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LCLS-II CRYOMODULE TRANSPORT SYSTEM TESTING

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Abstract

The Cryomodules (CM) for the Linear Coherent Light Source II (LCLS-II) will be shipped to SLAC (Menlo Park, California) from JLab (Newport News, Virginia) and FNAL (Batavia, Illinois). A transportation system has been designed and built to transport the CMs over the road in a safe manner. It uses an array of helical isolator springs to attenuate shocks on the CM to below 1.5g in all directions. The system rides on trailers equipped with Air-Ride suspension, which attenuates vibration loads. The prototype LCLS-II CM (pCM) was driven 750 miles to test the transport system; shock loggers recorded the shock attenuation on the pCM, and vacuum gauges were used to detect any compromises in beamline vacuum. Alignment measurements were taken before and after the trip to check for deformation of CM components. Passband frequencies and cavity gradients were measured at 2K at the Cryomodule Test Facility (CMTF) at JLab to identify any degradation of CM performance after transportation. The transport system was found to have safely carried the CM and is cleared to begin shipments from JLab and FNAL to SLAC.

INTRODUCTION

The transportation of a CM over the road poses many opportunities for absorbing damage. While there is always the risk of a catastrophic incident on the road that can destroy the CM, there is also the danger of damage caused by shocks and vibrations that are part of the regular journey. Road transport can often see shock loads as high as 3g – 4g [1], which can deform and misalign cavities and damage other sensitive components and piping. The transport system minimizes the effects of such shocks by attenuating them to acceptable levels.

The CM transportation system is based on that designed by the Deutsches Elektronen-Synchrotron (DESY) used to transport European X-ray Free Electron Laser (XFEL) CMs from Paris, France to Hamburg, Germany. Over one hundred CMs were successfully transported the ~500 miles between the two.

To gauge the types of shock loads that may be experienced during a trip, the JLab pCM was transported over the first leg of its planned route from JLab to SLAC. A study on XFEL CMs found that the maximum allowable load on a CM is 1.5g [2]. The following criteria determined whether the CMs may be safely transported during the remainder of the project:

- Shock attenuation from the transportation system.
- Physical deformation of CM components.
- Uncompromised beamline and insulating vacuums.
- Degradation of CM performance.

TRANSPORT SYSTEM DESIGN

The Shipping System consists of four main elements (Fig. 1): The CM itself, Shipping Frame, Shipping Caps and a flatbed trailer equipped with Air-Ride Suspension.

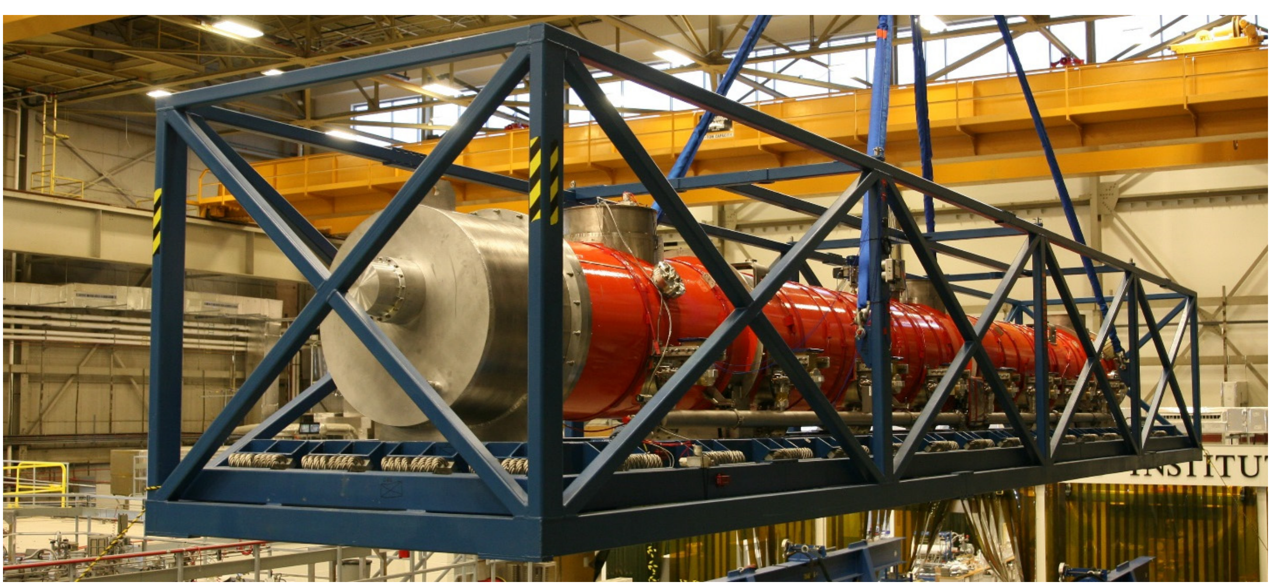

Figure 1: The LCLS-II CM installed in the shipping frame.

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Cryomodule

The structural frame of the CM relies on the solid outer shell called the vacuum vessel that is constructed from mild steel. The innards of the CM consist of the Upper Cold Mass (UCM) and the Cavity String (CS), which hangs off the former. The UCM is fixed to the vacuum vessel via three vertical support posts along the top of the CM. The interfaces to these posts rely on structures made from G-11 composite, which is considered the region most susceptible to damage during transport.

Shipping Frame

The Shipping Frame is a truss structure built with welded A36 rectangular hollow bar that encases the CM during shipping. The base of the structure (outer frame) is fitted with 26 helical isolator springs (Isolator Dynamics Corp, M28-525-08-H-A). Another flat frame known as the Isolation Fixture (inner frame) is installed atop the springs. The CM is attached to this Isolation Fixture.

The 26 isolator springs have a spring constant of 6,242 lb/in. The total weight on the Isolation Fixture is ~20,000 lbs. This means a load of 769 lbs per spring, a static deflection of 0.1 inches and a natural frequency of ~6.1 Hz [3].

Shipping Caps

The Shipping Caps are installed on both ends of the CM during shipping. Each cap has a central hub which holds a spindle. This spindle mates with the Gaseous Helium Return Pipe (GHRP) in the UCM. The GHRP is a 300 mm diameter pipe to which the cavity string is attached and from which it hangs. A force of 200 lbs is imparted by the spindles on to each end of the GHRP in the axial direction. This force supports the GHRP and the UCM in the transverse direction, protecting the G-11 supports from damage.

The shipping caps also serve to close off the insulating vacuum space inside the CM. During shipping, this space is filled with dry nitrogen under a positive pressure of 1050 mbar.

Flatbed Trailer

The trips from JLab and FNAL will be carried out on two custom-modified 48ft flatbed trailers. The key component of the trailers is the air-ride suspension, which is designed to attenuate vibrations from the road. A trailer fitted with an INTRAAX AANT 23K air-ride suspension system by Hendrickson USA was used for this test.

ACCEPTANCE CRITERIA

Vacuum

The beamline and coupler enclosures are to be under vacuum during the CM shipments. Both spaces are prescribed to have vacuums better than 10^{-6} mbar. The insulating vacuum region (enclosed by the vacuum vessel and the shipping caps) is backfilled with dry nitrogen to a positive pressure of 1050 mBar with no loss of pressure allowed except for that due to temperature changes [4].

Alignment

CMs arriving at SLAC will have fiducials on the beamline gate valves and the support posts measured to detect any distortion. These fiducials positions are measured with respect to other fiducial points that remain permanently on the outside of the vacuum vessel. These and other points on the support posts are restricted to ± 0.2 mm of deformation during shipping [4].

Shock Loads

During shipping, shocks on the CM are limited to 1.5g in the longitudinal, transverse and vertical axes [2]. Accelerometers similar to those used for this test will be installed on the shipping frame and vacuum vessel of each CM.

Cavity Performance

The cavities are expected to complete the trips with little to no damage or loss in performance. The cavity passband frequencies will be compared to those taken after tuner installation. The cavity tuner stepper motors will be used to determine whether the cavities could be tuned to resonance (1300.000 MHz) after being cooled to 2 K. The individual cavity gradients are not to change beyond that which is considered reasonable measurement error.

TESTING STRATEGY AND EQUIPMENT

Accelerometers

Two types of accelerometers are used for the shipping test. The accelerometers record shock profiles for every 'event', when a shock load exceeds a specified threshold. At such a time, the units save the data from their buffers for a specified time (pre-trigger time) and then continue to record data for a subsequent period (post-trigger time).

Lansmont SAVER9X GPS The SAVER9X main unit consists of a tri-axial accelerometer with six additional input channels. An external antenna provides GPS coordinates for any events that are recorded. Temperature and humidity are also measured. Two external triaxial accelerometers (PCB Piezotronics Model 356A70) are installed on the six input channels.

The main unit is fixed on to a magnetic mount, which is attached directly to the vertical member of the shipping frame (outer frame). The two satellite PCB units are mounted to a small aluminium block with a screw, and the blocks are fixed to surfaces with hot glue. One unit is fixed to the inner frame and the other is attached to the coupler waveguide.

The threshold for event recording was set to 0.5g; when any single channel experienced a shock greater than 0.5g, all nine channels would record the event. The sampling rate was 500/s.

SENSR GP1 The GP1s are self-contained triaxial accelerometers. Each has its own memory and batteries.

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The independent nature of the GP1s allows for more varied placement locations on the shipping system. These accelerometers were used as a backup system to the SAVER9X.

Four GP1 devices were used for the test. Three units were used to duplicate the SAVER9X position, with the one difference being that one unit was placed on the vacuum vessel instead of on the coupler waveguide, due to space constraints. An additional unit was attached to the downstream gate-valve. This unit was inside the insulating vacuum space, and was not accessible until the end of the testing.

The GP1s use DC current recording, which means a constant 1.0g reading in the downward direction due to gravity. To compensate for this, the even recording threshold was set to 1.6 g resultant force. The sampling rate was 100/s.

Vacuum and Pressure Gauges

Vacuum Gauge Two Pfeiffer PKR 251 cold-cathode gauges were installed at the downstream end of the beamline. A separate power source was installed on the trailer to power the gauges. Data was logged for the entire trip.

Pressure Gauge A 0-5 psig manometer gauge was attached to the pumping port on the shipping cap. There was no data logging on this gauge; however, at various points during the test trip, the gauge was visually inspected to ensure that the insulating vacuum space was still intact.

Alignment Measurements

Fiducial points on various parts of the CM were measured using the FARO Arm, which is a portable Coordinate Measurement Machine, and a FARO Laser Tracker. The latter uses spherically mounted retroreflectors (SMR) that reflects lasers beams back to their sources in order to identify the location of each SMR in space. SMRs at fixed locations on the floor are used for reference.

The outside of the vacuum vessel contains fixed fiducial points that are used throughout the production and installation of the CMs. In addition to these, fiducial points were set up adjacent to the tuner access ports on the vacuum vessel. The FARO Arm was used to reach into the ports and locate fiducial balls that were installed on threaded holes on the beamline bellows; these are used to define cavity position before and after the trip.

Fiducial balls were also installed on the gate valves at both ends of the beamline. The same points are to be measured after completed CMs are delivered to SLAC [4].

Road Testing

The CM installed in the shipping frame, and fitted with the shipping caps, was shipped with the trailer from Newport News, VA to Bristol, VA and back. This trip constitutes the first 375 miles that will be taken for the CMs to get to SLAC from JLab; the test covered a total of 750 miles.

RESULTS

Alignment

All fiducial point locations were re-measured after the road test. The results for the gate valves and the support post fiducial points are shown in Tables 1 and 2. The values in the tables represent the changes in the fiducial positions after the road test. The X-axis is the horizontal direction, the Y is the vertical and the Z is the longitudinal (beamline).

Table 1: Change in Gate Valve Position

	dX (mm)	dY (mm)	dZ (mm)
Specification	± 0.20	± 0.20	± 0.20
Upstream	-0.02	-0.38	-0.19
Downstream	-0.05	0.04	-0.44
Error	± 0.10	± 0.10	± 0.10

Table 2: Change in Support Post Fiducial Positions

	dX (mm)	dY (mm)	dZ (mm)
Specification	± 0.20	± 0.20	± 0.20
Upstream	0.03	-0.08	-0.11
Centre	-0.06	-0.11	0.13
Downstream	0.15	0.24	-0.05
Error	± 0.10	± 0.10	± 0.10

The gate valve positions on the upstream and downstream ends shifted to levels that were out of tolerance in the vertical and longitudinal directions respectively. A needle bearing on the downstream gate valve dislodged during the trip. The shift in the downstream gate valve may be related to the missing needle bearing.

The positions of the cavity flanges in the horizontal (X-axis) and vertical (Y-axis) before and after the road trip are shown in Fig. 2. Not all of the flanges could be measured due to limitations in access through the tuner port. The error bars shown here are ±0.18mm.

Only one cavity (Cavity 8) showed a large deviation (-0.45mm), and only in the horizontal plane. As this cavity is on the downstream side, this too may be related to the missing needle bearing.

The longitudinal shifts are greatest on cavities 6, 7 and 8. The entire cavity string seems to have shifted towards the downstream end of the CM. On the road test, this corresponds to the string shifting towards the rear of the truck, which is a common motion during acceleration. Shifts in this axis are not considered as significant as those in the horizontal and vertical axes.

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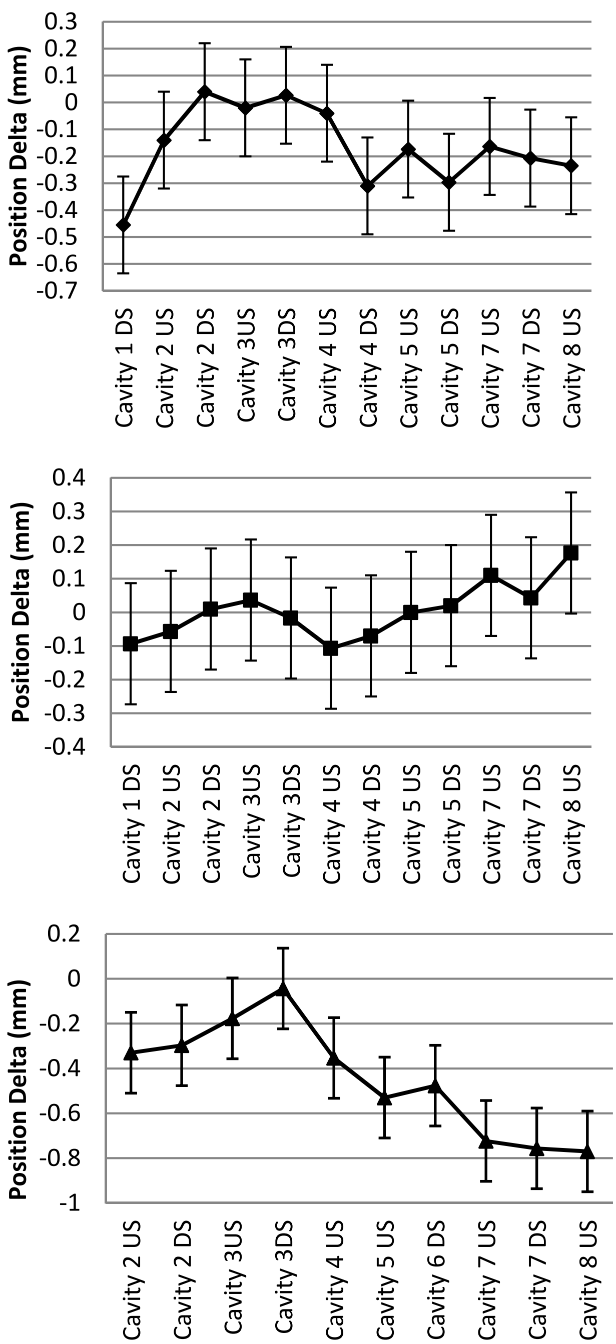

Figure 2: Changes in cavity flange position in the horizontal (top), vertical (middle) and longitudinal (bottom) axes.

Shock Loads

A major goal for this test was to determine the levels of shock attenuation achieved by the springs on the shipping frame. The accelerometers (SAVER9X and GP1) on the outer and inner frames are located on either side of the springs. The attenuation from the three highest recorded shock loads on in the X (longitudinal), Y (vertical) and Z (transverse) axes are shown in Table 3.

The levels of shock attenuation found during the test match those that were predicted [3]. The loads seen on the base frame are also very representative of general shipping loads. In nearly all of the cases here, the springs greatly reduce the shock loads. The transverse results shown here are overestimated due to the main SAVER9X unit being too high on the shipping frame. The swaying of the shipping frame would then lead to unrealistically high and erroneous shock loads. No transverse loads over 1.5g were recorded by the GP1 units.

A PCB tri-axial accelerometer was installed on the coupler waveguide to measure whether it was subject to any loads over the specified 1.5g. The three occasions where the shock limit was exceeded are shown in Table 4. The shocks are compared to the velocity of the accelerometer's movement during each event.

Table 3: Attenuation from Largest Shock Loads

	Outer Frame (g)	**Inner Frame (g)**	**Attent. (%)**
Longitudinal 1	3.53	1.25	65
Longitudinal 2	3.36	1.26	63
Longitudinal 3	2.84	0.68	76
Vertical 1	3.58	0.58	84
Vertical 2	3.47	1.00	71
Vertical 3	2.94	0.99	66
Transverse 1	4.77	2.18	54
Transverse 2	4.20	3.01	28
Transverse 3	4.29	1.60	63

Table 4: Y- Axis Events Where Coupler Shock Load Exceeded 1.5g

	Coupler Shock (g)	**Coupler ΔV (in/s)**	**Inner Frame ΔV (in/s)**
Event 1	1.74	16.3	3.54
Event 2	1.59	16.0	8.38
Event 3	2.08	18.5	6.14

The ΔV columns in Table 4 indicate that the speed of displacement of the coupler was far greater than that of the inner frame to which the CM is fixed. It makes sense that the coupler waveguide, the least restrained component outside the vacuum vessel, was set into oscillatory motion by these low-speed bumps; these oscillations would lead to the higher shock readings on the accelerometer.

Accelerometers on Vacuum Vessel and Gate Valves The GP1 accelerometer on the vacuum vessel did not register any shocks over 1.5g during the road trip. As the vacuum vessel is a heavier and sturdier mass than the coupler waveguides, motion would have less bearing on the readings.

Another GP1 unit fixed to the gate valve on the upstream end of the beamline recorded one event in which all three

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axes exceeded 1.5g (X-axis 1.63g; Y-axis 1.70g; Z-axis 2.20g). This event did not correspond with any other shocks recorded by the SAVER9X or the other GP1s outside the vacuum vessel. It is possible the overly-compliant attachment of the GP1 to the gate valve caused the high readings. The bracket used for fixing the unit was most free to move in the transverse direction, which could account for the higher value.

Cavity Performance

The CM was retested at 2K in the Cryomodule Test Facility (CMTF) at JLab. The cavity tuner stepper motors were used to bring the cavity frequencies back to resonance at 1300.000 MHz; all cavities were successfully tuned. One set of limit switches on cavity 4 suffered superficial damage – some Kapton tape used for electrical insulation became detached – but this did not affect successful tuner operation.

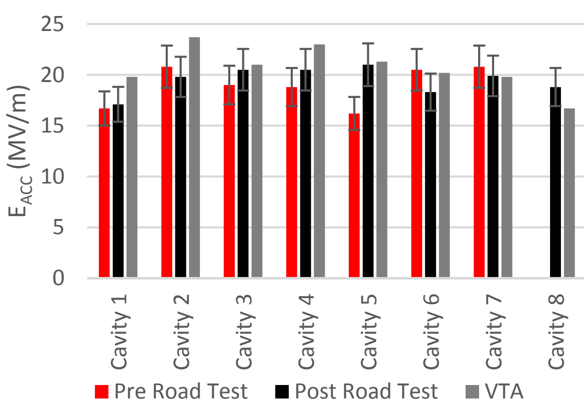

Figure 3: Comparison of cavity gradients before and after road test.

Figure 3 shows the cavity gradients before and after the road test. They are compared with the gradients recorded during testing in the Vertical Test Area (VTA) prior to assembly into the cavity string. There is no degradation of maximum cavity gradient found after the road test. The error bars shown in the graph are ±10%.

Another concern was an increase in cavity field emission due to metallic particulate dislodging during transport. There was no increase in field emission measured after the test.

Cavity 8 could not be tested prior to the road test due to a damaged fundamental power coupler (FPC). Due to time constraints, Cavity 5 was not brought up to full gradient prior to the road test. Q_0 measurements were not taken prior to the road test due to issues with the CMTF cryogenic systems.

Vacuum Levels

The beamline vacuum pressure was 7.0 x 10^{-7} mbar at the start of the road test. Changes in ambient temperature caused the pressure to go down to 9.0 x 10^{-8} mbar. The pressure returned to the level prior to the road test start after trailer was parked in the JLab high bay overnight. There was no compromise to the beamline vacuum.

The insulating vacuum space inside the CM was back-filled with dry nitrogen, to a positive pressure of 0.5 psig (~1050 mbar). Due to ambient temperature change, the pressure dropped to 0.1 psig, before returning to 0.5 psig overnight. There was no compromise to the insulating vacuum space.

Induced Magnetism

Magnetic field measurements from the flux gates in the cavities increased after the road test. The worst of the cavities – cavity 5, in the axial plane – had an initial reading of 6.7 mG; this increased to 21.5 mG after the test. The CM was demagnetized using active compensation coils, but the level could only be brought down to 18.0 mG after two degaussing runs; the specification is <5 mG [5].

PROPOSED CHANGES

- Entering and exiting weigh stations on the interstates caused movement and possible high loads on the coupler waveguides. Future trips could get a waiver to allow the truck to bypass weigh stations en route.
- The loss of a needle bearing on the gate valve is due to a design flaw. CMs are now fitted with 'stoppers' which will hold the bearings in place.
- Restraining brackets will be added to the gate valves on both ends of the beamline to restrict their motion during transport.
- The tuners will no longer be positioned to be in contact with the limit switches during transport; they will be positioned at the nominal warm frequency position of the cavity instead.

CONCLUSION

The CM successfully completed a road test with the shipping system without sustaining any damage or degradation in performance. The isolator springs on the shipping frame attenuated shocks by 60% – 80%. Instances where shock loads exceeded 1.5g on the CM couplers are likely due to the couplers' oscillating independently of the rest of the CM. The installation of additional restraint brackets will stop gate valve movement during transport. Further study is required to determine whether the road test directly contributed to the increase in remnant magnetic fields in cavity 5. The shipping system is ready to start transporting CMs to SLAC from FNAL and JLab.

ACKNOWLEDGMENTS

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