▪ The title of the item or system ▪ A description of the item ▪ WBS Number ▪ Type of design review ▪ Date of the review ▪ Names of the presenters ▪ Names, institutions and department of the reviewers ▪ Names of all the attendees (attach sign-in sheet) ▪ Completed Design Checklist (if utilized)	▪ Findings/List of Action Items – these are items that require formal action and closure in writing for the review to be approved. See Document LCLSII-1.1-QA-0009 for Design Review Requirements and Guidelines ▪ Concerns – these are comments that require action by the design/engineering team, but a response is not required to approve the review ▪ Observations – these are general comments and require no response

Type of Review:	Transportation Review	
Title of the Review:	LCLS-II CM Transportation Review	
WBS:		
Presented By:	C. Ginsburg, T. Peterson, B. Hartsell, N. Huque, J. Holzbauer, J. Blowers, R. Stanek	
Report Prepared By:	T. Nicol (Fermilab)	
Reviewers / Lab :	T. Nicol (chair), J. Adetunji (Fermilab), K. Jensch (DESY), G. Pile (Argonne), S. Sharma (BNL/SLAC), Q. Sun (JLab)	**Date:** June 12, 2018
Distribution:	C. Ginsburg, R. Stanek, M. Ross, T. Peterson	

Attachments:	☐ Review Slides	☐ Design Checklist	☐ Calculations	☐ Other

Purpose and Goal of the Review
The purpose of the review is to evaluate the LCLS-II CM shipping system design and implementation and to advise the management team on a path forward to restarting shipment of cryomodules between all the LCLS-II partner labs.

Charge
Charge to the committee 1. Assess the shipping system design and implementation. Is the design of the LCLS-II CM shipping system adequate to protect the cryomodule from transport vibration generated motion? Are the primary internal resonances, (i.e. resonances most likely to cause damage), properly restrained and / or damped. Is the system immune to temperature fluctuations such as those expected any time of the year along the route from Jlab / Fermilab to SLAC? Are the shipping restraint installation-procedures fully developed and adequate to ensure correct

installation? Is the instrumentation (logger) scheme well developed? Are logger up-load and interpretation criteria (GO/NO-GO) meaningful and understood?

2. Examine evidence showing performance to date (success and failure), and Is the project-team's interpretation of shipping-failure events (chiefly the loss of beamline vacuum F1.306) justified by the facts? Are there possible failure-modes that have been overlooked?
3. Determine whether the proposed improvements are adequate and reduce risks acceptably. Are the proposed restraint improvements and updated instrumentation workable and likely to be effective? Are there potential risks associated with the deployment of these improvements?
4. Advise the project team on a route-survey procedure.Please note the recently held DoE OPA review concluded with a recommendation (SC7) to hold a CM shipping review. This review serves to respond to that recommendation.

Agenda

08:30 - 09:00	Committee Closed Session 30'
09:00 - 09:10	Welcome 10'
	Speaker: Camille Ginsburg (Fermilab)
09:10 - 09:30	F1.3-06 Delivery Experience 20'
	Speaker: Tom Peterson (Fermilab)
09:30 - 10:00	Shipping System Requirements 30'
	Speaker: Brian Hartsell (Fermilab)
10:00 - 10:30	Shipping System Concept 30'
	Speakers: Naeem Huque, Brian Hartsell (Fermilab)
10:30 - 11:30	Shipping System Design Drawings and Potential Improvements 1h0'
	Speakers: Mr. Yuriy Orlov (FERMILAB), Joshua Kaluzny (Fermilab)
11:30 - 12:00	Discussion 30'
12:00 - 13:00	Lunch
13:00 - 13:30	Transportation Environment: Shipping Tests 30'
	Speakers: Brian Hartsell (Fermilab), Naeem Huque
13:30 - 14:00	Transportation Environment: Vibration data 30'
	Speaker: Dr. Jeremiah Holzbauer (Fermi National Accelerator Laboratory)
14:00 - 14:30	Transportation Environment: Pendulum Motion of Cold Mass 30'
	Speaker: Tom Peterson (Fermilab)
14:30 - 14:50	Lessons learned ex post facto: BPM assembly 20'
	Speakers: Dr. Andrei Lunin (FNAL), Peter Owen (Jefferson Lab)
14:50 - 15:10	Lessons learned ex post facto: cold coupler bellows 20'
	Speaker: Mr. Jamie Blowers (Fermilab - Technical Division)
15:10 - 15:30	Impact of external temperature excursions during shipment 20'
	Speaker: Tom Peterson (Fermilab)
15:30 - 16:00	Management Wrap-Up 30'

Agenda	
	Speakers: Richard Stanek (Fermilab), Edward Daly (Thomas Jefferson National Accelerator Facility), Camille Ginsburg (Fermilab), Marc Ross (Fermilab), Dr. Andrew Burrill (Jefferson Lab), Thomas Peterson (Fermilab)
16:00 - 16:30	Discussion 30'
16:30 - 17:00	Committee Closed Session 30'
17:00 - 17:30	Review Closeout 30'

Review materials can be found at: https://indico.fnal.gov/event/17239/

Introduction and Outcome Summary of the Review

The review provided a good forum for active and open discussion among reviewers, reviewees, and others in attendance. There were several formal presentations, but also good discussion throughout the course of the meeting. Its safe to assume the content of this review was interesting to all in attendance, many of whom have heard about the issues discussed, but knew little of the details. The committee is grateful to all the presenters for their candor and for the care that went into making their presentations complete and easy to understand. We hope information presented below is useful to the management team as it works to address the issues discussed.

With regard to outstanding issues and concerns, we have made a few recommendations, but all concerned are aware of what needs to be done and we encourage work proceed as quickly as possible. We understand that time is of the essence, but schedule concerns should not take precedence over completion of all the work aimed at ensuring the highest likelihood of successful future cryomodule shipments.

What follows are findings, comments, and recommendations from the committee and from any attendees wishing to contribute. With the exception of the responses to the charge there is no significance to the order of the content of any section.

Responses to the Charge

1. Assess the shipping system design and implementation. Is the design of the LCLS-II CM shipping system adequate to protect the cryomodule from transport vibration generated motion? Yes, there is still work to do, but all seems to be going the right direction. Are the primary internal resonances, (i.e. resonances most likely to cause damage), properly restrained and / or damped? Yes, assuming provisions are made to accommodate temperature variations. Is the system immune to temperature fluctuations such as those expected any time of the year along the route from Jlab / Fermilab to SLAC? No attempt is made at temperature control and the design to accommodate temperature variations is not complete. Are the shipping restraint installation-procedures fully developed and adequate to ensure correct installation? Yes, preliminary procedures are in development at both partner labs. Is the instrumentation (logger) scheme well developed? Yes, the concept, details need finalization. Are logger up-load and interpretation criteria (GO/NO-GO) meaningful and understood? Yes, assuming current experts remain invested in the project. This expertise should be distributed.

Responses to the Charge

2. Examine evidence showing performance to date (success and failure), and Is the project-team's interpretation of shipping-failure events (chiefly the loss of beamline vacuum F1.306) justified by the facts? Yes. Are there possible failure-modes that have been overlooked? Yes, due diligence should continue in identifying possible other failure modes.
3. Determine whether the proposed improvements are adequate and reduce risks acceptably. Are the proposed restraint improvements and updated instrumentation workable and likely to be effective? Yes, but installation procedures must be complete and reviewed. Travelers should be refined and well-utilized. Recommendations from previous reviews should be fully adopted. Are there potential risks associated with the deployment of these improvements? Yes, but they can be minimized by the above.
4. Advise the project team on a route-survey procedure. Please note the recently held DoE OPA review concluded with a recommendation (SC7) to hold a CM shipping review. This review serves to respond to that recommendation. See recommendations.

Findings

1. Abrasion on G-10 block indicates motion of at least several mm and parallel to coupler axis, perpendicular to cavity string axis. This would correspond to the cavity string swinging side-to-side. The bellows cracked due to occasional large motion of cavity string relative to the vacuum vessel.
2. Only 0.42 g is needed rock the cryomodule while the allowed acceleration is 1.5 g.
3. Static analysis shows the maximum displacement of the cryomodule is 4 mm if the posts are free to move and the ends of the gas return tube have a frictionless restraint. These conditions loosely simulated the constraints in the trip of F1.3-06. If the ends of the gas return tube are bonded to the vacuum vessel and the posts are clamped — these are the future constraints, the maximum displacement is 2.1 mm.
4. There is a five-month schedule delay for shipping the cryomodule from FNAL to SLAC which appears to be driving the aggressive timeline for the cryomodule shipment in July 2018.
5. A formal design review was not previously held for the transport fixture which could indicate inaccurate assumptions in other areas of the project.
6. FNAL is responsible for the cryomodule design and transportation frame.
7. Jefferson Lab is responsible for their own transportation frame and shipping cap procurement using the Fermilab design.
8. Two sets of shipping problems were identified with the delivery of F1.3-06 to SLAC and its return to FNAL – loose hardware and two cracked bellows.
9. There is a specification that governs the transport criteria dated for April 2015. The author has since retired from Fermilab.
10. Shipping frame spring placement and spring manufacturer are different than those used by XFEL.

Findings

11. The project decided to implement a different end cap design than XFEL's design which included aluminum over steel, thus cheaper to produce and lighter in weight.
12. A previous transportation test of a cryomodule from Fermilab to JLab was deemed to be successful.
13. The cryomodule CM-6 had a shock senor installed. The sensor showed the shocks to be essentially within specifications.
14. Torque was applied only on one end of the end caps for restraining the HGRP.
15. A previous review recommended an investigation into the transportation vibration issues including the end caps and the frame enclosure.
16. The other 6 couple bellows removed still need to go through a thorough inspection.
17. Upon receipt at SLAC there was a transverse misalignment of 1.5 mm.
18. JLab is of the opinion that the present end cap design is good. In their opinion, wrong installation led to the bellows failure.
19. An Investigation report from SGS/Msi concludes that the bellows failure was due to unidirectional bending stress with no mean stress.
20. From fatigue markings (striations), and the lengths of the cracks, estimated number of cycles, 472,000, at 1.8 Hz.
21. Fermilab is responsible for all the cryomodule design - DESY/XFEL and FLASH 3.9 GHz CM transport formed the design basis.
22. The transportation scheme was reviewed in both the 1.3 GHz and 3.9 GHz cryomodule final design reviews. Only the transportation scheme was described, few details. Neither review included recommendations specific to transportation.
23. On April 23, a leak check of the cavity string revealed leaks other than the likely BPM seal leaks.
24. Fermi does not know whether bellows cracking occurred on the first trip (to SLAC) or on the return trip (to Fermilab).
25. Bumpers are installed to limit thermal shield travel primarily due to the seismic environment at SLAC. Marks are present from their bumping the vacuum vessel during shipping.
26. The XFEL shipping frame and shipping caps were designed and built by RI and Babcock-Noell respectively. The designs and specifications were proprietary to RI and BN, and could not be replicated in the US. Modifications to the XFEL design would have been necessary anyway for use with LCLS-II cryomodules. Due to the cost of procuring the equipment from Germany, it was decided (February 2015) that a new system (loosely based on XFEL) would be designed at FNAL.
27. The XFEL shipping frame was attached to the trailer using straps and features on the shipping frame member. The LCLS-II design does not have these features.
28. JLab and Fermilab used different strapping techniques. The JLab version was successfully used for the three pCM trips. On one occasion, one of the 8 straps was found to have come loose.

Findings

The FNAL version was used on the F1.3-06 outbound trip. Several straps came loose periodically during the trip. Straps were found to be damaged from abrasion.

29. A low ride trailer may be better at not amplifying lateral motion, but would bring its own complications
30. The Isolation Frame does not seem to do much to suppress frequencies below 20 Hz.
31. Resonances have been identified in the system, including:
    - ~1.5 Hz for air ride system
    - ~10 Hz for the isolation frame in Z and cold mass in X
    - ~50-60 Hz for cavity/coupler modes
    - ~90-100 Hz modes for coupler
32. The cavity/coupler differential motion peaks to 3-4 mm in all three dimensions with the steady state motion a factor of 3 lower.
33. F1.3-06 to SLAC transport had minimal instrumentation, but what does exist indicates there were not many extreme events (e.g. Y motion > 100 mm).
34. Changes to Line D hangers and proposed shield shipping support will likely eliminate the large shocks observed.
35. Lower transport speed and better control of transportation route will improve vibration levels.

Comments

1. The DESY-style XFEL gas return tube end caps are made of aluminum. The XFEL prototype caps were carbon steel. Great care should be exercised to ensure their stiffness, especially under lateral forces.
2. No strain gauges were used to monitor the force applied to the gas return tube from the end caps. Fermilab plans to use strain gauges with the DESY-style end caps. The strain gauges are critical to ensure that an adequate preload force is applied.
3. There is no fatigue life, axial stroke, and lateral stroke requirements for the bellows in LCLS-II. The SGS report claimed that the fatigue life was only 16,300 cycles based on the observation and assumptions. It is important to test the fatigue life of the bellow under realistic road conditions.
4. XFEL cryomodules traveled 600 miles without any issue. However, the distance from JLab to SLAC is 2937 miles. Since the fatigue life of the bellows is cumulative, the bellows used in LCLS-II should have four times of fatigue life than that of the bellows in XFEL.
5. It would be good to use increased instrumentation for future trips. However, it might be more helpful to use a pilot car—at least for the first shipment—to provide real-time road conditions to the truck driver to mitigate any possible acceleration larger than 1.5 g.
6. Shims were used on the transport frame on the shipment to SLAC, however, no shims were in use on the return shipment to FNAL. This may have contributed to the issues with the

Comments
cryomodule. Other transportation considerations should be identified and codified in a procedure or checklist. 7. Sufficient time must be allocated to analyzing the data from the concrete transportation test and in identifying appropriate applications of the lessons learned. 8. Due to the lack of prototyping, the project team should consider other design aspects (e.g. major design changes from the XFEL design) that could benefit from a formal review. 9. Consider re-evaluating the specifications of the G-10 blocks that could help to minimize the impact of potential contact with bellows. 10. Suggest that consideration be made to investigating fatigue crack propagation stages in other bellows, including on JLab's cryomodules. This includes inspecting incoming materials (bellows) prior to installation. 11. It was identified that the HGRP adapter was improperly installed in CM06, therefore, other aspects of the cryomodule should be reviewed to verify alignment with the specification; including formal procedures and QC checks for use by Fermilab and JLab. 12. Ensure that GPS tracking and instrumentation is consistently applied throughout the transportation from Fermilab and JLab. 13. Consideration should be made to driving the routes with instrumentation prior to the shipment of the cryomodule. This may help to verify road conditions and possible detours. 14. Careful consideration must be given to the sensitivity of the instrumentation regarding reliability, temperature, etc. 15. The project team should assess the potential implications that foam placement could have on the temperature control. 16. The test trip should cover at least 50-75% of the miles expected to travel from Fermilab to SLAC and/or from JLab to SLAC. 17. Suggest conducting a formal FMEA on the final shipping process/plan. 18. It was not obvious from the presentation why the damage was limited to the bellows of couplers 4 and 5, and why the cracks were located only in 3 o'clock and 9 o'clock positions. 19. One of the presentations showed convincingly that a couple of degrees temperature difference between the vacuum vessel and HGRP will result in the ends of HGRP become unrestrained from the end caps. The HGRP will then be able to oscillate axially in addition to having a rocking mode. 20. The transportation frame is different than the one used for XFEL. The flatbed of the truck could also be different. The impact of these changes was not investigated. 21. The longitudinal (Z-direction) motion of the HGRP will be suppressed using Belleville washers. The design and analysis of the Belleville washers' stack was not discussed. Their design should ensure that they do not introduce unwanted natural frequencies in the Z-direction. 22. Be careful of the freight company switching drivers that don't know the rules.

Comments

23. There is some data that shows that 60Hz does this have anything to do with the truck averaging 60 miles per hour. Is it 3600 rpm of the engine, engine braking at 3600 rpm or something else? What happens at 60 times per second?
24. The truck is often at extreme angles while going up or down a hill. The end float is amplified by vibration and shock.
25. Shipping dynamics are not well understood. Time should be spent with experts deciding the difference between springs and shock absorbers. The isolation frame does not appear to be damped properly (or even at all) when tied directly to the truck bed. Basically, shock absorbers work together with springs to handle the vertical bumps, the rope springs provide the necessary movement of the load while the shock absorber would act as a vibration damper for the springs.
26. The air ride is only between the truck bed and the wheels.
27. Consider shimming transport frame with some sort of vibration pads and carefully consider their size and placement. In parallel, considered doing shaker tests at Fermi for some pre-determined time on each unit.
28. Request JLab personnel at Fermilab for prep of F1.3-05 take full advantage of strength of collaboration and lessons learned.
29. Send a vibration expert as a truck rider to get a real feel for what the trip is like.
30. Were there any lessons learned by Fermilab in the transport of Muon G-2 magnet? Has anyone spoken to the technical team who moved it?
31. What review was not held that should have been held that might have identified transport issues? When should this review have been held (during the transport frame FDR? End cap design FDR?). How did the design reviews not catch these changes and consequences? Or were the reviews focused on each part and not the overall transport concept? Did we use the DESY Lessons Learned documents when completing the transport equipment designs?
32. What constitutes a successful transport design? When a CM reaches SLAC without visual damage? Are there potential stresses occurring during transport that is not yet visually apparent when reaching SLAC that might be exposed after start of operation? Has any CM been transported without any issues found? It appears that something was loose, or missing, or required changes after every CM transport trip. The approach appears to be that if the patient doesn't die in arm surgery then the operation was successful. There needs to be a better and measurable definition of successful transport.
33. Do the bellows get inspected for cracks using Magnaflux or equivalent, for example?
34. Bending of 300mm pipe transversely due to g-loads seem serious with a 3 mm displacement. This would have occurred during all CM shipments to date. Are we near failure of a coupler bellows for J1.3-07 because it has been shipped over 2,000?

Recommendations

1. Complete the redesign and manufacture of end restraints capable of securely restraining the GHRP ends in all three directions.
2. Restrain the warm end of all three support posts to prevent rocking and reduce lateral motion.
3. Add temporary damping material at the ends of the thermal shield and, if possible, at the center of the 50 K shield (through one or more tuner access ports).
4. Remove or back out the earthquake bolts on the 50 K shield.
5. Continue instrumenting cryomodules throughout all shipments.
6. Continue bore-scoping end-most components, e.g. G-10 blocks.
7. Short shipping test should be out I-90/US-20 to Galena and back on I-80/I-88. Utilize a pilot car to assess the usefulness.
8. Pilot car is a good idea for a couple reasons, some feedback on road conditions, control of speed.
9. Advise on the route, with some flexibility, and limit the speed to no more than 55 mph.
10. Removing the warm coupler should be a last resort.
11. Continue bellows testing to better quantify the fatigue life.
12. Develop a scheme of securing the shipping frame to the trailer and use it consistently.
13. Ensure all requirements are in the contract with the shipping company including logging route deviations.
14. Study the viability of controlling the shipping environment, especially the temperature.
15. Ensure that all the work that has been identified is completed prior to shipping the next cryomodule.