論文の内容の要旨

Wavenumber Measurement of the Lower Hybrid Wave by an Electrostatic Probe with an Embedded High Impedance Resistor in the TST-2 Spherical Tokamak (TST-2球状トカマクにおける高抵抗素子内蔵型静電プローブを用いた低域混成波の波数計測)

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Nuclear fusion is expected to become one of the main energy sources in the future society. The tokamak, which confines the plasma in the shape of a "doughnut" by magnetic fields, is regarded as the leading candidate for magnetic fusion power plant. There is a special class of tokamak, called the spherical tokamak (ST), which confines the plasma in the shape closer to a sphere rather than a doughnut. The ST has two advantages over the conventional tokamak: being more compact and having better stability at high β (β is the ratio of the plasma pressure to the magnetic pressure), leading to the possibility of realizing a more economical fusion power plant.

In order to realize the ST fusion power plant, the elimination of (or at least reduction of the size of) the ohmic heating (OH) solenoid is necessary. The OH solenoid is the coil located on the inboard side of the torus which is normally used to drive the plasma current (necessary to confine the tokamak plasma) inductively. However, there are two fatal disadvantages: inductive current drive cannot be used to drive the plasma current in steady state, and it occupies the precious space on the inboard side of the torus. A new method of non-inductive plasma current drive, capable of steady state operation, is needed. Radio frequency (RF) waves offer a possibility to drive the plasma current in steady state by giving their momentum to the plasma continuously. Among RF waves, the lower hybrid wave (LHW) is promising due to its high current drive efficiency during the initial phase of tokamak (including ST) plasmas. Although many successful demonstrations of non-inductive plasma current drive using the LHW have been reported, the development of efficient plasma current drive by the LHW in ST devices has just begun.

In the Tokyo Spherical Tokamak-2 (TST-2) device, located on Kashiwa Campus of the University of Tokyo, non-inductive plasma current drive experiments using the LHW at a frequency of 200 MHz are being conducted. Although nearly 20 kA of plasma current has been achieved already, the current drive efficiency is still low, and needs to be improved. In order to accomplish this, it is necessary to understand the physics of current drive in the initial ST plasma driven by the LHW, and to use this knowledge to improve the efficiency and reach higher levels of plasma current. Direct measurements of the LHW amplitude and wave number in ST devices can provide important information because the wavenumber determines wave propagation and absorption in the plasma.

A new method for measuring the wavenumber of the LHW using an electrostatic probe with an embedded high impedance ($100\,\mathrm{k\Omega}$) non-magnetic resistor is suggested (Fig. 1) and used for LHW wavenumber measurement at 200 MHz in TST-2. The LHW is the slow wave and is an electrostatic wave, which is characterized by the oscillation of the electrostatic potential ϕ_p. The electrostatic probe is used with an expectation to measure the temporal variation of ϕ_p associated with the LHW directly because the electrostatic probe can measure the potential directly. The reason for using a high impedance resistor is to reduce the current drawn from the plasma to suppress the perturbation caused by the probe. Also, ϕ_p is linearly related to the floating potential V_f, which is measured by the electrostatic probe with high impedance. By measuring the phase difference between signals detected by such high-impedance-embedded electrostatic probes (high impedance Langmuir probes), the wavenumber of the LHW can be measured.

A probe assembly (Fig. 2) consisting of three high impedance Langmuir probes, a single magnetic loop, and a single plain electrostatic probe (plain Langmuir probe) is used to measure the LHW wavenumber at 200 MHz in RF start-up plasmas with the plasma current of up to 2 kA, electron density of $4 \times 10^{16}\,\mathrm{m}^{-3}$, and electron temperature of up to 50 eV in TST-2. The LHW is launched from the dielectric-loaded waveguide array antenna (grill antenna) and the wavenumber parallel to the toroidal magnetic field ($k_\parallel$) of the main lobe of the launched wave is $40\,\mathrm{m}^{-1}$. The experimental configuration is summarized in Fig. 3.

The waves which can exist in the RF start-up plasma are limited to three types: the fast wave, the slow wave (LHW) and the electromagnetic wave. Based on the calibrated sensitivity of the probe assembly to the electromagnetic wave using a coaxial calibrator, the ratio of signal amplitudes measured by the high impedance Langmuir probes ($\sim 4\,\mathrm{mV}$) to that measured by the magnetic probe ($\sim 6\,\mathrm{mV}$) cannot be explained by the fast wave nor the electromagnetic wave (Fig. 4(a)). Therefore, it can be concluded that the LHW makes the dominant contribution to the measured signal. It is also shown that the component of current at 200 MHz drawn from the high impedance Langmuir probe is estimated to be less than 0.64 mA, at least by 40 % smaller than that drawn by the plain Langmuir probe of 1.1 mA, signifying the effectiveness of using a high impedance resistor to measure the signal closer to the floating potential at 200 MHz, and therefore closer to that originating from the LHW.

Measurements of the identical wave using different pairs of the high impedance Langmuir probes by rotating the probe assembly gave the same phase difference, confirming the validity of wavenumber measurement. The direction of the measured wavenumber was nearly along the toroidal direction and counter-clockwise viewed from the top, consistent with the direction of the main component of the $k_\parallel$ spectrum of the launched wave. Meanwhile the measured absolute value of the toroidal wavenumber was $k_\parallel = 19.6 \pm 11.0\,\mathrm{m}^{-1}$ (Fig. 4(b)), smaller by a factor of two compared to the main wavenumber component of the wave launched by the grill antenna, $k_\parallel = 40\,\mathrm{m}^{-1}$. This difference cannot be explained by a spatially uniform cold plasma model with Maxwellian electron velocity distribution function, even with the inclusion of $k_\parallel$ upshift/downshift and the presence of two different wavenumbers.

A possible scenario to explain the measured toroidal wavenumber of $k_\parallel = 19.6 \pm 11.0\,\mathrm{m}^{-1}$ was given by a non-Maxwellian electron velocity distribution function with a larger population of fast electrons moving in the direction of the main lobe of the launched wave compared to the Maxwellian distribution (Fig. 4(c)), indicating that the contribution of fast electrons to wave damping is important. This scenario suggests that the main component of the launched wavenumber around $k_\parallel = 40\,\mathrm{m}^{-1}$ is absorbed by such fast electrons before reaching the probe assembly, and the wavenumber components not absorbed by the plasma reached the probe assembly, and were detected as $k_\parallel = 19.6 \pm 11.0\,\mathrm{m}^{-1}$ (Fig. 4(d)). From the Landau damping condition, the measured value of $k_\parallel = 19.6 \pm 11.0\,\mathrm{m}^{-1}$ requires fast electrons with energies in the range 2.8 keV (for $k_\parallel = 40\,\mathrm{m}^{-1}$) to 11.2 keV (for $k_\parallel = 20\,\mathrm{m}^{-1}$) during the initial phase of RF start-up plasmas in TST-2.

The work reported in this thesis provides a new method for the wavenumber measurement of the LHW. The measured wavenumbers provide information on wave excitation and propagation, as well as evidence of wave absorption by the plasma. These data can be used to characterize the initial plasmas driven by the LHW, and extract information such as the lower bound for the energy of fast electrons. Such information is useful for optimizing the plasma formation and plasma current ramp-up for ST plasmas, and for improving the design of the LHW antenna for the ST. Through such processes, the work reported in this thesis contributes to the realization of a more compact and economical magnetic fusion power plant.

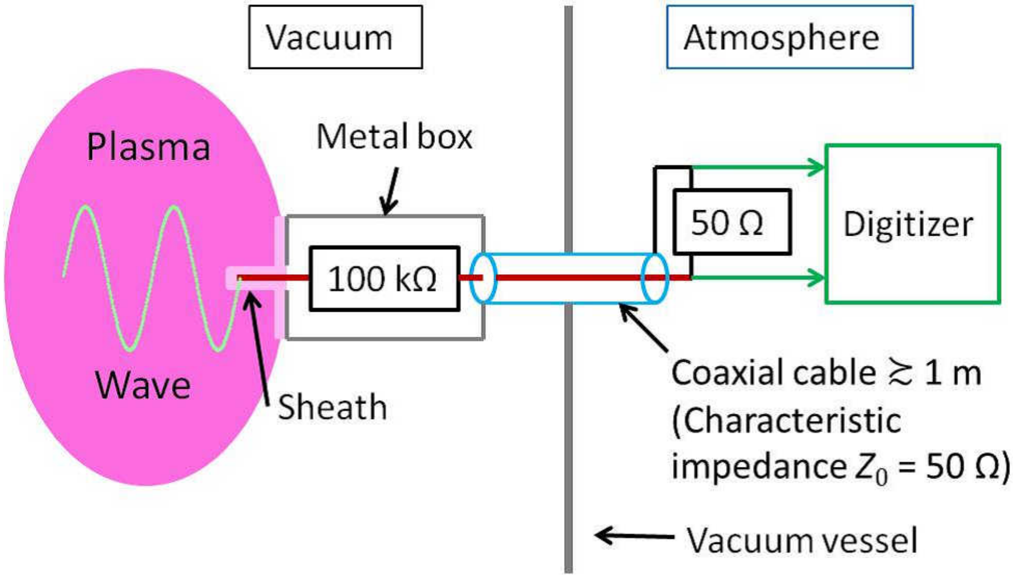

Figure 1: Proposed configuration for floating potential (V_{f}) measurement at high frequencies such as 200 MHz, with a high impedance resistor between the probe electrode and the signal transmission cable.

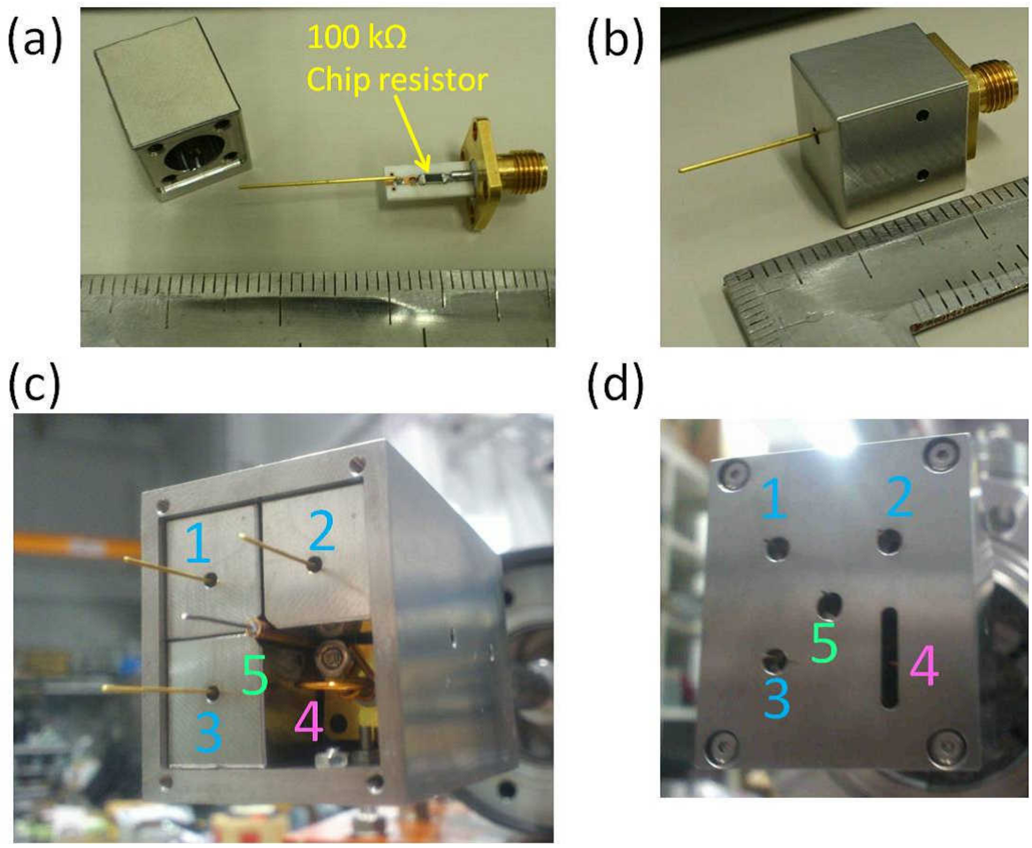

Figure 2: Photographs of the probe unit and the probe assembly. (a) Probe circuit with a high impedance chip resistor and a stainless steel (SUS304) shield box. (b) Assembled unit (high impedance Langmuir probe unit). (c) Probe assembly with the three high impedance Langmuir probes units (electrodes 1, 2, and 3), the magnetic probe (electrode 4), and the plain Langmuir probe (electrode 5). (d) Probe assembly with the stainless (SUS304) cover attached, showing the holes and the slit.

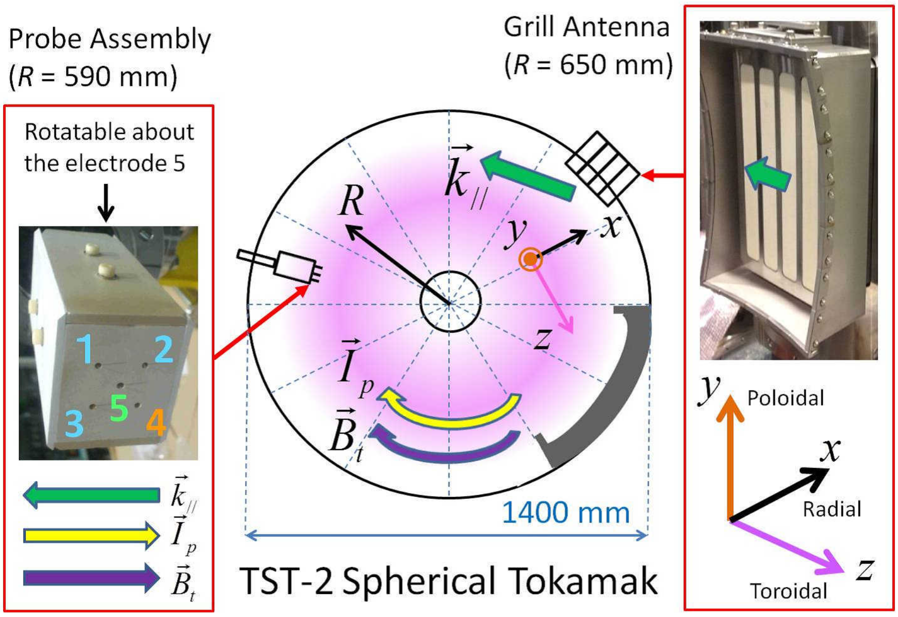

Figure 3: Cross sectional view of the experimental configuration as seen from the top. $k_{\parallel}$: wavenumber component parallel to the toroidal magnetic field, I_{p}: plasma current, and B_{t}: toroidal magnetic field.

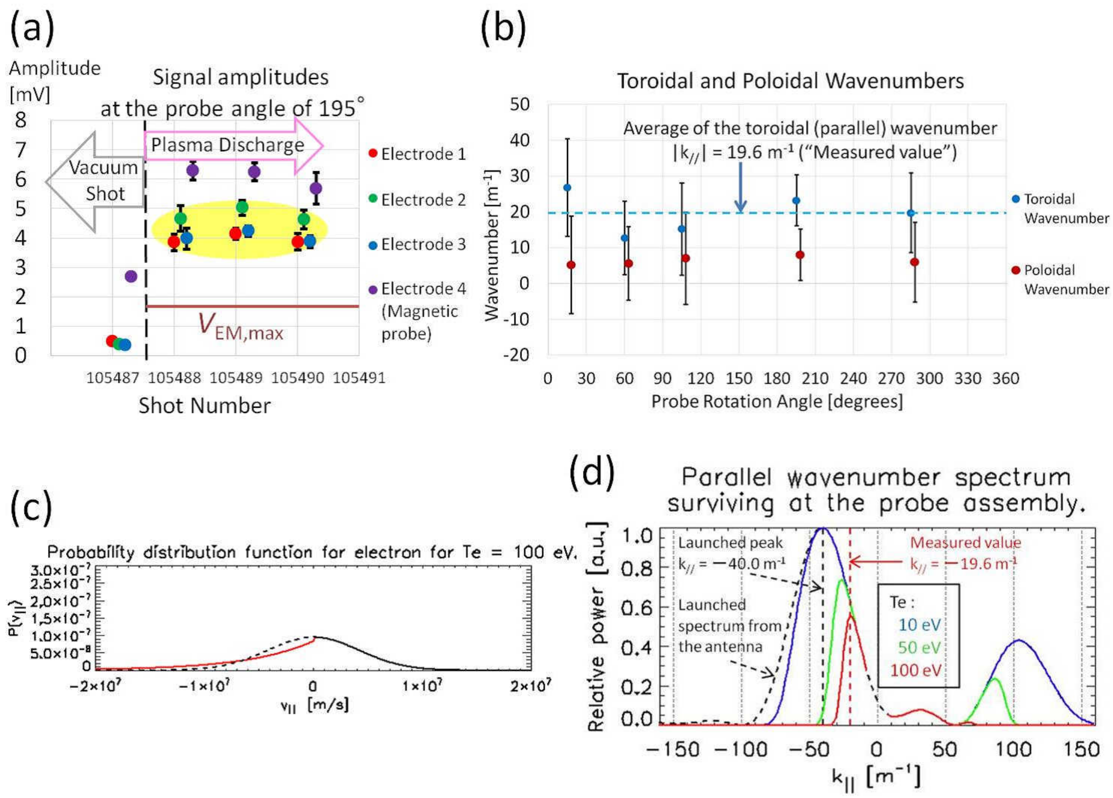

Figure 4: Summary of experimental results and discussions. (a) Wave type identification by comparison of signal amplitudes measured in plasmas by the three high impedance Langmuir probe units (yellow shaded region) with the estimated amplitude for the electromagnetic wave ($V_{\mathrm{EM,max}}$). (b) Experimentally measured toroidal and poloidal wavenumbers for different probe angles. (c) Non-Maxwellian model probability distribution function for the parallel electron velocity used for the absorption calculation. (d) Comparison of the calculated wavenumber spectra for different effective temperatures (solid lines) compared with the measured toroidal wavenumber of the launched LHW (red dashed line).