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Quantum computing testbed using existing SLAC Cryogenic infrastructure

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Abstract. SLAC National Accelerator Laboratory hosts the LCLS-II, a 700-meter LINAC supported by two large 4 kW @ 2.0 K cryoplants. Located in Menlo Park, on the Stanford University campus in the heart of Silicon Valley, a hub for groundbreaking advancements in quantum technologies, which often rely on cryogenic temperatures. Located just a few miles from SLAC, PsiQuantum headquartered in Palo Alto is developing quantum computing technology based on photonics that operates at cryogenic temperatures. PsiQuantum’s photonics-based quantum chips currently operates at 2.4 K. Through a strategic partnership, SLAC has integrated its advanced cryogenic infrastructure with PsiQuantum's testbed. This collaboration provides PsiQuantum with cryogenic capabilities delivering between 100 W and 300 W at 2.4 K. By leveraging SLAC's existing infrastructure, PsiQuantum has established a fully operational cryogenic system in a fraction of the time—avoiding what would have otherwise been a multi-year development timeline. This paper provides an overview of the partnership, focusing on the integration process, commissioning efforts, and challenges encountered.

1. Introduction

The Linac Coherent Light Source II (LCLS-II) at SLAC represents an advancement in X-ray laser technology, generating pulses up to 1 million times per second and is the world's most powerful X-ray free-electron laser. This sophisticated machine comprises 37 cryomodules, each equipped with a string of eight superconducting niobium cavities operating at cryogenic temperatures. To support this advanced accelerator, SLAC commissioned two helium cryoplants in 2022-2023, each providing 4 kW cooling at 2.0 K to maintain the superconducting state of the niobium cavities.

Photonic based quantum computing development requires similar cryogenic environments. This paper details how SLAC's cryogenic infrastructure has been adapted to support PsiQuantum's quantum computing tests while maintaining LCLS-II operations. This strategic repurposing creates a cost-effective pathway for quantum hardware validation without compromising SLAC's primary scientific mission.

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2. SLAC Cryogenic Infrastructure

Each cryoplant consists of warm compressors (three low pressure, one medium pressure, and one high pressure), a 4.5 K cold box with a capacity of 18 kW equivalent at 4.5 K coupled with a 2 K cold box, and shared auxiliaries including liquid nitrogen (LN_2) storages, GHe Storages, recovery compressors, external purifier, and oil processing unit. These systems are supported with essential utilities including instrument air, cooling water and electrical power [1].

The 4.5 K cold box is pre-cooled with LN_2 and designed to maintain helium at three distinct circuits at varying temperature levels: 35 K for the thermal shield (HTTS), 5 K for low temperature thermal intercept (LTTI), and sub-cooled helium at 4.5 K for the cavities. The cold box is also designed with an additional liquefaction capacity of 15 g/s. During commissioning of the system, each cold box underwent rigorous performance validation in which process parameters were configured to match specifications for the operational modes. Each configuration was subjected to comprehensive mass and energy balance verification to validate instrument readings for flow and temperature measurements. The "Maximum capacity mode" test results, documented in Tables 1 and 2 [2], demonstrated the system's ability to meet design requirements for nominal operational scenarios of LCLS-II LINAC. The available 15 g/s of liquefaction load is in excess to support transients during operation and is typically not utilized during nominal operation. A fraction of this available 4.5 K cold box 1 excess capacity was utilized to support the quantum computing testbed with PsiQuantum.

Table 1. 4K Cold box maximum capacity mode performance test results.

Heat Loads	Operating Pressure [bara]	Expected Flow [g/s]	Expected Heat [kW]	Observed Flow [g/s]	Observed Heat [kW]
HTTS: Shield	1.2 – 2.5	146	15.2	137	15
LTTI: Intercepts	2.6	41	1.3	44	1.3
4.5 Liquefaction	**3.25**	**15**	**-**	**15**	**-**
Cavities: 2K Load	0.031	200	4.0	200	4.0
Ideal Carnot Work		1,200 kW		1,200 kW	

Table 2. 4.5 K Cold box maximum capacity mode performance test results of utilities.

	Expected	Observed
Compressor Power	4,300 kW	4,000 kW
LN2 Flow	104 g/s	109 g/s

3. SLAC-PsiQuantum Collaboration

Through the collaboration between SLAC and PsiQuantum, SLAC provided approximately 6.5 g/s of liquid helium (LHe), along with utilities (instrument air, electrical power and LN_2), the unique cryogenic technical expertise and developed the cryogenic control system for integration and commissioning.

PsiQuantum designed and installed the cryostat (testbed), very low-pressure compressor (VLP), ambient heaters, valve box, interface box connection to SLAC system and other auxiliaries as show in Figure 1. This collaborative approach leveraged SLAC's established cryogenic infrastructure and expertise while allowing PsiQuantum to focus on the specialized quantum computing hardware components essential for their development program.

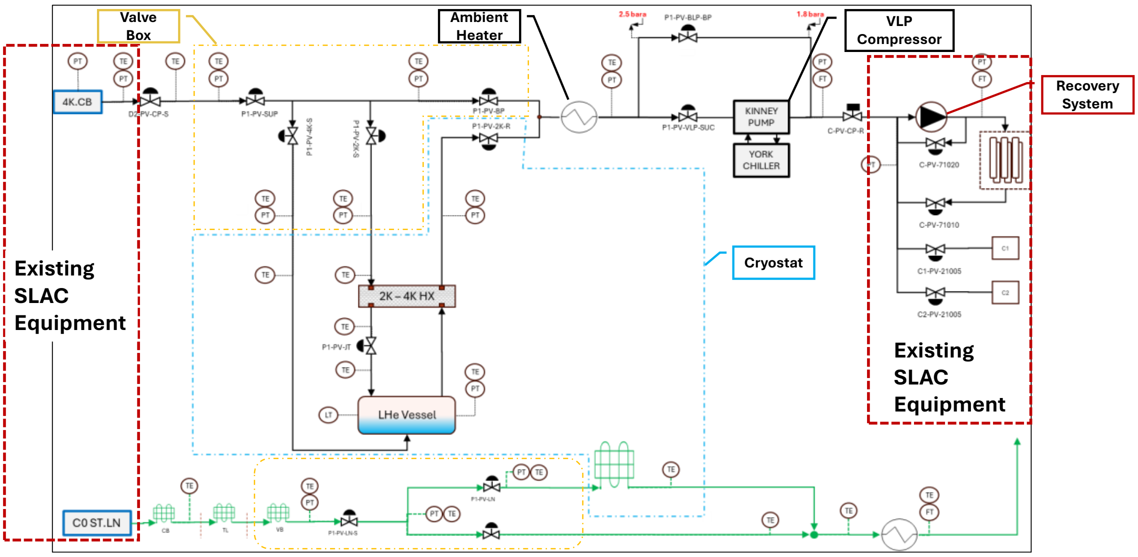

Figure 1. Integrated Cryogenic Process Flow Diagram.

3.1 SLAC Supply Interface

The 4.5 K cold box 1 connects to the LCLS-II LINAC via two interface boxes (IB) where IB1 connects to the upstream LINAC comprising 17 cryomodules and IB2 connecting downstream LINAC comprising 20 cryomodules. These interface boxes were designed to be interconnected using U-tubes and have bayonet connections with capability for future expansion. The interface boxes connect all three circuits with the LINAC through three supply and three return lines via a multi-transfer line (MTL) [1]. For the PsiQuantum integration, we utilized one of the pre-existing bayonet connections on the 4.5 K sub-cooled helium supply line at SLAC IB2 shown in Figure 2

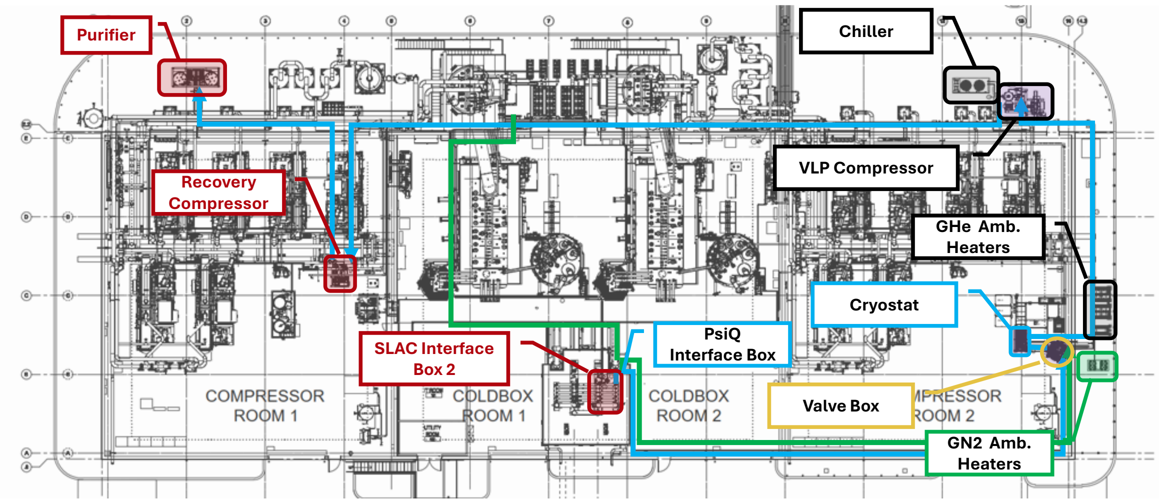

Figure 2. Layout of existing SLAC cryogenic infrastructure and new PsiQuantum test equipment. Blue line represents the helium flow while green represents the LN_2 flow.

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and 3. This connection point allowed direct integration of the quantum computing testbed without requiring modifications to the SLAC cryogenic infrastructure. Through this connection, 3 bara helium at 4.5 K flows from SLAC IB2 to the PsiQuantum Interface Box.

Additionally, liquid nitrogen is supplied to the PsiQuantum Interface Box from an existing connection point on the north side of the facility using a flexwell cryo pipe, completing the cryogen supply requirements for the quantum testbed. The selection of the flexible LN_2 supply line with a nominal DN15 process line and outer vacuum jacket diameter of 50 mm was driven by its thermal performance due to vacuum superinsulation, the ease of installation, and cost-effectiveness. This prefabricated, superinsulated cryogenic pipeline offers low heat inleak, ensuring minimal thermal losses during liquid nitrogen transport. Unlike traditional rigid systems, the flexible cryo line requires no onsite welding or complex assembly or evacuation, significantly reducing installation time and labor requirements. Its flexible design enables rapid deployment, even in constrained or irregular routing scenarios.

Both these connections were made during an accelerator maintenance day at SLAC when the LINAC was in 4.5 K operation, ensuring there was no impact to nominal LINAC operations.

3.2 PsiQuantum Test system

Both cryogens (LHe and LN_2) are transferred to the valve box through a rigid vacuum-jacketed stainless steel transfer line as shown in Figure 2. The valve box distributes cryogens to the cryostat and possess ability for addition of new cryostats. It includes a thermal shield cooled by LN_2 and a bypass line to assist with transfer line cooldown. The cryostat is designed to host PsiQuantum's photonics-based quantum chips on a copper cold plate. It contains a liquid helium vessel, a 2K–4K heat exchanger, a Joule-Thomson (JT) valve, a return valve, and an LN_2-cooled thermal shield as shown in Figure 1. To achieve the 2.4 K temperatures required for quantum operation, warm two stage VLP compressor composed of liquid ring pump and a roots blower generates the necessary process vacuum like the one used at ORNL-SNS [3]. Since the VLP operates at ambient temperature, GHe ambient heaters preheat the return gas from the cryostat to 300 K while maintaining low pressure drop and ensuring continuous operation. A water chiller completes the system by supplying cooling water for the VLP compressor for cooling the oil.

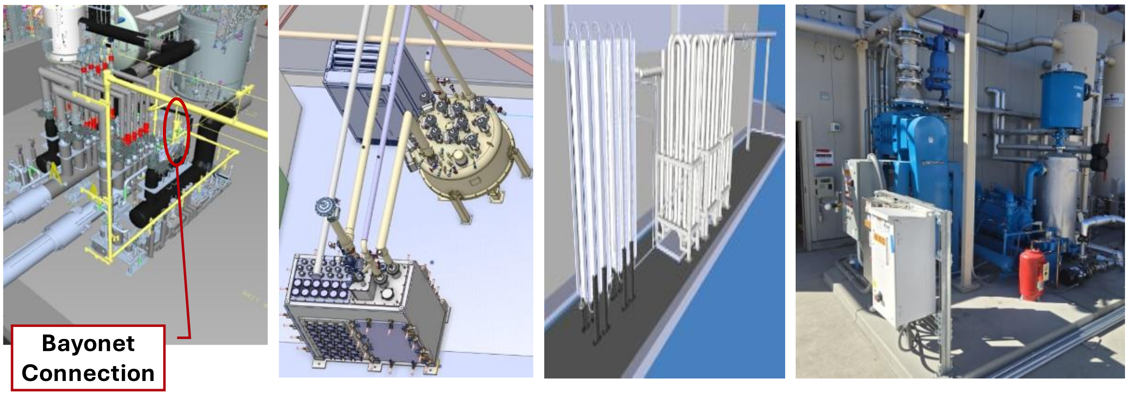

Figure 3. Images / 3D model of PsiQuantum's equipment from left to right: SLAC Interface boxes, PsiQuantum valve box and cryostat, LN_2 vaporizer and GHe ambient heaters, VLP Compressor system.

3.3 SLAC Return Interface

While the supplied liquid nitrogen (LN_2) is vented to the atmosphere, the helium is fully recovered. The outlet of the VLP compressor connects to the SLAC recovery compressor where the helium is compressed and then processed through a purifier to remove any impurities which may have been introduced in the process line due to the operation in a sub-atmospheric condition. This purified helium is then transferred back to the GHe storage tanks from where it returns to the Cryoplant for reliquefaction, completing the closed-loop helium cycle. This recovery strategy ensures efficient utilization of the helium resource while maintaining the purity standards required for the cryogenic system's long-term operation.

3.4 Controls Development

A key architectural feature is the implementation of two independent network environments: the secure SLAC PLC network and a separate PsiQuantum test network. This dual-network approach addresses the specific cybersecurity requirements of both organizations while maintaining operational efficiency. PsiQuantum's cryogenic control system operates exclusively on the SLAC network, with no communication pathways established between the cryogenic control system and the quantum testing network.

Given this capability, the SLAC team developed a comprehensive cryogenic control system for the PsiQuantum testbed, starting with a detailed functional analysis document that precisely mapped test requirements to control functionalities. This analysis formed the foundation for subsequent PLC code development. The system was designed with three primary objectives: maximizing availability, simplifying maintenance procedures, and ensuring operational ease. These goals were achieved through extensive automation that minimizes potential human error, coupled with traceability linkages connecting code elements to documentation and visualization interfaces. Integration between SLAC sub-system PLCs with PsiQuantum's cryogenic PLC was implemented using Common Industrial Protocol (CIP) messaging with produced and consumed tags for secure data exchange. The operator interface leverages SLAC's established Experimental Physics and Industrial Control System (EPICS) for human-machine interaction and comprehensive data acquisition [4]. This carefully designed control architecture enables seamless operation within SLAC's infrastructure while accommodating the specialized control requirements essential for quantum hardware testing.

3.5 Quantum computing technologies under test

PsiQuantum is utilizing this infrastructure to test multiple critical quantum computing technologies, including cryostat and cryogenic system operation and control, cascaded resonator sources, photon-number-resolving detectors (PNRDs), low-loss silicon nitride waveguides, directional couplers and crossings, fiber-to-chip coupling techniques, electro-optic switching mechanisms, and other advanced quantum components. SLAC supports these efforts by providing cryogenic delivery and managing cryogenic system operations.

3.6 Timeline

The SLAC-PsiQuantum collaboration continues to progress successfully. The agreement from project initiation to cryogenics commissioning completion spanned an efficient 18-month period as shown in Figure 4. It is essential to note that key activities such as design and procurement were strategically overlapped, with tasks performed in parallel whenever possible to optimize the schedule. This acceleration was facilitated by PsiQuantum managing all procurement activities directly. This streamlined timeline is remarkable, enabling PsiQuantum to access a sophisticated quantum testing facility with advanced cryogenic capabilities in a short duration.

This collaborative approach provides PsiQuantum with a valuable head-start, allowing them to develop their own cryogenic infrastructure while simultaneously training their staff at SLAC. Building a new facility with equivalent capabilities would typically require a multi-year effort and substantial capital investment.

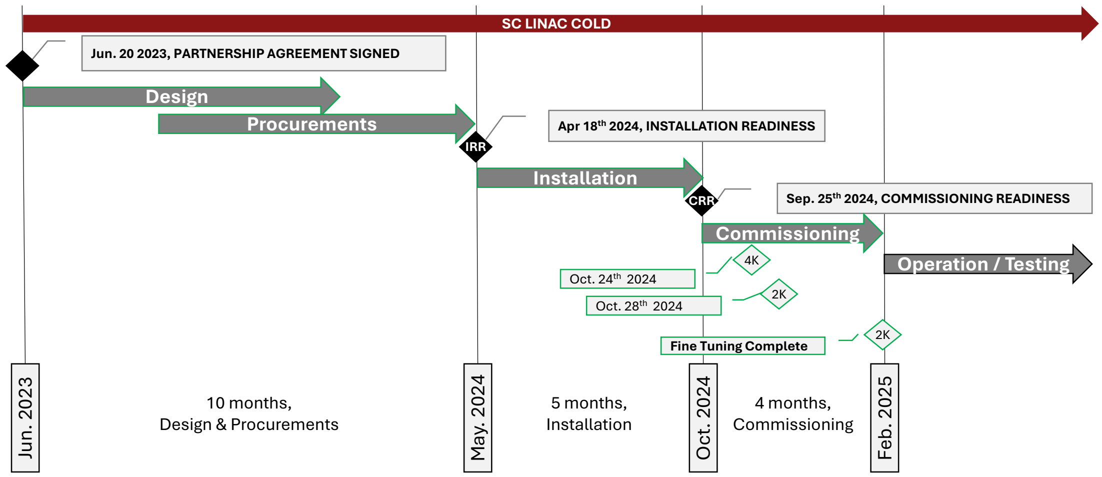

Figure 4. Timeline of SLAC – PsiQuantum Collaboration through quantum testing.

4. Commissioning

The cryogenic commissioning of this integrated system was performed in tandem with SLAC LCLS-II LINAC beam operations. Activities began in September 2024 with pre-commissioning activities followed by gas-circulation, start-up of individual sub-systems, and then cooldown of the system towards the end of October. The 300 K to 4.5 K cooldown was smooth and automated, achieved in approximately 8 hours, followed by pumpdown to 2.4 K in another 15 minutes using the VLP compressor. During this process, several challenges were encountered, including a non-functioning superconducting liquid level sensor, a thermal short between the thermal shield and 2 K circuit within the cryostat, leaks on the VLP compressor gaskets leading to contamination ingress, and various other installation issues. Despite these challenges, the commissioning team was able to successfully complete the process and bring the system to operational status while maintaining LCLS-II operations. With the system now fully operational and ready for quantum technology testing, performance monitoring has quantified the resource requirements for concurrent operation with LCLS-II. Supporting the quantum testbed increases facility electrical power consumption by approximately 150 kW (4% above baseline) and elevates LN_2 consumption by approximately 15 g/s (20% above baseline) – both well within the system's operational margins.

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5. Summary

This collaborative project between SLAC National Accelerator Laboratory and PsiQuantum has successfully established a quantum computing testbed while maintaining continuous operation of the LCLS-II LINAC. The technical implementation achieved several significant milestones:

- The project was completed within 18 months, from inception to operation.
- The testbed was integrated and commissioned without disrupting LCLS-II's mission.
- The quantum testbed is operating stably at 2.4 K, supported by 100 W of cooling.

This partnership exemplifies how national laboratory infrastructure can be leveraged to advance quantum computing development, creating a pathway that benefits both scientific research and technological innovation. As quantum chip testing progresses in this environment, this collaboration sets the stage for continued advances in quantum computing research and development.

Acknowledgments

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