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Measurement of Anomalous Resistance Induced by Chaotic Motion of Electrons in a Magnetic Null Point

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Abstract

Chaotic motion of particles in magnetic null regions can produce a large collisionless resistivity. In order to measure the macroscopic resistivity, a new instrument using a Pockels crystal has been developed. This measurement can detect a high frequency electric field in plasmas. The Pockels probe satisfies the frequency response with 13.56 MHz and the sensitivity as low as 3×10^2 V/m, which proves the capability of measuring the local electric fields in a plasma discharged by a radio-frequency method.

Keywords:

chaos-induced entropy, anomalous resistivity around magnetic null, anisotropic electric field measurement, pockels effect, neutral loop discharge plasma

1. Introduction

Over the past several decades, plasma resistivity has been one of the most puzzling problems in plasma physics. In most cases, the observed resistivity is anomalous, which shows a higher value than the classical value expected from Coulomb interactions. A typical example can be seen in the event of magnetic reconnection [1] where some mechanism to enhance the resistivity plays a role around the magnetic null region, and as a candidate mechanism, turbulent wave-particle interactions [2] or effects arising from two-fluid Hall dynamics [3] have been considered to explain the faster reconnection rate. However, recently, a new mechanism of anomalous resistivity around magnetic null regions was theoretically presented [4]. In fact, the paper clearly shows a possibility of existence of large enhancement resistivity produced by the charged particles which are scattered around a magnetic null point even in a collisionless plasma. Also, it points out that this chaos-induced resistivity may be the reason why a plasma can be discharged around a magnetic neutral loop (called Neutral Loop Discharge) [5] with a lower filling pressure (~ 10^{-4} Torr) than other methods of plasma discharges such as the inductively coupled plasmas [6].

To verify the above mechanism, we have produced an NLD plasma in the prototype ring trap device (Proto-RT) [7] and developed a new diagnostic of an electric field $\boldsymbol{E}$ since $\boldsymbol{E} \sim \eta \boldsymbol{J}$ at the magnetic neutral loop, where η and $\boldsymbol{J}$ are plasma resistivity tensor and current, respectively. Usually, it is very hard to measure $\boldsymbol{E}$ in plasmas. Many works on $\boldsymbol{E}$ of plasmas have been performed in several research areas such as sheared $\boldsymbol{E} \times \boldsymbol{B}$ flow [8] and toroidal equilibrium of nonneutral plasmas [7]. Generally, $\boldsymbol{E}$ consists of both electrostatic E_{es} and inductive E_{id} components. For the E_{es} case, the conventional methods using particle flux or ion processes [9] can be applied to determine it. In fact, the

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particle flux method investigated by Langmuir and his coworkers [9] has still been the most convenient tool to locally measure the value of E_{es} for low temperature plasmas. In higher temperature plasmas where the probe itself cannot survive, on the other hand, ion processes such as the charge exchange technique [9] and an appropriate model calculation have been used to determine E_{es}. However, for the plasmas with E_{id} besides E_{es}, there are as yet no methods to directly measure $\boldsymbol{E}$ in plasmas and actually, the NLD plasmas are produced by an inductive coupling technique with a magnetic field. On Proto-RT, the inductive field is generated by a high power (~ 1 kW) radiofrequency (RF) with 13.56 MHz. To answer the chaos-induced resistivity around the neutral loop, a new method is required for the Proto-RT experiments.

In this contributed paper, a new instrument using a Pockels crystal is presented, which has been so far used only in the researches of high-voltage engineering [10]. For the first time, the Pockels crystal is applied to measure an anisotropic $\boldsymbol{E}$ which oscillates with high frequency in plasmas. In Sec. **2**, the Pockels effect is briefly explained. The instrument developed here can measure $\boldsymbol{E}$ with up to 15 MHz. In Sec. **3**, the diagnostic system designed to detect such a small signal from the Pockels crystal is described. In Sec. **4**, the characteristics of the Pockels probe and the preliminary results are presented. Finally, a summary is appeared in Sec. **5**.

2. Pockels Effect

The Pockels effect is one of the electro-optical effects and has been used to measure a high voltage in research areas of electric engineering [10]. When an electric field is applied to such crystals that exhibit the Pockels effect, birefringence occurs. The difference in the two refractive indices for each orthogonal polarization component changes as the first order function of E as follows;

$$\Delta n = \Delta n_0 + \Delta a E \,, \tag{1}$$

where Δn_0 and $\Delta a E$ term represent the natural birefringence and the Pockels effect, respectively. Here, Δa can be written as

$$\Delta a = n_0^3 \gamma_p \,, \tag{2}$$

where n_0 is the normal refractive index and γ_p is the Pockels coefficient of the crystal. When a light passes through it, the birefringence causes a velocity difference between the two components and the phase shift between them occurs correspondingly. Assuming that Δn is constant during the light passes through it, the phase shift $\Delta\theta$ is given by

$$\Delta\theta = \frac{2\pi l}{\lambda} \Delta n \,, \tag{3}$$

where λ is the wave length of the light and l is the length of the crystal along the light path. Thus, if the Pockels crystal is placed between a pair of two polarizers, the corresponding phase shift can be measured as light intensity fluctuation. Furthermore, when the polarization orientation of them is orthogonal to each other, the output light intensity I_o normalized by the input one I_i is given by

$$\frac{I_o}{I_i} = \sin^2 \frac{\Delta\theta}{2} \,, \tag{4}$$

where the lights decay through the sensor is neglected.

3. Experimental Setup

We have applied the Pockels crystal to measure $\boldsymbol{E}$ in plasmas for the first time. As described in Fig. 1, the system consists of main three components: a light source with SLD (Super luminescent diode, λ = 840 nm), a Pockels ($Bi_4Ge_3O_{12}$) sensor, and a pin PD (pin photo diode) detector to measure light intensity. Those parts are connected with optical fibers each other. Figure 2 shows an enlarged photograph of the Pockels sensor indicated in Fig. 1. The light launched from the source passes through the PANDA (Polarization-maintaining AND Absorption-reducing) fiber and at first, enters in PBS (Polarization Beam Splitter) where the light is polarized linearly. This polarized light is immediately circular polarized by the $\lambda/4$ plate before entering in the Pockels sensor in order to obtain maximum sensitivity of it. Thus, the eq. (4) reads

$$\frac{I_o}{I_i} = \frac{1}{2}(1 - \sin \Delta\theta') \sim \frac{1}{2}(1 - \Delta\theta') \tag{5}$$

where $\Delta\theta'$ equals to $\Delta\theta + \pi/2$, in this system. The output light coming out from the sensor finally reaches the detector through the GI (Grated Index) fiber.

The values of Pockels coefficient γ_{41}, relative dielectric constant ε_r, and refractive index n_0 are 1.03×10^{-12} m/V, 16, and 2.07, respectively. Also, the length of the crystal along the light path is 2 cm (1cm×2). Since no natural birefringence occurs, substituting those parameters into eqs. (1), (2), and (3), the value of $\Delta\theta$ is calculated to be 8.54×10^{-8} E. Here it

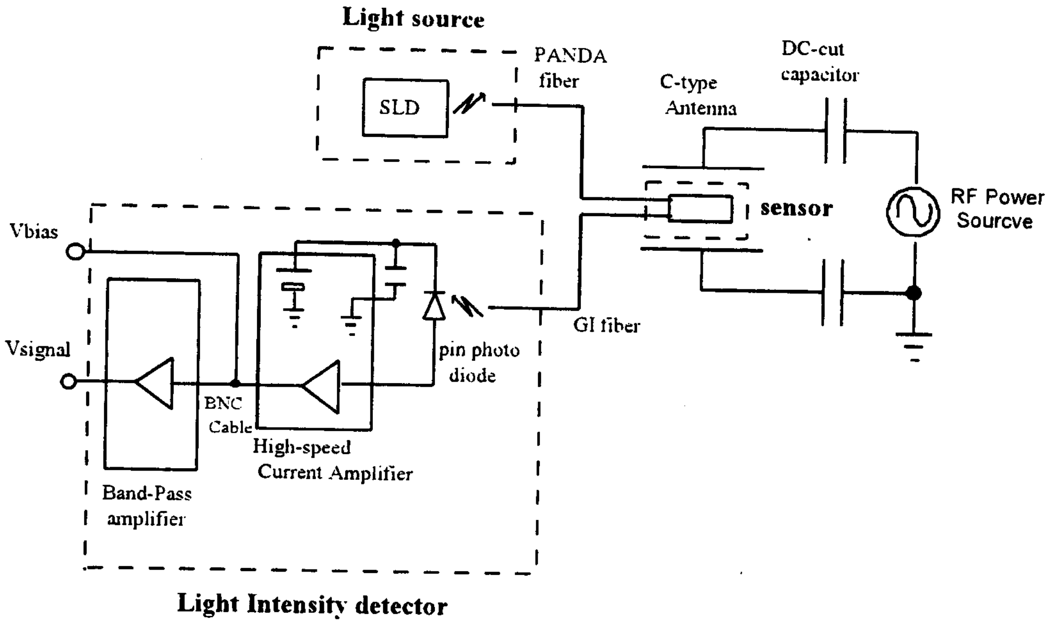

Fig. 1 A schematic diagram of the Pockels probe system. A pair of Pockels cells is used for the sensor.

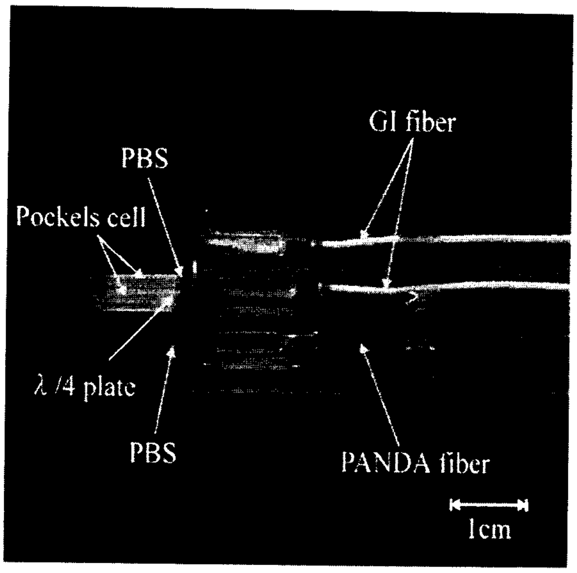

Fig. 2 An enlarged photograph of the sensor indicated in Fig. 1.

should be mentioned that the electric field strength inside the crystal decreases to E_0/ε_r. The sensitivity of pin PD is constant (0.55 A/W) in the range between DC and 100 MHz for the case of λ = 840 nm. The current from the pin PD is converted to the corresponding voltage by a high-speed current amplifier which also has a constant gain (50 kV/A) from DC to 50 MHz. This frequency response is enough to measure the high-frequency electric field oscillating with 13.56 MHz for the NLD experiments on Proto-RT. The output voltage from the current amplifier is described as 3.43×10^{-6} E when the biased voltage is 2.5 V. Thus, for the case of E ~ 1 kV/m, the signal voltage would be about 2.14×10^{-4} V which seems to be too small to be measured. Therefore, we have employed a band-pass amplifier just after the current amplifier. The gain of the band-pass amplifier is about 212 and the q-value is about 7.5 so that the output voltage is expected to be ~ 50 mV for the case of E ~ 1 kV/m.

4. Characteristics of Pockels Probe

To examine the characteristics of this new instrument, we have applied this probe to measure an electric field which is produced by a pair of parallel square metal plates. The size of the plates is 30 cm×30 cm and the distance between the two plates is 10 cm. As seen from the data plotted in Fig. 3, the output voltage against the strength of E shows linear dependence at any frequencies varying between 20 Hz and 1 kHz, which is also consistent with eq. (5). From the fitting line in Fig. 4, the value of phase shift can be expressed as $\Delta\theta$ = 5.20×10^{-9} E. The directional sensitivity is also well attained. Fig. 3 indicates the output voltage measured at different angles α between the Pockels sensor and $\boldsymbol{E}$. The fitted curve on the measured values is sinusoidal as

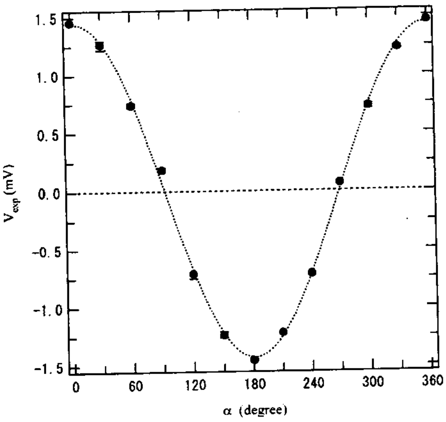

Fig. 3 Plots of V_{exp} at various angles a between the Pockels sensor and E. The plotted data are well fitted by a sinusoidal, showing that the sensor can distinguish the three component of E in a good resolution.

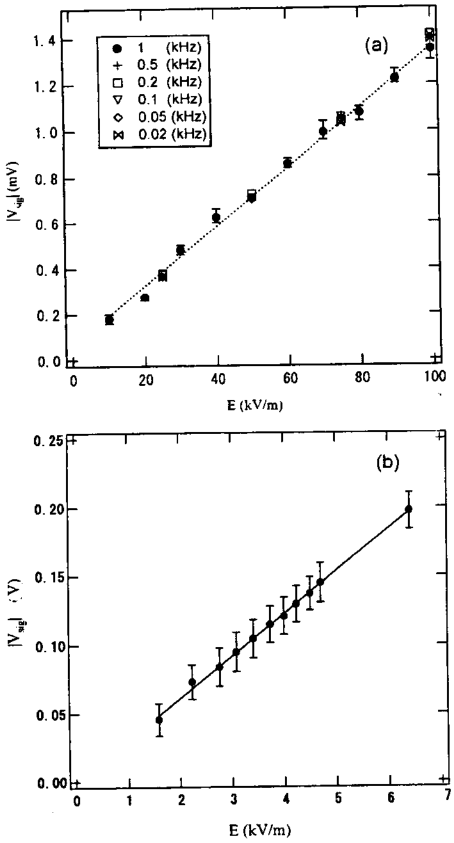

Fig. 4 Plots of the output voltage V_{exp} at various strengths of oscillating electric fields E: (a) f ~ 0.02–1.0 kHz (b) f ~ 13.56 MHz. The dotted and solid lines show a least square fitting from the data, which shows that values of V_{exp} increase linearly with E as expected.

expected, allowing $\boldsymbol{E}$ to be broken down into its components which determines anisotropy of the oscillating field.

However, the output voltage in experiments V_{exp} is lower than expected V_{anl}. As mentioned in Sec. **3**, the analytical value of $\Delta\theta$ is calculated from $\Delta\theta \sim 8.54\times10^{-8}$ E and thus the value of V_{anl} without the band-pass amplifier is expected to be ~ 0.24 mV for E ~ 1 kV/m. On the other hand, in experiments the probe outputs only V_{exp} ~ 0.015 mV for E ~ 1 kV/m if we extrapolate it from the measured data in Fig. 4. The value of V_{exp}/V_{anl} is so far 1/16. The reason is still unknown, however, it is probably owing to the sensitivity of the Pockels crystal itself.

With the present sensitivity of the Pockels crystal, the lower limit of detection against E would be about 300 V/m where V_{exp} is about 1 mV. This value corresponds to E^* ~ 0.4 in the NLD experiments. Here, E^* is the normalized electric field used in NLD studies. Since the chaotic effect is enhanced at E^* ~ 1, even with the lower sensitivity this Pockels probe could be applied to measure the oscillating electric fields with 13.56 MHz in a neutral loop produced in Proto-RT.

In fact, we have installed the Pockels probe in Proto-RT and tried to measure the 13.56 MHz of E by the probe. The electric field is produced by a capacitive coupled technique with a pair of torus plates made of SUS304. Under this setting in Proto-RT, the Pockels probe so far successfully detects E with 3.3 kV/m at which the value of the S/N is about unity, determining the lower limit of detection inside the Proto-RT device. This limit is higher than the calculated value as already described. However, the limit can be improved about 16 times better by fixing the sensitivity problem of the current Pockels crystal, which actually decreases lower limit of detection limit down to 330 V/m enough to be employed in Proto-RT for not only NLD but also nonneutral plasma experiments.

5. Summary

A new diagnostic for measuring anisotropy of high-frequency $\boldsymbol{E}$ in plasmas has been developed using a Pockels crystal. The test of the probe shows a good performance to distinguish directional components (three vector components) of oscillating electric fields up to 13.56 MHz which is too fast to be detected by a conventional probe technique. The lower limit of detection against $\boldsymbol{E}$ is so far about 3×10^2 V/m that is restricted possibly owing to the sensitivity of the Pockels crystal. In the Proto-RT device, the lower limit of detection increases up to ~ 3×10^3 V/m with present settings because of the S/N problem. In this case, the value of the lower limit corresponds to $E^* \sim 3.8$ which is the normalized electric field in the NLD studies. Although the chaos induced thermalization is occurred in $E^* \sim O(1)$ [4], this probe could be employed in NLD experiments to measure $\boldsymbol{E}$ and, with measurements of high-frequency current this Pockels probe would answer the anomalous resistivity observed in magnetic null. With better S/N values the first experiment of it is now going to be conducted on Proto-RT.

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