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DESIGN OF A TRANSPORT SYSTEM FOR THE PIP-II HB650 CRYOMODULE

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Abstract

The PIP-II Project at FNAL requires the assembly of 3 high-beta 650MHz cryomodules at STFC Daresbury (DL) in the UK. These modules must be safely transported from DL to FNAL in the USA. Previous experience with cryomodule transport was leveraged at both labs to design a transport system to protect the cryomodules during transit. Requirements for the system included mitigation of shocks, drops, and vibrations, and acting as a lifting fixture. It is comprised of a tessellated steel frame which encompasses the module with a wire rope isolator arrangement which the module mounts to. The frame was designed to withstand the weight of the 12.5 tonne cryomodule in various load cases. Details of shock and vibration profiles were obtained from MIL-STD-810H and were used to guide the sizing of passive isolators. The frame and the isolation system were analysed via FEA using the shock and vibration profiles as an input. The transport system was found to be suitable for the given isolation, frame stiffness, and lifting code requirements. The frame has been fabricated and successfully load tested at FNAL. It will now be road tested with a dummy cryomodule before undergoing a trial run to DL.

INTRODUCTION

For the Proton Improvement Plan II project, 3 high-beta 650 MHz (HB650) cryomodules will be assembled at STFC Daresbury Laboratory (DL) in the UK. The completed modules will be transported to the Fermi National Accelerator Laboratory (FNAL) in the USA. A transportation system was designed to protect the cryomodules from forces experienced during transit and facilitate handling operations.

REQUIREMENTS

The principle design conditions were defined as follows:

1. Transport the 12.5t, 10m long HB650 cryomodule in its transport configuration from DL to FNAL.
2. Suitable for road and air transport, therefore must fit within their respective cargo envelopes.
3. Mitigate logistical drops and mishandling events.
4. Isolate cryomodule from external shocks such that shocks experienced are less than 2.5g peak vertically, 3.5g longitudinal, and 1.5g transverse.
5. Isolate vibrations above 10 Hz by at least 80% relative to input vibrations.
6. Enable the cryomodule to be lifted via frame lifting points.
7. Resist sustained transportation loads, e.g., braking, cornering, accelerating.

DESIGN

The transport frame was influenced by lessons learnt from the LCLS-II and ELI-NP projects. These utilised wire rope isolators mounted between a base frame and inner frame to isolate the modules from transport forces (Fig. 1). The stiffness of the inner frame and the positioning of the isolators was found to be critical [1]. The current design for the HB650 cryomodule is displayed in Fig. 2. The following features can be identified:

- A tessellated steel outer frame encompassing the module to provide protection and restrict access.
- A removable top section for loading.
- 4 lifting points suitable for a 30° direct lift.
- Isolator mounts welded directly to the cryomodule.
- 7 isolators on each side, one positioned under each strongback support.
- 7 cradles to link pairs of isolators and ease assembly.
- Frame envelope minimised for transport compatibility.

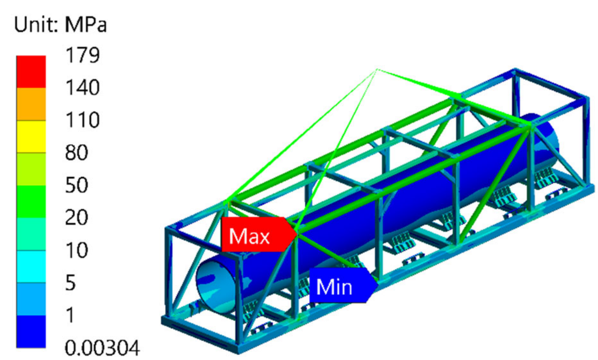

Figure 1: Von-Mises stress in the transport frame during a 200% lift.

Static Loading

BS EN 13155:2003 [2] was referenced to ensure that the outer frame met the requirements of a lifting fixture. Compliance required the frame to be designed to withstand 200% of the weight of the load, without exceeding the specified yield stress limits of the welds and main structure. Figure 1 shows the output of the FEA study for the design, which was used to iterate the design to achieve a 30° lift within the stress limits required.

Static loads associated with transport forces were also analysed against the lifting yield limits, though no case was as severe as the 200% lift.

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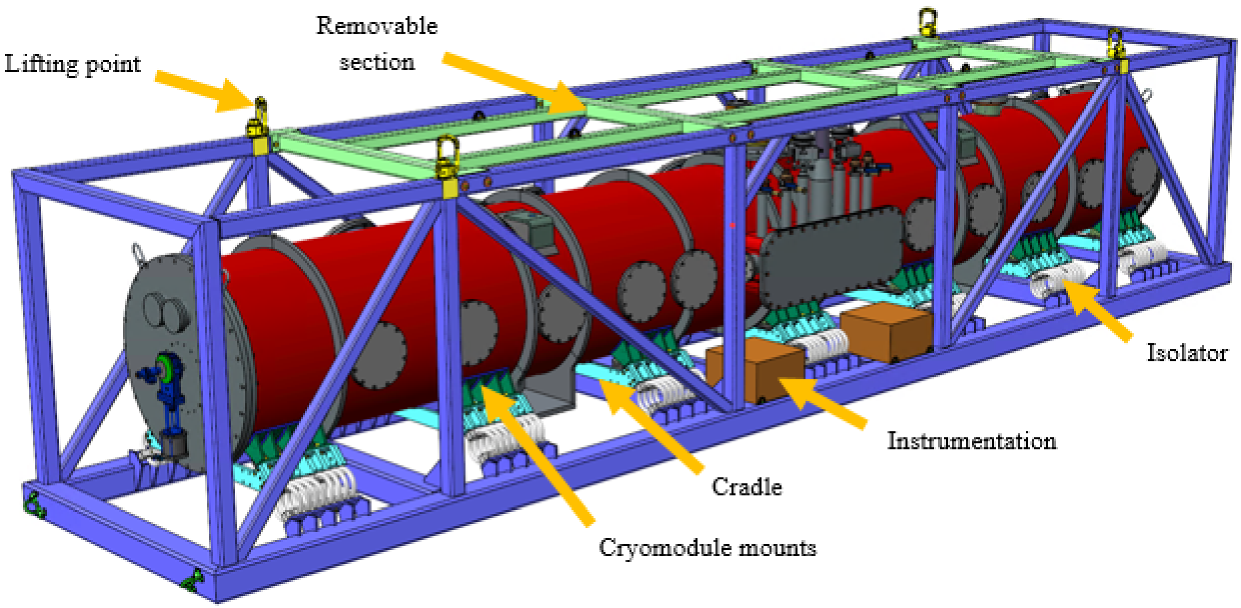

Figure 2: Transport system with mounted HB650 cryomodule.

Physical Constraints

The most challenging requirement was fitting the transport system within a Boeing 747-400F cargo envelope, which had a cross-section of 2.4m x 2.4m. It was not feasible to transport the 2.3m tall HB650 with its top extension port installed in addition to the isolation system. FNAL designed a transport configuration that reduced the height to 1.8m, however this was still a limiting constraint once the lifting eyes and movement of the module on the isolators had been considered.

Other considerations included the road vehicle envelope, available lifting height, and assembly requirements. Areas were also allocated for storing instrumentation and tooling.

Vibration

FEA was used to predict the vibration response of the transport system. Acceleration spectral density (ASD) profiles were obtained from various standards to serve as the input condition. These included ISO 13355:2016 [3] and ASTM D4169 - 16 [4] for road transport vibration, and MIL-STD-810H [5] for air and road transport vibration. To accommodate all transport environments, an input ASD profile was generated using the peaks of all 4 reference profiles, as shown in Fig. 2.

A simulation was conducted which included the transport frame, a mass representing the cryomodule, and wire-rope isolators modelled as bushing elements. The bushing elements enabled the entry of the non-linear wire-rope data. A modal analysis was conducted which was then input into a random vibration study with the combined ASD. This resulted in an expected isolation of the input vibration of at least 90% above 10Hz.

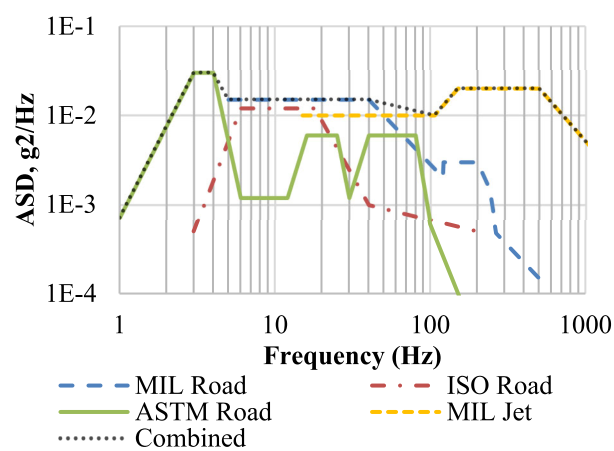

Figure 2: ASD data from various sources.

Shock

MIL-STD-810H [5] defines shock profiles for a variety of conditions in Method 516.8 procedure II. For the transport frame, the worst case on-road transportation shock was used as the input for the design. This is defined as a terminal peak saw tooth with 11ms duration and 7.6g peak.

A transient structural study was conducted which applied the reference shock to the base of the frame in each of the three directions separately. This resulted in a maximum response of 0.98g in the transverse direction.

Drop

Handling at each of the laboratories is well controlled, however, the airport handling operations are not. There is therefore a significant risk of damage due to logistical drops, which the transport system was required to mitigate. This involved sizing the wire-rope isolators to maximise their impact energy absorption while maintaining the de-

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celeration within the cryomodule specification. This ultimately resulted in the largest isolators that would fit within the space constraints.

Another design decision to reduce drop risk was to force the use of a crane by excluding forklift interfaces. ELI-NP data had shown that shocks during unloading were greater than those experienced across the journey itself.

VALIDATION

Little information was found regarding the performance of wire-rope isolators in practice, particularly for drop events. There was also some uncertainty with the data supplied by the wire-rope isolator manufacturers, therefore a drop experiment was conducted for clarification and validation of performance. The cryomodule transportation system designed for the HiLumi crab cavity cryomodule was used in lieu of the PIP-II system, however it was designed with the same isolators (Fig. 3). Pairs of accelerometers were mounted on either side of the isolators, and laser sensors were attached to measure the displacement between the frame, dummy module, and ground.

Figure 3: Drop test arrangement. Isolators between blue frame and red arms. Concrete mimics cryomodule mass.

Figure 4 shows vertical test data from a 30mm drop, where 80% isolation was observed between the base frame and dummy module. A mean isolation of 82% was achieved across all accelerometers in all axes. This demonstrated that the isolators could effectively mitigate drops events. The data also confirmed that the isolator system modes were generally within 10% of the corresponding FEA simulation. This gives confidence in the design methodology used and also highlights an opportunity for improvement.

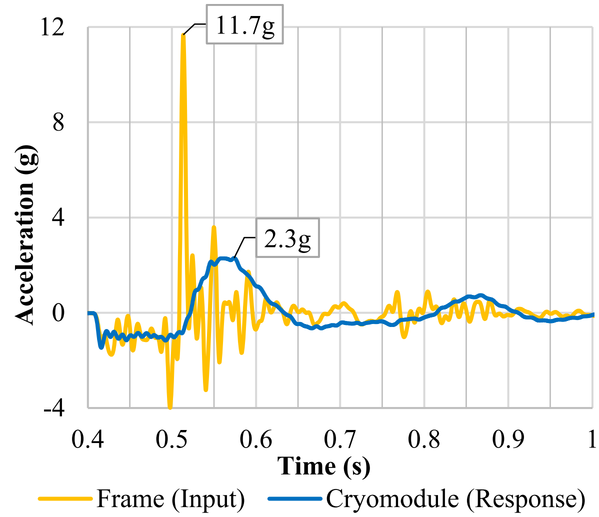

Figure 4: Data from a pair of accelerometers, vertical axis.

The PIP-II transport system has now been fabricated and passed its 200% load test, which proves the design is structurally sound. It has now undergone a road test with a load representative of the cryomodule to determine its shock and vibration characteristics [6].

CONCLUSION

A transport system has been designed to carry an HB650 cryomodule from DL to FNAL by both road and air. Analysis and preliminary testing indicates that the design is suitable for the given isolation and lifting code requirements. Incorporating lessons learnt, dedicating design effort to transportation, and conducting initial testing, has given the HB650 the best possible chance of arriving intact.

ACKNOWLEDGEMENTS

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