DISTRIBUTED CONTROL SYSTEM FOR KSTAR ICRF HEATING

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Received January 22, 2009
Accepted for Publication April 3, 2009

An ICRF discharge cleaning and a fast wave electron heating experiment were performed. For automated operation and providing the diagnostics of the ICRF system, the ICRF local network was designed and implemented. This internal network provides monitoring, RF protection, remote control, and RF diagnostics. All the functions of the control system were realized by customized DSP units. The DSP units were tied by a local network in parallel. Owing to the distributed feature of the control system, the ICRF local control system is quite flexible to maintain. Developing the subsystem is a more effective approach compared to developing a large controller that governs the entire system. During the first experimental campaign of the KSTAR tokamak, the control system operated as expected without any major problems that would affect the tokamak operation. The transmitter was protected from harmful over-voltage events through reliable operation of the system.

KEYWORDS : ICRF, KSTAR, Local Network

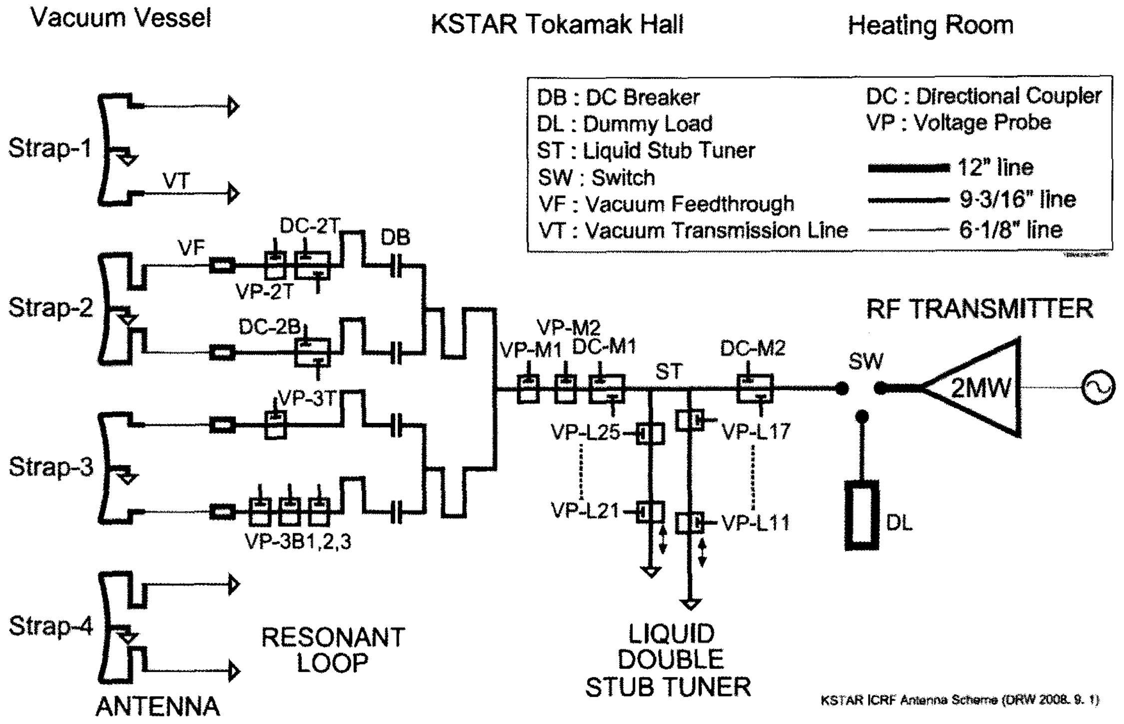
1. INTRODUCTION

Ion cyclotron range of frequency (ICRF) discharge cleaning [1] and heating [2] were performed on the KSTAR [3,4] tokamak during the first experimental campaign. A schematic of the ICRF system is shown in Fig. 1. RF power of a maximum 2 MW is transmitted to the antenna with two resonant loops through a liquid double stub tuner [5-8], and its frequency range is 30 ~ 60 MHz.

For efficient operation and providing the diagnostics of the ICRF system, an ICRF local network was designed and implemented. This network provides monitoring, RF protection, remote control, and RF diagnostics. The basic concept of the instrumentation is a distributed control system in which the controllers are distributed over the ICRF local network with the subsystems controlled by one or more controllers. The ICRF subsystem is a block of the ICRF system that can be isolated from the other systems. Any subsystem can be treated as an independent system.

There are several advantages of a distributed system over a traditional system having a large, concentrated controller. Because the physical or logical size of each controller is small, its development or maintenance may be easier for realizing a specific function. The developer can concentrate only a single function of the controller without being disturbed by the other functions, even if they are correlated. The correlation can be treated within a specific communication layer that connects the controllers. The electrical wires for connecting numerous probes or actuators to the controller can be significantly reduced, because the controller is physically located near to the probes or actuators. Basically, a standard communication wire is needed for inter-connecting each controller. Reduced wiring decreases the efforts involved in finding a fault location when there are wiring related problems. Because of the independent nature of the distributed system, upgrading can be achieved easily by adding or replacing a subsystem. It is not necessary to stop the whole system to replace hardware or rewrite software.

Because the workload of a controller for a subsystem is quite small, there may be many controller candidates. Among the numerous processor types, a digital signal processor (DSP) was selected on the merits of its flexible input/output configurations, high computing power, and similar developing environment to a personal computer. The DSP with appropriate input/output channels can be tied by a standard communication network such as a transmission control protocol/internet protocol (TCP/IP). Even though the response of the TCP/IP is not fast enough or deterministic for real-time control, we found that a few time-demanding signal connecting subsystems, such as interlocks or triggers, could be made of specific wiring. Most of the time sensitive functions can be treated in a DSP unit.



KSTAR ICRF Antenna Scheme (DRW 2008. 9. 1)

Fig. 1. RF Circuit of ICRF System. RF Power is Supplied to the Two Current Straps through a Double Stub Tuner

The governing controller of the ICRF local network could be made of another DSP unit in a parallel manner. However, because additional functions, such as those the provision of an operator interface or communication with a tokamak control system [9,10], should be provided by this governing controller, a personal computer with a Linux operating system equipped with EPICS middleware [11,12] was chosen. The EPICS software architecture of this computer manages collected signals from DSP units, and provides communication to the tokamak control system. The network connections to the tokamak control system are two giga-bit Ethernet networks for machine control and data transmission, a timing network for machine synchronization, and an interlock network.

This paper describes the details of the instrument configuration with the major functions of the controllers, and the experimental results of the first campaign of the KSTAR tokomak, showing successful operation of the ICRF local control system.

2. CONTROL SYSTEM

The basic configuration of the ICRF local network is comprised of multiple DSP controllers connected through a TCP/IP network with a governing computer, as shown in Fig. 2. Each DSP unit is in charge of a subsystem that is separated by a logical function, a physical location or an electrical ground potential. A DSP unit comprising serial communication ports and memory is assembled on the customized peripheral board. A moderate number of input/output channels (ADC: 18, DAC: 4, DIN: 16, DOUT: 8, Serial: 2 channels), which are thought to be sufficient for a specific function of a subsystem, are assembled on the peripheral board. Among these channels, the serial channels are reserved for TCP/IP data transferring and debugging.

Optical fibers are connected between the digital input and output ports of the DSP units for time-demanding signals. A trigger signal for synchronized data collection of the experimental shot and an RF interlock signal for preventing over-voltage are required. The time responses were set to be less than 10 μsec for these fast signals. The delay is caused by real-time computing in a DSP and electrical-optical media conversion. A RF signal of the local oscillator (LO) is also provided by this kind of optical wiring. This signal is used for the RF diagnostics.

2.1 Communication

The EPICS middleware manages the ICRF local network. It relays all the control parameters to the DSP units through operator interfaces, an EPICS channel access (CA) facility, and an EPICS input/output controller (IOC). Data collection is performed in reverse order. The data is collected periodically during operation in near real-time for monitoring purposes. Although the control and data

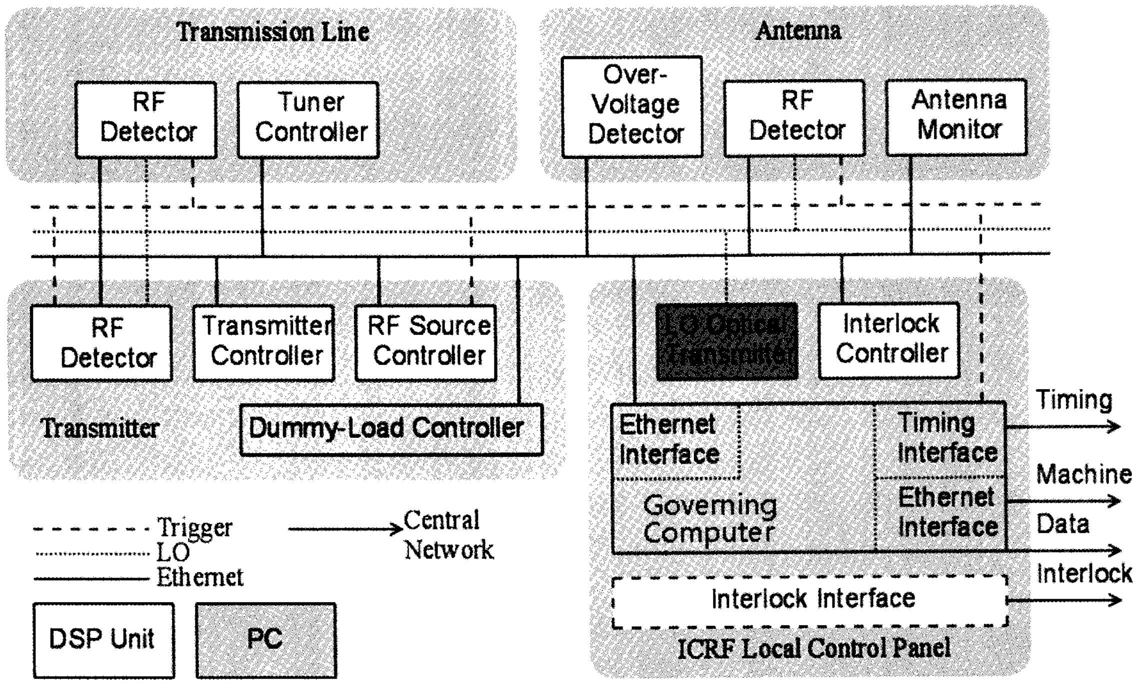


Fig. 2. ICRF Local Networks. DSP Units are Tied by an Ethernet Network and Optical Fiber Connections for the Triggers and Local Oscillator

acquisition are not real-time owing to the asynchronous nature of the TCP/IP network managed by the Linux operating system, the period of the data exchange is quite regular and fast for the purpose of monitoring. The functions that require strict real-time control are assigned to the DSP units.

Besides the near real-time data acquisition for monitoring, high speed data arrays initiated by a trigger are collected at the end of each shot for post-processing. If the pre-defined number of samples is full in the designated DSP unit, DSP begins transmitting the array to the EPICS IOC.

Two kinds of data achievements are provided by the EPICS. Slow, near real-time data is stored by means of a Channel Archiver, which is a part of the EPICS extensions. This data can be retrieved to find the time varying trends of the machine status. Because the performance for a large data array with the EPICS system, which is always busy processing near real-time signals, is not satisfactory, experimental arrays are stored in the MDSPlus [13] data system. An MDSPlus routine was written into the IOC to transfer the processed arrays to the MDSPlus data tree. This routine attaches the shot number and time stamps to the collected arrays for the MDSPlus data tree and sends this information through an interface provided by MDSPlus system.

The connection between the central control system and the ICRF local control system is comprised of two TCP/IP and two special networks. The tokamak machine network provides data exchange by means of the CA. Most of the control and monitoring signals are exchanged by the machine network. The experimental data network is another TCP/IP network that provides an MDSPlus connection. The timing network provides pre-programmed triggers and clock ticks to synchronize the local control systems to the central control system. Prior to a shot, the central control system defines all the necessary timing sequences in the timing host. Each local-timing unit attached to the network generates triggers and clock ticks at the defined absolute time. The ICRF system uses two triggers for RF generation and data collection. The inaccuracy of each trigger is less than 5 μsec. To protect both humans and machines, an independent interlock network was installed. Through this network, any operating status that can affect the ICRF local system can be received to activate adequate protection.

2.2 Protection

Unexpected voltage rise is the most harmful but probable event for the ICRF system. RF voltage exceeding a certain limit (35 kV for uncooled 9-3/16" transmission line pressurized by nitrogen gas at 2 atmospheric pressure) may destroy the RF components. High VSWR, which can be expressed by the maximum and the minimum RF voltages, also degrades the performance of transmitter. These events can arise by variation of the loading resistance due to an edge plasma fluctuation including an abrupt plasma termination or arcing in a transmission line.

To protect the system, three independent methods are provided. The first is self protection of the transmitter. High VSWR detected at the output of the transmitter cuts the RF input of the transmitter within tens of μsec. The input is recovered automatically after a delay of several μsec. The second is over-voltage protection. If one of the four voltages measured at the resonant loops exceeds the predefined value, the input of the transmitter is disconnected within μsec. This disconnection is not automatically recovered and recorded as an ICRF fault. The third method is activated by the central plasma control system (PCS). When the PCS detects a fault, it activates a no-go signal of the ICRF. These three methods were operated successfully for the first campaign of the KSTAR ICRF. There were many PCS fault events, since the KSTAR was in the initial phase of operation and more than ten intentional over-VSWR or over-voltage events were initiated by disconnecting the 'PCS fault no-go' signal. In all of these cases, one of the protection circuits was activated and RF components were protected.

2.3 RF Diagnostics

An antenna loading impedance, which is defined as the ratio of the voltage to the current at the antenna feed point, provides information on the antenna-plasma coupling status. The real component of the loading impedance is a direct measure of the RF efficiency, because the resistive RF loss along the transmission line and the radiation to the plasma are competitive. Furthermore, the loading impedance is closely related to the electron density in front of the antenna with a given frequency and magnetic field. Therefore, it provides information on the plasma parameters related to the ICRF heating efficiency.

A relevant RF configuration should be maintained for an ICRF scenario. For fast wave electron heating of the first KSTAR plasma, the phase difference between the upper and lower halves of a current strap should be 180 degrees.

These tasks require measurement of the RF voltage and current at various positions of the transmission lines. RF detectors based on a digital I/Q demodulation technique were installed as shown in Fig. 3. The signals coupled by capacitive voltage probes or directional couplers are down converted to an intermediate frequency (IF) of 21 kHz for removal of the frequency dependency of the measurement. A local oscillator (LO) signal with a frequency shift of 21 kHz, which is generated at the control room, is transmitted to the tokamak hall through an optical LO transmitting system. Because the electrical ground reference of the tokamak hall must be different from that of the other facilities, all the DC paths including the shield-braids of coaxial cable should be disconnected by optical fiber, a capacitive DC block, or an isolation transformer. The optical LO transmitting system was made of a fast optical logic transmitter and a receiver with band pass filters.

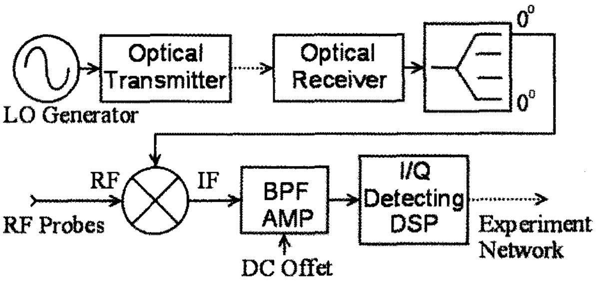


Fig. 3. Block Diagram of RF Diagnostics. The IF of the Probe Signal is Directly Sampled by an I/Q Detecting DSP Unit in which the Amplitude and Phase of the Original RF are Calculated

The IF is directly digitized after signal conditioning such as band-pass filtering, offsetting, and scaling. A few simple calculation steps result in the amplitude and phase of the original signal. The calculation is performed in a DSP, and then stored for a data request from any other client within the ICRF local network.

3. EXPERIMENTAL RESULTS

Typical experimental result is shown in Fig. 4. The modulated RF voltage V_L, which was measured by voltage probe VP-3B1 shown in Fig. 1, was applied to the resonant loop during the flat-top phase of the plasma current I_p. The impedances R and X, which were calculated from the measured complex RF voltages, were changed from the vacuum loading impedance shown by the grey line. These changes indicate that a portion of the RF power was radiated from the antenna. Even during application of the RF voltage, there was no apparent change of the electron temperature or electron density. The increase of the C_{III} line intensity during a high V_L without changing the plasma energy demonstrates that significant RF power was consumed to heat the graphite inboard and stainless-steel wall instead of the plasma.

During the first experimental campaign, several RF fault events were generated by disconnecting the signal from the PCS to test the protection circuits. Low loading resistance due to a loss of control of the plasma induced high voltage exceeding 25 kV. To provide an adequate safety margin, we chose 25 kV as an upper limit of the operating voltage. The RF protection system operated reliably for all these cases.

4. SUMMARY

For the ICRF heating of the KSTAR tokamak, a modular control system was designed and successfully

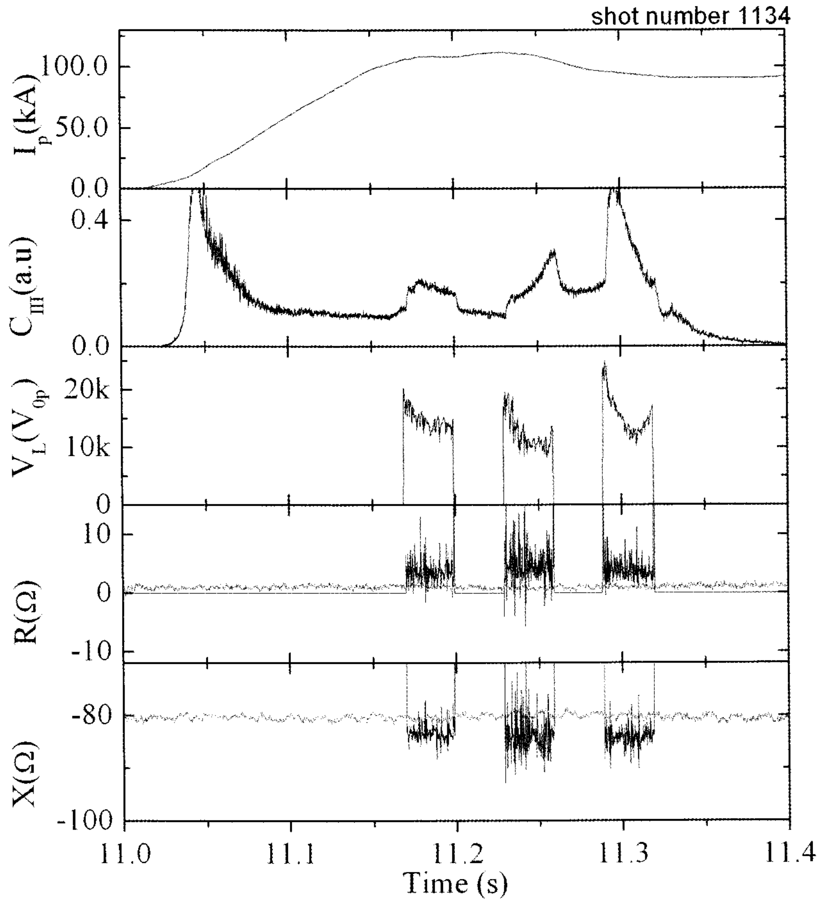


Fig. 4. During I_p Flat-top Period, ICRF is Applied with Maximum Transmission Line Voltage V_L for a Fast Wave Electron Heating Scenario. In Accordance with V_L, C_{III} Line Intensities are Increased while Electron Temperature and Electron Density are Unchanged. Transmission Line Impedance R and X are Changed from the Unloaded-vacuum (Grey Lines) Shot

operated during the first campaign. Most of the functions of the control and data acquisition are implemented by using DSP units, which are tied by a standard Ethernet local network and minimal wiring. Owing to the distributed feature of the control system, the ICRF local control system is quite flexible to maintain. Increasing the number of control subsystems or updating a specific function does not require that the whole system be stopped. Also, developing a subsystem is a more effective approach compared to developing a large controller that governs the entire system. During the experiment, the control system operated as expected without any major problems that would affect the tokamak operation. The transmitter was protected from harmful over-voltage events through reliable operation of the system.

ACKNOWLEDGMENTS

This work was supported by the KSTAR Project Contract of the Korean Ministry of Education, Science and Technology.

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