Readiness Review Close-out

HL-LHC AUP Vertical Magnet Test Stand at BNL

August 2, 2018

**Charges**

1. Requirements
   1. Are the Test Facility Functional Requirements properly specified, with special emphasis on cryogenic and quench protection requirements?

**Yes, cryogenic and quench protection functional requirements are properly specified in US-HiLumi-doc-1109. This document specifies the controlled cool-down/controlled warm-up requirements and documents details of the quench protection parameters.**

**The hipot requirements should either list or reference the magnet run plan for the various hipot levels required at different points in the run plan.**

1. Risk Assessment
   1. Are the test facility risks properly identified and are the risk mitigation plans adequate?

**Yes, post-mitigation risks are identified and documented in the Project risk registry (US-HiLumi-doc-79) using the method outlined in the Project risk management plan (US-HiLumi-doc-339).**

**Detailed mitigation plans were provided for each of the three identified risks.**

* 1. Is there any possible single-point failure that could causes a long (>3 months) delay?

**No, no single point failures were identified that could cause a > 3-month delay. However, it was noted that power supply contactors are old, and location and procurement of spares could cause a ~2-month delay.**

1. Equipment and Design Documentation

Have the BNL investments (both off-project and on-project) in cryogenic equipment been adequate to bring the vertical test facility to the cryogenic system availability needed for production testing of MQXFA magnets? If not, what additional cryogenic equipment investments are recommended? Does the quench detection and protection system design provide the necessary level of reliability for adequate equipment safety?

In particular:

1. Is the purpose and scope of the equipment properly identified to sustain the estimated number of 3 training quenches per day for ~10 successive working days during production?

**Yes, system modeling indicates that liquefaction from both the CTI 4000 and Linde 1610 into the storage dewar as a liquid buffer allows 3 quenches/day for 5 consecutive working days.  The storage dewar can then be refilled on the weekend to repeat the cycle. This precludes supplemental testing on the weekends.**

1. Is the equipment adequate to sustain a magnet test production rate of one magnet test every ~2 months?

**Yes, the equipment plus the reduction of training quenches to 25 per magnet results in a 38.5 day cold test duration. Use of a second top hat will allow cold tests to take place back-to-back without waiting for test preparations and test breakdown to be completed.**

1. Is the design of the system properly documented, including calculations, equipment drawings, material certifications, and test records?

**Yes, mostly. Calculations such as the helium usage model and predicted quench flow rates were presented, as were equipment 3-D models. As an operating system, these items would have been addressed during the previous successful BNL cryo safety committee reviews. Deficiencies were noted in the electrical system documentation, and resources are needed to address these.**

1. Is the plan for the final quench recovery system adequate to maximize He recovery after MQXFA quenches and prevent long test interruptions?

**Yes. Extensive analysis of operating data during quench testing has provided an opportunity to calculate the quench mass flow rates that must be accommodated. The resulting quench recovery system plan will maximize helium recovery and prevent long test interruptions.**

1. Is the quench protection system design and documentation complete and appropriate?

**The design is partially complete. There are potential issues with redundant voltage taps for the quench detection and how ground faults are interlocked.**

**No, formal documentation on the electrical systems for quench protection is not complete. This also includes formal configuration control for quench detection software.**

1. Is the cost and schedule estimate for the deployment of the Vertical Magnet Test system credible?

**Yes, cost and schedule estimates are credible because they are based on previous experience, previous procurements, current utility rates, and current cryogen prices.**

1. Personnel

Is the BNL test facility cryogenic team properly staffed with individuals that have the required skills to sustain the planned schedule of MQXFA magnet testing without delays because of unavailability of key personnel resources?

In particular:

1. Are plans to maintain He purification in place (or to act proactively on He purity issues) properly developed?

**Yes, the purifier operating procedures include regeneration steps. Contamination issues are otherwise dealt with through system design (quench relief system and quench recovery system to eliminate burst disk rupture, purification of pumped flow, and plans to keep the storage dewars cold between magnet tests using the new PNNL liquefier).**

1. Are operator shifts viable to ensure at least 3 training quenches/day for ~10 working days during production testing?

**No. The test facility currently has one cryo operator, and there are plans to hire a second cryo operator. To support two cryo operations shifts daily, a third cryo operator should be hired or cross-train other SMD operational staff to minimize reliance on a RHIC operator as back-up.**

**There is a potential issue with staffing for magnet test operators during production testing. Cross-training will be critical for maintaining the schedule.**

1. What, if any, additional cryogenic personnel resources are recommended?

**Listed critical personnel did not include any cryogenic or cryo-mechanical engineers. Primary and back-up engineers need to be identified.**

**See also response to Charge 4b.**

1. Operations

Are all operational issues being properly addressed for this stage of the Project?

In particular:

1. Are the necessary cryogenic and quench protection system operating procedures and training in place for operational readiness of the MQXFA test facility?

**Yes, cryogenic operating procedures (which are controlled documents) for the purifiers, Test Dewar #3, Test Dewar #2, and Nash refrigeration pumps were provided to the review panel. Each procedure lists prerequisite training. The run plan supplies the necessary information for quench protection systems.**

**A list of training certifications relevant to magnet testing was also provided.**

1. Is an appropriate e-log or other electronic “action-capturing” system available and operational for quick review and assessment of system configuration, probes readout, and daily activities?

**No. Information is collected and distributed using a variety of tools, including manual operations. Some data files are stored in a Google Drive or Google Team Drive. Operators record event in a manual logbook. A test e-log is being discussed and designed to provide more frequent distribution of the day’s events and results.**

1. Is there an adequate cryogenic system maintenance plan in place to minimize unscheduled downtime?

**Yes, a maintenance plan (including maintenance intervals) focusing on reciprocating machinery has been developed.**

**In addition, a short cryogenics maintenance period is planned between every other production magnet test.**

1. Is there an adequate quench protection system maintenance plan in place to minimize unscheduled downtime?

**No, there is no plan in place but the project relies heavily on system performance monitoring and pre-test system check-outs and verifications.**

1. Is the cost and schedule estimate for operations of the Vertical Magnet Test system during production credible?

**Yes, cost and schedule estimates are credible because they are based on previous experience, previous procurements, current utility rates, and current cryogen prices.**

**It was noted that the schedule includes 2 days of cryogenic maintenance after each magnet test rather than 4 days of cryogenic maintenance after every other magnet test.**

1. Safety
   1. Is there a written Hazard Analysis?

**Yes, a written Hazard Analysis exists. The identified hazards were listed, and the methodology for risk assessment calculations was presented. BNL collaborated with FNAL and LBNL to generate a project hazard analysis. A BNL-specific HA was also produced.**

**Work planning such as job-specific hazard analyses/procedures for operations such as magnet up-righting and magnet installation into the test dewar are captured by the travelers. The travelers are reviewed by ES&H and the SME for engineering lifts.**

* 1. Are failure modes and “What If” scenarios analyzed properly?

**Yes, failure modes/”what if” scenarios and mitigation strategies were analyzed properly and presented in a cryo risk assessment matrix.**

**Some failure modes of the electrical system have not been clearly identified.**

* 1. Are any BNL requirements related to NEPA and/or Environmental Evaluation Notification Forms reviewed and approved?

**Yes, NEPA requirements are reviewed as specified by 10 CFR 1021, DOE Rules for Implementing the National Environmental Policy Act.**

* 1. Is the Operational Readiness Clearance path at BNL fully understood and properly followed?

**Yes, for the cryogenic system. Recent BNL cryogenic safety reviews have been completed for commissioning of the new vertical test dewar and phases 1 & 2 of the quench relief system. Another review is planned to include the additional liquefier, the production quench relief system, and the helium recovery system.**

**No, the ORC process for the test facility electrical systems is not clear.**

**Findings**

* Delta-T constraints for cool-down/warm-up are longitudinal only. There are no radial delta-T constraints.
* CTI 4000 liquefaction is 80 gal/hr nominal, 65 gal/hr typical.
* Production testing requires 3 quenches/day. This consists of 12 hr test operations and 16 hr (2 shifts) cryo operations.
* Different hipot values are specified for different phases of the magnet test plan.
* Addition of a second test dewar in the test configuration for cold storage will minimize, perhaps eliminate, helium venting after quenching.
* Integration of the PNNL plant (stand-alone, includes compressors) will be done by BNL personnel.
* Pressure pulse bypass prevents freezing out the refrigerator cold box following a quench during horizontal testing by integrating a bypass with an ambient vaporizer. This is not an issue for vertical testing because all helium returns are warm.
* Crane maintenance (small items) are typically handled by BNL personnel, larger jobs are handled by contractors.
* Temperature sensors for monitoring cooldown/warmup are bobbin-mounted on the magnet end plates.
* Two new warm gas tanks (~8000 gallons each) have been moved close to the test facility but not plumbed in yet.
* The test dewar has ~140 gallons LHe below lambda plate. Much of this volume is within the magnet and cannot be addressed with displacers. The total LHe volume (4.5 K + 1.9 K) is ~500 liters.
* Shortfall in CTI 4000 liquefaction might be due to several inefficient/leaking transfer lines. Funds to replace these have been requested.
* Spring-energized lip seals (using Teflon) are used to seal the lambda plate rather than a tapered surface. Also used for warm finger penetration.
* Listed volumes in helium usage model are measured net usage (gross usage – hours \* liquefaction rate)
* Quench modeling indicates inner coil temperatures are somewhat higher than outer coil temperatures (visually estimated at 10-20 K). This increases the calculated quench flow rate.
* Flow rate to the warm quench tank is presently limited to ~450 g/s by system configuration/flow resistance.
* 4 days of cryo maintenance after every other magnet test is included in the cost, but not in the P6 schedule.
* 2 weeks of cryo maintenance after every magnet test includes system warm-up and cool-down, not just maintenance.
* Maintenance is being planned/laid out in an Excel spreadsheet and will be manually tracked by engineer & operator as to when things are due. Automatic notifications are not planned.
* Inlet of purifier is continuously monitored for O2, N2 and H2O.
* Purifiers are in parallel, not series as shown on the schematics.
* Relief valve venting noise level was measured (~100 dB) and used to locate where to place physical barriers. A magnetic field survey will be conducted during P2 testing.
* Electrical engineers listed as backups for testing support have varying specialities and levels of familiarity with the magnet test systems.
* A targeted hire is being pursued for an additional test facility cryo operator.
* 11,000 LHe storage capacity is based on matching to GHe storage capacity, not total available LHe storage capacity.
* All test system computers are on UPS. There is no emergency back-up generator.
* Project Functional Requirements have been established for the magnet (US-HiLumi-doc-36) as well as the vertical and horizontal testing (US-HiLumi-doc-1109)
* Vertical testing will take place in Building 902 using 6.1 m deep test dewar #2. Test dewar #3 will be used as a thermal buffer
* Testing will be in pressurized superfluid (~ 1 bar) at 1.9K
* The test dewar is equipped with 24 kA power leads. The nominal operating current is 16.5 kA and the desired ultimate current is >18 kA, 8% above operating
* The magnet structure has an end-to-end thermal gradient limit of 100 K during cool down or warm up. There are redundant thermometers at each end of the magnet for this purpose
* It is estimated that the magnet will train in about 20 quenches. Following training, there will be a thermal cycle and retesting. A threshold requirement is to have no more than three re-training quenches to nominal operating current
* Production testing requires three quenches per 16 hour day. The liquefaction capacity needs to be upgraded to achieve this rate
* Production requires testing six magnets per year
* Total quench energy is up to 6 MJ at 19 kA with 33 mH inductance
* The first long coil test was a single coil in iron to simulate full field (mirror magnet)
* The first long prototype magnet was tested, but developed a ground fault after 18 training quenches.
* Upgrades to the cryogenic quench return is planned to mitigate loss of helium gas
* A review of the AUP/BNL cryogenics took place May 10, 2018
* The relief system was modified to mitigate blowing of the rupture disk. The impedance of the relief line was reduced
* There are plans to add two more 30,000 liter gas tanks to help mitigate helium loss during quenches
* A Linde Model 1610 helium liquefier (80-100 L/hr) is being shipped from PNNL to supplement capacity of the existing CTI 4000 (250 L/hr) to levels required to meet testing rate requirements
* The CTI 4000 liquefier is reciprocating expander based
* A warm vacuum compressor (Tuthill blower and Nash liquid ring) is used to achieve 1.8K operation. It has a capacity of 2.7 g/s
* A second top plate will be required to meet the required testing schedule
* An indium joint is planned to connect the magnet leads to the fixture leads without soldering. The resistance of the joint will be tested at 4.5 K prior to use in magnet testing
* BNL funding request has been submitted for $378,066 to cover required cryogenic critical parts in FY19. This will include a new Nash pump
* The test facility cryogenic system dates to Isabelle project development
* BNL contributions to cryogenic reliability

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| --- | --- |
| Cost (k$) | Item |
| $313 | Spare long-lead cryogenic components |
| $220 | Commission Sullair 500, Nash pump |
| $125 | Refurbish magnetic field measuring equipment |
| $250 | Extension of reaction oven |
| $378 | Improve cryogenic reliability (requested) |
| $204 | Improve crane reliability (requested) |
| $1,492 | Total |

* A pressure pulse bypass was installed 7 years ago to help prevent freezing LN2 in the first heat exchanger during magnet quenches
* A new purifier compressor was purchased for the sub-atmospheric flow stream
* There are currently two purifiers in parallel
* There is a 10,000 liter LHe dewar with the possible addition of two other dewars totaling 7,500 liters
* There is 11,000 liter equivalent of warm gas storage
* Mixing 80 K helium with 300 K to achieve warm up/cool down flow. The 80 K helium is achieved using a heat exchanger in a LN2 dewar
* BNL has the only vertical dewar large enough to test these coils
* Vertical testing is close to being on the project critical path
* During testing of the first prototype, the rupture disk blew on quench. The impedance of the relief path was reduced in order to have all quench relieving through the relief valve and not the rupture disk. Subsequent quenches relieved in the desired manner.
* Approximately 40% of the quench helium is currently recovered. There are plans to upgrade the quench helium return system to recover more helium. The upgrade will include cold buffer (vertical cryostat #3) as well as two 30,000 liter warm buffer tanks. The upgrade is estimated to result in retaining 85% of the 19,000 scf of helium in the dewar at the time of the quench. The increase is 10% for the cold buffer and 35% for the warm buffers
* Twelve magnets will be produced, each consisting of two coils. 27 vertical tests are planned
* There is a plan to use an indium mechanical joint to connect the coil to the dewar insert in order to avoid soldering that could degrade the coil leads. The resistance of the joint will be measured before hand to ensure that it meets the requirements
* There are about 500 liters of liquid in the dewar during testing. There aren’t obvious opportunities to reduce the liquid volume
* An elastomer seal is used to seal the lambda plate as well as the warm bore
* A 4.5K thermal syphon is used to cool the thermal shield
* A two-way check valve is used to communicate through the lambda plate. The outer large portion is used for coil quenching. The inner smaller check valve is used to ensure that the 1.9K space does not go sub-atmospheric
* For three quenches per day, it is estimated that 9,861 liters of liquid will be required to refill and pump down to 1.9K. The total LHe production with the CTI 4000 and Linde 1610 is 7,800 liters per day. As a result, liquid level in the storage dewar will be depleted over the week of testing and will have to be replenished over the weekend. This process is limited by the capacity of the warm gas storage
* Heat transfer to helium during a quench was estimated using a film boiling correlation to estimate maximum relieving flow rates
* Plan to hire another cryogenic technician for testing
* There is continuous gas analysis at the inlet of the purifier capable of reading down to 1 PPM for N2 and O2
* The relief system has a relief valve (1,380 g/s at 30 psig), a 2” fast acting solenoid valve (1,400 g/s at 30 psig), a 3” fast acting solenoid valve (2,700 g/s at 30 psig) and a rupture disk (5,750 g/s at 40 psig) in parallel
* Travelers are in paper form
* A multiple day maintenance period for the reciprocating expanders will be required after two magnet tests.
* Reducing the relief system impedance appears to have solved venting through the rupture disk
* Sullair 350 (50 g/s) and 500 (78 g/s) can be run in the event the Mycom (156 g/s)is offline, albeit at reduced plant capacity.
* Two of the three protections systems (energy extraction, quench heaters, and CLIQ) must work to protect the magnet.
* Spare quench hardware is in hand to reduce downtime in case of equipment failure. If IGBTs fail, it was estimated that it would take ~6 weeks to procure and replace.
* Quench detection software is not currently under configuration control.
* The effectiveness of using dewar #3 as a cold buffer is planned to be tested in August and can then be compared with predictions.
* CTI 4000 capacity was listed as 246 L/hr as well as 320 L/hr.
* The quench protection system is designed to be failsafe and is redundant from the quench detectors to the quench protection control signals.
* There are 3 quench protection systems, and at least 2 need to be operational at all times to protect the magnet.

**Comments**

1. The test insert top hat should be hipotted prior to connecting the magnet.
2. Holding the test dewar liquid level below the current lead flags when not powering (e.g., during 1.9 K pumpdown) would reduce LHe usage.
3. There are other events that could result in freezing LN2 in the first heat exchanger that would not be addressed with the pressure pulse bypass.
4. It is not clear if the expander maintenance requirement fits within the magnet change period without affecting the testing schedule.
5. The integration of the Linde 1610 may be more involved than anticipated.
6. Great job with obtaining a duplicate system as a full backup for the old Vax computer running the DEC VMS-CRISP supervisory controls (i.e., cryoplant controls system) that controls the main plant and Magcool distribution system.
7. The ground current monitors have low resistance (~0.5 ohm) to ground. A hard short to ground could generate excessive ground current during energy extraction.
8. The schedule leaves little room for unexpected maintenance or equipment failures.
9. Identification and succession planning for all critical resources would reduce the effects of unexpected personnel turnover.
10. Leakage rate of helium for the cryo system is high. It will be better quantified when they get a chance to baseline the leakrate vs inventory loss from quench relief and purifier beds regeneration. Actual helium losses might alter the schedule and affect the vendor contract. For production run, it may be prudent to have 55,000 SCF tube trailer on hand.
11. Cross-training of existing BNL personnel would provide back-up of critical test support resources. Coordination of back-up resource requirements with the appropriate BNL organizations is needed.
12. The panel agrees with the plan to test the mechanical indium joint design prior to production testing, and consider using mechanical indium joints for the CLIQ connections.
13. Investigate options for test stand cold vapor returns to the cryoplant. (Currently the cold vapor returns to compressor suction and is not going to the cold end of plant, and thus the 4.5K load appears as a liquefaction load on the system. Around 2.7 g/s is required for current leads flow at full current.  Around 1.5-2 g/s goes to the 2K bath, the remaining 2-2.5 g/s can be converted back to extra net liquefaction  1.5 g/s [45 L/hr] if a cold vapor transfer line with control valve is installed to take this cold vapor back to plant. This is very useful when the test dewar is at 4.5K for a longer time before pumping down to 1.8K due to other reasons. The vapor return valve would close before the ramp-up, to prevent the quench flow from returning to the plant.)
14. The panel supports the repair of inefficient transfer lines that will be started shortly.
15. Impulse testing requirements should be revisited.
16. Consider adding AC input power signals into the power supplies’ IGBT monitoring systems, which could prove useful.

**Recommendations**

1. Hire the identified additional cryo operator as soon as possible. The alternative is to hire an operator who is not familiar with the test facility, requiring a longer training period.
2. To support two cryo operator shifts daily, hire a third cryo operator dedicated to the test facility or cross-train other SMD staff rather than relying on a RHIC operator as back-up.
3. Identify primary and backup engineers for critical cryo engineering resources during test support.
4. Ensure that quench detection software is under configuration review and control.
5. For the magnetic measurements and electrical systems, evaluate spares inventory, procurement lead times of critical parts, and generate a tracking document for maintaining this inventory.
6. Investigate options for test stand cold vapor returns to the cryoplant.
7. Investigate the CTI4000 250L/hr capacity. It may be a matter of optimizing the operating point for the plant to get a higher liquefaction rate.
8. There needs to be a ground current interlock for the power supply system. In addition, design the ground current interlock system to limit ground current in the event of a ground short in the magnet.
9. Implement a maintenance program for the electrical systems (power supplies, energy extraction, cooling).
10. The functional requirements and test plan must clearly state the hipot voltages and conditions.
11. The top hat voltage tap connectors need to be designed (potted) to meet the hipot requirements.
12. The 15 kA power supply contactors need to replaced and adequate spares procured.
13. Protective covers need to be installed to enclose the energy extraction resistors with proper high voltage signage.
14. The quench detection system needs to be reviewed for the use of redundant voltage taps. If redundant taps are not used, a fail-safe method of detecting an open voltage tap needs to be implemented and verified.
15. Investigate mechanical operation of the magnetic measurements probe/shafts to ensure reliable long-term operation.
16. Update travelers so the electrical testing section specifies enough details to meet the test requirements.
17. For production testing, a spare CLIQ system should be available at SMD.