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Remote monitoring system for the cryogenic system of superconducting magnets in the SuperKEKB interaction region

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Abstract. A remote monitoring system was developed based on the software infrastructure of the Experimental Physics and Industrial Control System (EPICS) for the cryogenic system of superconducting magnets in the interaction region of the SuperKEKB accelerator. The SuperKEKB has been constructed to conduct high-energy physics experiments at KEK. These superconducting magnets consist of three apparatuses, the Belle II detector solenoid, and QCSL and QCSR accelerator magnets. They are each contained in three cryostats cooled by dedicated helium cryogenic systems. The monitoring system was developed to read data of the EX-8000, which is an integrated instrumentation system to control all cryogenic components. The monitoring system uses the I/O control tools of EPICS software for TCP/IP, archiving techniques using a relational database, and easy human-computer interface. Using this monitoring system, it is possible to remotely monitor all real-time data of the superconducting magnets and cryogenic systems. It is also convenient to share data among multiple groups.

1. Introduction

The SuperKEKB accelerator [1, 2] and Belle II detector system [3] are under construction at the KEK Tsukuba campus. They are the upgraded systems of the previous KEKB accelerator and Belle detector and are designed to conduct high-energy physics experiments with extremely high luminosity. Physics experiments are planned to start in January 2019. Figure 1 shows a schematic of the SuperKEKB accelerator.

SuperKEKB is an electron–positron collider with a single interaction point. The target luminosity is 8×10^{35} cm^{-2} s^{-1}, which is 40 times higher than that of the previous KEKB. It can be achieved by doubling the beam current and reducing the beam cross-sectional area by a factor of 20. It requires nanoscale beam focusing in the vertical direction at the interaction point.

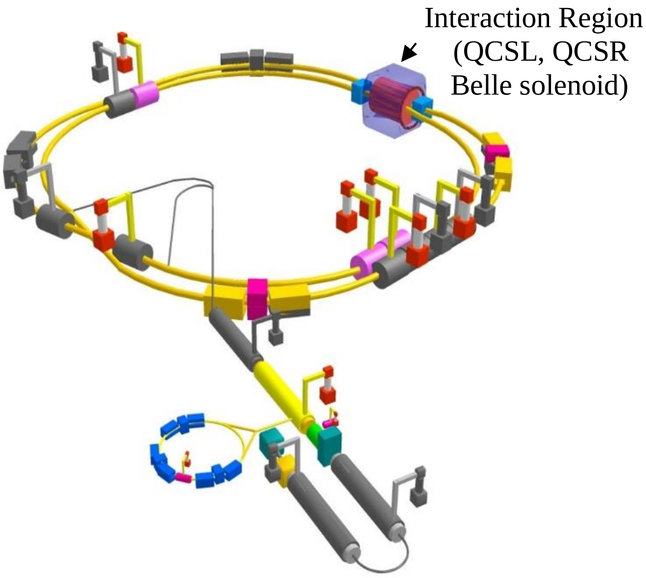
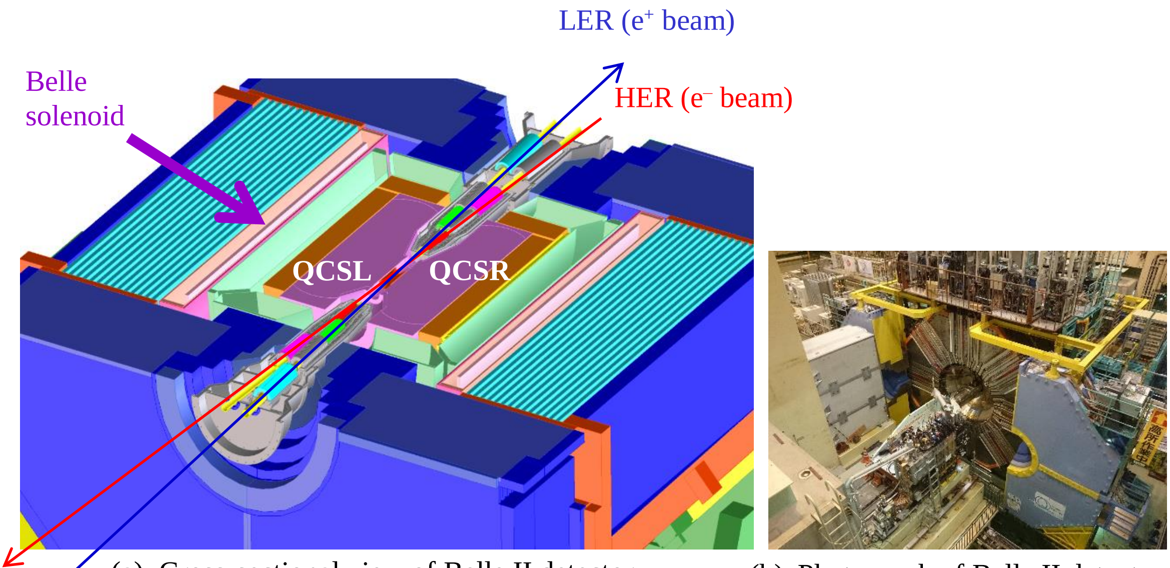


Figure 1. SuperKEKB accelerator.

The beam final focusing system of the accelerator at the interaction region, which consists of superconducting quadrupoles and corrective magnets [4], has been developed to achieve high luminosity. In contrast, the Belle II detector has a large Belle superconducting solenoid [5], which is the same magnet used in the previous Belle detector. The Belle solenoid surrounds the beam final focusing system. Figure 2 (a) shows a cross-sectional view of the interaction region in the horizontal direction. Figure 2 (b) shows a photograph of the Belle II detector and the QCSR cryostat.



(a) Cross-sectional view of Belle II detector

(b) Photograph of Belle II detector and QCSR

Figure 2. Placement of superconducting magnets in the interaction region.

These superconducting magnets, which interact with each other in a narrow area, are cooled by three helium cryogenic systems having the same structure. Considering the correlation of the beam final focusing system and the Belle solenoid, a remote monitoring system that can equally monitor both systems is required. In addition, the ability for users to monitor all cryogenic data in real-time with the fastest possible cycle time from PCs on the networks was requested. This implies that users should be able to equally monitor the data in the control room, experimental hall, other work places, houses, and anywhere else.

The ability for the remote monitoring system to share data with multiple groups, such as the accelerator control group and Belle II detector group, was also requested. Data-sharing with multiple groups is important in large-scale experiments.

2. Superconducting magnets and helium cryogenic system

SuperKEKB collides 7-GeV electrons from the high-energy ring (HER) with 4-GeV positrons from the low-energy ring (LER) at a single interaction point with a finite crossing angle of 83 mrad.

2.1. Superconducting magnets

The beam final focusing system has superconducting quadrupole doublets for each beam. These magnets are equipped with 43 superconducting corrector coils. The system has four compensation solenoids to reduce the influence from the surrounding Belle solenoid field on the beams. All magnets and corrector coils are assembled into two cryostats, QCSR and QCSL, which are displayed in figure 2.

The Belle solenoid housed in a dedicated cryostat is a large superconducting magnet with a central magnetic field of 1.5 T. The inner and outer diameters of the vacuum shell are 1700 and 2000 mm, respectively, and the coil length is 3910 mm. QCSR and QCSL are inserted into the bore of the Belle solenoid during physics experiments.

2.2. Cryogenic systems

The Belle solenoid, QCSR, and QCSL are each cooled by a medium-sized helium cryogenic system, which is composed of a Cold Box (Claude cycle), screw compressor, subcooler, and buffer tanks. Three cryogenic systems were constructed in 1989 and have the same structure and capacity. The capacity is 250 W at 4.4 K (or 160 W at 4.4 K + 28.4 L/h). Cryogenic systems for the Belle solenoid and QCSL were used in a previous KEKB and Belle experiment. In contrast, the cryogenic system for the QCSR was not used during that experiment. For the SuperKEKB project, it was moved after a few years and modified to cool the QCSR.

3. Control system for superconducting magnets and cryogenic systems

These cryogenic components are controlled by the Hitachi integrated instrumentation system EX-8000 on a dedicated local network. Figure 3 shows the EX-8000 on a dedicated local network as part of the developed remote monitoring system. The dedicated network for the EX-8000 was adopted from a safety standpoint. The EX-8000 has three multi-loop controllers (MLCs), operator consoles, and other common devices. One MLC was assigned to control one set of superconducting magnets and its cryogenic system. MLC1 was assigned for the Belle solenoid and its cryogenic system, MLC3 was assigned for QCSL and its cryogenic system, and MLC4 was assigned for QCSR and its cryogenic system. Data collected from the cryogenic components can be shared by each device on the EX-8000 dedicated network.

A gateway unit (GWU) is one of the shared devices of the EX-8000. Its purpose is to read/write data between the EX-8000 dedicated network and external devices. By using this GWU, it becomes possible to safely read data of the EX-8000 from outside the dedicated network. The developed remote monitoring system used this GWU to allow the user to monitor EX-8000 data remotely from PCs on other networks.

The cycle time of the collection and control by the EX-8000 is 1 s. However, it does not collect data on the order of microseconds, which is required when quenching occurs. The remote monitoring system was developed with the goal of realizing the same 1-s cycle time as the EX-8000.

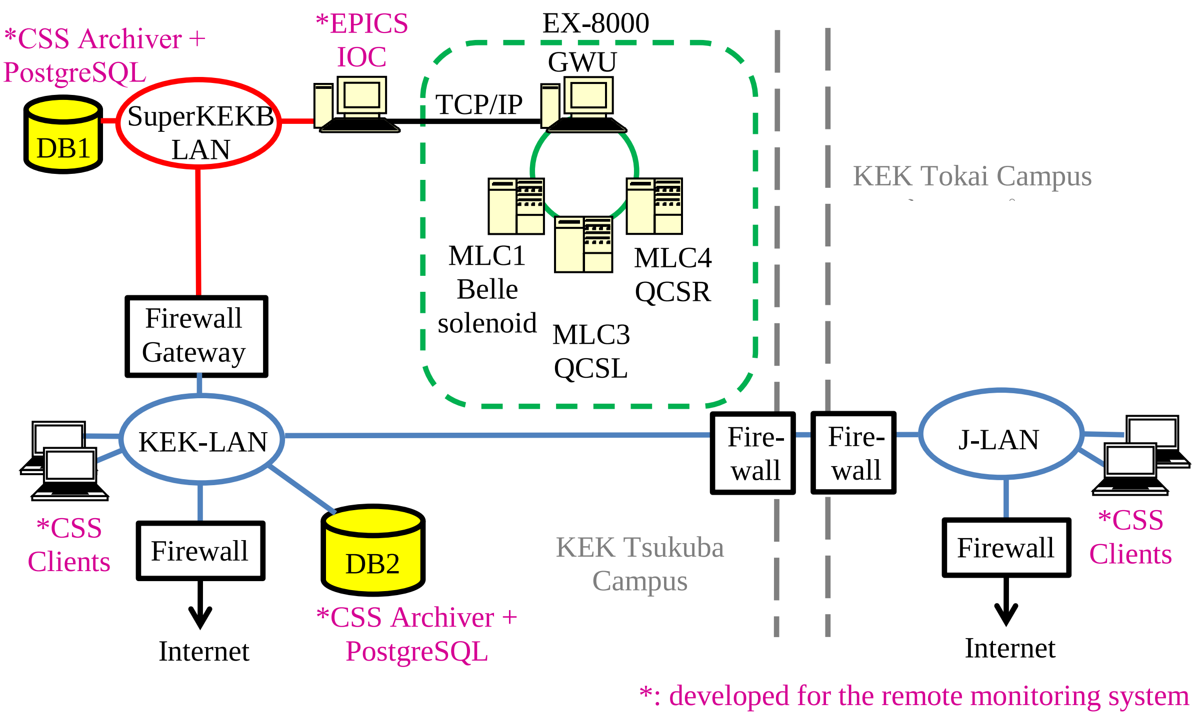


Figure 3. Remote monitoring system. J-LAN and KEK-LAN can both be accessed.

4. Software of remote monitoring system

It is important to share data of the SuperKEKB accelerator magnets (QCSL and QCSR) and Belle II detector magnet (Belle solenoid) between multiple groups. EPICS [6] allows the easy sharing of data between different groups via the network.

4.1. EPICS

EPICS is a set of open-source software tools, libraries, and applications developed collaboratively to create a distributed soft real-time control system and has been widely used for accelerator control. EPICS has been used by the accelerator control group and detector group in KEK. By using EPICS, easy data-sharing with multiple groups can be realized. For this reason, EPICS was chosen as the infrastructure to develop the remote monitoring system for superconducting magnets and cryogenic systems. EPICS uses Client/Server and Publish/Subscribe techniques to communicate between various computers. There is a certain degree of freedom in developing software based on EPICS. We have developed the remote monitoring system according to the following EPICS software components.

- Input/Output Controller (IOC)
  IOCs perform real-world I/O operations and publish information to clients using networking with a soft real-time protocol called Channel Access (CA). The IOC collects data from each device; then, it provides live data to clients via the CA.
- ArchiveEngine
  An ArchiveEngine, such as CSS archiver, takes data samples from the PC of the IOC via the CA and stores them in a data storage location. The archive client program, such as CSS client, then accesses the historic data samples from that location. ArchiveEngine is built as an Eclipse product. Eclipse is the most widely used Java integrated development environment.
- Relational Database (RDB)

Historic data are stored in the RDB, which is managed by object-relational database management software, such as PostgreSQL (free and open-source).

- Control System Studio (CSS)
  CSS is an Eclipse-based collection of tools to operate control systems. It is a user interface framework for the control system, which works as an archive client system from each user's PC on the network. It provides convenient tools for the user to develop real-time graphs and graphics. It can directly access live data on the IOC and historic data on the RDB. Real-time monitoring can be realized by CSS clients.

4.2. Application to the remote monitoring system

We applied EPICS to our system to develop the monitoring software. Figure 3 shows our developed monitoring system.

- IOC part
  In our system, the IOC runs on a single Linux PC. The PC running the IOC has two Ethernet ports. One is directly connected to the GWU and the other is connected to a SuperKEKB-accelerator-LAN, which is a highly security-controlled local network dedicated for accelerator operation only. To realize data exchange between the GWU and IOC on the PC, we used the "StreamDevice" software tool of the EPICS IOC, which is a generic supporting device for devices with a "byte stream"-based communication interface, such as TCP/IP. It is important to make the data read/write speed as fast as possible. A series of binary commands of the GWU in a line is used to read/write all data from/to the GWU using the "Stream Device."
- ArchiveEngine and RDB parts
  ArchiveEngine, using a CSS archiver, and an RDB, using PostgreSQL as a RDB management software, were built on the same Linux PC with 6 TB of storage. In the RDB, data is archived on a monthly basis. We installed two PCs with the same hardware and software structure. One was set on the SuperKEKB-accelerator-LAN and the other was set on the KEK-LAN, which is the common LAN in KEK. The former was intended to provide information from the RDB to the SuperKEKB accelerator control, whereas the latter was installed for general user access to the database. Both contain the same data. One is also the backup of the other. The SuperKEKB-accelerator-LAN is connected via a general gateway (CA gateway) and firewall to the KEK-LAN, as shown in figure 3.
- CSS-based client parts
  We have produced many graphs simulating the EX-8000 and graphics using CSS tools for the remote monitoring of the QCSL, QCSR, and Belle solenoid system. In the KEK-LAN, the wireless LAN can be used as well. Users can operate the developed CSS-based client on their own PCs from anywhere on the KEK-LAN to remotely monitor data from the superconducting magnets and cryogenic systems. There is another common local network at the KEK Tokai campus, J-LAN. KEK-LAN and J-LAN can both be accessed. The CSS archiver allows CSS-based client to access data from J-LAN, as shown in figure 3. In addition, users can access the KEK-LAN from the outside via a virtual private network (VPN) using the Internet. Users can operate the CSS-based client to monitor the data from anywhere using a PC connected to the Internet via a VPN.

5. Performance of remote monitoring system

Data on the EX-8000 are classified as Analog Input (AI), Analog Output (AO), Digital Input (DI), Digital Output (DO), and internal data such as the setting value. The developed IOC collects all AI, AO, DI, and DO data excluding the internal data from the EX-8000. Furthermore, a part of the collected data is converted using calculations and stored in the RDB with original data for user convenience.

- AI: process value (PV) of temperature, pressure, flow rate, liquid level, vacuum, turbine speed, current, voltage, strain, and other parameters.
- AO: manipulated value (MV) of valve opening/closing and heater input.
- DI: status of on/off valves and alarms.
- DO: instruction for on/off operations including on/off valves and others.
- Calculated data: there are two types of control valves: direct acting and reverse acting. In order to produce consistent graphics, the MVs of the direct acting valves are converted using calculations to display a consistent value with the reverse acting valves. MV 0% indicates a fully closed valve and MV 100% indicates a fully opened valve. Both original MVs and converted MVs are stored in the RDB.

Table 1 presents the number of data samples classified for each MLC of EX-8000.

Table 1. Number of data samples monitored by the remote monitoring system.

MLC No.	System	Number of data
MLC1	Belle solenoid & cryogenic system	260 (AI:101, AO:33, DI:64, DO:48, Calculated:14)
MLC3	QCSL & cryogenic system	410 (AI:224, AO:42, DI:72, DO:44, Calculated:28)
MLC4	QCSR & cryogenic system	378 (AI:199, AO:43, DI:68, DO:39, Calculated:29)

The most important reason for developing the remote monitoring system was to collect data via the GWU at a fast cycle time. The goal was 1 s. Therefore, a simple binary command of the GWU was used with “StreamDevice”. The IOC sends one binary command to the GWU. The binary command requests to read all 977 data points other than the calculated data. The GWU returns all 977 data points in binary form on one line. The purpose of using one request and one response in binary form is to avoid duplication for the TCP/IP connection setup. As a result, we realized data collection in the same 1-s cycle as the EX-8000.

Including calculated data, the total number of data points is 1048. PostgreSQL uses 160 bytes (data: 80 bytes, index: 80 bytes) to store one data point. As 1048 data points are collected per second, in a year, the capacity required for storage reaches 5.3 TB. The actual necessary capacity is expected to be reduced because the CSS archiver does not store unchanged data.

We tested the function and operation of the CSS client from PCs on various networks: SuperKEKB-accelerator-LAN, KEK-LAN and wireless LAN, and J-LAN and wireless LAN. We also tested them from outside KEK using a VPN. Connections from various networks worked well. Real-time data on the developed trend graphs and graphics were compared with the EX-8000 original data and proved to be accurate. Figure 4 displays an example of the graphs. It shows a precooling curve of the Belle solenoid. It took 7.5 days to cool from room temperature to liquid-helium temperature. Figure 5 shows an example of the real-time graphics. It displays the flow diagram for the QCSL magnets and cryogenic system.

Currently, performance tests for the QCSL and QCSR superconducting magnets are underway. At the present stage, one data point, which is the current value of the Belle solenoid, is shared among the SuperKEKB accelerator groups. According to the progress of construction and tests, the amount of data-sharing with other groups will increase.

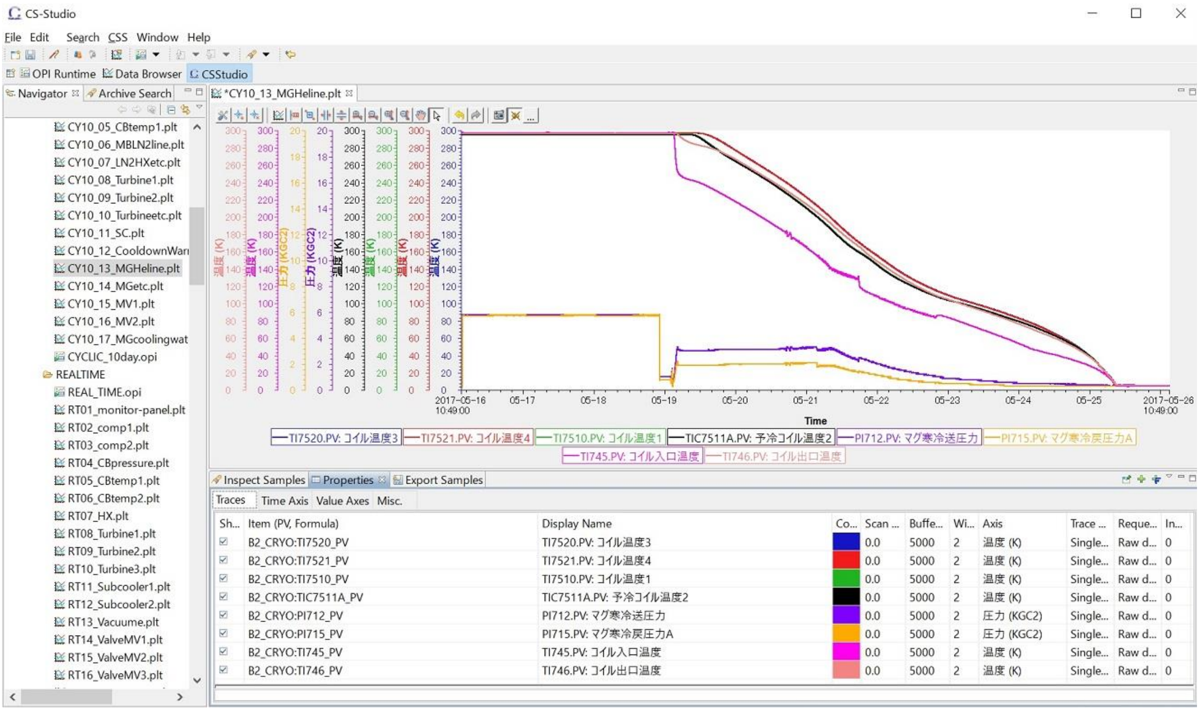


Figure 4. Graph of precooling curve of Belle solenoid. The horizontal axis spans 10 days.

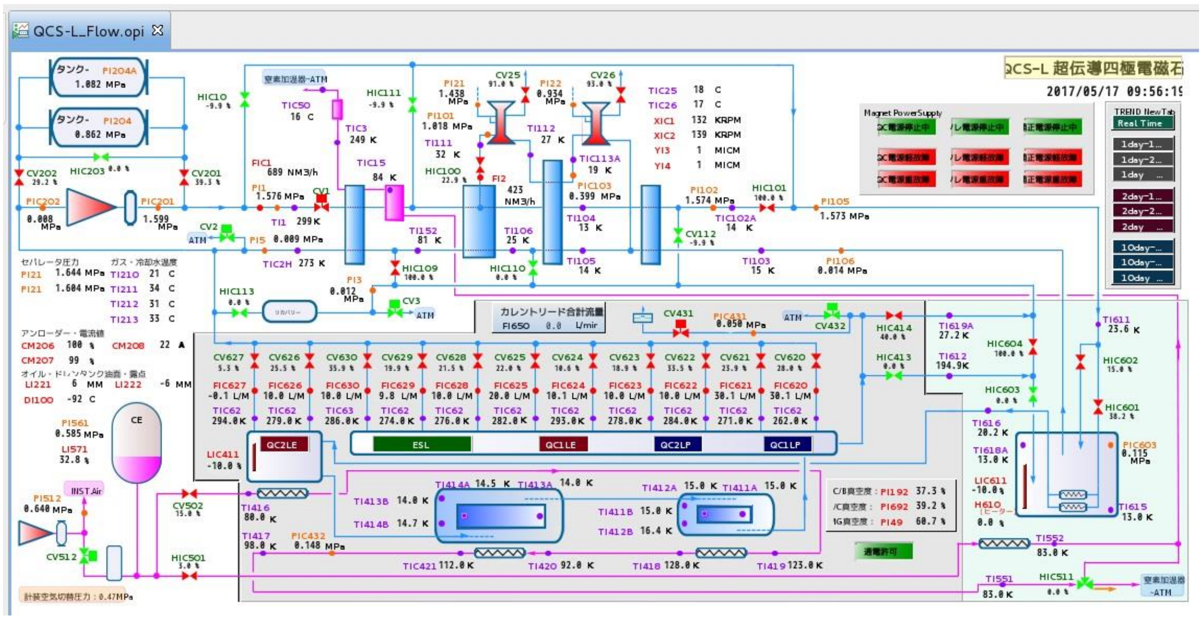


Figure 5. Real-time graphics showing the flow diagram of QCSL magnets and cryogenic system.

6. Summary

The remote monitoring system based on the software infrastructure of EPICS was developed for the superconducting magnets and cryogenic systems at the Interaction Region of the SuperKEKB accelerator at KEK. The superconducting magnets consist of a Belle solenoid, QCSL magnets, and QCSR magnets. The developed monitoring system allows the user to monitor real-time data of the EX-

8000, which is a large control system on the dedicated network for all cryogenic components. According to the EPICS software infrastructure, IOC, ArchiveEngine with an RDB, and CSS-based clients were developed. The monitoring system can monitor 977 data points of EX-8000 and 71 calculated data points with a 1-s cycle time, which is the same cycle time as the EX-8000. The EX-8000 original data consist of the AI, AO, DI and DO. Various graphs and graphics were developed using CSS tools to provide a useful human-computer interface. The functions were tested in various network environments and proved to be sufficiently useful. By using EPICS, data-sharing with multiple groups was easily realized. The developed remote monitoring system has been used in current performance tests of the QCSL and QCSR magnets. It will be useful in subsequent accelerator tests and actual operation during physics experiments.

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