Recent Diagnostic Developments on LHD

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Recent Photo of NIFS site: 470,000m²

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21 Contributions from LHD to 30th EPS Conf.

* Transport and Core Plasma Property
P-3.18 Structures on Electron Temperature Profiles of the Plasmas Confined in the Large Helical Device by K.Narihara et al.
P-2.160 Effect of Magnetic Field on Asymmetric Radiative Collapse in the Large Helical Device by N. Ashikawa et al.
P-4.67 Imaging Bolometer for a Burning Plasma Experiment by B.J. Peterson et al.

* Turbulence & Fluctuations
P-1.73 Imaging Interferometer for Plasma Density Profile and Microturbulence Study on LHD by A.L.Sanin et al.
P-3.11 Particle transports and related fluctuation on LHD by K.Tanaka et al.

* MHD
O-3.2A(P-2.230) Effect of L-H Transition on MHD Stability near the Plasma Edge in the Large Helical Device by K.Toi et al.
P-3.21 Sawtooth Oscillation in Current Carrying Helical Plasma in LHD by Y.Nagayama et al.
P-3.17 Interpretation of Low-Frequency and High-Frequency Alfven Instabilities in NBI Experiments on LHD by Y.I. Kolesnichenko et al.

*Heating
P-2.171 Achievement of a High Ion Temperature with Ne- and Ar-Seeded Discharges by High-Power NBI Heating in LHD by Y.Takeiri et al.
P-2.181 Analysis of ICRF Heating in LHD by Three-Dimensional Calculation by T.Seki et al.

* Fueling and Pellet
P-1.59 Fast spectroscopic measurements of the ablation clouds of Tracer-Encapsulated Solid Pellets injected into LHD plasmas by N.Tamura et al.
P-3.12 Repetitive Pellet Fueling on LHD by R.Sakamoto et al.
P-3.13 Observation of Plasma Response and Ion Temperature Increase after Impurity Pellet Injection in LHD by S.Morita et al.
P-3.14 Dynamics of pellet ablation cloud observed by a fast-framing tangentially viewing soft X-ray camera in LHD by S.Ohdachi et al.

* Edge and Divertor Plasma
P-3.20 Edge Density Profile Measurements on LHD with a Lithium Beam Probe by T.Morisaki et al.

* High Energy Particles
P-3.22 Horizontal and Vertical Distributions of High-Energy Particle on Large Helical Device by T.Ozaki et al.
P-3.23 Suprathermal Proton Distribution Function Measurements with a Multidirectional Charge Exchange Diagnostic on LHD by P.R.Goncharov et al.
Outline

• Introduction
• LHD Objective and Status
• Concept of LHD Diagnostics
• Diagnostics for
  • Fundamental Parameters
  • Imaging
  • Electric Field
  • Steady State Operation
• Edge and Divertor
• Innovative Diagnostics
• Summary
Objective of Large Helical Device

- Objective of LHD is to clarify physics of fusion relevant plasma in steady state.
- For this purpose, we are developing: Superconducting magnet, High power heating, Divertor, and Appropriate Diagnostics.

The LHD experiment started in the end of March 1998, and 6 experimental campaigns have been carried out since then.

Large Helical Device (LHD)

- Heliotron configuration with \( l=2/m=10 \) field period
- Major radius = 3.42 - 4.1 m
  Plasma radius = 0.6 m
  Plasma volume = 30 m³
  Toroidal field = 2.9 T

All Helical and Poloidal Coils are superconducting.

• LHD has better confinement than ISS95 scaling.
• Target temperatures have been achieved.
• High $\beta$ and long pulse are next targets.
Concept of LHD Diagnostics for 3-D Helical Plasma

- **Ability**
- **Reliability**
- **Flexibility**
- **Robustness**

**Subjects**
- Imaging (2D, 3D)
- Divertor & Edge Plasma
- Long Pulse
- Er, High Energy Particles, MHD

Overview of LHD Diagnostics

- Complete set of standard diagnostics for operation and physics study have been installed.
- Advanced diagnostics are being developed with collaboration.

VUV /Visible Spectroscopy
FIR/CO₂ Interferometer
SX Diode Array Reflectometer
MMW Imaging

VUV Spectroscopy
SX-PHA

Crystal Spectroscopy
1mm/2mm Interferometer

CCD Camera
Magnetics
SX Camera
Imaging
Bolometer
Diamond NPA
YAG
Thomson

HIBP
LID
ECH#2
ECH#1
ICH#2

N-NBI#3
N-NBI#2
N-NBI#1

H₂ Pellet

ICH#1

TESPEL/TECPEL

1. Reliable diagnostics for operation (TV, $n_e$, $I_p$, $W_p$, NBI interlock) and for fundamental plasma parameters ($T_e$, $T_i$, $n_e$).

• Plasma Operation (Feedback Control)
  – $n_e$: FIR Laser Interferometer
  – NBI Interlock: Reflectometer
  – $I_p$: Rogowskii Coil

(Unlike tokamaks, in LHD, plasma current is not needed. But, the bootstrap current and beam driven current appear to some extent.)

• Fundamental Plasma Diagnostics with Reliability and Flexibility
  – $T_e$: YAG Thomson, ECE (Michelson), SX-PHA
  – $T_i$: Crystal Spectroscopy, CXS, TOF-NPA
  – $n_e$: Interferometers (1&2mm microwave, FIR, CO$_2$+YAG Laser)
  – $W_p$, $\beta$: Diamagnetic Flux Loop
  – Data Acquisition: CAMAC, Object Oriented Database
Electron Temperature Diagnostics

- Time evolution of $T_e$ profile is measured with 3 systems.
- ECE is useful also for MHD diagnostics.
- SX-PHA is useful also for impurity measurement.

![Diagrams showing electron temperature diagnostics systems including ECE, SX-PHA, Notch Filters, Polarization Rotator, Michelson, GPC (14ch), 70GHz Radiometer (32ch), 132GHz Radiometer (32ch), 4 Si(Li) Detectors, Scanning System, 200 Channels, Filter Bank, YAG Thomson, YAG, YAG, YAG, YAG, Mirror.](image)
YAG Laser Thomson Scattering

- LHD Thomson uses an obliquely back-scattering configuration.
- Large mirror made of 100 modules condenses scattered light ($\Delta W > 10\text{msr}$).
- 144 radial points are measured every 0.1-0.01 sec (15mm $< \Delta x < 30\text{mm}$).
- YAG Thomson system works routinely with little trouble in LHD.

YAG Laser: 2J/pulse, 10pulse/sec

Before $H_2$ pellet injection

0.14 sec after pellet injection

K. Narihara, I. Yamada
Te and ne profiles by YAG Thomson

#33621 B = 2.8 T

Multiple-pellet injection

Te

ne

300µs

100ms

Flexibility!

K. Narihara, I. Yamada
• By focusing ECH at the plasma center, high $T_e$ plasma is obtained.
• $T_e$ measured with Thomson, ECE and SX are consistent.
• High $T_e$ plasma is accompanied with ITB in LHD.

Cross check \downarrow Reliability!


S. Kubo, K. Narihara, Y. Nagayama, K. Ida
Ion Temperature Diagnostics

- Central ion temperature is measured by the crystal spectrometer.
- Profiles of $T_i$ and the electric field are measured with CXS.
- $T_i$ and fast ion spectra are measured with NPA.

Crystal Spectroscopy

- Central ion temperature is measured by the crystal spectrometer.
- Profiles of $T_i$ and the electric field are measured with CXS.
- $T_i$ and fast ion spectra are measured with NPA.
Diagnostics of Fast Particles

• Fast neutral particles escaped from LHD plasma are detected by
  – **Time Of Flight Neutral Particle Analyzer**
  – **Natural Diamond Detectors**
  – **Silicon Diode Neutral Particle Analyzer**

• **TOF-NPA** is useful for detecting low energy particles.

• **NDD and SD-NPA** are compact and are useful for detecting high energy particle.

• **NDD** measurements reveal that ICH generates fast ions and confinement of fast ions is classical.

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*T. Ozaki, P. Goncharov, J. Lyon*

*T. Saida, M. Isobe, A.V. Krasilnikov, M. Sasao*
Electron Density Diagnostics

- For $n_e$ measurement, mm-wave (MMW) interferometer, FIR laser interferometer, 2-color CO$_2$ laser interferometer and polarimeter have been developed in LHD.

By FIR Laser Interferometer

S. Iio, K. Kawahata, T. Akiyama, K. Tanaka, T. Tokuzawa

A 2-color (CO₂+SH-YAG) laser interferometer has been installed on the structure of the FIR laser interferometer in LHD.

Even when phase jumps occur in the FIR interferometer (cf. H₂ pellets injection), phase jumps never occur in the CO₂ interferometer.


K. Tanaka, A. Sanin, T. Akiyama, L.N. Vyacheslavov
Impurity Diagnostics

Impurity species are monitored with many spectrometers. Radiation profile is monitored with bolometry. Impurity transport is investigated with tracer pellet injection.

**Impurity Monitor Station**
S. Morita, M. Goto

**SOX MOS**
K. Sato, T. Kobuchi

**Bolometer Arrays**
Imaging bolometry using gold foil & IR camera
B.J. Peterson

**Tracer material**
~100 µm

**TECPEL & TESPEL**
S. Sudo, N. Tamura
2. Imaging Diagnostics

- Imaging diagnostics with Soft X-ray, visible spectroscopy, Imaging bolometer camera, ECE and reflectometer are being developed.

3 Imaging bolometer cameras on LHD
Well suited to steady state operation:
(a) no electrical drift
(b) thermal drift automatically compensated

Advantages for reactor:
- Imaging provides hundreds of channels
- no electrical feedthroughs
- radiation hard

See Posters
P- 2.160, P- 4.67
B. Peterson, N. Ashikawa

Top View
Tangential View
Gold foil
Thickness: 1µm
Tomographic Measurement of Static Magnetic Island Using Tangential SX-CCD Camera

- Tomography of the static (2,1) magnetic island is obtained from the data of a tangential SX-CCD camera.

Fourier-Bessel expansion method

\[ g(\rho, \theta, \phi) = \sum_{l=0}^{L} a_{0,0}^{l} J_{0}(\lambda_{0}^{l+1} \rho) + (a_{2,1}^{l} \cos(2\theta - \phi)) + (b_{2,1}^{l} \sin(2\theta - \phi))J_{2}(\lambda_{2}^{l+1} \rho) \]

(m,n)=(2,1) component

\[ I_{ij}^{c} = \int_{P_{\text{pinhole}}}^{P_{\text{wall}}} g(\rho, \theta, \phi) ds \]

2D $T_e$ measurement using X-ray CCD

- By using photon counting with a X-ray CCD, the 2-D $T_e$ profile can be measured.
- Comparison is done for the plasmas with and without ITB in LHD.


Y. Liang, K. Ida
• SX image is tangentially measured by fast TV camera (4,500 frames/sec) coupled with the image intensifier.
• **Singular Value Decomposition** technique is used to extract the rotating $m = 2$ structure with constructing from three components ($U2-U4$).
3. Electric Field Diagnostics

- Radial electric field is a key to understand a helical plasma and especially ITB, and it is measured by CXS.
- Radial electric field has a reversed gradient at the ITB, which is generated by the ECH in LHD.
- Clear transition from L to ITB is observed.
- The $\chi_e$ is reduced to 1/30 of L-mode after the ITB transition.

![Graph showing electric field and temperature profiles](image)

\[ T_e \]

\[ E_r \]

\[ Q_{\text{cond+conv}}/n_e (\text{keVms}^{-1}) \]

\[ dT_e/dr (\text{keV}m^{-1}) \]

Fast CXS has been developed to study phase transition of ITB in LHD.
• Time resolution of poloidal rotation velocity was improved from 500ms to 100 ms.
• High throughput spectrometer
  – Large diameter camera Lens - F/2.8 (Traditionally F/5.6)
  – Back illuminated CCD Camera - Quantum Efficiency 80% (Traditionally 25 %)

Time evolution of poloidal rotation velocity and line averaged electron density.

The 6MeV HIBP accelerator operation has been officially approved! → HIBP testing.


M. Yoshinuma, K. Ida
4. Long Pulse Plasma Operation

- Long pulse plasma (150 s) is sustained by ICH.
  - \( n_e \sim 0.6 \times 10^{19} \text{ m}^{-3} \)
  - \( T_e \sim T_i \sim 2 \text{ keV} \)

- Gradual increase of \( n_e, H_\alpha, P_{\text{rad}} \) after 100s due to wall temperature increase.

The basic diagnostics are working well also for the long pulse operation.
Observation of recycling effect with SOX-MOS

- SOX-MOS spectrometer indicates that Ne and O gas comes out from the wall and causes radiation collapse. This experiment was done after the heavy neon glow discharge cleaning.
- The desorption of the gas, which is adsorbed on the walls, occurs in the late phase of the plasma discharge.
Polarimetry for $n_e$ in steady state operation

The Faraday rotation angle $\alpha$ is detected as the phase difference between reference and probing signals, and this system is free from fringe miscount.

Polarimetry with CO$_2$ laser is reliable, and refraction is small.

$$\alpha = \frac{e^3 \lambda^2}{8\pi^2 \varepsilon_0 m_e^2 c^3} \int_0^L n_e B_{\parallel} \, dz$$
Magnetics for Steady State Plasma

- New-type integrator using three operational amplifiers has been developed for steady state operations.
- The integrator avoids saturation of integrated signal linearity of thermal drift in short-time integration.

Integrated signals are transferred to VME system with DEC Alpha computer.

This system has been constructed, and its function will be verified soon.


S. Sakakibara
Data Acquisition and Storage/Retrieval

- Basic Data of steady state plasma are displayed in real time.
- Acquired data are increasing and data of 15TB have been stored.
- Big raw data are successfully managed using object oriented data base.
- Analyzed data are served by LINUX servers. 740 MB/shot, 150 shots/day
5. Diagnostics for Edge and Divertor Plasmas

- Peak positions of ion saturation current profile agree well with those of field line connection length profile.

\[ \text{Peak positions of ion saturation current profile agree well with those of field line connection length profile.} \]

\[ \text{Last Closed Flux Surface} \]

\[ \text{Fast Scanning Probe} \]

\[ \text{Stroke: 0.6 m, } V_{\text{scan}} = 3 \text{ m/s} \]

\[ \text{Helical Diverter} \]

\[ \text{Divertor legs} \]

\[ \text{Z=0} \]

\[ \text{A} \]

\[ \text{B} \]

\[ \text{Fast Scanning Probe} \]

\[ \text{Divertor legs} \]

\[ \text{A} \]

\[ \text{B} \]

\[ \text{Z=0} \]
Local measurement of neutral flux using Zeeman effect

- Locations of neutral emission are determined using Zeeman effect, since the magnetic field is different at different positions on the same line of sight. It is also confirmed that the line emission is localized.
- Emission comes from the divertor surface as confirmed by H\(\alpha\) TV image.

\[ R_{ax} = 3.5 \text{m} \]

\[ \text{H plasma} \]
\[ \text{H\(\alpha\)} \]
\[ \text{CCD TV camera} \]

\[ \text{Field line tracing} \]

\[ \text{He plasma} \]

\[ \text{X point} \]
\[ \text{Diverter leg} \]

\[ \text{Local emissivity of He line.} \]
Measurement of edge $n_e$ by Lithium Beam Probe

- 30 keV Li beam probe has been developed for the edge $n_e$ profile measurement.

- From the beam emission profile, $n_e$ profile is reconstructed.

- Differences in boundary and in $n_e$ gradient have been observed, suggesting the difference of the edge transport between different magnetic configurations ($R_{ax}=3.5m$ and 3.6m).

$T_e \approx 0.6 \text{keV}$

$n_e \approx 3 \times 10^{19} \text{m}^{-3}$


T. Morisaki
Pulse radar reflectometer for $n_e$ profile & fluctuation at the edge

- Pulsed radar reflectometer is useful to measure the $n_e$ profile and fluctuation in the edge region.

4 ch
(33,39,60, 65 GHz) heterodyne pulse radar system in LHD

Reflected 39GHz
33GHz
60GHz

Pulse width: 2 ns
Repetition rate: 200kHz
Resolution: 50ps (7.5mm)

T. Tokuzawa, A. Ejiri
6. Innovative Diagnostics through international collaboration

Tracer-Encapsulated Solid Pellet (TESPEL)

Developed for advanced particle transport study. Tracer particles, such as Li, Ti, can be deposited locally inside the plasma.


Spectra of Light Emissions from TESPEL Ablated Cloud
With Fast CCD + Spectrometer

Electron Density in Pellet Cloud!

Stark Broadening of Hβ

New Way to Atomic Data!

Experimental $D$ is larger than the neoclassical ones. This discrepancy is reduced in the higher density case.
Owing to the flexibility of the size and material, TESPEL injection makes appropriately a sudden drop in the electron temperature in the plasma ($\theta \sim 0.5-0.7$), the temperature drop (cold pulse) propagates across the flux surfaces. The $T_e(r, t)$ profile is measured every $5 \mu s$ with the 32ch radiometer (cross-calibrated with the Michelson interferometer) covering $R_{ax} = 2.9-3.5 \text{ m.}$

![Graph showing cold pulse propagation](image)

**Basic Equations**

$$\frac{3}{2} n_c \frac{\partial}{\partial t} \delta T_e = \nabla \cdot \left( n_c \kappa_{\text{tr}} \nabla \delta T_e - \frac{3}{2} n_c V_{\text{tr}} \delta T_c \right)$$

The transport equation for the perturbation is solved numerically and compared with the experimental data to obtain heat conduction coefficient $\theta_e.$
• TESPEL cold pulse technique is used to analyze the heat transport in the ITB region.
• Transport changes significantly at the barrier ($\delta \sim 0.3$).
• Reduced $\chi$ and Heat pinch are observed.
Cold pulse propagation in magnetic island induced by TESPEL

- When TESPEL is injected at X-point, not much direct interference in the magnetic island. The cold pulse in the core region propagates fast, but inside of the magnetic island the cold pulse propagates very slowly. Thus, the low heat conductivity of \( \chi_e = 0.2 \text{m}^2/\text{s} \) was obtained, while \( \chi_e = 2 \text{m}^2/\text{s} \) in the core plasma.

- \( R \) is the major radius and the last closed magnetic surface is at \( R - R_{ax} = -0.7 \text{ m} \).

- The ECE receiving antenna is mounted in the inboard side of LHD.
TECPEL (Tracer-encapsulated Cryogenic Pellet)

Carbon 230 µmφ as a tracer

TECPEL-1
Patents: S. Sudo (1996) in:
Japanese Patent No. 2113888
USA Patent No. 54887094
EPC Patent No. 647087

Solid Hydrogen 3 mmφ


Real-Time TECPEL Production Process

TECPEL: Tracer-encapsulated Cryogenic Pellet

T= 8K Solid H₂  SUS Ball 200μmφ

TECPEL in Flight

With gas gun utilizing high pressure helium gas (~30 atm.), TECPEL is ejected, and the photo of TECPEL in flight is taken. This shows also the remaining Tracer.

Summary

- Standard diagnostics for fundamental plasma parameters ($T_i$, $T_e$, $n_e$) and for plasma physics are routinely utilized for daily operation and physics studies in LHD with high reliability and flexibility.

- Diagnostics for steady state plasma are developed including a data acquisition system for handling large amount of data.

- 2-D or 3-D diagnostics are intensively developed:
  - Tomography (Tangential SX CCD, Bolometer)
  - Imaging (Bolometer, ECE, Reflectometer)

- Diagnostics for edge physics, needed for steady state operation, are developed and installed in LHD.

- Advanced diagnostics are also being developed in LHD through domestic and international collaborations.

New proposals for collaboration at LHD are welcome!