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Electron Density Profile Measurements on LHD

K. Kawahata, K. Tanaka, T. Tokuzawa, Y. Ito, T. Akiyama, A. Sanin, S. Okajima, S. Tsuji-Iio, L. Vyacheslavov, and the LHD Group

Abstract—Several kinds of density diagnostics have been developed and routinely operated to provide density profile information on the large helical device. A 13-channel far-infrared laser interferometer and a two-color millimeter-wave interferometer are used for monitoring the density profile. A CO₂ laser imaging interferometer has been developed for detailed profiled measurements of density and density fluctuations. A CO₂ laser densitometer measuring the Faraday rotation was developed for the long-pulse operations of large helical device. Details of each diagnostics and sample results are presented.

Index Terms—Helical plasma, interferometer, plasma, plasma diagnostics, polarimeter.

I. INTRODUCTION

THE large helical device (LHD) experiments have successfully started [1], [2] after the eight years of construction period (1990–1997). The major and minor radii of the plasma are 3.6–3.9 and 0.6–0.65 m, respectively. The magnetic field up to 3 T is generated by a pair of superconducting helical winding of pitch parameters of $m/l = 2/10$ and three sets of superconducting poloidal coils. The plasma is generated by electron-cyclotron resonance heating (ECRH) of 84 and 82.6 GHz, and heated up by NBI and ion-cyclotron range of frequency (ICRF). The plasma parameters obtained to date are: the electron/ion temperature of 1.0–10/7.0 keV, the line-averaged electron density of $< 1.5 \times 10^{20} \text{ m}^{-3}$, and the maximum stored energy of 1.2 MJ.

For the electron density measurements of the LHD plasma, several kinds of diagnostics have been used: a multichannel far-infrared (FIR) laser interferometer [3], a two-color millimeter-wave interferometer [4], a CO₂ laser imaging interferometer [5], a three-channel tangential CO₂ laser polarimeter [6], and a YAG Thomson scattering [7]. In this paper, the density diagnostics based on refractive-index measurements are described. A 13-channel FIR laser interferometer has been routinely operated for the precise measurements of the electron density profile. The optical configuration is of the Michelson interferometer type with a heterodyne detection system. This interferometer routinely provides 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 the fringe jumps at the corresponding channels. In order to solve this problem, a CO₂ laser imaging interferometer has been developed. The imaging system is employed by using three slab-like beams and multichannel detector arrays to measure the fine structures of the density profile and fluctuations. For the long-pulse operation of LHD, a three-channel CO₂ laser polarimeter was developed since polarimetry is free from fringe jump errors from which interferometers often suffer, and does not need the time history. The specifications of each density diagnostic are summarized in Table I.

II. ELECTRON DENSITY DIAGNOSTICS

A. FIR Laser Interferometer

A 13-channel FIR laser interferometer has been routinely operated for the precise measurements of the electron density profile. The optical configuration is of the Michelson interferometer type with a heterodyne detection system. The light source is a highly stable twin 118.8- μm CH₃OH laser pumped by a cw CO₂ laser [8]. 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-integrated density of $1.9 \times 10^{17} \text{ m}^{-2}$. This interferometer routinely provides density profile almost every shot except in the case of high-density plasma produced by ice pellet injection.

Fig. 1 shows a schematic drawing of the interferometer system. The FIR lasers are installed in the laser room 30 m away from the LHD, and the laser beams propagate about 40 m through a couple of the dielectric waveguides to reach the optical bench of the interferometer. The optical housing, where 150 optical components are installed, is mounted on a massive frame. The frame encircles the plasma vacuum vessel and floats on three pneumatic vibration isolation mounts. This isolation stand is 18.4 m tall and weights about 30 tons. The diameter of the three main supports is 712 mm. The upper shelf of the stand supports 13 corner cube reflectors, which are located immediately above the vacuum windows, while the interferometer housing ($3900 \times 1500 \times 4500 \text{ mm}^3$) is supported by the lower shelf which is located below the floor of the LHD. The optical housing is airtight and filled with dry air in order to reduce absorption of the CH₃OH laser radiation by atmospheric water vapor. Flexible airtight ducts are used between the optical housing and LHD.

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K. Kawahata, K. Tanaka, T. Tokuzawa, Y. Ito, T. Akiyama, and A. Sanin are with the National Institute for Fusion Science, Oroshi-cho, Toki 509-5292, Japan (e-mail: kawahata@nifs.ac.jp).

S. Okajima is with Chubu University, Kasugai 487-8501, Japan.

S. Tsuji-Iio is with the Tokyo Institute for Technology, Tokyo 152-8550, Japan.

L. Vyacheslavov is with the Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia.

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TABLE I
SPECIFICATIONS OF LHD DENSITY DIAGNOSTICS

Diagnostics	Sources	Specifications	Operational Strengths/Weaknesses
FIR Laser Interferometer	118.8 μm CH ₃ OH Laser	13 channel vertical chords with the spatial resolution of 90 mm Michelson interferometer type with a 1 MHz heterodyne detection Visible laser interferometer is equipped for vibration compensation	Routine density profile measurements High resolution measurement Fringe jump errors at high density plasma
MM Wave Interferometer	Gunn Oscillator	140/285 GHz two color interferometer Quasi-optical (QO) circuits using Gaussian beam-mode analysis	Easy to construct and operate Limited by the cut-off density
IR Laser Interferometer	10.6 μm CO ₂ Laser	Imaging interferometer using three slab-like beams Precise profile measurement without beam bending effects	Applicable to high density plasma Need vibration compensation
IR Laser Polarimeter	10.6 μm CO ₂ Laser	Three channel tangential polarimeter Density profile measurement for long pulse discharges	No need time history of signal Small rotation angle

Fig. 1. Schematic of the interferometer system installed on the pneumatic vibration isolation stand. The observed vibration level is about $1 \mu\text{m}$ with the typical frequency of 0.1 Hz.

One of the main objectives of the LHD project is to demonstrate currentless and disruption-free steady-state plasmas with high performance. Fig. 2(a) shows the time behavior of the line integrated densities of a long pulse discharge sustained by the NBI injection for 80 s. The injection energy and power of the beam are 100 keV and 0.5 MW, respectively. The line-averaged density is kept constant ($1.3 \times 10^{19} \text{ m}^{-3}$) by a gas puff system with a feedback loop using the central FIR chord signal as a feedback signal for the first 6 s, and subsequently controlled manually by watching the plasma light on a TV monitor. The density oscillation with the long period of 40 s is caused by the manual control of a gas puffing, and the density was maintained at $(1.5\text{--}2) \times 10^{19} \text{ m}^{-3}$. The wall pumping effect continues during the shot and enables the density control with the gas puffing for 80 s. Fig. 2(b) shows the time evolution of the density profile obtained by Abel inversion of the data in Fig. 2(a). The measured density profile is relatively uniform at the constant density phase and has steep gradient near the edge of the plasma.

B. Two-Color Millimeter-Wave Interferometer

A two-color millimeter-wave interferometer has been developed for the measurement of line integral electron density. To

Fig. 2. (a) Temporal behavior of line integrated densities obtained in a long pulse discharge sustained by the NBI. (b) Time behavior of the electron density profile.

reduce the refractive effects caused by the density gradient, the interferometer chord is located on the horizontal mid plane. In order to ensure good discrimination between phase changes due to the mechanical effects and those due to the plasma, we have used a wider range of two colors at 140 and 285 GHz. For combining two different frequency sources and reducing the internal losses of the standard waveguide components in high-frequency region, we have applied a low-loss quasi-optical (QO) circuit, as is shown in Fig. 3, where Gaussian beam-mode analysis was used to design the optics. The dynamic range of the QO system was measured to be more than 70 dB. The total loss in the transmission line including plasma losses is expected to be less than

Fig. 3. Photograph of the transmit side of the QO system. The main components constituting the QO system are Gunn oscillators at the frequencies of 140 and 285 GHz, Martin-Pupplet diplexer (M.P.D.), wire grids, and off-axis ellipsoidal mirrors.

40 dB. The difference between signal and local oscillators (LOs) at both 140 and 285 GHz is accurately fixed at 1 GHz and the heterodyne beat signals are down converted into 1-MHz IF signals, and finally fed to the fringe counters [9].

All of the components making up the two-color interferometer, except the transmission line, are attached on both sides of an aluminum plate (1700 × 1500 mm, 25 mm in thickness). Phase-locked solid-state sources generate Gaussian beams with the power of 20 and 12 mW for 140 and 285 GHz, respectively. These are overlaid in a Martin-Pupplet diplexer (M.P.D.) with a common polarization and fed into an HE11 corrugated waveguide which transports the copolarized beams to antennas, which in turn pass the wave across the plasma and back to the receiving side of the instrument. Adjustment of the M.P.D. path length will allow the polarization to be horizontal or vertical. A grid and dump on the LHD side of both the transmit and receive sides within the quasi-optics are used to insure that the polarizations are correct on both sides. Mechanical movements and changes in electron density in the plasma alter the effective path length traversed by the probing beams and, therefore, their phase. When the signal returns to the instrument a second M.P.D., which is attached on the receiver side, separates the beams into their two frequencies and passes them to mixers. The frequencies of phase-locked LOs are 139 and 284 GHz, which are exactly 1 GHz away from their probing frequencies. Using mixers, microwaves are down converted to 1-GHz beat signals with original phase information. By comparing the phase at both frequencies, both the mechanical movements and line electron density can be deconvolved.

Fig. 4 shows typical time behaviors of electron density measured by the 140 and 285-GHz interferometer on LHD, comparing with that by the FIR interferometer. The line density measured by the two frequencies agrees within the error of 2%, and is well consistent with that measured along the vertical chord with the FIR interferometer. Time resolution of the present measurement is 90 kHz, which comes from that of the fringe counter. Since the magnetic fields of the LHD are created by steady-state

Fig. 4. Time behavior of the line electron density measured by the two-color interferometer.

superconducting coils, there is no fringe shift induced by the change of the magnetic field, which is usually observed in the normal conducting devices [10]. The observed phase noise level is within the resolution of the phase detectors in the case of short pulse plasma. In a long period, the drift of the phase with 1/15 fringes/hr is observed in the trace of the 140-GHz interferometer, which corresponds to the path length change of 0.14 mm/h.

C. CO₂ Laser Imaging Interferometer

A CO₂ laser imaging interferometer has been developed for electron density profile and density fluctuation measurements in addition to the FIR laser interferometer. The purposes of this diagnostic are reliable electron density monitor in high-density operation of the plasma (especially in pellet injection plasmas), precise measurement of electron density profiles near the edge of the plasma, and observations of density fluctuations. When the large-sized pellet is injected into the plasma, a steep density gradient is formed in the peripheral region of the plasma, which sometimes causes the fringe jumps on the density traces measured by the FIR laser interferometer. In order to solve this problem, a CO₂ laser imaging interferometer has been developed. The imaging system is employed by using three slab-like beams and multichannel detector arrays to measure fine structure of the density profile.

Fig. 5 shows the schematic view of optical setup of the CO₂ laser imaging interferometer installed on LHD. This interferometer is of the Mach-Zehnder type to avoid the distortion of the image by diffraction. The wavelength is 10.6 μm and the probing beams are slab-like and are the size of 250 × 50 mm (probing beam 1) and 280 × 50 mm (probing beam 2 and 3). Three slab-like beams cover almost the whole cross section of a LHD plasma. One of the problems of a CO₂ laser interferometer is a large phase shift caused by mechanical vibrations due to the short wavelength. To overcome this problem all optical components are placed on the vibration isolation bench that is used for FIR laser interferometer, and coaxial YAG laser (wavelength of 1.06 μm) interferometer is set up as a second color interferometer. CO₂ and YAG laser beams are combined

Fig. 5. Schematic of the optical setup of the CO₂ laser imaging interferometer on the LHD.

Fig. 6. Time behavior of line integrated densities measured with the CO₂ laser interferometer on a multipellets injected discharge.

after passing through acousto-optic modulators (AOMs) for frequency shift with the difference of 1 MHz between probing and local beams. The probing beams are expanded with use of a couple of parabolic mirrors and injected into LHD plasma vertically. The edge part of probing beam 1 that views outside of plasma is used as a reference chord. On the detection bench, a LHD plasma is imaged on a 10- or 32-channel photoconductive HgCdTe (MCT) detection array for CO₂ laser radiation and on optical fiber array connected to avalanche photodiodes (APDs) for YAG laser radiation.

The first measurement was made by using probe beam 1 which passes through the plasma edge and a 10-channel detector array. The chord separation is 16 mm, improving the spatial resolution by a factor of 5 in comparison with that of the FIR interferometer. Fig. 6 shows phase distribution measured with a CO₂ laser interferometer, which shows no fringe jumps on the density traces even after large-sized pellet injections at the time of $t = 1.1$ and 1.5 s. Fig. 7(a) shows the comparison of time evolutions of line density measured with the CO₂ laser interferometer to that with the FIR laser interferometer. The waveforms of the CO₂ laser interferometer are similar to that of the FIR laser interferometer. The density profile estimated with use of slice and stack method is shown in Fig. 7(b). The profile is almost consistent with that from the FIR interferometer, while the fine structure around $\rho \sim 0.9$ is observed. YAG laser

Fig. 7. (a) Comparison of line integrated densities and (b) density profile slice and stack method from the CO₂ interferometer with those from the FIR laser interferometer. Open and closed circles indicate the measurement positions.

interferometer, however, was not operated on this discharge that it is necessary to reduce the effect of mechanical vibration and confirm whether the structure is real or not.

D. CO₂ Laser Polarimeter

A CO₂ laser polarimeter with three tangential chords developed [11] for the measurement of electron density files on LHD. A CO₂ laser whose wavelength is $10.6 \mu\text{m}$ is selected to avoid effects of the refraction. The Faraday rotation angle along toroidally tangential chords is of order α . The polarimeter utilizes the frequency-shifted heterodyne detection techniques, which was proposed by Dodel and [12], with the use of acousto-optic modulators. The accuracy resolution of the Faraday rotation angle is 0.01° with a response time of 3 ms by digital complex demodulation combined with digital filtering. In order to utilize the multichannel tangential polarimeter, three retroreflectors were directly attached on the first wall of the LHD vacuum vessel as is shown in Fig. 8. The retroreflectors are made of nonmagnetized stainless steel with mirror surface coated with gold. The effective aperture of the reflector is 70 mm and the realized parallelism accuracy is less than 0.5 mrad .

Fig. 9 shows one example of the Faraday rotation angle of a high-density plasma achieved by the ice pellet injection. The ratio of rotation angle of ch1 to that of ch3 is shown in Fig. 9. The broken and dotted lines indicate the ratios in the cases of parabolic and flat shape, respectively. After

Fig. 8. Photograph of retroreflectors installed in the LHD vacuum chamber. The reflector is located at the outward side mid plane.

Fig. 9. (a) Faraday rotation angle. (b) Ratio of rotation angle of ch1 to that of ch3. Broken and dotted lines indicate the ratio when density profile shape is parabolic and flat, respectively.

injection of the first pellet, the measured ratio became smaller than that in flat density profile shape and then the ratio increased gradually. This exhibits that the profile became hollow due to ablation of the pellet in a periphery region of the plasma and then the electron moved to plasma center. On the contrary, the ratio jumped up to that in parabolic profile after the second pellet injection. This is explained as follows: accompanied with the first pellet injection, the electron temperature lowered and then the second pellet was easily penetrated deeply into the plasma. Therefore, the density profile became peaked. The third and fourth pellets ablated in the peripheral region since their size is small, and then the density profile changed to the peaked one gradually. As is shown above, the tangential polarimeter could observe the time behavior of the density profile after pellet injections. Fig. 10 shows the electron density profile after the pellet injection estimated from the polarimeter data, comparing with the FIR data. Here, we used the β value, which affects the rotation angle, from diamagnetic measurement and calculated iteratively assuming the profile is parameterized as

$$n_e(\rho) = a(\rho^2 - \rho_{BC}^2) + b(\rho^3 - \rho_{BC}^3)$$

where ρ is the normalized magnetic flux radius and ρ_{BC} is the plasma boundary radius. The error of the profile is considerably

Fig. 10. Density profile estimated from the polarimeter in comparison with that from the FIR interferometer.

small because the rotation angle at the time of Fig. 10 is much larger than fluctuations of the base line, while in the case of a low-density plasma, an error caused by fluctuation cannot be neglected. The profile estimated from the polarimeter is almost consistent with the FIR interferometer data. This result substantiates that the CO₂ laser tangential polarimeter has the feasibility of the electron density profile measurement.

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K. Kawahata received the Ph.D. degree in physics from Nagoya University, Nagoya, Japan, in 1976.

After receiving the Ph.D. degree, he joined the research staff at the Institute of Plasma Physics, Nagoya University, specializing in millimeter/sub-millimeter-wave diagnostics for magnetic fusion plasmas. Since 1989, he has been with the Large Helical Device Project, National Institute for Fusion Science, Toki, Japan. His current research interests include the experimental physics of the large helical device and the development of millimeter/submillimeter-wave diagnostics in fusion experiments.

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K. Tanaka received the Ph.D. degree in the study of microturbulence using laser phase contrast interferometer on Helicorn E from Kyushu University, Fukuoka, Japan, in 1995.

He is with the diagnostic division of the National Institute for Fusion Science, Toki, Japan, since 1993. He developed and constructed far infrared interferometer, polarimeter and reflectometer to measure electron density, internal magnetic field and electron density fluctuation in CHS and LHD. He is currently studying particle transports and role of microturbulence on it by using far-infrared and infrared interferometer.

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T. Tokuzawa received the Ph.D. degree from University of Tsukuba, Tsukuba, Japan, in 1998.

Since 1998, he has been with the Large Helical Device Project, National Institute for Fusion Science, Toki, Japan, where he is currently investigating electron density profile and fluctuation measurement using the electromagnetic wave.

Y. Ito graduated from Nagoya Kougakuin Industrial Special School, Nagoya, Japan, in 1988.

In 1988, he joined the Technical Staff at the Plasma Research Center, Tsukuba University, Tsukuba, Japan. Since 1995, he has been with the Department of Engineering and Technical Services, National Institute for Fusion Science, Toki, Japan.

T. Akiyama received the D.Eng. degree from the Tokyo Institute Technology, Tokyo, Japan, in 2003.

After receiving the D.Eng. degree, he joined the Research Staff at the National Institute for Fusion Science, Toki, Japan, specializing in IR/FIR laser diagnostic for magnetic fusion plasmas. Since 2003, he has been with the Compact Helical System and the development of IR/FIR laser diagnostics needed to investigate plasma characteristics in fusion experiments.

A. Sanin received the Ph.D. degree in physics from Budker Institute of Nuclear Physics, Novosibirsk, Russia, in 1997.

His research was focused on the study of strong Langmuir turbulence excited by relativistic electron beam in a plasma. He specialized in measurements of plasma parameters and plasma fluctuations by optical diagnostics. During 2002–2003, he was with the National Institute for Fusion Science, Toki, Japan, as a Research Fellow. His work is concentrated on construction of imaging interferometer for plasma density profile and microturbulence study on LHD.

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S. Okajima was born in Nara, Japan, on June 2, 1942. He received the B.S. degree in applied physics from Tokyo University of Science, Tokyo, Japan, in 1967 and the M.S. and D.Eng. degrees in applied physics from Osaka-City University, Osaka, Japan, in 1970 and 1991, respectively.

Since 1977, he has been with the College of Engineering, Chubu University, Aichi, Japan, where he has been working in the field of physics education. His current research interests include the development of far-infrared molecular lasers and the applications, especially for high-density plasma diagnostics.

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S. Tsuji-Iio received the D.Sc. degree in physics from the University of Tokyo, Tokyo, Japan, in 1983.

In 1983, he joined the Research Staff at the Japan Atomic Energy Research Institute, Naka, Japan, specializing in plasma confinement and divertor physics in tokamaks. Since 1995, he has been at Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology, Tokyo, Japan. His current research interests include the development of plasma diagnostics for long pulsed magnetic fusion devices, the burn control of fusion reactors, and the efficient utilization of renewable energy.

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L. Vyacheslavov graduated from the Novosibirsk State University, Novosibirsk, U.S.S.R. (now Russia), in 1966. He received the Ph.D. degree in physics and the Doctor of Science degree from the Budker Institute of Nuclear Physics (BINP), Novosibirsk, in 1984 and 2000, respectively.

In 1966, he joined the Research Staff in the Fusion Department, BINP, specializing in optical and laser diagnostics for magnetic fusion plasmas. His current research interests include the experimental physics of turbulent plasmas and development of laser diagnostics needed to investigate characteristics of turbulent plasma in fusion experiments.

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