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Control Improvements for the DIII-D Cryo System*

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Abstract—The cryogenic system at General Atomics’ DIII-D Tokamak fusion facility provides cryo-pumping for the fusion vessel and neutral beams, cooling for the superconducting magnets for electron cyclotron heating, and cooling for the deuterium pellet injector. The cryo system, built in the 1980s, has been upgraded to integrate control using one programmable logic controller (PLC). This integration of control has provided the ability to make improvements to the control of the cryo system.

I. INTRODUCTION

A. Cryo System Description

The cryogenic system supporting General Atomics’ DIII-D Tokamak (Fig. 1) provides cryo-pumping of gases in the DIII-D vessel, neutral beamlines, and gyrotron magnets using liquid helium at a temperature of 4.6 K. All closed loop liquid helium users are arranged as seven parallel circuits for four neutral beams and three in-vessel cryo pumps (Fig. 2). Each of these seven users requires about five grams per second of liquid helium. The cryo system also provides once through batch-fill cooling for the heating gyrotrons’ super conducting magnets and cooling for the deuterium pellet injector.

DIII-D’s cryo system includes a two-turbine helium liquefier, shown in Fig. 1. The helium system is supplied by two helium compressors producing 1.62 MPa (220 psig) helium gas at 115 grams per second maximum combined flow rate. Helium gas is stored at atmospheric temperature in four horizontal cylindrical tanks. Liquefied helium is stored in a 3.8 m³ (1000 gal) storage dewar. The flow of liquid helium through the cryo system is driven by the difference in pressure between the liquid helium storage dewar at 0.143 MPa (6 psig) and the helium gas returning to the compressors, at about 0.105 MPa (0.6 psig).

The cryo system’s helium gas management system (GMS) (Fig. 2) is designed to maintain a constant pressure in the low pressure helium gas returning from users, accomplished by maintaining a constant inventory of helium gas in the system. When the pressure drops below the set point on the low pressure side, helium gas from the helium gas storage tanks enters the low pressure side through a PLC-controlled “make valve.” When the low pressure side rises above the set point, helium gas leaves the high pressure side, going to the helium gas storage tanks through a PLC-controlled “dump valve,” until the system’s helium gas inventory is reduced to the point that the low pressure side is at the set point again. The pressure in the high pressure (compressor discharge) side is maintained by a back-pressure-regulating bypass valve. This bypass valve discharges excess high pressure helium to the low pressure side. Some flow through the bypass valve is normal and contributes to system stability during transient events that change the amount of helium gas in the system’s inventory such as occurs during cryo pump defrost and cool down.

Liquid nitrogen is used for shielding liquid helium from thermal (heat) radiation on long cryo lines, distribution valve cold boxes, cryostats, subcoolers, heat exchangers, cryo pumps and cryo panels, and super conducting ECH magnets. Liquid nitrogen is also used for precooling helium gas entering the helium liquefier.

Liquid nitrogen is bought as bulk liquid and stored in a 42 m³ (11,000 gal) storage tank at 0.446 MPa (40 psig). All liquid nitrogen used in the cryo system ultimately is converted to gas, and is vented to the atmosphere. The flow of liquid nitrogen through the cryo system is driven by the pressure in the liquid nitrogen storage tank.

B. Cryo System Instrumentation and Control

Control and monitoring instrumentation for the cryo system has evolved over its 25 year life. Early 1980s technology included pneumatic instrumentation to provide input and output signals for valve controllers and analog instruments. This pneumatic instrumentation, along with hand toggle switches, indicator lights, electrical relays, solenoid valves, digital readouts and dial gauges were mounted in instrument panels, installed in rows of control cabinets. As upgrades and additions to the cryo system were made, control and monitoring instrumentation evolved into a combination of the original instrument panels and three PLCs (programmable logic controllers). Accurate mass flow transmitters were installed to measure gaseous helium flow at the compressor discharge, GMS bypass, liquefier inlet, return from the two upper cryo pumps and the lower cryo pump, return from the four neutral beams, and high pressure supply to the reliquefying heat exchangers. Over the last four years, the control and monitoring of the cryo system has been integrated into one PLC [1], a Siemens Simantic TI555 PLC, with Ethernet links to replace slower RS-232 serial communications and 4-20 mA input and output analog signals to replace older 3-15 psi pneumatic signals.



Figure 1. DIII-D cryo system’s liquefier, helium storage dewar, wet expander and distribution boxes.

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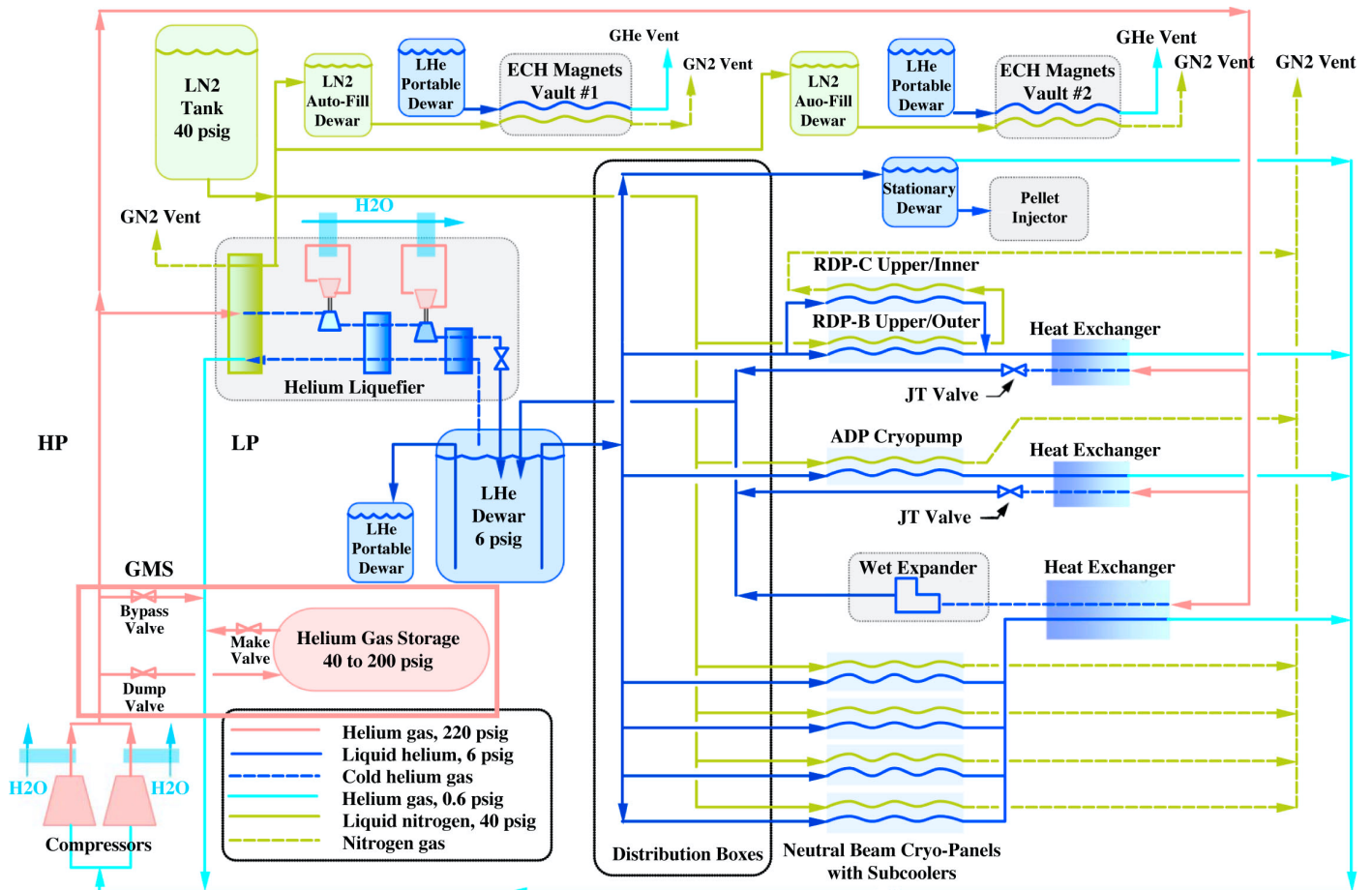


Figure 2. Block diagram of the DIII-D cryo system.

The integrated and faster control system allows real-time control and monitoring of process variables from the operator station located in the cryo control room. The cryo operator's station consists of a personal computer with an instrument input/output database and a graphical user interface. In addition to control loop screens, status screens, alarm screens, help screens, mode control screens, and an event logging screen, about 30 process diagram screens have been developed, displaying cryo system process variables. Each variable can be viewed on a real-time trending chart. Charts with trending of multiple process variables have provided increased understanding of the transients of two-phase cryogen flow, and how they affect the cryo system. Understanding of the cryo system's processes along with integrated control using a single PLC have lead to several improvements to the control of the cryo system.

II. CONTROL IMPROVEMENTS

A. Night/Weekend Mode

During normal physics operations, the cryo system runs at maximum capacity, with both helium compressors fully loaded. By the end of each day's experiments, the inventory of liquid helium needs to be replenished. This was previously accomplished by estimating the helium liquefier's make rate to fill the storage dewar by morning, and leaving the liquefier and compressors to run all night or all weekend.

After integrating the control of the cryo system, PLC logic was developed to create a "Night/Weekend Mode." Overnight and weekend operation of the system is automatic without an operator. Between physics operational days, the in-vessel cryo pumps are shut down leaving the neutral beams to be continuously cooled. At the end of daily operations, the cryo operator selects this mode at the operator's screen. In this mode, the PLC checks interlocks, then starts ramping up the liquefier's make rate to 100% while adjusting the loading of the secondary helium compressor to maintain helium flow in the bypass valve. When the liquid helium storage dewar is full, the PLC ramps down the liquefier's make rate to maintain a constant level in the storage dewar and adjusts the loading of the secondary compressor. The PLC will shut down the secondary compressor if enough flow is provided by the primary compressor. This occurs during the night, as opposed to running the secondary compressor continuously.

In addition, an "evening checklist" screen was developed to provide the cryo operator the ability to quickly and reliably check the status of the cryo system when leaving at the end of the day. This is a summary of important data normally shown on ten or more screens. This screen shows control modes on or off, valves open or closed, and the values of several variables such as tank and dewar levels. The normal status of each is highlighted in green; abnormal conditions are highlighted in red or yellow. This has been useful in reducing after-hour call-

ins due to operator errors, and in reducing the effort required to check the status of the cryo system.

B. Neutral Beam Cryo PLC Upgrades

The flow of liquid helium and liquid nitrogen through each of the four neutral beam cryo panels is controlled by a valve at the inlet of each cryo panel, eight control valves in all. The control valve actuators were converted from pneumatic to electro-pneumatic actuators, to allow the cryo PLC to control the valves instead of the older pneumatic controllers. The pneumatic controllers have performed reliably over the years, but the PLC allows integration of the control of these cryo panels with the rest of the cryo system.

The flow of liquid helium through a beamline cryo panel is controlled by maintaining a constant differential pressure between the inlet of the cryo panel and the two-phase outlet of the cryo panels. The flow of liquid nitrogen through a beamline cryo panel is controlled by maintaining a constant gas temperature at the outlet of the cryo panels. Control of the helium and nitrogen panels was previously accomplished by pneumatic controllers with adjustable setpoint and adjustable proportional, integral and differential control loop values. By converting these pneumatic controllers to PLC software control logic, several control improvements were achieved:

1. When upsets in the neutral beam helium cryo panels occur due to unusual heat loads on the cryo panels, temperature sensors on the cryo panels provide a signal to the PLC of a temperature excursion, which increases the flow of helium until the temperature is again cold and stable. Before implementing, this unpredictable occurrence was difficult and time consuming to recover from manually.
2. When starting or stopping certain helium cryo pumps in the DIII-D vessel, certain other neutral beam cryo panels were known to experience reduction of liquid helium flow. By trend analysis, the flow reduction was determined to be caused by variations in the back-pressure of the helium gas returning through a low pressure return line shared by the neutral beam and the cryo pump. Logic was implemented to automatically increase the flow of helium to the affected beamlines, to pre-empt a loss of flow, during these changes to the cryo system.
3. Beamline cryo panels can be remotely cooled or warmed through a remote laptop from off-site during nights and weekends. This allows earlier starting of physics operations after a maintenance shutdown.
4. Regeneration (defrosting) of beamline cryo panels can be accomplished automatically. Once implemented, this will replace manual regeneration and save operator time required.

C. Cryo Pump Tuning

Each of the three cryo pumps in DIII-D (Fig. 3) provides cryo-condensation of gases used in physics experiments, typically deuterium. When a cryo pump is used for a day's experiments, it is kept at about 4K during a tokamak shot by maintaining a minimum He flow rate of about 6 grams per second. At the end of each tokamak shot, the cryo pump is defrosted by warming it to greater than 20 K. This is

accomplished by closing the liquid helium inlet valve and introducing a small amount of room temperature helium gas for a short period of time. It is held at that condition until the end of glow discharge, about ten minutes, when it is then recooled by opening the inlet valve and allowing liquid helium to return to the cryo pump to a cold, steady-state condition. This defrost prevents buildup of frost on the pumping surfaces. The total defrost time is about fifteen minutes.

It was observed that after each tokamak shot, a lack of flow in the GMS bypass valve caused a loss of stability in the gas management system. When this occurred, interlocks intended to protect the cryo system would shut down the cryo pumps, and shut down the helium liquefier. Using multi-variable real-time trending charts, it became clear that the solution to preventing shutdowns was to reduce surges in helium gas returning from the cryo pumps. This was achieved by implementing several changes to the control logic of the cryo pumps:

1. During cryo pump recooling, helium gas leaving the cryo pump was discharged directly into the low pressure side of the cryo system. This caused a surge of gas into the low pressure side as liquid helium boiled as it cooled the cryo pump. The logic was changed so that helium leaving the cryo pump during recool passed through the boiling heat exchanger before entering the low pressure side. The heat exchanger provides a cold thermal mass to reduce the surge in helium gas.
2. After the cryo pumps were defrosted, the flow of liquid helium remained off until the end of glow discharge, typically lasting about ten minutes. Changes were made in the logic to keep a small flow of liquid helium through the cryo pumps during glow discharge. This reduced the surge of helium gas from the cryo pumps returning to the low pressure side of the cryo system at the start of recool.

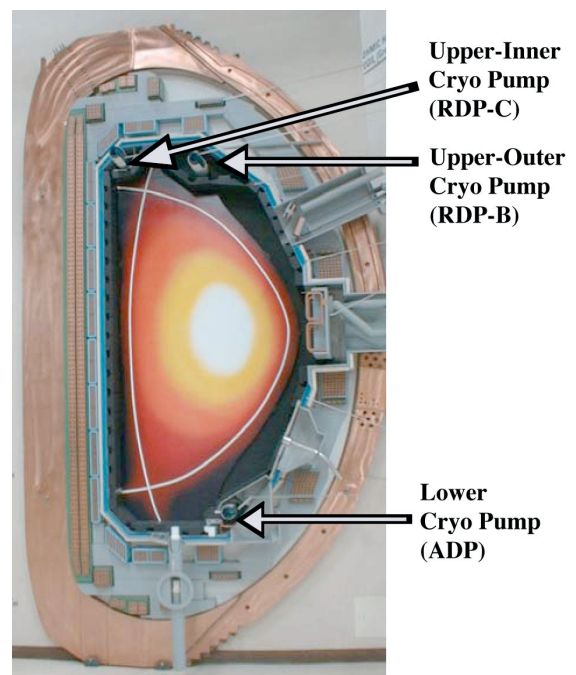


Figure 3. DIII-D's three in-vessel cryo pumps. Photo of the model of DIII-D.

D. Cool Down Improvements

Cooldown of the cryo system nitrogen circuits was optimized to reduce the cool down time at the beginning of physics operations.

- The liquefier's control valve for liquid nitrogen was increased from 35% to 100% open during cool down.
- The flow rate of liquid nitrogen for the cryo pump's cryostat shield was increased during cool down. A parallel line with a PLC-controlled solenoid valve was added to provide extra flow.
- Logic was implemented to control the nitrogen subcoolers for the neutral beam cryo panel. These subcoolers are used to increase the amount of liquid nitrogen in the two-phase flow through the cryo panels. However, they also increase the time required for cool down. By adding a solenoid valve bypassing the subcooler and a pressure relief valve at the outlet of the subcooler, the PLC is used to bypass the subcooler during cooldown.

E. Remote Operation

The cryo system at DIII-D operates continuously during operating periods. Remote monitoring and control of the cryo system from a laptop allows an operator to monitor and respond from home to cryo system alarms occurring after hours. When an alarm from the cryo system PLC notifies General Atomics' guard station, a security guard calls the cryo operator on-duty. The operator uses the laptop to identify the alarm, determine the cause, and take appropriate action. The remote laptop is also used to start the cooling of cryo panels and cryo pumps the evening before operations.

F. Monitoring of Nitrogen Use

The installation of nitrogen flow meters used for each neutral beam lead to the optimized tuning of the nitrogen controllers. These flow meters are accurate, temperature-compensated mass flow meters, connected to the PLC for observing and recording flow data. In a typical beamline, the average flow rate of nitrogen was reduced from 77.8 to 50.0 standard cubic centimeters per second (16.5 to 10.6 standard cubic feet per minute).

Mass flow meters are being implemented to measure the amount of liquid nitrogen used by each of the three in-vessel cryo pumps, the four neutral beam cryo panels, and the helium liquefier, and the amount vaporized for use by laboratories at DIII-D. These flows, measured after the liquid nitrogen is vaporized, are then totaled by the cryo PLC and compared to the drop in the level of the 11,000 gal liquid nitrogen tank, to provide an accurate accounting of the liquid nitrogen usage at the DIII-D facility. This accounting will be made continuously by the PLC.

III. RESULTS OF CONTROL IMPROVEMENTS

A. Power, Cost and Time Savings

The night/weekend mode shuts down the secondary compressor during the night as opposed to running the secondary compressor continuously, saving \$17,000 per year in electricity.

Tuning the control of nitrogen in the neutral beam cryo panels reduced the usage of liquid nitrogen, saving \$20,000 per year.

Reduced cool down time and the use of the remote lap have eliminated a three-hour delay at the beginning of physics operating periods.

Monitoring of nitrogen usage resulted in the discovery and correction of a nitrogen gas leak, saving \$25,000 per year.

B. After-Hour Call-Ins

Improvements to the cryo system control have made the system more reliable. The number of after hours call-ins has been reduced: in 1997 there were 42 call-ins; in 2004 there were 6 call-ins; in the 4 operating months of 2005 there was only 1 call-in, saving approximately \$20,000 in labor costs per year.

ACKNOWLEDGMENT

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REFERENCE

- [1] K.L. Holtrop, P.M. Anderson, and P.S. Mauzey, "Improvements to the cryogenic control system on DIII-D," Proc. 20th IEEE/NPSS Symp. on Fusion Engineering, San Diego, California (Institute of Electrical and Electronic Engineers, Inc., Piscataway, New Jersey, 2003), p. 401.