論文の内容の要旨

A Study of Electron Velocity Distribution Function in TST-2 Spherical Tokamak Plasma by Double-Pass Thomson Scattering Diagnostics

(ダブルパストムソン散乱計測を用いたTST-2球状トカマクプラズマの電子速度分布関数に関する研究)

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The electron distribution function of plasma tends to be an isotropic Maxwellian distribution function in an equilibrium. In high temperature fusion plasmas, however, the distribution functions can be distorted from various reasons, such as electric field, magnetic mirror effect, wave heating and neutral beam injection. Such anisotropy of velocity distribution function results in deformation of plasma pressure from flux function and destabilization of the ballooning modes. Therefore, it is important to measure the distribution function and to determine whether the distribution function is deformed or not. However, there was no diagnostics with which the anisotropy of velocity distribution function in the core of plasma can be measured.

Thomson scattering diagnostic is a method to measure electron temperature and density from Thomson scattering light of a laser beam injected to a plasma. The wavelength spectrum of the scattering light reflects Doppler shift of the electrons along the scattering vector. The width of the spectrum represents the electron temperature and the intensity of the scattering light is proportional to the electron density. A laser beam passes through a plasma once in a standard Thomson scattering diagnostic. In contrast, the laser beam is reflected back to the plasma and forward- and backward-scattering lights can be measured by a single collection optics in a double-pass Thomson scattering diagnostic. Therefore, measurements with two

different scattering vectors are possible, and we can obtain two dimensional velocity distribution function of thermal electrons.

The double-pass Thomson scattering diagnostic system was developed on the TST-2 device (Fig.1). This is the first diagnostics to measure two dimensional velocity distribution function of thermal electrons at the core of plasma. In our system, the velocity distribution functions parallel and perpendicular to the magnetic field can be measured (Fig.2).

The double-pass Thomson scattering system consists of a laser injection optics, a collection optics and a detection system. A Nd:YAG laser with a beam energy of 1.6 J and a pulse width of 10 ns was used. The laser is injected into the plasma, and reflected back by a spherical mirror. The Thomson scattering lights, which are excited by the double-passed laser, are collected with a collection spherical mirror and are transferred into a polychromator by a fiber with a numerical aperture of 0.37. There are six wavelength channels in each polychromator. Each channel consists of an interference filter, an avalanche photodiode and a two stage amplifier. The detected signal is digitized by an oscilloscope. The forward- and backward-scattering pulses are separated clearly with the fast and low-noise detection system.

Absolute and relative sensitivity calibrations are essential to estimate the electron density, the electron temperature and the electron current density. Particularly, it is important to evaluate and to reduce the error of the system in order to confirm finite temperature anisotropy. The systematic error of "absolute" sensitivity calibration was suppressed below 10% by reducing the noise source such as an oscillation of a fiber holder. The absolute calibration was validated by comparing with the result from the microwave interferometer, by which line integrated electron density is obtained. In addition, the systematic error of "relative" sensitivity calibration of each channel was suppressed below 10% by reducing the noise source such as dependence on environmental temperature. In addition to these systematic errors, random error was evaluated in detail. The result of evaluation was used as a typical noise level for Monte Carlo simulation and the fitting procedure of the experiments.

Several calculations were performed to evaluate various effects causing the velocity distribution function deformation and resultant current under the Ohmic electric field. The collision frequency of electron with neutral particles for the present plasma is calculated to be much lower than the collision of electron with ions. The contribution of fast electron was also estimated, and it was found to be negligible. The last candidate situation is that the velocity distribution function is determined by the collisions between thermal electrons and ions under the electric field. This situation is calculated by a Fokker-Planck code CQL3D. It was found that 10% temperature anisotropy is expected without any shift.

Electron velocity distribution functions of Ohmic heated plasmas, where we expect deformations of electron velocity distribution function, were measured with the double-pass Thomson scattering system. Measurement was performed at the plasma center and the plasma edge. The scattering light spectrum was analyzed assuming the following models: three temperature model, shifted model and hybrid model. Theoretically, any of these models can represent the velocity distribution function of electrons accelerated by the Ohmic electric field. The goodnesses of fitting for these three models were compared. As a result, the three temperature model is better than the shifted model at both of the plasma center and edge, while the measured velocity distribution was not expressed enough with both of the models. It suggests that other fitting parameter is required to represent the distribution.

We found finite difference between the perpendicular and the parallel temperatures (Fig.3). The co-directed (i.e., the direction of electron acceleration) parallel temperature is almost always higher than the perpendicular temperature, and the counter-directed parallel temperature is almost always lower than the others. Comparing the temperatures along the direction perpendicular and parallel to the magnetic field, there was temperature anisotropy of around 20% at the plasma center, while around 50% at the plasma edge. This is the first measurement of temperature anisotropy for thermal electrons in magnetically confined high temperature plasmas. The electron current density of the plasma was calculated with the assumption of the three temperature model. The values are close to the average current density estimated from the total current. The result suggests that the contribution of thermal electrons to the plasma current is relatively large in the Ohmic discharge. This is consistent with the calculation by the CQL3D. It was also revealed that anisotropy of thermal electron temperature appears even in plasmas with a relatively high collision frequency (which is about a hundred times higher than that in fusion plasmas).

The results of our investigation would contribute to the understanding of anisotropy of plasma velocity distribution function, and demonstrated the possibility of current density measurement with Thomson scattering.

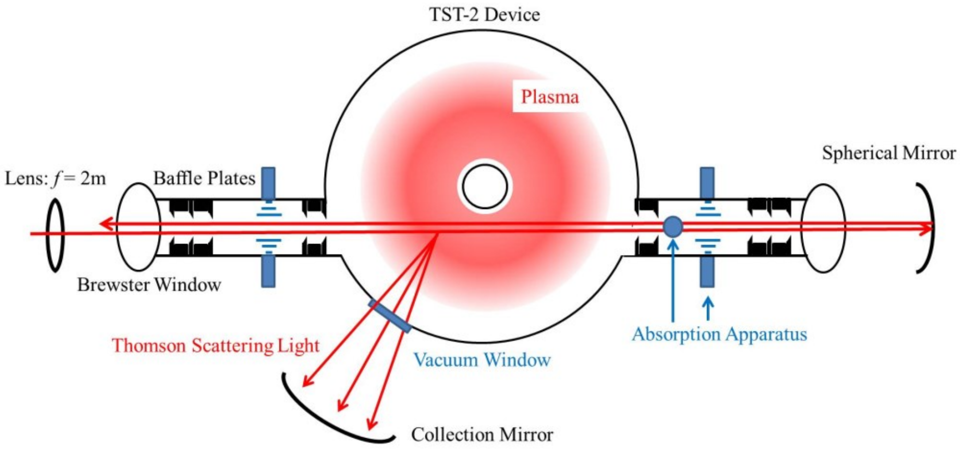

Fig.1: Schematic of the double-pass Thomson scattering diagnostic system.

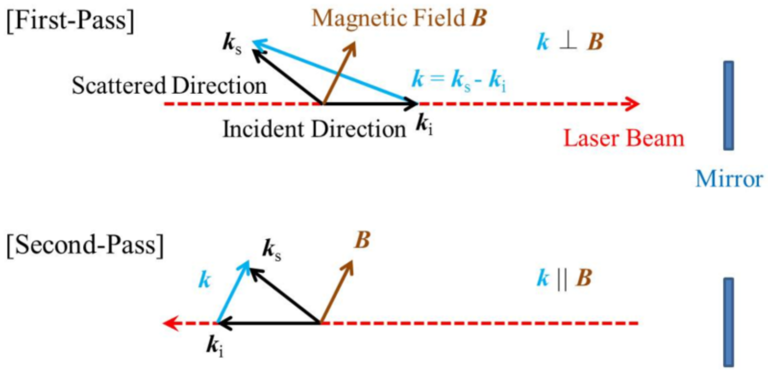

Fig.2: Principle of the measurement of two dimensional velocity distribution function with the double-pass Thomson scattering.

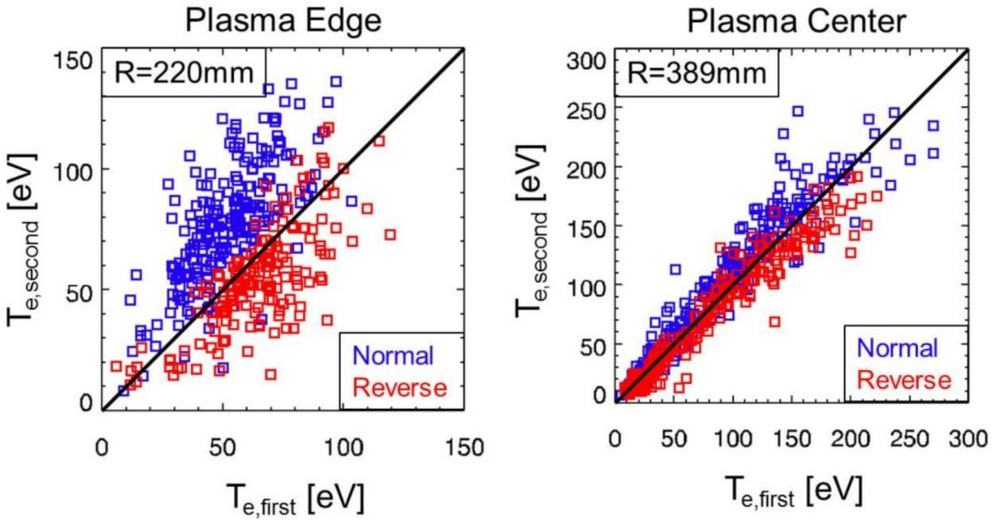

Fig.3: Relationship between temperatures measured by first- and second-pass. $T_{\mathrm{e,first}}$ corresponds to the temperature perpendicular to the field. $T_{\mathrm{e,second}}$ of blue and red symbol corresponds to co- and counter-directed temperature, respectively.