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154 GHz Collective Thomson Scattering in LHD

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ABSTRACT: Collective Thomson scattering (CTS) was developed by using a 154GHz gyrotron, and the first data has been obtained. Already, 77GHz CTS has worked successfully. However, in order to access higher density region, 154GHz option enhances the usability that reduces the refraction effect, which deteriorates in the local measurements. The system in the down converted frequency was almost identical to the system for 77GHz. Probing beam, a notch filter, a mixer, and a local oscillator in the receiver system for 77 GHz option were replaced to those for the 154GHz option. 154GHz gyrotron was originally prepared for the second harmonic electron cyclotron heating (ECRH) at 2.75T. However, scattering signal was masked by the second harmonic electron cyclotron emission (ECE) at 2.75T. Therefore, 154GHz CTS was operated at 1.375T with fourth harmonic ECE, and an acceptable signal to noise ratio was obtained. There is a signature of fast ion components with neutral beam (NB) injection. In addition, the CTS spectrum became broader in hydrogen discharge than in deuterium discharge, as the theoretical CTS spectrum expects. This observation indicates a possibility to identify ion species ratio by the 154 GHz CTS diagnostic.

KEYWORDS: microwave, collective Thomson scattering, gyrotron, fast ion

Contents

1. Introduction

The measurements of the confined fast ions is a very important physics quantity in the magnetically confined plasma experiments. While charge exchange spectroscopies are widely used in the present device, in the reactor-relevant machine such as ITER, measurements become difficult due to the strong attenuation of the diagnostic beam. Passive spectroscopy around X ray region is another candidate to measure confined thermal ions. However, Abel inversion or tomographic reconstruction is required with large number of channels and becomes difficult under severe port constraints. A collective Thomson scattering (CTS) using microwave is a powerful diagnostic to measure confined ions for the present and future devices, since it has a good accessibility with relatively small waveguide and powerful microwave probe which can be transmitted to the plasma core with the properly chosen frequency and polarization. CTS was developed to measure confined bulk ions by using high power far infrared pulsed laser [1,2]. Then, high power microwave sources were used to measure confined fast ions [3,4] as well as bulk ion ratio [5].

In Large Helical Device (LHD), 77GHz CTS was developed in order to measure both bulk and fast ion populations [6-11]. The advantage of 77GHz option is good signal intensity. Clear indication of fast ion components are observed at B_t = 2.75 operation [7,9,10]. However, the 77GHz CTS suffered from beam refraction at $n_e>\sim2x10^{19}m^{-3}$, and stray radiation can cause multiple scattering[11]. These cause uncertainty of measurement location. In order to reduce these problems, a 154GHz CTS was developed and installed in LHD. The 154GHz gyrotron was originally prepared for the second harmonic ECRH at 2.75T and is working routinely with good stability. For the CTS, mode purity becomes important rather than the power, thus, operation was tuned with optimized magnet of electron gun for the mode purity [8].

However, there is a critical disadvantage of the 154GHz option. It is the reduction of the scattering cross-section in comparison to the 77 GHz option. Figure 1 shows comparison of the spectrum between 77 and 154GHz for the same plasma parameters (T_e=1keV, $n_e=1x10^{19}m^{-3}$, T_i=1keV, T_{ifast}=40keV, $n_{ifast}=5x10^{17}m^{-3}$). The parameters are relevant to the LHD experiments.

As shown in Fig.1, scattering intensity becomes more than two orders of magnitude lower. On the other hand, ECE background significantly increases.

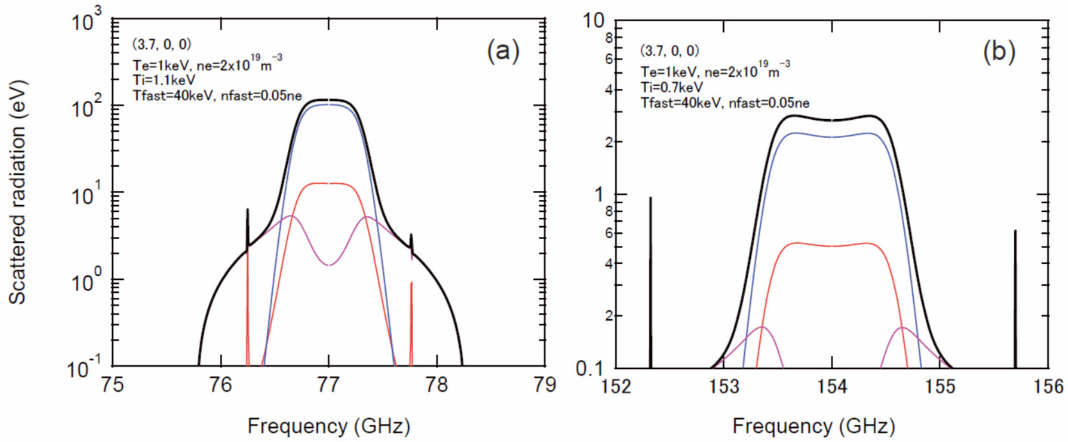

Fig.1 CTS spectra of (a) 77GHz and (b) 154GHz T_e=1keV, n_e=1x10^{19}m^{-3}, T_i=1keV, T_{ifast}=40keV, n_{ifast}=5x10^{17}m^{-3} black; total spectrum, blue; bulk ion components, orange; electron components, violet; fast ion components

Figure 2 shows ECE spectrum for different harmonics in the X mode. As shown in Fig.2, the second harmonic ECE is the highest, and then, higher harmonics become weaker. The 77GHz CTS can eliminate the ECE background from beam modulation at 2.75T[7,9]. However, this becomes very difficult for 154GHz CTS at 2.75T because of the much smaller scattering power as shown in Fig.1. In the 19th experimental campaign of LHD, which started in February 2017, CTS was tried at Bt=2.75T at first, however, no clear indication of the signal was obtained after subtracting background ECE using gyrotron modulation. Therefore, we decided to operate 154GHz CTS at 1.375T.

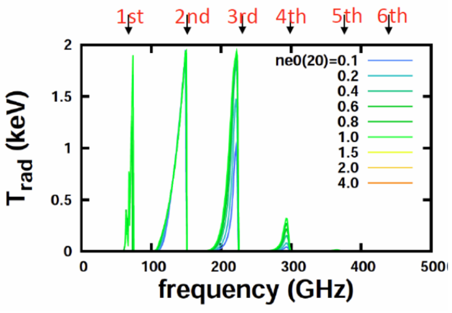

Fig.2 ECE spectrum at different density

This article describes the first result of 154GHz of CTS in LHD of the National Institute for Fusion Science. In Section 2, outlooks for the system (scattering geometry and detection system) are described. In Section 3, measurements results are shown. Finally, summary is described in Section 4.

2. System of 154GHz collective Thomson scattering in LHD

2.1 Scattering geometry

The 154GHz gyrotron was originally prepared for the EC heating for 2.75T second harmonic X mode heating. In LHD, there are presently three 77GHz and two 154GHz gyrotrons available [11]. Each has an output power of 1MW for short pulse operation (<2sec) and 0.3MW for CW operation. The beam travels from gyrotron hall to LHD experimental room about 100m distant by 1.25

inches corrugated waveguide. For the CTS operation, one of the waveguide lines was switched from gyrotron source to CTS detection.

Figure 3 shows scattering geometry of 154GHz CTS. The 154GHz gyrotron power was injected horizontally with a certain tangential angle. The scattering position is plasma center and the size of the scattering volume is around 20% of the minor radius. The refraction was negligible at the operational regime of CTS experiments (<~$2\text{x}10^{19}\text{m}^{-3}$), thus the position of the scattering volume was accurately determined.

With 1.375T, the fourth harmonic layer is existing on the injected beam path. However, heating was negligibly small and the 4th harmonic ECE background is negligibly small, as shown in Fig.2. The power is modulated with 10msec on and 40msec off. Due to the small ECE background, the modulation was not necessary to subtract the background ECE. However, since beam damping was not prepared, injection pulse length was restricted up to 10msec in order to prevent damage to the vessel wall. On the other hand, in the 77GHz option, fundamental resonance works as a beam dump, and ECH background subtraction was necessary with modulated ECH. Also, in 77GHz option heating power should be reduced so not to change bulk T_e [10].

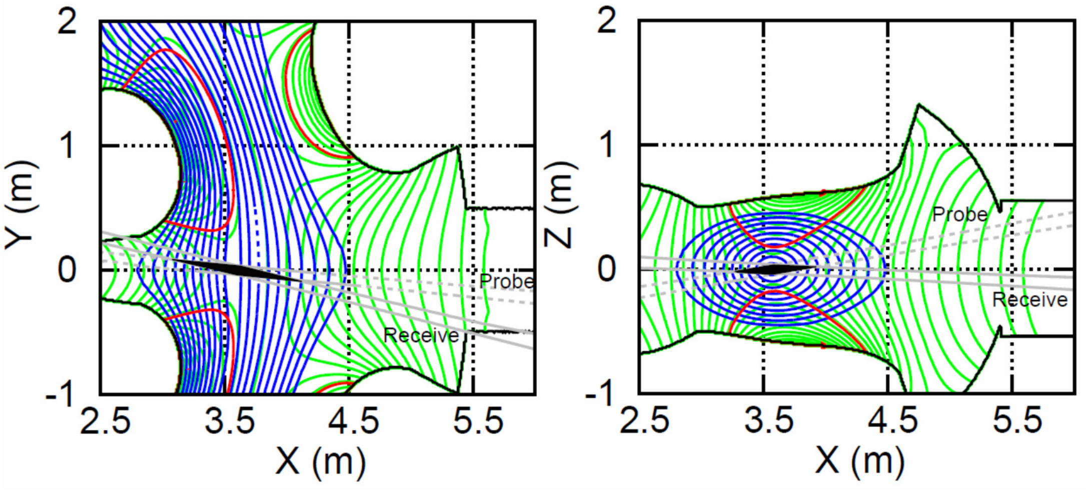

Fig.3 Scattering layout (a) top view and (b) side view
Blue: flux surface; Green: magnetic field strength contour; Red: 4th EC resonance of 1.375T; Plain gray: receiving beam; Dotted gray: probe beam. Black region indicates scattering volume

2.2 Detection System

Figure 4 show the detection system of the 154GHz CTS. The same detection system as for the 77GHz CTS is used. The notch filter and the local oscillator were replaced for 154GHz. These filters were manufactured by General Atomics. Two series of notch filter were connected. Each notch filter provides the attenuation of 60dB, then, totally stray radiation is attenuated by 120dB. The 3dB full width is 900MHz. Because of the technical difficulty, the band width of the notch filters is wider than that of 77GHz notch filter, which is 250MHz [7]. The harmonic synthesizer is used for the local oscillator, and can be used for both 77 and 154GHz. Thus, the detection system can be easily replaced from 77GHz to 154GHz and vice versa. Scattering signal has a bandwidth of around 3GHz around the probing frequency. Signal of 154+-3GHz is down-converted to 0~6GHz by heterodyne mixing.

Signals are divided into two acquisition systems. One is 32 channel filter bank system and the other is a digital acquisition system. Low frequency band +-1GHz around probing frequency is filtered by 100MHz band width and higher frequency components are filtered by 200MHz bandwidth. The output of the filter bank system is acquired at 100kHz sampling rate throughout the entire plasma discharge. Filter bank output is used to measure time history of overall spectrum. In particular, the filter bank system is a powerful tool to measure changes of the scattering signal in the volume scan experiments to identify the scattering volume location. Digital system is used to measure fine structure of the spectrum. The signal is acquired at 12.5GHz and acquisition duration is 80msec. Thus, the timing of the acquisition needs to be adjusted. Spurious modes become visible by the fast digital acquisition system [8]. The tuning of the gyrotron is performed by checking the fast digitized signal. Also, fine structure of the bulk ion components can be measured. In particular, the fast acquisition system is useful for the ion Bernstein wave measurements, which can provide the plasma isotope ratio[10]. The fast ion measurements are mainly done by the filter bank system because the fast ion-induced scattering power density is much smaller than bulk ion-induced scattering power density, and thus, the amplifier gains must be adjusted depending on the signal intensity.

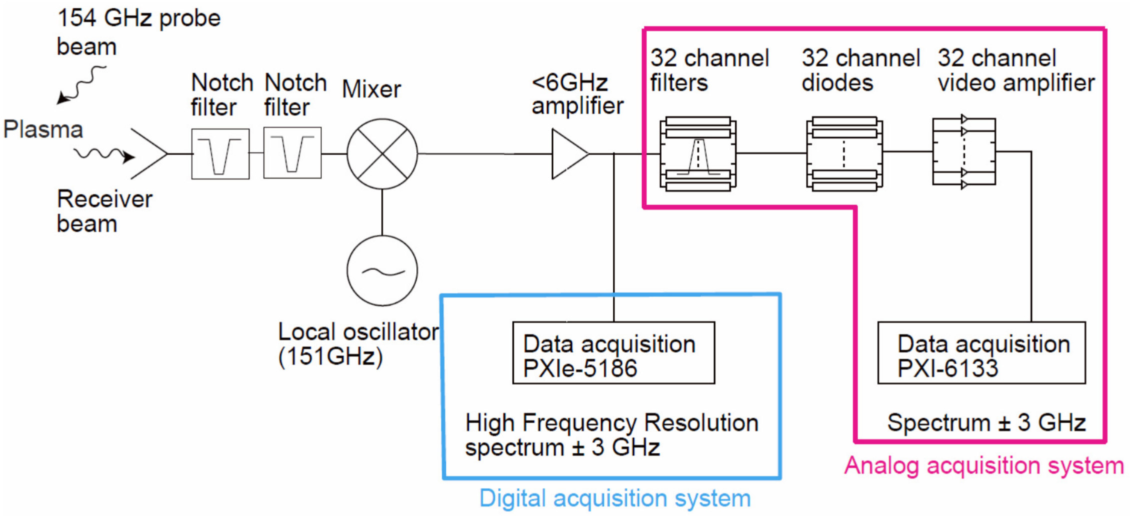

Fig. 4 Detection system of 154GHz CTS in LHD

3. Experimental results

3.1 Scattering volume scan experiments

Figure 5 shows a time trace of scattering signal in the volume scan experiment. The deuterium plasma was sustained by 13MW Neutral Beam Injection (NBI). The 154GHz gyrotron radiation was injected for CTS measurements. However, it did not affect plasma temperature, since there was no electron cyclotron resonance for this frequency at the used value of the magnetic field. As shown in Fig.5 (a) and (b), both electron density and ion temperatures were constant in time. Figure 5 (c) shows monitor of the 154GHz gyrotron power. Gyrotron was switched on for 10msec and off for 40msec. The shorter duty cycle (20%) compared with 77GHz CTS (50% duty cycle) is in order to prevent damage to the vacuum vessel wall due to the shine through radiation at 154GHz.

The injection angle of the probe beam was scanned by the motor driven antenna during the shot. The scattering volume, which is shown by black colored area in Fig.2, changes from zero to its maximum and simultaneously scattering signal changes proportionally to the scattering volume. These volume scan experiments are necessary to maximize the scattering signal and determine the location of the scattering volume.

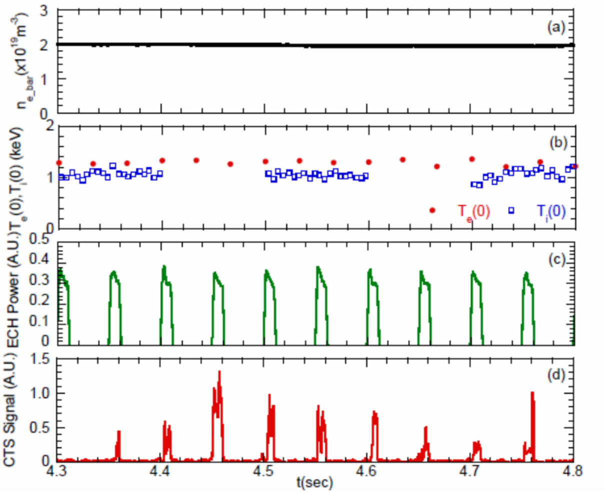

Fig. 5 Time trace of CTS spectrum of scattering volume scan experiment (a) line averaged density (b) central T_e and T_i (c) 154GHz ECH power (d) CTS signal, R_{ax}=3.6m, B_t=1.375T, shot138847

Figure 5 (d) shows the scattering signal at the low frequency band filter bank output. As shown in Fig.5 (d), clear scattering signal was observed, when gyrotron was switched on. It should be emphasized that the signal was almost zero during gyrotron-off phase and it is a large contrast to the 77GHz CTS, where signals due to ECE background were visible during gyrotron off phase (Fig.4 of ref. 9). The scattering signal became maximum at t = 4.45sec. At this time, the scattering volume became maximum and antenna alignment was optimal.

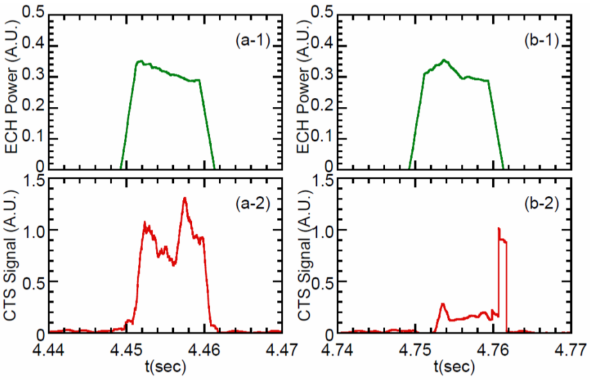

Fig.6 Expanded view of ECRH power and scattering signal at maximum ((a-1), (a-2)) and minimum signal timing ((b-1), (b-2))

Figure 6 shows the expanded view of the ECH power and scattering signal at the time of the maximal and minimal signals. As shown in Fig.6 (a-1) and (b-1), ECH power was almost identical. While scattering signal is clearly different as shown in Fig.6 (a-2) and (b-2). The time averaged scattering signal is clearly higher at t=4.45-4.46sec. However, as shown in Fig.6 (b-2), spike signal appears at t=4.76sec when the gyrotron turned off. This is due to the appearance of a spurious mode. In order to eliminate such spurious mode noise, Pin switch should be set before mixer.

3.2 CTS spectrum

CTS spectrum was obtained in deuterium and hydrogen plasma. In both plasmas, the bulk plasma parameters were almost identical (T_e=1keV, n_e=1x10^{19}m^{-3}, and T_i=1keV). Figure 7 shows examples of 154GHz CTS spectra. Presently, signals are not absolutely calibrated, but relatively calibrated assuming background ECE was constant. The relative calibration was performed at

Bt=2.75T. In Fig.7, experimental data and theoretical calculations with different bulk temperatures were shown. In theoretical calculations, T_e was fixed at 1keV, n_e was fixed at $1\text{x}10^{19}\text{m}^{-3}$, but different T_i were used for the calculations in order to match the measured spectrum. In the calculation, the fast ion components were not included. Both experimental data and theoretical calculations show broader spectrum in hydrogen plasma than deuterium plasma showing qualitative agreement between experiments and theory. The low frequency shifted channels (within 154+-0.5GHz) well agrees with the 1keV bulk ion temperature, which is close to measured T_i by the charge exchange spectroscopy and Argon Doppler broadening spectroscopy. There are clear discrepancies between calculations and experimental data in high frequency shifted band (<153.5 and >154.5GHz). The discrepancy is likely due to the contribution of the fast ion components generated by NBI.

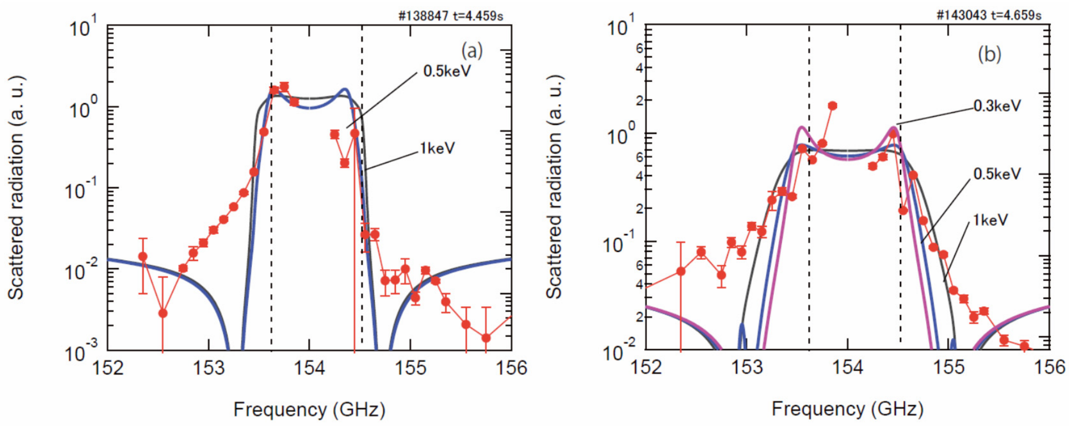

Fig.7 154GHz CTS spectrum of almost identical plasma (a) deuterium and (b) hydrogen Experimental data are shown by symbol, and theoretical calculations are shown by lines.

4. Summary

In LHD, collective Thomson scattering using the 154GHz gyrotron is installed and the first data has been obtained. In comparison with the 77GHz diagnostic, refraction and multiple scattering effects are expected to be small and measurements become more local. However, scattering signal becomes more than one order magnitude weaker. At Bt=2.74T, signals were completely masked by the ECE background radiation. At Bt=1.375T with 4th harmonic ECE resonance, CTS signals were detected. ECE background was almost negligible and scattering volume scan experiments determined the position of scattering volume. Broader CTS spectrum was obtained in hydrogen than in deuterium plasmas, as theory predicts. There are some indications of the fast ion components. However, further analysis with fast ion simulation is necessary to confirm the phenomena. Negligible ECE is a great advantage of 154GHz option at 1.375T. 300GHz option will be attractive as a future CTS probe, since ECE background around 300GHz is negligible at 2.75T, where plasma performance is the best in LHD[12-14].

Acknowledgments

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