(5) Diagnostics Systems

For the precise measurement of plasma quantities in a three dimensional helical plasma, an extensive set of diagnostics have been developed with national and international collaborators, and are routinely operated in the Large Helical Device (LHD). The diagnostic system operating now consists of about 60 diagnostic instruments which are summarized in Table I. For the installation of various kinds of diagnostics instruments, large sized ports are equipped. The diameter of the largest horizontal ports is 2410 mm, which enables us to easily access the full plasma cross section with multi-channel viewing chords aligned parallel to one another. The key issues of diagnostics for LHD are: (a) the capability for multi-dimensional (2-D or 3-D) measurements to investigate non-axisymmetric helical plasmas; (b) cross-check of fundamental plasma parameters using different methods; (c) measurements of the electric field and plasma turbulence in the center of the plasma for understanding the classical and anomalous transport in a helical system; (d) advanced measurements appropriate for steady-state operation; and (e) an adequate data acquisition system to handle the large amounts of data expected for steady-state operation. Considering these key issues the design and R&D of the LHD diagnostics were carried out.

The YAG laser Thomson scattering (TS) system and the ECE system have proven as reliable diagnostics for the temporal evolution of the electron temperature profile. The YAG laser TS system works routinely to provide the electron temperature profile with a flexible repetition rate (from 5 ms to hundreds of ms). The LHD TS has an oblique backward scattering configuration, in which the typical scattering angle is 167 degrees. This unique configuration enables us to measure the electron temperature/density profiles from the boundary to the center of the LHD plasma. The system can measure the scattered light at 144 points along a major radius with the spatial resolution of 20 – 40 mm. In this scattering configuration, the TS spectrum width becomes wider than those in a conventional right angle scattering configuration. The measurable temperature range is 20 eV – 20 keV. The LHD TS has two kinds of YAG lasers, three 10Hz/2.3 J lasers and four 50 Hz/0.5 J lasers, and flexible multi-laser operations (2 J/50 Hz and 0.5 J/200 Hz) are possible. T_e more than 15 keV has been observed by the YAG TS in high temperature plasma experiments.

For the electron density measurements of the LHD plasma, three kinds of diagnostics have been used: a multi-channel far infrared (FIR) laser interferometer, a two color mm wave interferometer, and a CO_2 laser imaging interferometer. A 13-channel FIR laser interferometer has been routinely operated for the precise measurements of the electron density profile. The spatial and time resolutions are 90 mm and 1 μs, respectively. The overall accuracy of the system is about 1/100 of a fringe, corresponding to a minimum measurable line-averaged density of 5.6 x 10^{16} m^{-3} at the central chord. The FIR interferometer routinely provides a density profile almost every shot except in the case of high-density plasma by ice pellet injection. When the large sized pellet is injected to the plasma a steep density gradient is formed in the peripheral region of the plasma, which sometimes causes fringe jumps at the corresponding channels. To solve this problem, a 10.6-μm CO_2 laser imaging interferometer has been developed. The system is employed by using three slab-like beams (one 250 x 50 mm^2 and two 280 x 50 mm^2 beams) and detector arrays (liquid nitrogen cooled photoconductive type HgCdTe detectors) to measure the fine structures of the density profile and fluctuations. The total channel number is 81 with a chord spacing of 7.5 – 15 mm.

The plasma potential profile, or radial electric field distribution, is an important quantity in a helical system, because it is closely related to the plasma confinement characteristics of helical plasmas. For the direct measurement of the electrostatic potential, a heavy ion beam probe (HIBP) has been developed in LHD. Due to the large size of the plasma confined in the magnetic field of up to 3 T, a MeV-range beam of heavy ions is needed for the LHD-HIBP. The probing beam of gold is accelerated up to 6 MeV by means of a tandem accelerator. The error in potential measurement is estimated to be about 340 V, in which the main error sources are fluctuations of the acceleration and analyzer voltages, and electric noise of the amplifier. E_r measured by the HIBP agrees with that estimated by charge exchange spectroscopy.

For multi-dimensional measurements 2-D or 3-D imaging diagnostics are under intensive development with national and international collaborators. A 3-D ECE imaging (ECEI) system has been developed in collaboration with Kyushu University for the measurement of an electron temperature profile and its fluctuations. The ECEI system is composed of focusing optics installed inside the vacuum chamber of LHD and planar-type detectors fabricated by monolithic microwave integrated circuit technology. The detector consists of the integration of a bowtie antenna, a down-converting mixer using a Schottky barrier diode, and hetero-junction bipolar transistors on a GaAs substrate. The ECE signal and local oscillator beam are irradiated from both sides of the detector. The time evolution and the intensity of the ECE signals detected agree with those obtained by a conventional heterodyne receiver.

Table I List of Main Diagnostics of the LHD

DIAGNOSTICS	PURPOSE	BRIFF DESCRIPTION
Magnetic probes	I_p, plasma pressure, magnetic fluctuations	Rogowski, Mirnov, saddle coils
MM-wave interferometer	$n_e l$	2 mm-/1 mm-wave, single channel
FIR laser interfeometer	$n_e l$(r,t)	119-μm CH_3OH laser, 13 vertical chords channels with 90 mm spacing
CO_2 laser interferometer	$n_e l$(r,t)	81 vertical chords, 7.5 - 15 mm spacing
Microwave reflectometer	n_e profiles and fluctuations	Ultra-short pulsed-rader, Frequency hopping, and heterodyne reflectometer
Thomson scattering	T_e(r,t), n_e(r,t)	200 spatial points, 20 - 100 ms time resolution
ECE Fourier spsctroscopy	T_e(r,t) with scan time of	f = 60 ~ 600GHz, Δf ~ 4 GHz, scan time of 25 ms
ECE Radiometer	T_e(r,t) and fluctuations	High time (~μs) and spatial resolutions
X-ray PulseHeight Analysis	T_e(r,t), impurities	Si(Li) and Ge detectors
Neutral Particle Analyzer	T_i(t) and energy spectra fE)	Energy range: 0.8 - 167 keV, 40 ch, Δt ~ 0.1 ms
CXS	T_i(r,t) and plasma rotation Vp(r)	Combination of heating NBI and visible spectrometer
MSE	Rotational transform angle	Combination of heating NBI and visible spectrometer and CCD detector
X-ray Crystal Spectroscopy	T_i (0) and plasma rotation Vp	ArXXI, TiXXI, CrXXIII, FeXXV, Δt = 20 ms
Bolometers	P_{rad}(r,t)	Resistive metal film, infrared imaging bolometers, Extreme ultraviolet photodiode
VUV Spectroscopy	Highly ionized impurity line	2 - 130 nm (Δλ = 0.01 nm), 0.4 - 4 nm (0.001 nm)
Impurity monitor	Monitoring impurity behaviors	Hα, HeI, CIII, CIV, OV, OVI, FeXVI, Δt = 0.1 ms
Zeff	Radial profile of Z_{eff}	500-600 nm, Δt = 0.1 ~ 100 ms, Δr ~ 2 cm
Soft X-ray and AXUV array	Impurity ions and MHD activities	20 chs photodiode array, Δt < 200 kHz
Soft X-ray Camera	MHD oscillations	2D image of soft x-ray radiation, Δt ~ 50 μs
Plasma monitor camera	Plasma position and shape	Real time video signal
CO_2 Laser PCI	Micro-turbulence	6 x 8 = 48 two dimensional detector Δr ~1/3 (k = 0.1 ~ 1 mm^{-1}), 1/10 (k = 3 mm^{-1})
Diagnostic Pellet (TESPEL)	Impurity transport	TESPEL (Tracer-Encapsulated Solid Pellet)
Heavy Ion Beam Probe	Plasma potential and fluctuation	Au+ (6 MeV, 10 μA), Spatial and time tesolutions: 1 cm and 1 μs
Langmuir Probe	SOL plasma parameters 3D structure of the helical divertor	Fast scanning (1m/s) in the SOL Probe array on the divertor plate
Li beam probe	edge density and its fluctuation	20 keV, 70 μA, FWHM ~ 20 mm
Visible/Infrared TV	Plasma-Wall interaction	TV systems
Divertor interferometer	$n_e l$ of divertor leg	Density resolutions of 2.3 x $10^{16}m^{-3}$, Δt = 10 ms
Lost ion probe	Escaping fast ions	Scintillator-based lost ion probe
Natural Diamond Detector	Charge exchange fast neutral	E = 0.03 ~ 3 MeV, ΔE ~ 9 % (FWHM)

A data acquisition system with parallel processing technology has been developed for diagnostics with a 3 minute cycle and a steady-state plasma sustainment during LHD operation. Data of most diagnostics are taken by CAMAC digitizers, WE7000, and CompactPCI digitizers. The total number of digitizer modules and channels are about 300 and 2000, respectively. In the 13^{th} campagin in 2009, the maximum acquisition amount has increased up to 10.6 GB/shot, constantly having about 180 shots per day. In the 9^{th} campain the longest discharge duration of LHD was over one hour. The LHD data acquisition system had established the world record for the acquired data amount (~90 GB) in a single plasma discharge. For effective remote participation by domestic universities and institutes, LHD has a powerfull network realizing 1 Gbps streaming by introducing the Super SINET. This system enables remote participants to see the same images and to access their diagnostic data from their institutes like the researchers in the controle room of LHD.

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