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Control, data acquisition and remote participation for steady-state operation in LHD

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Abstract

Control, data acquisition, plasma monitoring and remote participation for steady state operation in the large helical device (LHD) are reviewed. By controlling the impedance matching of ICH, the plasma position and the electron density, high temperature plasma is confined for 1905s. The plasma parameters are monitored in real time. Data are continuously sampled by the YOKOGAWA WE7000 system and by the NATIONAL INSTRUMENTS CompactPCI system. Those data are managed by the object-oriented database system based on ObjectStore in distributed servers with mass storage. By using the multi protocol label switching-virtual private network (MPLS-VPN) technology, the local area network of LHD is expanded to the Japanese fusion community. This provides the remote participants with the same environment of the LHD control room.
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Keywords: Large helical device; Long pulse operation; Huge data amount handling; Continuous data acquisition; Remote participation

1. Introduction

The Large Helical Device (LHD) is a helical confinement system, which has the advantage to confine plasma in steady state because the plasma current is not necessary for the plasma confinement [1]. For instance, the plasma with $T_{i0} \sim 2\,\mathrm{keV}$ and $n_e \sim 0.8 \times 10^{19}\,\mathrm{m}^{-3}$ was confined for 1905s [2]. In this case, the total amount of the plasma heating energy is about 1.3 GJ. Lower density plasma was maintained for 3900 s by means of ECH.

In order to operate such long pulse plasma, heating is the most important issue in plasma control. The heat treatment is important, and the concentration of heat to a particular local location, such as divertor plates, has to be also avoided. In LHD, the divertor leg position is swung by controlling the super conducting coil current.

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In order to control the plasma in steady state, the plasma parameters are monitored in real time using the YOKOGAWA WE7000 system, which is independent of the LHD data acquisition system. Data acquisition is an important issue. The conventional CAMAC system uses transient recorders, which do not operate in steady state. Two digitizing systems are employed for steady state operation: a WE7000 system and a NATIONAL INSTRUMENTS CompactPCI system. Continuous data streaming is implemented via the LHD-LAN.

For remote participation, the LHD-LAN is extended to remote sites all over Japan through SuperSINET, a 1 Gbps network for the Japanese academic research community.

The LHD diagnostics and the data acquisition system were reviewed a few years ago [3]. They have been steadily upgraded since then. Significant improvements have been made for the data acquisition and monitoring systems for the steady state operation, regarding plasma control, data acquisition and plasma monitoring.

2. Control for steady state operation

2.1. Long pulse plasma in LHD

LHD has a heliotron configuration with $l = 2/m = 10$ field period, a major radius (R_{ax}) of 3.42–4.1 m, an averaged minor radius (a) of 0.6 m, a plasma volume of 30 m^3 and a toroidal field (B_{ax}) of 2.4–2.9 T. LHD has super conducting coils (three pairs of poloidal coils and two pairs of helical coils having three segments individually) with a stored energy of 1 GJ. The plasma is heated by NBI (13 MW), ICH (2.5 MW) and ECH (2 MW). A complete set of standard diagnostics for operation and physics study has been installed. Advanced diagnostics, heating and plasma control systems are intensively being developed.

Steady state plasma is maintained mainly by ICH. The total input energy is 1.3 GJ mainly consisting of the ICH power of 0.98 GJ. Typical plasma parameters are: $n_e = 0.7 \times 10^{19}\ \mathrm{m}^{-3}$, $T_{i0} = 2$ keV, and pulse length = 1905 s. The magnetic axis is swung ($3.67 < R_{ax} < 3.7$ m) every 105 s to limit the temperature increase of the divertor plate.

Discharges with duration of more than 1 h (3900 s) are being performed with $B_{ax} = 1.48$ T and $R_{ax} = 3.6$ m by using the second harmonic ECH with $P_{in} = 110$ kW. The plasma parameters are: $T_{e0} > 1.0$–1.5 keV, $n_e > 1.5 \times 10^{18}\ \mathrm{m}^{-3}$. Rising pressure inside the waveguide has been a serious problem in the steady state operation of ECH. By inserting a mode filter to reduce reflection, a gyrotron is operated for 3900 s with 160 kW. By cooling and pumping the waveguide, the rise of the temperature and the pressure is almost saturated within a safe level. ECH is turned off manually so that the plasma duration time does not exceed the maximum time of the DAQ system. The DAQ system uses a common 1 MHz clock. The clock counter is limited to 2^{32}, and this limits the plasma duration. Therefore, the system is now being upgraded to 64 bits in order to extend the plasma duration for the next experimental campaign.

2.2. ICH

Four antennas are connected to the RF generators (38.47 MHz, 0.5 MW × 4, 1 h). Feedback control of the liquid impedance matching system [4,5] is used for reducing the reflected power. Reflection of RF is a severe problem for the steady state operation. Reflected RF power is significantly reduced by the feedback control of the RF frequency and the impedance matching. Liquid surface control in the impedance matching system is done every 7 s. Finally, the reflection ratio of the power becomes is less than 4%.

2.3. Super conducting magnet

Fig. 1 shows a cross-section of LHD and the schematic diagram of the control system of the super conducting coils. There are 6 power supplies to excite the 12 super conducting coils. The requirement for the control system are as follows: the steady state control error is less than 0.01% of the preset value; the overshoot in the coil current at the normal ramp-up rate is not allowed; the settling time for the control error of the order of 0.1% should be less than 1 s for normal ramp-up rate; the control system should be robust against the turbulence.

Each super conducting coil is coupled with the other coils and metal structures so strongly that the current change in one coil disturbs the current

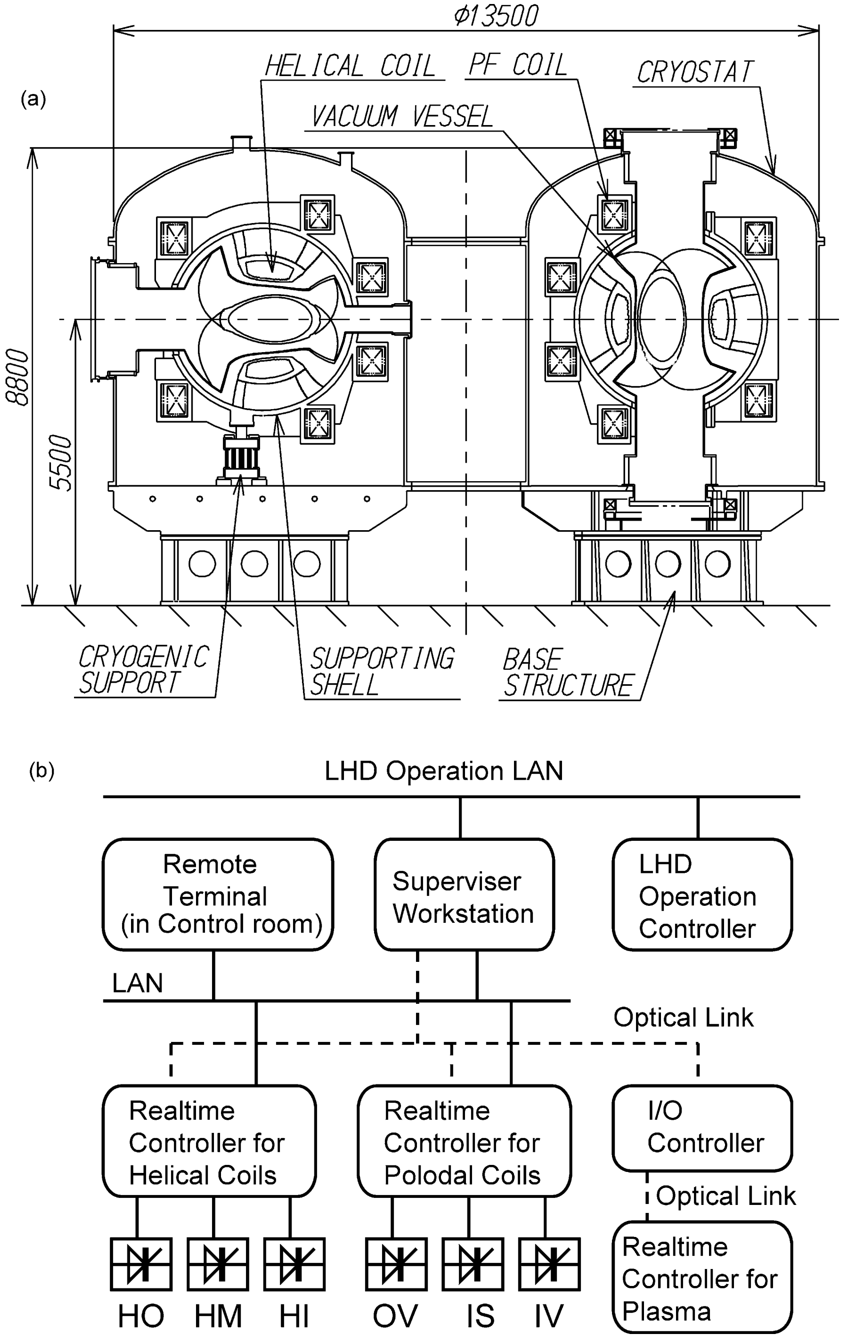

Fig. 1. (a) Cross-sectional view of LHD. (b) Schematic diagram of control system of the super conducting coils.

controller of the other coils. Since a traditional PI controller cannot satisfy the above requirements, a new control system, based on state variable theory, has been developed [6]. This system uses a matrix of circuit parameters (cf. inductances, resistances, etc.) of super conducting coils and structures. Those parameters are measured from the coil terminals. This control system runs on a UNIX workstation and two VxWorks based computers. With this control system and power supplies, the radial plasma position is scanned with $t = 100$ s in order to limit the heat load to the divertor tiles. An advanced control system is being developed for the super conducting coil [7].

2.4. Plasma density control

The plasma density is controlled by gas puffing and/or hydrogen ice pellet injection. For gas puffing, 16 piezo-electric valves and 2 mass-flow controllers are installed on 7 ports at different toroidal locations. The mass flow controller is mainly used for discharge cleaning, since it automatically controls the gas flow rate to the requested value. The piezo-valves are operated with pre-programmed waveforms in the usual way. According to the request from the experiment, density feedback via gas puffing is also available, where the density signal is provided by the FIR laser interferometer.

The target parameters for feedback control can be set by the operators during the discharge by monitoring the plasma and device parameters, which are acquired through the WE7000 system. Fig. 2 shows the real time plasma monitoring system and the output of the monitoring system. The main plasma parameters (n_e, T_e, etc.) and the wall temperature are sampled by the WE7000 digitizers. Data are displayed on a 150-inch rear projection TV with a delay of less than 1 s.

Two hydrogen ice pellet injectors are installed on LHD. One has 10 pellet gun barrels in order to inject large pellets within short time interval. The other one injects small ice pellets repetitively. The electron density is also controlled using the repetitive pellet injector by monitoring the density signal from the FIR laser interferometer.

3. Data acquisition for steady state operation

The LHD data acquisition system uses personal computer (PC) cluster, as shown in Fig. 3. Most plasma parameters are acquired using a conventional CAMAC system in batch processing every 3 min. Each CAMAC crate is connected to a PC via SCSI or Ethernet. PCs are located in one room close to the control room to facilitate maintenance; the CAMAC crates are located in the diagnostics room and connected via optical cables with the PCs [8].

The CAMAC system uses transient recorders, which cannot work in steady state. The steady state data acquisition system uses WE7000 and CompactPCI. Both WE7000 and CPCI systems consist of a controller with an interface to PC and a power-crate with module slots, where digitizers are installed. The PC cluster based data acquisition system is easily connected to WE7000 or CPCI systems [9]. WE7000 and CPCI systems are connected to the PCs via optical cables.

Fig. 4 shows the acquired data size of each shot and the total amount of the accumulated data in the LHD data management systems. The amount of data per shot is rapidly increasing due to the steady state operation. The number of complete data acquisition systems (DAQ: digitizer + computer) increased from 30 to 45 in the last campaign, and the short pulse data increased from 1 to 2.5 GB/shot. Steady state DAQ increased from 4 to 15, and the data amount increases from 3 to 84 GB/shot. There are nine steady state digitizers in WE7000 systems (2.2 MB/s) and six in CompactPCIs (80 MB/s).

Fig. 5 shows a schematic diagram of the LHD data management systems, which use a name server and an object-oriented data-base. Short-term raw data (24 h) are stored in each data acquisition computer, and the data for the whole period are stored in the juke-box backed-up by RAID. LHD data are managed by the name server and an object-oriented data-base (ObjectStore) so that short- and long-term data are accessed with the same software utility [10]. In WE7000 and CPCI systems, the digitized data are continuously acquired by each PC. Real time data are sliced every 10 s, and are labeled with sub-shot-number and stored in the hard-disk in each PC. Each time slice of data can be retrieved by the same program as for the CAMAC data.

The physics data are necessarily based on the raw data. For example, the electron temperature is deduced from the raw data of Thomson scattering. In LHD, the calculation of the physics parameters from the raw data is carried out by each diagnostic group. The physics

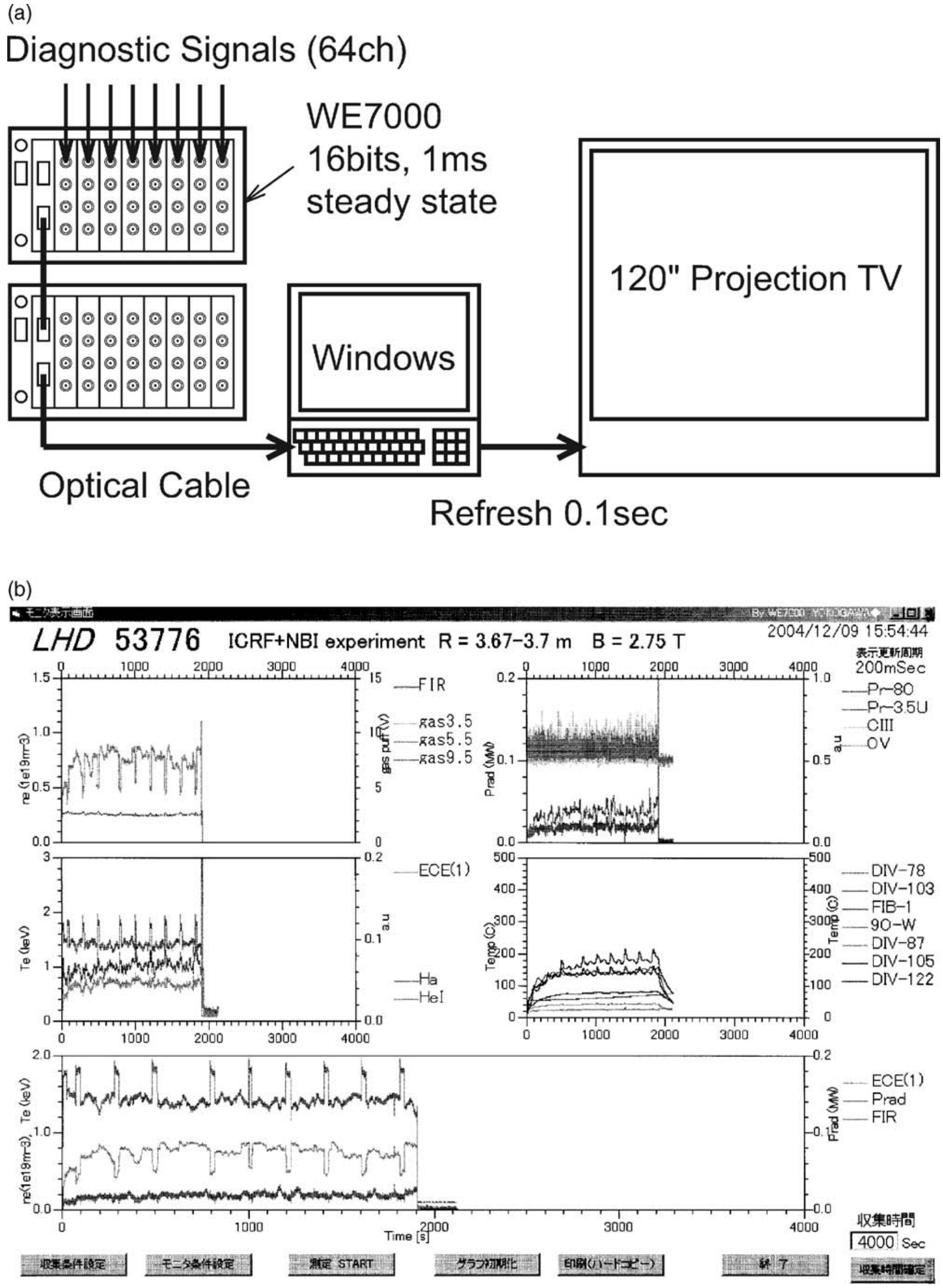

Fig. 2. (a) Real time plasma monitoring system. (b) Output of monitoring system.

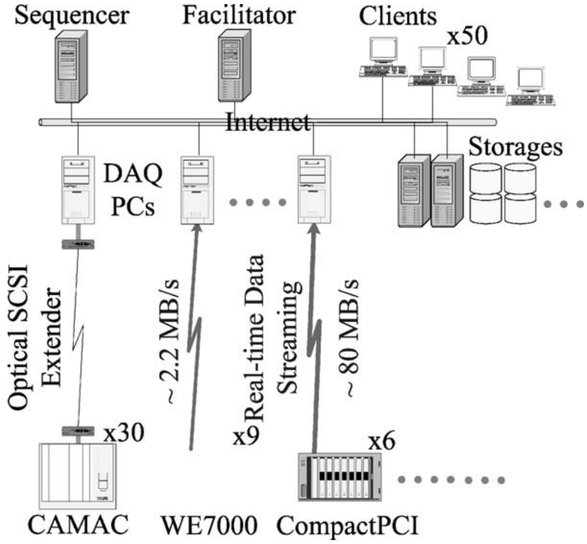

Fig. 3. PC cluster based data acquisition system.

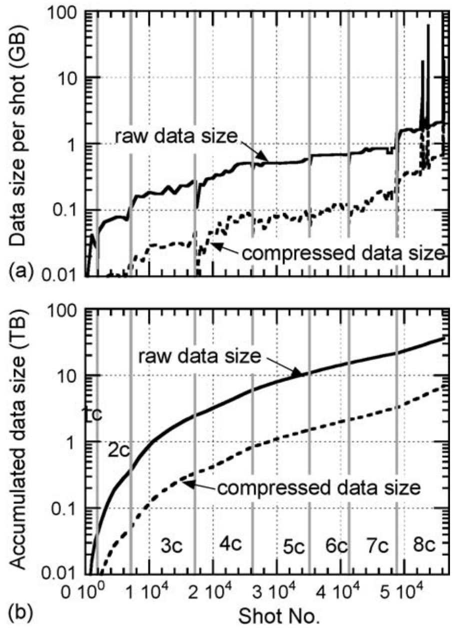

Fig. 4. (a) Acquired data size of each shot. (b) Total amount of accumulated data in the LHD data management systems.

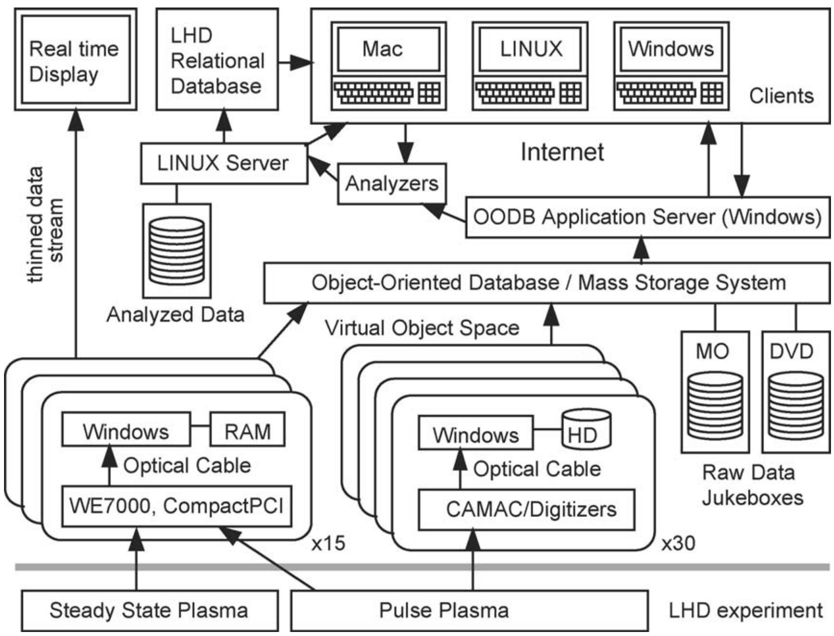

Fig. 5. Schematic diagram of the LHD data systems using object-oriented and relational databases for raw and analyzed data, respectively.

data are stored in a database server, which is named ‘Kaiseki server’. It consists of a relational database server and FTP servers. The database catalogues the location of the data files, which are supplied by the FTP servers. Data are served in text format. The Kaiseki server uses a common technology, which is easily used in different computer environments [11].

The ‘NIFScope’ data browser and its graphical user interface have been developed for short pulse operation. It can access analyzed and raw data. It is written in C++ and RUBY. The GUI uses the GTK tool kit and it can be used on Windows and LINUX [12].

A thinned data stream is also continuously served to clients through the LAN with a latency time of less than 1 s [13]. A JAVA browser for real time data has been developed. Since, JAVA has multi-task capability, in the case of multi-frame browsing the browser receives and plots several data streams simultaneously. Being written in JAVA, the real time data browsing system can run under Windows, MacOS, LINUX, etc.

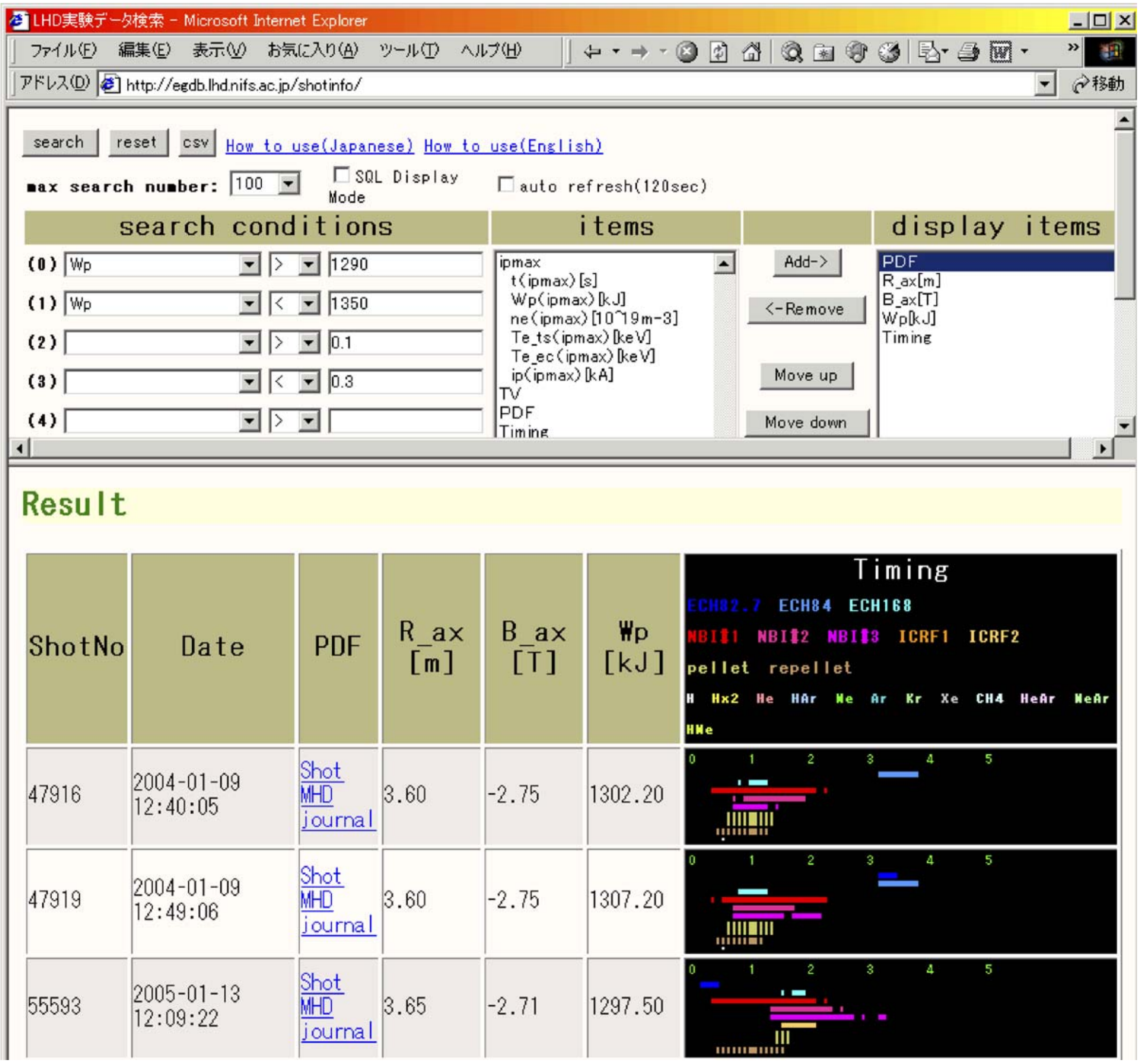

Fig. 6. Image of the WEB browser of the search engine of LHD experiment using relational database.

LHD shots can be searched on the WEB site using a relational database system, which is based on PostgreSQL. Fig. 6 shows the browser of the search system. Search keys are as follows: set-up parameters (R_{ax}, B_{ax}, P_{NBI}, etc.), plasma parameters (β_{max}, n_e^{max}, T_e^{max}, etc.). Parameters presented in the search output table can be selected. The output table and the SQL statement that was employed for the search can be saved as a text file. The output table includes links to PDF files of waveforms of typical plasma parameters and movie files of LHD plasmas.

The LHD relational database comprises many tables. Set-up parameters are immediately registered after the plasma shot; heating power is registered after some calculation using the power monitor and the calibration factor. Plasma maximum parameters and plasma duration are calculated after the physics data are recorded in the analyzed data base.

4. Remote participation in LHD

The facilities to enable remote users to participate in LHD experiments can be categorized as follows: (1) remote communication and monitoring, (2) remote data access and (3) remote computer access. Those are based on different security level. Remote communication and monitoring are on the lowest security level and are available via the TV conference system and WEB pages. Because LHD is a long-pulse experiment with pulse duration of about an hour, it is important for the scientists to observe the plasma in real time. For this purpose TV picture of LHD plasma are broadcast on the Internet using video streaming technology. Experimental data can be remotely accessed on the data server. Remote access to computers in LHD-LAN allows control of diagnostic devices in LHD.

The remote access is established using SuperSINET, a fast network with 10 Gbps backbone and 1 Gbps branches that is operated by National Institute of Information (NII). There are now eight remote stations at various locations around Japan, using the multi protocol label switching-virtual private network (MPLS-VPN). This extension is named ‘SNET’. SNET is located inside the firewall of NIFS-LAN. In a SNET remote station, users can manipulate diagnostic devices and access LHD data without any firewall to make maximum use of network bandwidth. Since, SNET is based on a standard MPLS technology, it can easily establish international virtual connections through the Internet. This will enable international remote participation on LHD experiments in the future.

The TV conference system is also connected to SNET. Users can hold TV conferences with international partners through the NIFS firewall. Using a multi connection system, users can watch the LHD plasma in a remote station, nearly as if they were in the LHD control room.

Basically, the whole campus network is protected by the firewall. The LHD network is a part of NIFS LAN, but it is administrated by the different security policy from the NIFS LAN. We provide the Virtual Private Network (VPN) to allow users direct access to the experiment LAN from the Internet. However, they are not allowed to access the campus LAN, which includes other computers, such as those of administration sections. To make it secure, we use one-time password authentication. We issue RSA’s SecurID cards to those who want to access the experiment LAN. The card generates random one-time passcodes for every time the user accesses the network.

5. Conclusion

In LHD, the plasma is successfully kept for a long time (1905 s). For LHD steady state operation, suitable systems have been developed for the control of plasma position, of electron density, and of the heating system, as well as for monitoring of the plasma parameters and the wall temperature. The LHD data acquisition system has been extended to real time data operation by using CPCI and WE7000 digitizers in flexible PC cluster based systems. A Java based real time data browser has been newly developed. A relational database for typical LHD parameters has been newly developed using PostgreSQL. Using the LHD relational database system, shots with particular plasma parameters and experiment set-up are easily retrieved. LHD remote stations have been spread over the Japanese fusion community through an 1 Gbps network. In remote stations, the collaborators can manipulate experimental devices in the LHD hall, and they can browse and analyze LHD data as if they were in the LHD control room. An easy-to-use browser for raw data and analyzed data has been developed so that collaborators in remote stations can look at LHD data without special training.

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