FRIB cryogenic control system

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Abstract. The cryogenic system at the Facility for Rare Isotope Beams (FRIB) supports loads for 2 K refrigeration, 4.5 K refrigeration and liquefaction, and a 35-55 K thermal shield for the linear accelerator consisting of 46 cryomodules, 4 superconducting dipoles and 14 superconducting magnets for the experimental system. The control system for cryogenics was designed, installed, and commissioned with the goal of high availability, ease of maintenance, and simplicity of operation. The personnel protection system (PPS) is a separate system which monitors for oxygen deficiency hazards (ODH) throughout the cryo-plant and around the cryogenic loads. The system consists of Allen-Bradley programmable logic controllers (PLCs) with local human machine interfaces (HMIs) along with the Experimental Physics and Industrial Controls System (EPICS) for normal operations and data acquisition. Two separate networks are utilized in the cryogenic facility. One is a network cluster that houses EPICS. It is designed with high redundancy and is completely separate from the network used for the rest of the particle accelerator. The second network only includes PLCs and HMIs for faster data transfer between PLCs, increased flexibility for changing operating conditions, and complete system operation in the case of an EPICS network failure. This paper reports on the design choices selected and experiences in integrating and commissioning the FRIB cryogenic control system.

1. Introduction
The Facility for Rare Isotope Beams (FRIB) is anticipated to enable scientists to make discoveries about the properties of short-lived nuclei not normally found on Earth (i.e., rare isotopes), nuclear astrophysics, fundamental nuclear interactions, and applications for society in medicine, homeland security, and industry. The helium refrigerator system at FRIB supports loads for 2 K refrigeration, 4.5 K refrigeration and liquefaction, and a 35-55 K thermal shield for 46 cryomodules and 4 superconducting dipoles in the linear accelerator (Linac), and 14 superconducting magnets for the experimental systems (ES).

2. Control system overview
The control system design, construction, and installation were governed by the aspects of personnel protection, equipment protection, and automation. These were accomplished by focusing on electrical power planning, system communications, equipment control system design, standardization, troubleshooting and alarm handling.
3. Personnel protection
The National Electrical Code and recognized engineering practices guided the decisions in personnel protection [1]. Safety disconnect switches were used for all electric motors, heaters, pumps, etc. National Electrical Manufacturers Association electrical panels were employed to provide arc flash protection. Work control and lock-out tag-out (LOTO) programs are in place to safely perform work. Grounding/bonding were used to safely ground all equipment and conducting parts, and conduits were routed to avoid trip hazards.

4. Equipment protection
A hierarchy of alarms, interlocks, and trips ensure the equipment operates within safe bounds. If alarms are not addressed in a timely manner, an interlock or a software or hard-wired trip will prevent or mitigate equipment damage. There are also hard-wired emergency stop buttons and controls to initiate trips for specific pieces of equipment.

5. Automation
The goal is the unattended continuous operation of the cryo-plant. Except for the routine checks and maintenance of the equipment, control system based alarms are the primary signals that alert the operator that action is needed.

6. Electrical power planning
The FRIB cryo-controls group was responsible for determining the electrical power requirements to support the cryogenic systems. This included conduit and cable tray routing, the requirements for uninterruptible power sources (UPS), and emergency power generators.

6.1. Conduit and cable tray routing
A detailed under-floor conduit plan was developed according to the planned layout of the sub-system equipment skid locations. All conduit routing to the warm compressor skids was carefully planned and placed within the concrete, eliminating space allocation competition with the large helium piping, overhead crane access and maintenance of the large equipment.

![Figure 1](image-url)  
**Figure 1.** Typical control panel design. Feeds land on terminals. Left hand dual power supplies are PLC power and right hand dual power supplies are field power with a redundancy module.
6.2. Redundant power
Power for all control system programmable logic controller (PLC) enclosures, workstations, and network components is provided by both a normal building source and a UPS. In the event of a power shutdown, all control system components are planned to remain running [1]. Such an approach makes the control system fault tolerant and allows for servicing of components and power feed circuits with minimal impact to the operation of the cryo-plant. A typical controls equipment hardware layout is shown in figure 1.

A generator system is used for restarting instrument air compressors, recovery compressors, vacuum skids, etc. Up to 3 MW of power can also be provided to the warm compressors by routing the power feed to a backup source through the Michigan State University (MSU) power plant. A simulated power outage was performed to confirm the proper operation of the redundant and back-up power systems [3].

7. Control system communications
In order to ensure a highly reliable system, redundant devices are provided for certain essential components like input/output controllers (IOCs), archivers, and web servers. The FRIB cryo-plant has a dedicated network designed with a three-server cluster. Services are divided among two primary servers. The third server automatically runs the services of a failed primary server.

7.1. Network
Communication to the rest of the FRIB controls system is through a channel access (CA) gateway which allows specific read-only data to be accessed outside of the FRIB cryogenics controls network. No data is allowed to be transferred from any outside source to the FRIB cryogenics controls network. Communication among PLCs is accomplished through a separate input/output (I/O) PLC-to-PLC device-level ring network via produced and consumed tags and Common Industrial Protocol (CIP) messaging.

7.2. PLC-to-PLC communications
The Allen-Bradley (AB) redundant Ethernet/IP device level ring, shown in figure 2, enables easy transfer of data from one PLC to another without the need of any additional hardware, network switches or servers. This provides the cryo-plant with a robust data transfer system that includes flexible features required for efficient operation of the facility. For example, the PLC-to-PLC communications allow for using the value of a process instrument monitored by one cryogenic control system PLC as the process variable (PV) in a process control loop operating in another cryo-system PLC.

Figure 2. PLC-to-PLC network design. The red encircled numbers identify Ethernet media.
The health of the PV, running status of the remote PLC, and current value of the PV are all available for review by the operator before final selection. Process control loop PVs can be changed during plant operation and include signal and PLC health checks, as well as interlocks such as holding the control variable constant if a health check fails, to provide continued smooth operation of the plant equipment.

8. Equipment control system design

Start-up and commissioning of the cryo-plant was accomplished over a 3 year period, and was essentially separated in the following order: utility systems (e.g., helium gas storage, helium purifiers, and liquid/gaseous nitrogen), warm compressor system, 4.5 K cold box, cryo-distribution system (LS1 first), and the sub-atmospheric cold box [3]. Due to the staggered commissioning of these sub-systems, modular control systems were developed and implemented.

A substantial amount of effort went into developing the operating code for commissioning, normal operation, trouble shooting and maintenance modes of each skid and then later for each sub-system and for the integrated overall system. As part of this effort, human machine interface (HMI) screens were developed. These screens were extensively used for pre-checks, commissioning, trouble-shooting and setting up for efficient operation in each mode with minimal operator intervention. After setup, the code then automatically manages the system. Hard-wired interlocks and software interlocks (set to operate before the hard-wired interlocks activate) were carefully verified during commissioning for the protection of the personnel and equipment. Alarms are setup to occur before interlocks to inform the on-call operator of any unexpected operating condition. Alarm limit settings take operator response time into consideration (e.g., 30 minutes is typical). Operation of all process instrumentation was also validated.

8.1. Cryo-plant utility systems

The instrument air, helium purifiers, process cooling water, gas analysers, and gas distribution systems are all controlled by the utility PLC. The recovery compressor skids for the purifiers each have a separate-dedicated PLC. As an example of these utility controls, the cryo-plant instrument air is provided by primary and back-up facility air compressors. In the event of low instrument air pressure, an alarm is generated and an interlock is activated. The facility supply is isolated, and the cryo-plant instrument air system is automatically started. This type of back-up system operation is automatically verified periodically by the utility PLC.

8.2. Main helium compressors

![Figure 3. Warm compressor skid interfaces.](image-url)
The 6 main warm helium compressors each have their own PLC allowing independent operation. The warm compressor interfaces are illustrated in figure 3. A separate-dedicated PLC is used for the main compressor gas management control valves.

8.3. 4.5 K helium cold box
The 4.5 K cold box control system block diagram and interfaces is shown in figure 4. The manufacturer provided a control cabinet that included hardwired trip interlocks for the turbine strings. The 4.5 K cold box is physically composed of an upper vertical cold box (300 – 60 K) and a lower horizontal cold box (60 – 4.5 K); the latter housing all the turbines. The cold box control system is installed such that the upper cold box instrumentation and control equipment is connected to a remote I/O rack. The lower cold box equipment is connected to the main 4.5 K PLC processor rack located next to the lower cold box. This allowed two separate teams to work on the installation and component testing for the 4.5 K cold box instrumentation and controls equipment. This was done after the warm compressor system had been commissioned [3].

8.4. Cryo-distribution system
The cryo-distribution control system monitors and controls the components for the 3 FRIB Linac transfer line segments, and a 4th transfer line system for the ES magnets. The Linac transfer line controls consists of a main PLC with 2 remote I/O racks. In the Linac, each cryomodule has a similar set of instrumentation and control equipment and the same is true for each Linac superconducting magnet (SCM) [4]. The controls for the radiation tolerant electrical valve actuators located in the Linac were optimized for precision control while minimizing motor action to limit wear on the valve and actuator parts.

The ES transfer line system is handled by a combination of 3 PLCs. In the target and vertical pre-separator areas, each SCM has a similar set of instrumentation and control equipment [4]. Control valves used for the ES superconducting magnets all use standard pneumatic actuators. Since a number of these valves require fast operation during a quench, fast acting solenoid valves are installed between the positioner and the actuator to rapidly vent or pressurize the actuator.

8.5. Sub-atmospheric cold box
The sub-atmospheric cold box system was designed and fabricated by the FRIB cryogenics group. It includes an independent PLC based control system. This cold box houses 5 stages of cryogenic (“cold”)...
centrifugal compressors that are used to produce a sub-atmospheric condition (31 mbar) in the cryomodule superconducting radio frequency cavities. This pressure equates to a temperature of ~2 K. The cold compressors are driven by ambient temperature permanent magnet synchronous motors and are suspended by 5-axis active magnetic bearings (AMB). The vendor for the cold compressors supplied control cabinets that house the hardware necessary for the control of the motor variable frequency drives (VFD) and AMB. Prior to their installation, extensive programming, testing, and validation was performed to ensure successful operation. The cold compressor motor and associated controls are proprietary and are composed of exclusive components. During installation, the FRIB controls group tested all signal I/O and control communication between the PLC cabinet and the vendor provided equipment [5]. The major portion of this work began after the commissioning of the 4.5 K cold box and the first Linac segment [3].

9. Standardization
A standard set of hardware, PLC firmware/software versions, program format, and user interfaces provide consistency across all cryo-plant control systems. Each PLC has a dedicated AB PanelView allowing operators to locally monitor/operate the plant in the case of a total network failure. All PLC processors are AB ControlLogix L7 or L8 processors. The L8 processors provide some advantages, such as options with more memory, faster processing (quad-core processor), faster communication speeds with embedded 1 gigabit Ethernet port, and the ability to operate using the newest PLC firmware versions. The newer L8 processors are used for the 4.5 K cold box, sub-atmospheric cold box and ES cryogenic controls only since they were not available during installation of the other systems.

9.1. Hardware and software specifics
Each PLC has a dedicated AB PanelView allowing operators to locally monitor/operate the system in the case of a total network failure. Standard Add-On Instructions (AOI’s) were developed that provide an easy way to buffer I/O, create a standard set of functions for each signal, and streamline signal scaling and troubleshooting. The PLC program uses structured text and AOI’s for buffering signals, ladder logic for functions that are best represented by finite state logic, and function block programming for process controls.

The use of the velocity form of the proportional-integral-derivative (PID) algorithm was standardized across all PLCs in the cryo-plant. This means the PID control loops use the change in the error for the integral action, inherently preventing control loop ‘wind-up’ [5]. To improve the EPICs communication rate for archiving and user interfaces, all PLC tags are buffered into arrays. Control System Studio (CSS) screens use a standard set of templates for each type of process component to maintain consistency for the operator and to ease integration for the controls engineers (a PID example is shown in figure 5).

![Figure 5](image-url)

Figure 5. Typical FRIB cryogenic system PID interface. Blue fields are writable and represent operator requests, and white fields are read only and represent what the PLC is actually using.
10. Troubleshooting

All PLCs are time synchronized across the PLC-to-PLC communications Ethernet ring network. Timestamps are captured in the PLC with an accuracy of the PLC scan time of about 5 milliseconds (ms). All PLC signals, alarms, and timestamps are archived using the Experimental Physics and Industrial Control System (EPICS) archiver. While data is generally archived at rates of 200 to 1000 ms, timestamps captured in the PLC make the archived data useful for determining the sequence of events such as alarms and trips. A large portion of the code is dedicated to capturing system states and fault data. Screens are available to display this information when troubleshooting is needed (figure 6).

![Figure 6](image)

Figure 6. Sub-atmospheric cold box trip capture screen. Every PV and the timestamp are latched in the PLC immediately following a trip and mapped to EPICS for HMI display.

11. Alarm handling

Every condition requiring operator action has an associated alarm which triggers an automated phone dialer system. An operator interface screen is shown in figure 7.

![Figure 7](image)

Figure 7. Typical alarm screen. Transparent is inactive, yellow is in alarm.

The FRIB cryogenic alarm handling is based on the International Society of Automation (ISA) 18.2 standard [1]. It facilitates acknowledgements, shelving, suppressing, and timestamps for alarms that are accessible through HMI’s which include the CSS application (refer to figure 8 for a typical example). Enabling/disabling alarms and setting alarm delay, dead band, and shelve duration through CSS requires a password.
Figure 8. Typical HMI screen for analog alarms.

12. Conclusions
The around the clock, unattended, safe, and efficient operation of the FRIB cryo-systems has demonstrated for more than a year that the goals of personnel protection, equipment protection, and automation have been achieved. The control system flexibility also provided the means for operators to easily transition between the various modes of cryo-system operation. It concisely and clearly delivered all the information necessary for process operation and troubleshooting activities during the stepwise commissioning of each of the cryogenic sub-systems including the cryomodules and superconducting magnets.

13. References
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