Heterodyne wave number measurement using a double B-dot probe

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An *in situ* method of wave number measurement inside a helicon plasma has been developed using a double B-dot probe with a heterodyne detection scheme. Each probe in the double B-dot probe measures the wave magnetic field. The signals from the two separately located probes inside the plasma are mixed with a local oscillator signal transforming the signals into transistor–transistor logic signals with intermediate frequency. The phase difference is obtained by a phase comparator yielding wave number information of a plasma wave.
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I. INTRODUCTION

Time-varying magnetic fields are considered to be very important in some types of plasmas since they not only determine plasma characteristics but also maintain the discharge. For instance, in rf plasma sources such as an inductively coupled plasma which is used for materials processing in microelectronics fabrication, knowledge of the ac magnetic field helps understand power coupling to the plasma from the rf source since the time variation of the magnetic field induces the electric field which maintains the plasma.[1–3] Study of wave propagation excited in a variety of rf plasmas also requires information on time-harmonic magnetic fields.[4–7]

A commonly utilized diagnostic for measuring time-varying magnetic fields is a B-dot or inductive loop probe. Especially for measuring magnetic field distribution in plasmas, double B-dot probes have been used that were separated by a distance so that the probe set gives phase information as well as amplitude.[8,9]

In order to study plasmas produced by relatively high frequency rf and/or to study high frequency plasma waves, it would be more convenient to convert the signal frequency to a much lower frequency by mixing a signal of a similar frequency while keeping the important phase information unchanged. In fact, this heterodyne detection method is widely used in mm-wave or far infrared interferometers for plasma density measurement.[10,11] In this work, we present an *in situ* diagnostic method of measuring time-varying magnetic fields in real-time utilizing a double B-dot probe in the heterodyne detection scheme. This method is simple and is applicable to various purposes.

II. PRINCIPLE

By Faraday's law, the induced voltage on a conducting loop in the presence of time-varying magnetic field dB/dt or $\dot{B}$ is given by $V=-d\Phi/dt$ where Φ is the magnetic flux through the loop. With the probe area $A, dB/dt=-V/A$ and this can easily be measured by a loop (or B-dot probe) of appropriate size and number of turns. Suppose that the magnetic field inside a cylindrical plasma behaves sinusoidally as $\exp[i(m\theta+kz-\omega t)]$ where θ,z are azimuthal and axial coordinates, respectively, m is the azimuthal mode number, and k is the axial wave number. If dB/dt is measured by each of the two B-dot probes that are separated by a distance ℓ, there exists phase difference $\Delta\phi$ in the measured dB/dt. For two B-dot probes aligned in the axial direction, the wave number in the direction is then given as $k=\Delta\phi/\ell$.

When the signal frequency (rf) from the B-dot probe is high, it is more convenient to convert the frequency to a more manageable lower frequency for phase comparison. Figure 1 illustrates the heterodyne phase detection system to measure the phase difference from the double B-dot probe. The obtained rf signal is mixed with the signal from the local oscillator (LO) resulting in intermediate frequency (IF) which is in general much lower frequency than rf. The rf, LO, and IF frequencies that were used in this work are 98 MHz, 97.5 MHz, and 500 kHz, respectively. For eliminating electrostatic effects, the B-dot probe and mixer are separated by a hybrid combiner.[5,6]

Before going into the phase comparison circuit, the IF signal is transformed into transistor–transistor logic (TTL) signal by a zero-crossing detector which transforms the positive IF signal to 5 V and the negative to 0 V. Figure 2 shows the input IF signal and the output TTL signal. There may exist non-negligible noise in the TTL signal that originates

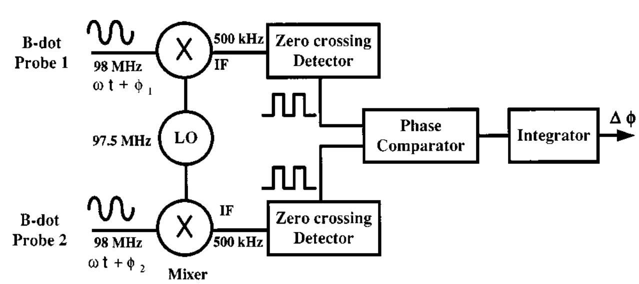

FIG. 1. Schematic diagram of the heterodyne phase detection system. For eliminating electrostatic effects, hybrid combiners are connected between the B-dot probe and the mixer.

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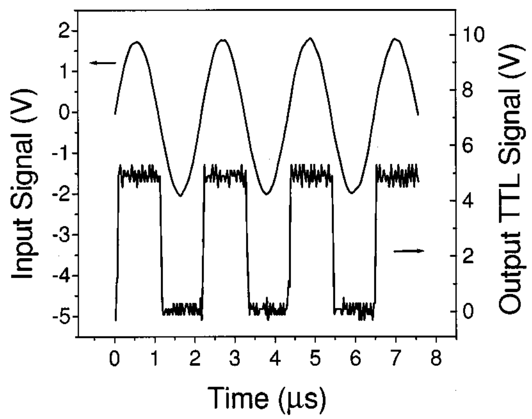

FIG. 2. Input sinusoidal IF signal and the corresponding TTL signal which is the output of the zero-crossing detector.

from frequency fluctuations of the rf generator or LO and the characteristic resonance frequency of various electronic devices in the circuit. Therefore, care must be taken to reduce the noise level for accurate measurement by using a stable LO and using appropriate filter circuits. In our measurements, the error could be reduced less than a few degrees of phase difference by noise elimination. In Fig. 3, the input and output signals of the zero-crossing detectors are depicted, where the phase difference between the two output signals $\Delta\phi$ is kept unchanged.

The two TTL output signals are then fed into the phase comparator in which the signals are combined by an exclusive-OR circuit. The phase difference is therefore linearly proportional to the signal area which can be obtained by an integrator circuit. Calibration showed that the output voltage of the integrator is linearly proportional to the known phase difference. The phase difference measured in this way is in the range of 0°–180°. For measuring the phase difference larger than 180°, a feedback loop can be used. The time resolution of the phase detection circuit in Fig. 1 is typically a few microseconds.

III. PLASMA MEASUREMENTS

The developed double B-dot probe and the associated heterodyne phase detection system were installed and tested

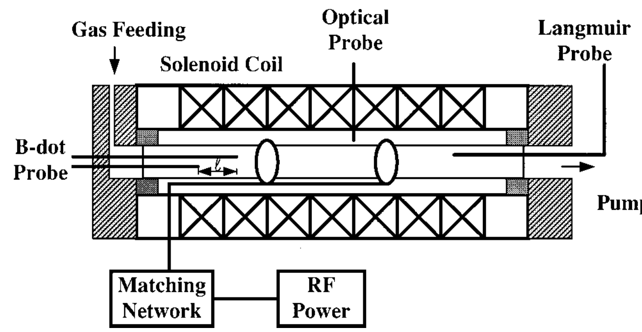

FIG. 4. Schematic diagram of the helicon plasma experimental setup.

on the 98 MHz helicon plasma source that was designed for helicon wave propagation study. A schematic diagram of the experimental setup is depicted in Fig. 4. The plasma is generated in a Pyrex tube of 5 cm in diameter and 30 cm in length under the axial magnetic field provided by several discrete solenoidal coils. The maximum field strength is 800 G from $z=0$ (center) to $z=\pm 9$ cm which is rather uniform with the field ripple less than 2% at the plasma boundary. A double loop or a Nagoya-type III antenna is used which is made of silver-coated copper to reduce antenna resistance. The length and diameter of the Nagoya-type III antenna used for the experiment are 3.5 and 5.5 cm, respectively.

Each of the B-dot probes of 2 mm in diameter has two turns to provide enough signal level and to prevent unwanted rf pickup. Each probe is encased in a 1/4 in. outside diameter (o.d.) Pyrex tube for isolation from the plasma. The probe signal is transmitted through a 50 Ω transmission line.

Examples of phase detection in argon plasmas are given in Figs. 5 and 6. Figure 5 shows the phase variation of helicon wave in the axial direction obtained by moving one of the B-dot probes. The measurement (solid line) matches well with the theoretical value (dotted line) calculated from the helicon wave dispersion relation under the experimental condition with 65 W of rf power and 700 G of axial field strength. For this case, the rather large size of the error bars (~10°) seems to be due to a change of plasma state. Figure 6 shows a real-time measurement of the axial wave number

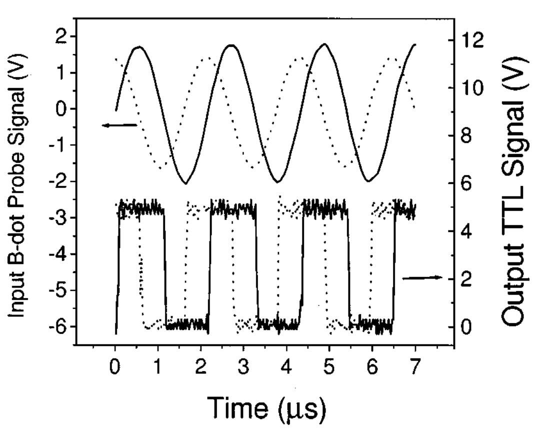

FIG. 3. Sinusoidal IF signals from each B-dot probe (solid and dotted curve) are transformed into TTL signals by the zero-crossing detector. Phase difference between the two IF signals $\Delta\phi$ is kept unchanged after being transformed into the TTL signals.

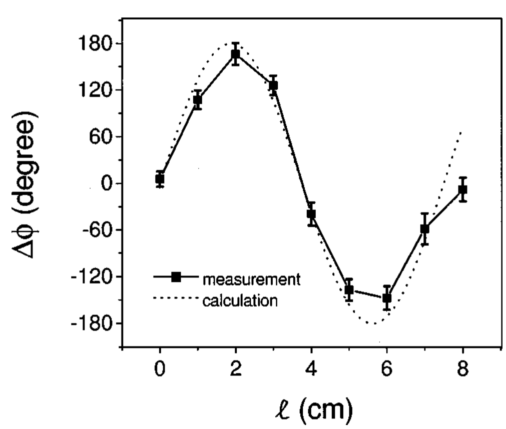

FIG. 5. Phase difference of the helicon wave as a function of the distance between the two B-dot probes. Measurement (solid line) agrees well with the theoretical value (dotted line) calculated from the helicon wave dispersion relation under the experimental condition.

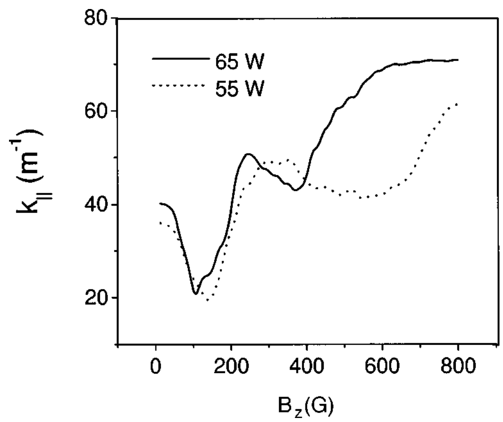

FIG. 6. Real-time measurement of the axial wave number obtained while sweeping the axial magnetic field strength at two different rf powers.

obtained while sweeping the axial magnetic field strength at two different values of rf power. Currently, active experiments are ongoing with various plasma conditions, and a detailed analysis will be reported in the near future.

ACKNOWLEDGMENTS

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