LHD Diagnostics Toward Steady-State Operation

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Invited Paper

***Abstract*—The large helical device (LHD) is the world largest helical system having all superconducting coils. After completion of LHD in 1998, six experimental campaigns have been carried out successfully. The maximum stored energy, central electron temperature, and volume averaged beta value are 1.16 MJ, 10 keV, and 3.2%, respectively. The confinement time of the LHD plasma appears to be equivalent to that of tokamaks. One of the most important missions for LHD is to prove steady-state operation, which is also significant to international thermonuclear experimental reactor (ITER) and to future fusion reactors. LHD is quite appropriate for this purpose based upon the beneficial feature of a helical system, that is, no necessity of the plasma current. So far, the plasma discharge duration was achieved up to 150 s. The plasma density was kept constant by feedback control of gas puffing with real time information of the line density. The issue for demonstrating steady-state operation is whether divertor function to control particle and heat flux is effective enough. Relevant to this, LHD diagnostics should be consistent with the following:**

1) **continuous operation of main diagnostics during long-pulse operation for feedback control and physics understanding;**
2) **measurement of fraction of H, He, and impurities in the plasma;**
3) **heat removal and measure against possible damage or surface erosion of diagnostic components inside of the vacuum chamber;**
4) **data acquisition system for handling real time data display and a huge amount of data.**

Although there are already some achievements on the above subjects, there remain still several issues to be resolved.

On the other hand, the long-pulse operation of the plasma gives benefits to the diagnostics. For example, the polarizing angle of ECE emission can be changed during the discharge, and the intensity dependence on the polarizing angle has been obtained. The spatial scanning of the neutral particle analyzer and the spectrometer can supply the spatial profiles of the fast neutral particle flux and the specific impurity lines.

In this paper, the present status of these issues and future plans are described.

***Index Terms*—Fusion reactors, helical system, plasma measurements, stellarators.**

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I. Introduction

In RECENT years, magnetic plasma confinement experiments for fusion energy have begun to progress beyond short pulse physics experiments to machines designed to test the feasibility for steady-state plasma confinement, which is essential for reactor operation [1]–[3]. Concomitant with the design and operation of such experiments is the need to develop the measurement capabilities to diagnose such long duration plasmas. In addition, the special challenges posed by a fusion reactor environment demand modifications and new techniques for measuring the parameters needed for reactor operation and plasma characterization [4].

Among the handful of devices, which are currently pursuing the limits of long-pulse, high performance plasmas [1], [2], the large helical device (LHD) is unique in its use of superconducting helical coils (one pair) and vertical field coils (three pairs) in a heliotron configuration ($l/m = 2/10$) to provide, in steady state, the entire confining magnetic field (up to 2.9 T) [3]. This externally formed confining field precludes the need for the driven plasma current which is essential in a tokamak and which limits the density by leading to discharge terminating current disruptions in those types of devices. Therefore LHD is inherently suited to steady-state operation and the development of steady-state diagnostics.

LHD is one of the largest operating magnetic plasma confinement devices with a major radius which can be varied from 3.42 to 4.1 m, a minor radius which averages 60 cm and a plasma volume on the order of 30 m^3 [3]. LHD is well equipped with a variety of plasma heating methods: neutral beam injection (NBI)—3 beam lines, 150–180 keV negative ion, ~10 MW total; ion cyclotron resonance heating (ICRH)—6 antenna, ~2.7 MW total; electron cyclotron resonance heating (ECRH) 84 and 168 GHz, ~2.1 MW total. The flexible combination of these heating sources has enabled several notable achievements in LHD: peak electron and ion temperatures exceeding 10 keV [5] and 7 keV [6], respectively, the formation of an electron internal transport barrier [7], averaged beta of ~3.2% and a stored energy of 1.16 MJ [8] and a long-pulse duration of 120 s [9] which has recently been extended to 150 s. In addition line-averaged electron densities up to 1.6×10^{20} m^{-3} have been achieved [8] and confinement time scaling which rivals ELMy H-mode tokamaks has been demonstrated [10].

The LHD experiment has a five-fold objective, which includes the following:

1) to realize high $n\tau_E T$ plasmas and to study the transport physics relevant to fusion plasmas;
2) to demonstrate high β stable plasmas ($\langle\beta\rangle \geq 5\%$) and to study the related physics;
3) to study energetic particle behaviors in order to simulate α particles in fusion plasmas;
4) to increase the physics understanding of toroidal plasmas by an approach that is complementary with the other helical systems and tokamaks;
5) to develop the physics and technology for steady-state operation and control using a divertor.

In this paper, diagnostic developments related to steady-state plasma experiments on LHD are described. In Section II, the description of diagnostics is divided into four categories: Primary diagnostics for physics studies and their suitability for long-pulse experiments, diagnostics needed specifically for steady-state operation, diagnostics which have been enhanced through long-pulse experiments and development of data acquisition systems for steady-state experiments. In Section III, recent long-pulse experiments on LHD and their diagnosis are described. Finally, in Section IV, unresolved issues related to the steady-state experiments, particularly in a reactor environment are discussed and the article is summarized.

II. LHD Diagnostics

LHD has an extensive set of diagnostics for studying the physics of plasma confinement [11], [44] as shown in Table I. The arrangements of diagnostics and heating systems are shown in Fig. 1.

TABLE I
LHD Plasma Diagnostics

DIAGNOSTIC	MEASUREMENT	*BRIEF DESCRIPTION*
Magnetic Probes	I_p, W_p, Plasma Position	Rogowski, Mirnov, Flux Loops
μW Interferometer	n_eL	2mm/1mm wave, single channel
FIR Laser Interferometer	$n_eL(r)$	119μm-CH_3OH laser, 13 chords
μW Reflectometer	NBI Interlock, n_e Fluct.	33, 35, 39, 60, 65 GHz
Polarimeter		10.6 μm CO_2 laser
Thomson Scattering	$T_e(r)$, $n_e(r)$	130 spatial points, 20 ms, 2.5 J
TV Thomson Scattering	$T_e(r)$, $n_e(r)$	YAG laser high spatial resolution
ECE (GPC, radiometer, Michelson)	$T_e(r, z)$ 2-D Imaging	14 ch 32 ch
X-ray PHA	T_e, Impurities	20 ch Si(Li) , 4 ch Ge detector
Soft X-ray CCD	T_e, Shafranov Shift	Soft X-ray tangential imaging
TOF-FNA	T_i, Energy Spectra f(E)	Time-of-flight method, radial scan
CXS	$T_i(r)$, $V_p(r)$	Radial profile
X-ray Crystal Spect	T_i (r)	0.1-4nm, $\lambda/\Delta\lambda$: 10^4
Neutron Diagnostics	Neutron flux, T_i	NE-213 detectors, 3He counters
Bolometers	$P_{rad}(r)$	metal film type 56 channels
	$P_{rad}(r)$ 2-D Imaging	3 Imaging Bolometer Cameras
	AXUV Diodes	1,2-D tomography 75 channels
VUV Spectroscopy	Impurities, T_i	1- 200 nm, $\lambda/\Delta\lambda$: 10^4
Visible Spectroscopy	$n_0(H)$, Z_{eff}	200- 700 nm, $\lambda/\Delta\lambda$: 5 x 10^4
	Impurity line	nine 20 cm monochromators, etc.
Real time video	Visible, H_α, C_{III}, O_{II}	tangential core & divertor views
Soft X-ray Diode Array	MHD Oscillations	silicon surface-barrier diodes
Soft X-ray Camera	MHD Oscillations	high speed imaging
μW/FIR Scattering	Micro-instabilities	1mm/195μm multichannel
Heavy Ion Beam Probe	Φp, Φp Fluctuation	Au^-, 6MeV, 100μA (developing)
Langmuir Probes	T_e, n_e, Φp	Fast scanning and fixed probes
Divertor Spectroscopy	Recycling, Particle Flux	
Li Beam Probe	Density Fluctuation	20 keV Li Beam
High-energy Particle Diagnostics	High-energy Particles	Silicon Detector Array, Diamond Detectors, TOF-FNA
Diagnostic Pellet	Particle Transport	TESPEL/ *TECPEL, C, Li
Visible/Infrared TV	Plasma position, PWI	TV system
Fast Ion Gauge	Neutral Gas Pressure	
Magnetic Surface Mapping	Magnetic Surface	Electron Beam, Fluorescent Mesh and Rod

*Tracer-Encapsulated Cryogenic Pellet

A. *Primary Diagnostics and Suitability for Steady State*

The primary diagnostics on LHD can be classified into five categories: 1) electron density diagnostics; 2) electron temperature diagnostics; 3) ion temperature diagnostics; 4) impurity radiation diagnostics; and 5) others. In general, the diagnostics on LHD are working routinely, also during long-pulse experiments. The primary limitation on diagnostics in terms of steady-state operation is the memory size of the data acquisition system. This issue is discussed further is Section II-D. In this section, we will briefly introduce each system and remark on any performance issues related to steady-state operation.

1) Electron Density Diagnostics: On LHD various diagnostics for measuring the electron density exist. A two-color millimeter wave (MMW) interferometer is used to monitor the line-averaged density [12]. A 13-channel far infrared (FIR) interferometer provides density profile measurements [13]. A multichord CO_2 laser imaging interferometer is also under development for detailed profile measurements of density and density fluctuations [14], [45]. In addition reflectometer [15] and polarimeter [16] diagnostics are under development. For edge density measurements Thomson scattering [17] can be used, and also a lithium beam probe has recently begun operation [18].

2) Electron Temperature Diagnostics: Electron temperature measurements include a high spatial resolution YAG laser Thomson scattering system [19] with flexible repetition (from microseconds to hundreds of milliseconds) as shown in Fig. 2. The calibration for the density is not yet completed, so the density profile should be taken only as a reference. In the figure, the short and long intervals are 300 μs and 100 ms, respectively. These numbers can be changed according to the purpose. In addition to this, a TV Thomson scattering system has been introduced recently with the goal of the high spatial resolution. Also, three types of electron cyclotron emission (ECE) diagnostics have been installed, grating polychromator, radiometer and Michelson [20]. The ECE is proven as a reliable diagnostic for the temporal development of the electron temperature profile. The absolute electron temperature agrees well with the Thomson scattering data in case of medium density. When the electron density increases to $n_e > 0.6n_{cutoff}$, then the ECE temperature starts to decrease due to the diffraction of the ray. This is due to the highly elliptical and twisted shape of the LHD plasma resulting in a curved plasma surface in the viewing field of the ECE antenna. Therefore, the refraction of the ECE ray is not negligible if the electron density is more than half of the cut off density. The refraction causes the diffusion of the ECE ray so that the detected ECE intensity is reduced. Soft X-ray diagnostics include a pulse height analyzer system [21] and a soft X-ray charge-coupled device (CCD) imaging system [22]. The electron temperature measured by the Soft

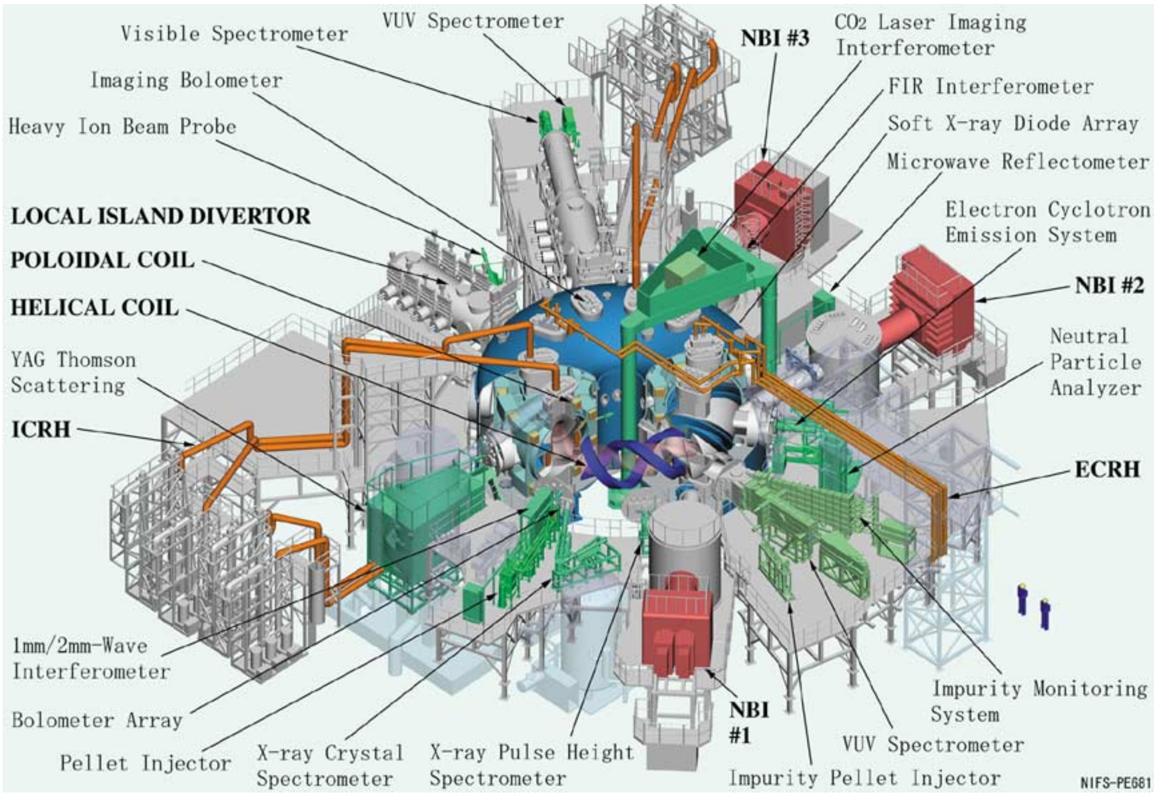

Fig. 1. Arrangement of diagnostics and heating systems on LHD.

X-ray diagnostics agrees well also with the data measured by the Thomson scattering system.

3) Ion Temperature Diagnostics: Ion temperature is measured on LHD using a crystal spectrometer for peak temperature (and also toroidal rotation velocity) [23], a charge exchange recombination spectroscopy (CXRS) system for profile information [24], and neutral particle analyzers for energy spectra [25], [26], [46], [47]. The highest central ion temperature is obtained from the Doppler broadening of Ar XVII measured by the crystal spectrometer.

4) Impurity Radiation Diagnostics: Impurity radiation from the LHD plasma is monitored with various arrays of spectrometers and bolometers. A 2-m soft X-ray duo-multichannel spectrometer (SOXMOS) (0.5–34 nm) [27], a 3-m VUV spectrometer using a CCD detector to provide a vertical profile of the spectra [28] and a 50-cm UV-visible Czerny-Turner type spectrometer (200–550 nm) [29] have been installed. An impurity monitoring station consisting of nine 20-cm normal incidence monochromators (30–180 nm), a 2.2-m grazing incidence monochromator (10–120 nm), a 20-cm normal incidence polychromator (30–550 nm), a flat field extreme UV polychromator (1–10 nm, planned), H_α and He_I visible monitors, total radiation monitor (using a secondary electron multiplier), and a soft X-ray monitor [30]. The X-ray pulse height analyzer is also used to measure heavy impurity emission [21]. Bolometers of three different types (resistive—56 ch, absolute extreme UV photodiode (AXUVD)—75 ch and infrared (IR) imaging—three cameras) are used to measure the total radiated power distribution from the plasma [31]. Resistive bolometers suffer from an uncompensated thermal drift of the signal which is difficult to correct in the case of long-pulse experiments. One possible solution to this problem would be to have two sets of bolometers with shutters which would be alternately closed for zeroing the amplifiers. Tracer encapsulated solid pellets are used to investigate impurity transport [32].

5) Other Diagnostics: For measuring the electric field the CXRS system is used [24] and a heavy ion beam probe is under development. MHD fluctuations are studied using arrays of soft X-ray detectors, mirnov coils and the ECE diagnostics [20]. The soft X-ray detectors include PIN photodiode arrays [33] and a high-speed soft X-ray imaging camera [34]. In addition magnetic probes are used to measure the stored energy, plasma current and the plasma position. Magnetic probes and other diagnostics using integrator circuits are not suitable for continuous operation beyond ∼10 s due to saturation of the integrated signal. One possible countermeasure to this problem is the use of multiple integrator circuits, which are multiplexed to produce a continuous measurement. Such a system is currently under testing at NIFS. Another possible solution uses a rotating coil probe and has been tested on the TRIAM device [35]. Langmuir probes are installed in several locations in the divertor strike plates and also a fast scanning probe is used to measure plasma parameters in the divertor leg region [36].

B. Diagnostics for Steady-State Experiments

Diagnostics which are essential for steady-state operations can be classified as either those for real-time monitoring or those for feed-back control. Real-time monitoring is necessary to insure that certain parameters do not exceed the limits of safe

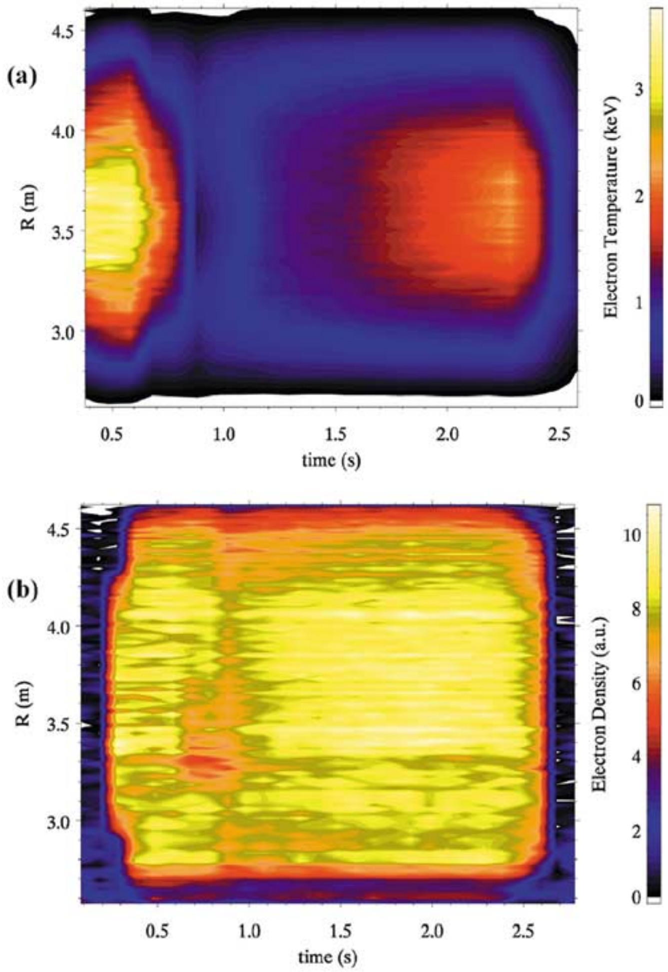

Fig. 2. One example (Shot no. 33 621) of (a) electron temperature and (b) density profiles measured by a high spatial resolution YAG laser Thomson scattering system.

operation. Feedback control is necessary when one measured parameter is used to control a device in order to maintain the plasma in a steady-state condition. These diagnostics and their use on LHD are described in the following.

1) Real Time Monitoring: Real-time monitoring and display of various parameters carried out during long-pulse experiments in LHD using the WE7000 system described below in Section II-D. These include core line-averaged electron density from the FIR interferometer, electron temperature at several radii from the ECE radiometer, H_α, C_{II}, and O_V signals from the impurity monitoring station, total radiated power from AXUV photodiodes, ion saturation current from divertor Langmuir probes and the temperatures of vacuum window flanges using thermocouples at two different locations. In addition to these, real-time video signals of visible light and of various impurity lines (H_α, C_{III}, and O_{II}) are available [37]. One example of the CCD camera (3-O) view with $H\alpha$ filter at the bottom part of vertically elongated cross-section is shown in Fig. 3, and the calculated magnetic field line trace is also shown in Fig. 3. The characteristic structure agrees well. Real time video is also used to monitor ICRF antennas and the Local Island Divertor head for arcing and hot spots. Also, IR thermography measurements monitor the temperature of the graphite armor tiles of the neutral beam injection (NBI) beam dumps [38]. Finally, for machine operation purposes numerous thermocouples are installed throughout LHD [36] and are sampled continuously and displayed at a 1-Hz sampling rate along with measurements of the vacuum tank and cryostat pressures.

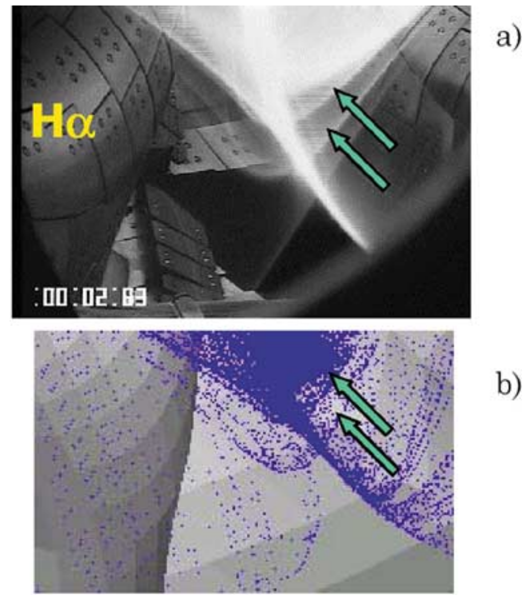

Fig. 3. (a) CCD camera (3-O) view with $H\alpha$ filter at the bottom part of vertically elongated cross-section. (b) Calculated magnetic field line trace.

2) Feed-Back Control: Various signals are used for feedback control of various devices to insure steady-state conditions and device protection. Line averaged density signals from the FIR interferometer are used to control the gas puff to maintain a constant density during long-pulse discharges. Plasma current signals from the Rogowski coils can be used to adjust the coil currents to control the plasma current. This is done by calculating the necessary coil currents to change the plasma current from the measured value to the target value and then adjusting the coil currents accordingly in real time with a 100-ms control period [39]. These plasma current signals, in addition to measurements of the super conducting coil currents, can be used to keep the coil currents constant or to keep the total magnetic flux through the coils constant. A reflectometer is used to monitor the density as an interlock signal for the NBI, to turn off the beams in case of a premature termination of the plasma. The super-conducting coils are protected by emergency shutdown which can be triggered by various conditions: excessive coil balance voltage; loss of vacuum in coil cryostat; loss of power supply; strong earthquake; etc.

C. Benefits to Diagnostics From Steady-State Operation

Several diagnostics can benefit from the long time scales of steady-state experiments. The VUV spectrometer can be slowly rotated vertically (0.022–0.044 deg/s) during a steady-state discharge to measure the spatial profile of the spectra [27]. As shown in Fig. 4, radial distributions of spectral line intensities have been obtained during a long-pulse discharge. Taking advantage of a stationary state of the plasma, the localization property depending on ionization degree was clearly observed with

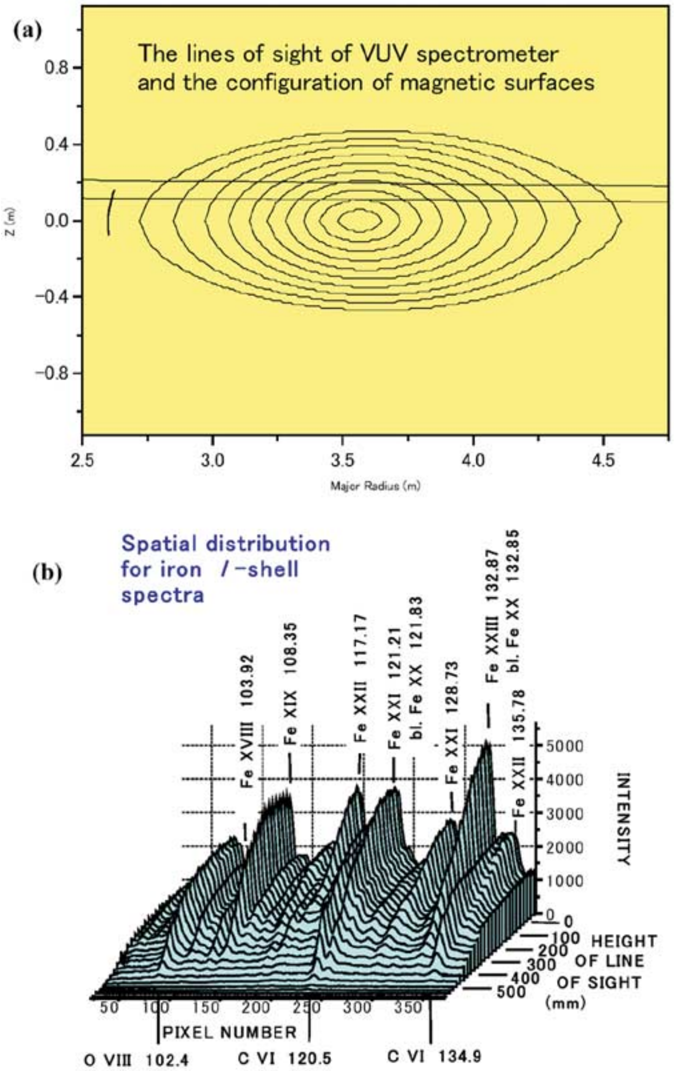

Fig. 4. VUV spectrometer can be (a) rotated vertically during a steady-state discharge to measure the (b) spatial profile of the spectra.

chord scanning. The 3-m VUV spectrometer is also designed to be scanned toroidally providing a two-dimensional diagnostic [28]. The polarizer for the ECE diagnostics [20] can be rotated during the experiment to give a real-time measurement of the polarization. The viewing angle of the NPA [25] can be scanned to provide a measure of the loss cone. Many diagnostics can benefit from increased integration times to improve photon statistics or spatial resolution, at the cost of time resolution during discharges which are held in a steady state for a long period of time. Examples of these diagnostics are TV Thomson scattering, X-ray CCD camera [22] and imaging bolometers [30].

D. Data Acquisition

The data acquisition system for the LHD experiment uses two systems, the standard one for data acquisition for post shot analysis and one for real-time display. The real-time display is handled by a Yokogawa WE7000 system[1] , which can sample at 20 kHz and display up to 32 channels in real-time. The standard LHD data acquisition system is based on a massively parallel CAMAC (30 crates, ∼2000 diagnostic channels) /PC (30 sets) /RAID (50 GB/PC) acquisition hardware, hierarchical double/mirrored storage media (RAID—2 TB, MO jukebox—1.2 TB, DVD-ROM changer—3.2 TB), and a cluster of data retrieval clients (50), all connected by a gigabit-based network structure. The raw data are stored in an object-oriented database which handles over 700 MB (100 MB compressed)/shot with approximately 150 shots per experiment day with one shot every 3 min for standard short pulse experiments (less than 10 s). For long-pulse experiments typically the CAMAC sampling time is lengthened to extend the acquisition period to match the pulselength, however, for those diagnostics that require it (for example diagnostics used to investigate fluctuations), event-driven triggering is available for short acquisition periods with high sampling speeds. Dual alternating systems with iterative operation (2–3 min) are envisioned to allow indefinite continuous data acquisition and storage at intermediate sampling rates (1–5 kHz).

A new real-time data acquisition system, which would replace the current CAMAC system, and is based on compact platform component interconnect (PCI) technology[2] is currently under prototype testing at NIFS in cooperation with National Instruments Corporation. The objective is to reach 1 MS/s/ch with 100 MB/s continuous data transfer. Currently, achieved parameters are 2.5 MS/s/ch and 84-MB/s transfer rate with improvements expected as systems are gradually upgraded [40].

TABLE II
SUMMARY OF LONG-PULSE ACHIEVEMENTS IN LHD

Heating source	Input power (kW)	Duration (s)	Density ($10^{18}/m^3$)	Plasma temperature (keV)
ECH	50	120	0.3	$T_e \sim 0.65$
NBI	600	80	16	$T_e \sim 1.5$
NBI	100	110	10	$T_e \sim 0.35$
ICH	350	120	8	$T_e \sim T_i \sim 1.3$
ICH	520	150	6	$T_e \sim T_i \sim 2$

III. LHD STEADY-STATE EXPERIMENTS

Long-pulse experiments have progressed steadily [3] since LHD's first experimental campaign to reach the parameters listed in Table II. Some notable achievements have been the control of heavy impurities through the introduction of a graphite helical divertor [41], and steady-state fueling by means of continuous repetitive (11 Hz) injection of cryogenic Hydrogen pellets [42], [48]. The vacuum vessel walls and the helical divertor are actively cooled with flowing water with the capability to remove 0.3 MW/m_2 of power at the divertor in steady state. This design would allow 3 MW of input power assuming all was conducted to the divertor. Therefore, the development of heating power supplies is being pursued with the long term goal of 3 MW of ICH heating for one hour. The short term goal for the next experimental campaign is to

[1]Yokogawa Corporation of America. http://us.yokogawa.com.

[2]National Instruments Inc. http://www.ni.com.

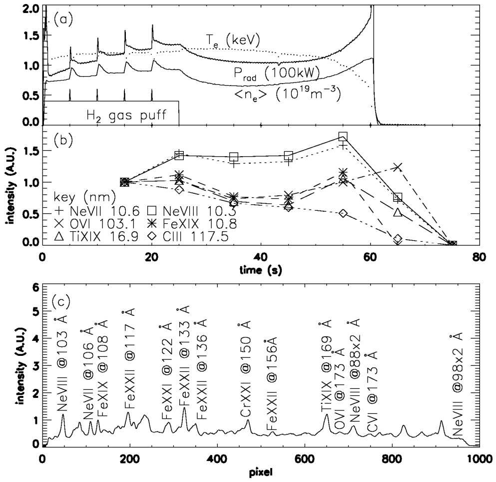

Fig. 5. Long-pulse discharge in LHD heated with NBI and terminated by radiative collapse showing: (a) time evolution of major parameters: line-averaged electron density from FIR interferometer, electron temperature from ECE and total radiated power from AXUVD with hydrogen gas puffing; (b) time evolution of selected spectral lines from the VUV spectrometer; and (c) impurity radiation spectra in the 10 ÿ 20 nm region from the VUV spectrometer just prior to the radiative collapse.

TABLE III
UNRESOLVED ISSUES FOR STEADY STATE FUSION REACTOR DIAGNOSTICS

Issue	Counter Measure
Heat removal	Water cooling plasma facing components (PFCs)
Erosion	Modular construction of PFC for easy replacement
Magnetic measurements	Multiplexing of integrator circuits
Real-time monitoring	Event triggering, C-PCI based system
Nuclear heating	Shielding, cooling of affected parts
Alpha particle measurement	Collective Thomson Scattering, TESPEL CXS

perform a 5-min ECH discharge with 100 kW of input power. In Fig. 5, the desorption effect during an NBI long-pulse experiment is shown with emphasis on the time evolution of the neon radiation [9]. In this plasma, the working gas was hydrogen, but neon plasma experiments had been done in the previous days.

IV. DISCUSSION CONCLUSION

In this paper, we have described the diagnostics in LHD in terms of their suitability for and benefits from long-pulse experiments. However, several topics related to diagnostics for a fusion reactor have not been mentioned and are listed in Table III; these include heat removal, shielding from neutrons, nuclear heating, and activation.

In the case of heat removal for diagnostics in LHD, most diagnostics are mounted on the large port flanges outside of the vacuum vessel. Since they are relatively far from the plasma the steady-state heat load from radiation is quite low ($< 1\ \mathrm{kW/m^2}$) and can be handled by the connection to the vacuum vessel. As a precautionary measure, diagnostics that are located inside the vacuum vessel and have components that might outgas at high temperature are water-cooled (e.g., SX diode arrays and AXUVD arrays). In a reactor environment, however, much more attention should be paid to heat removal as the heat loads would be much higher.

Another important issue is the coating of vacuum windows by dust and other deposited materials. Analysis of dust collected from LHD after the third campaign (in March of 2001) showed very small amounts of Fe-C composite dust spread throughout the machine [43]. In terms of coating of windows, shutters are used to prevent this from happening during glow discharge cleaning and wall conditioning. However, the large number of discharges during one campaign (up to 10 000) has lead to some loss of transmission in some windows. For instance the Thomson scattering system has a large vacuum window which is covered on the vacuum side by another window ($65 \times 40 \times 12$mm) which is replaced annually. The reduction in transmission on this window is typically less than 10%. Slight reductions in transmission have been observed in other windows in the visible range, but this effect is harder to estimate for the UV range.

Also in a reactor, the consequences of the high-energy neutrons must be considered. This would include neutron shielding of sensitive diagnostics, remote handling for maintenance of activated components, nuclear heating of diagnostics, etc. Since in LHD we will not use tritium fuel and the expected neutron fluxes from planned D–D experiments are much lower than expected in a reactor, this is not an important issue for LHD.

Other important and challenging issues for reactors are the diagnosis of fast neutron fluxes of the transport of fast alpha products. However, these reactor-related issues are difficult to address in a nonreactor environment.

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K. Toi, photograph and biography not available at the time of publication.

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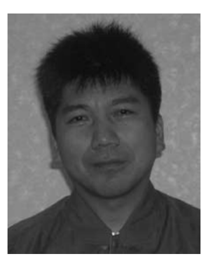

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S. Mutoh, photograph and biography not available at the time of publication.

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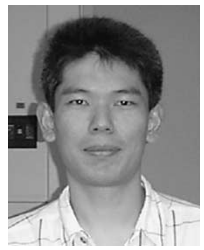

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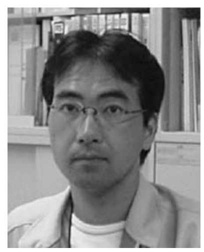

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