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IMPROVEMENTS TO LCLS-II CRYOMODULE TRANSPORTATION

N. Huque, E. F. Daly, P. Owen, Jefferson Lab, Newport News, USA
J. Holzbauer, B. Hartsell, Fermi National Laboratory, Batavia, USA

Abstract

The Linear Coherent Light Source (LCLS-II) is currently being constructed at the SLAC National Laboratory. A total of 35 cryomodules (CMs) will be fabricated at Jefferson Lab (JLab) in Virginia and Fermi National Laboratory (FNAL) in Illinois and transported via road to SLAC. A shipping frame with an inner bed isolated by springs was designed to protect the CMs from shocks and vibrations during shipments. Successful road testing of the JLab prototype CM (pCM) paved the way for production CM shipments. The initial production shipments lead to several catastrophic failures in beamline vacuum in the cryomodules. The failures were determined to be due to fatigue in Fundamental Power Coupler (FPC) bellows due to excessive motion during shipment. A series of instrumented CM shipping tests and component tests were undertaken to develop a solution. A modified spring layout on the shipping frame was tested and implemented which reduced shocks on the CMs. FPC coupler bellows restraints were tested on a shaker table and on a CM during shipping; they were able to reduce bellows motion by a factor of three. The updated shipping system is currently in use and has successfully delivered fourteen cryomodules to SLAC from JLab and FNAL.

INTRODUCTION

LCLS-II CMs are transported to SLAC by road from JLab (~3,000 miles) and FNAL (~2,000 miles). The transportation system uses a flatbed trailer fitted, with air-ride suspension, and a shipping frame that uses wire isolator springs to reduce shock loads on the CM [1]. The system is based on that which had been used by DESY to transport 100 XFEL CMs from Paris to Hamburg (~500 miles). Short distance test runs were conducted using the JLab pCM to Bristol, VA, and FNAL; the pCM successfully completed the tests, and the system was deemed ready for production shipments.

Initial Failures

In November 2017, the first LCLS-II CM (F1.3-06) arrived at SLAC from FNAL with its beamline vented to atmosphere. As the vacuum gauges on the beamline were not actively logged, there was no way of determining exactly when the vacuum was lost. An initial inspection found that several of the SHCS on the Beam Position Monitor (BPM) feedthroughs had been shaken loose during the trip, breaking the aluminum gasket seal. It was discovered that the SHCSs were Grade-2 Titanium instead of the specified Grade-5 Titanium. Alignment measurements found that the upper cold mass (UCM) supports had shifted 1.7 mm during the trip; the amount of movement allowed as per the specifications is +/- 0.2 mm [2], and nothing over +/- 0.1 mm was recorded during the practice trips. This was likely due to the shipping caps being incorrectly installed prior to the shipment.

Further inspection after the cold mass was taken out of the vacuum vessel found ruptures in the FPC bellows on cavities 4 and 5. It is not known whether this occurred on the initial trip to SLAC or when the CM was traveling back to FNAL.

A short 750-mile road test was conducted using J1.3-07 which did not have any vacuum issues. A series of alterations were made to the shipping system configuration prior to the shipment of the next CM (F1.3-05) to SLAC. This CM also had a failure in the cavity 1 FPC bellows in a manner similar to F06. The bellows were identified as the primary source of failure for both CMs.

FAILURE MODE DESCRIPTION

The FPC bellows in question is attached to the FPC flange on the cavity on one side and the FPC main body on the other side. The 5K heat intercept flange is attached to the cavity side of the bellows and the 50K intercept shroud is attached to the other side. The central section of the FPC (containing the shroud) is relatively free to move in the vertical (Y-axis) and beamline (Z-axis) directions; it is only supported at the vacuum vessel and at the cavity.

The bellows were found to have ruptured in the 3 o'clock and 9 o'clock positions relative to the bellows central axis (Fig. 1) [3]. This region of failure implied that repetitive motion in the horizontal plane lateral to the bellows axis (and parallel to the beamline axis, Z) caused the failures. Material analysis of the dismantled bellows also indicated fatigue failure.

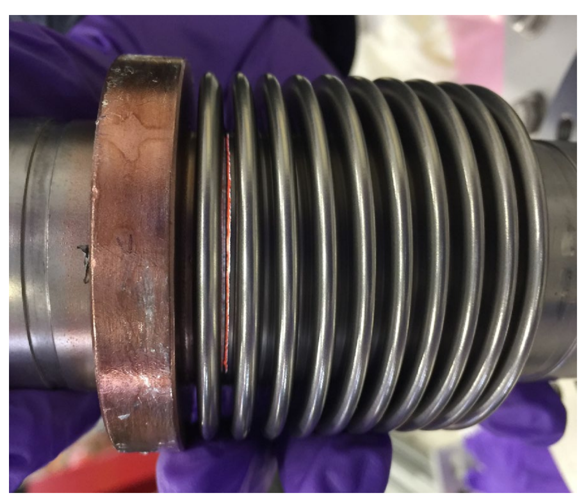

Figure 1: Ruptured bellows from F1.3-06.

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No information regarding the motion of the bellows was available from the F1.3-06 trip; only shock sensors on the shipping frame were installed, and no high shocks were recorded. The F1.3-05 shipment had Slam Stick-X (SSX) units installed to measure the motion of the bellows. A sensor was installed on both the 5K intercept and the 50K shroud; the relative motion of the 50K shroud to the 5K intercept was equated to be the motion of the bellows. The bellows were found to be moving +/- 2.6 mm from the mean position, with a peak frequency of 15 Hz. Modal analysis confirmed that the FPC bellows had a natural frequency of 15 Hz, which was being excited by the road transportation.

BELLOWS FATIGUE TESTING

Bellows assemblies identical to those used in the FPCs were put through cyclic testing at Brookhaven National Laboratory (BNL). The results were compared to predicted fatigue life derived from the Expansion Joint Manufacturers Association (EJMA) guidelines, shown as the solid line in Fig. 2. The results showed the bellows fatigue life was close to that predicted by literature, but could not explain why the bellows on the two cryomodules failed at low cycles.

It has also been theorized that cycling the bellows at cryogenic temperatures may have weakened their fatigue life at room temperature. All failed bellows were exercised in this manner via a stepper motor. Tests were conducted to prove this hypothesis but were inconclusive due to defective testing samples.

A separate 3,000 mile cryomodule road test was conducted with the outer FPCs removed from a cryomodule and the bellows held in place by threaded rods. The dashed line in Fig. 2 shows the measured displacement and cycles; the bellows remained intact. Though removing the FPCs in this manner was considered impractical, it was shown that keeping the bellows' lateral displacement below +/- 2.0mm would not result in failure.

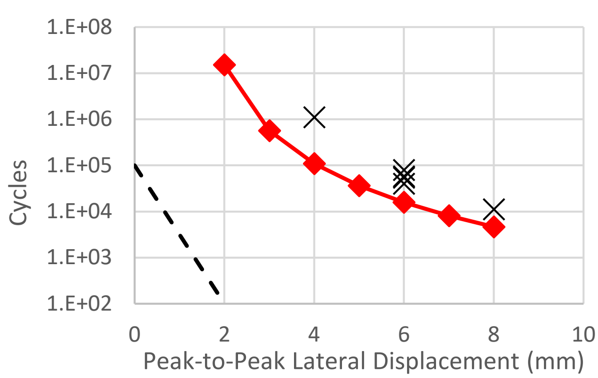

Figure 2: Bellows testing cycles to failure.

BELLOWS MOTION RESTRAINT

The shipping failures and analysis established that the FPC bellows were the CMs' weak point. A restraint mechanism would be developed for future shipments which would aim to limit the motion of the FPC bellows in the beamline axis (Z-axis).

At the time that the issues with the FPC bellows were discovered, each of the partner labs had eight cryomodules fully assembled and awaiting shipment to SLAC. A full-scale retrofit of the bellows would mean each CM would need to be partially disassembled and reassembled, which would be both time-consuming and expensive. As such, a restraint mechanism would be required that could be installed on CMs that were already complete; the following criteria would need to be met:

- Restraints would need to be installed through the tuner access ports, without requiring any further disassembly
- The restraints should restrict movement in the vertical and beamline directions (Y and Z axes) but allow the bellows to compress in its axial direction (X-axis).
- For safety, no metallic components would be used for the restraint installation to avoid accidentally damaging the bellows
- Testing on a shaker table and then a CM road trip would be conducted to ensure that the restraints would limit motion of the bellows to an acceptable level.

RESTRAINT DEVELOPMENT AND TESTING

Five restraint designs were shortlisted for possible use on CMs. Each was first tested on a shaker table to determine its performance and reliability. A summary of the designs is given in Table 1.

The Partial M-Mount, E-Clamp and Delrin E-Clamp made use of the G10 Shipping Support which was already a part of the FPC design. The support only restricted motion in the downward vertical direction; the three restraints would extend this to the beamline axis and upward vertical directions. The M-Mount replaces the G10 and is attached via the same M6 screws which held the G10 in place. Both versions of the M-Mount make use of a zip-tie to aid in vertical restraint. The E-Clamp uses a Quick-Grip ratcheting clamp to compress the Neoprene with a maximum force of 150lb. The Sliding Shroud Support (SSS) made use of threaded holes in the 50K shroud and 5K intercept. The cylinders attached to each side may slide in the bellows axial direction but are restrained in the axial and vertical directions.

Table 1: Comparison of Restraint Materials and Clamping Mechanism

	Material	Clamp
Partial M -Mount	Neoprene Durometer 60	Zip-Tie
E-Clamp	Neoprene Durometer 60	Quick-Grip Clamp
Sliding Shroud Support	Stainless Steel/Brass	Threads
Delrin E-Clamp	Delrin	None
M-Mount	Neoprene Durometer 60	Zip-Tie

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Prior to testing, each of the restraints (apart from the SSS) were installed on a completed CM through the tuner port. The SSS was excluded as a further degree of disassembly would have been required for its use.

Shaker Table Testing

A coupler assembly was set up on a custom shaker table at SEG (Fig. 3) [4]. The coupler was fixed at points representing the connections to the vacuum vessel and the cavity. The table itself was capable of oscillating with an amplitude of +/- 2.0 mm and a frequency of up to 30 Hz. Tests would be conducted at 7.5 Hz and 9.0 Hz to avoid going through the couplers' resonant frequency of ~15 Hz.

Accelerometers were installed on the base of the shaker table, the 5K intercept, and the 50K shroud. The relative motion of the bellows was measured using two laser distance indicators pointed at the spool next to the bellows and the 5K intercept; the motion of the bellows was calculated by taking the difference between the movement of the spool and 5K intercept. The coupler was rotated 90 degrees along its central axis during the installation on the shaker table. The vertical motion of the table corresponded to the bellows motion in the beamline direction (Z-axis). The coupler was pumped down to 10-7 torr and a vacuum gauge was attached to indicate any loss of vacuum.

Each of the restraints was tested at the two frequencies and the bellows displacements were compared to a baseline test in which no restraint was used.

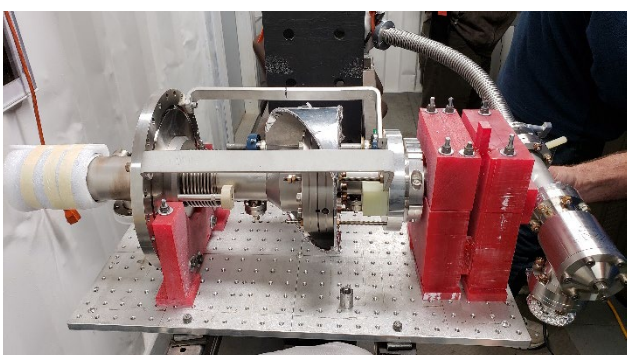

Figure 3: An FPC set up on the shaker table at SEG.

Shaker Table Testing Results

The displacements for each of the restraints are shown in Table 2. The Partial M-Mount was measured at 7.1 Hz instead of 7.5 Hz. The final selection criteria included both the performance of the restraints and the ease of installation in a completed cryomodule. Table 3 shows a ranking of the restraints' performance and the relative ease of installation; a score of 1 represents the best and 5 represents the worst.

Despite being the best performer, the installation process for the SSS was deemed too intensive to be a practical solution. The E-Clamp and Partial M-Mount were chosen for further testing. There was a suspicion that the Quick-Grip clamp on the E-Clamp may come loose during a prolonged journey. As such, it was tested further at 9.0 Hz for 24 hours; the Quick-Grip clamp remained in place and did not loosen. The Partial M-Mount was re-tested at 9.0 Hz for 5 hours to test the stability of the zip-tie; it too passed with no degradation. Both the E-Clamp and Partial M-Mount were selected to be tested on a CM.

Table 2: Comparison of Measured Bellows Displacements During Testing

Restraint	7.5 Hz	9.0 Hz
Partial M -Mount	+/- 0.4 mm	+/- 0.1 mm
E-Clamp	+/- 0.1 mm	+/- 0.2 mm
SSS	+/- 0.05mm	+/- 0.15mm
Delrin E-Clamp	+/- 0.05mm	+/- 0.4 mm
M-Mount	+/-0.2 mm	+/-1.0 mm
Baseline	+/- 1.2 mm	-

Table 3: Ratings of the Restraints' Performance and Ease of Installation on a Scale of 1 – 5

Restraint	Performance	Installation
Partial M -Mount	3	2
E-Clamp	2	3
SSS	1	5
Delrin E-Clamp	4	1
M-Mount	5	4

SHIPPING FRAME SPRING CONFIGURATION TESTING

The original spring configuration of the springs (Fig. 4) on the shipping frame was thought to be too stiff to be providing enough cushioning to the CM. During initial testing with the JLab pCM, the total number of springs had been brought down from the maximum of 36 to 32.

The original shipping frame design had assumed the inner isolated frame to be rigid. This did not prove to be the case, and it was found that large deflections of the frame under the weight of the CM were further degrading the ability of the springs to soften shocks.

The new proposed spring configurations would have the springs concentrated near the points of attachment to the cryomodule, negating the effects of the flexible inner frame. A series of tests were conducted using configurations of 8, 10 and 12 springs. The new spring configurations were designed to lower the acceptable shocks on the CM from +/- 1.5g in all directions to 0.3g in the X-axis (lateral), 1.0g in the Y-axis (vertical), and 0.3g in the Z-axis (beamline/longitudinal); only shocks below 50 Hz were considered in the analysis, as those with higher frequencies were considered harmless to the CM. In addition, the resonant frequency in the Z direction should be significantly lower than the natural frequency of the FPC bellows (15 Hz), while being higher than the natural frequency of the air-ride suspension (1.5 – 2.0 Hz)

A series of tests were conducted at JLab using a concrete dummy CM with each of the three spring configurations [5]. SSXs and a SAVER9X accelerometer were used to

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measure the shocks and vibrations during the short trips from JLab to Richmond, VA (~100 miles). The 8-spring configuration was found to best reduce the shocks; the natural frequency of the system was 6.5 Hz in the Z-axis.

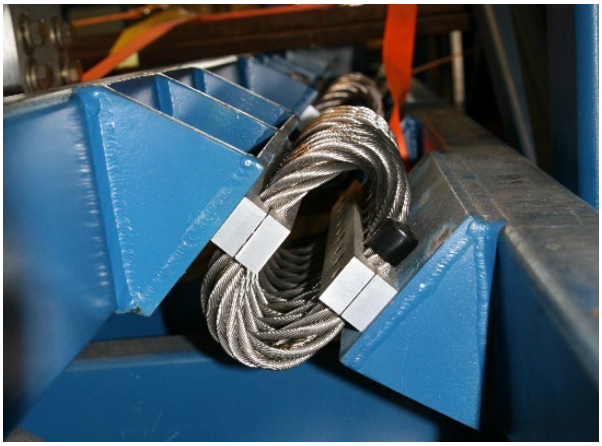

Figure 4: Helical isolator springs used on shipping frame.

CRYOMODULE ROAD TESTING

The broken coupler bellows on F1.3-05 were replaced to allow the CM to be used as a test bed for the new shipping restraints. Cavities 1 – 4 would have the E-Clamp installed and cavities 5 – 8 would have the Partial M-Mount. The CM installed on the 8-spring shipping frame would travel ~3,000 miles from Newport News, VA to Nebraska and back, which represents the distance between SLAC and JLab.

SSXs were installed on the 50K shroud and the 5K intercept on each cavity. Additional SSX unites were installed on the shipping frame on either side of the springs. A SAVER9X accelerometer was set up to record triggered shocks on the Inner Frame, Outer Frame and the cavity 2 coupler waveguide. Vacuum gauges logged the beamline vacuum throughout the trip and transmitted the readings live during the trip. The following was defined as the criteria for success:

- Beamline vacuum was not compromised
- The motion of the bellows was below +/- 2.0 mm
- The natural frequency in the Z-axis of the bellows system with the restraints was higher than the resonant 15 Hz
- The shocks on the CM were below 0.3g, 1.0g and 0.3g in the X, Y and Z directions

Cryomodule Road Testing Results

The tested CM returned from the 3,000 mile trip with no loss of beamline vacuum. The bellows displacement results in the Z direction from the SSX units on the couplers are shown in Fig 5. Cavity 4 had the E-Clamp and Cavity 6 had the M-Mount; a reading from when no restraint was used, and with 32 springs, is also given for comparison.

The graphs in Fig. 5 represent a random one-hour interval taken near the end of the trip; the horizontal axis defines the peak-to-peak bellows movement and the vertical axis defines the number of times the bellows made such a movement in the given hour. The amplitude for which there were 10 movement events is taken as the reported result in the following analysis.

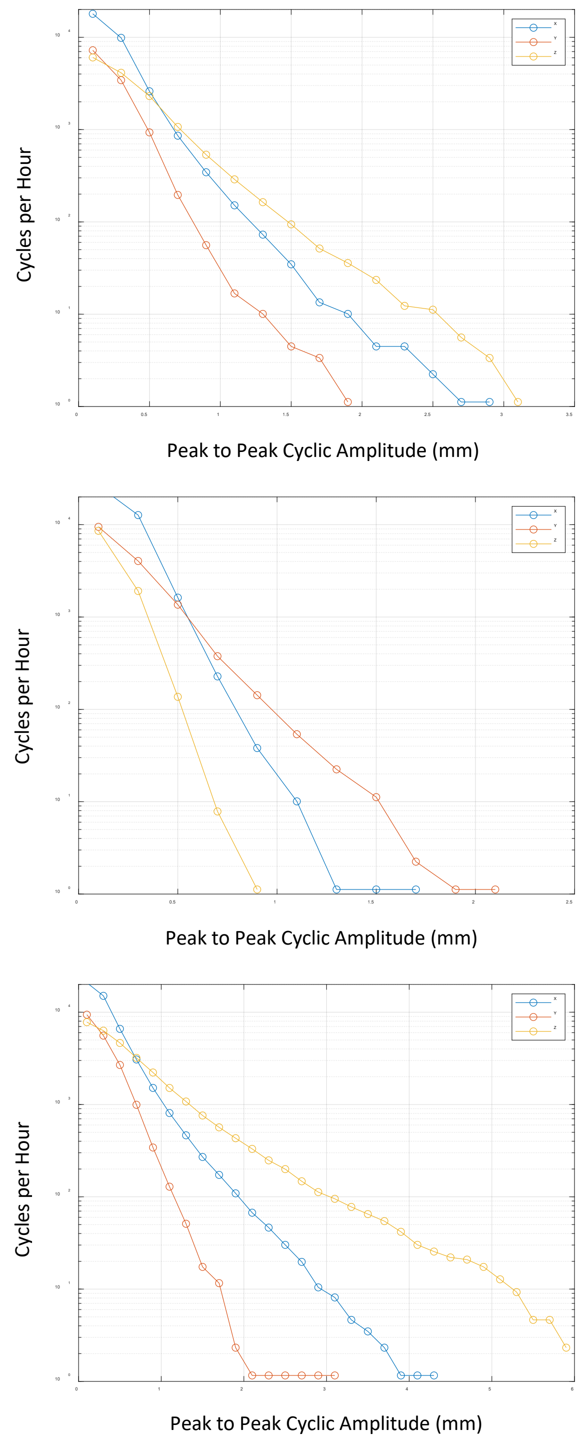

Figure 5: Peak-to-peak bellows motion with 8-springs on Cavity 4 with the E-Clamp (top), Cavity 7 with the Partial M-Mount (middle) and with 32 springs and no restraint (bottom).

Cavity 4 had a motion of +/- 1.2 mm while cavity 7 had +/- 0.35 mm. Without the restraint, the movement of cavity

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4 was +/- 2.6 mm. The cyclic movement of the bellows on each cavity and the resonant frequencies of each bellows system is shown in Table 4.

Table 4: Bellows Motion and Natural Frequencies During F1.3-05 3,000 Mile Road Test

Cavity	Motion - 10 count (+/- mm)	Frequency (Hz)
1 (E-Clamp)	0.60	33.0
2 (E-Clamp)	0.70	-
3 (E-Clamp)	1.05	40.0
4 (E-Clamp)	1.25	-
5 (M-Mount)	-	-
6 (M-Mount)	0.85	30.0
7 (M-Mount)	0.35	40.0
8 (M-Mount)	0.55	37.0

A sensor on Cavity 5 shook loose during the trip and did not provide accurate data. No discernible resonant frequency peak could be calculated for cavities 2 and 4; this may be due to the quick-grip clamp used on the E-Clamp interfering with other components inside the CM. All the cavities showed a reduction in bellows movement below the +/- 2.0 mm goal, and a resonant frequency raised above the 15 Hz excited during transportation. Due to its better performance and unobtrusive presence in the CM, the M-Mount (Fig. 6) was selected for future CM shipments.

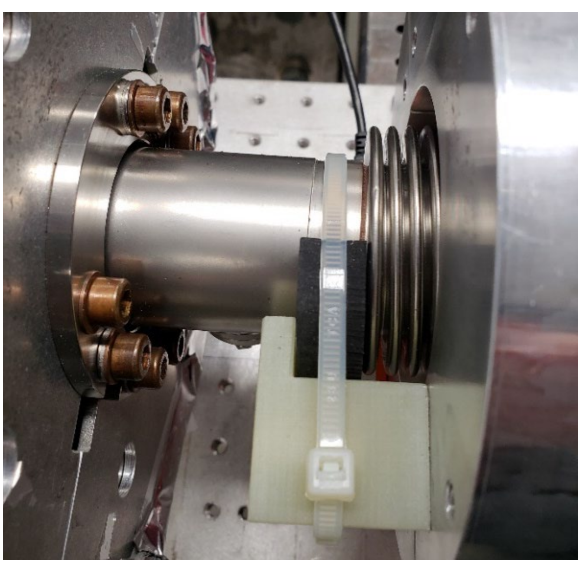

Figure 6: Partial M-Mount installed on a coupler with a zip-tie.

PRODUCTION CRYOMODULE SHIPMENTS

Since the successful road testing with F1.3-05, a further 14 CMs have been delivered to SLAC from JLab and FNAL using M-Mounts and the reduced spring configuration. There have been no failures in beamline vacuum due to shipment.

Table 5 shows the bellows motion on the CMs shipped from JLab and FNAL; all are below the outlined spec. Table 6 shows the highest shocks on the Inner and Outer Frames for the JLab shipments and the level of shock attenuation achieved by the new spring configuration. The highest shocks were seen in the vertical (Y-axis) direction, and are presented here.

Table 5: Bellows Motion (10 counts per hour) During Cryomodule Trips from JLab to SLAC

Cryomodule (Cavity)	Bellows Motion (+/- mm)
F1.3-05 (C1)	0.95
F1.3-05 (C6)	1.4
J1.3-10 (C6)	0.95
J1.3-12 (C1)	0.60
J1.3-12 (C6)	0.70
J1.3-14 (C1)	0.85
J1.3-14 (C6)	0.95

Table 6: Comparison of Highest Vertical (Y-axis) Shocks on CMs Shipped from JLab to SLAC

CM	Outer Frame (g)	Inner Frame (g)	Attenuation (%)
J1.3-04	3.14	1.26	59.9
J1.3-08	2.82	0.64	77.3
J1.3-10	3.06	0.88	71.2
J1.3-13	3.68	1.03	72.0
J1.3-14	3.01	0.56	81.4
J1.3-12	1.82	0.50	72.5

SUMMARY

Early failures in CM shipments to SLAC were attributed to excessive motion in the FPC bellows, which lead to fatigue failure and venting of the beamline vacuums. A removable restraint was developed that could lessen the amplitude of the bellows motion, while also increasing the system's natural frequency to one not excited by the road transport. The restraints were designed with the aim of retrofitting them on CMs that had been fully assembled and tested. The spring configuration of the shipping frame was also changed to lower the shocks on the CMs during shipment. After successful testing on a shaker table and an already vented CM, the restraints were put in service for all production CM shipments. Sixteen CMs have been shipped from JLab and FNAL to SLAC to date with no failures from shipping.

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