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keywords: central control system, LHD, operation scenario, protective interlock, man-machine interface, cryogenic control, computer network

# OVERVIEW OF THE LARGE HELICAL DEVICE (LHD) CONTROL SYSTEM AND ITS FIRST OPERATION

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*Abstract*

The first plasma operation of the Large Helical Device (LHD) fusion system has been successfully performed on March 31 in 1998 by means of the Central ('Chu-oh' in Japanese) Control System (COCOS) connected to ~50 subsystems using hard-wired interlock, optical-fiber timing and computer information network. From January 1998, the protective supervision system of COCOS went into service and the vacuum pumping control system started operation. The cryogenic control and the coil power supply control systems were utilized to cool down and energize the superconducting coils. The sequential control and timing control systems of COCOS have successfully started operation for a first plasma production. A variety of machine operations and plasma experiments will be continued on LHD using these flexible, reliable and advanced control systems.

## 1 INTRODUCTION

Helical confinement systems have distinctive merits of steady-state operations for fusion reactors. The Large Helical Device (LHD)[1-3] (Fig.1), the superconducting helical fusion machine with the major radius of 3.9 m, the minor plasma radius of 0.6 m and the magnetic field strength of 3 Tesla, has been completed after the 8-year construction schedule in Toki-City, Japan. This is a world-largest helical fusion experiment aiming at steady-state operation by means of superconducting coil system. One of the main objectives of this LHD project is to demonstrate steady-state operations of helical fusion plasmas that can be extrapolated to the future fusion reactor. For these purposes the National Institute for Fusion Science (NIFS) had been established in 1989 and the LHD machine construction was started in 1990.

As for the LHD main control system (see Figure 2), in April 1996 we started the real construction of the Central ('Chu-oh' in Japanese) Control System (COCOS), the LHD Man-machine Interface System (LMS) and the LHD experimental network [4-5]. In addition to this central control system, about 50 sub-control systems have been constructed. These systems are composed of a variety of computers such as UNIX engineering workstations, Windows NT personal computers (PCs), VME computer boards with real-time OS and programmable logic controllers (PLC).

In this paper, we will explain the overview of the LHD control system in the following:

(1) LHD operation scenario and its control concept.
(2) Central control system COCOS with hard-wired interlock, soft sequential control and optical timing control units.
(3) FDDI/ATM network architecture.
(4) Client/server LHD Man-machine-interface System (LMS) using Windows NT with Visual Basic.
(5) Control sub-systems relevant to machine commissioning, such as vacuum pumping control, cryogenic control, and coil power supply control systems.
(6) Real-time control data monitoring system with VME (VxWorks), Windows NT using Visual C++ and/or Unix workstation using Java.
(7) Distributed control systems for plasma diagnostics, and advanced data acquisition system by Windows NT network.

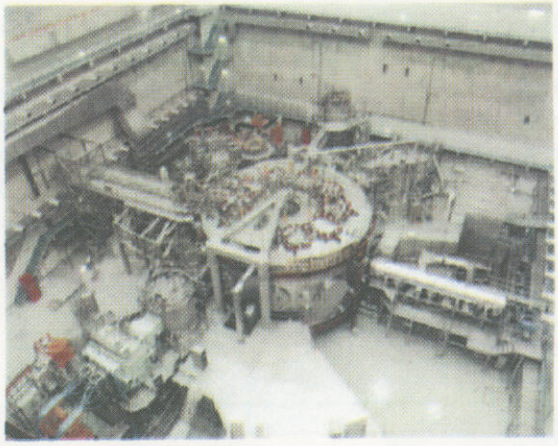

Figure1: Photograph of LHD (Large Helical Device)

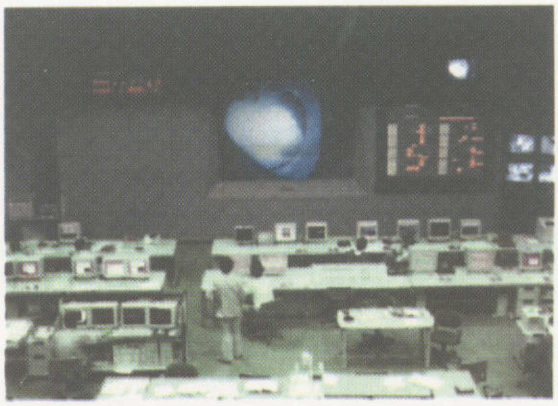

Figure2: Photograph of LHD Central Control Room

## 2 MACHINE OPERATION AND CONTROL CONCEPT

### *2.1 LHD Operation Scenario*

The LHD system consists of a variety of complicated systems that should be worked cooperatively. In order to clarify that, the LHD normal operation modes were classified into six modes (Fig.3); shut-down mode, facility operation mode, vacuum pumping mode, coil cooling mode, coil operation mode and plasma experiment mode. These modes are related to the personnel entrance permission with respect to electricity and vacuum, the magnetic field hazard and the X-ray radiation production, respectively.

The LHD coil system is cooled down once or twice a year after pumping out the cryostat. It takes a few weeks to cool down or warm up the helical and poloidal magnets, which should be operated safely and reliably, and the plasma experiment will be carried out flexibly. These magnets will be operated for about 10 hours per day, and the number of short-pulsed plasma operations with 10 second duration will be typically 50 - 100 shots per day. The LHD is also going to be operated in steady state (more than one-hour pulse length) and requires interactive control of the machine and the plasma.

For the analysis and protection of abnormal operation (for example, coil quench, electric power failure or earthquake accidents), the following six modes were defined; "1Q mode" (quick coil-current dump mode for coil quench protection), "1M mode" (medium coil-current decay mode), "1S mode" (slow coil-current decay mode), "2 mode" (plasma shut-down mode), "3 mode" (next sequence stop mode) and "4 mode" (warning mode). These signals are used in the interlock design, and its concepts had been successfully demonstrated in the real LHD experiment.

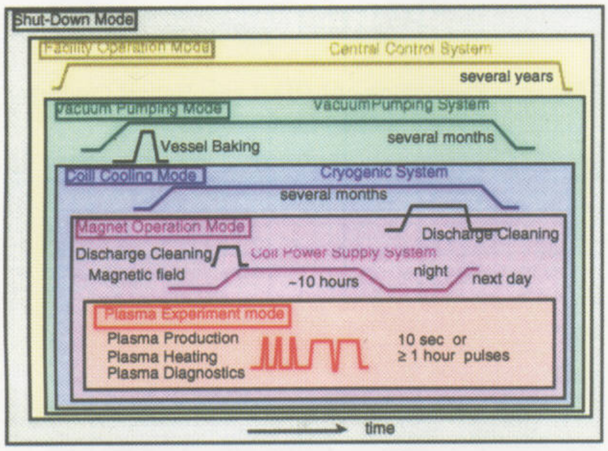


Figure 3: Six Operation Modes on LHD.

### *2.2 Control Concept and its Architecture*

The latest mission of the LHD project was to produce a first plasma as soon as possible, and as reliable as possible. On the basis of above-stated operation scenarios, the designed control system is composed of the central experimental control system and several sub-supervisory facilities which are connected by the FDDI-LAN in addition to hard-wired interlock/sequence control and first timing optical signals (Fig.3).

The real construction of the main unit of the COCOS was started in April, 1996 based on the following design philosophies;

(1) Flexibility for the physics experiment,
(2) Reliability for the large engineering machine and
(3) Extensibility for the central control system.

The design philosophy (1) requires human-friendly man-machine interface and advanced real-time plasma control systems, the item (2) requires reliable protective interlock systems with hardwires, and the philosophy (3) leads to the requirement of distributed and modularized control/ monitoring systems.

Figure 3 shows the outline of this system architecture. The conventional hard-wired logic system has been used between COCOS and about 50 sub-systems in addition to the FDDI computer network communication. The initial LHD operation should be carried out reliably on the schedule. The central boards with programmable logic controllers directly connected to sub-systems with hardwires were used for this initial purpose. Especially, the simple protective interlock system in COCOS was quite helpful to connect among a variety of complicated subsystems, some of which had been behind schedule. The computer systems such as man-machine interface may sometimes suffer from programming bugs and will waste a lot of time, however they should be used finally as flexible experimental tools. We decided to develop these friendly computer control systems step by step. The optical triggering signals were used in the fast timing system for sequential control of plasma discharges in addition to hard-wired signals and computer digital signals.

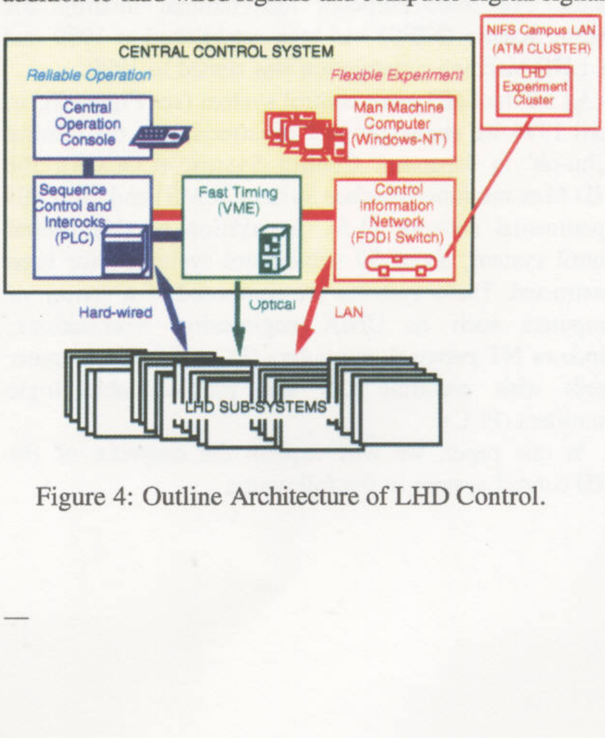


Figure 4: Outline Architecture of LHD Control.

## 3 CENTRAL CONTROL SYSTEM

### 3.1 COCOS Overview

On the basis of the LHD operation scenarios, the designed control system is composed of the COCOS central unit (Fig.5) and several tens of sub-supervisory facilities which are connected by the hard-wired interlock and soft sequential control link in addition to the FDDI/ATM communication network [4-5].

At the beginning of the LHD proposal (morethan10 years ago), the control system was considered based on the centralized control "process computer". Around several years later the UNIX engineering workstation system with VME computer connected by Ethernet-LAN was proposed. Now, some client-server systems by personal computers (PCs) are added for control and data acquisition. These various systems are presently connected by the advanced FDDI / ATM switching network system.

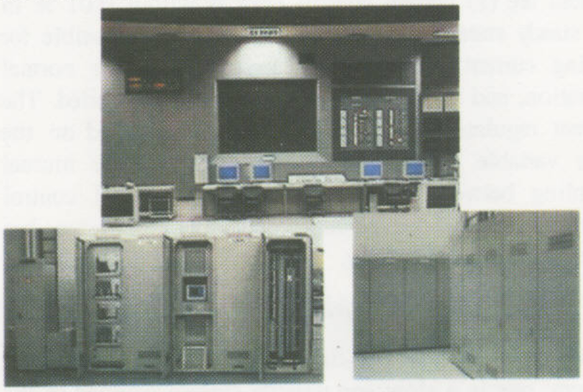

Figure 5: Central Unit of COCOS
Top: central operation console, four central control computer, central supervision panel and large-scale display in the central control room.
Lower left: VME timing board, central sequence control board, and I/O board in the basement of the control building.
Lower right: protective interlock board and so on in the LHD building.

The central control system COCOS is composed of the central control unit (including central operation console, central sequence control board, central control computer, central supervision panel, large-scale display, and the VME timing board), the torus instrumentation unit (torus supervision computer, torus supervision VME board and protective interlock board), the LHD Man-machine interface System (LMS), the control data monitoring system, the LHD experimental LAN and the uninterrupted power supply (UPS) systems. This system is provided with a variety of computers such as UNIX engineering workstations, Windows NT personal computers, VME computer boards with real time OS (VxWorks) and programmable logic controllers (PLCs).

The outline of this system architecture was shown in Figure 4. The central control board with PLCs directly connected to sub-systems via hardwires was used for the quick and reliable operation of LHD. Especially, the reliable protective interlock system is available in COCOS. The fast timing system with 64 channel optical signals (accuracy: < 1 micro-second, setting-up interval: 1 ms ~ 10 hr) was distributed to sub-systems. The feedback control for plasma current, position and cross-sectional shape will be carried out in the near future using intelligent VME control systems, such as applications of fuzzy logic or neural networks in addition to standard PID plasma control algorithm.

### 3.2 LMS

For flexible and elaborate experimental setup, the LHD Man-machine System (LMS) is installed for experimental operation using Windows NT, Oracle 7 and Visual Basic. This is a client/server system based on 3-Layer standard model (presentation, transmission and data house, and device control layer). This system is used for (1) presentation of operation mode, (2) setting-up of experimental condition, and (3) supervision of machine data. At present 8 clients and 2 servers for LMS are connecting to 6 subsystems, and will be extended to all sub-systems in the future. The details of this system are presented in this conference [6].

### 3.3 LHD Experimental Network

In the LHD experiment, we may have three kinds of data from the LHD computer systems: machine operation data (from main torus and plasma heating system), plasma diagnostics acquisition and control data, and plasma analysis data. These kinds of data should be transferred to the NIFS Campus ATM network. As shown in Fig.6, three network sub-clusters are used in the LHD experimental cluster. For machine control data , we added a fire wall system for safety. Plasma diagnostics data and analysis data are strongly coupled and we are trying to install ATM switches between diagnostics sub-cluster and experimental analysis sub-cluster. The large-scale computer system for theoretical analysis using experimental data is connected to the LHD experimental computers via this ATM campus LAN system.

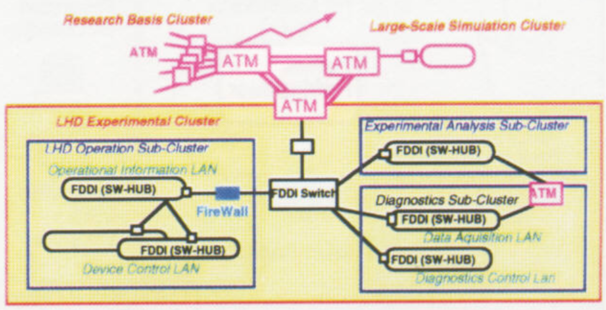


Figure 6: LHD experimental network connected to NIFS campus LAN.

## 4 TYPICAL SUB-CONTROL SYSTEMS

According to the above-mentioned operation scenarios, various sub-systems started operation in turn. Typical subsystems among ~50 systems are described below, which are connected to the central control system by means of three kinds of signals; PLC interlock hardwire ON/OFF signals, timing optical-fiber signals and TCP/IP computer network signals.

### 4.1 *Vacuum Control*

The initial important device at the machine start-up is the vacuum pumping system that consists of pumps, valves, pressure gauges and so on. Its device controllers are installed in the basement of the LHD building and four PCs are installed in the central control room for remote and automatic operation. More than 100 of status flags are programmed for operation and interlocks. The software is now in progress for upgrading the control system.

### 4.2 *Cryogenic Control*

Since the cooling scheme of the LHD system is fairly complicated, a reliable and flexible duplex control system is required for cryogenic control. Figure 7 shows the LHD cryogenic control system (TESS) arrangement [7] which is composed of two clusters: helium refrigerator control and cooling objet control for helical coil, poloidal coil and superconducting bus lines. The control system is based on open system and consists of Unix workstation, VME-VxWorks controllers, LAN and operation graphic consoles. This system is composed as a duplex redundancy system that significantly improves the reliable operation with fault diagnoses of each component. The VME controllers are used as a pair of one in service and the another in waiting. Two VME controllers are identical in both hardware and software. In case the running VME has trouble, the service is instantly switched over to the another VME controller which is in the waiting mode. The workstation and LAN are also duplicated, and controlled by the master workstation. The network is the optical duplex link type LAN that is compatible with Ethernet. At present the upgrade of the automatic operation programming is being in progress.

### 4.3 *Coil Power Supply Control*

For the achievement of excellent plasma, high accuracy of coil current control is required. The coil power supply control system is composed of VME controllers and Unix workstations. The required performance criteria of this system are (1) current control error is within 0.01 % in the steady state operation, (2) 0.1% error permissible for setting current value within 1 second in the normal operation, and (3) overshoot of current is prohibited. The current regulator in the VME machine is based on the state variable control theory to uncouple the mutual coupling between coils. At present P and PI control scheme is applied and the superconducting coil system has been operated successfully.

### 4.4 *Real-Time Machine Monitoring System*

We installed two real-time machine data monitoring system; one is a slow and reliable system coupled to the COCOS, another is a fast and flexible system for

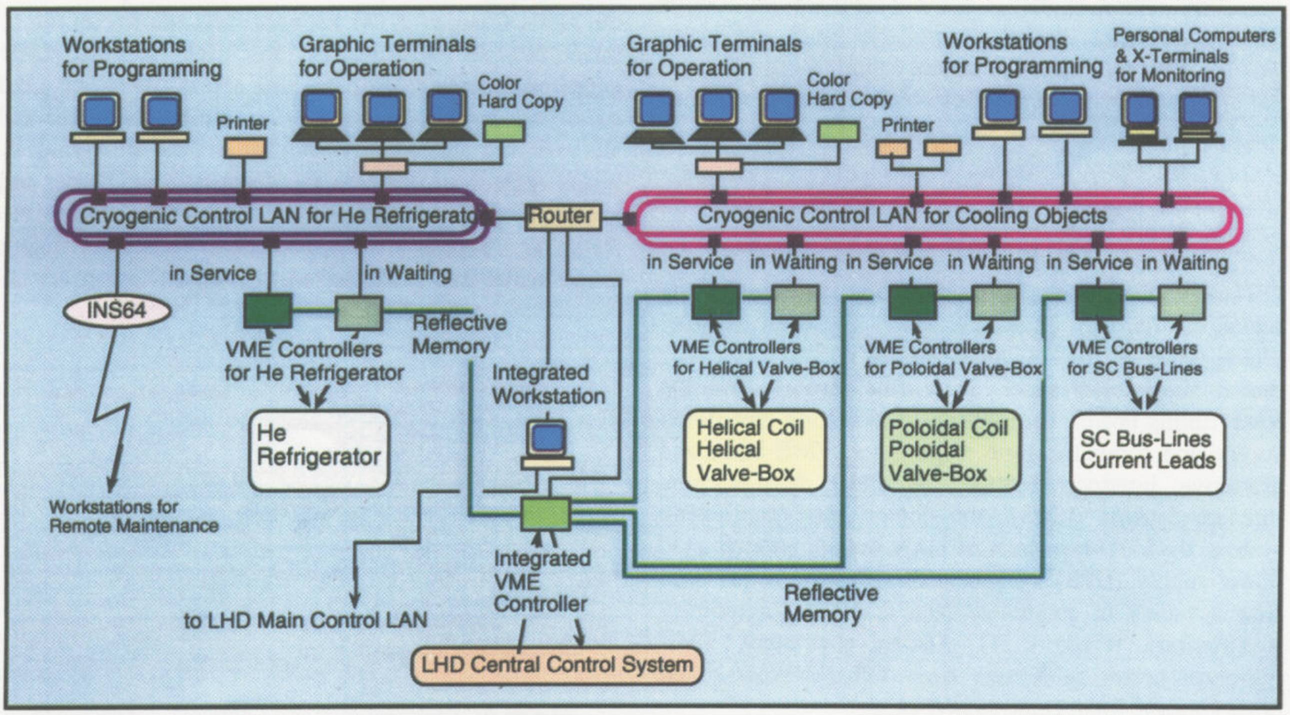


Figure 7: Cryogenic Control System

experimental data handling, as shown bellow.

For reliable machine supervision one of the data monitoring systems is based on Windows-NT using 1300 channel VME boards within COCOS [4-5]. This treats with a variety of signals such as machine temperature, mechanical stress, vacuum gauge signal, magnetic field strength and so on. These are used as both protective soft interlock signals for LHD operations and real-time slow display with sampling time of 1~10 s. The man-machine interface of this monitoring system was programmed by Visual C++. In this system the relational database Oracle is used.

For flexible real-time data monitoring, another LHD data monitoring system with 512 channel VME and the UNIX workstation was also constructed [8]. The sampling time is 1 second for real-time data, and 1 milli-second for batch data by the same acquisition system. Full Java computer software on WWW Browser was used in this system and will be extended to 4000 channels in the future. To manage Data, relational database (SyBase) was used in this system. The special data compression scheme is adopted here.

### *4.5 Diagnostics Control and Data Acquisition*

High quality data from the various plasma diagnostics is key to good experiment and good physics. Here the data acquisition and control for diagnostics were divided and connected by FDDI switch as shown in Fig.6.

The data acquisition system [9] is using distributed and object-oriented technology. The plasma data from ~20 diagnostic instruments are managed by CAMAC-VME and Windows-NT distributed systems. The typical raw data amount is a few 100MB per each shot, and maximum 10GB per day. It adopted the object-oriented database. For diagnostics control, the system is parallel to the diagnostics data acquisition system. Figure 8 shows the photograph of this diagnostics system with more than 50 clients and 30 servers (Windows-NT) .

Figure 8: Photographs of Diagnostic client PCs in the Central Control Room (upper) and a cluster of server computers in the Diagnostics Computer Room (lower right)

## 5 SUMMARY

The first plasma operation of the Large Helical Device (LHD) fusion system has been successfully carried out just on schedule after eight-year construction period. This has been achieved by the help of the Central Control System (COCOS) connected to ~50 subsystems using hard-wired interlock, optical-fiber timing and computer network information. From January 1998, the protective supervision system of COCOS went into service and the vacuum pumping control system was started. The duplex cryogenic control system and the high-accuracy coil power supply control system were used to cool down and energize the superconducting coils. Sequence control and timing triggering systems of COCOS have successfully started operation for a first plasma production. The COCOS man-machine system for monitoring and timing is based on Windows NT personal computers (PCs) with Visual C++. The LHD Man-machine interface System (LMS) based on Windows NT PCs with Visual Basic also stated in service and communicates with several sub-systems. The plasma diagnostics control and data acquisition system is also based on Windows NT client/server distributed system. The real-time monitoring system using Unix workstation with Java programming is also running. Using these flexible, reliable and advanced control systems, a variety of machine operations and plasma experiments will be continued on LHD.

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