CONTROL SYSTEM OF CRYOMODULE TEST FACILITIES FOR SHINE*

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Abstract

Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE) is under construction. The 8 GeV superconducting Linac consists of seventy-five 1.3 GHz and two 3.9 GHz cryomodules. A cryomodule assembling and test workshop is established.Multiple facilities have been built for cryomodule and superconducting cavity test, including two vertical test facilities, two horizontal test facility, one multiple test facility and one liquid helium visualization facility.The local control systems are all based on Yokogawa PLC, which monitor and control the process variables such as temperature, pressure, liquid level and power of the heater. PID and other algorithms are used to keep liquid level and power balance. EPICS is adopted to integrate these facilities along with vacuum devices, solid state amplifiers, LLRF and RF measurement system, etc. The details of the control system design, development and commissioning will be reported in this paper.

OVERVIEW

Owing to the wide range of applications of X-rays in the research fields of physics, chemistry and biology, facilities with the ability to generate X-rays were developed continuously in the last century. The free electron laser (FEL) is a novel light source, producing high-brightness X-ray pulses. To achieve high-intensity and ultra-fast short wavelength radiation, several X-ray FEL facilities have been completed or under construction around the world [1].

The first hard X-ray FEL light source in China, the so-called Shanghai HIgh repetition rate XFEL aNd Extreme light facility (SHINE), is under construction. It will utilize a photocathode electron gun combined with the superconducting Linac to produce 8 GeV FEL quality electron beams with 1.003086MHz repetition rate.

CRYOMODULE

Cryomodule (Fig. 1) is the key components of the superconducting linear accelerator, which composes of superconducting cavities, superconducting magnet components, beam position detectors, cryogenic cooling system, vacuum system, and mechanical support system. SHINE requires 75 1.3GHz superconducting cryomodules, which are connected in series to form the accelerator L1, L2, L3, and L4. In addition, two third-harmonic cavities with a frequency of 3.9GHz superconducting modules will be used to linearize the longitudinal emittance of the electron beam [2].

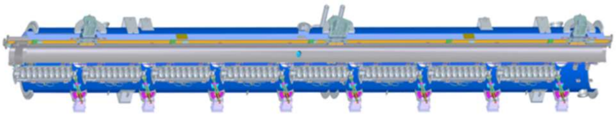

Figure 1: Cryomodule.

CRYOMODULE TEST FACILITY

A superconducting cryomodule workshop is built for SHINE project. The infrastructure(shown in Fig. 2) includes ultra-clean processing and assembly, precision mechanical assembly and testing, cryogenic component multi-functional test facility system, superconducting cavity vertical and horizontal test facility system. They are used for superconducting cryomodule assembly and functional testing.

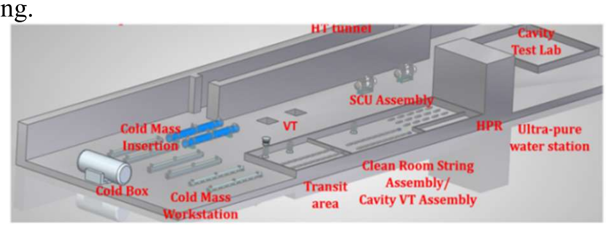

Figure 2: Layout of test facility.

The cryogenic component multi-functional test facility is used to test the working life of the tuner at cryogenic, the vacuum leakage rate and electrical performance at cryogenic of cold BPM, the working stability of superconducting magnet and current lead at cryogenic, the thermal load of each temperature zone, and the vacuum leakage rate of the coupler at cryogenic.

The superconducting cavity vertical test facility is used to test the performance of the superconducting cavity vertically to check whether the cavity has reached the design goal, so that it can meet the needs of engineering. The superconducting cavity horizontal test facility is used to test the performance of the cryomodule, check whether the cryomodule meets the design goal, and make it meet the needs of engineering. it includes cryomodule section and Feed Cap & End Cap.

CONTROL SYSTEM

The control system is responsible for the device control, data acquisition, functional safety, high level database or application, as well as network and computing platform. It will provide operators, engineers and physicists with a comprehensive and easy-to-use tool to control the components of cryomodule test facility.

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The control system will be mainly based on EPICS to reach the balance between the high performance and costs of maintenance. EPICS is a set of open source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments such as particle accelerators, telescopes and other large scientific experiments [3].

As shown in Fig. 3, the control system can be divided into there layers to ensure the performance and scalability, which are operator interface layer, input/output controller layer and device local control layer.

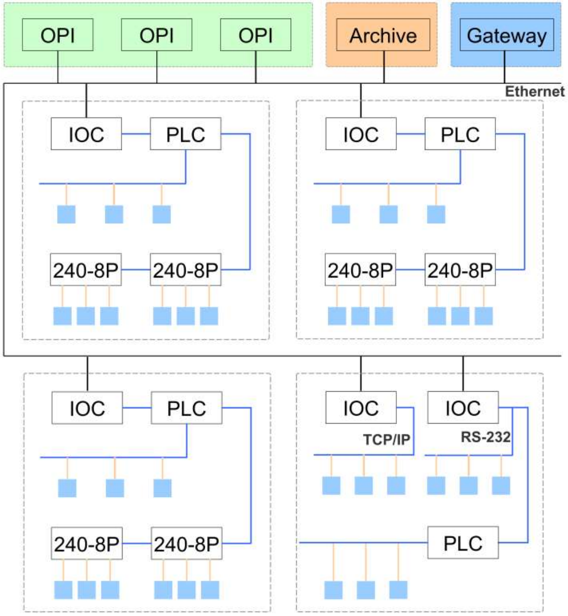

Figure 3: Architecture of the control system.

The local control layer is responsible for the monitor and control of temperature, pressure, cryogenic valve, liquid level, heater power supply, vacuum and so on. The signal of horizontal test facility is shown as Table 1. The multi-functional test facility and vertical test facility are similar.

Table 1: The Signal of Horizontal Test Facility

Signal	Qty	Type	
Temperature	120	Input	CX-1030-CU-HT
Pressure	2	Input	Analog
Liquid Level	3	Input	Analog
Cryogenic valve	4	Input	Analog
Cryogenic valve	4	Output	Analog, PID
Function safety	14	Input/Output	Digital
Heater Power Supply	16	Input/Output	Analog, Digital
Vacuum Gauge	3	Input	Serial port
Ion Pump	3	Input	Serial port
Magnet Power Supply	3	Input	Ethernet

TEMPERATURE MONITORING

Temperature monitoring(Fig. 4) is one of the key technologies for the test facility. LakeShore Cernox CX-1030-CU-HT is considered to be used as the temperature sensor(Fig. 5). Because the resistance of the cryogenic probe is not in the range of the PLC temperature monitoring module, temperature meter is used. The Cernox temperature probe is connected with temperature meter 240-8P by four wires to reduce error and reduce interference during transmission. 240-8P has 8 channels to connect temperature probe. The data from temperature meter is transmitted to PLC temperature module in sequence via profibus protocol. As shown in Fig. 6, F3LB01-0N is utilized as the model of PLC temperature module.

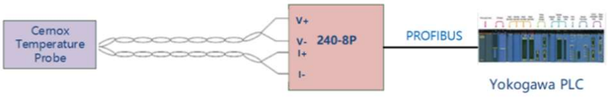

Figure 4: Temperature monitoring

Figure 5: Temperature sensor.

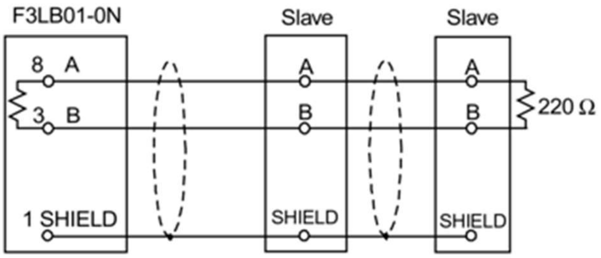

Figure 6: Structure of F3LB01-0N.

PRESSURE MONITORING

Pressure Transmitters(shown in Fig. 7) has 3 types applied to pressure monitoring. KELLER PAA-41X (0-100mbar, 4-20mA), KELLER PAA-33X (0-1600mbar, 4-20mA), and KELLER PAA-33X (0-3000mbar, 4-20mA). PLC module is Yokogawa F3AD08-4R (analog input module, 8 channels, 4-20mA), the internal circuit diagram of F3AD08-4R is displayed in Fig. 8.

Pressure Transmitters measures 2K helium circuit pressure(high pressure), 2K helium circuit pressure(low pressure), along with cryogenic pipeline pressure. 16-bit analog-to-digital module is selected, and the acquisition accuracy meets the equirement.

Figure 7: Pressure transmitter.

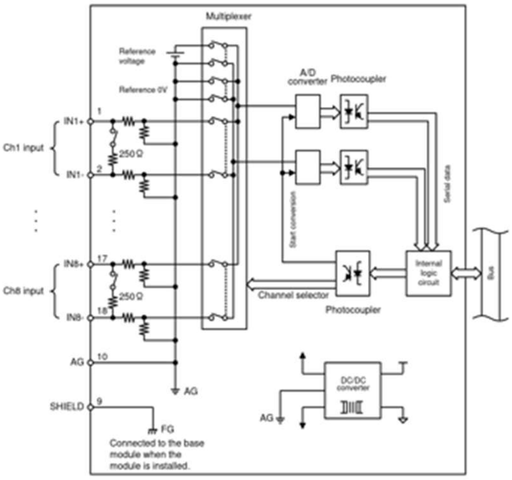

Figure 8: Internal circuit diagram of F3AD08-4R.

MONITORING AND CONTROL OF CRYOGENIC VALVE

The model of cryogenic valve selects Toko Valex T-8800, while the model of digital electropneumatic valve positioner(Fig. 9) picks SAMSON 3730-2. PLC modules are Yokogawa F3AD08-4R (analog input module, 8 channels, 4-20mA) and Yokogawa F3DA04-5R (analog output module, 4 channels, 4-20mA). The internal circuit diagram of F3DA04-6R is displayed in Fig. 10.

Cryogenic valve contains cooling valve and bypass valve. Its function is to control the flow of helium gas. When needed, open the valve to allow helium to enter the pipeline to cool the cryomodule.

Figure 9: Digital electropneumatic valve positioner.

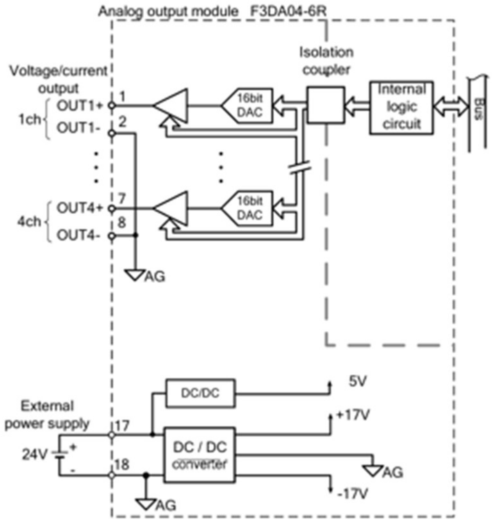

Figure 10: Internal circuit diagram of F3DA04-6R.

LIQUID LEVEL MONITORING AND STABILITY CONTROL

Liquid level monitoring and stability control(Fig. 11) is another key technology for the test facility. Level gauge has AMI 2K level probe. Liquid level gauge obtains AMI 1700-2K (0-10V analog output) as its model. The PID algorithm is used to realize the closed-loop control of the 2K liquid helium level. There are two control methods: manual control and PID control. The manual control is to set cryogenic valve opening on the interface while the PID control is that the PID program automatically sets the opening of the cryogenic valve. PLC module is Yokogawa F3CU04-1S (PID module, 0-10V analog input, 4-20mA analog output).

The final goal is to stabilize the height of the liquid level at a certain value. The liquid level gauge is partly in liquid helium and partly in air. The level gauge is connected with the liquid level acquisition instrument by four wires to reduce error. AMI 1700 is the liquid level acquisition instrument, it displays liquid level height, and it supports 4-20mA signal and 0-10V signal. AMI 1700 converts the height of the liquid level to voltage, and exports the voltage signal to the PID module F3CU04-1S. F3CU04-1S has its own algorithm, the parameters include setting value and output value. F3CU04-1S receives 0-10V voltage signal, which corresponds to the valve opening. It controls the valve dynamically according to the linear conversion relationship.

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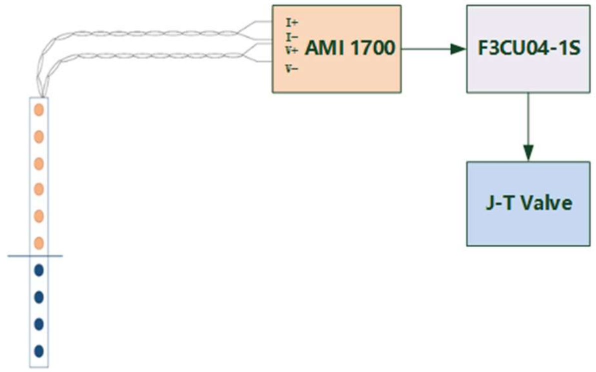

Figure 111: Liquid level monitoring and stability control.

As the algorithm diagram is shown in Fig. 12, e is the difference of setting value and target value. The target value is obtained from the liquid level sensor. u is the output of PID control, which conforms to the algorithm formula with 3 diagnostic parameters(k_P,T_I,T_D) in Fig. 13. These 3 parameters should be determined in the commissioning site.

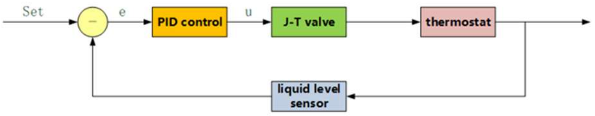

Figure 12: Algorithm diagram.

$$u(t)=K_P[e(t)+\frac{1}{T_I}\int_{s=0}^{t}e(s)\mathrm{d}s+T_D\frac{\mathrm{d}(e(t))}{\mathrm{d}t}]$$

Figure 13: Algorithm formula.

MONITORING AND CONTROL OF HEATER POWER SUPPLY

Omega KH-112/10 50W is utilized as the model of the heater, which is used for cryomodule heating up and cryomodule compensation of total thermal load power. Heater power supply model(shown in Fig. 14) is TDK Z60-3.5-C, the heater power supply has two modes (constant voltage and constant current), and constant current mode is used in this project. PLC includes Yokogawa F3XD16-3F DC digital input module, F3YC08-0C relay digital output module, F3AD08-5R 0-10V analog input module, and F3DA08-5R 0-10V analog output module. It realizes switching on/off power supply remotely, power failure status readback, and power operation mode readback (constant voltage, constant current). It achieves power supply output current value readback, power supply output voltage value readback, and power supply output power value readback. It fulfills current output setting. Constant control of the total thermal load power of the cryomodule has two methods: manual control and automatic control. The manual control is to set the current setting value on the interface while the automatic control automatically sets the current setting value, which is realized with Python + cothread. Cavity dynamic load + heater compensation output power = total power (constant).

Figure 14: Heater power supply model.

FUNCTION SAFETY CONTROL

The function safety logic is established between the system and the device. When a fault occurs, it can reliably and quickly protect the important components, send an alarm signal, and report the fault information to the control system. For input signals, the system can realize alarm latch, reset, and bypass processing from the software. Latch refers to saving the signal alarm state. Reset refers to releasing the alarm latch. Bypass means that the software temporarily releases the function safety response to the input signal. Yokogawa F3XD16-3F DC digital input module and F3YC08-0C relay digital output module are adopted for the PLC modules. The Interface of function safety control is shown in Fig. 15.

	Real value(Pa)	Setting(Pa)	Alarm	Bypass	Latched	Reset
VAC01: (Cryostat)	0.0e+00 Pascal		🔴	Bypassed	🟢	Reset
VAC02: (Beam)	0.0e+00 Pascal		🔴	Not Bypassed	🔴	Reset
VAC03: (Coupler)	0.0e+00 Pascal		🔴	Not Bypassed	🔴	Reset
PT01:	-1.75100 bar	1.5	🟢	Not Bypassed	🔴	Reset
CP1TT02:	0.000 K	300.0	🟢	Not Bypassed	🟢	Reset
CP2TT02:	0.000 K	300.0	🟢	Not Bypassed	🟢	Reset
CP3TT02:	0.000 K	300.0	🟢	Not Bypassed	🔴	Reset
CP4TT02:	0.000 K	300.0	🟢	Not Bypassed	🔴	Reset
CP5TT02:	0.000 K	300.0	🟢	Not Bypassed	🟢	Reset
CP6TT02:	0.000 K	300.0	🟢	Not Bypassed	🔴	Reset
CP7TT02:	0.000 K	300.0	🟢	Not Bypassed	🔴	Reset
CP8TT02:	0.000 K	300.0	🟢	Not Bypassed	🟢	Reset
From ColdBox:			🔴	Not Bypassed	🔴	Reset
LT02:			🟢	Not Bypassed	🔴	Reset

Figure 15: Interface of function safety control.

IOC AND OPI

MOXA DA-682B running Linux/CentOS is chosen as IOC to communicate with local I/O devices with serial port, using Modbus/TCP protocol. We make use of PyDM (Python Display Manager) to build the graphic user interface. It is a new framework for building control system GUI based on PyQt, allowing us to make a rich desktop app including all types of buttons (push, toggle), images and a lot more. It is also convenient to add new functions to existing widgets and add new widgets. A user interface of vertical Dewar is shown in Fig. 16.

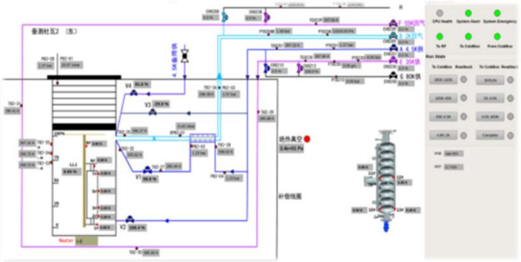

Figure 16: Control interface of vertical test platform.

Hundreds of EPICS PVs are archived by Archiver Appliance which is deployed on dual-server cluster as hot backup. Each server can provide data query service for all PV channels. Besides, with its excellent data retrieval performance, the archive client can be launched from a web page and used to browse and plot data as shown in Fig. 17.

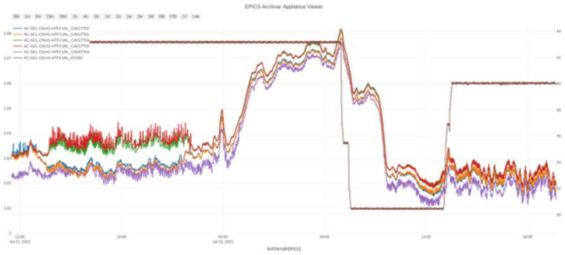

Figure 17: Temperature of archiver appliance.

The control system of cryomodule test facilities has been operating stably for several months. The local control system makes use of Yokogawa PLCs and the corresponding algorithms, such as PID to keep liquid level and power balance. It is mainly used to monitor and control the parameters of temperature, pressure, liquid level, power of the heater and so on. The high level control system is based on EPICS to integrate all the devices in various systems, networked together to allow communication between them.

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