Options for longitudinal welding AUP cold masses at CERN

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CERN: November 2024

Outline

- Requirements
- Welding parameters and feedback from construction
- Options for longitudinal welding:
  - Option 1: AUP ‘MQXFA’ procedure
  - Option 2: CERN ‘MQXFB’ procedure
  - Option 3: CERN ‘modified’ procedure (see slides from Herve)
- Conclusions

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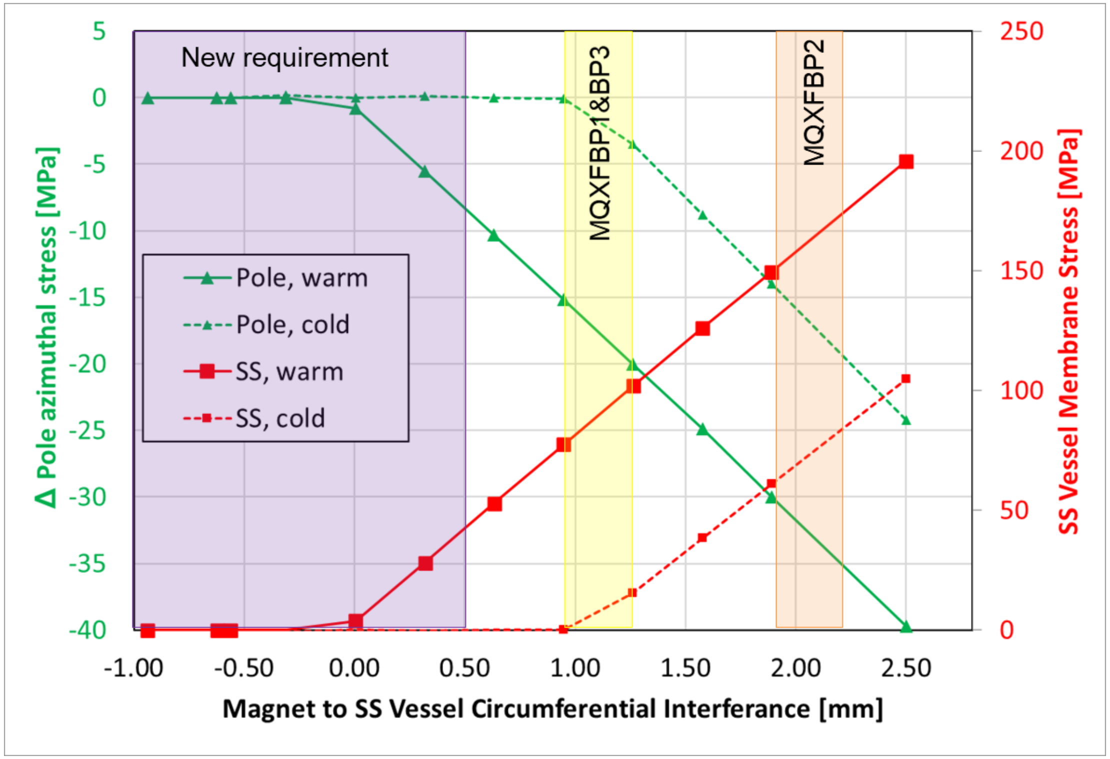
Requirements for welding interference

- Welding requirements were modified, to assure no coupling of the SS vessel to the magnet (**Same** requirements for **AUP** and **CERN**)
  - **Previous target**: 8 ± 8 MPa ΔCoil stress from welding
  - **New target**: 0 + 8 MPa ΔCoil stress from welding



Technical Review of MQXFB Cold Mass: https://indico.cern.ch/event/1142636/

Fixed point – requirements (RT)

- The fixed point (and the magnet components in contact) must withstand the loads appearing during handling/transport and during operation.
  - During **transport**:
    - **MQXFB: 0.5 g**. The estimated weight of the magnet is 11 tons, so the fixed point shall be designed for a minimum load of **55 kN.**
    - **MQXFA:**
      - **AUP Requirement: 2 g**, since it will be shipped to CERN by boat → the fixed point shall be designed for a minimum load of **135 kN.**
      - **Proposed requirement for re-worked cold masses at CERN: 0.5 g**, same handling requirements as MQXFB magnets at CERN → the fixed point shall be designed for a minimum load of **32 kN.**

Fixed point – requirements (operation)

- The fixed point (and the magnet components in contact) must withstand the loads appearing during handling/transport and during operation.

- During **operation** of the **cryogenic system (**EDMS 2675955**)**

  - the MQXFB magnet inside the cold mass shall not move when subject to **4 bar differential pressure between the ends of each MQXFB magnet** (induced by cryogenic operation or by quench of other magnets) and shall withstand this load without physical damage or performance degradation (**4 bars** to **96 kN**).

  - the MQXFA magnet inside the cold mass shall not move when subject to **2.5 bar differential pressure between the ends of each MQXFA magnet** (induced by cryogenic operation or by quench of other magnets) and shall withstand this load without physical damage or performance degradation (**2.5 bars** to **62 kN**).

“New” data from the definition of requirements in 2022

- MQXFBP2 had identical magnet performance when assembled in a temporary cold mass (tight contact) and in Q2 cold mass (new welding procedure)

- Pressure wave attempted to be measured in two cold masses:

  - MQXFBP3 was equipped with special sensors, that were not read during test in spite of a reminder just before the cool down… hopefully they will be read in the string (added a comment to MAB assessment, and Marta was informed explicitly)

  - AUP CA02 (MQXFA05&06), based on a test at 6 kA they extrapolate 0.32 bars, more tests are planned in the future link from Guram, slide 15

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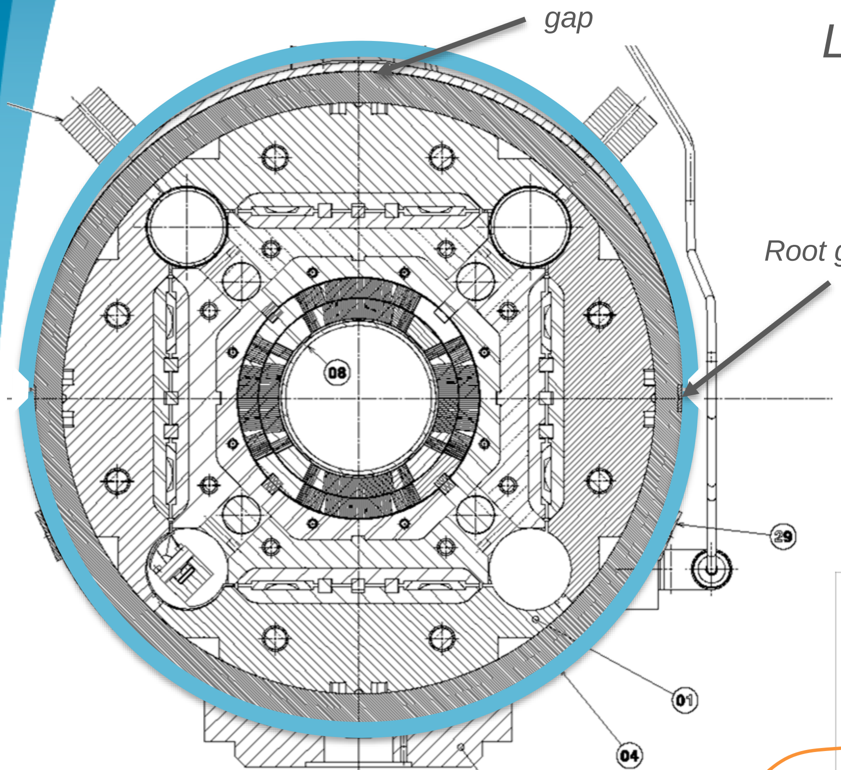
Determination of the shell developed length required after MQXFBP2 cold test

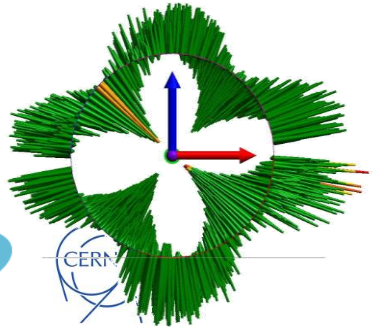


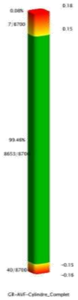
$$Ldev_{Shells} = Ldev_{Mag_{max}} + 2x\ shrinkage - 2x\ root\ gap$$

$$= 1931.3 \quad + 2x\ 2.2 \quad - 2x\ 3.4$$

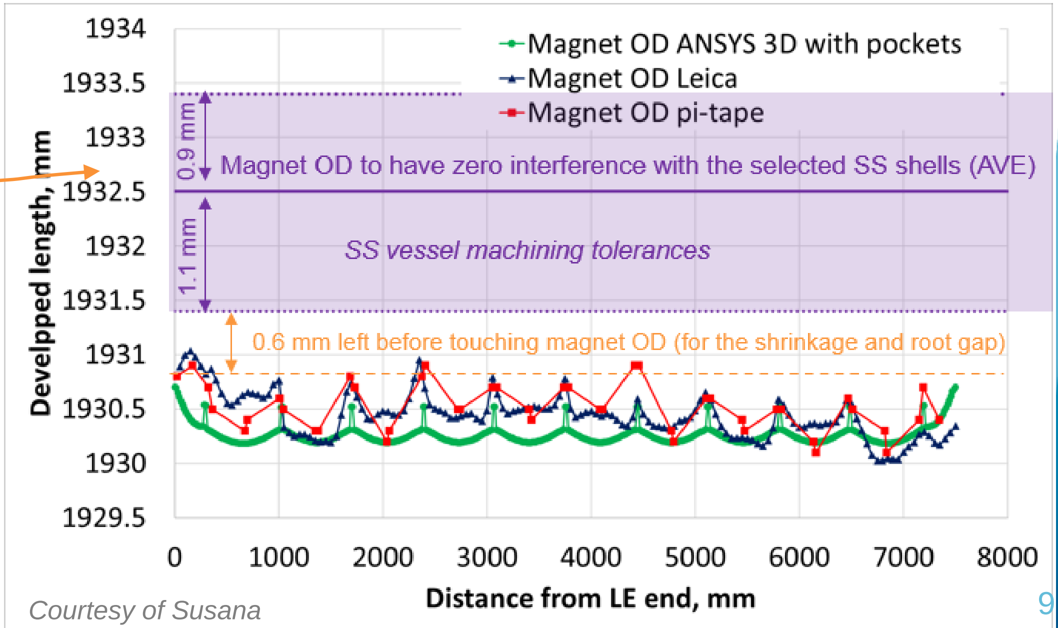
= 1928.9mm ⇨ **1929mm**

Pairing of shells 5 and 102 according to their developed lengths





Shell pairing for LMQXFBT04, the second cold mass with MQXFBP3:

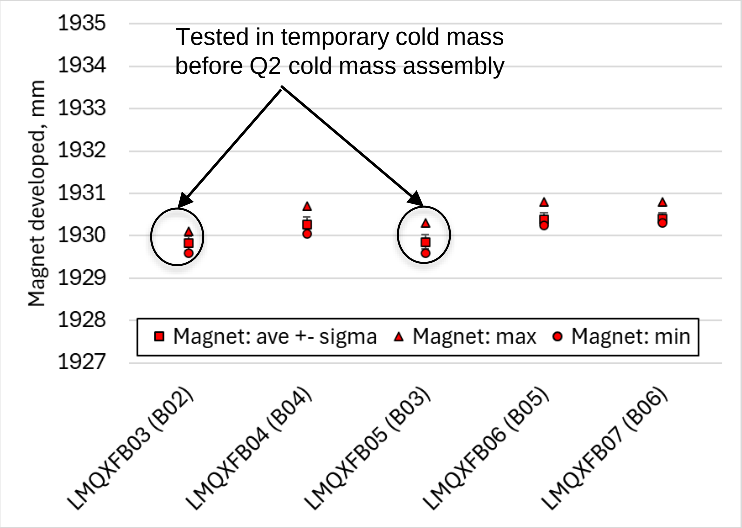


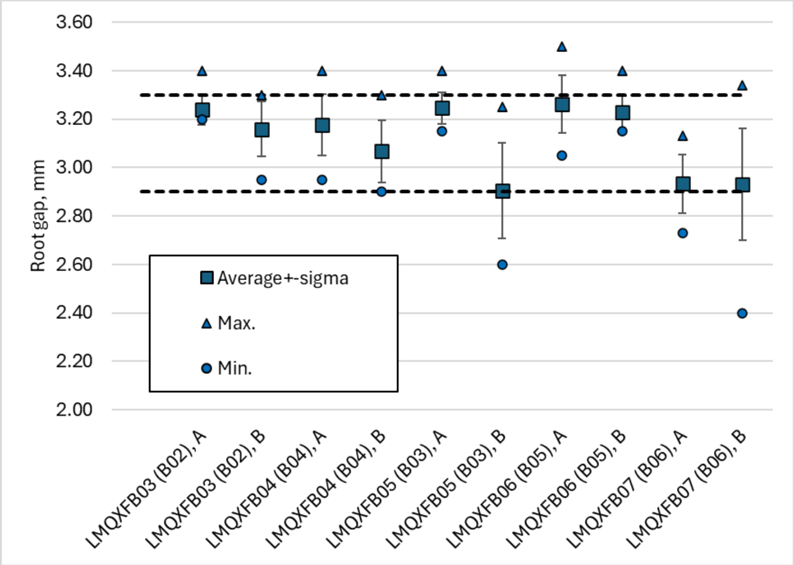
Courtesy of Susana

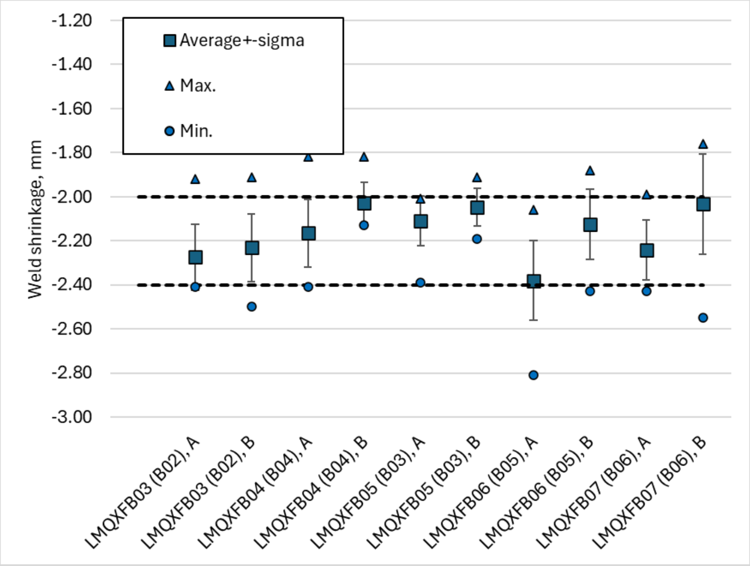
Geometrical tolerances: experience

- **Magnet OD** very reproducible (std along the length 0.20 mm, max – min along the length = 0.5 mm). Nice tool to derive the coil pre-stress within 10 MPa see link.
- We can control the **average root gap and welding** shrinkage within ± 0.2 mm. Along the length, we can have variations up to ± 0.4 mm.

	Average, mm	STD, mm
Root gap	3.12	0.14
Welding shrinkage	-2.12	0.09

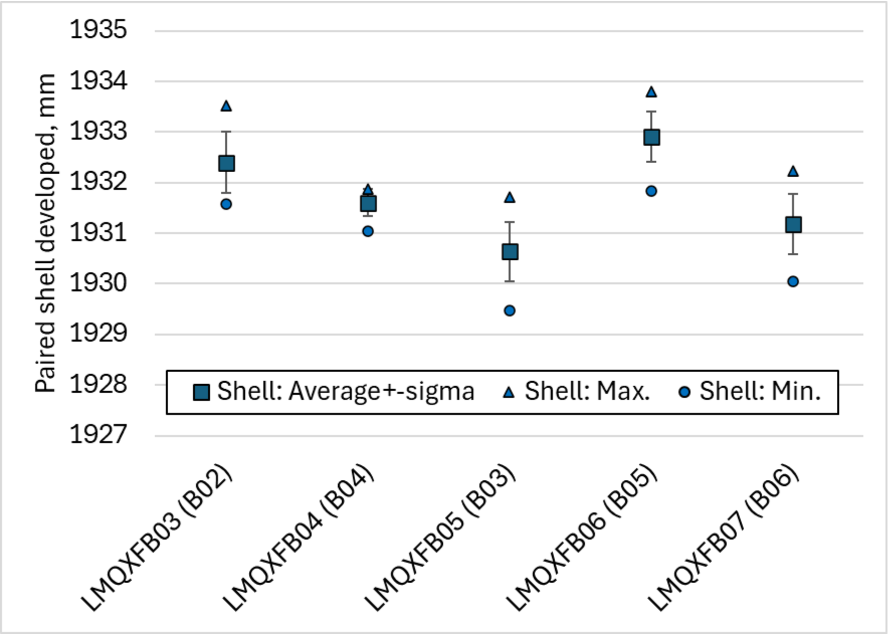


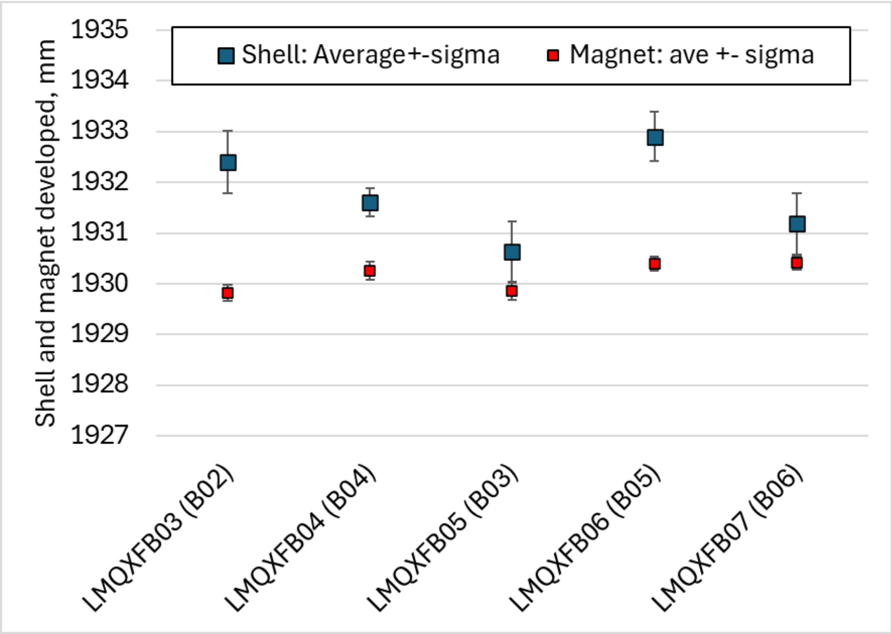




Shell-Magnet Pairing

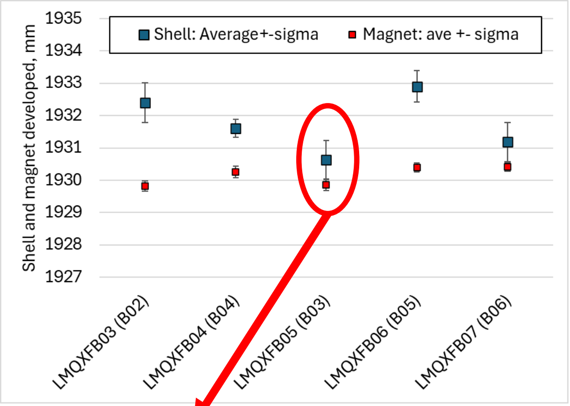
- The shell paired developed length (including root gap and welding shrinkage) is within the expected geometrical tolerances (std along the length 0.50 mm, max – min along the length = 2 mm).
- The goal is to be 'as close' as possible to the magnet (minimize 'micky mouse' effect) but without touching.

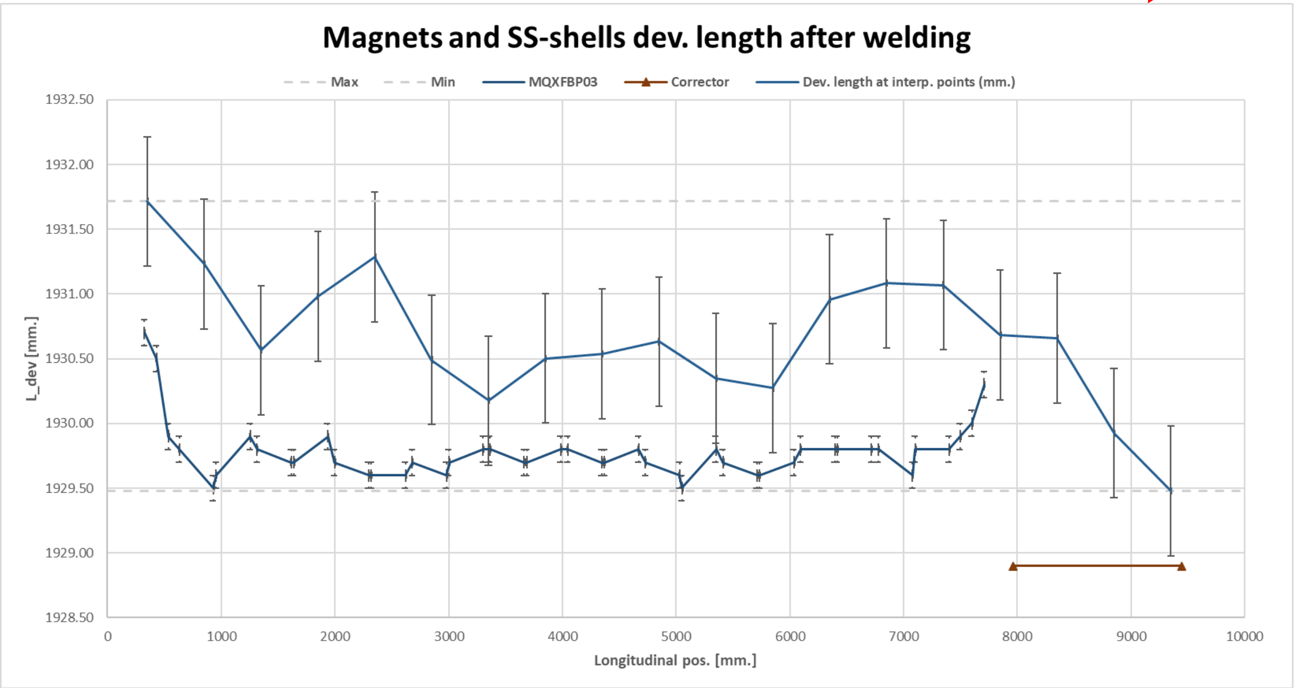




Shell-Magnet Pairing

- Even in the case with 'less margin' we had always at least 0.5 mm margin
  - Note that in case of welding repairs following PAUT inspection, one can expect a local increase of the welding interference
- Only one case with a marginal interference in one longitudinal location (see EDMS 3180091)





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AUP 'MQXFA' procedure

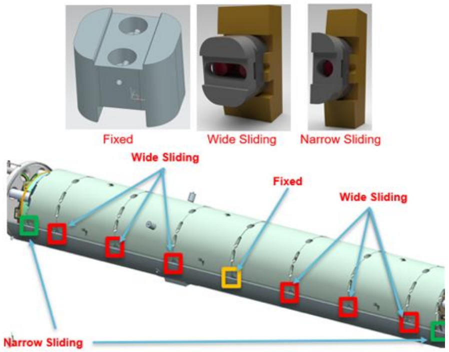
302.4.02 Cold Mass Design Change

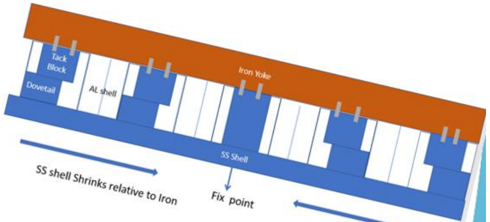
- Cold Mass design change
  - SS shell has minimal (as low as zero) interference with the magnet
  - The new requirement made it necessary changing the way how the magnet is supported by the SS shell to withstand shipping loads
    - SS friction was the primary support
    - Tack blocks are the new support
  - New design change has been reviewed and accepted internally within AUP
  - 2.2 g load equivalent to 152 kN force to withstand
    - 4 Bolts are good up to 32 kN
    - Two tack block welds are good to 78 kN (tack blocks are touching the aluminum shell)
    - Planned to be used:
      - Two tack block with four bolts 32 kN
      - 6 welded tack blocks 234 kN
      - Total 266 kN
    - Sliding tack blocks have been extensively tested at cryogenic conditions. Easy sliding have been observed without any sign of galling.
    - During cool down SS shell shrinks more than the iron supported segmented Al shells. Tack blocks will move away from the Al shells and warm up the reverse process will happen ensuring the tack blocks to move back to their original location.

A priory we are OK with the 4 bolts at warms (0.5 g)

At cold we are probably tight, load (2.5 bars) is 62 kN (62/32 = 1.9; 375/290* = 1.3)

*$R_{p0.2,SS}$ (RT) = 290 MPa
* $R_{p0.2,SS}$ (1.9 K) = 375 MPa





Sliding tack blocks if positioned in the middle of the slot will not provide any additional support.
Tack blocks are offset to withstand shipping forces.

US HL-LHC AUP

5th AUP-CERN Technical Steering Meeting – January 18th, 2021 7

[CA Series Production Readiness Review (6-September 8, 2023) · INDICO-FNAL (Indico)]

HiLumi HL-LHC PROJECT CERN

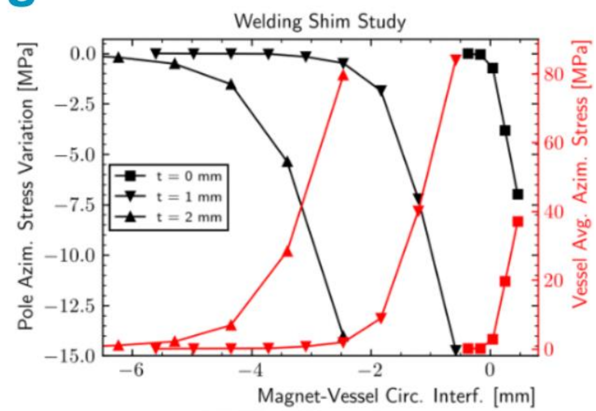
AUP ‘MQXFA’ procedure

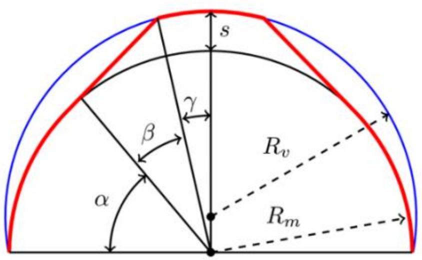
Requires modification and re-qualification of our welding procedure

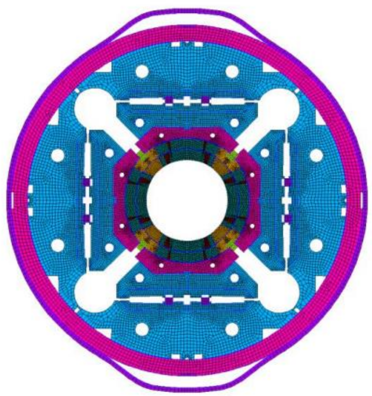
Cold Mass Production Achievements and Challenges

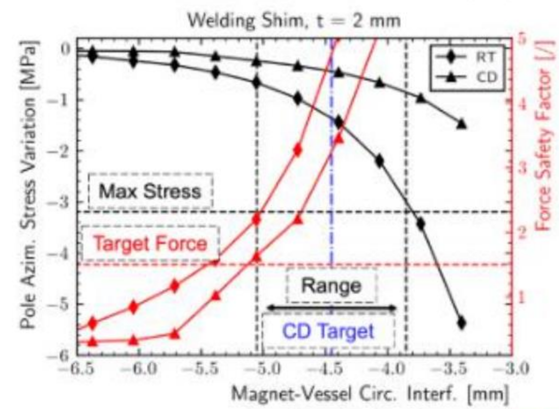
Starting with CM02 we are using the welding shims

- 2 mm target value for the shims were used (proposed by the analysis presented at MT 28) to calculate the SS vessel circumference based on the measured magnet circumference values
- It was important to machine and measure the shell correctly









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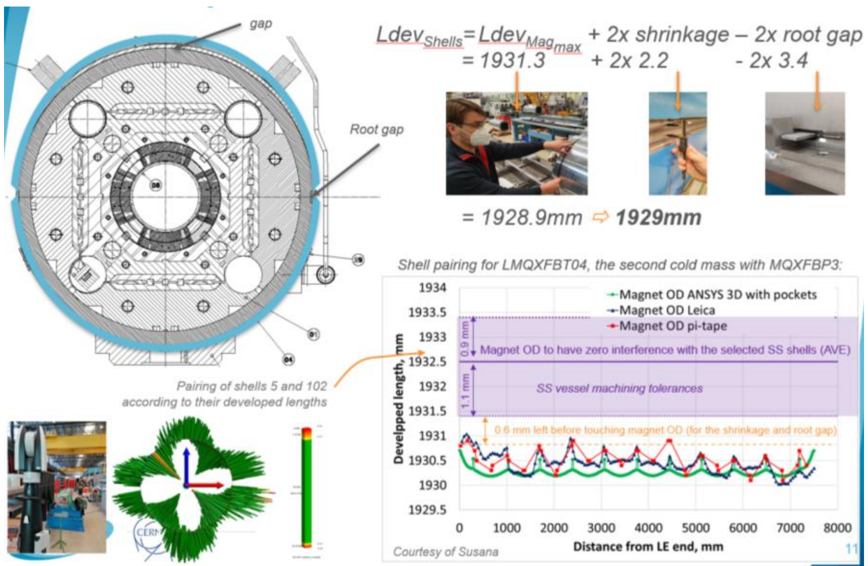
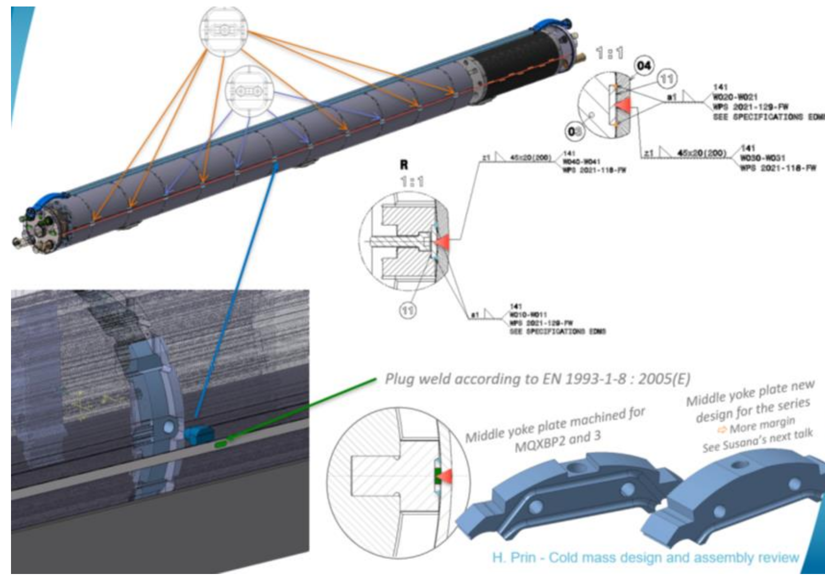
MQXFB approach

- Shell pairing with a gap in the top of the shell, such that after welding we are not in full contact with the magnet OD
- Fixed point from the SS shell to the yoke to handle the expected load warm/cold



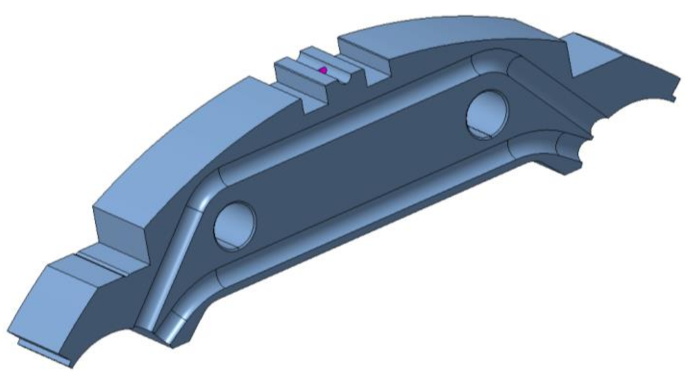


Technical Review of MQXFB Cold Mass: https://indico.cern.ch/event/1142636/

MQXFB – Fixed point

- Machine new central yoke piece in ARMCO (2 per magnet), to optimize the iron geometry for the hosting of the pin:
  - Upper cooling channels removed (approved by CRG, we are removing 4 out of 192 cooling channels)
  - Removal of the tack welding block grooves
  - The thickness of the lamination was increased from 45 mm to 91.4 mm such that even if the longitudinal stiffness provided by the adjacent thin laminations is neglected, the stand-alone yoke can hold the forces
- Exception for existing prototype magnets (MQXFBP2&BP3), where the proposal is to re-machine the already assembled yoke

3D geometry for the old piece



LHCMQXFBS0025

3D geometry for the new piece

LHCMQXFBS0037

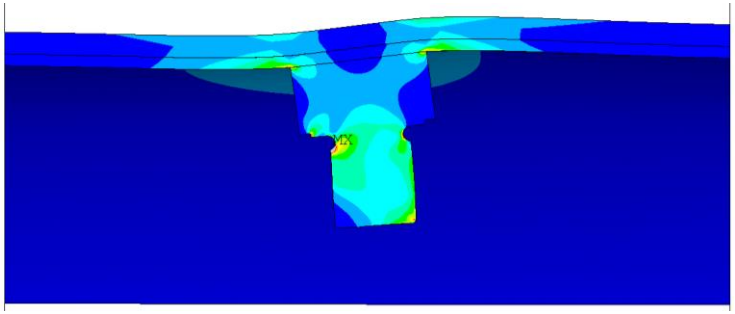
Technical Review of MQXFB Cold Mass: https://indico.cern.ch/event/1142636/

Jose Ferradas Troitino

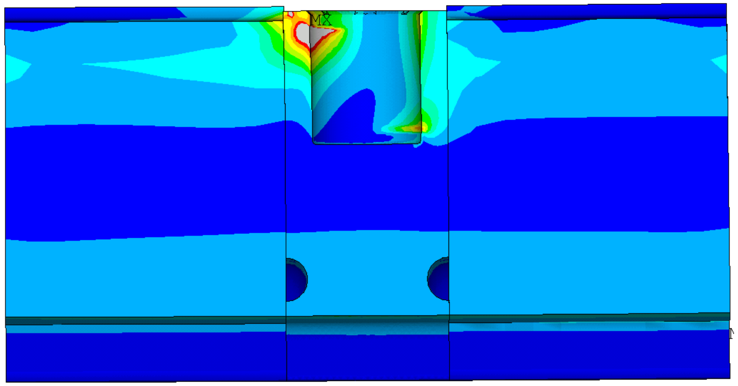
Overall system behavior and material limits

Stress concentration on the upper and lower edge due to the bending of the pin.
Inhomogeneous contact with a stress concentration region going above the yield limit

- **Pin, welding strip and vessel**
  - Material: Stainless-steel 316LN
  - $R_{p0.2}$ (RT): 290 MPa
  - $R_{p0.2}$ (1.9 K): 375 MPa



- **Iron yoke**
  - Material: ARMCO (brittle at 1.9 K!)
  - $R_{p0.2}$ (RT): 230 MPa
  - R_m (1.9 K): 970 MPa
  - K_{IC} (1.9 K): 25-29 MPa·m$^{0.5}$
  - See [1] for a full characterization of the material



- **Welds** (see talk from Herve Prin)

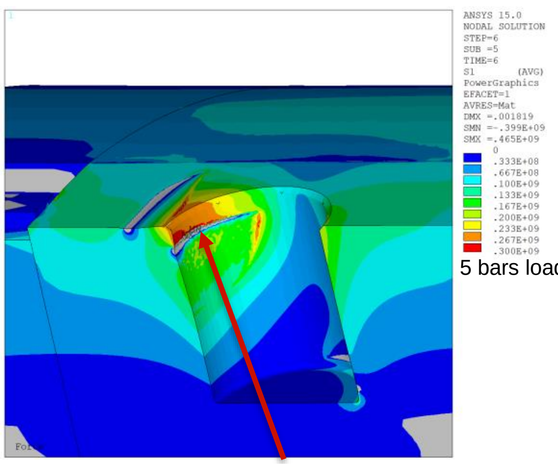
[1] I. A. Santillana et al., "Mechanical Characterization of Low-Carbon Steels for High-Field Accelerator Magnets: Application to Nb_3Sn Low-β Quadrupole MQXF," in IEEE Transactions on Applied Superconductivity, vol. 32, no. 6, pp. 1-7, Sept. 2022, Art no. 4100507, DOI: 10.1109/TASC.2022.3149853. D

Jose Ferradas Troitino

Yoke, cryogenic temperature BP2&BP3 cases

- For the existing magnets, the yoke will be re-machined after magnet assembly
  - Central lamination will be 45 mm instead of 91.4 mm (stand alone yoke cannot hold the full load, longitudinal stiffness provided by the yoke laminations needed)
  - Flattening of surfaces needed to avoid stress concentration singularities. Nevertheless, S1 ≈ 700 MPa (3 times the expected S1 for the series magnets); SEQV ≈ 1200 MPa (20 % higher than the limit in traction; assessment of the limit of the iron in compression on-going)
    - As a back up, the depth of the pin can be increased to limit the bending of the pin

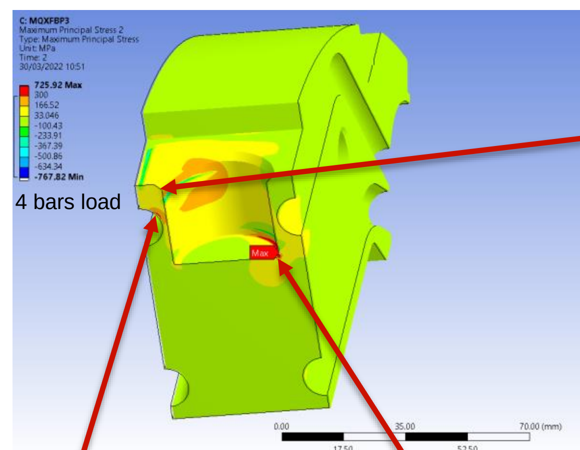
Series magnets configuration



5 bars load

First principal stress (S1)
Peak ~ 250 MPa (4 bars)

MQXFBP2 & BP3 configuration



200 MPa S1 (4 bars)

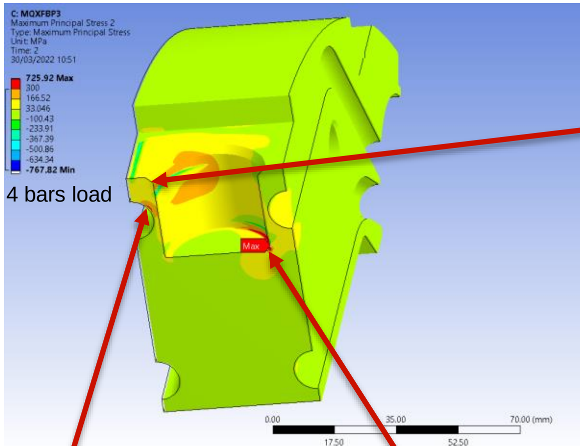
Due to the presence of the cooling hole channel, 360 MPa S1 (4 bars)

Due to the larger bending of the pin, 700 MPa S1 (4 bars)

*Thermal contraction the pin assumed to be as iron instead of stainless steel, to assure contact of the pin to the yoke after cool down
* ANSYS color maps for 120 kN (5 bars), with a linear elastic model; results for assessment of the maximum stress scaled to 4 bars (96 kN)

Jose Ferradas Troitino, Giorgio Vallone

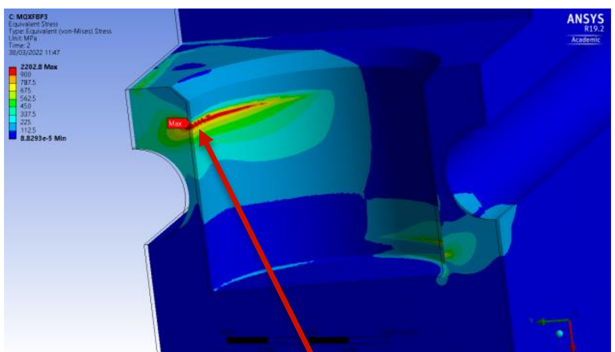
Yoke, cryogenic temperature BP2&BP3 cases



200 MPa S1 (4 bars)

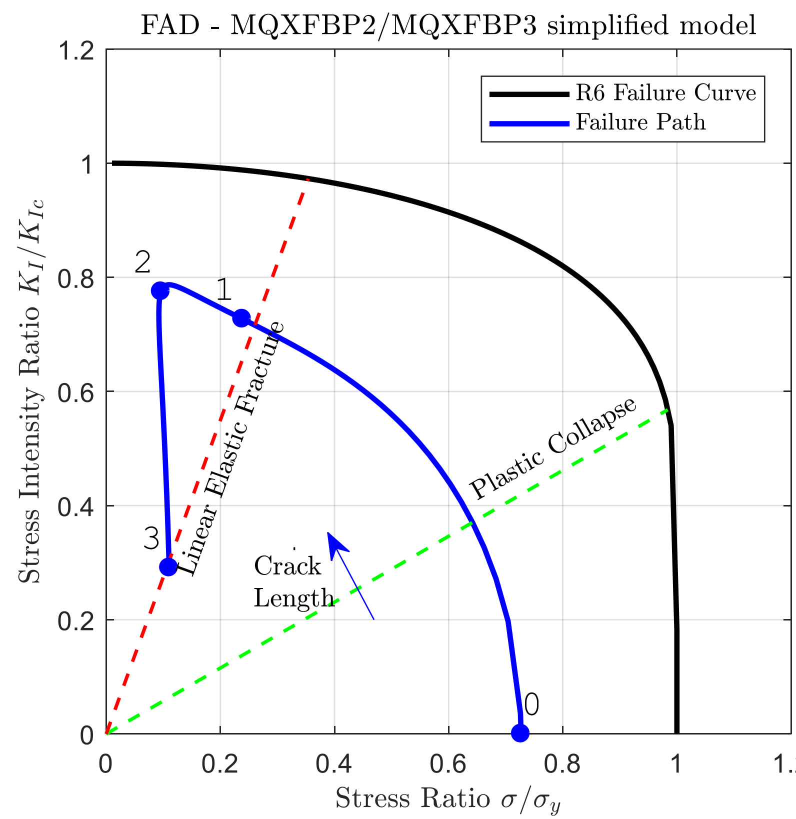
Due to the presence of the cooling hole channel, 360 MPa S1 (4 bars)

Due to the larger bending of the pin 700 MPa S1 (4 bars)



Due to the larger bending of the pin 1200 MPa SEQV (4 bars)

- Assuming that the stress along the crack length is equal to the peak stress, 700 MPa traction stress is not acceptable (see table in slide 13). FAD accounting for the actual stress profile along the most likely crack propagation path shows that the design has sufficient margin
- The VM stress, mainly compressive, is very locally above R_m (traction tests)



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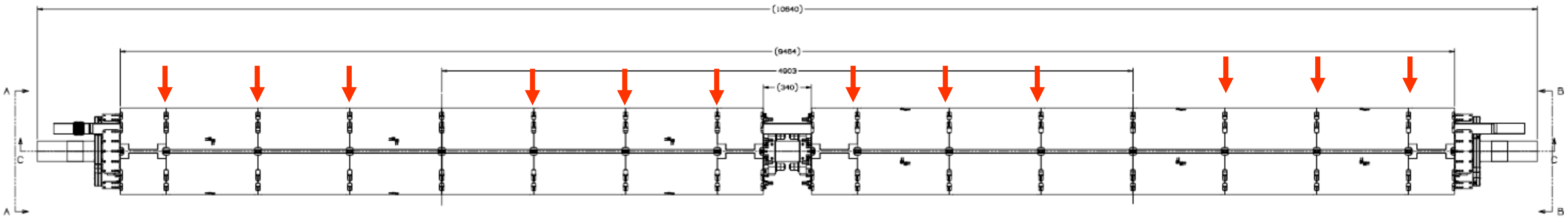
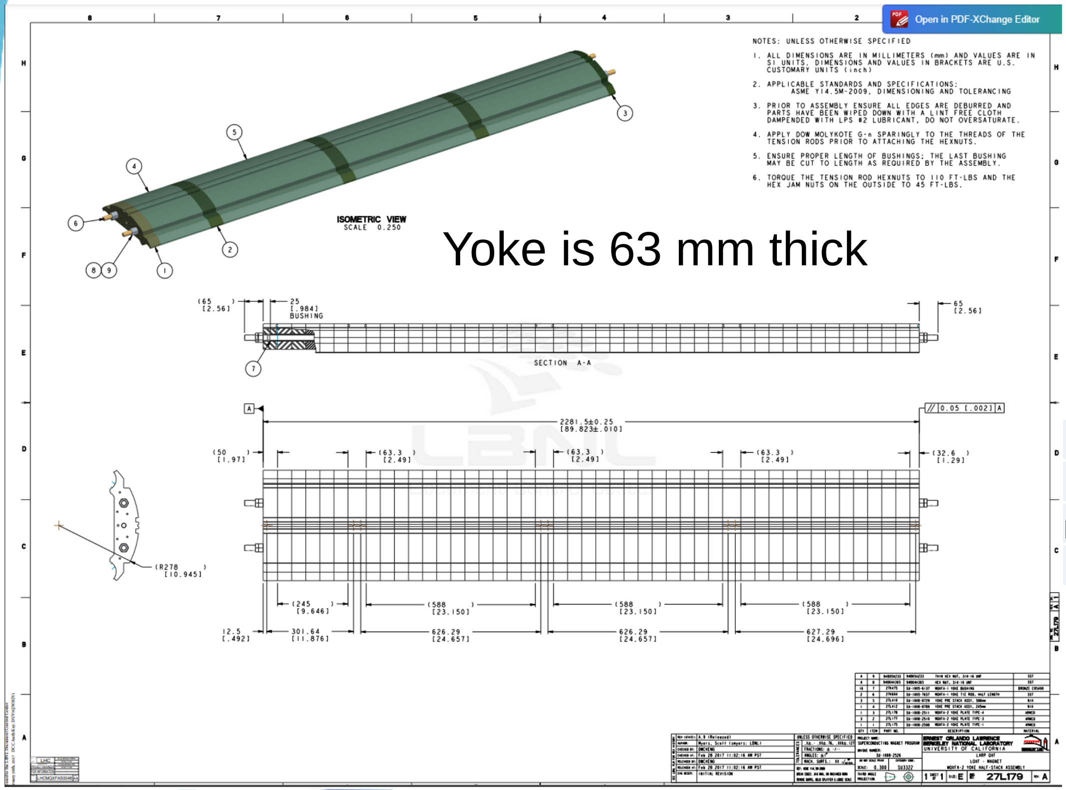
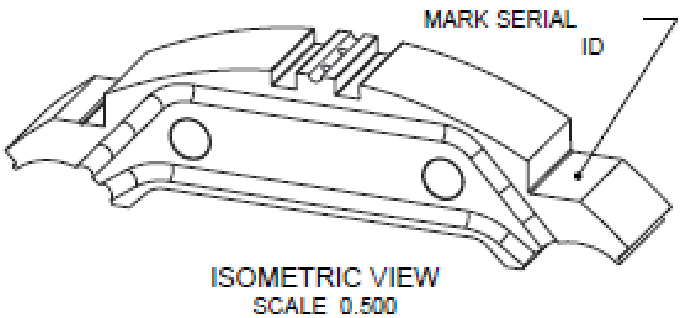
Implementing "MQXFBP" approach in MQXFA magnets







MQXFA-2 YOKE PLATE TYPE-1	LHCMQXFAS0044
MQXFA-2 YOKE PLATE TYPE-2	LHCMQXFAS0045
MQXFA-2 YOKE PLATE TYPE-3	**LHCMQXFAS0046**
MQXFA-2 YOKE PLATE TYPE-4	LHCMQXFAS0047

https://edms.cern.ch/ui/file/2264829/AA/lhcmqxfas0048-vAA.pdf

Penelope Matilde Quassolo

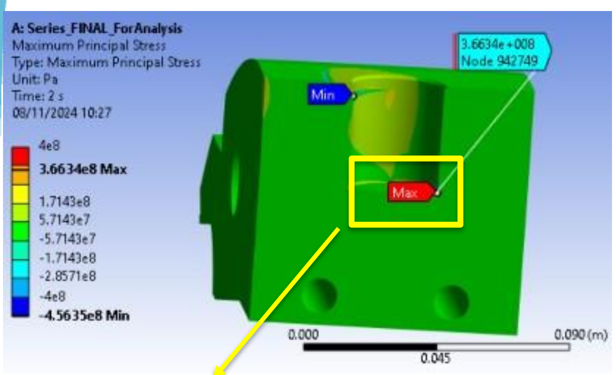
Comparing MQXFB/MQXFBP/MQXFA cases at cold

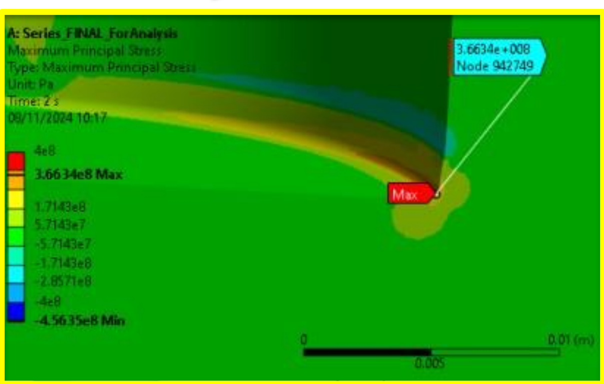
	MQXFB	MQXFBP	MQXFA
Width of the central lamination, mm	91.4	45	63
Max. load warm, kN	55 (0.5g)	55 (0.5g)	32 (0.5g)
Max. load at cold, kN	96 (4 bar)	96 (4 bar)	62 (2.5 bar)
Peak S1 stress, MPa	366	866	379

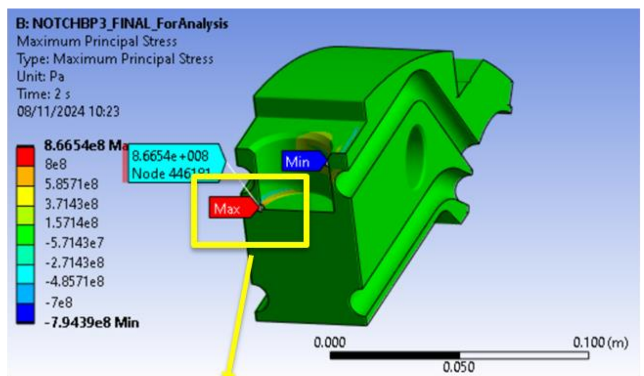
MQXFB Series magnets configuration

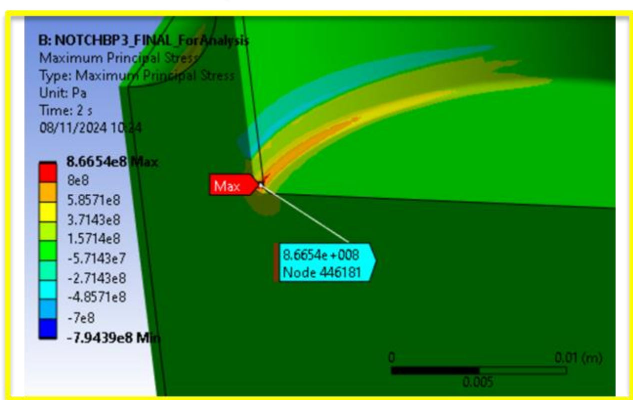
MQXFBP2 & BP3 configuration *(different scale)*

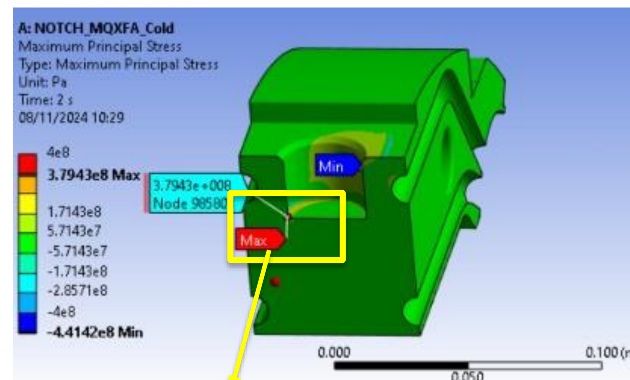
MQXFA configuration

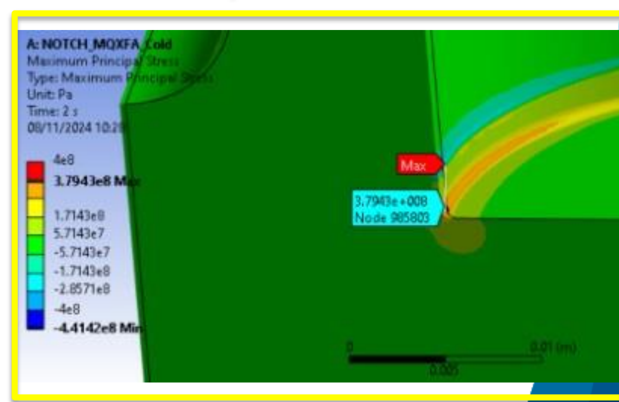






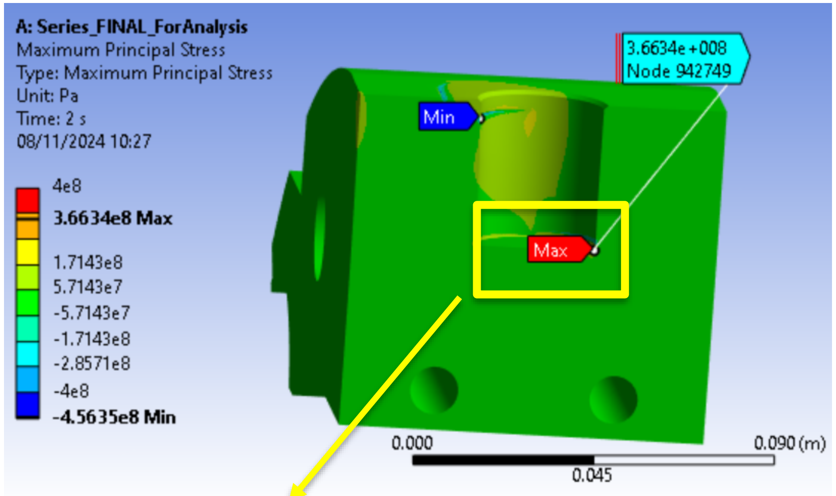


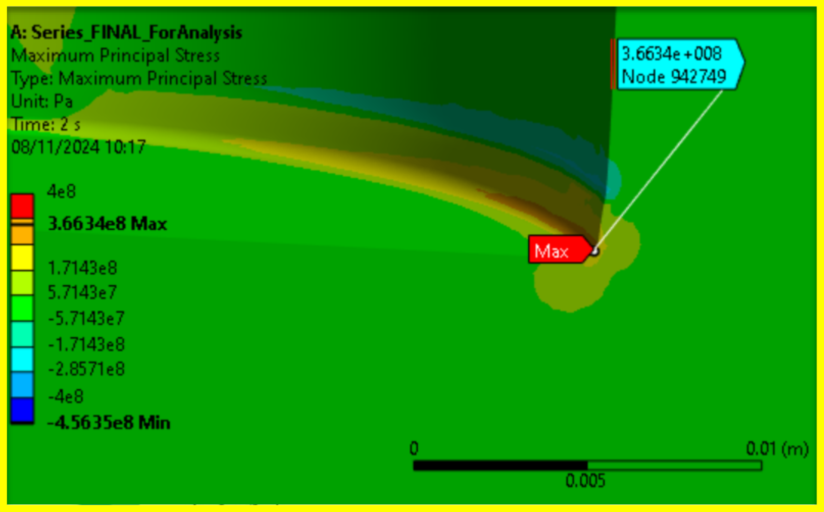




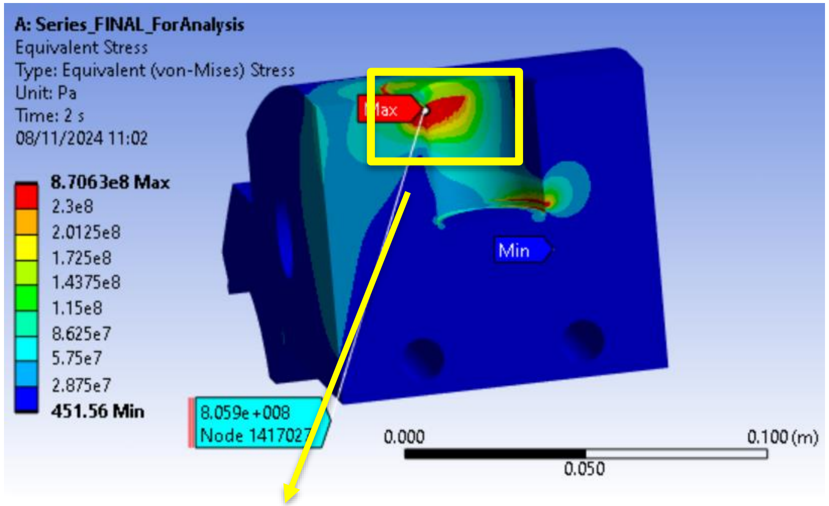
MQXFB results at cold

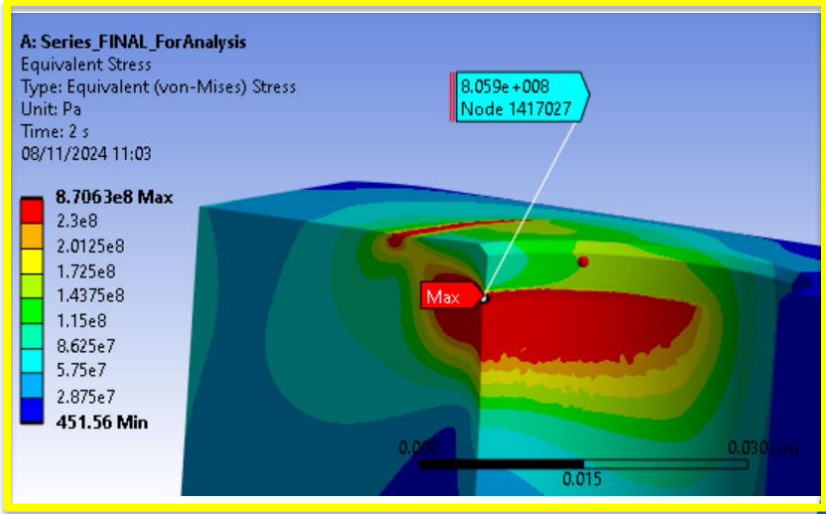
S1





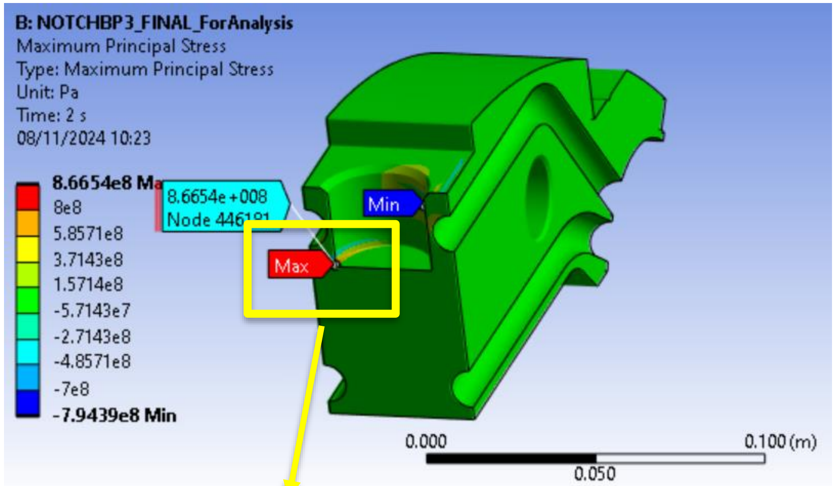
Eqv stress

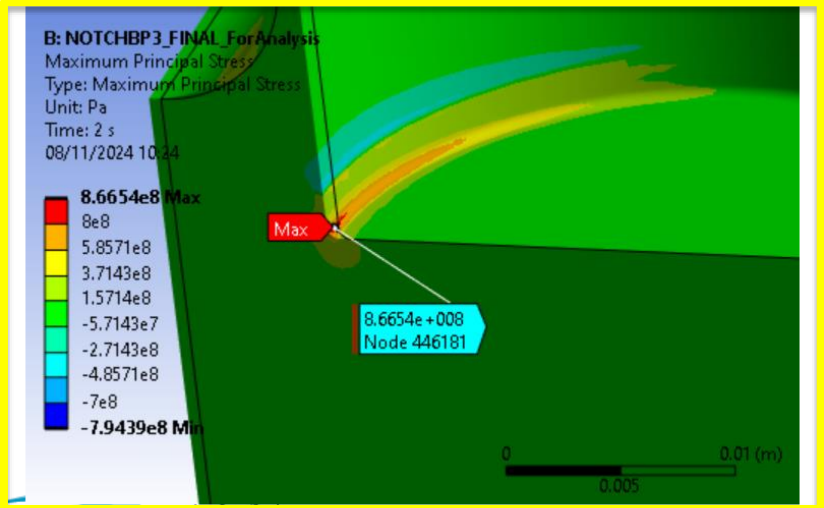




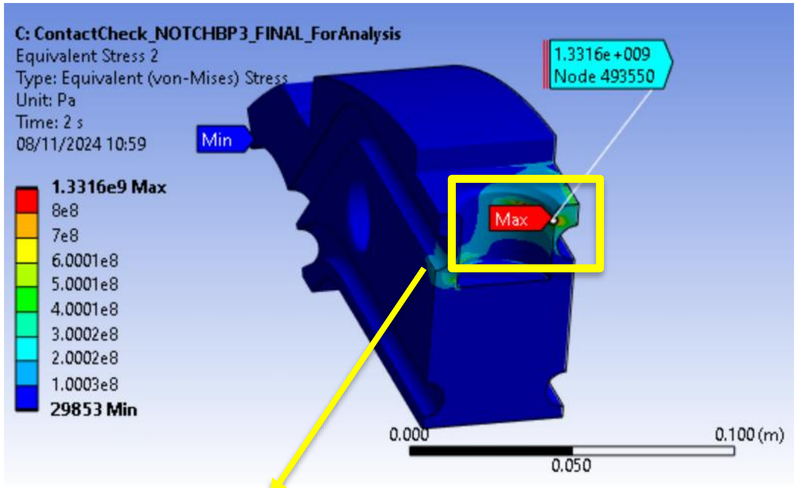
MQXFBP results at cold

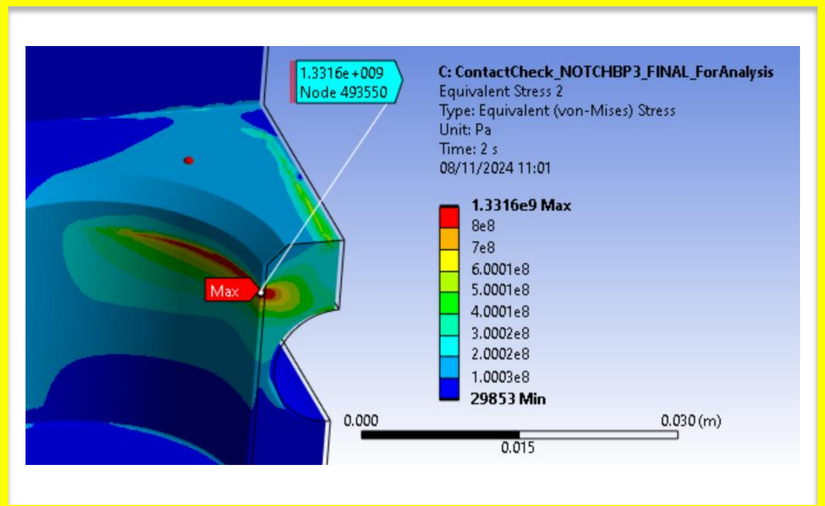
_S1_





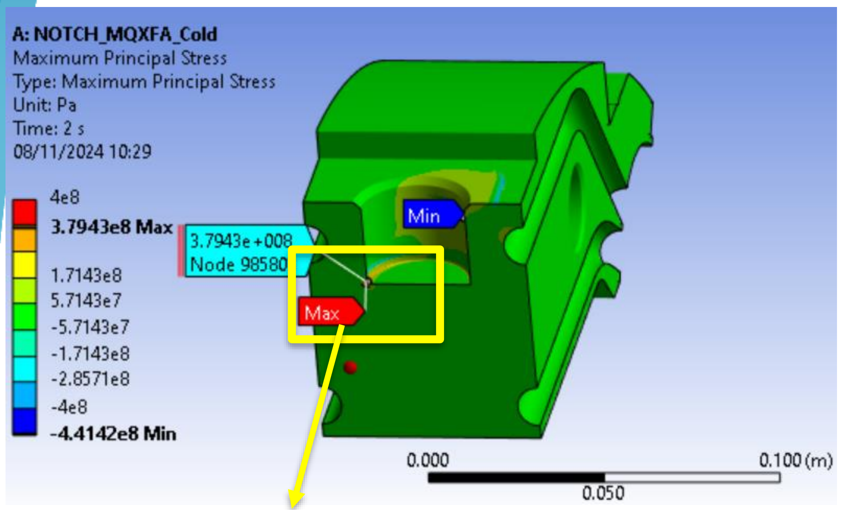
Eqv stress

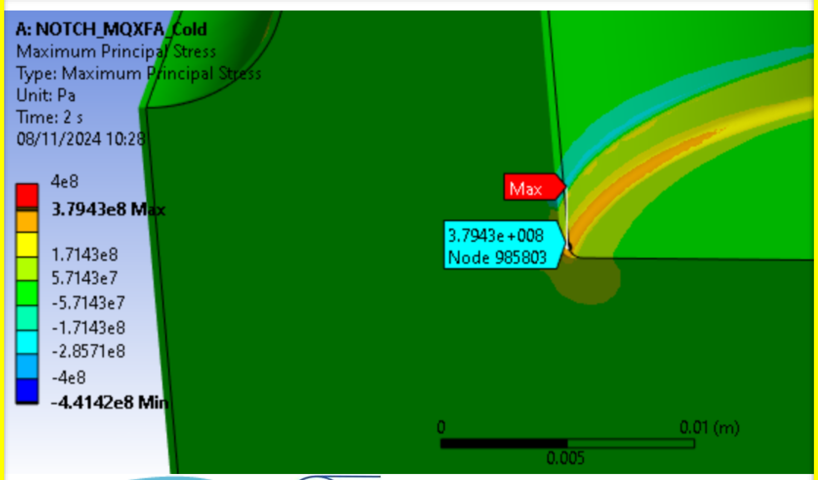




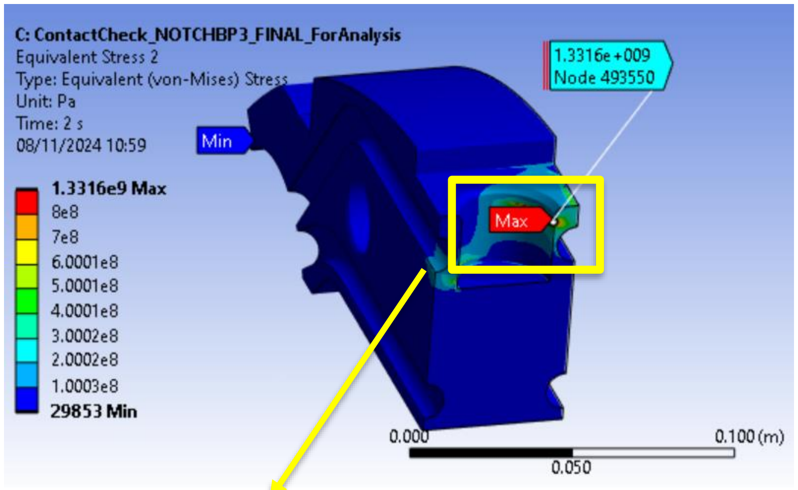
MQXFA results at cold

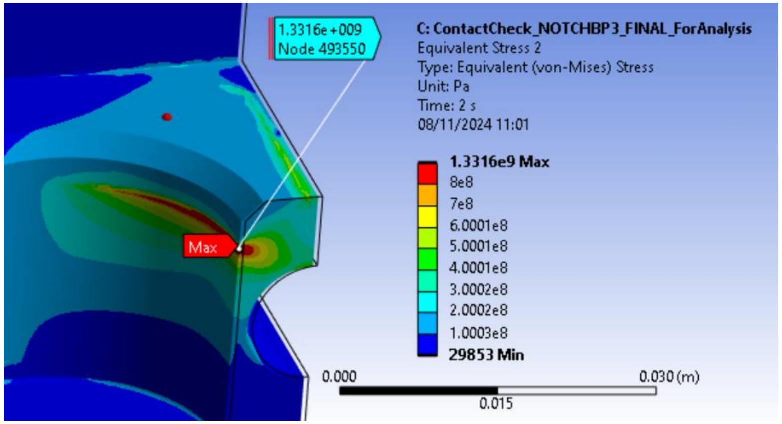
S1





Eqv stress





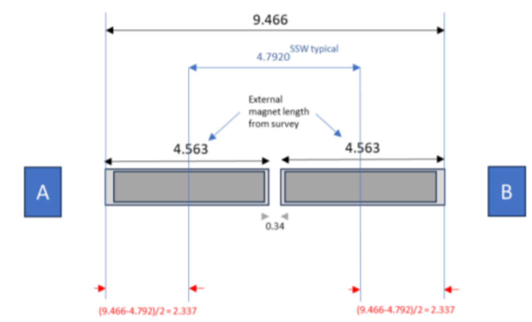
HiLumi HL-LHC PROJECT

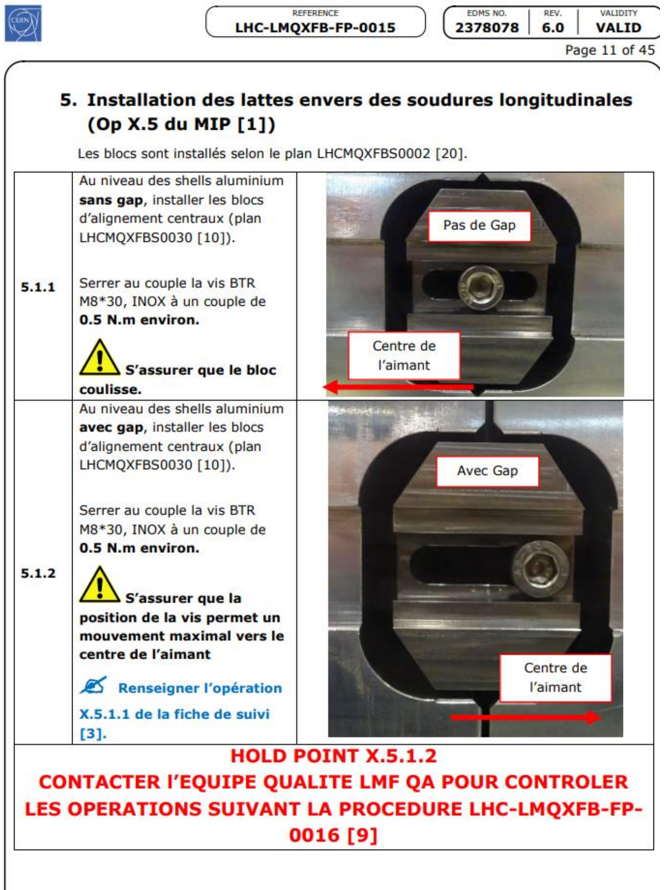
CERN

One cold mass, two fixed points…

- A drawback with respect to MQXFB is that we will have two fixed points, the stainless steel will try to move the two magnets towards the middle, everything should move with the SS dl/L so should be ok, but we can have some ‘additional’ force in the pin… (4.792 m * 3 mm/m = 14.4 mm; measured shrinkage 17 mm (i.e., dl/l = 3.55 mm/m)
- Nevertheless, AUP is having two fixed points, one per magnet, so it should not be critical

Nominally, assuming magnetic lengths are similarly centered in mechanical lengths





REFERENCE	EDMS NO.	REV.	VALIDITY
LHC-LMQXFB-FP-0015	2378078	6.0	VALID

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5. Installation des lattes envers des soudures longitudinales (Op X.5 du MIP [1])

Les blocs sont installés selon le plan LHCMQXFBS0002 [20].

5.1.1	Au niveau des shells aluminium **sans gap**, installer les blocs d’alignement centraux (plan LHCMQXFBS0030 [10]). Serrer au couple la vis BTR M8*30, INOX à un couple de **0.5 N.m environ.** **S’assurer que le bloc coulisse.**	Pas de Gap Centre de l’aimant
5.1.2	Au niveau des shells aluminium **avec gap**, installer les blocs d’alignement centraux (plan LHCMQXFBS0030 [10]). Serrer au couple la vis BTR M8*30, INOX à un couple de **0.5 N.m environ.** **S’assurer que la position de la vis permet un mouvement maximal vers le centre de l’aimant** **Renseigner l’opération X.5.1.1 de la fiche de suivi [3].**	Avec Gap Centre de l’aimant

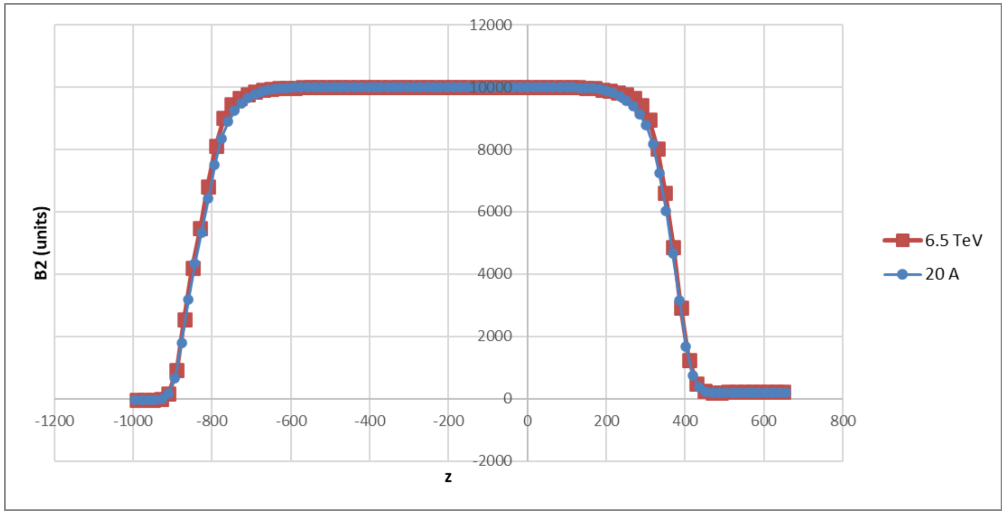
HOLD POINT X.5.1.2
CONTACTER L’EQUIPE QUALITE LMF QA POUR CONTROLER LES OPERATIONS SUIVANT LA PROCEDURE LHC-LMQXFB-FP-0016 [9]

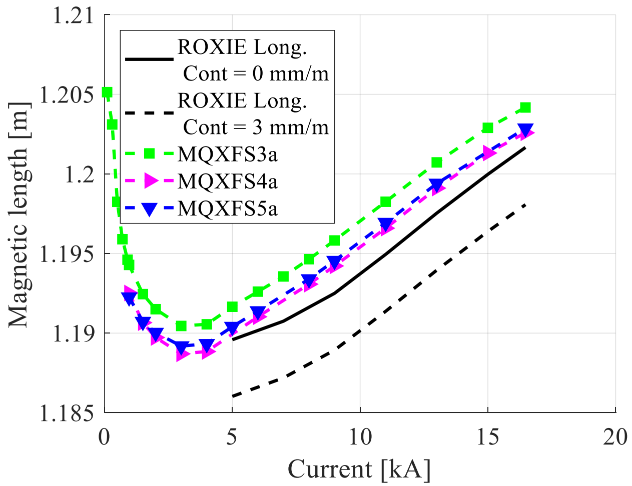
Magnetic center separation, m

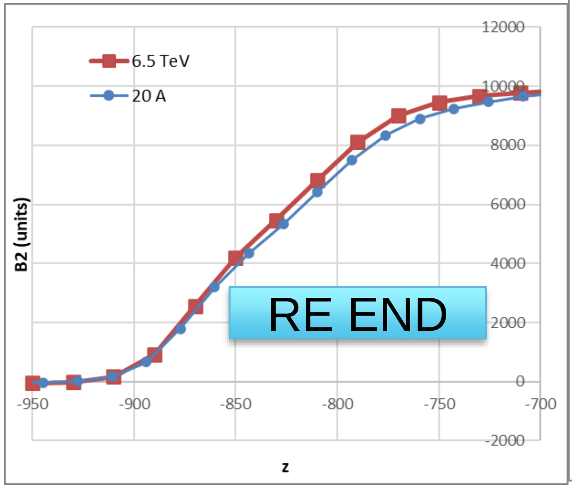
	Warm	Cold, I_{nom}
CM01 (A04/A03)	4.7895	4.7721
CM02 (A05/A06)	4.7930	4.776
CM03 (A11/A10)	4.7933	
CM04 (A14b/A08b)	4.7928	
CM05 (A15/A07b)	4.7895	

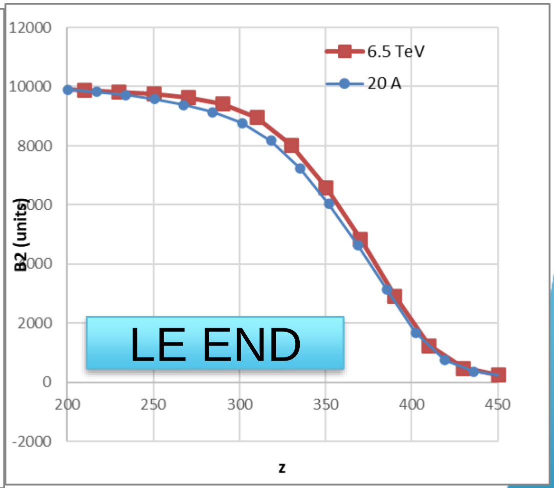
Can the 3D iron saturation effect explain the difference in magnetic centers?

- Not really…
  - There is an iron saturation effect in the magnetic length (magnetic length at Inom + 12 mm), but it is symmetric (only 0.2 mm shift on the axial magnetic center)









Outline

- Requirements
- Welding parameters and feedback from construction
- Options for longitudinal welding:
  - Option 1: AUP ‘MQXFA’ procedure
  - Option 2: CERN ‘MQXFB’ procedure
  - Option 3: CERN ‘modified’ procedure (see slides from Herve)
- **Conclusions**

Conclusions

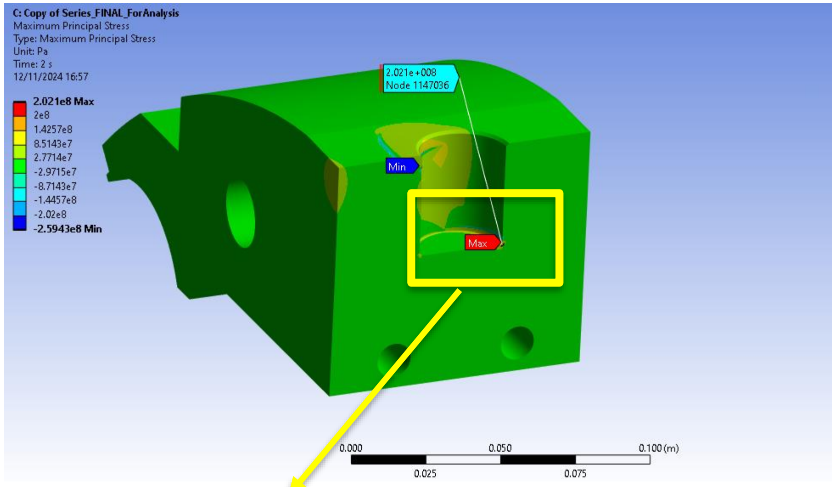
- Longitudinal welding using AUP approach (shims) requires significant development on the welding process (different welding gap/shrinkage…)
  - However, one might argue that the bolts in the central yoke are enough to keep the loads at warm, and that we will also have some help form friction: we could take AUP blocks but CERN welding (without shims)
- No apparent showstopper on applying 'MQXFB' procedure, situation will be close to MQXFB series configuration. However, there will be two fixed points in one cold mass, and the pin will not be in the mechanical center of the magnet.
- As an alternative, we could have only one fixed point in between the two magnets, joining mechanically the yokes of both magnets (see slides from Herve)

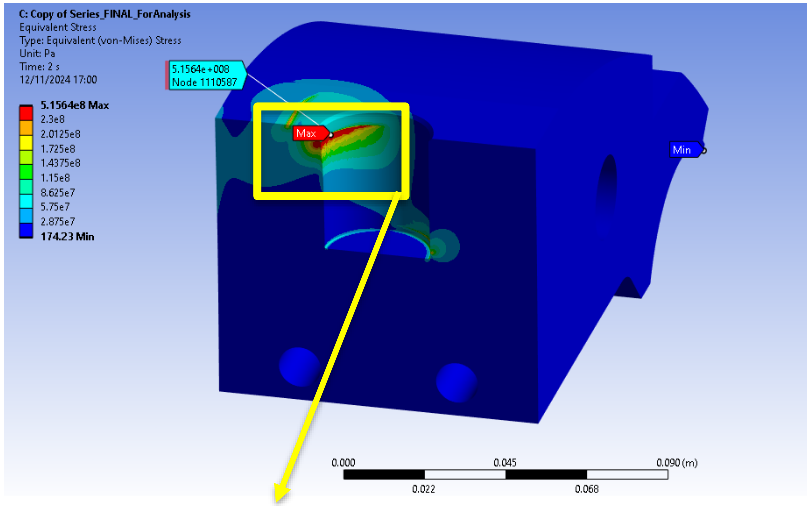
Additional slides

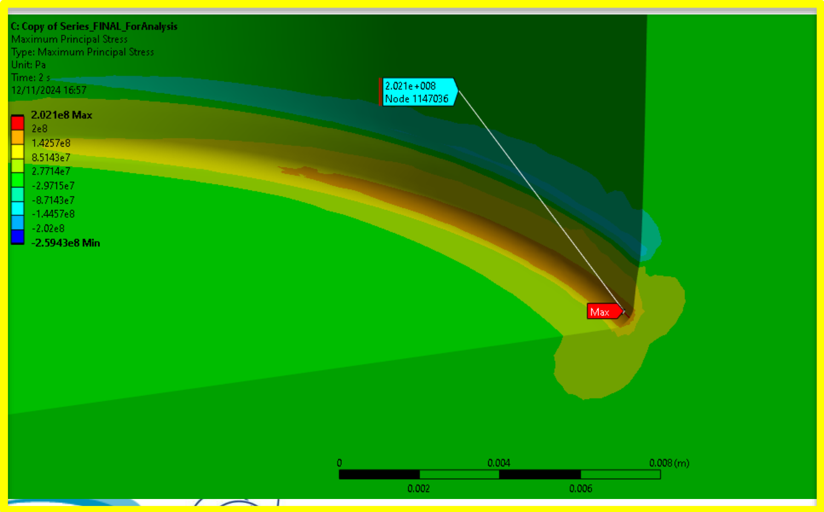
MQXFB results at warm

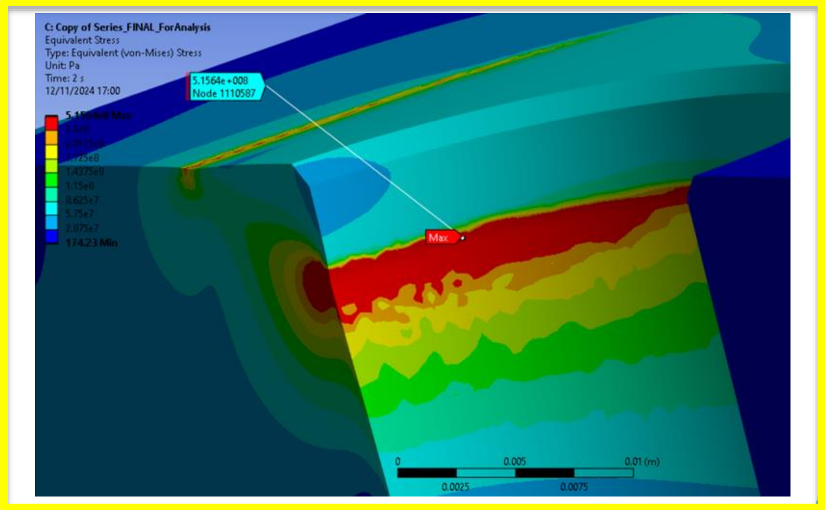
S1

Eqv stress





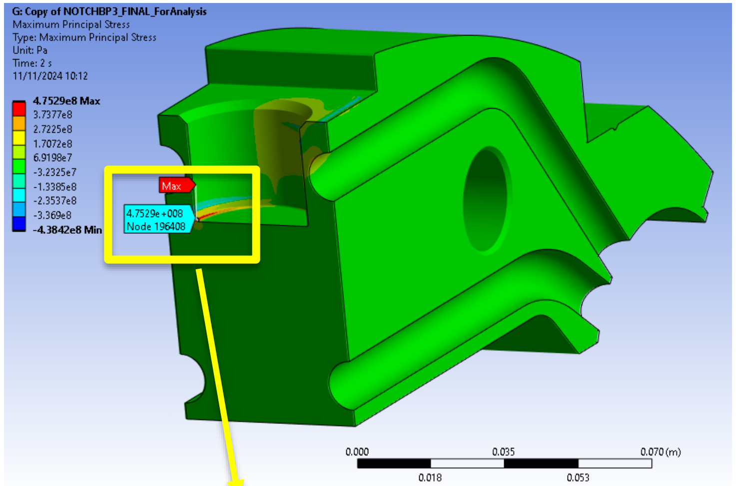


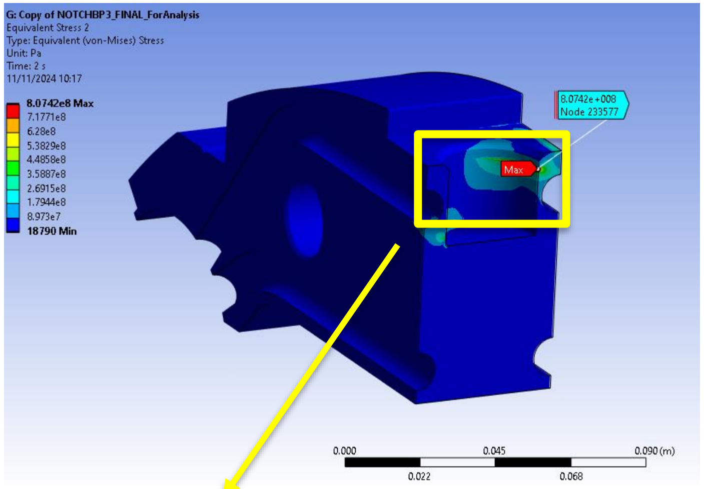


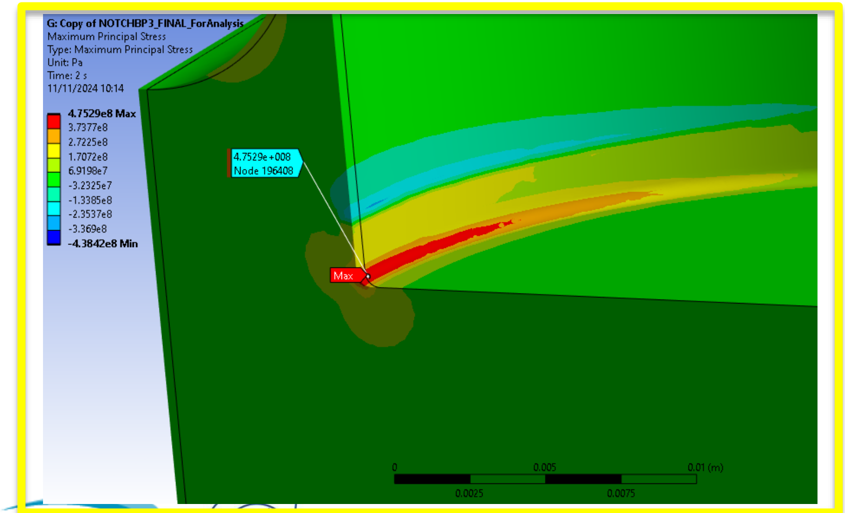
MQXFBP results at warm

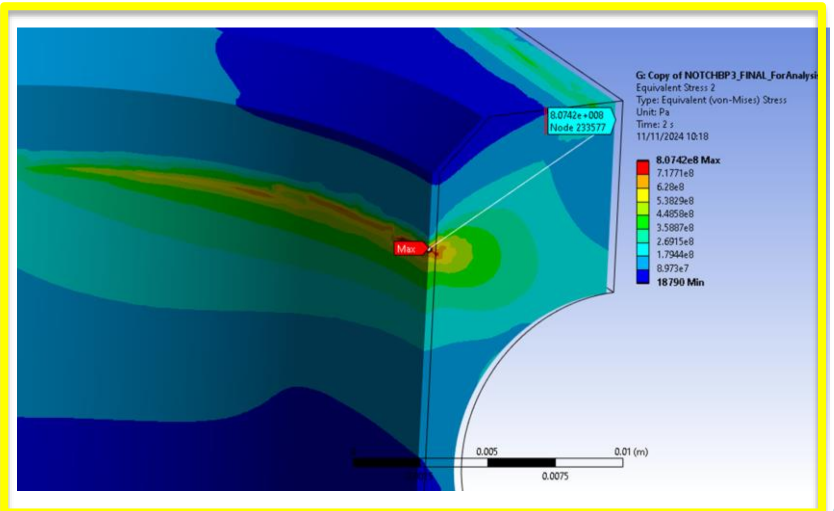
S1

Eqv stress





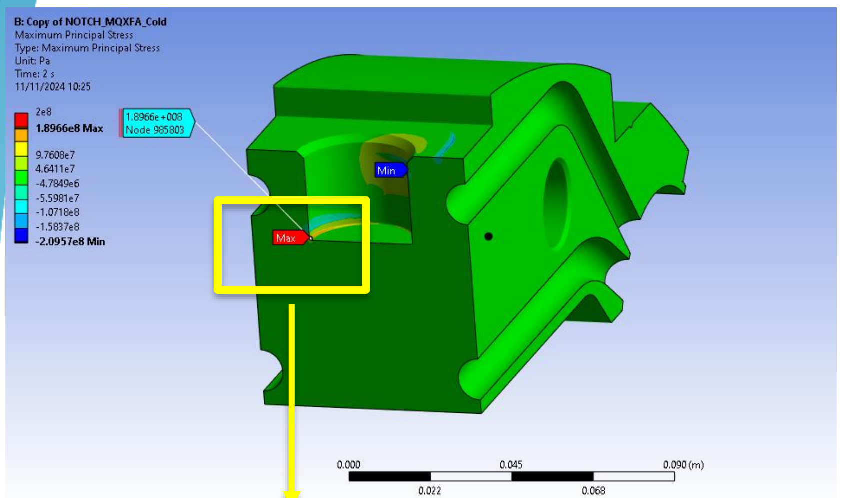


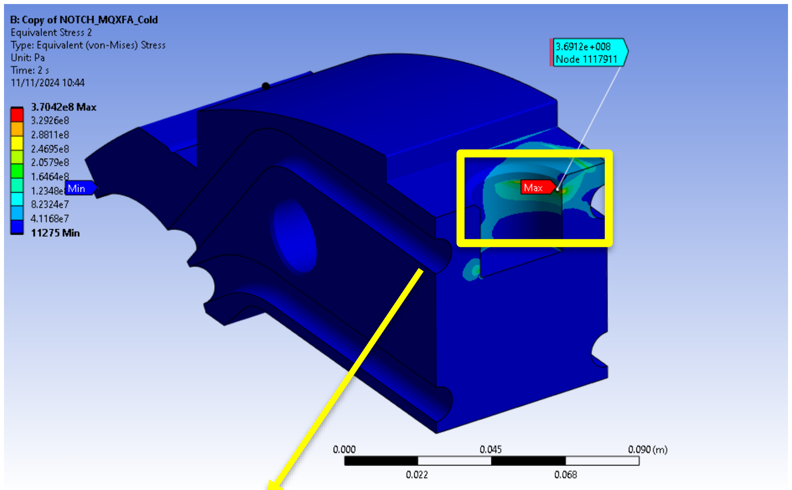


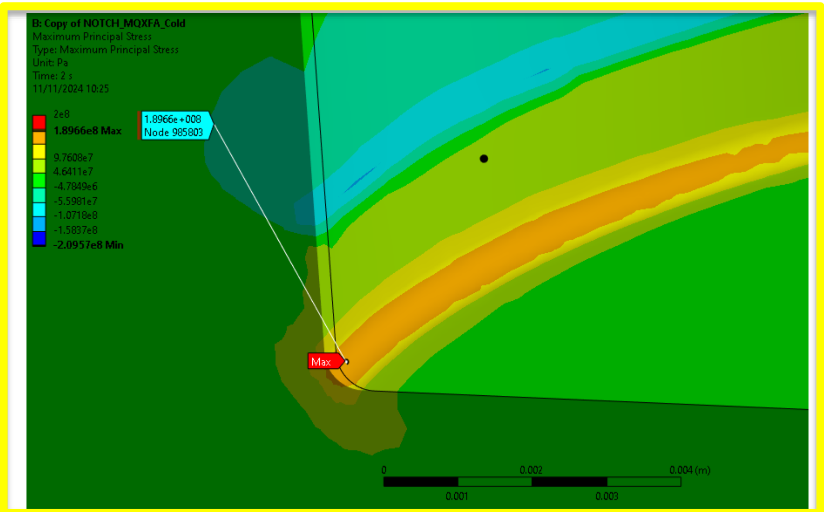
MQXFA results at warm

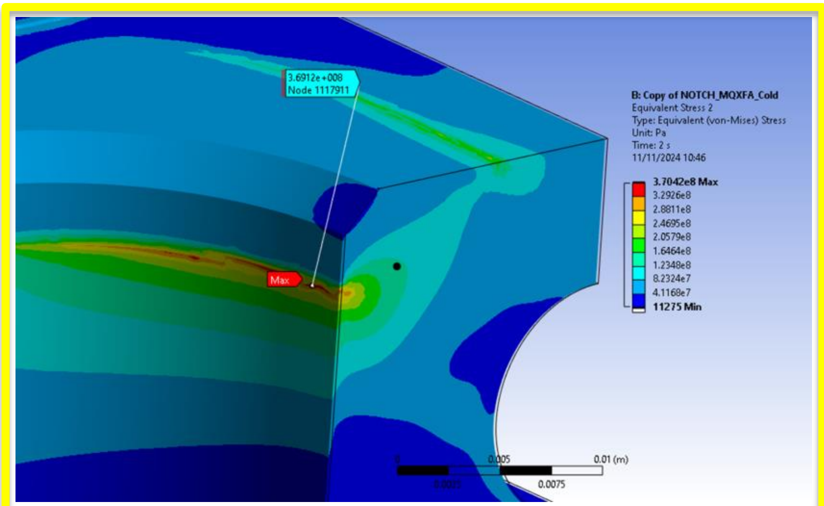
S1

Eqv stress

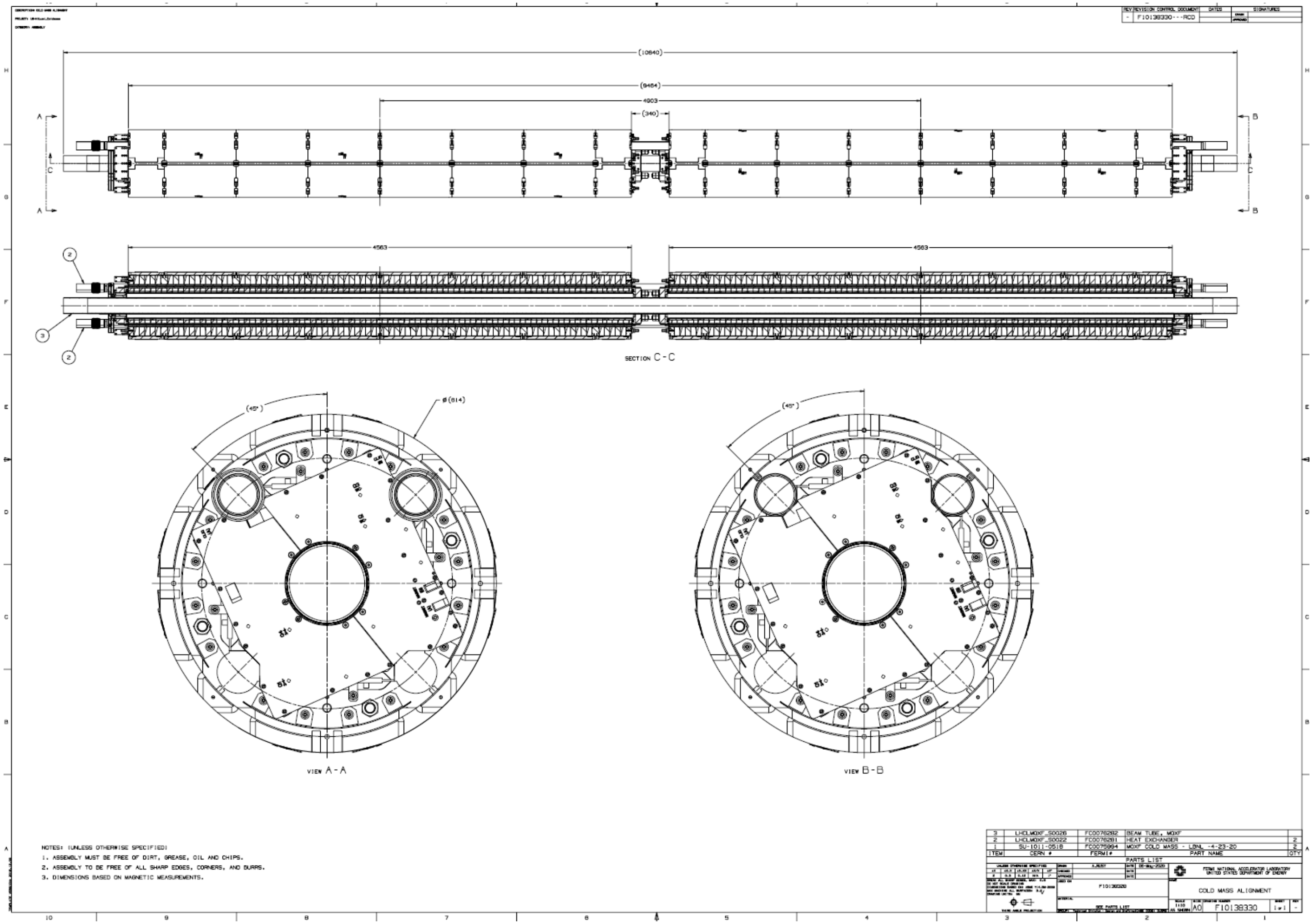




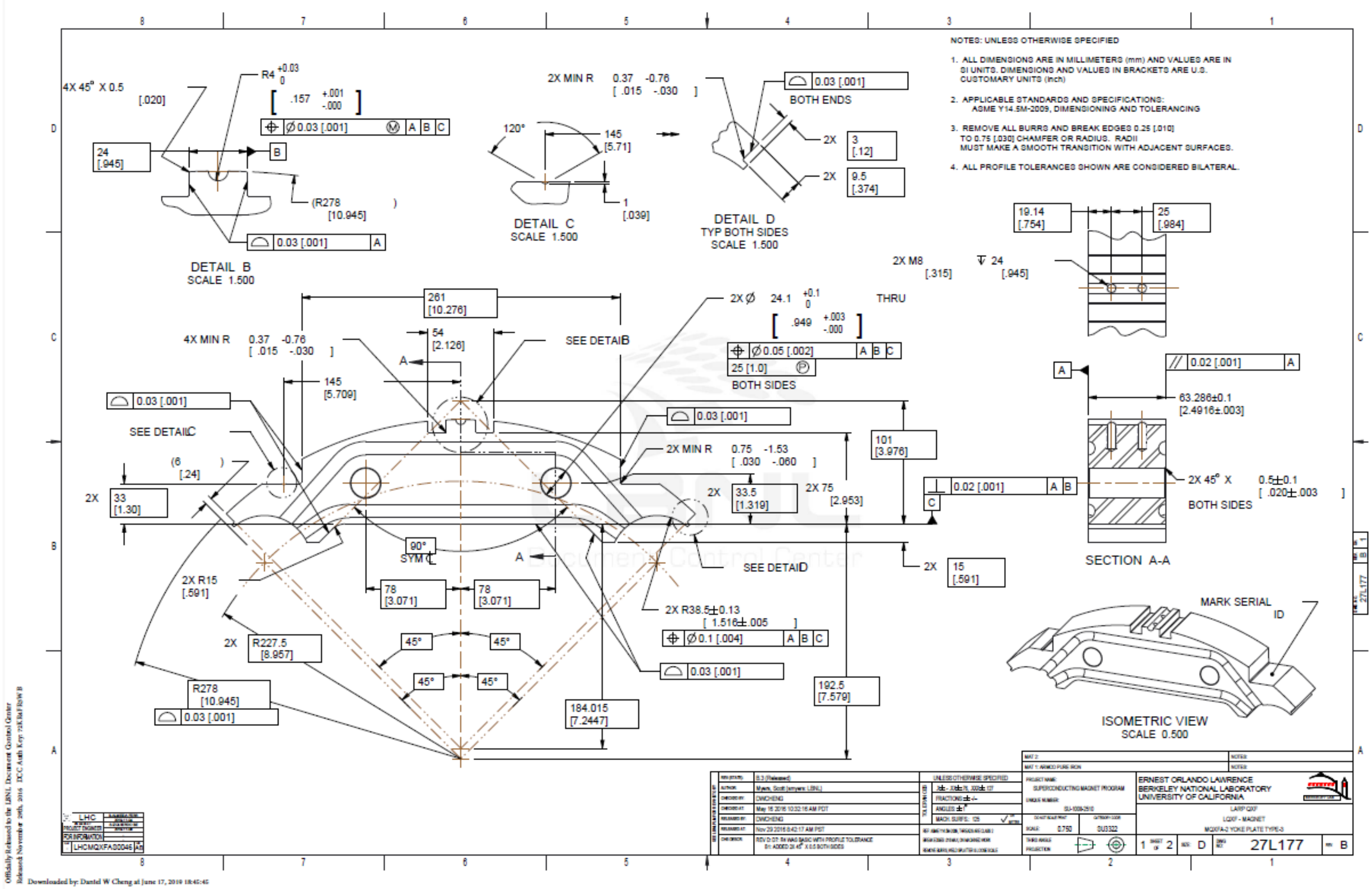




Implementing “MQXFBP” approach in MQXFA magnets



https://edms.cern.ch/document/2264827



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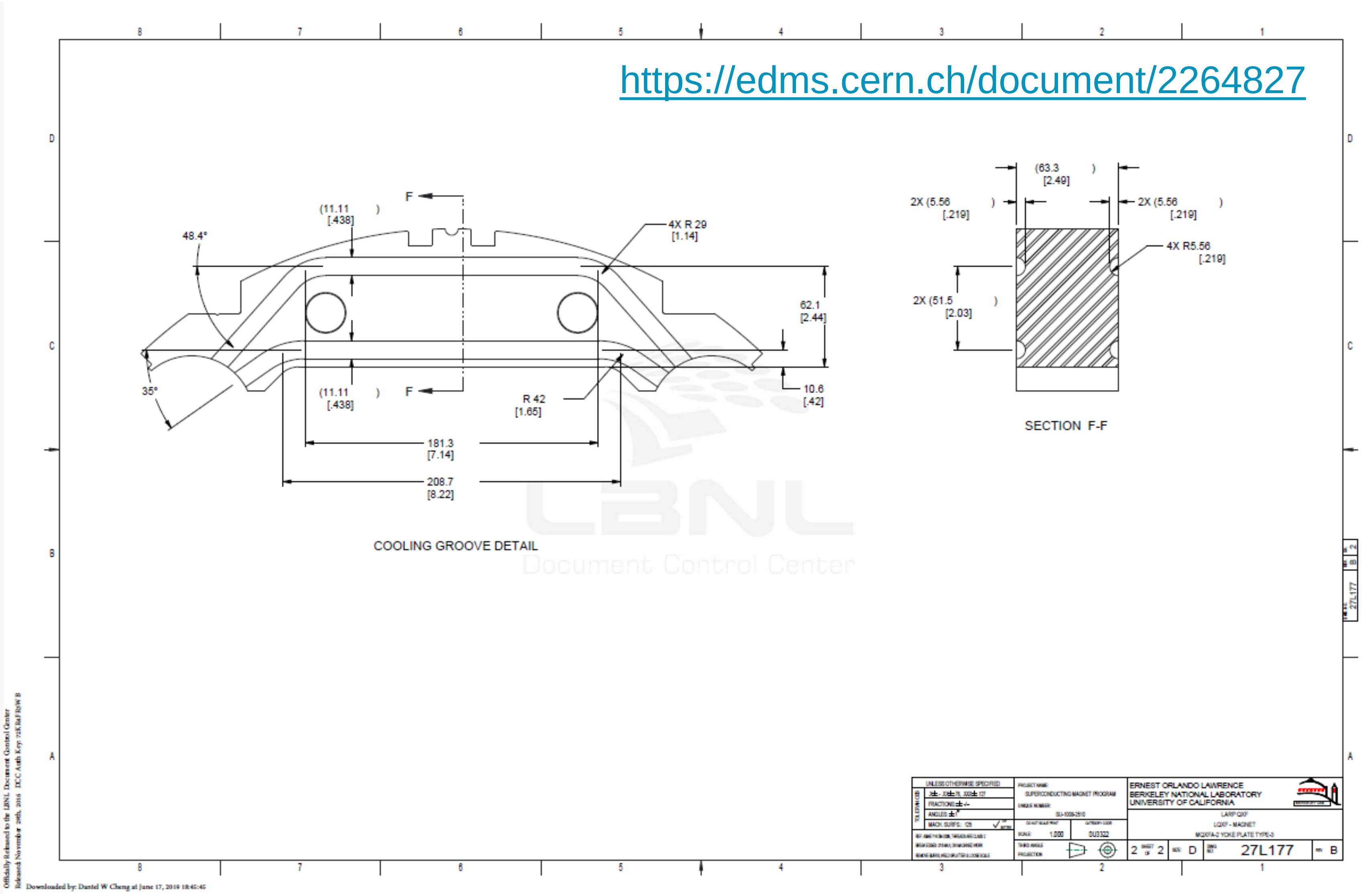
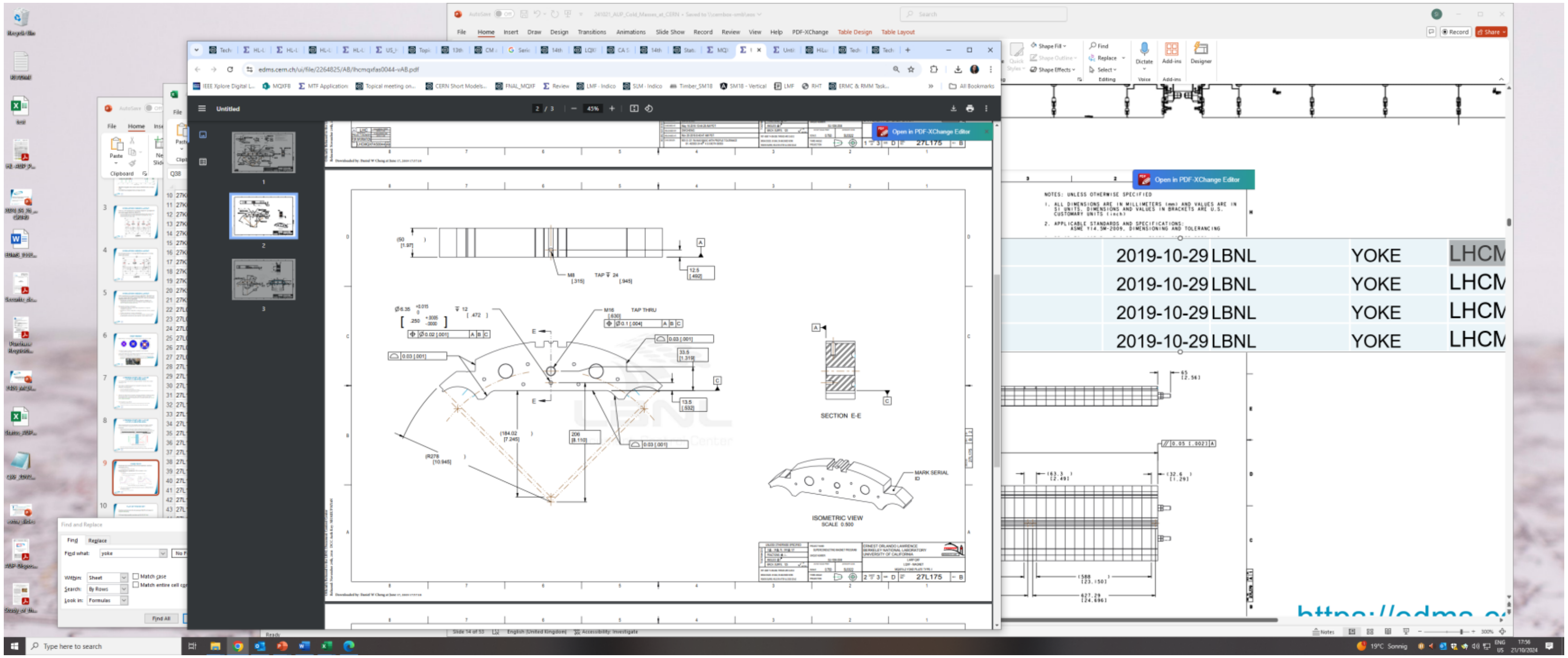
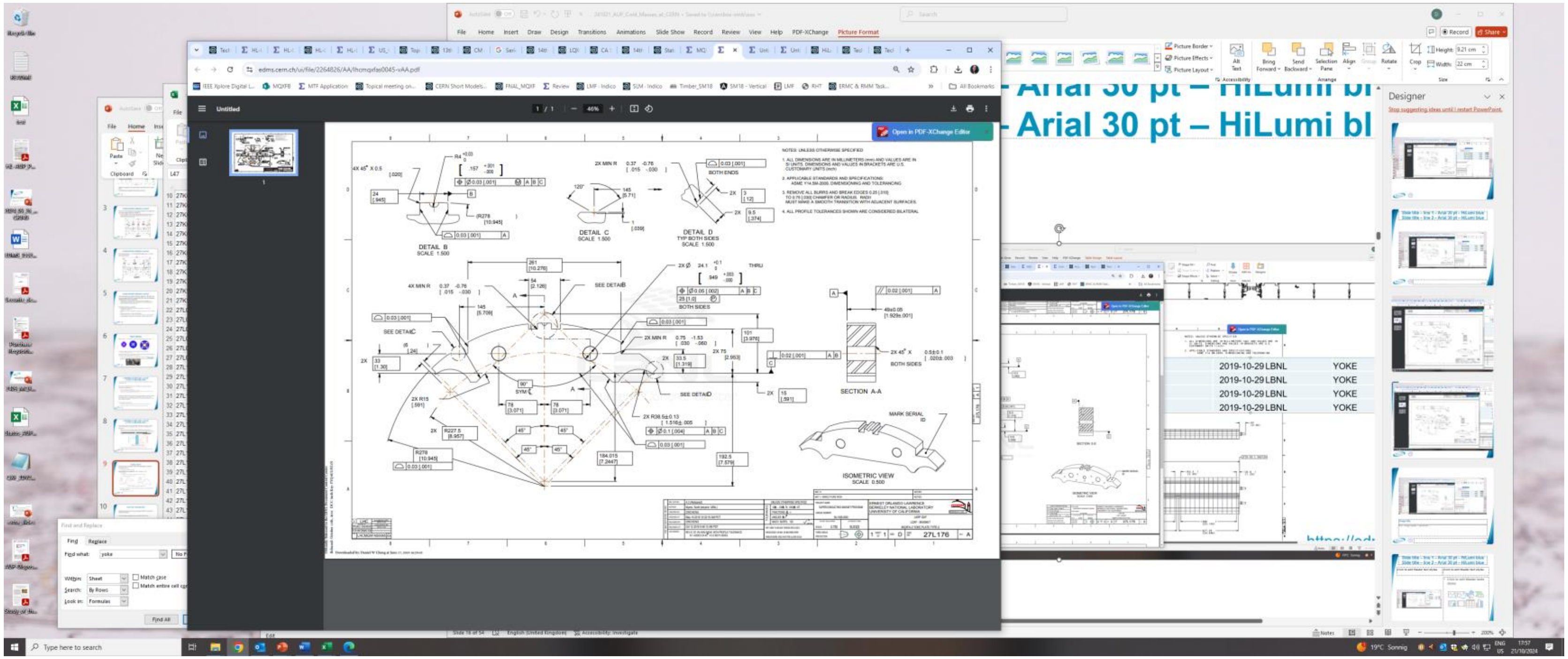


Other yokes…

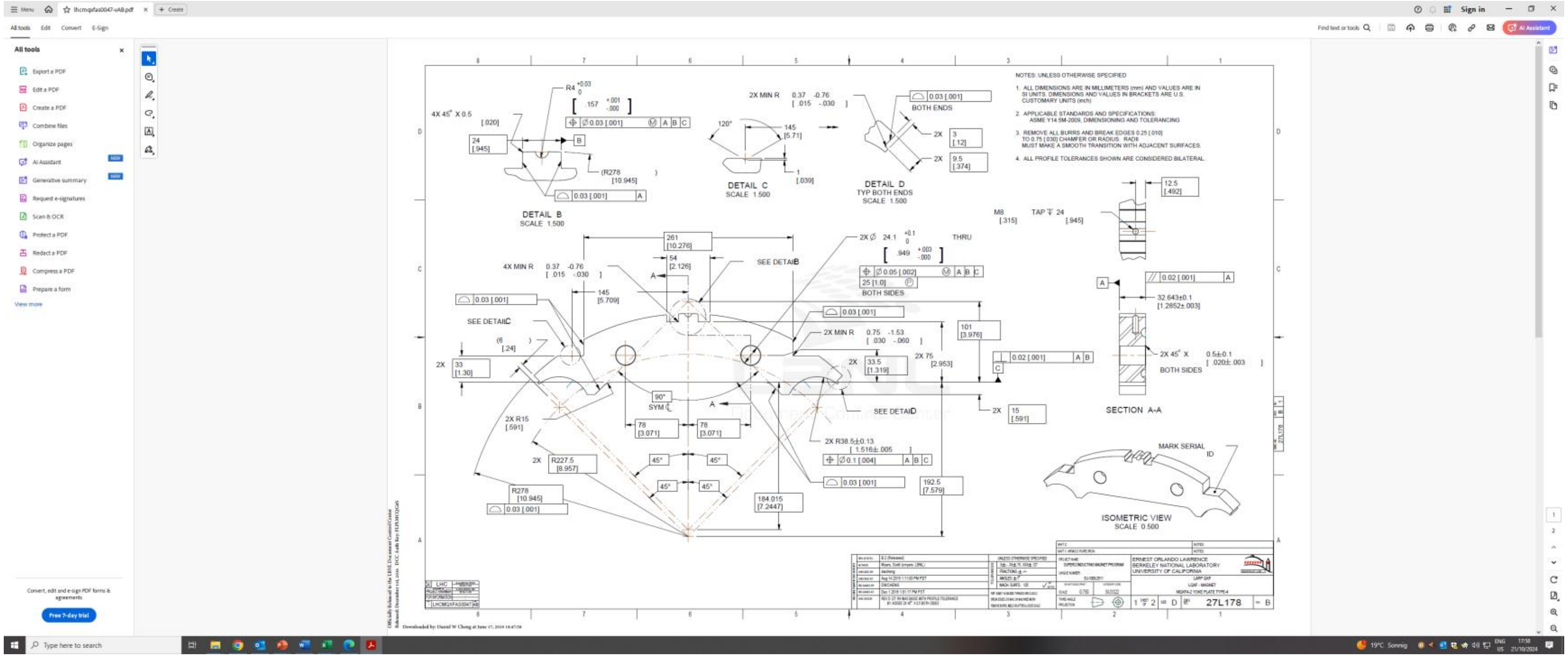
MQXFA-2 YOKE PLATE TYPE-1	2019-10-29	LBNL	YOKE	LHCMQXFAS0044
MQXFA-2 YOKE PLATE TYPE-2	2019-10-29	LBNL	YOKE	LHCMQXFAS0045
MQXFA-2 YOKE PLATE TYPE-3	2019-10-29	LBNL	YOKE	LHCMQXFAS0046
MQXFA-2 YOKE PLATE TYPE-4	2019-10-29	LBNL	YOKE	LHCMQXFAS0047



Other yokes…


- Arial 30 pt – HiLumi bl
Designer
Open in PDF-XChange Editor
2019-10-29 LBNL YOKE
2019-10-29 LBNL YOKE
2019-10-29 LBNL YOKE
2019-10-29 LBNL YOKE

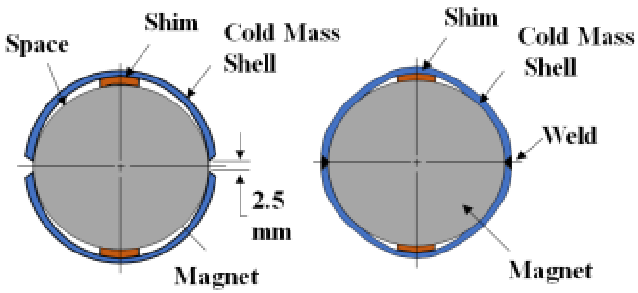
Other yokes…

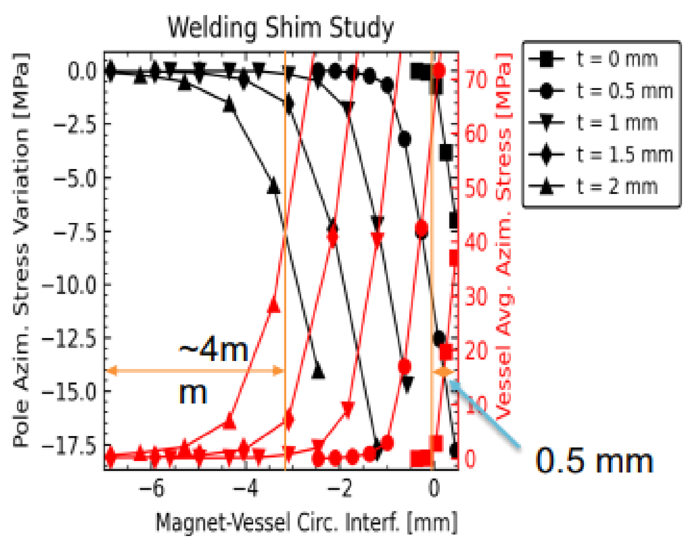


DETAIL B
SCALE 1.500
DETAIL C
SCALE 1.500
DETAIL D
TYP BOTH ENDS
SCALE 1.500
SECTION A-A
ISOMETRIC VIEW
SCALE 0.500
MARK SERIAL ID
SEE DETAIL C
SEE DETAIL B
SEE DETAIL D
BOTH ENDS
BOTH SIDES
27L178

MQXFA approach

Applied **forces**:
Transportation: 135 kN
Quench/Cryogenic operation:
61.8 kN (2.5 bar pressure wave)
Allowable **pole stress** increase:
-3.2 MPa on the average
-9.6 MPa at any location





- Without shims the 0.5 mm change in the interference generates ~7 MPa coil stress (~40 MPa SS shell stress)
- With 2 mm shim the same stress change requires ~ 4 mm interference change
- This drastically changes the requirement on tolerances

US HL-LHC AUP

[13th HL-LHC Collaboration meeting]

References

- Technical Review of MQXFB Cold Mass: https://indico.cern.ch/event/1142636/
- Structural Analysis of WP3 Q2 LMQXFB Triplet Cold Masses https://edms.cern.ch/document/2363726
- HL-LHC-AUP Engineering Note for Q1/Q3 cold mass shell https://edms.cern.ch/document/2659173
- HL-LHC: Decision Management Differential longitudinal pressures across the HL-LHC Inner Triplet Cold Masses https://edms.cern.ch/document/2675955
- CA Series Production Readiness Review (6-September 8, 2023) · INDICO-FNAL (Indico)
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