Initial result of collective Thomson scattering using 77 GHz gyrotron for bulk and tail ion diagnostics in the Large Helical Device

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Abstract. The collective Thomson scattering (CTS) technique has been utilized with the backscattering configuration in the collective scattering regime to diagnose the velocity distribution functions in the Large Helical Device (LHD). The receiver was equipped with 16 channels and the first test has been carried out using the eight channels for scattered radiation and these channels cover a few GHz frequency shift from the 76.95 GHz probe beam. During the discharge, the electron density and temperature at the central region of the LHD are $1 \times 10^{19} \text{m}^{-3}$ and 1.0 keV, respectively. The probing beam with rectangular wave modulation is injected by 50 Hz in order to be distinct from the background electron cyclotron emission (ECE). The scattered radiation is resolved successfully at each channel of CTS receiver system. The detected signals of bulk ion and electron components are by a factor of $10 \sim 10^2$ larger than the background ECE signal. We found that the measured spectra are in reasonably agreement with the theoretical spectra calculated by using the reliable measured electron temperature and density for input parameters. The CTS receiver system will be improved to obtain more accurate velocity distributions in high temperature plasmas.

1. Introduction
Confined energetic particle diagnostics is a major concern to thermo nuclear fusion for maintaining and controlling the self burning. One of the strong tools considered is a collective Thomson scattering diagnostic. Recent developments of powerful radiation sources, like mega watt class gyrotrons, made it possible to detect the scattered electromagnetic waves by fluctuations in plasmas [1, 2, 3]. For the bulk and tail ion temperature measurements in the LHD, the collective Thomson scattering (CTS) diagnostic has been proposed using the existing electron cyclotron resonance heating (ECRH) by gyrotron with the frequency of 77 GHz. The CTS is also assessed numerically using the injector and receiver geometry of the LHD with accessible plasma parameters[4]. The results show that with the CTS technique is possible to obtain useful information on both the thermal and fast ions from the scattered radiation. However the careful analysis is still required, because it is found that the shape and radiation power of scattered spectra depend strongly on the geometrical and experimental conditions. In addition, electron cyclotron emission (ECE) should be taken into account as a background noise for
CTS diagnostic. The ECE levels in some scattering geometries and magnetic configurations are estimated from the calculation on the line of sight [5]. The study found that the ECE noise becomes the minimum for O-mode radiation at the magnetic field of 2.2 Tesla. Even though the ECE level at 2.75 Tesla is relatively high compared with that of 2.2 Tesla, the preliminary results in a LHD discharge, and found a more effective CTS signal in a LHD discharge.

In this paper we show the progress in calculated spectra based on the density fluctuation and the estimated output signals by using the receiver configuration with 8 channels. The output signals estimated here are compared with those of the measured scattered radiations. These results are discussed, and the receiver system will be improved toward the forthcoming LHD campaign in autumn on 2009.

2. Collective region in LHD

The CTS diagnostic requires the spectrum analysis of the fluctuation wave vector $k^\delta$ to obtain the thermal and fast ion distribution functions with the relation $k^\delta = k^i - k^i$. Here $k^i$ and $k^s$ are the incident and the scattered radiations, respectively. Since the existing ECRH system is utilized as an initial trial, the port locations for probing and receiving beams are limited to the backscattering and near perpendicular to the toroidal magnetic field. Figure 1 shows the collective scattering region, where the electron and the ion distribution functions are distinguished from the scattered radiations. The Salpeter parameter $\alpha = 1/(k^\delta \lambda_D) = 1/(2 |k^i| \lambda_D \sin(\theta/2))$ as a function of scattering angle for 77 GHz probing radiation at different plasma parameters. Here $\lambda_D$ is the Debye length. The Salpeter parameter should be larger than a unity. In any case, we found that $\alpha$ is more than a unity for the scattering angle from 0 to $\pi$ radians in LHD discharges with the electron temperature of 1~10 keV and the density of $5x10^{18}$~$10^{20}$ m$^{-3}$.

![Figure 1. The Salpeter parameter $\alpha$ as a function of scattering angle for CTS diagnostics in LHD. Gyrotron frequency of 77 GHz is used.](image)

3. Scattering geometries in LHD

The CTS diagnostics in LHD has the potential to give us the information on the bulk and the fast ion velocity distribution function. Figure 2 shows the probing and the scattered beams in the same poloidal cross section of LHD. The variation to the toroidal angle is not so large for both beams. Therefore the measured velocity distribution function is in the perpendicular direction and not in parallel due to the backscattering and near perpendicular geometries. This geometry was set to the LHD discharge of #91756, which is shown in the later section. The scattering volume is located at $z = 0.5$ m from the mid plane of LHD, and is located at the most probable value of the normalized minor radius $r/a \sim 0.7$ [5]. The probe and receiving beams are Gaussian in shape and have a beam waist of a few cm. The width of beam overlap extends from $r/a = 0.5$ to 1.0. When the $z$ is increased, the bulk and tail levels decrease, as is shown in figure 2 right. Our present CTS diagnostic neglect the width of beam overlap. The toroidal magnetic field at the magnetic axis on R=3.6 m becomes 2.75 Tesla.
The small amount of the impurity has a possibility to change the CTS spectrum shape. The precision of measured ion and electron temperatures becomes worse due to the shape changes. In the typical case, the impurity carbon $C_{6}^{+}$ is added to 10% of the electron density. In this paper, the impurity effect is neglected, but it should be included for more accurate measurement of $T_e$.

![Figure 2](image)

**Figure 2.** The incident and scattered wave vectors at the magnetic field of 2.75 Tesla at the magnetic axis of 3.6 m in LHD(left figure). Different scattering geometries are shown where the scattering volume is localized at $Z = 0.0, 0.3, 0.5, 0.7,$ and $1.0$. ECR layers and magnetic flux surfaces are drawn. The CTS spectra are varied with the same scattering geometries as the left figure. The electron density $n_e$ and the ion density $n_i$ are equal to $1 \times 10^{19} \text{ m}^{-3}$, and their temperatures are set to $1 \text{ keV}$.

### 4. CTS spectra and their output at detectors of a receiver system

The CTS spectra are calculated based on the collective scattering theory, proposed in the references of [6, 7]. In the previous paper [4], the fluctuation power is provided by a scattering form factor and the geometrical factor $\Gamma \sim 1$. This assumption is valid for the rough estimate. However, the geometrical factor can change in the X-/O-mode and their frequencies. For more accurate CTS spectra, the X-/O-mode electromagnetic wave in plasmas of the incident and the scattered beams was calculated, based on the references of [6, 7, 8]. However, the theory does not treat the complete electromagnetic fluctuation, and it will be included in the future. The incident and scattered waves of O-mode are chosen in the experiments, because of free from the cut off in this condition, hence less prone to reflection.

The receiver system employed is a high sensitive heterodyne radiometer. It consists of mainly the notch filter, a pin switch, the mixer with local oscillator, filter bank with band pass filters, and crystal detectors. The details are noted in the references of [4, 5]. The specification of the notch filter at the centre frequency of 76.95GHz is the attenuation of 120 dB with the bandwidth of 200 MHz, and -3dB with bandwidth of 400 MHz.

The scattered electromagnetic wave propagates through the notch filter, and is converted at the mixer in the range from 300 MHz to 10 GHz. The following filter bank separates the wave into 16 channels, which can detect the scattered radiations with the bandwidth of 100 MHz for bulk component channels and 200 MHz for high energy ones. The local oscillator frequency of 74 GHz was chosen originally, but in the experiment we had to use the alternative oscillator frequency of 77.845 GHz temporarily, thus only 8 channels are used.

In LHD discharge #91756, the CTS probing beam is injected at the modulation frequency of 50 Hz to subtract the background ECE radiation from the scattered radiation. The background ECE radiation
signal is averaged for a few ms from the trailing edge during the gyrotron off periods. During \( t = 0.9 \sim 1.8 \) sec the discharge is sustained by ECRH without energetic neutral beams. The spatial profiles of the electron temperature and density are measured by incoherent Thomson scattering. The reliable parameters become \( T_e = 0.5 \) keV and \( n_e = 1 \times 10^{19} \) m\(^{-3}\) at \( R = 4.1 \) m. The measured and expected CTS spectra are plotted for the resolved 8 channels in figure 3. The calculated CTS spectrum is obtained by assuming that the ion and the electron temperatures are equilibrium condition. It is found that the expected CTS spectrum for the temperatures of 0.5 keV is in better agreement with the measured one, while the discrepancy becomes larger for the temperatures of more than 1.0 keV. The spectrum shape is in agreement. However we still need to check the validity of absolute signal levels.

The CTS diagnostics is demonstrated successfully. We expand the number of filter bank channels from 8 to 32 with using the original local frequency of 74 GHz in the forthcoming experimental campaign.

![Figure 3](image)

**Figure 3.** Measured CTS spectrum (closed circles) is resolved into 8 channels during \( t = 0.7 \sim 0.9 \) s (left). Each channel is the sum of both side band signals. The calculated CTS spectrum (line) is plotted for \( T_e = T_i = 0.5 \) keV. Right figure shows that the characteristics on the notch filter including the PIN-switch and the 8 channel band pass filters are overlaid at the local oscillator frequency of 77.845 GHz, which corresponds to 0.895 GHz on the abscissa.

**Acknowledgment**

We would like to thank Dr. Korsholm and CTS group of RISØ national laboratory for useful discussions.

**5. References**

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