Design of Thomson scattering diagnostic system on linear magnetized plasma device

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Abstract

In addition to the magnetic confinement fusion plasma, Thomson scattering has been applied to measure electron density and temperature of low-temperature plasmas. Based on a linear magnetized plasma device, a set of Thomson scattering diagnostic system is designed to diagnose the plasma with $n_e = 10^{18}$–10^{19} m^{-3} and $T_e = 2$–5 eV. Due to low plasma temperature and density, this diagnostic system needs high spectral resolution and collection efficiency to meet the requirements of electron velocity distribution function measurements. Through the bench test, it is confirmed that the spectral resolution reaches 0.01 nm, and theoretical collection efficiency is high enough to obtain a Thomson scattering spectrum by 1000 accumulations.

Keywords: Thomson scattering, low temperature plasma, EVDF

(Some figures may appear in colour only in the online journal)

1. Introduction

As an active and non-intrusive diagnostic technique, Thomson scattering (TS) is the most reliable method to measure electron temperature or velocity distribution with high temporal-spatial resolution. Since Peacock first applied Thomson scattering in tokamak plasma in 1969 [1], it has been widely used to measure electron temperature T_e on major tokamaks such as EAST [2], DIII-D [3], ASDEX [4], JT-60U [5], HL-2A [6], etc. In recent decades, the TS application scenario has been extended from the traditional high T_e measurement in fusion plasmas to the low-temperature plasmas, e.g. glow discharge [7], inductively coupled plasmas [8], argon microwave plasmas [9] and Hall thruster [10]. These plasma sources are characterized by very low electron temperature in the order of several eV and low density ranging from 10^{16} to 10^{19} m^{-3}. Due to the low plasma density and electron temperature, the challenges are the low scattering signal intensity and the narrow spectral width.

In this work, a set of incoherent Thomson scattering diagnostic system has been designed for the Linear Magnetized Plasma (LMP) device in USTC. The main research topics of LMP are focused on fundamental plasma physics,

such as drift instability, wave-particle interaction, magnetic field reconnection problems [11]. Apparently, the diagnostic of electron dynamics is very important for these experimental researches. For example, the heating and acceleration of electrons during the magnetic reconnection process is still a hot research topic [12]. Compared with traditional Langmuir probes and other diagnostics, Thomson scattering is a better choice which is capable of performing the T_e and even the electron velocity distribution function (EVDF) measurements with high temporal and spatial resolution.

The LMP TS system consists of a Nd:YAG pulsed laser and a grating spectrometer with an intensified CCD (ICCD). Theoretically, the TS spectrum FWHM is 5.54 nm taking the typical LMP T_e value as 5 eV, thus it requires the spectral resolution to be less than 0.01 nm. The capability of the TS system has been verified through the bench test, the results of Rayleigh and rotating Raman scattering are also presented.

2. Experimental setup

The vacuum chamber of LMP is surrounded by 12 sets of magnetic field coils, which generate a steady-state magnetic
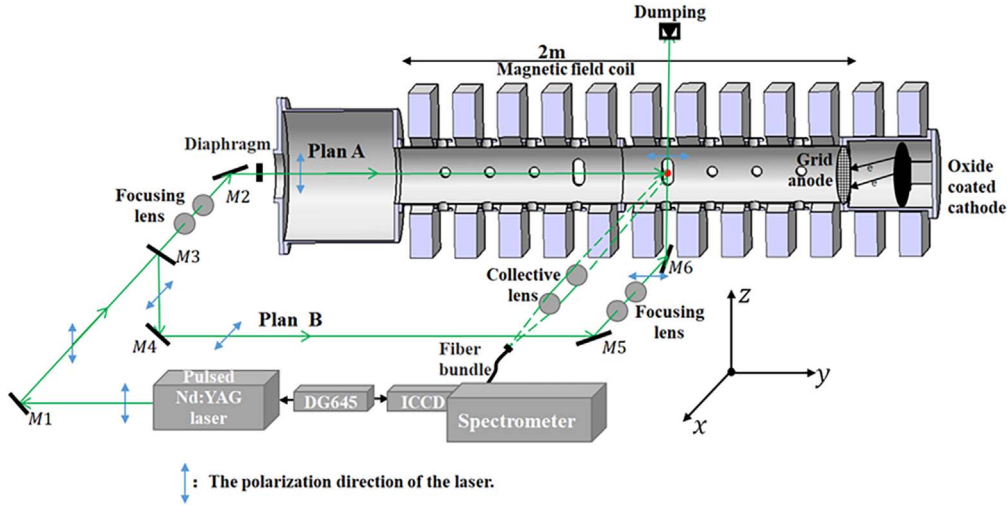
Figure 1. Experimental setup of the TS system on the LMP.

field varying from 180 to 1000 Gs which is used to confine the diffusion of plasma from the source to the experimental region. The experimental region is 2 m in length and 0.25 m in diameter. LMP operates in an oxide-coated cathode [13] pulse discharge mode with 1 Hz repetition frequency and a duration time from 10 to 20 ms. The typical plasma parameters are A electron density of 10^{17}–10^{19} m^{-3} and electron temperature of 2–5 eV.

The incident laser is provided by a Quanta-Ray Nd:YAG laser operating at its second harmonic mode with a 30 Hz repetition frequency. The laser pulse length is 10 ns, the maximum energy of one pulse is 500 mJ. Although the number of the scattered photons with an incident laser at 1064 nm will be twice the number with a laser at 532 nm, the quantum efficiency at 532 nm of the ICCD with Gen III intensifier is much higher than the quantum efficiency at 1064 nm, which is the reason that the laser is set working at its harmonic mode.

As shown in figure 1, there are two TS diagnostic settings for EVDF measurements. For configuration A, the direction of the incident laser is along the y-axis and the polarization direction is along the z-axis. For configuration B, the incident laser is propagated along the z-axis and polarized in the y-direction. In both schemes, the scattered photons are collected along the x-direction which ensures the TS differential cross-section reaches its maximum. According to the definition of scattering factor $\alpha = \frac{1}{k\lambda_{\mathrm{D}}} = \frac{1}{2\lambda_{\mathrm{D}}k_0 \sin\left(\frac{\theta}{2}\right)}$, where k is the scattering vector, λ_{D} is the Debye length and k_0 is the wavenumber of the incident laser, the scattering factor α for our experiments is around 0.001, which satisfies the incoherent Thomson scattering condition $\alpha \ll 1$ [14].

The laser incident optics consists of 10 transmission mirrors and a set of focusing lenses including a planoconcave lens with −200 mm focal length and a planoconvex lens with 200 mm focal length. The focusing lens set is used to reduce the beam width from 9.5 mm at the exit portal to 2 mm in the

detection region. The overall transmission efficiency of the incident optics is about 54%.

The collective lens group adopts two lenses with 50 mm in diameter, the focal lengths are 250 mm and 500 mm. The collecting solid angle is 6.25×10^{-4} sr and the transmittance of the lens group is 76%. Then the scattered photons are transmitted by the optical fiber with input numerical aperture of 0.22. The fiber bundle consists of 19 single fibers with 200 μm in diameter and the transmissivity is 77%. The fiber bundles are stacked in a circle with a diameter of 1 mm in the receiving plane, and are reorganized to 1×19 to match the entrance slit of the spectrometer. The spectrometer has a 2400 l mm^{-1} grating with a size of 76 mm $\times$ 76 mm and the spectral dispersion is 0.53 nm mm^{-1} at 500 nm. The diffraction efficiency of grating is around 80%. The total transmission efficiency of the collection system is estimated at 45%. The array format of the ICCD is 1024×1024 and each pixel size is 13 μm $\times$ 13 μm. The quantum efficiency of the image intensifier at 532 nm is 49%.

The total collected TS photons for one laser pulse can be estimated according to the formula

$$N_{\mathrm{s}}^{\mathrm{T}} = n_{\mathrm{e}} \cdot \frac{\mathrm{d}\sigma_{\mathrm{T}}}{\mathrm{d}\Omega} \cdot \Delta L \cdot N_L \cdot \Delta\Omega \cdot A.$$

Here $N_{\mathrm{s}}^{\mathrm{T}}$ is the total number of collected scattered photons, $\frac{\mathrm{d}\sigma_{\mathrm{T}}}{\mathrm{d}\Omega} = r_{\mathrm{e}}^2$ is the maximum of the TS differential cross-section where r_{e} is the classical electron radius, n_{e} is the plasma density, ΔL is the length of the scattering volume, N_L is the number of incident photons, A is the total system transmission efficiency and $\Delta\Omega$ is the solid angle of collection optics. The maximum of the TS differential cross-section can be written as $\frac{\mathrm{d}\sigma_{\mathrm{T}}}{\mathrm{d}\Omega} = r_{\mathrm{e}}^2$. Considering the typical LMP TS case with $n_{\mathrm{e}} = 10^{19}$ m^{-3} and $\Delta L = 2$ mm, the total number of scattered photons received by the ICCD will be $N_{\mathrm{s}}^{\mathrm{T}} = 32$ photons.

In order to improve the signal-to-noise ratio, the stray light photons need to be suppressed. The beam dump is mounted at the laser output end and the internal surface of the LMP vacuum chamber is covered with black foils. In
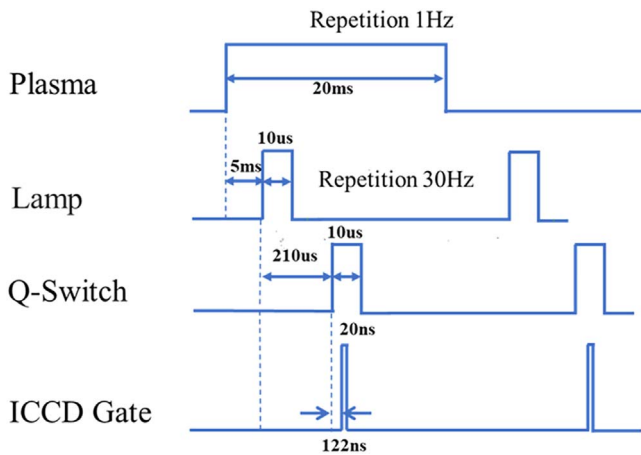
Figure 2. The timing schematic of the TS system.

addition, a narrow baffle is placed between the spectrometer and the ICCD to block the light with a wavelength close to 532 nm.

Since the repetition frequencies of the plasma source and the incident laser are different, the operation sequences of each instrument should be carefully tuned to make sure the TS diagnostic system works correctly in the expected time period for every plasma pulse. The timing sequences of the trigger signals are shown in figure 2. The master trigger signal is a 1 Hz Transistor-Transistor Logic signal, which is provided to the plasma discharge controller and a function generator. The function generator outputs a 30 Hz signal to digital delay generator DG645. Then DG645 provides the trigger signals for the pulsed laser and ICCD with different time delays. The laser output time is set at $t = 5$ ms when the plasma column has been steadily established. The time delay of the laser flash lamp and Q-switch is set to near 210 μs for best laser output. Due to the finite optical path and instrument response time, the delay time between the Q-switch and ICCD is adjusted to 122 ns, which is optimized via the *in situ* monitoring of laser signal by photodiodes. Considering the laser pulse length is 10 ns, the ICCD gate open time is set to 20 ns, which is the detector integrating period.

3. Bench test

The performances of the spectrometer and ICCD are calibrated by the sodium lamp which has two characteristic lines at 589 nm and 589.6 nm. The spectrum shown in figure 3(b) is obtained by the summation of the intensities along the vertical direction. Based on the pixel number between the two peaks, the spectral dispersion is 0.45 nm mm^{-1} corresponding to a spectral resolution of 0.006 nm. The spectral measurement range is around 6 nm (1024 × 0.006), which is larger than the FWHM of the TS spectrum with $T_e = 5$ eV. The measured line broadening is around 0.033 nm, which is dominated by the instrument broadening of the spectrometer.

Rayleigh scattering is conducted when the LMP chamber is filled with pure nitrogen. The spectra at different filling pressures are shown in figure 4(a). The spectrum under one
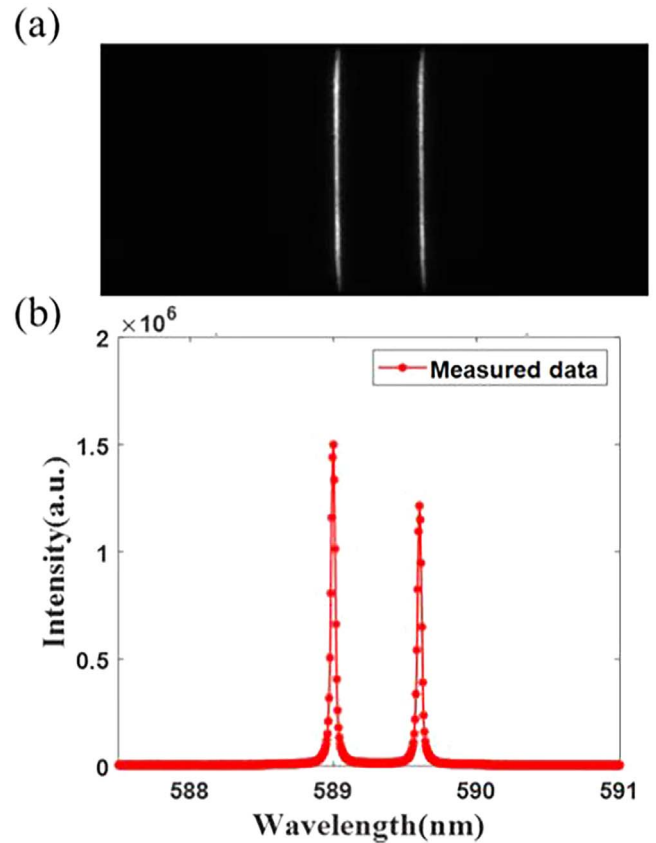

Figure 3. (a) ICCD imaging, (b) the spectrum of the sodium lamp.

bar is obtained within only one laser pulse due to the high molecular density. The RS spectral width is estimated as 0.048 nm, which is the convolution of laser linewidth and instrument broadening. By changing the neutral pressure of nitrogen in the chamber, it is clearly shown that the total scattering intensity is proportional to the nitrogen density. As shown in figure 4(b), a narrow baffle is added in front of the ICCD to filter out Rayleigh scattering and stray light photons. The baffle with 2 mm width and 0.3 mm thickness is made of black aluminum alloy, and the transmittance function has a notch of 0.8 nm around 532 nm shown in figure 4(d). With the baffle installed, the Raman scattering spectrum of the nitrogen is obtained with 30 accumulations at a filling pressure one bar, shown in figure 4(c). The measured spectrum is consistent with the simulated spectrum based on a rotational Raman scattering model of the nitrogen [15].

According to table 1, the intensity of Raman scattering in N_2 is 20 times stronger than Thomson scattering intensity on LMP. It is expected that the TS diagnostic will need around 600 accumulations to get a clear broadened spectrum in theory.

4. Summary

A TS diagnostic system has been designed on an LMP device, which is expected to provide EVDF measurements for the oxide-coated cathode plasma source with $T_e = 2–5$ eV and
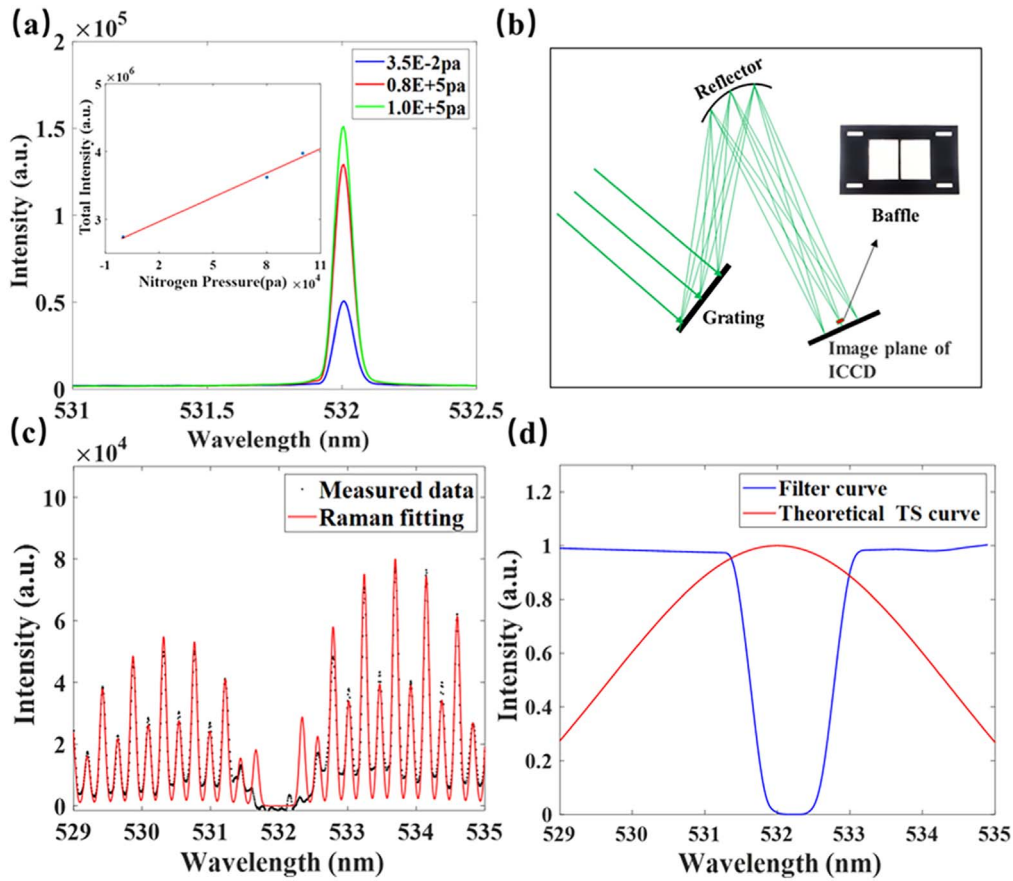
Figure 4. (a) Rayleigh scattering spectrum of N$_2$. (b) Schematic diagram of filter baffle. (c) Raman scattering spectrum of N$_2$. (d) Transmittance of filter baffle near 532 nm.

Table 1. Differential scattering cross-section and number density.

Scattering type	Differential scattering cross-section (m^2)	Density (m^{-3})
Rayleigh scattering	6.07 × 10^{-32} (N$_2$)	2.67 × 10^{25} (@1 bar)
Raman scattering	6.49 × 10^{-34} (N$_2$)	2.67 × 10^{25} (@1 bar)
Thomson scattering	6.65 × 10^{-29}	10^{19}

$n_e = 10^{18}$–10^{19} m^{-3}. The spectrometer system has been characterized using a sodium lamp, and a baffle is added to the spectrometer as a notch filter. Both Rayleigh scattering and Raman scattering have been conducted, which verifies that the system has the ability to obtain a TS spectrum with 600 accumulations in this case.

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