CO_2 Laser Collective Thomson scattering for Alpha-particle Diagnostics

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In JT-60U (JAEA Tokamak 60 - Upgrade), a collective Thomson scattering (CTS) technique based on a CO_2 laser is being developed in order to establish a diagnostic method of confined alpha-particles in burning plasmas. In order to the demonstrate feasibility of the CTS system, a new laser systems is being developed, with which improved signal-to-Noise (S/N) ratio of a detection signal and temporal resolution will be obtained. The laser has cavity length of ~ 4 m and has high repetition rate (10 Hz). To improve the spectral purity of the laser, cavity length will be feedback-controlled and a spectral filter will be installed in the output of the laser. Numerical calculation shows that ion temperature will be evaluated from the scattered spectrum with the new CO_2 laser.

1. Introduction

In order to understand the behavior of alpha-particles which are the dominant heat source in a burning plasma, it is necessary to measure the spatial distribution of the density of the alpha-particles and their energy spectrum. In a collective Thomson scattering (CTS) technique, the plasma scatters a laser light and the frequency broadens due to the Doppler shift, and the scattered radiation is detected. In principle, the number density and energy spectrum of the fast ions can be determined from the spectrum of scattered radiation, however, the development of measurement techniques and hardware are at a very early stage. A technique based on CTS is being developed using CO_2 lasers [1-5] and gyrotrons [6] to measure spatial distribution and energy spectrum of the alpha-particles. The CTS technique based on the CO_2 laser has the advantage of small plasma refraction, simplifying the tracking of the scattered radiation. On the other hand, it is necessary to choose a small scattering angle, θ, so that the scattering wave length is larger than Debye length λ_D which satisfies $\alpha_s = (k\cdot\lambda_D)^{-1} > 1$, where k is the scattering wave number, $k = 2\cdot k_i \cdot \sin(\theta/2)$, k_i is the wave number of incident beam. In the JT-60U parameter region (T_e > 1 keV、 $n_e > 10^{19}\mathrm{m}^{-3}$), it is necessary to take the scattering angle of 0.5 degree or less.

A preliminary design of a beam line and a receiver system with the vertical scattering geometry has been developed for International Thermonuclear Experimental Reactor (ITER). To realize the CTS measurement, a proof-of-principle test on the CTS system using the JT-60U plasma is being conducted. Also present status of newly developed CO_2 laser is described.

2. Collective Thomson Scattering System proposed for ITER

ITER requires diagnostics of confined alpha-particles with time resolution of 0.1 s and spatial resolution of $a/10$, where a is minor radius of the plasma. A CTS system based on a pulsed CO_2 laser is under consideration for alpha-particle measurements on ITER, because there is no experimental data obtained at present tokamaks. Therefore demonstration of the CTS system is strongly required.

Heating neutral beams (NB) (E = 1 MeV) are normally co-injected in ITER and have a velocity similar to alpha-particles at birth. An important point is that the CTS measurement cannot, in general, distinguish between beam ions and alpha-particles which have the same velocity. The diagnostic scattering geometry must be oriented so that the scattering $\boldsymbol{k}$ vector is

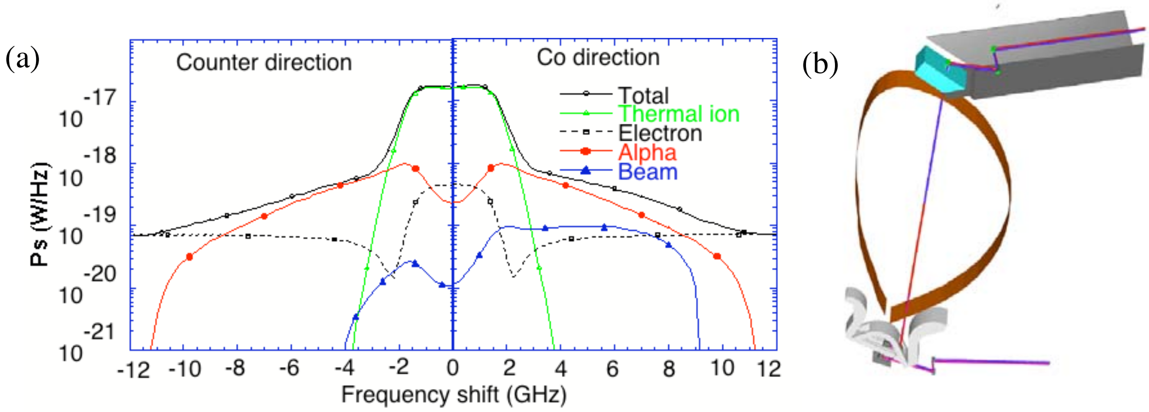

Fig.1 (a) Calculated spectra of CTS system on ITER. (b) Preliminary design of vertically viewing CTS on ITER.

near the toroidal direction to minimize contributions of NB-ions to the scattering spectrum. The distribution function of co- and counter-direction can be measured with the vertical geometry.

Figure 1 (a) shows the calculated spectrum of scattered radiation for the proposed ITER CTS system shown in Fig. 1 (b). Individual contributions to the scattered power due to alpha-particles, beam ions, electrons and thermal ions are indicated in Fig. 1(a). In the calculation, $n_e = n_i = 1\mathrm{x}\ 10^{20}\ \mathrm{m}^{-3}$, $T_e = T_i = 20$ keV, $Z_{eff} = 1.8$, laser power $P_{laser} = 50$ MW, scattering angle $\theta = 0.5°$, and solid angle, $\Delta\Omega = 0.1$ sr were assumed. It is clearly shown that the vertically viewing CTS could resolve counter-travelling alphas without being masked by beam ions.

The laser is injected to the plasma through the divertor. The scattered radiation is collected by a mirror optics located in the upper port and is transferred to the diagnostic room. The present CTS system in JT-60U cannot distinguish between co- and counter-ions because the frequencies of the local oscillator of the heterodyne receiver and the pulsed laser are the same (10.6 μm). In this case, the spectrum obtained is the summation of co- and counter-directions. In order to distinguish co- and counter-ions, isotope CO_2 and N_2O lasers which have shifted frequencies (2 - 10 GHz) from the pulsed laser can be used as the local oscillator laser and this was proposed for ITER[7].

Since the scattering angle, θ, must be small (~0.5°), 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 $\Delta v/v$, is described as follows;

$$L = w/sin(\theta/2) \qquad (1)$$

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

where, w is radius of Gaussian beam waist (e^{-2} power level) which is equal to the radius of Gaussian sensitivity profile, and k_i is the wave number of incident laser at the plasma. Scattering length and spectral resolution as a function of the beam radius is shown in Fig. 2 (a) and (b). Scattering length of L ~ 0.92 m and spectral resolution of $\Delta f/f$ ~ 0.32 is obtained with beam radius of 4 mm, or L ~ 0.69 m and $\Delta f/f$ ~ 0.43 is obtained with beam radius of 3 mm. Beam radius of 3 mm is easily obtained with the mirror of 3 cm in diameter in the beam propagation optics of ITER. To obtain better spatial and spectral resolution, combination with tangentially viewing CTS system is needed to be considered.

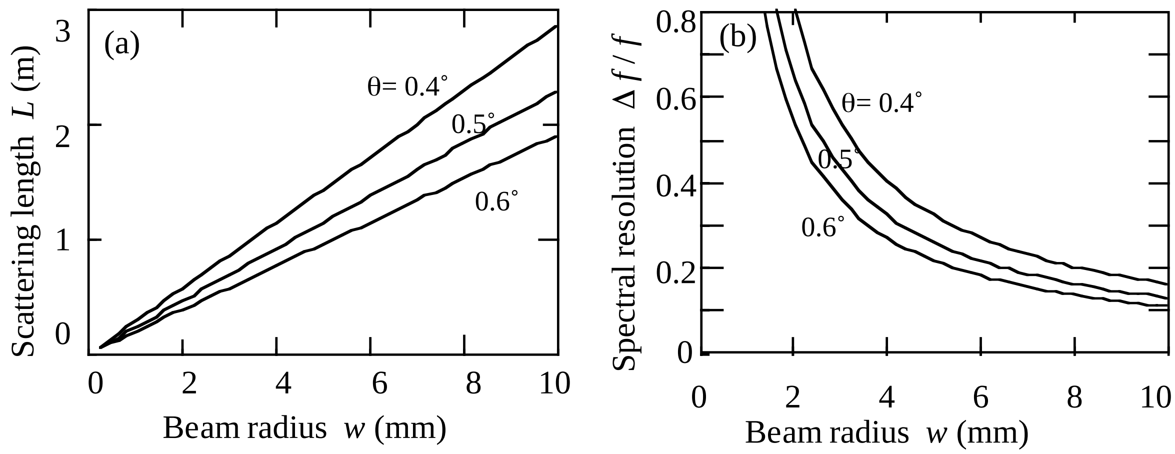

Fig. 2. (a) Scattering length L and (b) spectral resolution Δf/f as a function of beam radius w.

3. Test of the Collective Thomson Scattering System on JT-60U

In order to demonstrate the feasibility of the measurement, the CTS technique is being developed in the JT-60U tokamak [3-5]. A schematic view of the CTS system in JT-60U is shown in Fig. 3. A CO_2 laser system, a stray light filter, and a heterodyne receiver system are developed in collaboration with Oak Ridge National Laboratory (ORNL). The pulse shape and wavelength of a transversely excited atmospheric pressure (TEA) laser are controlled by injecting a beam from a 10W continuous wave (CW) CO_2 laser. It has a pulse width of about 1 μs and repetition rate of 0.5 Hz. The maximum output energy is about 15 J. The beam diameter is about 4 cm and divergence of the beam is 0.5 mrad. He-Ne laser beam is combined with the CO_2 laser and also combined with line of sight of the receiver for optical axis alignment. The scattering angle must be small (0.5°) to obtain large ion contribution on the scattered spectrum. Vacuum windows on JT-60U are made of zinc selenide (ZnSe) with antireflection coatings that have high damage thresholds (19.9 J/cm^2). Distance between the CO_2 laser and the plasma center is about 70 m. The laser beam is focused at the plasma center using a molybdenum spherical mirror (focal length f = 13.1 m) of 150 cm in diameter. The scattered light is collected by a spherical mirror (f = 7.8 m) 50 cm in diameter. Stray light is

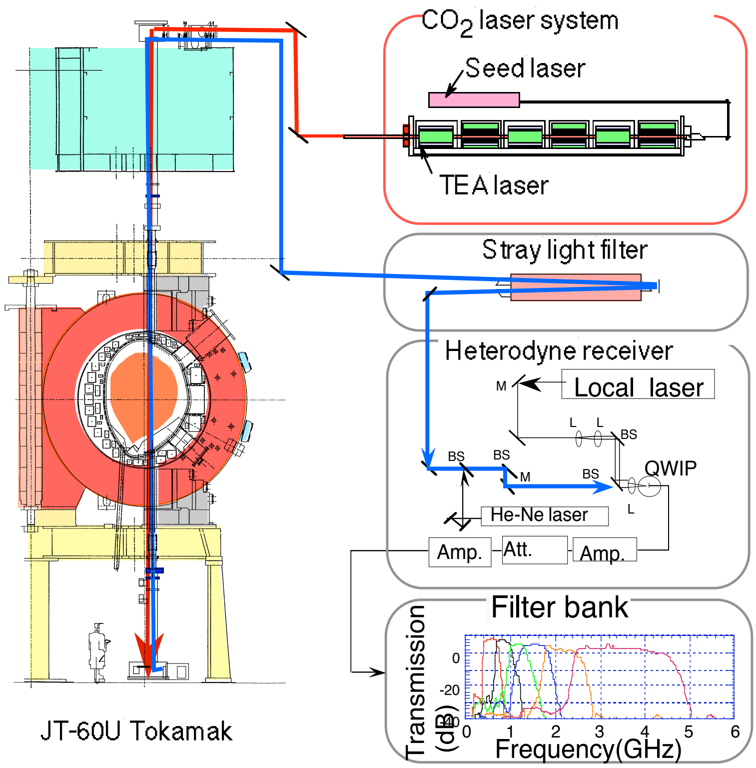

Fig. 3 Schematic diagram of the Collective Thomson scattering system in JT-60U

reduced by a notch filter with hot CO_2 gas. The scattered signal is detected by a heterodyne receiver and the spectrum is analyzed by a filter bank with six channels.

Measurements of the scattered signal from the JT-60U plasma were performed with a NB heated plasma. However, scattered signal was not detected due to electrical noise originating from the pulsed laser discharge and stray signal coming from mode impurities in the laser.

4. Development of CO_2 Laser

In order to improve *S/N* ratio of detection signal and to improve temporal resolution and spectral purity, a new laser systems is being developed. The laser has unstable cavity which has a length of ~ 4 m and has high-repetition rate. Schematic view of the newly developed CO_2 laser is shown in Fig. 4. Expected performance of the laser are as follows; repetition-rate is 20 Hz, output energy is 18 J, beam divergence is 1 mrad, and diameter of the beam is 4 cm. The cavity is comprised of six discharge units, which consists of main-discharge electrodes, pre-ionization pins (not shown in the figure), and two heat exchangers. To achieve high-repetition rate, working gas is cooled by the heat exchangers. Though the electrodes and the heat exchanger are designed to have capability of 20 Hz operations, the laser will be operated at a frequency of 10 Hz at first. Since discharge unit and power supply are component of a commercial laser, it is easy to improve its performances. To improve the spectral purity of the laser, cavity length will be feedback-controlled and a spectral filter will be installed to the output of the laser.

5. Summary

One of the candidates to measure confined alpha-particles is collective Thomson scattering technique using a pulsed CO_2 laser. By using a vertical viewing CTS geometry, it is possible in principle to distinguish the alpha-particle distribution from the energetic NB ions. Scattering length of L ~ 0.92 m and spectral resolution $\Delta f/f$ ~0.32 will be obtained with beam radius of 4 mm. New laser system is being developed in order to improve the measurement performance (S/N ratio, temporal resolution) and proof-of-principle test will be performed with the improved laser system on JT-60U in next year.

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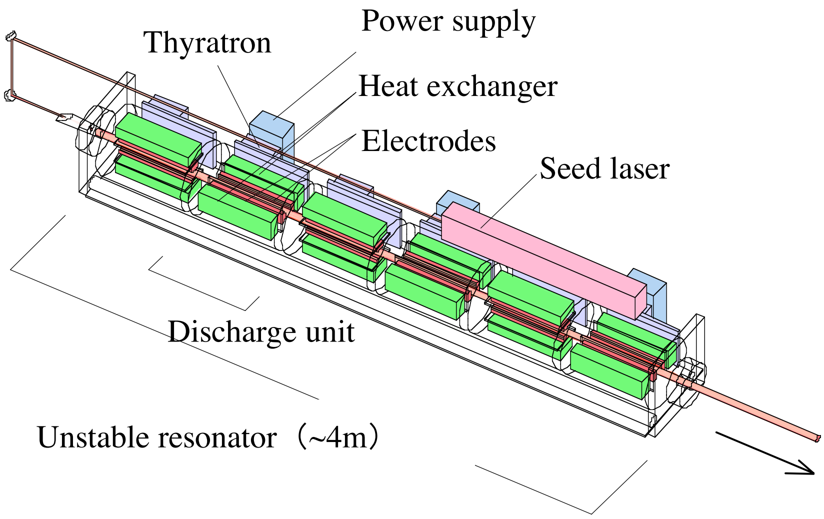

Fig. 4. Newly developed high-repetition CO_2 TEA laser.

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