OVERVIEW OF KSTAR INTEGRATED CONTROL SYSTEM

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After more than 10 years construction, KSTAR (Korea Superconducting Tokamak Advanced Research) had finally completed its assembly in June 2007, and then achieved the goal of first-plasma in July 2008 through the four month's commissioning. KSTAR was constructed with fully superconducting magnets with material of Nb_3Sn and NbTi, and their operation temperatures are maintained below 4.5K by the help of Helium Refrigerator System. During the first-plasma operation, plasmas of maximum current of 133kA and maximum pulse width of 865ms were obtained. The KSTAR Integrated Control System (KICS) has successfully fulfilled its missions of surveillance, device operation, machine protection interlock, and data acquisition and management. These and more were all KSTAR commissioning requirements.

For reliable and safe operation of KSTAR, 17 local control systems were developed. Those systems must be integrated into the logically single control system, and operate regardless of their platforms and location installed. In order to meet these requirements, KICS was developed as a network-based distributed system and adopted a new framework, named as EPICS (Experimental Physics and Industrial Control System). Also, KICS has some features in KSTAR operation. It performs not only 24 hour continuous plant operation, but the shot-based real-time feedback control by exchanging the initiatives of operation between a central controller and a plasma control system in accordance with the operation sequence. For the diagnosis and analysis of plasma, 11 types of diagnostic system were implemented in KSTAR, and the acquired data from them were archived using MDSplus (Model Driven System), which is widely used in data management of fusion control systems.

This paper will cover the design and implementation of the KSTAR integrated control system and the data management and visualization systems. Commissioning results will be introduced in brief.

KEYWORDS : KSTAR, Tokamak, Control System, EPICS, MDSplus

1. INTRODUCTION

After the completion of the assembly in the past year, KSTAR (Korea Superconducting Tokamak Advanced Research) achieved the goal of first-plasma in July 2008 through the commissioning of the machine cool-down, the superconducting magnet test, and the plasma discharge experiment for four months. During the commissioning period, the temperatures of the magnets were maintained below 4.5K, and all superconducting magnets were operated in the superconducting region. Plasmas of maximum current of 133kA and maximum pulse width of 865ms were obtained. The KSTAR Integrated Control System (KICS) has successfully fulfilled its missions of surveillance, device operation, machine protection interlock, and data acquisition and management. These and more were all KSTAR commissioning requirements.

KSTAR is very a complex device with many subsystems installed in a large area around it. KICS integrates all of these subsystem controllers in a logically unified, single control system, controlling and supervising them remotely. In order to meet this requirement, KICS adopted a new framework, named as EPICS (Experimental Physics and Industrial Control System). EPICS is proven technology that has been used in many large experimental facilities such as accelerators, astronomical telescopes, and so on. By using EPICS, local control systems implemented in various platforms could be operated in the same manner of single platform type. Other substantial KICS requirements included supervision of the real-time feedback operation and 24 hour continuous plant operation. It was performed by the Central Controller interfaced with Plasma Control System (PCS) which controlled plasma in current and position during the plasma discharge. KICS also included both machine protection and personal safety interlock functionalities. Data acquisition and management was another responsibility of KICS. For first-plasma operation, 11 types of diagnostic system were implemented in KSTAR. To acquire the data from these diagnostics, DAQ systems were developed. The data thus obtained were stored using MDSplus (Model Driven System), which is widely used in data management of fusion control systems. The main control room was constructed for remote operation and included 22 operator consoles.

Described in this paper is the design and implementation of the KSTAR integrated control system and the data management and visualization systems. Commissioning results will be introduced in brief.

2. DESIGN REQUIREMENTS

The fusion device has some operational features that set it apart from other experimental facilities. Some operations common to many experimental facilities include the operation of essential systems such as vacuum pumping, cryogenics, electrical power, and cooling systems, etc. These must all operate continuously without interruption. In addition to these common requirements, KSTAR itself must conduct shot-based pulse operation for the plasma discharge experiment. The industry-standard as well as specialized KSTAR requirements are listed below.

Common requirements are as follows:
- Distributed Control
- Platform Diversity
- System Scalability
- System Reliability
- Easy to integrate heterogeneous systems

Specialized requirements are as follows:
- Wide bandwidth of control & monitoring
- High-resolution data acquisition
- High performance, real-time MIMO (Message Input Message Output)
- Low latency, high throughput networking
- Precise operation synchronization

Control and operation of KSTAR required many local subsystems, each with their own local control systems implemented in various platforms, such as, VME, VXI, PXI, cPCI, PLC and PC systems. Integration of the many heterogeneous systems into the centralized control system required much effort. Several commercially available products as the solution for the integration proved to be cost prohibitive. In addition, there was some doubt regarding the ability of these products to adapt to future expansion avenues envisaged for KSTAR. Ultimately, EPICS, an open source software suite, was chosen to act as a middleware software, a developing tool, a data archive, and a user interface tool. EPICS is performance-proven software used in over 40 sites worldwide, including domestic sites. Furthermore, as many application programs are already provided (in EIPCS), development time can be saved by only minor modification of some.

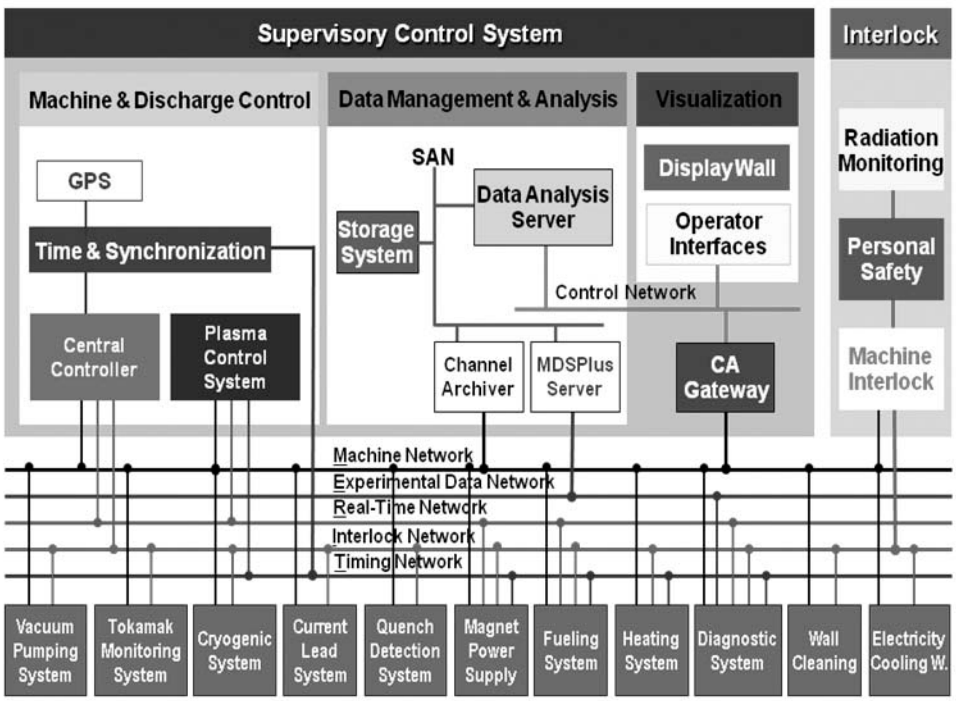

Fig. 1. Schematic of KSTAR Integrated Control System

Another important requirement was the management of data of varying and complex type, such as low-rate continuous plant monitoring data and high-rate, shot-based experimental data. As these data collection rates were vastly different, adoption of two different data management systems was agreed upon; EPICS Channel Archiver for plant monitoring data and MDSPlus for experimental data. Two separate networks were used for the low and high rate data collection. The low-rate continuous plant monitoring data was transferred to the KSTAR main storage via an Ethernet-based machine network, and the shot-based experimental data was transferred via experimental data network. The KSTAR network system includes up to 5 different networks between the central control system and the distributed local control systems depending on the specific purpose.[1]

The KSTAR integrated control system as described and implemented in shown schematically in figure 1. It is divided into three main parts: the supervisory control system, the local control systems and the interlock system. The supervisory control system is further divided into three functional parts: machine operation & discharge control, data management & analysis, and visualization. The interlock system is responsible for machine interlock, personal safety, and radiation monitoring. The local control systems were implemented for 17 different subsystems. KICS contains more than 200 controllers and workstations monitoring and controlling approximately 18,000 processing variables. It communicates about 55,200 events per second between various internal systems.

3. IMPLEMENTATION

3.1 Central Control System

The central control system is comprised of three essential systems for machine operation & discharge control in the supervisory control system. These are the central controller, the plasma control system, and the time & synchronization system (TSS).

KSTAR operation proceeds sequentially from pre-shot sequence to plasma discharge to post-shot sequence. Operational control is exchanged between the central controller and the plasma control system according to the shot sequence state. During the pre-shot sequence, status of all system involved in the operation is monitored. Plasma shot parameters are then established by the central controller. After the shot, these systems are reinitialized and returned to nominal. The central controller supervises the operational status of all of those stages. This is the so-called 'Machine Operation' mode.

The mode of 'Discharge control' is activated at the beginning of the plasma shot sequence. Control of plasma operation is then assigned to the plasma control system. While the discharge operation is being performed by the plasma control system in sequence, the central controller supervises the plasma control system as well as plant systems.

The central controller contains a VMEbus based PowerPC CPU board to accept various hardware modules designed for the VMEbus system. It is operated under the VxWorks real-time OS to achieve real-time performance in accordance with the software. The central controller has two interlock interface modules and one reflective memory module on the VMEbus. These are located in the VME crate and are connected with the CPU board through the backplane bus. The central timing unit (CTU) module, a part of the TSS, is a PMC mezzanine type and is located directly on the CPU board. Table 1 shows the hardware modules implemented in the central controller. In addition to the above, the central controller is connected (via five networks) to the plasma control system, the machine interlock system, the time synchronization system, and various plant systems.[2]

The mission of the TSS is to synchronize operations between the systems participating in the discharge experiment. It therefore, provides triggering signals to the relevant discharge system and sampling clock signals to the data acquisition systems for accurate analysis of the experimental data. In addition, the TSS also serves the current time information from the GPS receiver to all controllers and workstations distributed around KSTAR.

Table 1. Component List of the Central Controller

Classification	Product	Specification
CPU board	VMIVME-7050	VME 6U, PowerPC 1GHz, 2GEthernet
Timing module (CTU)	In-house Development	PMC , Optical , 100MHz master clock, Time accuracy < 5usec
Interlock Interface	VMIVME-2534	VME 6U, 32 CH DI/O
Reflective memory module(RFM)	VMIVME-5565	VME 6U, Optical, 128MB Dual-port memory thru-put 176MB/s Delay 0.7us/node

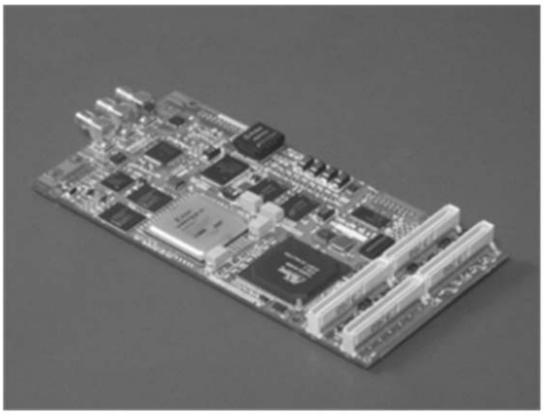

Fig. 2. Picture of CLTU in PMC Card Type

The TSS is divided into a central timing system, local timing systems, and a dedicated timing network. The central timing system is comprised of a Central Timing Unit (CTU), a GPS receiver set, and a 24-port optical signal distribution switch. The local timing function is conducted by Local Timing Unit (LTU), which is installed in the local system controller.

Before the discharge shot, and depending on the operational scenario, timing parameters for each system are distributed to the local systems equipped with LTUs via the Ethernet-based machine network. Once 'Start of Shot' is released by the main operator, the shot start signal is sent from the CTU to the LTUs as optical signals thru the timing network. LTUs triggered by the shot start signal generate triggers and clock signals in accordance with the pre-loaded timing parameters. Note that the CTU transmits a 100MHz master clock signal continuously from the time the system is turned on, and a GPS current time at the rate of 1 per second. [3] These functions for central and local timing are realized in single PMC mezzanine card with a PCI interface. For this hardware implementation, the timing unit has several advantages. It can be used for either CTU or LTU and can be installed regardless of the platform type of the local control system (assuming of course, that a PCI interface is available). The CLTU is shown in figure 2.

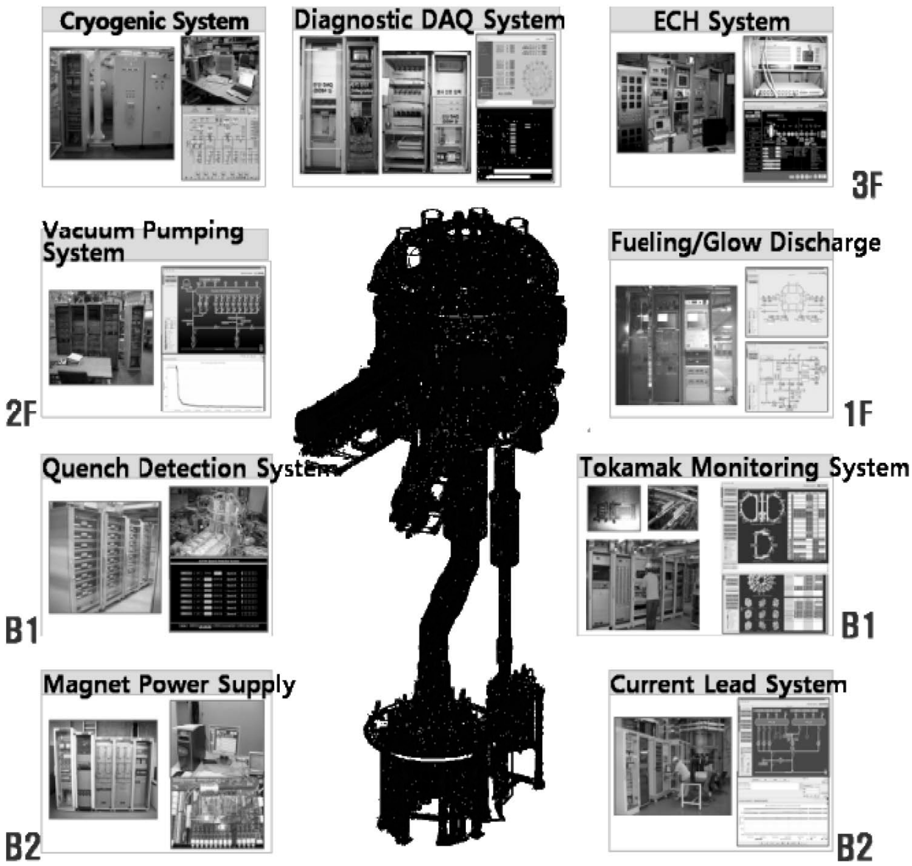

Fig. 3. Local Control Systems Developed for KSTAR

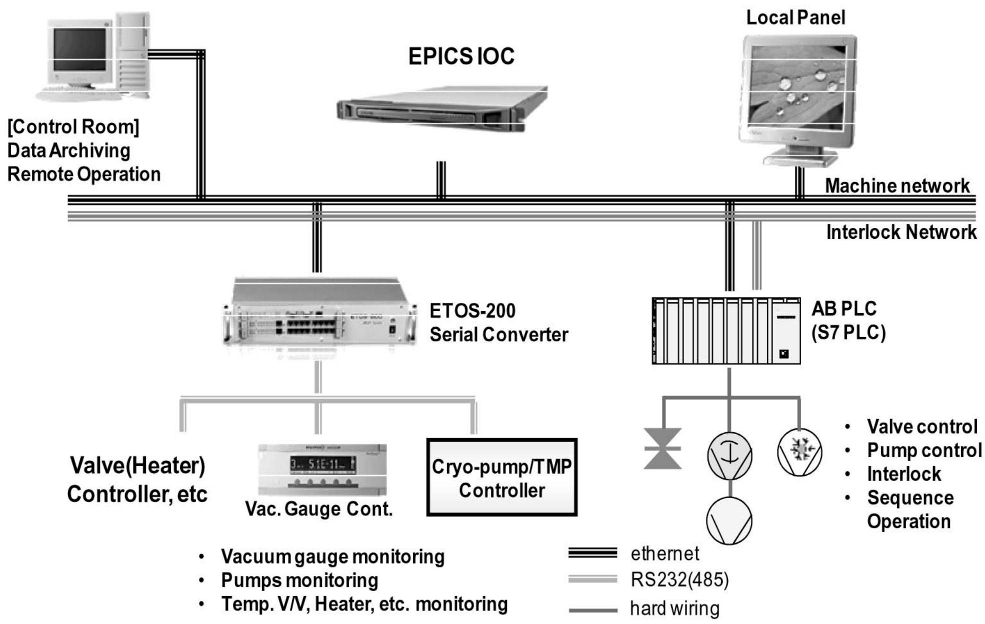

Fig. 4. Integration of PLC-Based Local Control System

3.2 Local Control System Integration

For the first campaign operation, 17 local systems were developed and distributed in KSTAR. Their local control systems can be grouped into several classes.

One is primarily for the plant control systems, which are responsible for the continuous operation of plant systems, such as, the cryogenic systems, the vacuum pumping system, the tokamak monitoring system, and so on. The local control systems for those systems that use PLCs (except for the tokamak monitoring system implemented in the PXI system), and the integration thereof with EPICS is shown in figure 4. The interface with the central control system is only the machine network for remote control, monitoring, data archiving, and the interlock network for machine protection. The software platform thus implemented is based on the EPICS R3.14.8.2. It is composed of the operating system, the EPICS base code, and a few device drivers.

The system responsible for observing the behavior of the KSTAR device during tokamak cool-down to cryogenic temperatures and coil charge is the Tokamak Monitoring System (TMS). Cryogenic and structural behavior of the KSTAR device is monitored by more than 800 sensors including temperature, strain, displacement, and hall sensors placed inside and outside of the tokamak and superconducting coils. Signals from these sensors are measured with PXI-based DAQ system with robust and cheap I/O modules.

The EPICS IOC (Input Output Controller) for the TMS was embedded on an Intel Pentium CPU board (PXI platform) running Linux (kernel-2.6). It provides standard communication and data processing from the measured data to physical meaning data, and so forth [4]. The system has two interfaces for control & monitoring, data archiving, and interlocks.

Another class is the local system involved in real-time feedback control by the plasma control system, and magnet power supplies belong to this category. The local control system was implemented in 8 VME systems running in the VxWorks real-time OS and EPICS IOC embedded in VME systems. The magnet power supply has four interfaces for the exchange of data and commands, synchronized operation and machine protection such as the machine network, the reflective memory-based real-time network, the timing network, and the interlock network.

The other category contains the systems to participate in the discharge operation such as ECH, ICRH, and fueling systems which are implemented in PC systems that also acts as EPICS IOCs.

3.3 Machine Interlock System

The machine interlock system is an indispensable system that protects the tokamak device from harmful faults and unintended events and keeps it in safe condition. Therefore, a mandatory requirement for the interlock system is that it must work without interruptions of any (and all) kinds. It must be robust, redundant, and be able to operate in fail-safe mode. The machine interlock system is composed of a centralized Supervisory Interlock

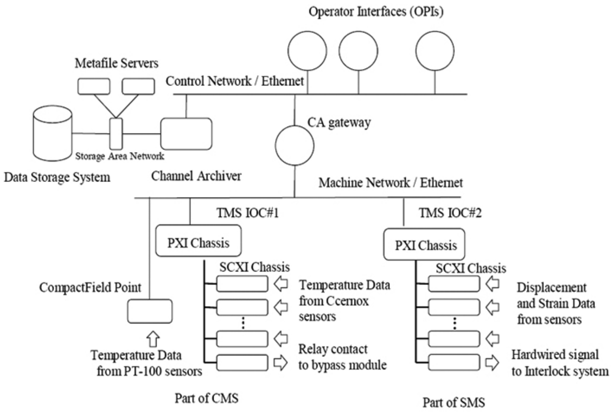

Fig. 5. Schematics of Tokamak Monitoring System

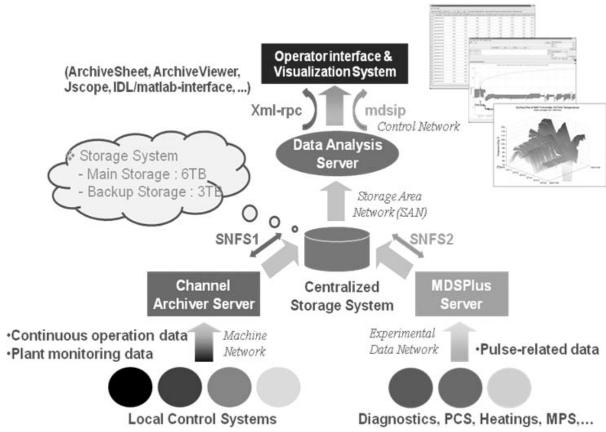

Fig. 6. Operation and Experimental Data Flow

System (SIS), 11 local interlock subsystems, and a dedicated interlock network, named ControlNet. The PLC-based unit interlock system has two CPU modules, two power supplies, and two communication modules for redundancy. It operates with an interlock voltage signal level of +/-12V, which is sufficiently high so as to be immune to noise generated by the charging magnets and/or RF power injected into the tokamak. As an aid to the interlock system, we manage a Short Message Service (SMS) system for operators to use, immediately, when faults are detected.

The principal target systems in terms of machine protection are the superconducting coils and buslines. The charged TF & PF coils can lose their superconductivity due to the AC loss, defects in superconducting wire, and contact resistance, to name a few. This can result in irreparably damaged coils and buslines. For the detection of this kind of failure, 83 quench voltage detectors were developed. When the measured quench voltage goes above a threshold voltage and maintains it for a predefined holding time, a quench interlock signal is sent to the magnet power supply protection circuit via optical wire. The magnet energies are then discharged to external dump resistors. The interlock signal is transferred to the machine interlock system as well. The SIS then again activates the quench protection circuit. [5]

3.4 Data management and User Interface

The data generated during the operation of KSTAR is grouped into two types; the machine operation data and the plasma experimental data in accordance with the source of data generated and data features. The plant control systems produce their operational status and

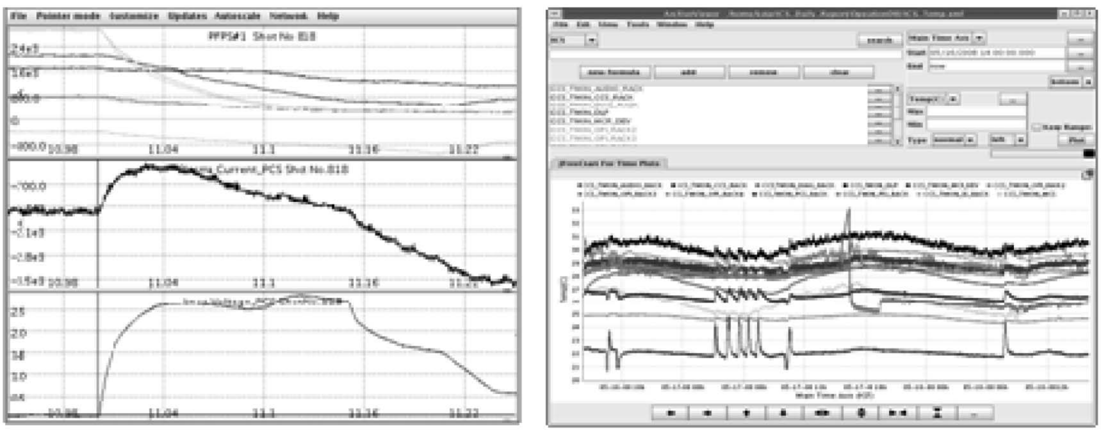

Fig. 7. Visualized Operation Data and Experimental Data

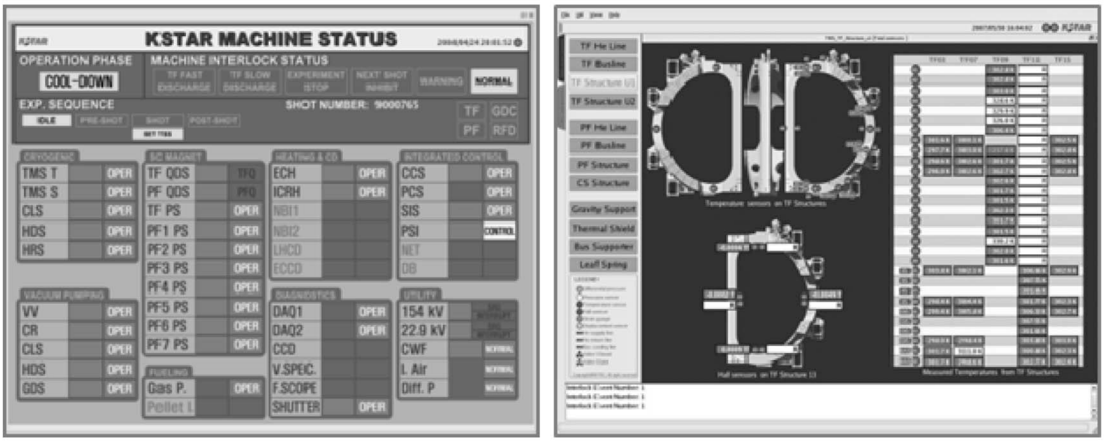

Fig. 8. In-House OPI Panels Developed with Qt

measured data continuously (at low rate) and receive control parameters only when they are issued. This type of data is treated as the machine operation data and is archived by using its own archiving system (EPICS channel archiver) thru the Ethernet-based machine network. For the first-plasma operation, 13 archiving engines worked for managing about 8,400 signals with each archiving policy.

During the plasma discharge shot, a large amount of physics data is produced from the diagnostic DAQ systems, the plasma control system, the heating system, and so on. After the completion of plasma shot sequence, this data is transferred to the main storage system thru a different network, called the Experimental data network. The experimental data is stored in the tree structure and managed or referenced by the shot number using a data management tool of MDSplus running on the MDSplus server where mdsplus-2.0-1.i386rpm (MDSplus) and jdk-6-linux-i586.bin (Java) were installed. A four-tree structure for 8,485 signal nodes was designed for first-plasma operation.

Both the machine operation data and experimental data can be retrieved via the Data Analysis Server using XML-RPC protocols and mdsip. The data can then be analyzed (and visualized) using jScope, Matlab, IDL, and in-house software tools. The flow of data from the local systems to users through several servers and storage systems is explained in figure 6.

Figure 7. shows the retrieved operation data and experimental data with jScope and ArchiveViewer.

Actions to supervise and control the systems are issued by operators either manually via the local control panels or with graphical user interfaces via the operator's consoles. The OPerator Interface panels more than 150 panels have been developed for 10 target systems with Qt4.3.1, an open-source tool, and include utilities to display the run-time data chart, retrieve data in sheet format, and log the results of discharge shots and machine fault information. Figure 8. shows some examples of an OPI panel developed with Qt.

Finally, the state-of-the-art KSTAR main control room is introduced in brief. All information regarding the systems working at KSTAR must be collected. In addition, the operation of KSTAR is performed under a centralized administration in one location, the main control room. There are 22 operator consoles running Linux and 12 70-inch DLP cubes in the operator's area. The central control system hardware, parts of the plasma control system, the supervisory interlock system & personal safety system, and so forth, are located in the central equipment room beside the operator's area.

Fig. 9. The View of KSTAR Main Control Room

4. CONCLUSIONS

In developing KSTAR control system, several design strategies needed to be satisfied. For instance, integration of heterogeneous control systems with EPICS, future expansion capabilities, economical considerations via open-source software solutions, and relative ease of maintenance were all keys to a successful undertaking. Beyond the initial apprehension, the KSTAR integrated control system accomplished the mission during first-plasma operation and was proved in its performance. For the next campaign, more efforts will be concentrated in the development of the data management technology and the data analysis tools.

ACKNOWLEDGEMENTS

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