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TEST SHIPMENT OF THE PIP-II 650 MHz TRANSPORT FRAME BETWEEN FNAL TO STFC-UKRI*

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Abstract

The PIP-II Project will receive fully assembled cryomodules from CEA and STFC-UKRI as in-kind contributions. Damage to these cryomodules during transport is understood to be a significant risk to the project, so an extensive testing and validation program is in process to mitigate this risk. The centerpiece of this effort is the eventual shipment from FNAL to STFC-UKRI and back of a prototype HB650 cryomodule with cold testing before and after shipment to verify no functionality changes from shipment. Most recently, a test shipment was completed to the UK and back using a cryomodule analog using realistic logistics, handling, instrumentation, and planning. The process of executing this test shipment, lessons learned, and plan moving forward will be presented here.

INTRODUCTION

The PIP-II SRF linac is composed of five types of cryomodules at 3 sub-harmonics of 1.3 GHz (162.5, 325, and 650 MHz) [1]. The 650 MHz section of the linac is composed of two cryomodule types, Low-Beta (LB) and High-Beta (HB). The PIP-II Project has significant international contributions in almost every part of the machine, and the 650 section is no exception. The LB modules are being designed and produced by CEA in France while the HB modules are produced by STFC-UKRI in the UK as in-kind contributions to the project. The PIP-II project has adopted the design philosophy of convergent design, aligning the techniques and technologies between different modules as much as possible. This philosophy extends to transportation of the LB and HB modules from the partner labs in Europe to FNAL. Transportation experts at all three labs have worked closely to ensure that a consistent and systematic approach is used for assessing and mitigating the risks of these critical cryomodule transports.

TRANSPORT SYSTEM VALIDATION STRATEGY

A conservative approach to transportation and transport validation has been adopted by PIP-II driven by past experience with cryomodule shipping for LCLS-II [2]. This includes the choice to forego sea and rail, relying on air transport for the transatlantic segments. The following major stages are chosen to systematically validate the integrated transport system design (cryomodule plus shipping frame) while minimizing risk to critical equipment.

1. Design, fabrication, and integration of HB650 transport frame with cryomodule analog (Dummy Load)
2. Local road testing with Dummy Load to validate isolation and handling performance
3. Realistic transport of Dummy Load from FNAL to STFC-UKRI to validate air transport and handling
4. Local road testing with a cold-tested and validated prototype HB650 (pHB650) to reverify isolation performance as well as any module-internal resonances
5. Realistic transport of the pHB650 module from FNAL to STFC-UKRI and back, concluding with second cold-test to assess impacts of transatlantic shipment on cavity performance.
6. Design optimization of HB650 and LB650 transport frames by the respective partner labs.
7. Integration tests and local road testing with first article modules produced by partners.
8. First shipment of production modules from partners to FNAL for the PIP-II Linac, proceeding to regular shipment of the remaining items.

The transportation scope of each partner is distributed based on many factors which are outside the scope of this document. The diversity of activities and design details of both transport systems and cryomodules means that it is critical that the transportation approaches are aligned and designs and lessons learned are shared strongly as early as possible within the project to minimize duplicated effort or increased risk.

TRANSPORT SYSTEM DESIGN

The transport system, designed by STFC-UKRI [3], is a tessellated steel frame meant to enclose the cryomodule during transport, isolating the CM during transport with wire-rope isolators sized for the weight and shocks/vibrations expected during transport. The model of the transport system (frame, isolators, and CM) can be seen in Fig. 1. The frame is covered in plywood panels during transport to prevent access and protect from weather. Access ports were added to allow instrumentation inspection during transport, viewing windows in case of customs inspections, and labeling for ease of assembly.

VALIDATION PROGRESS

The documentation and specification process used by the PIP-II project to manage this transportation work, especially across the international collaboration, is detailed in a previ-

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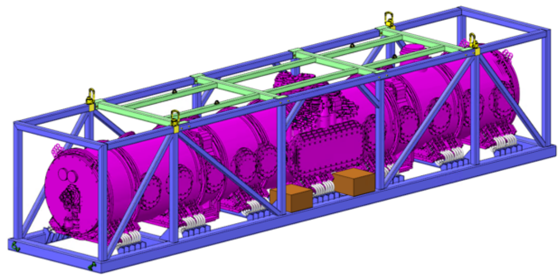

Figure 1: Model of the HB650 Transport System including support frame (blue and green), isolators, space reserved for instrumentation (brown), and cryomodule envelope (purple).

ous paper [4]. This reference also documents the successful completion of stages 1 and 2 listed above.

This paper will document the successful completion of the 3rd item, realistic shipment of the Dummy Load from FNAL to STFC-UKRI including results, lessons learned, and implications for the remaining validation stages.

Transport Description

Transport was contracted with a shipping vendor (AIT) who subcontracted with CargoLUX for air and European truck transport. The major transport stages were:

1. Integration of the Dummy Load in Transport System at FNAL
2. Loading onto Trailer at FNAL
3. Road shipment to O'Hare
4. Unloading at O'Hare and storage
5. Aircraft loading at O'Hare
6. Air transport to LUX
7. Aircraft unloading at LUX and storage
8. Truck loading at LUX
9. Transport to EU-UK border
10. Channel transit
11. Road transport from Chunnel to STFC-UKRI including customs clearance
12. Unloading at STFC-UKRI
13. Load turnaround at STFC-UKRI

Each of these stages has an equivalent reverse stage on the transit from STFC-UKRI to FNAL. Outbound and inbound equivalent stages will be discussed in the same sections. The broad categories of these activities are covered below.

Transport System Integration

The dummy load was prepared per reviewed assembly procedures and travelers several times, first at FNAL prior to departure, then disassembly and reassembly at STFC-UKRI. This stage includes removal/installation of outer paneling, rigging of top frame, rigging of dummy load, and disconnection and connection of dummy load to cradle/isolator systems. Overall, this process had been practiced and refined significantly prior to this shipment, mostly because of the complex transport frame/cryomodule interfaces (seen in Fig. 2). Despite this practice, there were some major lessons learned, especially when the procedures were performed for the first time by the STFC-UKRI crews.

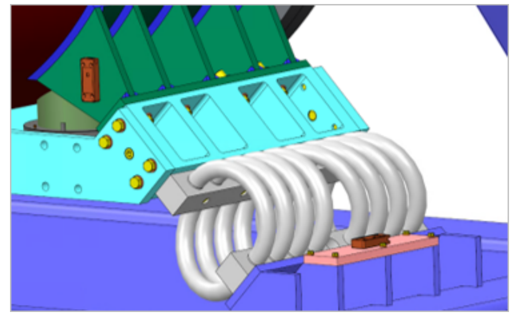

Figure 2: Isolator (gray), cradle (aqua), cryomodule interface (green) detail with mounted instrumentation packages (orange).

First, the removal and installation of the outer panels (seen in Fig. 3) was challenging and caused rapid damage to tapped holes in the tube steel frame. These tapped holes will be replaced with welded studs and cap nuts in future designs.

Figure 3: Transport System assembled with outer panels in place.

Second, repeated assembly of the isolator interfaces reinforced the need for generous throughhole clearances, slotted connections, and manipulation techniques during installation like keeping weight of the load on the crane and jack between floor and cryomodule foot to roll the load. Also, potential interference between CM feet and isolator assemblies (see Fig. 4) complicates assembly and must be avoided. 3D printed visual flags were developed to be installed on the isolators as both visual reminder and indicator of interference. All of these refinements are included in the updated procedures and released.

Third, the original frame design included an aggressive hook height restriction and thus bespoke slings with a 30 degree lift angle (seen in Fig. 5). This pushed the requirements for lifting fixtures and was often mentioned by people involved in rigging. Experience during all transport stages that required rigging indicate that this hook height restriction can be reduced in future designs.

Securing of Transport System of Vehicles

At each stage of transport, the transport system was, by third party personnel, mounted to either trailer for road trans-

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Figure 4: Dummy Load being installed into the Transport Frame at STFC-UKRI.

Figure 5: Transport System during unloading at STFC-UKRI with bespoke bale and slings.

port or the moving platforms for airport storage and air transport. This was intended to be done by straps over the top of the frame, but ultimately the method used was at the discretion of the vendor. In most cases, small engineered anchors were built into the frame and used as tie-down points. Figure 6 shows both methods. The lesson learned from this experience is to be more intentional about including these engineered tie down points, considering their load rating, and labeling them for easy usage. We were fortunate to have added sufficient mounting points with sufficient rating, but this could just as easily not been the case. It is certainly true that the details and ratings of these points will not be considered by the handlers, so forethought is warranted.

During handling at the airports, the transport frame was secured to a base plate via netting, seen in Fig. 6. This base plate has universal bearings and interfaces cleanly with standard handling and moving equipment at the airports, including scissor lifts to allow insertion of the frame into plane. The floor of the plane has the same universal bearings and powered wheel movers, allowing manipulation of the load supplemented by human power.

Handling at airports (loading and unloading from the planes specifically) represented the largest shock events the frame saw during the entire shipment. It was challenging to gain access to the airports during loading and unloading due to security issues, logistics of our travel, and varying logistics of the transport (flights, etc.). The strong impression on handling oversight is that signage, early communication,

Figure 6: Securing methods of the frame for road (top) and air (bottom).

Figure 7: Loading of the frame onto plane, including scissor lifts (top) and universal floor bearing and powered movers (bottom).

and other warnings are valuable, but the presence of FNAL personnel during the handling stages does the best to communicate the transport criticality. PIP-II will strive to have in-person monitoring of all handling, especially loading and unloading events, either by FNAL personnel or transport vendor representatives. One limiting factor is that non-airport

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personnel must be escorted by a dedicated employee when inside the secured cargo area, which may incur additional costs.

Weather Protection Tarping and weather protection was the most significant point of logistical failure during the test transport. Road transports where FNAL personnel were present resulted in robust tarping when the expected weather called for it, but even this was not enough to prevent water exposure and damage during transport. The tarps from Luxembourg airport to the UK (seen in Fig. 8) well covered the top and most of the sides of the load, including a significant overall between the two parts of the tarp.

Figure 8: Tarping of the frame in two parts by vendor at LUX airport.

This was insufficient to prevent rain, during an overnight stop before transit of the Chunnel, from penetrating the gap in the tarps and leaving significant water on top of the concrete shielding blocks that comprised the dummy load and water damaging an instrumentation package. While the tarps were overlaps such that they did not catch the wind during road travel, the trailer was pitched forward slightly, allowing rain water to flow forward toward the cab, between the layers of tarp and down onto the load. During the road transport from O'Hare to FNAL, the tarps used were insufficient to cover most of the load, despite the forecast of rain that day. No FNAL personnel were present for that loading stage.

Lessons learned from this transports include:

1. The cryomodule, during transport, must be shrink-wrapped and directly protected from water
2. A dedicated tarp, sufficient to cover the entire load, has been procured and will be specified to use during all road transport stages
3. In addition to this tarp, we will also specify a backward pitch of the trailer to ensure that water cannot flow against the overlapped tarps.

Additionally, this reinforces the benefit of FNAL/transport vendor personnel on location for all handling stages if possible.

Logistics and Communication

Several minor delays during transport were caused by paperwork not being ready on time (FNAL-internal and customs) as well as miscommunications with driver. While none of these amounted to more than a few hours each, they can be improved with more explicit planning and pre-briefing like is done by LCLS-II. On example is customs clearance between the EU and UK. This process is less straight-forward than previously, and the driver was required to drive from the border to Manchester Airport for customs clearance, but instead drove directly to STFC-UKRI. This required a minor back-track and several hours of customs paperwork that could have been done earlier.

Figure 9: Trailer after delivery at STFC-UKRI. Note sharp trailer angle relative to the entry door to avoid the experimental hutch (left).

One success, seen in Fig. 9, was the use of rear-wheel steering trailer. The high-bay entry at STFC-UKRI is challenging because of interference from an experimental building. While serious delays and issues have been encountered in the past by STFC-UKRI bringing trailers into the high-bay, the flexibility of the rear-wheel steering trailers made this a straight-forward delivery.

Rigging of the load at all stages was very smooth, with all third party riggers using their own flings, shackles, and spreader bars as necessary. The labeling of lifting points and code certifications of the lifting fixture (both ASME B30.20, BTH-1 and BS EN 13155:2011) meant there was no confusion about the process.

Vibration Data During Transport

The major event during transport was two large shocks during unloading of the frame from the aircraft in Luxembough. FNAL personnel were not present for this event, but all sensors were working properly and full acceleration data from the event was captured. The largest shock was on the upstream outer frame (see Fig. 10) at 10 g peak acceleration, with smaller (7 g and 5 g) shocks in the middle and other end of the frame. The isolation system performed extremely well, reducing the maximum shock observed on the inner frame to below 1 g in all directions.

During the transport, many hours of data were captured for road and air transport, including Chunnel transit. This last was of concern because it is technically rail transport which traditionally has quite high peak shocks. Overall, the vibrations seen were very good in all situations, summarized

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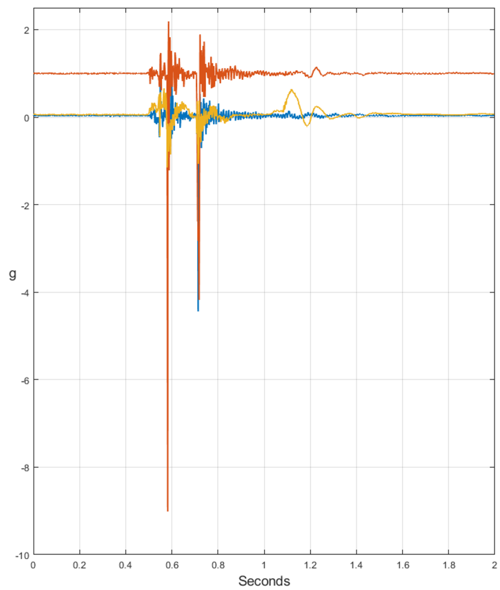

Figure 10: Tri-axial acceleration measured on outer frame during handling event at LUX during unloading.

in Fig. 11. The PSD used in design is a worst case envelope of input spectra for road and air were taken from several standards [5–7]. The worst acceleration (road - vertical), is an order of magnitude below the design values, so the design process is considered validated.

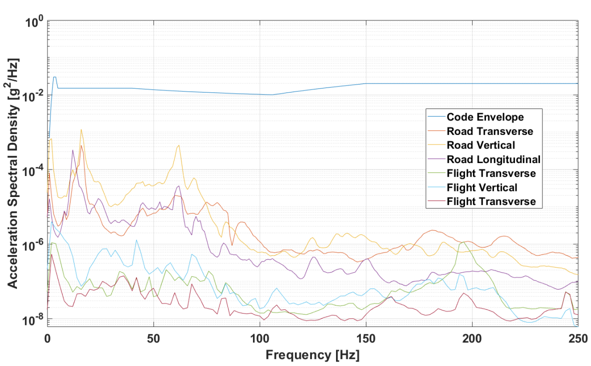

Figure 11: Tri-axial acceleration power spectral density of road and flight transport compared to a worst case envelope from code.

CONCLUSIONS

The long-range shipment of the HB650 Transport System has been completed successfully, validating the logistics, handling, procurement, and design features needed for this potentially high risk transportation. Many minor lessons were learned and will be corrected in the next transport. The shock isolation (10+ g isolated to under 1 g) and vibration design is considered well validated and the procedure used to achieve this vibration is well-documented and repeatable. Final validation of the integrated system with cryomodule will proceed shortly, first with local road testing to measure internal cryomodule modes versus simulation [8], then full shipment from FNAL to STFC-UKRI and back. This module has already undergone cold validation testing, and will be retested after shipment to verify no performance degradation from shipment, likely late 2023 or early 2024. Once done, this will be considered final validation of the overall cryomodule shipment strategy for PIP-II, including HB650 and LB650 production cryomodule transportation from Partners to FNAL.

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