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Impact of power outage for large scale cryogenic system operation at SLAC

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Abstract. The SLAC National Accelerator Laboratory is home to LCLS-II, a world-class X-ray laser. The LCLS-II superconducting linac is supported by a cryogenic system comprising two identical subsystems with a cooling capacity of 4 kW at 2.0 K per cryoplant. Each cryoplant features a warm helium compressor station, a 4.5 K cold box, and a 5-stage 2 K cold compressor train. Installed and commissioned between 2018 and 2023, the cryogenic system has encountered several power outages since beginning of commissioning in 2023, presenting significant operational challenges. This paper highlights the most notable power outage incidents, their impact on the cryogenic infrastructure, and the measures undertaken to address these challenges. The lessons learned provide valuable insights into enhancing the resilience of complex cryogenic systems to power and other utility outages.

1. Cryogenic system

1.1 Overview

The LCLS-II cryogenic system is composed of two identical cryoplants (CP)[1], a distribution system (CDS) comprising interface boxes (IB), distribution boxes (DB) with vacuum jacketed

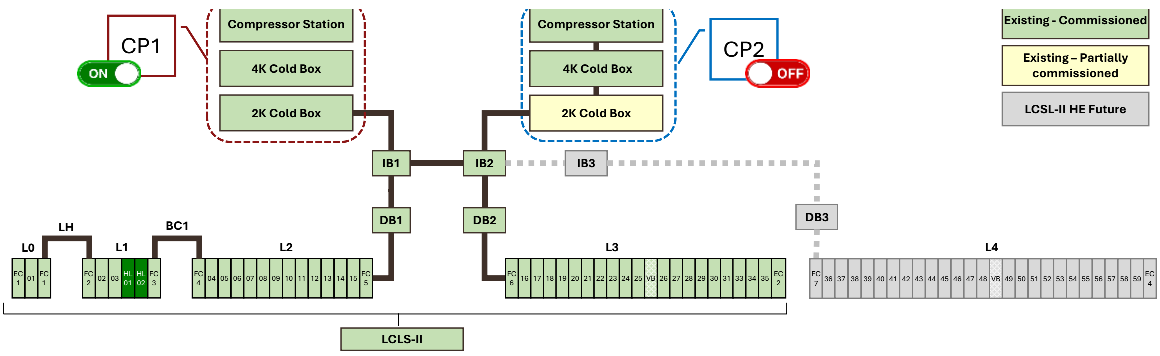

Figure 1. Simplified block diagram of cryogenic system at SLAC showing present and future upgrade.

multi transfer line (MTL), and a LINAC with two separate sections as shown in figure 1. The upstream LINAC connected to DB1 consists of sub-sections L0, L1, and L2 with a total of 17 cryomodules (CM), while the downstream LINAC connected to DB2 comprises sub-section L3 with 20 CM. Each CM consist of three circuits: cavities (2 K), low temperature thermal intercept

(LTTI) and high temperature thermal shield (HTTS). Each of these circuits have a supply and return line named in alphabetical order from A to F [2]. These 6 lines are common to each LINAC section with no isolation or separation except for Line A which has JT and cooldown (CD) valves on each CM. As illustrated in figures 1 and 2, the LINAC sections are inter-connected at interface boxes IB1 and IB2 via U-tubes, connecting all six cryogenic lines with CP #1. At present, only CP #1 is operational, supporting all 37 CM for LCLS-II activities. The commissioning of LCLS-II High Energy upgrade is scheduled for early 2027, which will incorporate an additional 23 cryomodules to double the energy capacity from 4 GeV to 8 GeV [2].

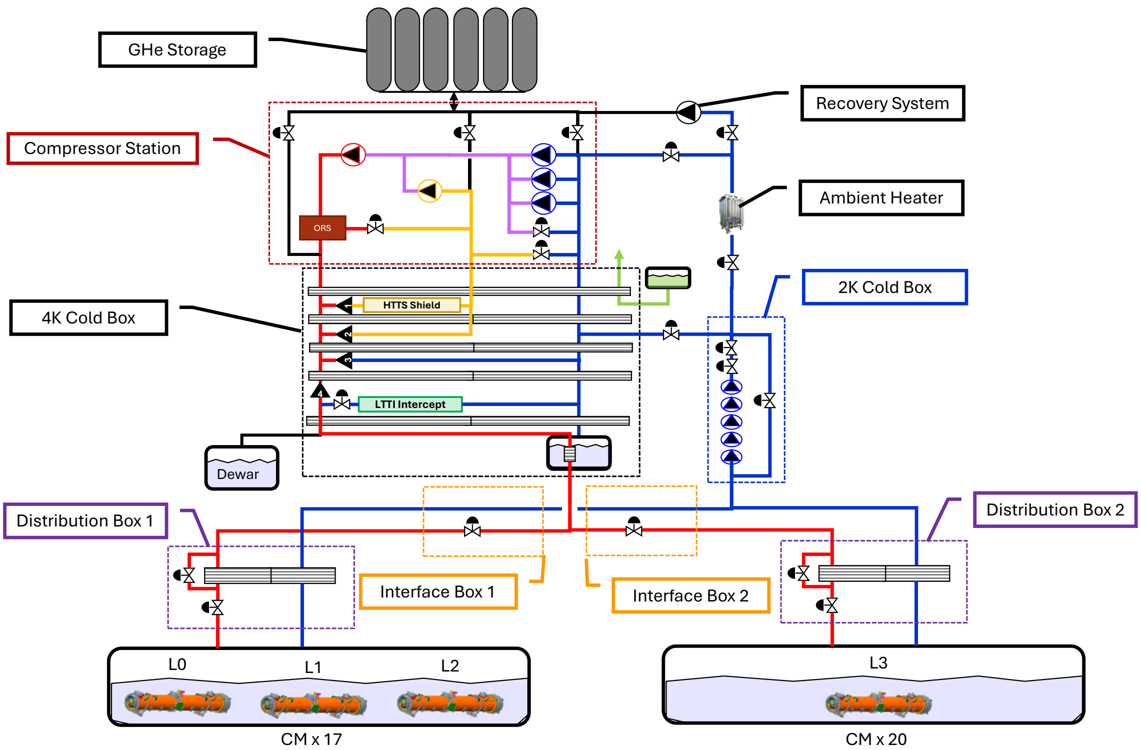

Figure 2. Simplified process flow diagram of showing CP1 supporting all 37 CM in LCLS-II LINAC.

1.2 Helium inventory

During nominal 2.0 K operations with CP1 supporting LINAC sections L0-L3, the total helium inventory comprises approximately 3300 kg, distributed between gaseous and liquid states. The gaseous helium component, accounting for approximately 400 kg, is stored in six 113 m^3 storage tanks maintained at approximately 300 K and 4 bara. Process piping throughout the facility contains an additional 100 kg of gaseous helium. The liquid helium (LHe) component is distributed across three primary locations: a 10 m^3 LHe dewar typically maintained at 70% capacity (approximately 800 kg), a 2 m^3 sub-cooler in the 4K CB typically maintained at 50% (approximately 50 kg), and within the LINAC CMs, which collectively contain up to 1700 kg of liquid helium. It should be noted that SLAC's existing warm storage capacity is insufficient to accommodate the complete LHe inventory should full recovery from the cryogenic system be required.

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1.3 Electrical power distribution

SLAC's electrical infrastructure operates via two independent transmission feeds as shown in figure 3 primary 230 kV transmission line that delivers approximately 35 MW during nominal operations, and a secondary 60 kV transmission line with a limited capacity to support critical infrastructure. Upon failure of the primary 230 kV line, operations can be transferred to the 60 kV backup line; however, this transition necessitates coordination with external grid stakeholders to ensure proper load distribution. The switchover process requires 1-2 hours to complete during unplanned outages. The SLAC master substation interfaces with both the incoming 230 kV and 60 kV transmission lines as shown in figure 3, enabling close transitions between the primary and backup power sources.

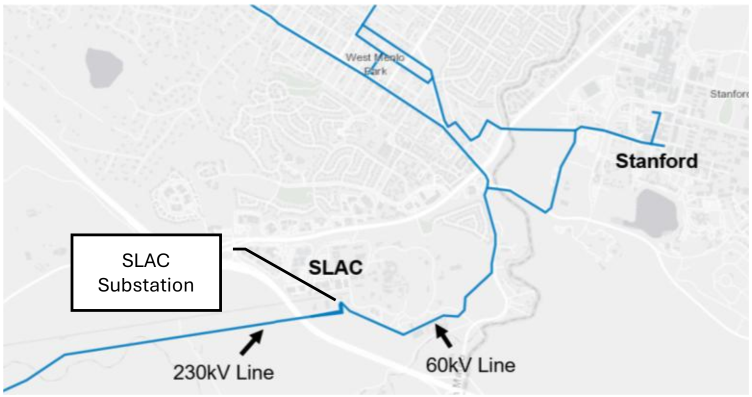

Figure 3. Showing the map of the transmission lines feeding into the SLAC sub-station.

1.4 LINAC: Insulating vacuum issue

The LINAC utilizes a compartmentalized insulating vacuum system divided into five discrete sections: three segments (L0, L1, and L2) in the upstream region and two segments (L3US and L3DS) in the downstream region, with the downstream segments collectively constituting the L3 section but physically isolated from each other by an intermediate vacuum break. During nominal operations, continuous pumping maintains the insulating vacuum throughout all sections, though with varying performance metrics. The L0-L2 sections demonstrate expected performance parameters, maintaining vacuum levels of approximately 10^{-6} mbar with corresponding static heat loads of 9 W/CM. However, the downstream sections exhibit higher vacuum pressures of 10^{-5} mbar, with L3DS showing increased static heat loads of 16 W/CM and L3US initially presenting significantly higher heat loads of 47 W/CM, though this was subsequently reduced to 16 W/CM through the installation of additional vacuum pumps. The correlation between elevated heat loads and degraded vacuum levels in the L3US sections strongly suggests the presence of a leak within the insulating vacuum, requiring further complex investigation.

2. Power outage

Since 2023, SLAC has experienced 2-3 power disruptions annually, ranging from brief 30 minute interruptions to extended 24 hour outages. The severity and cause of these incidents have varied considerably. The most significant disruption occurred in March 2023 when a fallen tree damaged the 230 kV transmission line while the backup 60 kV line was unavailable. This 24 hour outage allowed LINAC temperatures to rise to 150 K, necessitating a complete warm-up to 300 K followed by a full cooldown to 2.0 K. The recovery process required approximately 350 hours and resulted in 2,400 kg of helium loss. Two less severe weather-related outages in early 2024 lasted 4 and 6 hours, causing LINAC temperatures to increase to 50 K and 100 K respectively. These events resulted in helium losses of approximately 850 kg and 1,350 kg, with recovery times of 30 and 75 hours. Minor incidents included a September 2024 transformer trip (2 hour outage) and an April 2025 rodent-induced ground fault in the substation (30 minute outage).

Figure 4 illustrates the direct correlation between outage duration and recovery time. The data indicates that even for brief outages under 1 hour, a baseline recovery period of 12-16 hours is required to restore the system to nominal 2.0 K operations. Just in 2 years SLAC observed 5 tons of helium loss resulting from power outages.

2.1 What happens during a power outage?

When a power failure occurs, the warm helium compressor station which serves as the primary circulation mechanism for the cryogenic system and requires approximately 5 MW per CP immediately shuts down, precipitating a cascading system failure.

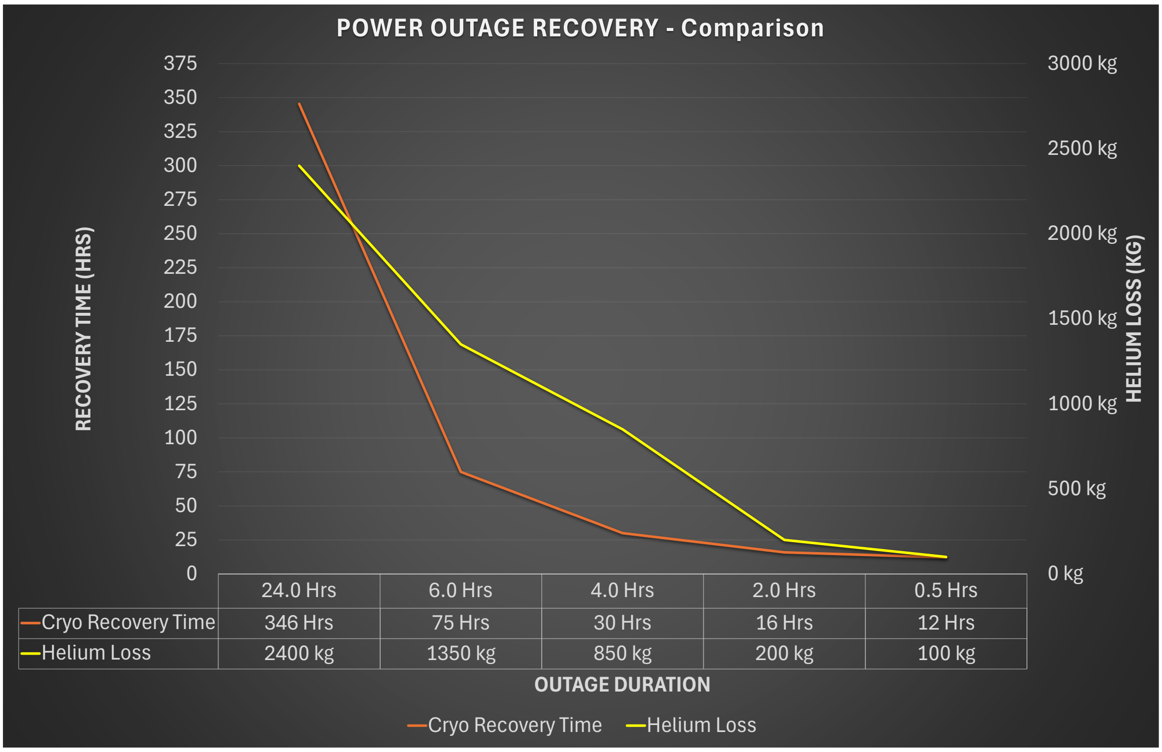

Figure 4. Comparison of notable power outage duration with the recovery time and corresponding helium loss. The graph displays :

- Orange fitted curve: Cryogenic system recovery time for each notable power outage
- Yellow fitted curve: Helium loss for each notable power outage

The LINAC's insulating vacuum system simultaneously shuts down. Without active helium circulation and proper vacuum insulation, liquid helium rapidly evaporates due to persistent static heat loads. At SLAC, two critical circuits experience pressure safety valve (PSV) reflief approximately one hour after power loss due to trapped cryogen and subsequent pressure rise. A concerning operational issue has been observed where these PSVs occasionally fail to properly reseal after relief, resulting in continuous helium inventory loss rather than the intended temporary pressure relief function.

The power outage creates additional risks as brazed aluminum heat exchangers (BAHX) begin to thermalize, increasing their vulnerability to failure. Furthermore, superconducting radio frequency (SRF) cavities may suffer inelastic deformation and permanent damage if not previously configured in a safe, detuned cold-landing state as system begins to warm-up.

The impact of power outage extends beyond cryogenic components to essential facility infrastructure, affecting building lighting, PLC control systems, building access control, and personel safety systems (fire alarms and oxygen defincieny monitoring). Though uninterruptible power supplies (UPS) temporarily support these critical functions, they provide only approximately 30 minutes of backup power before complete depletion. Safety systems with dedicated secondary UPS units activate high-volume audible alarms exceeding 100 dBA upon detecting power loss, creating challenging working conditions for personnel responding to the outage.

Existing insulating vacuum leaks significantly intensify these effects of power outage at SLAC. Without active vacuum pumping during an outage, insulating vacuum deteriorates rapidly, dramatically increasing heat transfer to cryogenic components. This deterioration substantially increases static heat loads throughout the system, accelerating boil off and pressure buildup. As illustrated in Figure 5, the timeframe for pressure rise varies dramatically depending on vacuum system status. When operating at nominal 2.0 K conditions with functional insulating vacuum, the LINAC requires more than 3 hours to experience pressure rise from 31 mbar to 1.2 bara following a system trip. However, with the insulating vacuum system offline, this same pressure increase occurs within just 2 hours. The situation deteriorates rapidly thereafter, with pressure rising from 1.2 bara to 2.05 bara in approximately one additional hour. This 2.05 bara threshold is

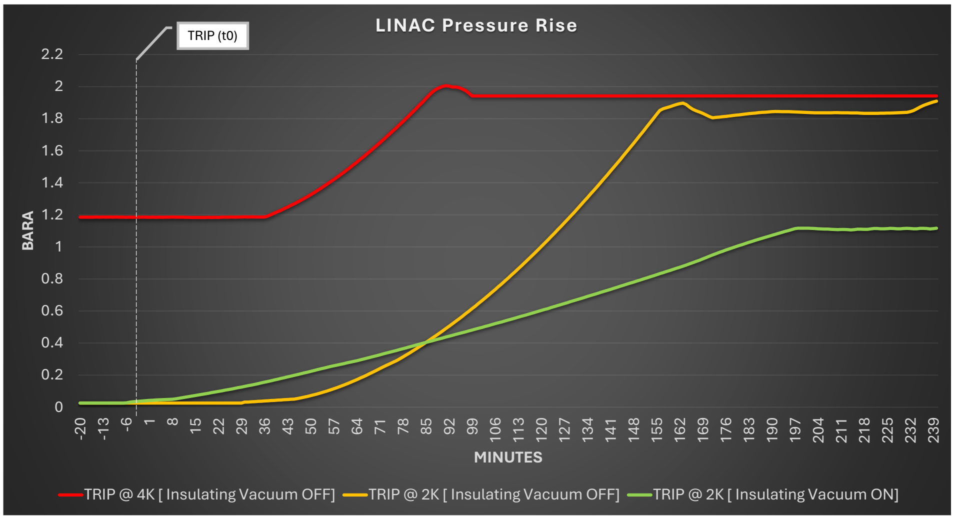

Figure 5. Effect of insulating vacuum on LINAC cryomodule return line pressure increase. The graph displays three scenarios:

- Red curve: Pressure rise at 4 K operation with insulating vacuum pumps off.
- Yellow curve: Pressure rise at 2 K operation with insulating vacuum pumps off.
- Green curve: Standard pressure rise at 2 K with insulating vacuum pumps on.

particularly significant as it corresponds to the LINAC thermal pressure safety valve setpoint. When this valve activates, helium inventory is released from the system, resulting in helium losses.

3. Recovery of the cryogenic system

3.1 What are the pre-requisites to recover from a power outage?
Restoration of electrical power alone is insufficient to resume cryogenic system operations. Several critical support systems must be sequentially reestablished before CP recovery can begin. Initially, the stability of the restored electrical feed must be verified to prevent subsequent disruptions during the restart process. Following power verification, the cooling water system must be restarted as a priority, as it provides essential thermal management for the oil-lubricated screw compressors in the warm helium compression station [3]. Concurrently, the instrument air compressor system requires restoration to enable functionality of all pneumatic control valves throughout the facility. The comprehensive controls architecture - encompassing both operational technology (OT) and information technology (IT) networks, must be brought online to provide the necessary monitoring and control capabilities for safe system restart. Additionally, several auxiliary systems require restarting, including the recovery compressors, secondary cooling water circuits that support turbines in the 4K cold box and cold compressors in the 2 K cold box; the insulating vacuum system; and various other support utilities essential for cryogenic operations. The complete start of these utilities and auxiliary systems typically requires approximately one hour following power restoration. However, SLAC has experienced couple incidents where IT network complications during restart introduced significant additional delays to the recovery process, extending overall system recovery time.

3.2 How is the system restarted from a power outage?
After all prerequisite systems are operational, the cryogenic recovery process commences with the automated startup of the compressor station. This initiates the controlled depressurization of both the LINAC and 4K cold box, allowing the systematic recovery of helium into gas storage tanks. The depressurization must be executed methodically to prevent overwhelming the compressor station's capacity, a task effectively facilitated through automation [4]. SLAC has additional recovery capabilities with a dedicated system (shown in Figure 2) featuring two specialized 20 g/s compressors and an integrated purifier, which can operate simultaneously with the main compressor station.

During the recovery phase, liquid nitrogen is manually drained from the 4K cold box to protect the brazed aluminum heat exchangers (BAHX) from thermal stress and possible LN_2 freeze out. BAHX are particularly susceptible to damage when they thermalize under no-flow conditions during system trips. Following LN_2 draining, gas helium circulation is reestablished in the 4K cold box using carefully developed automated sequences. This represents the most critical restart phase, requiring meticulous system monitoring.

As room temperature helium enters the partially thermalized (cold) 4K cold box, temperature differentials (ΔT) across the BAHX increase significantly. These gradients must be continuously monitored, as high flow during this stage combined with high temperature differentials can cause BAHX failure. Figure 6 demonstrates that delayed restoration of gas circulation correlates with extended recovery times, as larger ΔT are observed and must be gradually normalized. Consequently, flow is introduced incrementally, with rates increasing slowly only as temperature gradients diminish.

After stable circulation effectively reestablishes the thermal profile of the BAHX within the 4K cold box, the system transitions through a methodical, automated sequential cooldown process [2]. The procedure begins with the 4K cold box, then progresses to the LINAC circuits, shields, and intercepts, before finally reconnecting the LINAC cavities through the 37 JT valves. Throughout this sequence, operators maintain vigilant control when reconnecting liquid helium vessels (including the LHe dewar, sub-cooler, and cryomodules) to prevent rapid helium evaporation. This comprehensive automation strategy not only safeguards against equipment failure by standardizing critical operations but also facilitates prompt and safe system recovery.

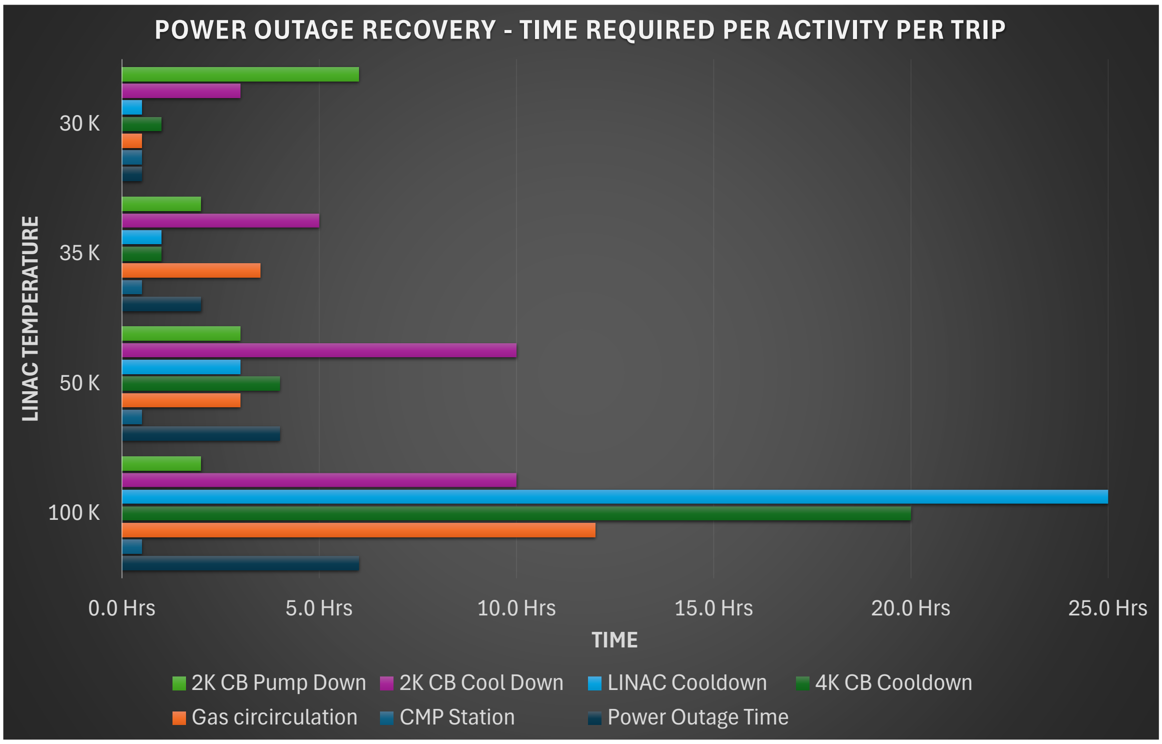

Figure 6. Comparison of notable power outage duration with the recovery time for each restart activity with corresponding LINAC Temperature during restart.

Notably, the automation significantly reduces human error probability during these complex procedures, which often must be performed during high-stress conditions and outside normal working hours.

4. Mitigation projects

An uninterruptible power supply (UPS) with back-up generator supports the CP's OT systems comprising of PLC and for basic building functions including lighting, access, and personnel safety systems. The back-up generator has been unreliable because regular maintenance is required to verify it's availability during unique times. To address the significant operational and equipment risks posed by power disruptions, SLAC is implementing several critical mitigation projects. Central to these improvements is the installation of a 6 MW generator system designed to support essential facility loads including utilities and auxiliaries, cryogenic system and insulating vacuum systems. Additional targeted improvements include a dedicated UPS for the LINAC insulating vacuum system to prevent vacuum degradation and the associated runaway conditions during outages. The IT infrastructure will receive UPS and generator backup to maintain control system visibility and operator response capability during disruptions.

Other cryogenic technical improvements include pressure safety valve (PSV) duplication to facilitate repairs when valves fail to reseal after activation — a recurring issue during outage recovery. Finally, SLAC plans to address the persistent L3 insulation vacuum leak during the scheduled LCLS-II HE extended downtime, eliminating a known vulnerability that significantly worsens outage impacts. These comprehensive upgrades will substantially reduce both the frequency and severity of outage-related impacts on SLAC's cryogenic systems.

5. Summary

Power outages initiate a sequence of cascading failures throughout the cryogenic system, necessitating rapid and precise operational response. This challenge is intensified by the timing of most disruptions, which frequently occur outside regular working hours. Although SLAC maintains 24/7 onsite operator coverage, engineering support typically requires approximately 30 minutes to arrive following system trips. The LINAC's substantial static heat loads accelerate liquid helium boil-off, contributing to the facility's considerable helium losses, approximately 5 tons over a two-year period. SLAC has addressed these challenges by developing comprehensive procedural protocols and implementing extensive system automation to facilitate methodical restart sequences. Recovery timelines exhibit a non-linear relationship with outage duration: brief interruptions under 2 hours typically require 12-16 hours to restore 2 K operations which is typical, while a 6 hour outage extends recovery to 75 hours, and a 24 hour disruption can necessitate complete system warm-up with total helium inventory loss. This exponential time increase highlights the essential role of both promptly responding, well-trained personnel and reliable automated systems supported by detailed procedures in preserving cryogenic system integrity during power interruptions.

Acknowledgments

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