Operation Results of KSTAR Integrated Control System for First Plasma

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Abstract. After the successful accomplishment of vacuum commissioning assisted by vacuum vessel baking and glow discharge cleaning, KSTAR had shifted to the cool-down phase in April 2, 2008 and completed cooling of all superconducting coils and structures down to the operation temperature of 4.5K for about a month by the helium refrigerator system with 9KW cooling capacity. For the next a month, all superconducting coils were tested individually and conjunctively to investigate the controllability of coil current and field configuration for plasma discharge. Finally, we achieved the plasma with the current up to 130mA and pulse width over 800msec.
For the surveillance and operation of KSTAR for Day-I campaign, 11 plant measurement & control systems were implemented, and also diagnostic DAQ systems for gathering the plasma physics data. Furthermore, machine interlock system and personal safety system worked to prevent KSTAR from serious damages and to protect personnel from hazardous events, respectively. The peculiar feature of KSTAR integrated control system is to has introduced EPICS(Experimental Physics and Industrial Control System) as the middleware to integrate whole above heterogeneous local control systems. Therefore, it was highly demanded to verify the adaptability of EPICS and the performance of our control system to meet the requirements of Tokamak operation in the continuous plant operation and the pulse-related experiment. Throughout the Day-I operation, the KSTAR integrated control system thoroughly demonstrated its reliable and eminent performance in not only the plant operation but the discharge control.

1. Introduction

After the completion of the assembly in 2007, KSTAR achieved the goal of the first plasma in July 2008 through the commissioning of the machine cool-down, superconducting magnets test, and plasma discharge experiment for about 4 months. During the commissioning period, the base pressure of vacuum vessel and cryostat were maintained in the range of 2.5×10^{-6} Pa using baking and DC & RF-assisted glow discharge cleaning, and the temperature of all superconducting coils below 4.5K. Consequently, the plasmas with max current of 133kA, and max pulse width of 865msec were obtained by using the ECH-assisted start-up and the real-time feedback control on plasma current and radial position by the plasma control system.[1] Also, the KSTAR Integrated Control System (KICS) to contain a supervisory control system, many local control systems, and even machine & safety interlock systems, fulfilled successfully its mission of surveillance & control of plant systems, sequential operation of tokamak, machine protection, data acquisition & management, etc for the commissioning.
To control and monitor the complicated and elaborate device, KSTAR, many plant monitoring & control systems have been developed, therefore, the KICS must integrate all those plant system controllers into the logically unified single control system, and establish the interfaces to operate them. For this requirement, the KICS was developed as a networked-based distributed system, and employed the new framework, EPICS which is a proven technology in the large experimental facilities such as accelerators, astronomical telescope, etc. Also, the KICS provides machine protection interlock and personal safety interlock functionalities by conducting the corresponding actions in accordance with the operation state and protection sequence when the interlock event occurs. Another substantial mission of the KICS is to implement data acquisition systems to obtain diagnostics data from plasma to analyze plasma characteristics and use for the feedback control of plasma. For the Day-I operation, 11 types of diagnostics system were implemented in KSTAR, and these collected

data were stored by using MDSplus(Model Driven System), which is widely used in data management of fusion control system.[2] All the operation of systems involved in the KSTAR control system are supervised by the central controller (CC), which manages plant operation, treats interlock events, and performs sequential discharge control in connection with the plasma control system (PCS).

2. Development of KSTAR Control System

2.1. Design Requirements

In the design phase of KSTAR control system, necessarily considered requirements are summarized as followings.

- To meet the conflicting requirements in terms of tokamak-specific operation; 24 hours continuous plant operation and shot-based pulse operation.
- To integrate many local control systems being developed with almost all kinds of platforms in a market into the logically unified system.
- To precisely synchronize the operation between systems to intimately participate in the plasma experiment such as PCS, CC, MPS, Fueling, ECH, etc, during the plasma discharge shot operation.
- To ensure system expandability for the ultimate goal of 300msec, 2MA

The first requirement led to the decision of tokamak operation schema named as Machine (or Plant) Operation and Discharge Control Operation, accordingly distinguished systems such as the Central Controller and the Plasma Control System were charge of the respective roles. The Central Controller with the initiative of KSTAR operation supervises the whole machine operation including the other part of KSTAR control system itself, performs the sequential operation, and also looks out the PCS during the real-time feedback. When shifted to the discharge shot, the PCS takes over the control from the central controller, proceedes the real-time feedback operation, and then returnes the control back to the central controller. For the data with different characteristics depending on the operation mode, data management systems and data networks were developed separately; one was Channel Archiver and Ethernet-based Machine Network for the low-rate continuous plant operation data, the other was MDSPlus and Experimental Data Network for the shot-based huge experimental data.
Because many local control systems were going on the development before the establishment of control system standards such as platform type, operation system, etc, these systems resulted in the implementation with various platforms of VME, VXI, PXI, cPCI, PLC and PC. Thereafter, it was needed much efforts to integrate all these heterogeneous systems into the centralized control system. For the decision of the solution for integration, we investigated several candidates including commercial products in terms of their performance, reliability, development time, cost, future expansion, etc, and finally we chose EPICS(Experimental Physics and Industrial Control System), open source software, as a middleware, developing tool, data archive, and user interface tool. The EPICS has been used in over 40 sites including domestic sites and demonstrated its performance in the control systems of large experimental facilities with control points over order of 100,000. Furthermore, as we already retained experience to utilize EPICS and many application programs were also provided, there were advantages to save the development time by using them with only minor modification.
Because even the systems which tightly related with plasma discharge operation would be dispersedly installed in wide area, it was highly demanded to provide precise timing signals for the synchronized operation. After we had failed to search the COTS to exactly match with our requirements, we developed the timing system named as Time & Synchronizes System (TSS) with platform-free, compact form factor. The design criteria of the TSS was that timing

accuracy of less than 1µs, 100MHz master clock, fully-programmable 64-bit triggering & time information, and reference time from GPS must be provided. FIG.1. shows the configuration of the entire KSTAR integrated control system, and TABLE 1. lists the compositions of KSTAR network system.

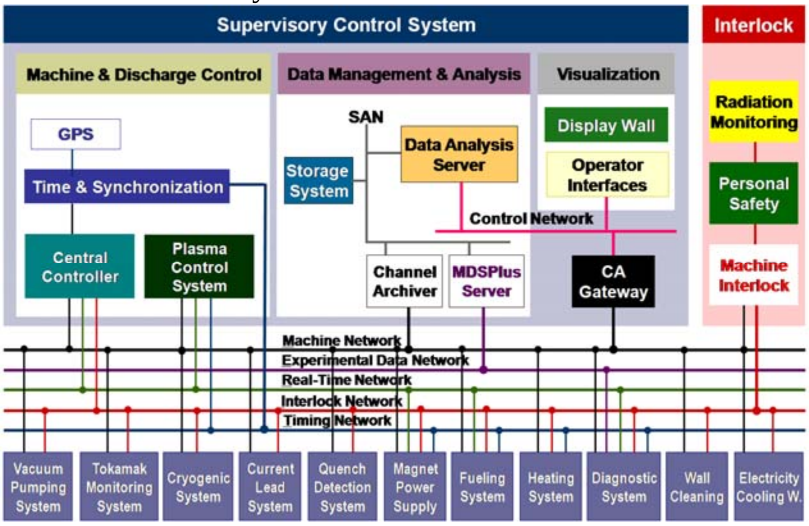


FIG. 1. Schematic of KSTAR Integrated Control System

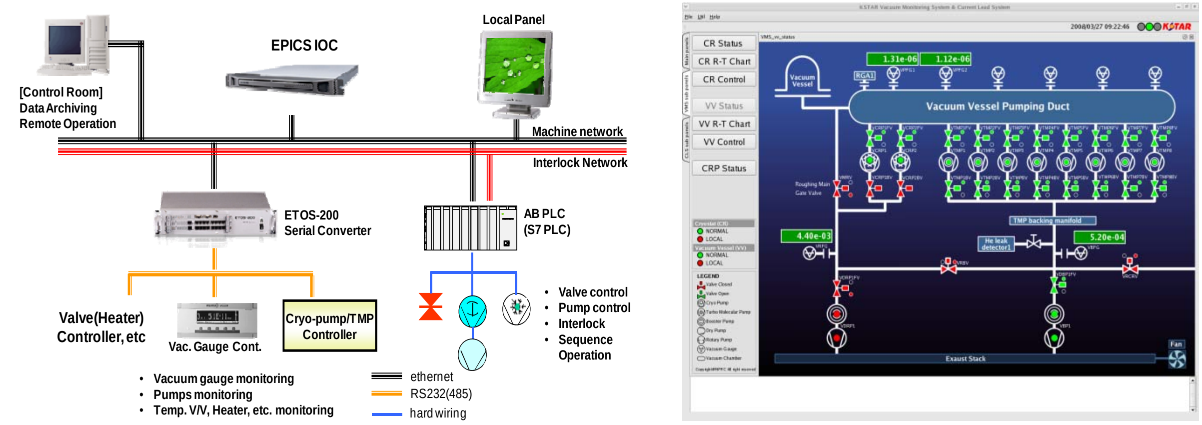
TABLE I: List of KSTAR Network System

Name	Classification	Function	Interface
Machine Network	Ethernet	Machine control data/event EPICS Channel Access	Ethernet Card
Experimental Data Network	Ethernet	Diagnostic data MDSip protocol	Ethernet Card
Real-time Network	Reflective memory (RFM) network	Real-time Information CCS/PCS/MPS/(TSS, future)	RFM Module
Interlock Network	ControlNET (Optical/Redundant)	Interlock information Redundant optical network	ControlNet Interface Module
Timing Network	In-house development	GPS Time, 100MHz Master Clock, Triggering/Clock Information	CTU/LTU Module

For the initial operation of KSTAR, 11 plant monitoring & control systems, 2 utility systems, 4 types of diagnostic DAQ systems were implemented, and the more than 200 controllers and workstations performed monitoring & control of about 18,000 processing variables, and communicated about 55,200 events per second between the internal systems.

2.2. Integration of Heterogeneous Local Control Systems with EPICS

The local control systems can be categorized in several groups. One group is plant control & monitoring system, and a vacuum pumping system, cryogenic systems, and wall cleaning systems, etc are categorized into this group, which are mainly composed of PLC systems and Legacy I/O measurement systems. The EPICS(R3.14.8.2) interface with this type of local control systems was implemented with x86 Linux-based EPICS Soft IOC (Input Output Controller) server, a LAN-to-serial converter for Legacy I/O instruments and PLCs, and measurement/control data could be exchanged using EPICS channel access protocol via Ethernet-based machine network to EPICS Channel Archiver for storing and operator interface through CA gateway for operation.[3] FIG.2. shows EPICS interface for vacuum monitoring system (VMS) and operator interface panel developed by Qt 4.3.1.



(a) Vacuum Pumping System I&C *(b) Vacuum Vessel Status panel*

FIG. 2. Integration example of PLC-based Local control system

Another group of local control system has the systems involved in the real-time feedback control in conjunction with the PCS; the magnet power supply systems (MPSs) belong to this category. For the achievement of a control cycle with 200μsec, the MPS local control systems were implemented with 64-bit VMEbus systems running on the real-time OS, vxWorks and interfaced with the PCS and the central controller via the reflective memory (RFM) based real-time network. Any system connected with the real-time network can read data simultaneously whenever the content of RFM with 128MB memory is updated. The real-time network has a throughput of 174MB/s, network speed of 2.2Gbaudrate with average latency of 0.4μsec per hop.

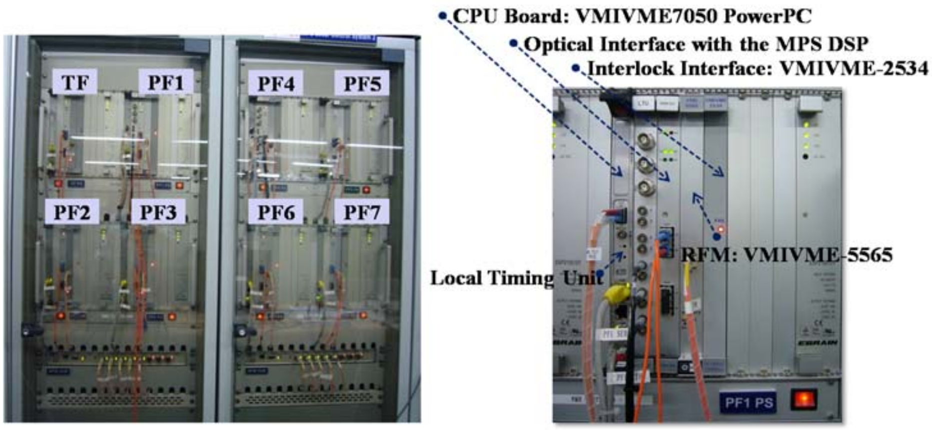


FIG. 3. Installation of VME-based MPS Local Control Systems

The charged TF & PF coils can lose their superconductivity due to the AC loss, defects in superconducting wire and contact resistance, etc, and eventually they are degraded and damaged permanently. For the detection of this kind of failure, quench detection system (QDS) with 83 quench voltage detectors was developed. When the measured quench voltage goes above the threshold voltage and the predefined holding time, the quench interlock signal is sent to the protection circuit of magnet power supply systems via optical wire, and then magnet energies are discharged to external dump resistors. This interlock signal is also sent to the machine interlock system to activate the quench protection circuit again. [4]
One of an important monitoring system is Tokamak monitoring system (TMS) to observe the cryogenic and structural behavior of KSTAR device during the tokamak cooled down to the cryogenic temperature and coils charged. For the measurement, over 800 sensors such as temperature, strain, displacement and hall sensors were installed inside and outside of the tokamak and superconducting coils, and signals from these sensors are measured by PXI-based DAQ system. The EPICS IOC for the TMS was embedded in an Intel Pentium CPU

board of PXI system running in Linux-kernel-2.6, and provides the standard communication and data processing from the measured data to physical meaning data, etc. [5]
The other category contains the systems like as ECH, ICRH, and fueling systems which were implemented in basically PC systems which also acts as EPICS IOCs.

2.2. Central Control System (CCS)

The central control system comprised of three essential systems in charging of machine operation & discharge control which are the central controller, the plasma control system and the time & synchronization system. The central controller as the brain for the KSTAR operation fulfills the supervision of the entire plant operation, the sequential tokamak operation, watchdog the PCS operation, and interlock interface. The central controller comprises of a VMEbus based PowerPC CPU board to carry a central timing unit (CTU) as a part of the TSS, two interlock interface modules and one reflective memory module, and is operated under the vxWorks real-time OS to achieve real-time performance with the software. In addition, the central controller has all five networks to connect with all plant systems, the PCS, the machine interlock system and the time synchronization system.[6]
The KSTAR plasma control system to provide real-time controllability of creating and sustaining plasma was developed with software derived from DIII-D PCS and KSTAR-specific hardware such as an employment of RFM-based real-time data communication and an interface with EPICS.

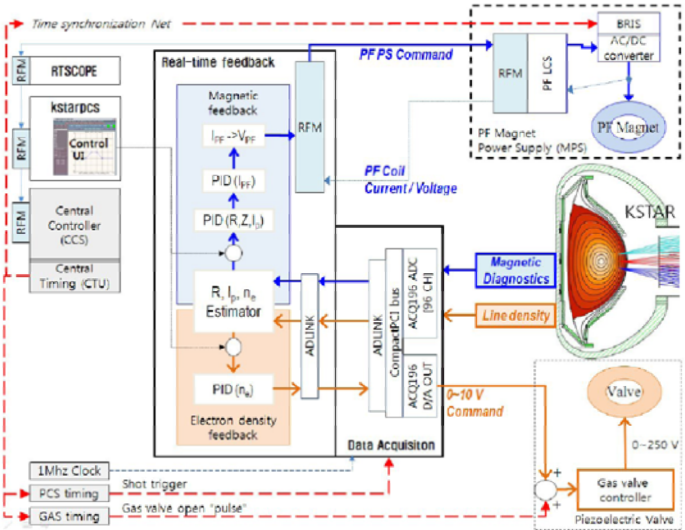


FIG. 4. Hardware Layout of PCS for the Day-I operation

The PCS hardware consists of three parts; data acquisition for 82CH magnetic diagnostics and 1CH line integral density, real-time CPUs for feedback calculation and communication interface with actuators such as 7 PF power supplies and the fueling system. The measured diagnostic data in a cPCI-based digitizer at a rate of 20KSps are sent to the x86 Linux-based real-time CPUs thru a 66MHz PXI-PCI bridge, and after the calculation feedback to the PF power supplies via the shared memory real-time network.[7] In contrast to the PF MPS control, a piezoelectric valve is controlled by 10V analog signal from D/A converter in the PCS. It is considered to modify using fully digital control with the RFM network to have immunity from EMI and to avoid the possibility of noise pickup by ground loop.
The functions of the TSS are the provision of triggering signals to the system involved in the discharge operation, sampling clock signals for the data acquisition, and the current time information at the update rate of 1 sec from the GPS receiver to the all controllers and workstations distributed. Also, it transmits a 100MHz master clock signal continuously since

the system turned on. The timing hardware called as a central timing unit (CTU) and a local timing unit (LTU) was developed in a PMC mezzanine card with PCI interface, and the CTU and all LTUs were connected thru the dedicated timing network with star topology.[8]

2.3. Data Management and Visualization

The data generated during the operation of KSTAR is divided into the machine operation data and the plasma experimental data in accordance with the characteristics of data generated. The machine operation data which are continuously produced at the low rate from plant systems are archived by using EPICS channel archiver thru the machine network. For the 1st plasma operation, 13 archiving engines runned for managing about 8,400 data with each archiving policy. During the plasma discharge shot, the large number of physics data(8485 signal nodes for 1st plasma operation) from the diagnostic DAQ systems, the PCS and the heating systems, are transferred thru the Experimental data network after the completion of plasma shot sequence, and managed with the shot number by the MDSplus(-2.0-1.i386rpm). Both data could be retrieved via the Data Analysis Server using XML-RPC protocol and mdsip, and then visualized and analyzed with the tools of jScope, Matlab, IDL, and home-made tools. FIG. 5. presents the KSTAR data system for Day-I operation.

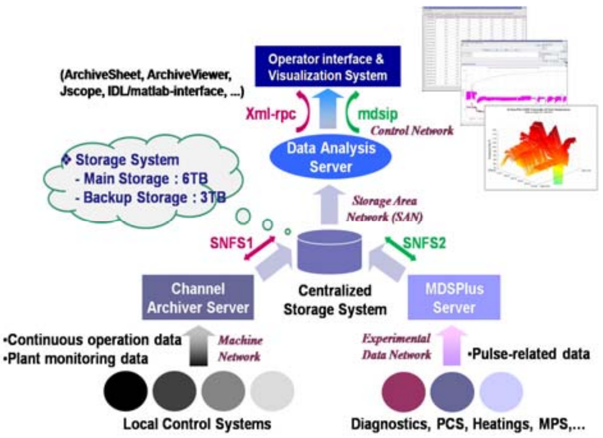


FIG. 5. Operation and Experimental Data Flow

FIG. 6. The view of KSTAR main control room

Finally, the KSTAR main control room using the up-to-date technology was constructed for the purpose of supervising the whole working systems and executing the operation of KSTAR under the centralized administration in the one location.

3. Result of the First Plasma Operation

KSTAR operation proceeds sequentially from the pre-shot sequence, the plasma discharge and the post-shot sequence, and the initiative on the operation are exchanged between the central controller and the PCS according to the shot sequence state. During the pre-shot sequence, status of all system involved in the operation is monitored and parameters are established by the central controller for the plasma shot. After the shot, these systems are initialized and return to the stable state, and all those operation status are supervised by the central controller, too. This operation mode is called as ‘Machine Operation’. The mode of ‘Discharge control’ is activated at the moment of coming into the plasma shot sequence, and the control on the plasma operation is assigned to the PCS. While the discharge operation is performed by the PCS with real-time feedback control, the central controller still keeps the supervision on the PCS as well as plant systems.

3.1. Discharge Control Operation

For the preparation of the discharge shot, although control inputs generated by the PCS for PF power supply operation and fuel control are transferred to the target systems thru the real-time network, the timing parameters referenced to an operation scenario are distributed to the local systems equipped with LTUs via the machine network. At the moment of 'Start of Shot' released by a main operator, the shot start signal is sent from CTU to LTUs as optical signal thru the timing network, and then LTUs generate signals to trigger PCS, MPS, Heating, Fuel and DAQ systems in accordance with the pre-loaded timing parameters. The Blip starts at 11sec after the shot start signal generated, and the other systems turn on before the blip start based on a discharge scenario. FIG. 7. Shows the sequence of a discharge shot operation.

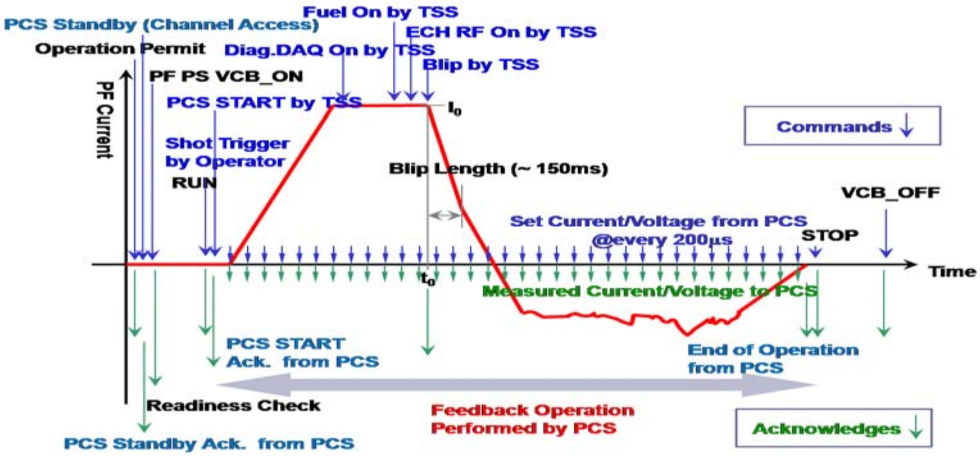
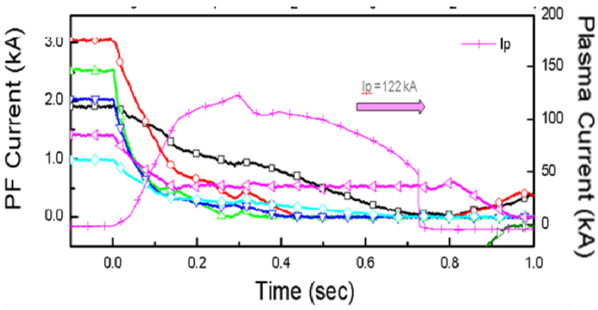
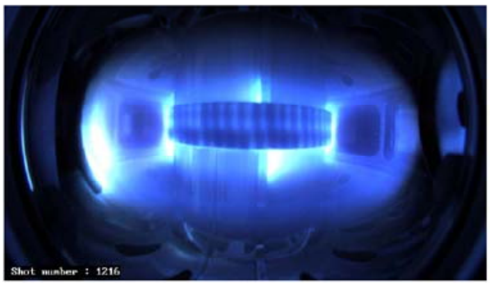


FIG. 7. Operation Sequence of Synchronized Real-time Feedback Operation

During the first plasma experiment, we conducted 1283 shots including MPS commissioning shots to investigate all superconducting coils, to verify the controllability by the PCS, to examine the feasible startup scenario, and finally to create the second harmonic ECH-assisted hydrogen plasma. The plasma control system showed the real-time feedback control on plasma parameter of plasma current, radial position and density with 200µs control cycle as well as the reliable operation on the control of PF power supplies and fueling. The FIG. 7 and FIG.8 show the waveform of PF coil and plasma current, and image of ECH-assisted ohmic plasma in KSTAR.



(a) PF coils currents



(b) ECH-assisted Ohmic Plasma

FIG. 8. Results of 1st plasma experiment of KSTAR

3.2. Operation results of KSTAR Control System

In the operation of the KICS during the KSTAR commissioning, there was not any serious fault especially in conjunction with EPICS migration. Most of faults were caused by operator, sequence violations, communications error and a few of hardware & software error. For the points of the interruption to the plasma operation, although the serious faults were derived from three times of electricity interruption by the public electricity and an oil pump trouble of the helium refrigerator system, most of faults in the KICS occurred in the operation of the diagnostic DAQ systems. Because the diagnostic DAQ system has exchanged data and control not only with EPICS interface, but with MDSplus, it was needed to debug the IOC software and device drivers used in data acquisition. For about 4 months' commissioning, totally 147 times fault events occurred in the KICS operation and the time of the system stoppage or malfunction amounted to about 36hours. On the other hands, we experienced the data loss during the plant monitoring data archiving with the rate above 5 Hz in the beginning of the KSTAR commissioning. It was due to the mismatch of file system used by EPICS channel archiver and StoreNext file system (SNFS) implemented in KSTAR. After the completion of the KSTAR commissioning with NFS temporally, we changed with Global File System (GFS) and are going on the verification of it. Through the KSTAR commission, we got the operation data of 1.14TB from 16 subsystems and the experimental data of 260GB from 233CH.

4. Conclusions

The KSTAR control system had been successfully developed with correspondence to the KSTAR-specific strategies to integrate heterogeneous local systems with EPICS, to establish the structure for the future expansion, and to utilize available open-source tools for the economical aspect and the facile maintenance. Through the first plasma operation, the KSTAR integrated control system thoroughly accomplished the mission in the plant operation and plasma discharge experiment, and proved the performance, reliability and operability of EPICS implemented in the tokamak control system. For the next campaign, more efforts should be concentrated in the development of diagnostics DAQ systems and interfaces with the heating system, In-vessel systems scheduled to install. Moreover, the development of technology of data management and analysis as well as image data handling becomes tomorrow's mission.

ACKNOWLEDGEMENTS

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