REFERENCING AND STABILITY STUDIES OF THE FERMILAB 3.9 GHZ (3RD HARMONIC) CRYOMODULE FOR DESY TTF/FLASH*

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Abstract

As a part of TESLA Technology Collaboration activities and Fermilab/DESY technology transfer agreement, Fermilab is involved in an effort to build and deliver a 3.9 GHz (3rd harmonic) cryomodule for use at DESY TTF/FLASH facility in 2008. Transport and alignment stability studies were performed in order to assess risk associated with transatlantic travel of a fully assembled cryomodule. The paper discusses preliminary shock and vibration measurements and deformation analysis results during transport studies, as well as stabilization techniques.

INTRODUCTION

Fermilab will provide a 3.9 GHz cryomodule to Deutsches Elektron-Synchrotron (DESY) Laboratory in Hamburg, Germany for the Tesla Test Facility (TTF)/FLASH in an exchange of technology agreement between the laboratories. In this exchange, last year DESY provided a 1.3 GHz TTF cryomodule to Fermilab. Cryomodule transport design acceleration criteria were initially established by considering the Spallation Neutron Source (SNS) transport [1]. A transport analysis completed by Babcock Noell found that the shock limits for the input coupler (perpendicular to the antenna) must be less than 1.5 g [2]. During the Fermilab transport studies, minimum design shock values for testing was established as 4 g (vertical), 5 g (transverse) and 1.5 g (longitudinal).

Two configurations of 3.9 GHz cryomodule shipment to DESY were considered: as individual components or as a fully assembled cryomodule. The optimal configuration from an assembly perspective was a fully assembled cryomodule, yet the assembly would not only need to survive, but also maintain pre-transport alignment. Also, the transport studies provided a unique opportunity to investigate cryomodule shipping. The development of a coldmass mockup shown in Figure 1 was essential in this shipment configuration selection process as testing actual components was not possible. Use of this coldmass mockup continues to provide important information regarding relative shock experienced at each cavity, movement and resulting relative misalignment.

A 3.9 GHz cryomodule consists of four dressed 9-cell niobium superconducting radio frequency (RF) cavities. The coldmass hangs from two column support posts constructed from G-10 fiberglass composite, which are attached to the top of the vacuum vessel. The helium gas return pipe (HeGRP), supported by the two columns, act as the coldmass spine supporting the cavity string and ancillaries. Brackets with blocks on two sides provide a connection between each cavity and the HeGRP. Two aluminum heat shields (80 K and 5 K) hang from the same two column supports. The coldmass consists of all components found within the 80 K shield shown in red (Figure 1).

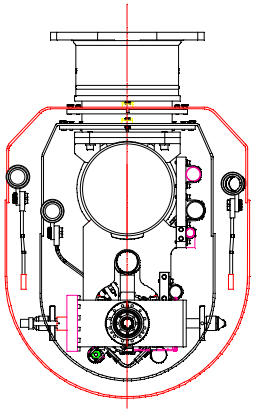

Figure 1: Cross-sectional view of coldmass mockup.

Transport and Alignment Strategy

Only a combination of transport modes is possible as this is a transatlantic shipment. Transport via rail and ship was ruled out, since shock and vibration loads with such modes are quite large [3]. With air freight travel being most viable, initially the studies focused on shock and vibration associated with aircraft and truck transport. SNS cryomodules have been successfully transported via air-ride truck from Thomas Jefferson National Accelerator Laboratory (JLab) in Newport News, Virginia to Oak Ridge National Laboratory in Tennessee [1]. Given the modes of transport, shock limit criteria and final relative alignment requirements, a strategy for testing was developed. This strategy involved the development of an isolation system, exposing the coldmass mockup to peak and accumulative shock, and subsequent evaluation of alignment during this process.

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TRANSPORT ASSEMBLY DESIGN

The system shown in Figure 2 is relatively stiff and slightly under-damped with isolation which reduces shock by a factor of 2. It was determined that the center of gravity (CG) was high with respect to the center line of the isolators. This effect caused an exaggeration of cryomodule motion, and increased transverse and longitudinal shock due to forces acting on the cryomodules from rotation. In the proposed isolation system the distance from the CG to the isolator centerline will be halved. Realizing that changes in the base frame and isolation fixture were necessary, studies continued to optimize our understanding towards improvement. Meanwhile, the proposed isolation system is under design.

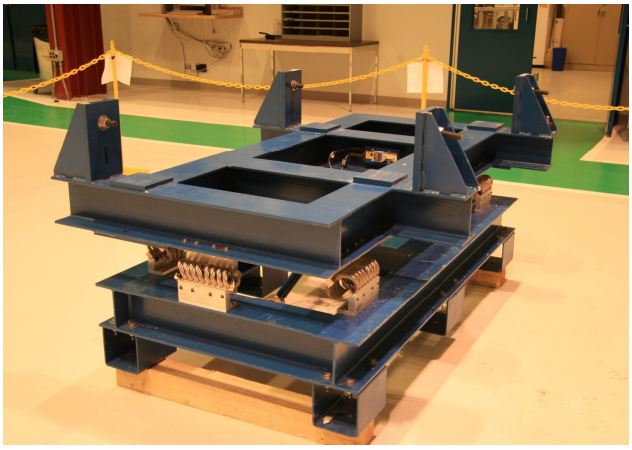

Figure 2: Initial base frame and isolation fixture.

Coldmass & Cryomodule Mockup

A combination of composite plastic (REN471) and stainless steel were used to simulate the coldmass: dressed cavities, interconnect bellows and beam valves in a model form, shown in Figure 3. This mockup was identical to the original coldmass in terms of geometry and mass. Instrumentation fixtures with geophones were added at this point of the assembly.

Figure 3: Coldmass mockup.

Subsequently, two heat shields were added to the coldmass mockup, and the assembly was inserted into a vacuum vessel, shown in Figure 4. The DS column is allowed to move longitudinally to allow for thermal contraction during cooldown. However, during transport the support columns will be locked against the vacuum vessel penetration flange. The constraints are being closely evaluated during the initial transport studies.

Figure 4: Insertion of coldmass mockup into vessel.

Special alignment panels shown in Figure 5, two per cavity were used for relative optical measurement to an external reference. Two intersecting wires cross along the diagonal, one cross hair per cavity provided a target. The main challenge of the actual transport involves limited access to the internal cryomodule components after shipment to DESY. Fully assembled, the cryomodule must hold a stringent relative cavity alignment vertically and transverse (to beam) direction. If a relative cavity misalignment occurs, DESY personnel would not have the fixtures necessary to remove the cavity string from the vacuum vessel. The alignment panels have a two-fold function: assist in initial assessment of transport stability studies and provide an efficient means for post-transport survey.

Figure 5: Special alignment panels (found on both sides).

TRANSPORT STUDIES

The effects of shock and vibration are important from both a perspective of protection and maintaining alignment. Two types of testing were implemented: subjecting the base frame to peak shock by using a pendulum hammer apparatus and accumulative effects via over-the-road loading. Peak shocks were applied uniformly in three-axis at six points along the base frame.

Preliminary Results

Three periods of testing to date have involved both over-the-road studies and peak shock testing. As a first pass, the coldmass mockup was tested using an air ride step-back flatbed truck, over-the-road covering a 5 km route within the Fermilab site. Three geophones were mounted onto each cavity with three geophones also attached to the isolation fixture and base frame in October 2007. Following the coldmass insertion into the vacuum vessel, a similar Fermilab site cryomodule mockup transport study was performed in December 2007. Two subsequent off-site interstate cryomodule mockup over-the-road transport studies were completed. Figure 6 gives the velocity profile of the truck during the Fermilab site transport study, reaching over 61 km/hr, yet the maximum acceleration in any direction was beneath 1.5 g.

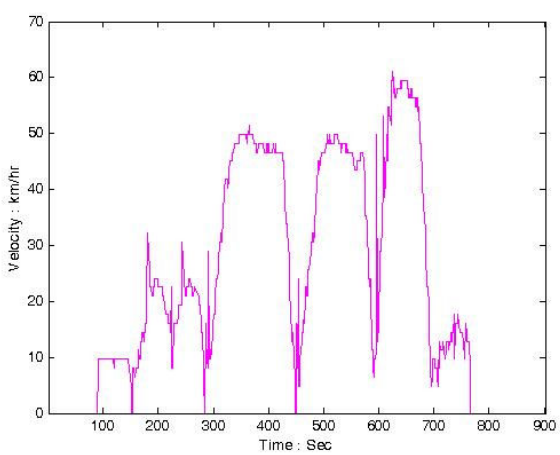

Figure 6: Truck velocity during Fermilab site study.

Figure 7 depicts the transverse peak shock found on individual cavities, 1 through 4 compared to the base frame and truck acceleration/de-acceleration. Absolute longitudinal acceleration and de-acceleration of the truck was measured using a GPS unit. No correlation was found between these loads with the peak values reported. The peak values were estimated each second by differentiating velocity (measured using geophones). The transverse case reflects the most extreme shock condition during the Fermilab site transport study, reaching ~1 g at cavity #4. The shock values of these cavities are comparable.

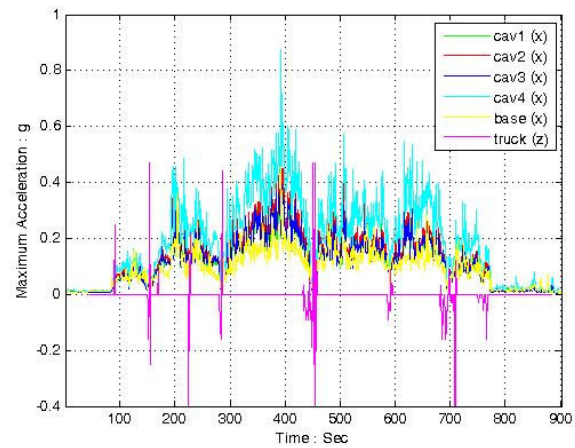

Figure 7: Transverse shock values on individual cavities.

Longitudinal peak shock values averaged across all four cavities reached 0.48 g, shown in Figure 8. Peak shock values found on the isolation fixture and base frame are also given. Lower values of shock observed on the isolation fixture as compared to the cavities indicate that the cavities are moving or flexing with respect to the vacuum vessel.

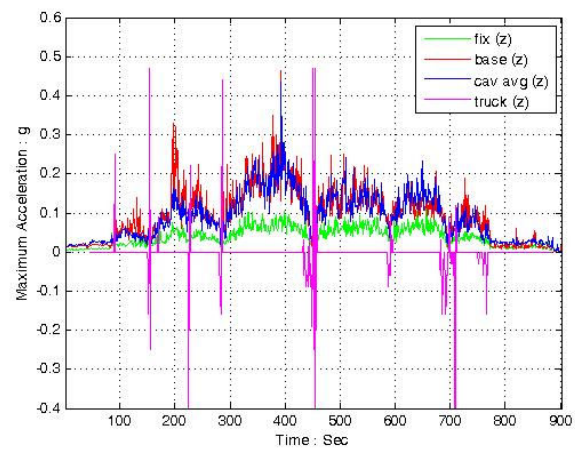

Figure 8: Longitudinal shock values.

Vibrational response during the Fermilab site road test was dominated by low frequency. This response of the cryomodule was driven by increasing speed, coupled through the vehicle's drive train. The isolation system was effective at high frequencies, above 10 Hz, damping vibration from the flatbed. At low frequency, coherently, cavities moved transversely more than the isolation system. The cavities (and coldmass) are very stable vertically, shown in Figure 9. The cavities were not affected by vertical shock.

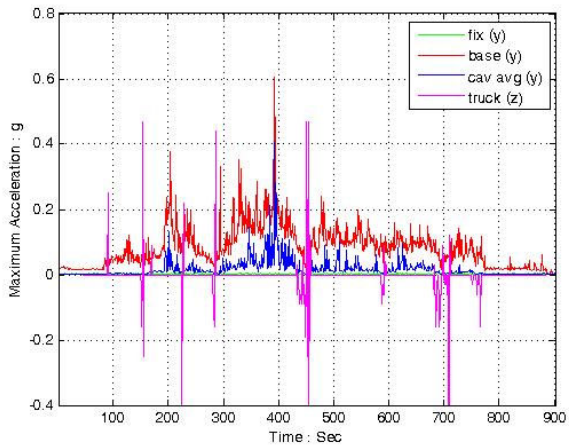

Figure 9: Vertical shock values.

Figure 10 provides the peak displacement during transport of the base frame and cavities in x, y and z-direction. Transverse motion of the isolation fixture reaches 1.6 mm with longitudinal displacement lagging around a peak of ~1.4 mm. The cavities are affected by low frequency transverse and longitudinal shock. Currently, the coldmass is not constrained longitudinally or in the transverse direction. However, dampers applied in these areas can significantly reduce shock and motion in these directions.

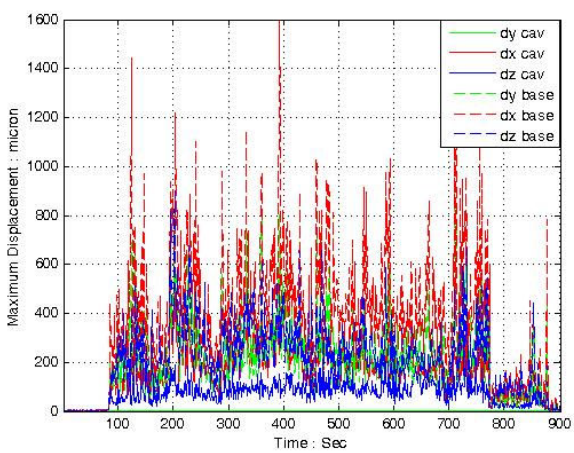

Figure 10: Maximum displacement of components.

ALIGNMENT STUDIES

The alignment stability aspect of the transport studies involved monitoring the deformation or displacement of the cryomodule components and assess if proper alignment within the cryostat vessel is maintained. Of greatest concern are the alignment tolerances and the long-term position stability of the cavities within the cryostat vessel. In principal, the cavities must maintain their relative alignment within the cavity string, while to a lesser extent also maintaining the alignment with respect to the vacuum vessel.

DESY has indicated the overall alignment tolerance requirement of the cold cryomodule for the TTF/FLASH accelerator to be 0.5 mm. An error budget analysis, including among others the referencing of cavities centerline, thermal cycling (warm up cool down), cavity string alignment and referencing to the vessel, string misalignments due to shipping, gave a maximum tolerance for alignment and cavities shift during transport of 0.25 mm.

The precision required for monitoring the alignment deformation places stringent requirements on the methodology and instrumentation used to measure and analyze anomalous drifts in the cavity string. An optimization study on alignment sensitivities led to a 1.5 ratio of required resolution for quantifying physical misalignments, representing 60% from the total budgeted allowance of 0.25 mm. Consequently, the surveying methodology, techniques, and instrumentation employed amounted to an absolute maximum error of 0.15 mm, while the relative measurement errors between observation points were in the 0.050 mm range.

Prior to the test, a high-accuracy Laser Tracker reference control network was established throughout the Industrial Central Building, where the cryomodule resides in the Vacuum Vessel Assembly Area. The network was processed as three-dimensional trilateration (with distances derived from Laser Tracker observations), and supported by precision leveling. The relative errors obtained between reference control points were below ±0.1 mm at 95% confidence level throughout the network.

Besides the special alignment panels attached to each cavity implemented during the engineering design, more referencing points were installed on the coldmass, as shown in Figure 11, and the vacuum vessel to provide adequate densification for identifying possible deformation sources. Cavity off-axis travel can result through a deformation or a shift of its supporting structure, which must remain in position to a tolerance of about 0.1 mm to permit the cavity string to stay aligned within tolerance.

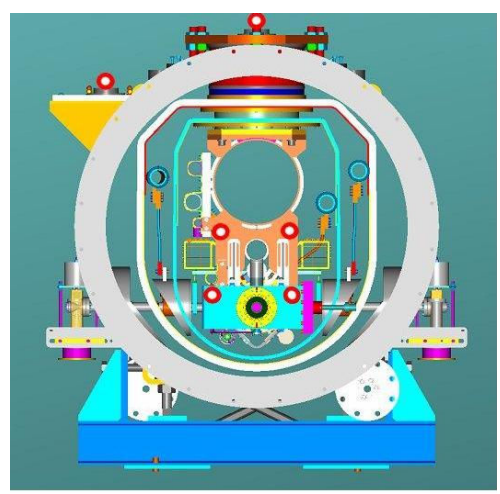

Figure 11: End view of cryomodule solid model.

After an initial precision survey before the transport studies, subsequent survey epochs were performed following each testing phase, using the same procedure and instrumentation, in a carefully controlled environment.

The instrumentation used was the API Laser Tracker, precision optical levels and precision optical alignment telescopes. All the referencing points on the vessel and coldmass were measured each epoch with the Laser Tracker and with optical instrumentation. This provided data redundancy and also means to better estimate observation accuracy and weighting parameters for the different type of instrumentation employed.

Only the special alignment panels were measured with optical instruments, not being accessible with the Laser Tracker inside the vessel. All the points were observed horizontally from two alignment telescopes, as shown in Figure 12, operating on precision digital tooling bars positioned rigorously perpendicular to the axis of the vessel at each end of the cryomodule.

Figure 12: Dual alignment telescopes setup

Additionally, the following features were determined by Laser Tracker observations: the centerlines of the vacuum vessel and HeGRP, and the planes of the support posts and the vessel's coldmass mount flanges.

A two-step process was used to integrate the Laser Tracker and optical measurements. A set of coordinates in a local system and their associated variance-covariance matrix was calculated for all the points observed, for each survey epoch.

The standard local coordinate system, shown in Figure 13, is invariant to deformations. It is a right-handed system, with the origin at the upstream post survey monument and the following axis orientation: the Y axis (axial) passes through the two posts survey monuments (along the cryomodule pointing downstream), the Z axis (vertical) is normal to the posts plane and pointing upward and the X axis (lateral) is orthogonal to the other two axes and pointing toward beam right looking downstream cryomodule.

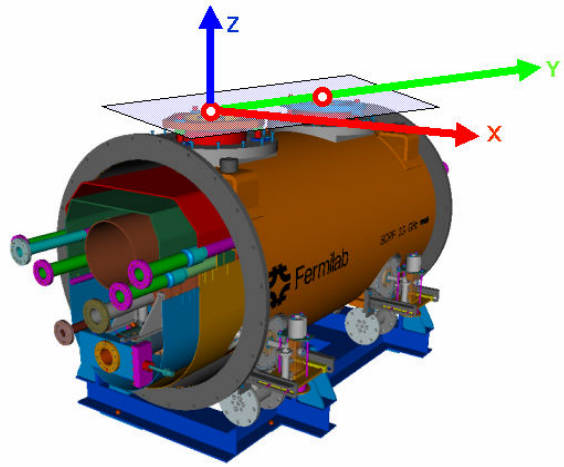

Figure 13: Local coordinate system invariant to deformations

Preliminary Alignment Results

An analysis including physical misalignments, their amplitude and associated errors was performed after each transport test. Two deformation studies were analyzed: one regarding relative displacements with respect to a local fix coordinate system that remains invariable to deformation, the other in terms of displacements between subsequent tests. A threshold based on the root mean square (rms) alignment sensitivities corresponding to 0.150 mm error bar was used to flag misalignments.

The first study indicates lateral movements of the coldmass (pendulum effect) around a rotation center located where the supporting posts sit on the vessel mount flanges. As shown in the vector deformation model in Figure 14, the resting position of the coldmass after the first peak shock test indicates a clockwise rotation (roll).

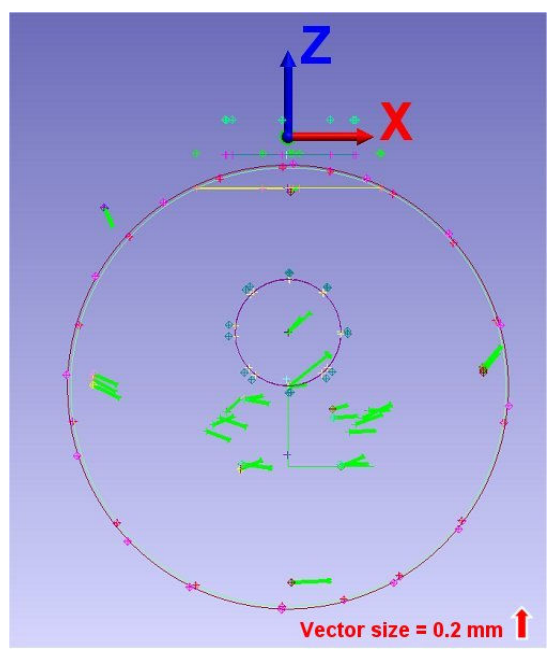

Figure 14: Vector deformation model post peak shock test 1

Figure 15 shows that after second peak shock test, the coldmass rests in a counterclockwise rotation position with respect to the invariant coordinate system.

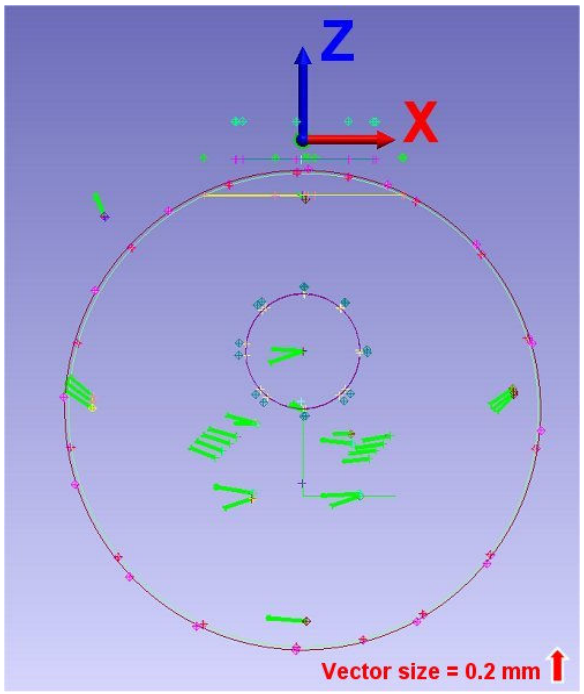

Figure 15: Vector deformation model post peak shock test 2

The results of this study indicate that all the deformation vectors are within the admissible tolerance and the cavities still maintain their relative alignment within the cavity string.

The second study also indicates that, while the cavity string ensemble was subject to small displacements between subsequent transport tests, the cavities still maintain their relative horizontal and vertical alignment with respect to a straight line within 0.1 mm, as shown in Figures 16-19.

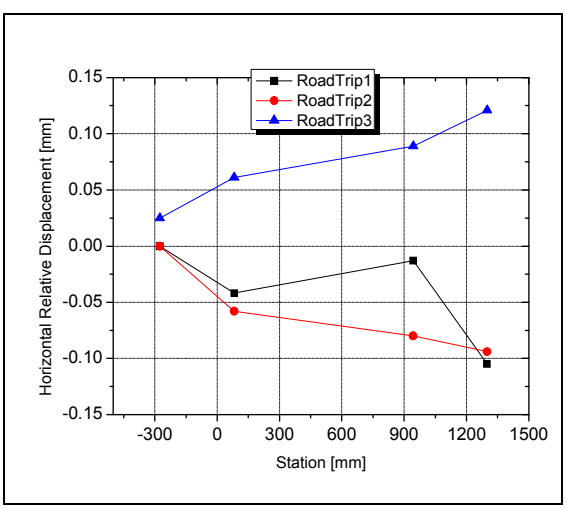

Figure 16: Cavities horizontal displacements post road tests

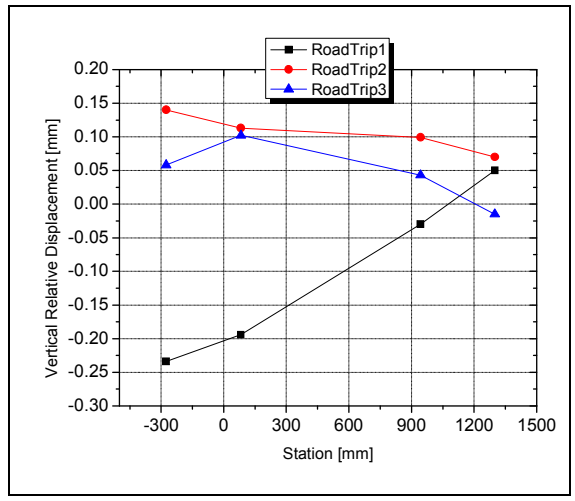

Figure 17: Cavities vertical displacements post road tests

The overall maximum transversal shift of the cavity string among all the tests was 0.3 mm horizontal (Figure 18) and 0.4 mm vertical (Figure 19).

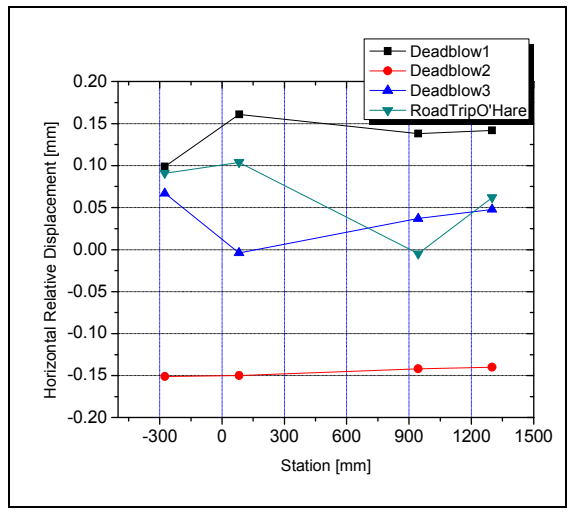

Figure 18: Cavities horizontal displacements post peak shock tests

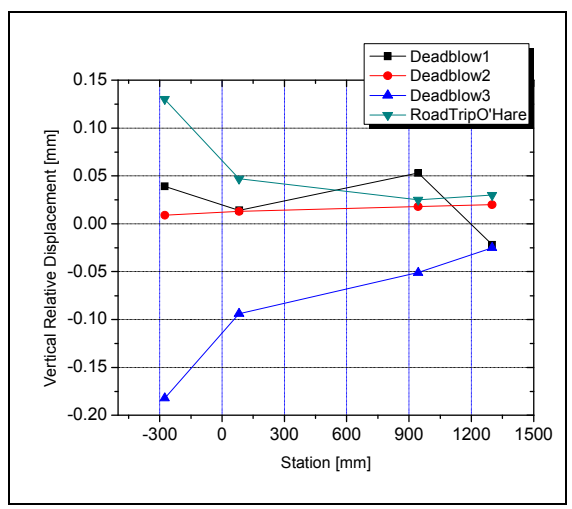

Figure 19: Cavities vertical displacements post peak shock tests

This condition would imply that a re-referencing of the vacuum vessel's fiducials with respect to the new position of the cavity string might be necessary at destination. Additionally, the unsupported ends of the gate valves showed displacements as much us 0.8 mm on one of the road trips.

The efficiency of this analysis procedure permitted us to have a dynamic response during the transport studies by providing preliminary results within days of each test phase. The immediate feedback provided to the mechanical engineering team helped them correlate the various measurements collected during the tests with the alignment results.

In the next step regarding the alignment deformation monitoring studies, a Stable Point Analyses including all the survey epochs for all the transport tests will be performed, as a more refined and sensitive approach of identifying displacement vectors, employing the Iterative Weighted Similarity Transformation (IWST) method.

CONCLUSIONS

Preliminary analyses indicate that the cavities maintain their relative alignment of 0.1 mm with respect to a straight line within the cavity string; however, the alignment with respect to the vacuum vessel is only marginal to the allowable tolerance. During the transport studies the cavity string was affected by transverse and longitudinal shock at low frequencies (beneath 10 Hz). Cavities moved coherently (as one) in the transverse direction, responding to shock and vibration.

We are encouraged by the measured reduction in shock of roughly one-half, yet further isolation system tuning is needed to ensure proper shock attenuation and vibrational stability, while shifting the system's natural frequency. Further work (or damping) is also needed to minimize the transverse and longitudinal motion of the coldmass. Implementation of the new base frame with the coldmass mockup is planned.

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