US HL-LHC Accelerator Upgrade Project

Report of the Review of the MQXFAP2 Al-Shell Issue and Lessons Learned

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1. Goal and scope

The HL-LHC AUP project is planning to start assembly of MQXFA Pre-series magnets in April2019. In fall 2018 the second MQXFA prototype (MQXFAP2) demonstrated limited performance caused by the fracture of an aluminum shell. It is mandatory for the AUP project to assure that all causes of the MQXFAP2 shell failure are understood, and that the proposed design has enough margin to prevent similar failures in future MQXFA magnets. Samples of shell material (Al-7075) have been tested at cold temperature in order to assess material properties and their dependence from different tempers: T6 samples (proposed for production), T652 samples extracted from the fractured shell, and T652 samples from other shells. Computations of peak stresses and stress intensity factors vs. fault size have been performed. AUP has developed Structural Design Criteria (SDC), and the SDC for the aluminum shells were reviewed on October 5, 2018. The reviewers are requested to assess the understanding of the MQXFAP2 issue, and the margin of the proposed design based on measured properties and implementation of the Structural Design Criteria.

2. Charge Questions

1. **Is the mechanism of the MQXFAP2 issue well understood? Is the explanation satisfactory?**

Yes the mechanism is understood. However the explanation might not be complete.

Findings

- The issues which led to the MQXFAP2 shell failure have been identified as follow:
  - Accepted non conform sharp corners in the shell cut outs inducing high stress concentrations
  - Accepted non conform 7075 temper (T652)
  - Possibly high shell stress level

Potential other elements might have aggravated the situation:

- RE shell is the first to see cold gas potentially leading to high temperature gradient in the magnet/shell and high transient stresses.
- Unfavorable tolerances in the shell (See summary statements from S. Prestemon)

2. **Is the FEM analysis adequate to understand failure mechanism and identify critical parameters?**

Mostly yes

Comments

- The recent elasto-plastic FE work by LBNL clearly shows that the shell mechanical behavior, in its operating conditions (temperatures and stresses), can be well represented/simulated by elastic analyses. Therefore, and unless new work (see next bullet) shows that current results may not be valid, linear elastic based analysis is sufficient for any additional work
- Earlier and more current modeling of the assembly and its loading sequence considers steady-state (non-transient) conditions for temperatures (and hence stresses) in the assembly based on the assumption (fact?) that the "loading" (shimming and cooling) of this system is so slow that transient conditions are non-existent or insignificant. However, the situation in the failed piece during testing may suggest the susceptibility of the design to potential thermal shock/transient conditions – at least during testing.

Recommendation

Ensure that, through simulation and/or testing, the cool down is slow enough to limit the temperature gradient and therefore the peak stress in the shell is limited to what has already been estimated through various simulations.

3. **Are the cold measurements on shells samples sufficient to assess critical material properties, their variability and dependence from Al-7075 temper?**

Conditionally yes pending upon additionally planned 7075-T6 and T652 tests.

Findings

- Additional material testing of involved alloys in the design (7075-T6 & T652 and 7175-T74) at room and minimum operating temperature have been performed.
- More tests are planned

Comments

- Given the limited test results (more being performed to provide statistically significant results and hence confidence), we believe the choice of 7075-T6 is prudent and reasonable. As an alternative, 7175-T74 can provide a good replacement for this material in case it becomes necessary (e.g. additional material testing shows unexpected results) or more economical. This material (T74) seems to provide an improvement (~5-10%) over T6 of fracture toughness, probably the most important material property for this design, for the shell at operating temperatures.

Recommendations

- At the present time, we do reserve and postpone our acceptance/recommendation for using 7075-T652 unless and until more statistically significant results are obtained from further testing and if such test results are (especially on fracture toughness) similar to those obtained for 7075-T6 material.

4. **Do the proposed design (choice of material, temper and fillet radii) and QC plan meet the AUP Structural Design Criteria (SDC)?**

Yes

Findings

Based on analysis and measurement work performed, some of the key results/findings and changes to the criteria by LBNL are listed below:

- Adopting a Design Criteria (based on Design against Failure criteria) for the aluminum shell system which provides a more reasonable approach to this specific part and is a "separation" from the ASME-B&PV Code approach and its extensive and somewhat non-relevant requirements
- Acceptance and adoption of 1.2 (0.8) as Load-Factor/Design-Margins instead of what was proposed earlier (based on B&PV Code)
- Additional material testing for the various materials for the shell
- Changes to the design to minimize/eliminate "sharp" corners (large stress risers). This has been adopted for two of such areas (10mm and 15mm roots) but evaluation for the 3rd area (0.5mm root) is still underway
- Adoption by LBNL of a new/updated QC which now includes:
    - Both ultrasonic testing (UT) for detecting subsurface flaws and dye-Penetrant Testing (PT) for detecting surface flaws in critical areas. These methods are capable of detecting much smaller flaws (surface and subsurface) in those areas
    - Capture of a material drop for each forging aiming at evaluating K_{1c} on more samples
    - The fact that AUP L3 and L2 management must review and approve any non-conformity
- Extensive elasto-plastic analyses (FEM) to estimate plastic zone in critical areas which showed such areas to be quite small compared to geometrical features of this design hence confirming that LEFM-based analyses (for Fracture Control Plan and failure analysis) are sufficient
- Fractography/Metallography of the failed section as part of its failure analysis which showed an unstable brittle crack growth followed by plastic instability of the remaining ligament.

5. Have all recommendations of the aluminum shell SDC review been addressed?

The recommendation listed below have been addressed:

- From the US HL-LHC AUP MQXF Design Criteria Review Committee Final Report (p.13), the review committee suggests increasing the safety margin to 1.5 on the K_{IC} using FAD approach. If the fracture toughness test data measured at 4K (1.8K?) were reasonably consistent among the test samples, the finite element stress analyses/models were accurate, fatigue crack growth was not an issue, and the NDE measurements were thorough and reliable, then the FAD safety margin could be confidently reduced to 1.2. The state of the structure would still be located within the safe zone of the FAD.

- Per our conversation, because of brittleness, we highly recommend mitigating (minimizing and/or removing) stress concentrators within the geometry – especially at its higher stress locations and directions.

6. **Have all Lessons Learned been appropriately addressed, and have all improvements been implemented, from Design Analysis to Non-Conformity Reporting?**

The lessons learned have been listed and are in the process of being implemented.

7. **Do the proposed design and QC plan provide enough margin to avoid similar issues in MQXFA production magnets?**

Mostly yes

Comments

- Considering that during operation the most probable/potential failure mode is an unstable/fast brittle crack growth ($K_I \geq K_{IC}$) starting from an undetectable flaw at high stressed areas of the shell (cutouts' roots, etc.), an LEFM-based evaluation of potential flaws in critical areas should be a prudent approach. Therefore, and based on the extensive modeling/analysis and material testing work that is being performed, we continue to concur with the proposed R6 (FAD) approach and using 1.20 as margin on acceptance criteria.
- The new adopted QC/Acceptance procedure, consisting of both RT and PT for flaw detection, is a significant improvement and should be capable of detecting small flaws in critical areas of the shell. Furthermore, we understand that, while the analytical work considers a 2mm depth as the largest undetectable flaw in such areas, the new NDE approach is capable of finding smaller flaws (as small as ~1.2mm depth by UT and even smaller surface flaws by PT). Therefore, this provides additional safety margins (a large one at that) and hence we concur with this approach.

Recommendation

- Considering all the above and pending verification of material behavior and that thermal shock/gradient conditions are not significant[1], we agree with the lab's

[1]For verifying thermal transient effect during cooling is not an issue, *we suggest that FEM based approach thermal analysis of a plane-strain model of a typical (or few typical) cross section(s) subjected to gas/liquid cooling can be conducted. For this, proper surface heat transfer conditions between the cooling gas/liquid to the metal may need to be estimated/developed. This analysis should check for temperature shock/transient conditions (gradient) across the shell thickness as well as between various parts. If such analysis indicates a small/negligible gradient, then the results obtained so far are validated. However if such work shows significant deviations from the assumed conditions, either the analytical work should be revisited for such effects and/or changes to loading/cooling procedure be recommended to CERN.*

findings about the acceptability of the design especially for the two cutouts with 10mm and 15mm roots. However, we recommend extending this work to the other groove cutout with only 0.5mm root. While we expect these results will be similar to and consistent with the other areas, thus validating the approach, we reserve the final comment till after we review such work.

- In case of non-conformity on material (such as temper or geometric features) proposed by a supplier, the supplier should provide supporting documentation (analyses, testing, etc.) to demonstrate such non-conformance does not materially affect the design.

8. Do you have any other comment or recommendation to assure MQXFA magnets will not experience the MQXFAP2 issue?

Comment

- Project to consider modeling assumed flaws/cracks in the finite element model of the geometry to better represent stresses and relaxation (compliance effect) at those flaws. Results of this work (in form of calculated K_I's) can be compared to estimated K_I's using handbook solutions to not only verify that approach but also provide a better estimate for the actual level of stress intensity factors.

3. Technical details

Committee
Helene Felice – CEA, chairperson
Paolo Ferracin – CERN
Manuchehr Shirmohamadi (Shir) – San Francisco State University
Raymond Yee – San Jose State University

Date and Time
March 22, 2019

Location/Connection
LBNL, room B47
Video-link by Zoom

Link to agenda with talks and other documents
https://indico.fnal.gov/event/19886/