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PROTOTYPE HB650 TRANSPORTATION VALIDATION FOR THE PIP-II PROJECT*

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Abstract

The PIP-II Project at Fermilab (FNAL) is centered around a superconducting 800 MeV proton linac to upgrade and modernize the Fermilab accelerator complex, allowing increased beam current to intensity frontier experiments such as LBNF-DUNE. PIP-II includes strong international collaborations, including the delivery of 13 cryomodules from European labs to FNAL (3 from STFC-UKRI in the UK and 10 from CEA in France). The transatlantic shipment of these completed modules is identified as a serious risk for the project. To mitigate this risk, a rigorous and systematic process has been developed to design and validate a transport system, including specification, procedures, logistics, and realistic testing. This paper will detail the engineering process used to manage this effort across the collaboration and the results of the first major validation testing of the integrated shipping system prior to use with a cryomodule.

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.

- Design, fabrication, and integration of HB650 transport frame with cryomodule analog (Dummy Load)
- Local road testing with Dummy Load to validate isolation and handling performance
- Realistic transport of Dummy Load from FNAL to STFC-UKRI to validate air transport and handling
- Local road testing with a cold-tested and validated prototype HB650 (pHB650) to reverify isolation performance as well as any module-internal resonances
- 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.

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.

VALIDATION RESULTS

PIP-II uses a formal systems engineering approach, including strong documentation and review philosophies. Detailed risk assessments are matched to systematic risk mitigation and detailed validation efforts. All work is documented formally and reviewed, both internally and, periodically, by external transportation experts. This process and associated documentation is described below.

Risk Assessment and Planning

The foundational documents for the transport process are the Failure Mode and Effect Analysis (FMEA) and Prevention through Design (PtD) tables. The FMEA gathers all technical risks including human factors during all procedures (e.g., incorrect installation of shipping supports), design failure modes (e.g., resonant excitation and fatigue

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of a thin-walled bellows), and external failure modes (e.g., delays in shipping, mishandling by third parties). The PtD table is the equivalent assessment but for personnel safety risks. Both tables assess likelihood of each event, their severity, and likelihood of detecting after they occur. Each risk includes a mitigation plan to be implemented (e.g., design change, calculation, procedural change). The implementation of those mitigations is tracked via updates to these documents.

In addition to the FMEA and PtD tables, a Transport Specification and Transport Plan were created in collaboration with partners. The Transport Plan was a codification of the validation strategy, scope, and roles outlined in the previous sections. The Transport Specification provided requirements for the shipping system, including:

- Shipping envelopes including cryomodule drawings and interface references
- Vibration and shock requirements of the shipping frame and the cryomodule (what environment the frame must provide, and what the cryomodule must survive)
- Handling and logistics requirements (e.g., no fork trucks, no rail or sea handling) including use of the frame as a certified lifting fixture for the full transported system and providing internal storage space for instrumentation equipment and protection from elements and unintended access.

The uncertainty involved in wire-rope isolator designs leads to the inclusion of margin in the shock isolation requirements, seen in Table 1. This separation of design was critical because separate teams would be designing the frame and the cryomodule itself. This strategy allowed these designs to proceed independently.

Table 1: Transport System Shock Specifications (Coordinates are Beam Coordinates, X is Transverse, Y is Vertical, Z is Longitudinal)

	X	Y	Z
Frame Isolates to Better than	1.5g	2.5g	3.5g
Cryomodule can Survive	1.5g	3.0g	5.0g

Additional specifications for vibration were included to drive the designs, including a designed 80% isolation of shocks above 10 Hz for the frame, and all major resonances with vulnerable components in the cryomodule above 20 Hz. The shock validation procedures were taken from the US Military transportation standard [3], and input spectra for road and air were taken as a worst case envelope from several standards [3–5].

Design and Fabrication

The transport frame was designed by STFC-UKRI to the agreed specification [6]. The frame design report and drawing package were matched by a cryomodule transportation design report [7], both verifying that the respective components met their parts of the overall design transportation system requirements. The designs as well as fabrication and validation plans were reviewed prior to start of procurement.

The approved frame design package was sent to a vendor who modified the design for fabrication and code compliance. The fabricated frame was load tested by the vendor shown in Figure 1.

Figure 1: Transport frame 200% load test, or 30.4 tons.

The vendor, based on calculations and load test, certified the frame to both US (ASME B30.20, BTH-1) and EU (BS EN 13155:2011) lifting codes to 110% of the expected cryomodule weight. This should ensure that lifting from the frame alone, without spreader bar, during handling and loading steps at airports by third parties is procedurally simple.

The mating interface between frame and cryomodule is 14 transportation weldments directly on the cryomodule vacuum vessel at 45° below horizontal. In order to simplify integration, cradles were introduced (see Figure 2) to align opposing springs and fasteners.

All side and top openings are covered with plywood panels in transport with plexiglass access doors on either side for instrumentation and rigging storage.

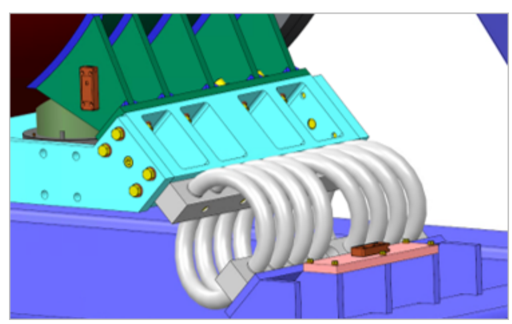

Figure 2: Isolator (gray), cradle (aqua), cryomodule interface (green) detail with mounted instrumentation packages (orange).

System Integration

The dummy load was designed as cryomodule analog, matching the cryomodule feet and transportation interfaces. The strongback, (seen in Fig. 3) was procured from the same vendor as the frame, and supports two concrete shielding

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blocks, giving accurate module interfaces and mass. The concrete blocks are secured to the strongback via chain and turnbuckles at each isolator pair mounting site.

Figure 3: Transport Frame during Dummy Load installation.

Assembly of 14 interfaces at 45° was a point of concern, but careful preparation ensured that integration tests went smoothly, only requiring minor effort with a jack to roll the load slightly during tests.

Local Validation

After final assembly and static displacement checks, the integrated transport system (21.9 tons) was loaded on a flatbed trailer and driven on local freeways known to provide a rough ride. No speed or handling restrictions were given to the driver beyond the route, which was approximately 3 hours long. Three road tests were performed this way. Pairs of tri-axial accelerometers were mounted across isolators to give comparative acceleration. A summary of the test configurations can be seen in Table 2.

Table 2: Transportation Test Configurations

Test	Isolator Count	Sensor Pairs	Trailer
1	14	3	A
2	10	3	A
3	10	8	B

Shock performance for all tests met specification in all axes, as seen in Table 3. The peak shock events seen were all found to be singular events of short duration (<40 ms).

Table 3: Peak Shocks on Load During Local Validation

Test	X	Y	Z
1	1.33	0.93	0.38
2	1.21	0.85	0.35
3	0.74	1.47	0.56
Specification	<1.5	<2.5	<3.5

Multiple tests were conducted in an effort to diagnose resonant behavior observed during transport. While this did not lead to large peak shocks, the isolation system design did not indicate any resonances around the observed frequency (roughly 20 Hz). Two isolator pairs were removed with no observed change in behavior, and a third test with a more detailed sensor array was performed to give better spatial information of the motion. Detailed modal analysis was done both at FNAL and STFC-UKRI, and non-linear mechanical analysis of a spare wire-rope isolator was done at the University of Pisa. This body of evidence indicates that the resonance observed is the vertical bucking mode of the dummy load driven by the tractor engine vibration. Given the dummy load-internal nature of the mode, it is expected that this will not be present in the cryomodule.

CONCLUSION AND OUTLOOK

The design, fabrication, and local validation of the HB650 transport system is proceeding well. Planning is well underway to ship the system with dummy load to STFC-UKRI in preparation for the shipment of the pHB650 cryomodule early next year as final validation. Lessons learned from all stages are being collected and integrated into future designs. The resonant behavior observed on the dummy load will be monitored during first local testing with the pHB650 module to confirm our assessments.

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