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Integrated radiation monitoring and interlock system for the LHD deuterium experiments

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Abstract

The Large Helical Device (LHD) successfully started the deuterium experiment in March 2017, in which further plasma performance improvement is envisaged to provide a firm basis for the helical reactor design. Some major upgrades of facilities have been made for safe and productive deuterium experiments. For radiation safety, the tritium removal system, the integrated radiation monitoring system, and the access control system have been newly installed. Each system has new interlock signals that will prevent any unsafe plasma operation or plant condition. Major interlock extensions have been implemented as a part of the integrated radiation monitoring system, which also has an inter-connection to the LHD central operation and control system. The radiation monitoring system RMSAFE (Radiation Monitoring System Applicable to Fusion Experiments) is already operating for monitoring γ (X)-rays in LHD. Some neutron measurements have been additionally applied for the deuterium experiments. The LHD data acquisition system LABCOM can acquire and process twenty-four hours every day continuous data streams. Since γ (X)-ray and neutron measurements require higher availability, the sensors, controllers, data acquisition computers, network connections, and visualization servers have been designed to be duplicated or multiplexed for redundancy. The radiation monitoring displays in the LHD control room have been carefully designed to have excellent visual recognition, and to make users immediately aware of several alerts regarding the dose limits. The radiation safety web pages have been also upgraded to always show both dose rates of γ (X)-rays and neutrons in real time.

Keywords:
LHD, deuterium experiment, integrated radiation monitoring, RMSAFE, interlock

1. Introduction

The Large Helical Device (LHD) successfully started the deuterium experiment in March 2017, in which further plasma performance improvement is envisaged to provide a firm basis for the helical reactor design [1]. After agreements for the LHD deuterium experiment were concluded with the local governments, some major upgrades of facilities have been made for safe and productive deuterium experiments.

For high performance deuterium plasmas, upgrades of the plasma heating systems such as NBI, ECH, and ICRF, upgrades for plasma diagnostics systems especially for neutron measurements, closed helical divertor with an in-vessel pumping system [2, 3, 4, 5], and also some extensions for steady state data acquisition have been implemented. For radiation safety, the tritium removal system, the integrated radiation monitoring system, and the access control system for radiation controlled areas have been newly installed in LHD. The tritium removal system is operated to manage the tritium release less than 3.7 GBq/year by removing more than 95% of the estimated maximum tritium production of 37 GBq/year in the first six years and 55.5 GBq in the remaining three years [6, 7, 8].

Those newly installed radiation safety subsystems require a major extension of the central interlock system because of the increased number of interlock signals. They have been integrated as an important part of the newly developed integrated radiation monitoring and interlock system, and the central operation and control (COCO) system of LHD has provided some additional inter-connections to them [9, 10].

The LABCOM data acquisition and archiving system of LHD has already implemented the necessary functions to acquire and process twenty-four hours every day (i.e. 24×7) continuous data streams. Therefore, endless radiation monitoring data can be handled by the same system and in the same way as the physics measured data for plasmas [11, 12, 13].

For a nuclear fusion experimental facility, radiation monitors such as γ (X)-ray and neutron measurements are required to provide nonstop operability against any device malfunctions [14, 15]. Therefore, all the equipment adopted in this system, such as sensors, controllers, data acquisition (DAQ) computers, network connections, and visualization servers and displaying clients, have been duplexed or multiplexed for redundancy.

In the following sections, newly implemented subsystems related to the LHD integrated radiation monitoring and interlock system will be explained with their functionalities and applied technology.

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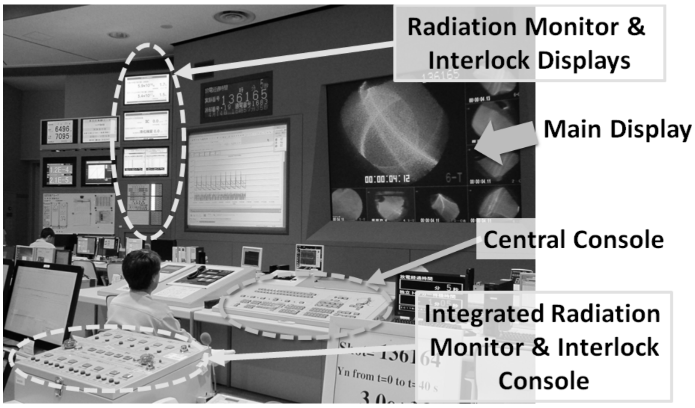

Figure 1: Reinforced displays and console in the LHD control room. The 200-inch main display and the central console continue to be used. New displays and the console are mostly for the integrated radiation monitoring and interlock system.

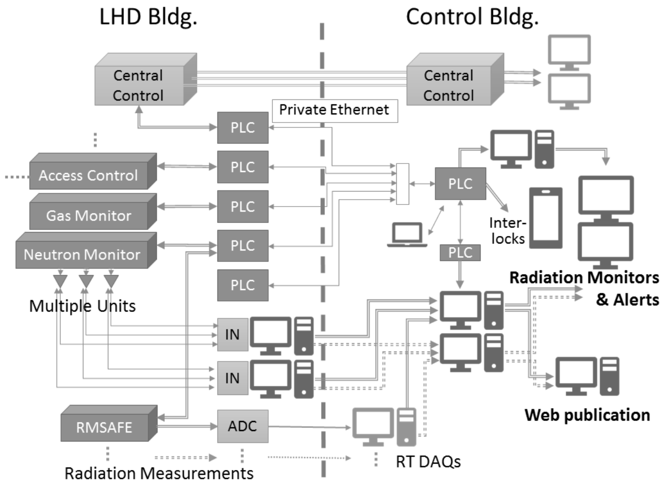

Figure 2: Schematic diagram of newly implemented integrated radiation monitoring and interlock system. Neutron and γ(X)-ray data are transferred via the duplexed or multiplexed paths parallel links and devices. The interlock signals are independently provided from their controller units to the central control system.

2. Integrated Radiation Monitoring System

Figure 1 shows a photograph of the front view of the LHD control room. This room has been upgraded for the deuterium experiments. Some displays and a console have been additionally installed principally for the integrated radiation monitoring and interlock system. Newly added monitoring and interlock functions are implemented as an extension of the LHD central control and interlock system, as shown in Fig. 2.

The newly implemented radiation monitoring and interlock system consists primarily of six programmable logic controllers (PLCs) connected by the isolated local Ethernet with each other. OMRON's Sysmac CJ1/CJ2 series products are used for the PLCs and the input/output modules. Except for one PLC installed in the control building, the remaining five PLCs are installed in different rooms in order to control each subsystem.

Since the γ(X)-ray and neutron measurements require high availability against any unexpected failure of a single device or link, all the sensors, controllers, data acquisition computers, network links, and the visualization servers are duplicated or multiplexed for redundancy. In addition, the interlock signals from their controllers are independently provided to the central control system. Figure 2 also shows the redundant system structure and Figs. 3 and 4 show the deployment of multiple sensors.

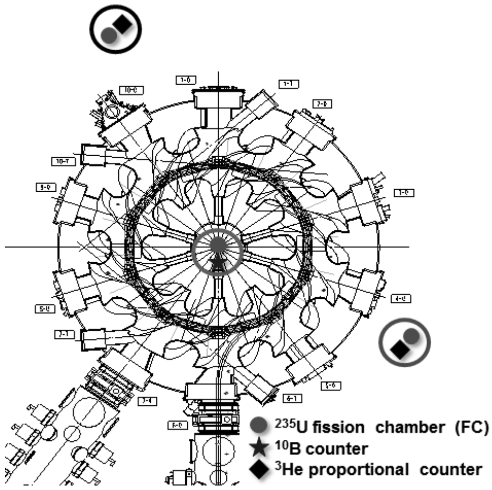

Figure 3: Installation of neutron detectors for neutron flux monitors in LHD [22, 23].

2.1. 24×7 continuous and time segmented virtual DAQ

The LHD radiation monitoring system, which is named RMSAFE (Radiation Monitoring System Applicable to Fusion Experiments), continually monitors the γ(X)-ray doses for the LHD fusion plasma experiments [16, 17, 18, 19]. For the deuterium experiments, some neutron measurements have been additionally applied [20]. Figure 3 shows where and what kind of neutron detectors have been installed near the LHD device. ^{235}U fission chamber (FC) uses a new product of TOSHIBA which has been redesigned for nuclear fusion neutrons by using a digital signal processor (DSP) to provide $\sim 10^{-3}$ s fast signal processing with $\sim 10^{6}$ wide dynamic range [21]. In addition, ^{10}B counter (TOSHIBA E6863-558) and two ^{3}He proportional counters (TOSHIBA E6862-500) are employed so that the LHD neutron flux measurement can expand the dynamic range further according to their high sensitivity to thermal neutrons and in low neutron yield cases [20, 22, 23].

Figure 4 shows the distribution of the environmental radiation monitoring posts of RMSAFE outside the LHD building. The radiation safety web pages have been also upgraded to show both dose rates of γ(X)-rays and neutrons in real time. These pages are open for providing environmental safety information.

Since the sensors count the sum of both the plasma emitted neutrons and the background neutrons, it is necessary to correctly separate those two values in order to obtain the accurate amount of the neutron yield by the fusion plasmas. The detectors must continuously measure the neutron fluxes 24×7 for safety monitoring and interlock purposes. The plasma-derived

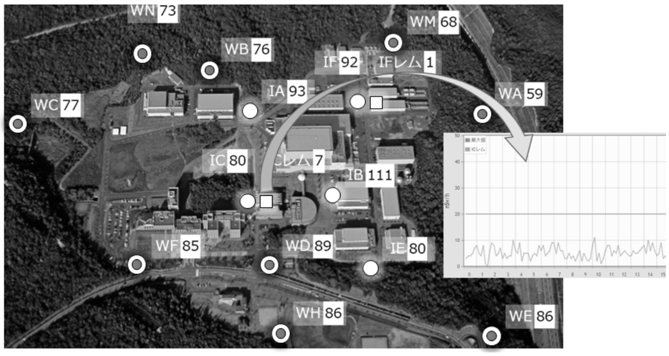

Figure 4: RMSAFE monitoring posts: γ (X)-ray doses are monitored at 9 points on the site border (hollow circles) and 5 points near the LHD building (white circles). Two neutron rem counters (white squares) have been added for the deuterium experiments. γ (X) and neutron doses are always published on the web at https://sewebserv.nifs.ac.jp/map.php.

Figure 5: Three radiation monitoring displays and the interlock status indicator (right bottom): Top three screens usually show weekly and yearly neutron yield, plasma derived yearly and three-month cumulative doses (Sv), and gas radioactivity concentration (Bq/cm^3) at the exhaust tower and the torus hall, respectively.

emissions should be calculated from the sum for the plasma duration periods by subtracting the background value which can be measured when there is no plasma.

Such data cutting only during the experimental sequence can be regarded as an additional "virtual DAQ" node, which was originally developed for the γ (X)-ray dose diagnostics of RMSAFE [24, 25].

Since the time windows of the environmental radiation monitoring are of 1 or several seconds, the data rates are much smaller than those of plasma physics measurements. Acquired raw data are stored in the same manner as the plasma measurements so that users can retrieve the corresponding time block by specifying date and time numbers, e.g., "retrieve, 'RMSAFE', 20171231, 2359", at any time thereafter [25].

2.2. *Visualizations*

Visualizations of the radiation monitors have been carefully designed to provide good conspicuousness at the front of the LHD control room. It is mandatory for the experiment operators and responsible researchers to be immediately aware of the alerts when any unusual situation may occur especially regarding the predefined dose limits.

Figure 5 shows the detailed view of the sub-displays used for the radiation monitoring results and the interlock conditions. These displays are installed at the left-hand side of the main large screens in the LHD control room, as shown in Fig. 1.

The top screens can selectively show three of the numerous observation views for the radiation monitoring systems. However, in most cases, weekly and yearly cumulated neutron yields inside the LHD hall, yearly cumulated radiation dose at the site border, and three months cumulated dose at the border of the radiation controlled area are displayed in order to continue observing the radiation safety for proceeding with the plasma experiments.

At the bottom of this vertical row, the interlock signal conditions are displayed for all subsystems. Each subsystem must issue permission to the LHD central control system in order to continue the plasma generation sequence.

For rapid recognition by the responsible staff members for the current situation, all monitoring and alert displays use the Japanese language.

2.3. *Alert expressions*

The above mentioned radiation monitoring displays are designed to be able to indicate the so-called yellow alert and the so-called red alert. If the γ (X)-ray doses or the neutron counts were to exceed 60 % of the maximum controlled value, the background color of the display in Fig. 5 will turn from the normal white color to the yellow color. Then, the experimental sequence will automatically stop in order not to allow entry into the next plasma sequence. This is to provide sufficient time for the session leader and the team to verify the situation and discuss whether the operation should be restarted or not.

If the dose amount or the count number were to exceed 80 % of the maximum controlled limit, then the indicating numbers will turn from the normal color of black to red. If this situation were to occur, the experimental sequence could not be restarted until the monitoring value decreased according to a longer accumulation time.

In all cases in which the interlock system were to detect unusual conditions, the warning light on the interlock status indicator board (Fig. 5 right bottom) will turn on and at the same time the audible alarm will ring.

3. HMI for Plant Automation and Monitoring

For high efficiency development of the human-machine interface (HMI) programs, a .NET template and class library has been developed and used for implementing the LHD control subsystems. This is called SHMIT (Standard HMI Template) [26].

Figure 6 shows the graphical view of the exhaust gas flow monitoring system, which is a typical example of the SHMIT-based plant monitoring HMI. The exhaust gas flow monitoring

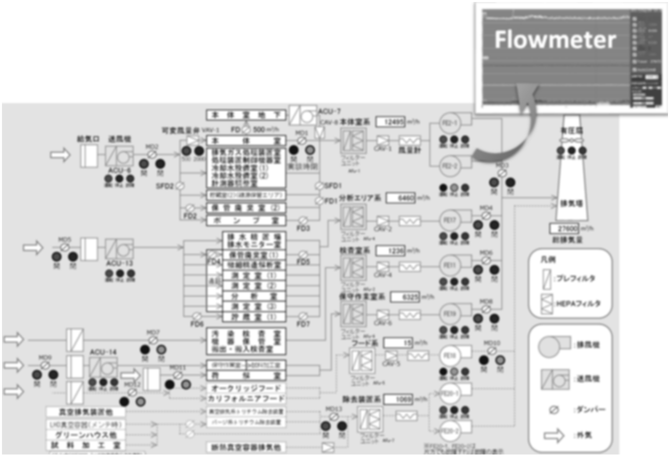

Figure 6: Exhaust gas flow monitor: The air flows come from the LHD and other equipment to the exhaust tower. All the air flows are monitored as are blowers and valves. This graphical view is developed by using SHMIT [26] and some open frameworks for Microsoft Windows.

system has been also developed in close cooperation with the integrated radiation monitoring and interlock system. This is because the normal operation of steady gas flows must be carefully monitored for the atmospheric radiation safety in the torus hall.

The graphical expressions are implemented using some open programming frameworks provided on Microsoft Windows. These include Extensible Application Markup Language (XAML), Windows Presentation Foundation (WPF), and also the .NET framework [27]. These programming frameworks are helpful for us to develop graphically expressive presentations for the individual control subsystems in LHD. For more sophisticated implementations or larger-scale integrations, some commercial products, such as LabVIEW, WinCC, and NB-Designer [28, 29, 30], and also some open source software such as EPICS/CS-Studio might provide some advantages [31].

4. Summary

For starting the deuterium experiments in LHD, major upgrades and implementations of new facilities were successfully completed by March 2017. For radiation safety, the integrated radiation monitoring system covers a number of interlock extensions for additionally implemented subsystems and also has inter-connections to the LHD central control system.

Indispensable fail-safe behaviors as a part of the safety interlock system have been verified before the beginning of the 2017 campaign, including artificially-made tripping operations on those new subsystems. The radiation monitors are also checked by the daily routine of the radiation safety operation.

Because γ(X)-ray and neutron measurements require 24×7 and higher availability, the entire system from the detectors to the monitoring displays have been carefully designed to have sufficient redundancy by making every device and connection duplicated or multiplexed. Functional separations are also taken into consideration for the system design. Most of the radiation monitoring displays are implemented by means of the web-based client–server model so that downstream data processing and visualization never affect the upstream detectors and DAQs.

The RMSAFE displays in the LHD control room have been carefully designed to use both visual and audible alerts for good conspicuousness. For the complicated plant monitoring visualizations, .NET template and class library have been compiled as the SHMIT package so that reproductions of similar graphical user interface programs become easier.

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