Development of Collective Thomson Scattering for Alpha-Particle Diagnostic in Burning Plasmas

Takashi KONDOH, Toshimitsu HAYASHI, Yasunori KAWANO, Yoshinori KUSAMA and Tatsuo SUGIE

Japan Atomic Energy Agency, Naka, Ibaraki 311-0193, Japan

(Received 4 December 2006 / Accepted 8 May 2007)

A collective Thomson scattering (CTS) diagnostic using carbon dioxide (CO_2) laser is being developed to establish a diagnostic method of confined α-particles in burning plasmas. To realize the CTS diagnostic, a transversely excited atmospheric CO_2 laser has been developed. To obtain single-mode output, which is needed for the CTS diagnostic, seed laser is injected to the cavity with an unstable resonator. Using this technique, output energy of 17 J at a repetition rate of 15 Hz has been achieved. This result gives a prospect for the CTS diagnostic on International Thermonuclear Experimental Reactor (ITER). Proof-of-principle test of the CTS diagnostic is being performed with the new laser system on JT-60U. A method to improve spatial and spectral resolutions, which is subject to be resolved for the CO_2 laser CTS, is proposed using a resonance at the lower hybrid frequency. Calculation results show that the scattering power increases more than a factor of 10, and spatial and spectral resolution improve about 30% if the scattered wave vector is nearly perpendicular to the magnetic field.

Keywords: collective Thomson scattering, burning plasma, carbon-dioxide laser, international thermonuclear experimental reactor, JT-60U

DOI: 10.1585/pfr.2.S1111

1. Introduction

A collective Thomson scattering (CTS) diagnostic is a very attractive technique to measure confined α-particles in burning plasmas. In the CTS technique, the plasma scatters a laser light and the frequency broadens due to the Doppler shift, and the scattered radiation is detected. The number density and energy spectrum of the fast ions can be determined from the spectrum of scattered radiation. The CTS diagnostic for the measurement of α-particles is being developed using carbon dioxide (CO_2) lasers [1–6] and gyrotrons [7]. The CTS based on the CO_2 laser (wavelength 10.6 μm) has an advantage of small plasma refraction due to the short wavelength, simplifying the tracking of the scattered radiation. Subjects to be resolved for the CO_2 laser CTS are development of high-power and high-repetition laser and proof-of-principle test using high temperature plasmas. In Fig. 1, progress of the energy and the repetition rate of CO_2 lasers are plotted.

This article consists of two parts. One is development of the CO_2 laser, and the other is proposal for improving spatial and spectral resolutions using a resonance at a lower-hybrid frequency.

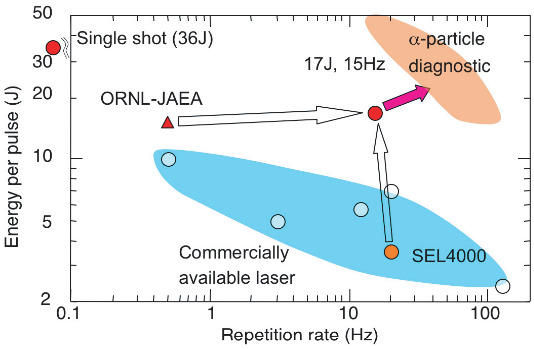

Fig. 1 Progress of the energy and the repetition rate of CO_2 laser for α-particle diagnostic. Output energy of 17 J at a repetition rate of 15 Hz has been obtained. Maximum output energy of 36 J has been obtained.

2. Development of High-Repetition CO_2 Laser

Main subject of CO_2 laser CTS was development of high-power and high-repetition laser. A previous CO_2 laser system in JT-60U developed in collaboration with Oak Ridge National Laboratory (ORNL) has output energy of 15 J at a repetition rate of 0.5 Hz [3]. For the CTS diagnostic on International Thermonuclear Experimental Reactor (ITER), CO_2 laser energy of 20 J with a repetition rate of 40 Hz is needed to provide a good signal-to-noise ratio (> 10). The estimation assumes that fusion alpha density is 1×10^{18} m^{-3} and to have a classical slow down distribution.

Since high-repetition is a key issue for CTS diagnostic, new laser should be developed based on high-repetition TEA laser with cooling system of the laser gas. A TEA

author's e-mail: kondoh.takashi@jaea.go.jp

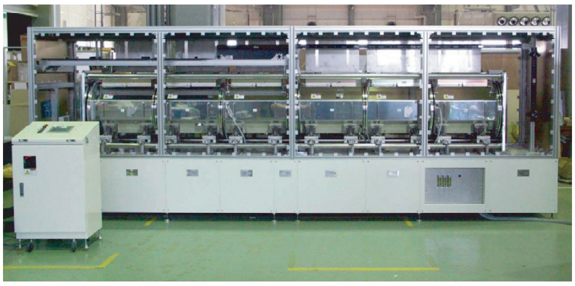

Fig. 2 Newly developed high-repetition CO_2 laser. The size of the casing is 5.3 m long ×1.9 m high × 1.1 m wide.

laser has been designed and fabricated [6] based on an industrial TEA CO_2 laser SEL4000 (Shibuya Kogyo Co., Ltd.), which has the output energy of 3.5 J at a repetition rate of 20 Hz. The output beam shape is 27 mm wide × 24 mm high. In order to increase the output energy, six discharge units of the original laser were combined in series to a cavity of the new laser. The discharge voltage for excitation of the laser gas was increased from 30 to 35 kV to increase electric stored energy in the capacitors for discharges. Electrical insulation of the power supply and electrodes was reinforced to increase the voltage. While the original laser was a stable resonator, an unstable resonator was adopted to obtain a single-transverse mode. Photograph of the newly developed CO_2 laser is shown in Fig. 2. Cavity length is 4.4 m and the size of the casing is 5.3 m long × 1.9 m high × 1.1 m wide. The beam size was changed to a circle with the diameter of 40 mm in order to enlarge the excitation volume. The pulse shape and wavelength of the TEA laser are controlled by injecting an 11 W continuous wave (CW) CO_2 laser.

Output energy of 17 J at the repetition rate of 15 Hz with single-mode output has been achieved so far. Maximum output energy of 36 J has been also obtained with a cavity configuration of the stable resonator in single shot operation. From this result, prospect for CTS diagnostic on ITER has been obtained.

3. Experimental Setup in JT-60U

3.1 Collective thomson scattering system in JT-60U

In order to demonstrate the feasibility of the measurement, the CTS technique is being developed in the JT-60U tokamak [3–6]. A schematic diagram of the CTS diagnostic system is shown in Fig. 3 (a). Scattering angle must be small ($\theta = 0.5°$) in order to obtain larger contribution from ions than electrons. An absorption cell with hot CO_2 gas is used as a stray light notch filter. The bandwidth of the absorption is less than 500 MHz, and the attenuation is larger than 10^{-6} at 10.6 µm. Scattered laser power is detected by a heterodyne receiver with a CW CO_2 laser as a local oscillator. Frequency spectrum of output signal from quantum-well infrared photodetector (QWIP) is analyzed

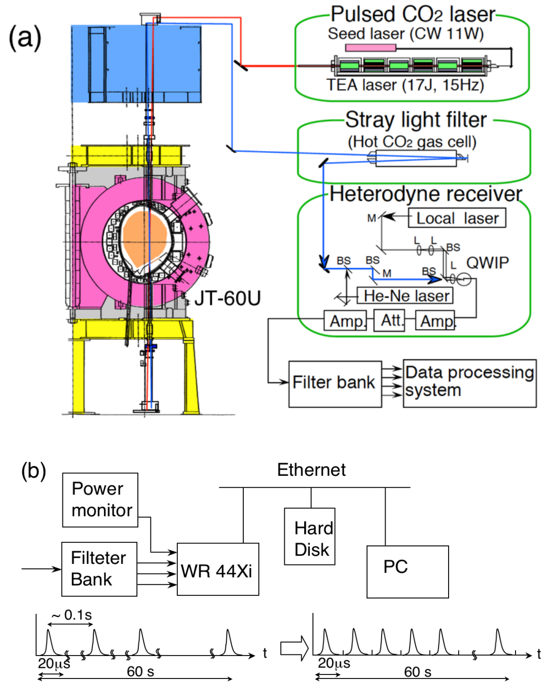

Fig. 3 (a) The CTS system on JT-60U. (b) Data processing system using the digital oscilloscope WaveRunner 44Xi.

by a filter bank (0.4-4.5 GHz) with six channels.

3.2 Data processing system

In the previous system [3, 5], the output signals were digitized by a CAMAC system in every 2 s. Since the repetition rate of the CO_2 laser increased to 15 Hz, the CAMAC system could not be used. A new fast data processing system has been developed using a Windows XP based digital oscilloscope (LeCroy WaveRunner 44 Xi). Specification of the WaveRunner 44Xi is as follows: bandwidth 400 MHz, sampling time 5 GS/s, number of channels 4, vertical resolution 8 bit, memory 12 M words/ch, sequential data acquisition 1.25 M waveforms/s/ch. Data acquisition, analysis, and storage are carried out by the oscilloscope. The memory is divided into 1000, and waveforms are collected at 15 Hz into the divided memory during 60 s. Data is analyzed using graphical program and programming script and then stored in the hard disk on the oscilloscope temporally. Then the data is transferred to the hard disk via Ethernet and detailed analysis is performed with a computer.

3.3 Injection test to the JT-60U tokamak

The laser injection test to vacuum vessel of the JT-60U tokamak has been carried out to check the electric noise and stray signals using the new CO_2 laser. Figure 4 shows an example of the waveforms of the laser power monitor and output of the filter bank. Electrical noise originated from discharges of the TEA laser was a serious problem in the previous laser system [5]. The pulse laser discharge fired about 1 µs before the lasing occurred for excitation

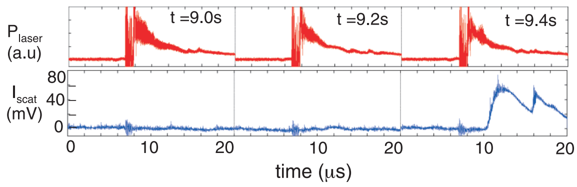

Fig. 4 Waveform of CO_2 laser power monitor, P_{laser}, and output of the filter-bank (1 ch 0.4 -0.7 GHz), I_{scat}.

of the laser gas. Large electric noise was generated from the initiation of the discharge in the previous system. Laser tube of the previous system was made of glass and the electric noise was emitted through the tube. In the new laser system, laser tube is made of stainless steel and the casing of the laser is also carefully shielded to prevent electric noise radiation. Electrical noise in the output of the filter-bank has been clearly reduced as show in the figure.

In the figure of $t = 9.4$ s, a stray signal was observed after $t = 10$ μs. The stray signal was generated by degenerated components of the laser frequency. The stray signal could not be attenuated because the frequency width of the stray light was wider than bandwidth of the stray light filter (~500 MHz). At present, about 30% of the laser pulses causes stray signals and about 70% of the laser pulses do not generate the stray signal as in the figures in $t = 9.0$ and 9.2 s. It is necessary to improve the percentage of the laser pulses without stray signal.

4. Proposal for Improving Spatial and Spectral Resolutions at Lower-Hybrid Frequency

In this section, we propose a method to improve the resolutions using a resonance at the lower hybrid frequency. Since the scattering angle of the CO_2 laser CTS is very small, spatial and spectral resolution are low compared with gyrotron based CTS. In 1990's, there was an attempt to enhance signal intensity by using lower hybrid frequency in Tokamak Fusion Test Reactor (TFTR). However, a signal has not been detected in the lower hybrid frequency range which correlates to alpha particles [8]. The attempt was carried out using low power (200 W) gyrotron frequency of 60 GHz, and then the expected alpha scattered signal was near the detection limit at the power. Difference of our proposal from the experiment using gyrotron is wavelength and power of the source. And then, the expected S/N ratio is larger than 10.

Scattering geometry of the CTS diagnostic is shown schematically in Fig. 5. The incident laser at the wave number k_i is scattered and Doppler shifted by electrons in the plasma to the scattered wave number k_S. The ions are too massive to scatter high-frequency waves directly, but the measurement of the scattered wave spectrum yields infor-

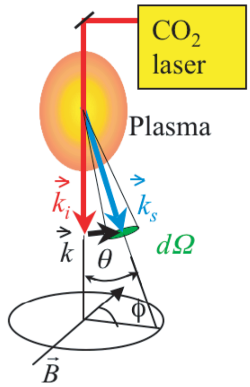

Fig. 5 Schematic diagram of the scattering geometry for the collective Thomson scattering.

mation on the ions if the wavelength of the fluctuations is larger than the Debye length λ_D, so that the Debye electron cloud surrounding the ions behaves collectively in the scattering process. This condition requires very small scattering angle ($\theta \sim 0.5°$) for CO_2 laser CTS to obtain a larger contribution from the ions than electrons. Since the scattering angle, θ, must be very small, optimization of spatial and spectral resolution is one of the major task for CO_2 laser CTS in ITER. Scattering length (84% of the CTS signal comes from the length of L), and spectral resolution (FWHM), $\Delta f/f$, which is equal to the velocity resolution $\Delta f/f$, is described as follows;

$$L = w/\sin(\theta/2) \tag{1}$$

$$\frac{\Delta f}{f} = \frac{6.7/w}{2k_i \sin(\theta/2)} \tag{2}$$

where, w is radius of Gaussian beam waist (e^{-2} power level) which is assumed to be equal to the radius of Gaussian sensitivity profile. Scattering length of $L \sim 0.92$ m and spectral resolution of $\Delta f/f \sim 0.32$ is obtained with beam radius of 4 mm, or $L \sim 0.69$ m and $\Delta f/f \sim 0.43$ is obtained with beam radius of 3 mm. In order to improve spatial and spectral resolution, scattering angle θ should be increased.

Vahara [9] shows a strong resonance at the lower hybrid frequency in the scattered power theoretically. To obtain better spatial and spectral resolution, we propose to measure enhanced scattered power at the frequency of the lower hybrid in ITER as well as to measure without the enhancement. Combination of the two scattering angles is important to obtain detailed information on α-particles.

The scattered power in the frequency range dω and solid angle dΩ from a length L of the incident beam of electromagnetic radiation is given by [9]

$$P_s \mathrm{d}\Omega \mathrm{d}\omega = P_L r_0^2 n_{e0} L \mathrm{d}\Omega \mathrm{d}\omega S(\vec{k}, \omega) \tag{3}$$

where r_0 is the classical electron radius, n_e is electron density, and $S(k, \omega)$ is the spectral density function.

Figure 6 (a) shows the calculated spectral density $S(k, \omega)$. The plasma parameters used in the calculation

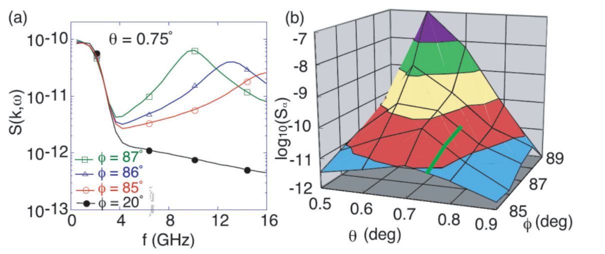

Fig. 6 (a) Spectral density function, $S(k,\ \omega)$, for various ϕ at a scattering angle of $\theta = 0.75°$. (b) Contribution of α-particles on $S(k,\ \omega)$ in $(\theta,\ \phi)$ space.

are electron density $n_e = 1 \times 10^{20}\,\mathrm{m}^{-3}$, α-particle density $n_\alpha = 7.5 \times 10^{17}\,\mathrm{m}^{-3}$, electron and ion temperature $T_e = T_i = 20\,\mathrm{keV}$, and toroidal magnetic field $B_T = 5\,\mathrm{T}$. Distribution function of the α-particles is assumed to a slow-down distribution. Curve with closed circle shows the spectral density without enhancement at lower-hybrid frequency. Strong enhancement on $S(k,\omega)$ is obtained at $\phi \sim 90°$ as shown in the figure. Resonance feature on $S(k,\omega)$ appears at the condition of the scattered wave vector is nearly perpendicular to the magnetic field. Figure 6 (b) shows the maximum of the α-particle contribution on $S(k,\omega)$ in the $(\theta,\ \phi)$ space. $S(k,\omega)$ remarkably increases by five orders. Since enhancement on $S(k,\omega)$ is too abrupt to measure α-particle feature at $\phi \sim 90°$, we propose suitable choice of $\theta = 0.75$, $\phi = 86°$. At this scattering angle spatial and spectral resolution improve to $L \sim 0.46\,\mathrm{m}$, $\Delta f/f \sim 0.29$ ($w = 3\,\mathrm{mm}$, $\theta = 0.75°$) or $L \sim 0.61\,\mathrm{m}$, $\Delta f/f \sim 0.21$ ($w = 4\,\mathrm{mm}$, $\theta = 0.75°$).

Since the resonance condition and enhancement strongly depend on the plasma parameters, measurement of scattering spectrum with original scattering angle ($\theta = 0.5°$, $\phi \neq 90°$) is also required. Combination measurement with two angles will provide more detail information on α-particles.

5. Summary

A high-repetition and high-power CO_2 laser has been developed and output energy of 17 J at the repetition rate of 15 Hz has been obtained. Strong resonance at hybrid resonance frequency enhances scattering power more than a factor of 10 and improves the spatial and spectral resolutions about 30%. Combination measurement with original scattering angle ($\theta = 0.5°$, $\phi \neq 90°$) will provide more detail information on α-particles.

Acknowledgment

This work was supported by Grant-in-Aid for Scientific Research on Priority Areas “Advanced Diagnostics for Burning Plasmas” from the Ministry of Education, Culture, Sports, Science and Technology, No.16082210.

[1] D.P. Hutchinson *et al.*, Rev. Sci. Instrum. **58**, 1075 (1985).
[2] R.K. Richards *et al.*, Appl. Phys. Lett. **62**, 28 (1993).
[3] T. Kondoh *et al.*, Rev. Sci. Instrum. **72**, 1143 (2001).
[4] S. Lee, T. Kondoh *et al.*, Rev. Sci. Instrum. **71**, 4445 (2000).
[5] T. Kondoh *et al.*, Rev. Sci. Instrum. **74**, 1642 (2003).
[6] T. Kondoh *et al.*, Rev. Sci. Instrum. **77**, 10E505 (2006).
[7] H. Bindslev *et al.*, Phys. Rev. Lett. **83**, 3206 (1999).
[8] J.S. Machuzak *et al.*, Rev. Sci. Instrum. **68**, 458 (1997).
[9] L. Vahara *et al.*, Nucl. Fusion **26**, 51 (1986).