Design of a laser Thomson scattering system for atmospheric plasma sources

Y.-G. Kim[1] and S. Park[1]

[1] Institute of Plasma Technology, Korea Institute of Fusion Energy, Gunsan, Korea

Abstract: Research on the relationship between the plasma properties and reactive species generated by the plasma is important. The Korea Institute of Fusion Energy is currently developing a plasma diagnostic system to investigate the production of radicals and metastable species from atmospheric plasma. As the first diagnostics, a Thomson scattering system is being designed to measure the electron temperature and density. To overcome problems that can occur in atmospheric plasma measurement, such as air breakdown and narrow scattering spectrum, a low energy laser with a high repetition rate is used as the incident laser. Additionally, a triple grating spectrometer has been developed to effectively block stray light.

Keywords: Plasma diagnostics, Thomson scattering, electron temperature, triple grating spectrometer

1. Introduction

In the plasma chemistry and biomedical field, reactive oxygen and nitrogen species (RONS), including oxygen atoms (O), ozone (O_3), hydroxyl radicals (OH), nitric oxide (NO), and nitrogen dioxide (NO_2), play an important role because of their high reactivity [1, 2]. Cold atmospheric plasma is known to produce a wide range of RONS. And a variety of methods to generate the plasma at atmospheric pressure and room temperature were developed such as corona discharge, dielectric barrier discharge (DBD), radio frequency (RF) discharge, and microwave discharge. However, study on the relationship between plasma properties and radical generation is relatively rare because of the difficulty of measuring the physical parameters of cold atmospheric plasma, compared to the properties of RONS.

Recently, the Korea Institute of Fusion Energy (KFE) has begun developing a complex plasma diagnostic system for quantitative research on the production of radicals and metastable species and their relationship with electron kinetics. It will include spectroscopic systems, including laser-induced fluorescence (LIF), tunable diode laser absorption spectroscopy (TDLAS), cavity ring-down spectroscopy (CRDS), and Thomson scattering (TS). Among the various methods, the TS diagnostic system has been chosen as the first to be developed, as it is a key diagnostic for the plasma measurement.

The laser Thomson scattering (TS) is widely recognized as a powerful diagnostic method for measuring the absolute electron temperature and the density within a given scattering volume. However, due to the extremely small cross section of Thomson scattering (6.65×10^{-29} m^2), TS system requires careful alignment, efficient optical components, and highly sensitive detectors for accurate measurement. One of the biggest challenges of applying TS in cold atmospheric plasma is its low electron density, which is far lower compared to the densities of inductively coupled plasmas or fusion plasmas. There are two main approaches to improve the signal-to-noise (SNR) of TS signal measurement. The first is to increase the laser energy. Since the intensity of TS radiation is directly proportional to the intensity of the incident laser, higher SNR can be obtained by using a more powerful laser is used. For example, nuclear fusion experiments measuring TS signals from every laser pulse utilize the laser with the energy levels of 1-10 J [3-6]. However, the strong electric field around the focal point of the laser beam can cause the breakdown of the background air at the atmospheric pressure. Furthermore, it was reported that the laser energy of about 20 mJ can cause perturbation to the plasma density through photo-ionization of atoms in a metastable state, at a pressure of 200 Torr [7]. Therefore, increasing laser energy for higher SNR may not be a viable option. Another way to achieve a high SNR is to accumulate a number of scattered signals over a long period of laser repetition. The uncertainty that inevitably arises in spectroscopy is mainly determined by the shot noise that occurs during photon detection. Since, the shot noise is proportional to the square-root of the number of measured photoelectrons ($N^{0.5}$) and the signal is proportional to N, the SNR increases proportionally to $N^{0.5}$ as the number of measurements increases. This is the approach for the efficient TS systems currently being developed.

2. Thomson scattering system

A schematic diagram of the Thomson scattering system is depicted in Fig. 1. In Thomson scattering system, it is important to synchronize the detector and the laser. In particular, since the atmospheric pressure plasma does not sustain the discharge continuously due to collision with the background gas, the plasma is repeatedly turned on/off, so a power system for the plasma must also be included in the synchronization system. To turn on the plasma, the sinusoidal wave generated from function generator is transmitted to the RF amplifier and matcher. At the same time, the delay generator, triggered by the function generator, drives the Nd:YAG laser with two input signals: *sync in* and *Q-sw*. When the laser beam has been introduced to the plasma, the scattered light is measured at an intensified charge-coupled device (ICCD) considering the delay due to the light flight path. The green line in the figure represents the beam flight pass of the laser and the scattered light. The laser beam is absorbed by the beam dump passing through the plasma. The scattered light is collected by two lenses at the scattering angle of 90 degree and transferred to the triple grating spectrometer (TGS). Finally, the spectral intensity is measured by the ICCD and stored in a computer.

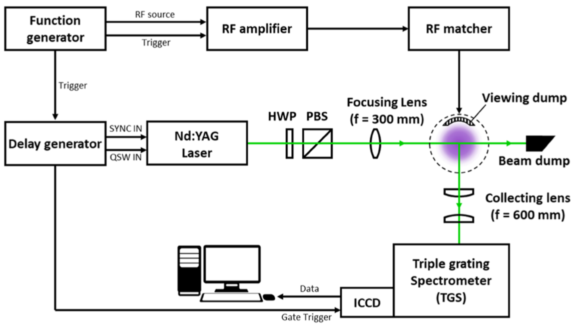

Fig. 1. Block diagram of the Thomson scattering system. Black and green lines indicate electrical signals and light, respectively.

2.1. Laser injection system

Laser injection system transfers the laser beam to the plasma with the optical loss as low as possible. The polarization direction and a focal point are controlled by the system. Unlike the typical TS systems for vacuum plasmas, the high energy laser cannot be adopted due to the breakdown of the background gas and multi-photon ionization will give perturbations to the target plasma. In this reason, a commercial Nd:YAG laser (NL220, EKSPLA) with a high repetition rate of 1 kHz is adopted as a light source of the TS system. Its energy is 5 mJ at the second harmonic wavelength of 532 nm and the pulse duration is 8 ns. Along the beam flight path of 1 m, it passes a combination of half wave-plate (HWP) and an polarization beam splitter (PBS), a focusing lens (f = 300 mm), and absorbed by a beam dump. In the system, the beam is polarized in vertical direction (*s-like*) at the plasma so that the differential cross section of TS towards collection optics to be maximized.

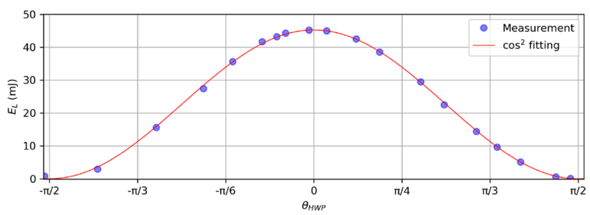

Fig. 2. Test result of laser attenuator consist of a half-wave plate and a polarization beam splitter.

It should be noted that the purpose of the HWP and PBS is controlling not only the polarization direction but also the laser energy, as a laser attenuator. Since the installed laser has only *on* and *off* modes, continuous energy control is done by the attenuator. Fig. 2 is the test result of the attenuator using a different Nd:YAG laser, which shows the variation of the laser energy with respect to the angle of the HWP.

2.2. Collection optics

The intensity of the Thomson scattered light depends on the incident laser energy, plasma density, the total transmission of the system, and the collection solid angle. Therefore, the collection optics should have minimum optical loss and its structure, such as lens housing, should not limit the optical transmission. We installed two achromatic anti-reflection coated lenes. The reflection of each lens is < 0.6% at 532 nm ± 15 nm, and the effective diameter of coating is 90 mm. The focal length of both lens is 600 mm to maintain the magnification of one, so the performance of the spectrometer is not to be affected.

2.3. Triple grating spectrometer

For successful TS measurement, the stray light and Rayleigh scattering must be cared, because such a high intensity signal at the laser wavelength can give an influence to the ICCD pixels for TS spectrum. In the case of high temperature plasmas, interference filter can be installed to block the wavelength of the incident laser as the TS spectrum has broad wavelength range [3, 4]. However, it is not suitable for low temperature plasma, because the typical bandwidth of the filters is similar to the wavelength range of the TS spectrum.

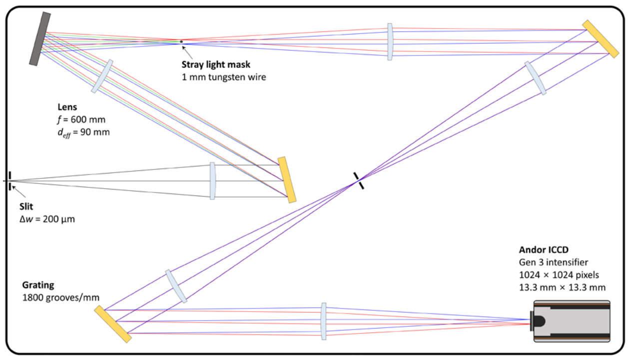

Fig. 3. Design of a triple grating spectrometer

Triple grating spectrometer (TGS) is powerful spectrometer which has been utilized on the TS systems for low temperature atmospheric plasmas [8-10]. The TGS is designed to effectively block out unwanted wavelength, allowing for precise measurement of the TS spectrum. The TGS can be separated by two parts: one is a double monochromator which blocks the input laser wavelength (532 nm), and the other part is a single monochromator that spreads the TS spectrum. The TGS (made by WEVE, Korea) is based on the work of van de Sande (reference [8]), who has extensively studied and developed TGS for the low temperature plasmas.

As shown in Fig. 3, the scattered light is first focused onto the entrance slit of the spectrometer by the collection optics. The light then passes through three diffraction gratings and achromatic lenses. The gratings equipped in the spectrometer are identical, and the line density of 1800 grooves/mm is selected. The lenses in the spectrometer have the focal length of 600 mm and the effective diameter of 90 mm, which match the collection optics. The narrow wavelength range of 532 nm ± 0.8 nm is blocked by a 1-mm-thick tungsten wire. The light spread at the final grating will be focused onto the ICCD (ISTAR 334T-18F-63, ANDOR), which is synchronized to the laser and the plasma.

3. Conclusion

As the first diagnostic system of the experiment for quantitative measurement of radicals and plasma, Thomson scattering system for the cold atmospheric plasma has been designed. To increase the SNR, a high repetition rate laser was employed to accumulate a large number of laser pulses. The triple grating spectrometer is prepared to reject the stray light and Rayleigh scattered light. In initial phase of development, we will start with a microwave plasma jet which can provide sufficiently high electron density for TS, to determine the efficiency of the diagnostic system as well as the minimum measurable electron density.

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