LCLS-II ACCELERATOR VACUUM CONTROL SYSTEM DESIGN, INSTALLATION AND CHECKOUT*

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Abstract

The LCLS-II Project at SLAC National Accelerator Laboratory has constructed a new superconducting accelerator which occupies the first kilometre of SLAC's original 2-mile-long linear accelerator tunnel. The LCLS-II Vacuum System consists of a combination of particle free (PF) and non-particle free vacuum (non-PF) areas and multiple independent and interdependent systems, including the beamline vacuum, RF system vacuum, cryogenic system vacuum and support systems vacuum.

The Vacuum Control System incorporates controls and monitoring of a variety of gauges, pumps, valves and Hiden RGAs. The design uses a Programmable Logic Controller (PLC) to perform valve interlocking functions to isolate bad vacuum areas. In PF areas, a voting scheme has been implemented for slow and fast shutter interlock logic to prevent spurious trips. Additional auxiliary control functions and high-level monitoring of vacuum components is reported to global control system via an Experimental Physics and Industrial Control System (EPICS) input output controller (IOC). This paper will discuss the design as well as the phased approach to installation and successful checkout of LCLS-II Vacuum Control System.

SCOPE

This paper covers the LCLS-II Accelerator Vacuum Control System requirements from Injector to the Electron Beam Dump. Vacuum Control requirements for the experimental areas are not included in the scope of this paper. The LCLS-II Accelerator Vacuum System consists of multiple independent and interdependent systems, including the beamline vacuum, RF system vacuum, cryogenic system vacuum and support systems vacuum with details below:

Beamline Vacuum System begins at the gun, continues through the superconducting RF accelerator, bypasses the existing warm linac and then it is spread into three lines going to the primary dump, Soft Xray (SXR) and Hard Xray (HXR) lines in the Beam Switch Yard (BSY). These require ultra-high vacuum (UHV). These electron beamlines include the cryogenic beamlines (cold) and conventional warm electron beamlines as well. The design of the vacuum interface between two neighbouring regions operating at disparate temperatures must consider the impacts of their temperatures on the vacuum environments. An additional characteristic that applies to all the cryogenic beamline and a portion of the warm electron beamline is very low particle count (also referred to as “particle-free (PF)”) cleanliness. [1]

Cryogenic System Vacuum consists of several copies of physically and functionally separated vacuum systems including insulating vacuum systems and sub-atmospheric helium vacuum systems. These systems are high vacuum systems with high gas loads. [1]

RF System Vacuum includes RF coupler vacuum and laser transport tube vacuum. The RF coupler vacuum system can be characterized as warm UHV vacuum system with particle cleanliness requirements due to the RF fields and will be treated as particle free. Laser Transport Tubes provide vacuum transport lines for the UV and IR laser beams between the Laser Room and their respective use locations and require high vacuum (HV). [1]

Support System Vacuum includes the various pump down carts like the Insulating vacuum roughing carts, Insulating Vacuum High Vacuum carts, UHV pump down cart and particle free UHV pump down cart. [1]

SYSTEM DESIGN

LCLS-II Vacuum System can be separated into two parts: mechanical vacuum devices and controls vacuum devices. Mechanical devices are those that are physically part of the beam line or waveguide: vacuum valves, vacuum gauges, and vacuum pumps. These devices are specified, tested, and installed by the Mechanical Engineering and Technical Services Department (METSD). Controls devices are the remaining hardware needed to build a complete vacuum system: cables and controllers for the vacuum valves, gauges, and pumps; devices used to perform interlocking functions; and the vacuum section of the EPICS control system. These are specified, tested, and installed by the Electrical Engineering Dept [2].

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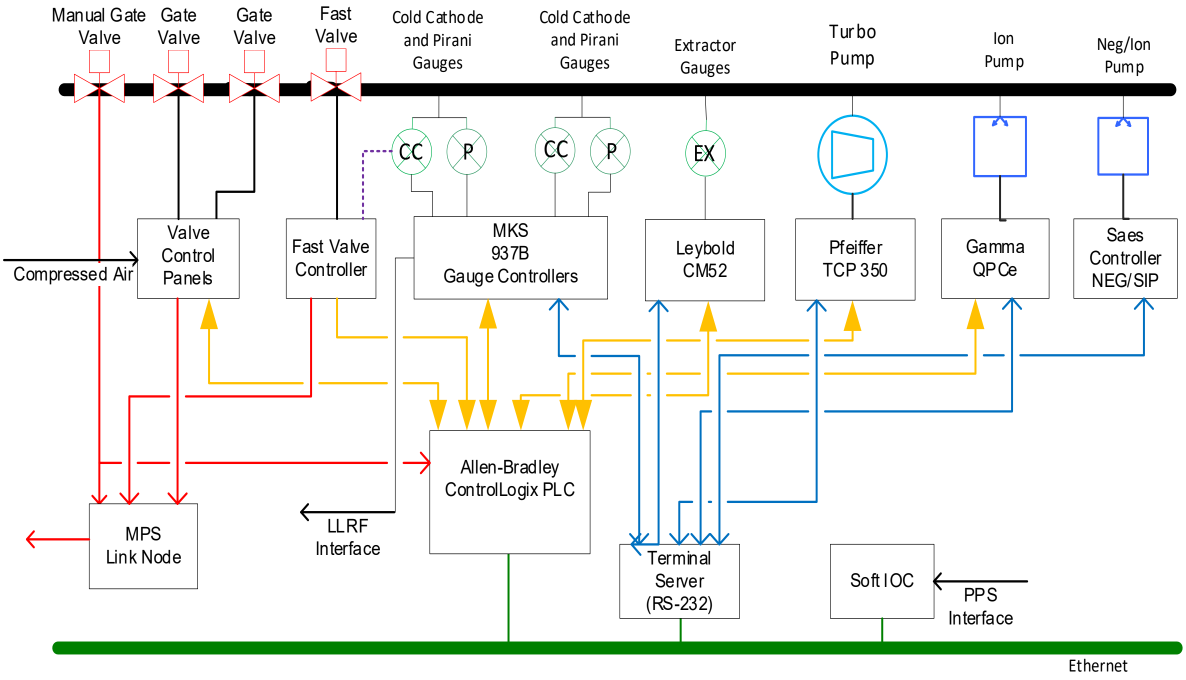


Figure 1: LCLS-II Accelerator Vacuum Control System Overview.

The block diagram in Fig. 1 captures most of the vacuum controls' hardware and the interfaces for each of them. These can be broadly categorized into four layers of devices: mechanical vacuum devices (gauges, pumps, valves), controllers for the I/O and individual mechanical devices (gauge controllers, pump controllers, valve controllers), PLC to monitor implement interlocks and EPICS IOC to provide monitoring to global EPICS Control System.

Mechanical devices are those that are physically part of the beam line or waveguide: vacuum valves like pneumatic valves, manual valves, and fast shutters, vacuum gauges like cold cathode and Pirani gauges, extractor gauges, and hot filament gauges, and vacuum pumps like Ion Pumps, Turbo Pumps. The METSD Group is responsible for specifications of these devices like model choices, locations on the beamline and connector details in close collaboration with relevant EED personnel at SLAC.

Controllers typically provide power to the mechanical vacuum devices and provide local status and control of the device: vacuum gauge controllers, vacuum pump controllers, valve controllers. The LCLS-II Accelerator Vacuum Controls Group within EED is responsible for the selection of controllers based on multiple parameters like electrical specifications, supported cable lengths, available I/O interfaces and is a collaborative decision between EED personnel and mechanical engineering METSD personnel. The various controller models and their interface signals to the PLC and the EPICS Infrastructure are captured in Table 1 and Table 2.

PLC The purpose of the Vacuum PLC is to read status from the controllers and take appropriate actions for the vacuum interlocks. It interfaces with the controllers using 24V digital or 0-10V analog signals. Details of the controller interfaces to the PLC are provided in Table 1.

Table 1: Controller Interface to PLC

Controller	Interface Function (per Channel)	Interface Signal Type
MKS 937B	Setpoint Readback Pressure	Digital In Analog In
MKS 350	Setpoint Readback Pressure	Digital In Analog In
CM 52	Setpoint Readback Pressure	Digital In Analog In
Gamma QPCe	Setpoint Readback On/Off Status Pressure	Digital In- Digital In Analog In
Pfieffer TCP 350	On/Off Status Speed	Digital In Analog Out
SAES NEG Controller	No PLC Interface	No Interface
SAES NEG Controller	No PLC Interface	No Interface

The architecture will consist of primary and secondary crates communicating over EthernetI/P modules. The primary crate will have the Central Processing Unit (CPU) from ControlLogix 5580 Controller Family 1756-L83E which has an EthernetI/P port to connect the PLC to the EPICS Control System via etherip driver. Multiple digital and analog modules will be installed in the primary and secondary crates to set up interface between controllers, other and the PLC. The vacuum interlocks for LCLS-II will be implemented in ladder logic code in the ControlLogix PLC. This PLC will store its logic code in non-volatile memory so that the programmed code is retained even after a power failure.

The Allen-Bradley ControlLogix PLC and components are used by the vacuum controls for LCLS-II Accelerator Vacuum Control System. The LCLS Vacuum Control System also uses the Allen-Bradley ControlLogix PLC to implement the vacuum interlocks and has been proven to work. Allen Bradley PLCs are used widely at SLAC for various projects like Cryomodule Control Systems, Cooling Water Systems, SSRL MPS system and so on.

EPICS The EPICS IOC will communicate to the vacuum devices in two ways:

1. The IOC can communicate to the PLC over the Ethernet network using the EPICS etherip driver. The etherip driver allows an EPICS IOC to read and write “tags” to the PLC. This provides a means to read all the vacuum status information from the PLC and can be then available to be displayed and archived by the global control system. The write to the PLC from the IOC provides a means for the IOC to control the available device parameters via the PLC.

2. The Vacuum controllers with available RS-232 serial interfaces are connected to the EPICS IOC via terminal server. Additionally, some devices provide a remote communication option of MODBUS over TCP/IP or RS 485. This communication is used to monitor non-essential status as well as control of the vacuum controllers. The vacuum control system is designed to function properly even if this remote serial / Modbus communication fails.

Table 2: Controller Interface to EPICS

Controller	Interface Type	EPICS Support
MKS 937B	RS 232	Asyn Module StreamDevice
CM 52	RS 232	Asyn Module StreamDevice
MKS 350	RS 232	Asyn Module StreamDevice
Gamma QPCe	RS 232	Asyn Module StreamDevice
Pfieffer TCP 350	RS 232	Asyn Module StreamDevice
SAES NEG Controller	Modbus (TCP/IP)	Asyn Module Modbus

VALVE CONTROLS

Pneumatic Slow Valve Pneumatic gate valves are installed at certain intervals on the beam line. Each valve is interlocked to a group of gauges and/or pumps in order close the valve automatically if the pressure near the valve increases beyond a predetermined set point. Controls for valves allow users to close valves and open valves provided that the interlocks are made up. Expert users can override or bypass the interlocks. A typical valve installation and implementation is shown in Fig. 2.

VAT series 48 valves are typically used for LCLS-II. Each valve has two limit switches indicating opened or closed status of the valves. Each valve requires a 24V input signal to hold the valve in the open position. To prevent possible radiation damage or introduction of unwanted magnetic fields on the electron beam, these valves will not have a solenoid directly attached to the body. Instead, each valve has an adapter plate installed which has the ports to connect the air inputs feeding compressed air to either cause the valve to open or close.

A panel with valve related equipment like air solenoid, incoming air supply line, regulator & pressure switch is installed in the tunnel near each gate valve. This panel also contains a custom-built control box (J-Box) which has lights indicating the status of the valve opened limit switch, closed limit switch and the compressed air status. The J-Box also has a key switch which allows vacuum experts to open or close gate valves, overriding all valve interlocks from the tunnel for ease of maintenance related activities. This is allowed only when the mode of operation of the valve is selected to be J-Box previously.

HMI Control Panel The Allen Bradley PLC HMI Control Panel is installed in the vacuum racks in the support buildings located close to PLC crate. There are four valve control modes available for vacuum user :

- Remote Control: Open valve and close valve commands must come from the EPICS control system. Valve interlocks are active in this mode.
- Local Control: Open valve and close valve commands must come from buttons on the Allen Bradley PLC HMI Panel. Valve interlocks are active in this mode.
- J-Box Control: The valve can be opened or closed using the valve’s J-Box, which is installed in the tunnel near the valve. All valve Interlocks are bypassed in this mode. The J-Box has absolute control of the valve.
- Closed: The valve is locked closed. The control system cannot open the valve.

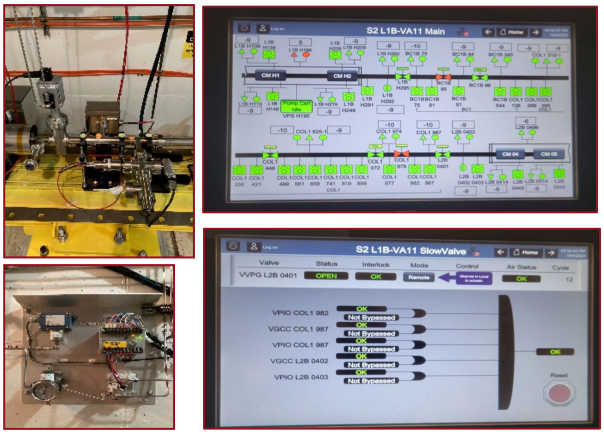
The valve modes can be changed only by a group of users with valid group username and password. In local mode, the HMI Panel will allow opening and closing of valves, interlock reset only with valid group username and password. Without the valid username and password, the HMI Panel only provides read access to the valve, gauge, and pump settings. This HMI Panel will indicate the status of the valve limit switches, interlock status, air pressure status.

Valve Interlocks are required to isolate a vacuum leak or bad vacuum regions of the accelerator beamline. Gate valve interlock logic is stored in the PLC. The PLC monitors the setpoints from the gauge and/or pump controllers associated with the valve and closes the valves if there is an interlock fault. Cold Cathode Gauges and Ion Pumps will be used interlock inputs. If an ion pump is used as an interlock input, it will not be daisy chained with other pumps on the same channel of the Power Supply. Ion gauges are used as interlock inputs in areas where CCGs are not available specifically LCLS-II Gun (GunB) area. The setpoint to trigger an interlock input fault and the interlock logic will be defined by vacuum engineering team.

- **Particle Free Area Interlocks** In the particle free areas, a voting scheme is used for interlock logic. Atleast 2 out of 3 interlock inputs should be faulted to trigger an interlock fault which will result in closing of two valves of the vacuum section. This scheme has been implemented in place to make sure that any gate valves do not close because of some electrical glitch. An interlock fault in this area will close the two valves of the section to ensure that the vacuum problem remains confined in that section.
- **Non-Particle Free Area Interlocks** For the Vacuum sections interlock in the non particle free area, any interlock sensor fault will trigger closing the two valves of that vacuum section. This will confine the vacuum problem to the faulted section.

FAST SHUTTERS

Fast shutters are included in the design to provide protection between vacuum regions in the event of significant vacuum faults in one region. They are intended to limit the propagation of acoustic shock waves and limit contamination of large regions of vacuum system with atmospheric gases in the event of a break to atmosphere. Fast shutters do not function as complete isolation valves but are intended to limit the conductance between vacuum regions. They are installed in conjunction with isolation gate valves.



Valve	Status	Interlock	Mode	Control	Air Status	Cycle
VVPG L2B 0401	OPEN	OK	Remote		OK	12

VPIO COL1 982 OK Not Bypassed
VGCC COL1 987 OK Not Bypassed
VPIO COL1 987 OK Not Bypassed
VGCC L2B 0402 OK Not Bypassed
VPIO L2B 0403 OK Not Bypassed
OK

Figure 2 : Valve Implementation.

The fast shutter controller is installed in support building racks along with other vacuum equipment. The fast shutter controller has a key switch that allows the user to select one of following modes of operation:

- Remote Control: Open valve and close valve commands must come from the EPICS control system. Valve interlocks are active in this mode.
- Local Control: Open valve and close valve commands must come from buttons on the Fast Valve Controller Front Panel. Valve interlocks are bypassed in this mode.
- Disabled: The valve is locked closed. The control system cannot operate the valve.

The Fast Shutter Controller chassis has buttons that allow the user to open or close the valve or to reset the interlock summary. These buttons are active only when the valve is in Local Control mode. It also has lights indicating the status of the valve limit switches and air pressure sensor. Each of the lights show OK, Faulted or Bypassed status. The fast valve/shutter interlocks are not located in the PLC. The PLC only reads the status of the fast valve/shutter. The PLC can also reset the interlock as well as open the valve in the remote mode. This status is also treated as an interlock input for the adjacent gate valves so that the gate valves close when the fast shutter is triggered to isolate the bad vacuum region. The EPICS IOC receives from the PLC valve opened limit switch status, valve closed limit switch status, air pressure indicator status, valve interlock summary status and current mode of operation. The EPICS IOC sends commands to the PLC to open and close valves, reset valve interlocks.

Based on the vacuum calculations, the trigger sensor should be located far enough from the vacuum device for the pressure rise to be sensed, the electronics to respond and the fast vacuum device to close before the pressure wave reaches the fast vacuum device. The response time of MKS937B fast TTL output sensor is specified to be < 5msec in the MKS937B manual. This fast output sensor is directly connected to the fast valve controller to reduce response time of the fast vacuum device system.

- **Particle Free Area Interlocks** In the particle free area, fast shutters are triggered by two CCGs faults. Both the interlock sensors are located at the same position. To meet the intent of the redundant gauges providing improved immunity to electronic noise, the two CCGs will be monitored by separate MKS 937B Controllers, and the cable routing will follow separate paths between sensor and controller as much as possible. The status of the fast shutters will be read into the PLC. The PLC will trigger the closing of adjacent gate valves when the fast valve is not open. Fast shutters do not completely seal the section, hence the adjacent gate valves will be triggered to close following a fast shutter closure to isolate the section.
- **Non Particle Free Area Interlock** In the non particle free area, fast shutters are triggered by a single CCG fault. Like the particle free area, the status of the fast shutter will be read into the PLC which will close the adjacent gate valves to isolate the bad vacuum section.

INTERSYSTEM INTERFACES

Machine Protection System Status of all pneumatic beamline valves including fast shutters is provided to the Machine Protection System (MPS). The interlock status of the fast shutters is also provided to the MPS so that the MPS can revoke the beam permit as soon as the fast shutter interlock faults to prevent the beam from hitting the fast shutter to the best of its ability. For manual valves with position indicators, status of these valves is also provided to the MPS. This is done so that MPS can take the necessary action to prevent the electron beam from striking the valve. This will be available as a 24V digital output to the MPS system from a terminal block installed by the Vacuum System and will remain as a valid readback even if the Vacuum Control System PLC is unavailable for some reason.

Low Level RF System The LLRF system will receive the Cryomodule Coupler Vacuum Summary and beamline vacuum summary per cryomodule to be interlocked into their system. The LLRF vacuum trip points will be lower than the vacuum interlock trip points and will be specified by the LLRF and Vacuum Engineers. This will ensure that the LLRF system interlock will trip before an actual vacuum event that trips the valves. These signals will be available as 24V digital output from the Vacuum System to the LLRF system.

Personnel Protection System Status of each PPS zone will be read from the PPS system to the Vacuum Controls System via EPICS. For the PF areas, this signal will be not cause the valves to close when the PPS zone is in controlled or permitted access.

For the non-PF areas, this signal will be used to close the valves when the PPS zone transitions to controlled or permitted access. The valves in the non-PF areas will not be interlocked to the PPS zone access state to ensure vacuum maintenance activities can continue during access.

PLC ARCHITECTURE

The architecture will be made up of primary and secondary Allen Bradley PLC crates communicating over private EthernetIP network. There will be multiple primary and secondary PLC installations for LCLS-II. The neighbouring Primary-Secondary PLC installations will interface to each other to manage the status of interface boundary valve. The separate vacuum sections will be controlled by a Primary PLC Crate with Secondary Crates located in individual sectors. The various PLC modules used are:

- 1756-L83E Controller
- 1756-EN2TR Ethernet Module
- 1756-IF16 Analog Input Module
- 1756-OF8I Analog Output Module
- 1756-IB32 Digital Input Module
- 1756-OB16I Digital Output Module

The 18 Primary-Secondary PLC crates and the supported sections were chosen to make the system modular, scalable, and reliable. In the high risk, high consequence PF areas, 1 primary crate with CPU controls 2 adjacent sectors. The isolation vacuum pump carts which actively pump on the Cryomodule Isoaltion Vacuum are also supported within the corresponding PF PLC installations. The details of the cart implementation can be found in paper titled LCLS-II Cryomodule Isolation vacuum Pump Cart [6]. In the non-particle free areas, 1 primary crate with CPU controls 7 adjacent sectors. The sections of the accelerator paste the Beam Switch Yard to the Electron Beam Dump have individual support buildings and there is 1 primary crate per building since connecting the support buildings over the network infrastructure proved to be more costly than individual PLC installation.

INSTALLATION AND CHECKOUT

The LCLS-II Accelerator Vacuum Control system utilizes 18 PLC primary-secondary installations to monitor the system and to isolate unexpected loss of vacuum. A typical vacuum controls rack is shown in Fig. 3.

Checkout Since protection of the particle free & CM vacuum was critical to the success of the Project, the checkout of this system involved extensive documentation and rigorous WPC ensuring a successful certification of the system. The LCLS-II installation commenced with the installation of the Gun, which was commissioned as a part of the Early Injector Commissioning Effort by the Project.[3].

Figure 3: Typical LCLS-II Vacuum Controls Rack.

commenced with the installation of the Gun, which was commissioned as a part of the Early Injector Commissioning Effort by the Project.[3][4]. The next phase of installation and checkout was for the Beam Switch Yard through Soft Undulator Xray Line to the Soft Xray Beam Dump. Finally, the Super-Conducting Accelerator with the Cryomodules and the bypass lines was installed and checked out with a final integrated checkout of the entire accelerator from the LCLS-II Gun through the SC Linac to both the Hard and Soft Xray Lines. For each phase of checkout and installation, checkout was conducted and documented with the following steps:

- **LCLS-II Vacuum Controls Pumps and Gauges Cable Connection Procedure** documents the steps of testing & connecting long haul cables for the vacuum system pumps and gauges beamline.
- **LCLS-II Vacuum Controls Beamline Pneumatic Valve Connection and Checkout** documents the steps of connecting and testing the beamline pneumatic valves. This document is used as a template for every primary secondary installation and all relevant devices are added to the corresponding installation document.
- **LCLS-II Vacuum Controls Integrated Checkout** After all the pumps, gauges and valves are connected and tested, every Vacuum PLC gets certified before transition to Operations. The certification procedures are documented below and after certification is complete for each PLC, the document will be uploaded for record keeping in the folder / location specified by the LCLS-II Project. Each PLC and HMI code is version controlled using the Concurrent Versioning System (CVS) System. Once certified, the PLC and HMI program are tagged. If any change is made to the PLC

code, the certification procedure is used for validating the system entirely to prevent any wanted changes.

CONCLUSION

The LCLS-II Accelerator Vacuum Control system successfully deployed over 65 racks and instrumented approximately 364 Pumps, 407 Gauges, 118 Valves & 9 Pump Carts [5]. It utilized 18 PLC primary-secondary installations to monitor the system and to isolate unexpected loss of vacuum. Since protection of the particle free & CM vacuum was critical to the success of the Project, the checkout of this system involved extensive documentation and rigorous WPC ensuring a successful certification of the system. The system has been operating reliably with minimal disruptions and has been low maintenance. The newly upgraded Linac Coherent Light Source (LCLS) X-ray free-electron laser (XFEL) at the Department of Energy's SLAC National Accelerator Laboratory successfully produced its first X-rays in September 2023. [7]

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