LARGE-SCALE FUSION RESEARCH SYSTEM INTEGRATION BASED ON THE SUPERCONDUCTING LARGE HELICAL DEVICE AND PLASMA SIMULATOR AT NIFS

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Abstract

The representative facilities at NIFS for developing nuclear fusion research are the superconducting LHD and Plasma Simulator. LHD is the plasma confining machine with having superconducting helical and poloidal coils. The LHD experiment started in 1998, and stable operation under the condition of liquid He temperature with a continuous operation for half a year typically at each year has been so far successfully demonstrated for the period of 11 years. Real-time machine control and data acquisition of diagnostics are also established for long pulse operation so far up to 54 min. For understanding the plasma properties, large-scale simulation has been developed with Plasma Simulator. The main aim of the Plasma Simulator is to construct LHD Numerical Test Reactor for designing an optimum reactor. Experimental remote participation to the LHD experiment and remote utilization of Plasma Simulator are realized with the fast network. Such successful system integration at NIFS is contributing to promotion of fusion science and to designing a future fusion reactor.

INTRODUCTION

National Institute for Fusion Science (NIFS) is developing nuclear fusion science from the academic viewpoint. The representative experimental facility at NIFS is the superconducting Large Helical Device (LHD) [1, 2]. LHD is the machine for confining a plasma with the nested magnetic fields. It has a pair of superconducting helical coils and three pairs of superconducting poloidal coils. With these coils, the plasma confining magnetic fields can be produced in steady state without the plasma current unlike a tokamak. The configuration of the magnetic field can be flexibly changed by adjusting the current in the coils [3]. The LHD experiment started in 1998, and stable operation under the cooling condition of liquid He temperature with a continuous operation for half a year typically at each year has been so far successfully demonstrated for the period of 11 years. Such a reliable operation experience will be useful for the future fusion experiment with superconducting coils such as ITER. LHD has advantage for long pulse operation because of no necessity of plasma current, so long pulse operation is one of important experimental subjects. Long pulse operation so far up to 54 min has been carried out, and both real-time machine control of LHD and heating systems and data acquisition scheme for diagnostics in case of long pulse operation are established.

For understanding the experimental results and for the prediction of the plasma behaviour, theory and simulation are also developed at NIFS. It is important to develop experiments, theory and simulation in the integrated manner for advancing fusion research. For understanding the complicated plasma properties, large-scale simulation is being developed at NIFS. For that, a supercomputer has been up graded in March 2009. The new "Plasma Simulator" consists of a supercomputer having 77 TF computing speed and 16 TB main memory（these will be upgraded to 315 TF and 32 TB respectively in 2012). The main aim of the Plasma Simulator is to construct the LHD Numerical Test Reactor for designing an optimum reactor.

Experimental remote participation to the LHD experiment and remote utilization of Plasma Simulator for the collaborator in Japan are realized with the fast network SINET3. The technology of fast communication through internet is also developed for international collaboration. The experiment of the efficient communication between NIFS, Japan and Cadarache, France has been carried out. The result of more than 90 % of the nominal network speed is very encouraging.

Such successful system integration of the experiment, simulation and high speed network is contributing to promotion of fusion research and also to acceleration of designing a future fusion reactor.

LHD

LHD has a heliotron configuration in a helical form, and a twisted plasma is confined in closed flux surfaces. The property of no necessity of plasma current in LHD gives advantage in no current disruption and also in the operation of super high density plasma. The basic parameters of LHD are as follows: external diameter of 13.5 m, plasma major radius of 3.75 m, plasma minor radius of 0.6 m, plasma volume of 30 m^3, magnetic field of 3 T, and the total weight of 1,500 tons. The cold mass of the cryostat is 820 tons. High accuracy and stability of superconducting coil have been achieved. The accuracy of ±2 mm for the positioning of the superconducting coils has been achieved. And the current density of 36 A/mm^2 for the helical coils has been realized.

Schematic view of LHD superconducting magnets, control systems of plasma heating and density in LHD is shown in Figure 1. At LHD, so far following plasma parameters are achieved: ion temperature of 5.6 keV (central Ti) at density of $1.6x10^{19}m^{-3}$, central Ti of 13.5 keV at density of $3x10^{18}m^{-3}$ (Ar gas), electron temperature (central Te) of 10 keV at density of $5x10^{18}m^{-3}$, volume averaged β of 5.1 % (at the magnetic field of 0.425T), steady state operation of 54min 28sec with heating power of 500 kW (ICRF and ECH) which gives integrated energy input of 1.6GJ. During these experiments for 11 years, the total operation time of the cryogenic system is more than 55,000 hr with the rate of 5,000 hr/year. The availability of higher than 99% shows very high reliability and availability of this cryogenic system. Thus, an engineering base for construction and stable operation of a large-scale superconducting system for a fusion experimental reactor has been proven.

A steady state plasma is maintained mainly by ICH and partly by ECH. The maximum total input energy is so far 1.6 GJ (world record). Four ICRF antennas are connected to RF generators (38.47MHz, 0.5MWx4, 1 hour). In order to reduce the temperature rise of the diverter plate, the magnetic axis position is swung between 3.65m to 3.67m every 105s with controlling the current in the superconducting poloidal coils. The feedback control with the liquid impedance matching system reduces the reflected power of ICRF drastically from 70% to 2%.

Neutral Beam Injection (NBI) is contributing to high plasma performance such as high density, high beta, high stored energy plasamas. The NBI power of 23 MW is avilable in total at present. The NBI for LHD consists of tangential and perpendicular beams. The 16 MW power with acceleration voltage of 180 kV comes from the tangential beams having negative-ion sources. The power of 7 MW with acceleration voltage of 40 kV comes from the perpendicular beam with the positive-ion sources. The beam works as a diagnostic beam for Charge eXchange Recombination Spectroscopy (CXRS) for measuirng Ti and the plasma rotation velocity.

The Internal Diffusion Barrier (IDB) was produced with repetitive hydrogen pellet Injection and with edge plasma particle control. This mode resulted in the achievement of the very high density of $1.2x10^{21}$ m^{-3}. This result invokes a new ignition scenario, namely with high density and relatively low temperature core.

For handling the huge LHD data, the LABCOM system is established, and it succeeded in handling the LHD data of 90 GB/shot for long pulse operation. Based on this experience, the LABCOM system is considered to be extended to the level of 1000 GB/shot. For the real time data acquisition and monitoring, thinned data stream is sent to the WEB browser to monitor in real time, and it is utilized also for feedback control and real time data analysis. Sliced full data taken every 10 sec in case of long pulse operation can be retrieved even during the plasma shot. NIFS serves data access and remote participation to collaborators with easy tools to view and analyze data, and also with the WEB GUI of supercomputer and Remote participation system.

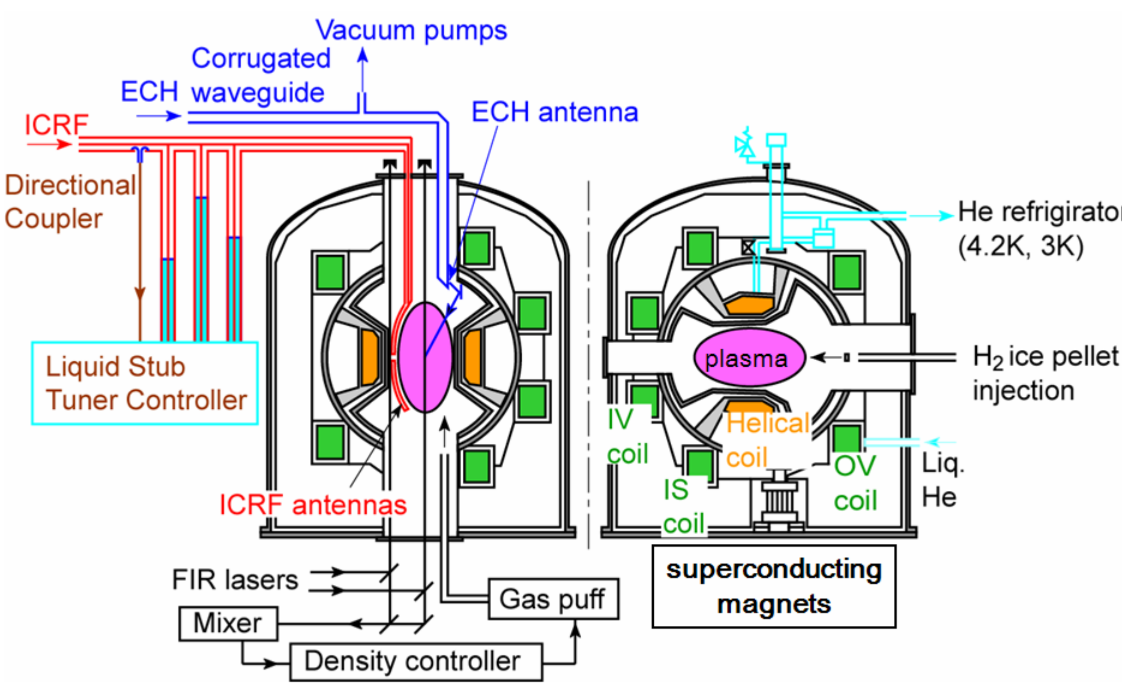

Figure 1: Schematic view of LHD superconducting magnets and control systems of plasma heating and density control.

PLASMA SIMULATOR

For understanding the experimental results and for the prediction of the plasma behaviour, simulation research is also promoted at NIFS. It is important to develop experiments, theory and simulation in the integrated manner for advancing fusion research. For understanding the complicated plasma properties, large-scale simulation is being developed at NIFS [4]. For that, a supercomputer has been upgraded in March 2009. The new “Plasma Simulator” consists of a supercomputer having 77 TF computing speed and 16 TB main memory（these will be upgraded to 315 TF and 32 TB respectively in 2012). The main aim of the Plasma Simulator is to construct the LHD Numerical Test Reactor for designing an optimum reactor. Concept of fusion simulation development based on LHD and Plasma Simulator is shown in Figure 2. Large-scale simulation has been so far carried out with fluid codes mainly for MHD and with particle codes mainly for high energy particle behaviours and so on. For future application, these codes should be connected adequately for the integration system. Such hybrid simulation will become the important feature at the Plasma Simulator.

FAST COMMUNICATION NETWORK

Experimental remote participation in the LHD experiment and remote utilization of Plasma Simulator for the collaborator in Japan are realized with the fast network SINET3. LHD remote participation and supercomputing with closed network are realized [5]. The technology of fast communication through internet is also developed for international collaboration. The experiments of the efficient communication between NIFS, Japan and Cadarache, France were carried out. In June 2009, data of 1.2 TB was sent in 3 hours with the average speed of 881 Mbps through a 1 Gbps network. In September 2009, 85 GB was sent in 205 sec with the average speed of 3.3 Gbps through a 4 Gbps network. The results of more than 80 % efficiency of the nominal network speed are very encouraging.

Such successful system integration of the experiment, simulation and high speed network is contributing to promotion of fusion research and also to acceleration of designing a future fusion reactor.

SUMMARY

At LHD, steady state operation has been successfully implemented based on reliable superconducting system, various heating systems with adequate control, flexible plasma control methods, and adequate data acquisition system. Large-scale simulation with Plasma Simulator are being developed aiming at a numerical test reactor. International collaboration and remote participation in experiments and simulation are being developed with high speed network. The total integration of the superconducting Large Helical Device and the Plasma Simulator at NIFS with massive network connection forms an efficient Large-scale Fusion Research System.

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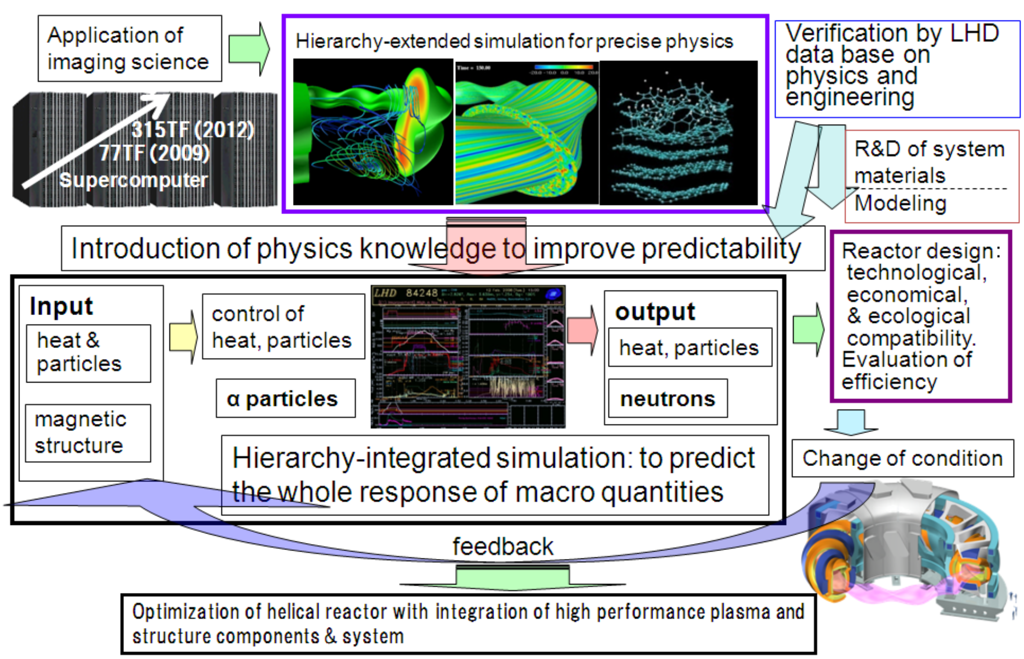

Figure 2: Concept of fusion simulation development based on LHD and Plasma Simulator.