • Pre-load sequence and level as MQXFS4
  • Pole key clearance until after cool-down
  • Radial shimming to optimize coil stress

• MQXFAP1b finite element investigation launched
  • So far no clear “smoking gun” found in the end region and along the wedge
  • Effect of coil replacement under investigation, but the coil stress variation seems to be of the order of 10 MPa
Items to be discussed

- Coil size measurements
  - Nominal radius vs real radius
  - Faro vs. CMM
- Coil-pack shimming
  - Mid-plane shims vs radial shims
    - What about variable shims along the length?
  - Historical missing radial shim
  - Pole keys
    - Material
    - Length (end region)
    - Pole key gaps
- Pre-load at room temperature
  - Stress levels in shell, rods, and coils
    - Optimal levels based on MQXF quench performance?
  - Pre-load sequence
  - “Transfer function” plots
- Simulations
  - Properties of coil in FEM
    - 20 GPa linear, 40 GPa linear, or 20-40 GPa not-linear (plastic)
      - Comparison with experimental data during cool-down and excitation
  - Pole to coil glued or separation models
  - Multiple assemblies
    - Do we simulate well multiple assemblies/loading?
    - Should we use different module for first/second assembly?
- Review of quench performance/locations
  - Segment A3A4
  - Ends vs straight section
Action items

• FE models
  ✓ 3D
    ✓ Compare pre-load sequences (S4 type and AP1 type) during pre-load, cool-down, end excitation
      ✓ Axial strain in the winding pole
      ✓ Contact pressure coil to end-spacers
      ✓ Shear between wedge and coil in the straight section
      ✓ Axial strain in the coil close to the wedge in the straight section
    • Analyze smaller ends effect (ET)

• Check how the contact between the key and the pole groove
  • Side: contact sliding/separation/friction
  • Bottom:
    • Contact elements sliding/separation/friction
    • Fix (coupled in all directions) one keypoint (z=0, theta=45)
    • All the other nodes at theta=45 are coupled in r
Action items

- Investigating wedge issue (HP)
  - 3D model
    - Current MQXFA model with all contact sliding/separation with friction and no symmetry boundary condition on the wedge (z=0)
      - Verify that the tip of the wedge is not glued to the spacer
      - Investigate
        - A) axial strain in the coil close to the wedge and check for possible spikes (TQ type)
        - B) The possible gaps between wedge and spacer and at z=0
    - Explore then the impact on A and B of
      - the loading sequence
      - Axial loading level
    - If the analysis indicates a potential issue with A, investigate the effect of reducing the length of the wedge segments
      - Either by cutting the wedge volume or by “killing” elements
Action items

- Investigation of effect of modulus and of loading-reloading
  - As output, check the coil peak stress in the following cases

- 2D model: 1 octant (ET)
  - Full history with 20/40 GPa
    - Simple Thermal cycle
    - Increase of pre-load S1a → S1b

- 2D model: 4 quadrants (HP)
  - 3 coils with 40 Gpa and 1 coil with 20 GPa
  - Compare bladder operation 2 quadrant vs 1 quadrant

- For a normal virgin loading, we stay with the 20 GPa modulus bonded (baseline).
  - This will allow to compare to previous magnets

- Run the baseline loading conditions of MQXFA03 (3D model) (HP)
**MQXFA03 azimuthal pre-load level**

- **Azimuthal pre-load** The target is MQXFS4, with a reduction of 10 MPa to account for possible larger spread due to the longer length.
  - Therefore, target pre-stress at cold is: 100 MPa.
  - This means pre-stress at warm of about 80 MPa after creep:
    - Assume 5-10 MPa of creep
    - We set as maximum coil stress to 110 MPa during loading.

- **Axial pre-load** The target is MQXFS4, with a reduction of 0.2 MN to limit the rod stress at room temperature and meet the design criteria.
  - MQXFA has rods with smaller radius than MQXFB (33 vs 31 mm).
  - Therefore, the total force at cold is: 1.0 MN.
  - This means that the total force after cool-down (and at room temperature) will be 0.1 MN higher than in MQXFAP1/P2.

Paolo Ferracin
MQXFA03

[Graphs showing relationships between stresses and thicknesses]