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Measuring the magnetic field of a magnetized plasma using Raman scattering

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We studied the Raman scattering in a magnetized plasma by one-dimensional particle-in-cell (PIC) simulations in non-relativistic regime. It is found from the X-mode dispersion relation that the frequency of the backward scattered wave is downshifted by an amount of upper hybrid frequency, while that of the forward scattered wave merely depends on the magnetic field. We propose such a spectral difference be used to measure simultaneously the plasma density and magnetic field of magnetized plasmas. The idea was verified by a series of PIC simulations, where we used the directional field splitting method to obtain accurate peak position of the scattered waves' frequencies. We compared the frequency shift and the growth rate of the scattering from theory and simulations to obtain reasonably good agreement between them for different external magnetic fields. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4868870]

Raman Scattering in a plasma is a prominent non-linear process in high power laser plasma interaction and is considered as an important diagnostic tool for various plasma applications such as plasma-based electron acceleration and inertial confinement fusion (ICF). These plasma-based applications are highly dependent on the status of plasma such as the homogeneity of plasma density, the temperature, and magnetic field. For example, both of the Raman forward scattering (RFS) and the Raman backward scattering (RBS) were used to measure the plasma density in underdense plasmas.[1–3] It was also shown by particle-in-cell (PIC) simulations that the temperature and density of a homogeneous plasma are simultaneously detectable by measuring RBS and RFS together.[4] Meanwhile, one recent experimental result has shown that the spatial information of a plasma density is extractable using the Raman backward amplification technique based on stimulated Raman scattering.[5] Properties of laser propagation in magnetized plasmas have been also studied widely, where most of the works are focused on self-generated high magnetic field or Cerenkov wake radiation.[6–9] Theoretical works for the case of X-mode[10,11] showed that RBS spectroscopic peak shifts from the incident laser's frequency by an amount of upper hybrid frequency ω_h and the scattering growth rate decreases as the magnetic field increases. However, there has been almost no experimental or simulation study on the effects of external magnetic field on RBS and RFS. The reason may be partially that in the regime of short-wavelength laser pulses ($\lambda \sim 1\,\mu$m), a huge magnetic field reaching a few hundred Tesla is required to clearly see its effects. Fortunately, the development of highly intense lasers with tens-of-micrometer-wavelength like a *maser* can give a more chance of studying experimentally the Raman scattering in a magnetized plasma; for instance, terawatt-level and 5-ps pulse of $10\,\mu$m CO_2 lasers are now available.[12]

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In a previous publication by one of the authors of this Letter, they proposed a method to measure the plasma density and temperature simultaneously utilizing the different sensitivities of the RBS and RFS to the plasma temperature.[4] Specifically, the thermal frequency shift of the Bohm-Gross wave, $v_{th}^2 k^2$, depends on the wave number, so the RBS, which has a large wave number, is influenced more significantly by the plasma temperature than the RFS which has only a small wave number. By detecting and comparing the RFS and RBS frequency shifts simultaneously, the plasma density and temperature informations can be extracted together.

In this Letter, we suggest another method to measure simultaneously the time- and space-averaged *magnetic field* as well as the plasma density utilizing the different behaviors of the RBS and RFS in a magnetized plasma. When a pump laser pulse is irradiated onto a magnetized plasma, it can be Raman-scattered into another electromagnetic waves and plasma waves. Theoretically, the plasma wave in such an environment is not purely electrostatic, but it contains an electromagnetic component. So the three waves, i.e., the pump, scattered, and the plasma waves, follow the X-mode dispersion relation as follows:[13]

$$\frac{c^2k^2}{\omega^2} = \frac{c^2}{v_\phi^2} = \frac{1}{\beta_\phi^2} = 1 - \frac{\omega_p^2}{\omega^2}\frac{\omega^2 - \omega_p^2}{\omega^2 - \omega_h^2}, \qquad (1)$$

where v_ϕ is the phase velocity. Note that we assumed the relativistic effect can be neglected and the ions are stationary in the time scale of the scattering. In this scattering process, RFS yields two sidebands: one is the upshifted, and the other is the downshifted by an amount of plasma wave frequency. On the other hand, RBS yields only a downshifted sideband.[14] Usually, such a scattering occurs with a maximum growth rate, when the three waves, i.e., the pump $(\omega_0, \mathbf{k}_0)$, scattered $(\omega_s, \mathbf{k}_s)$, and the plasma $(\omega, \mathbf{k})$ waves, satisfy the resonance condition. When the forward-scattering is relevant, the resonance condition between the three waves is

$$k_0 = k_f + k_{fs}, \quad \omega_0 = \omega_f + \omega_{fs}. \tag{2}$$

Here, the subscripts s and f represent the "scattered" and "forward," respectively. For this case, the phase velocity of the plasma wave is *fast*, i.e., $\beta_{\phi f} = d\omega_f/cdk_f \simeq |\omega_0 - \omega_{fs}|/c|k_0 - k_{fs}| \approx 1$, which is nothing but a group velocity of the high-frequency pump wave. On the contrary, the wave number of the plasma wave for an exactly backward scattering is roughly twice the pump's wave number

$$k_b = k_0 + k_{bs} \simeq 2k_0, \quad \omega_b = \omega_0 - \omega_{bs}. \tag{3}$$

Therefore, the RBS induces a *slow* plasma wave with $\beta_{\phi,b} \approx (\omega_0 - \omega_{bs})/2k_0c \ll 1$. Note that all those resonance condition can be interpreted as results of energy and momentum conservation between the photons and plasmons.

As the phase velocities of the plasma waves involved in RFS and RBS are hugely different to each other, the spectral dependence of the scattered waves on the magnetic field shows a significantly different behavior. Such a point can be easily seen by representing the frequency of the plasma wave as a function of the phase velocity from Eq. (1) as follows:

$$\frac{\omega^2}{\omega_p^2} = \frac{1 + A + \omega_c^2/\omega_p^2}{2} + \sqrt{\frac{\left(1 + A + \omega_c^2/\omega_p^2\right)^2}{4} - A}, \tag{4}$$

where

$$A = \frac{1}{1 - 1/\beta_\phi^2}. \tag{5}$$

For the case of RFS, $\beta_{\phi f} \sim 1$, so the frequency of the plasma wave from Eq. (4) becomes, up to the first order of A^{-1}

$$\omega_f^2 \simeq \omega_p^2\left(1 - \frac{1}{A}\left(1 + \frac{\omega_c^2}{\omega_p^2}\right)\right). \tag{6}$$

In Eq. (6), the magnetic field effect is only a small term because $|A| \gg 1$, so the forward plasma wave frequency is very close to the plasma frequency ω_p. Consequently, we can expect the RFS frequency is *not* affected significantly by the external magnetic field. Especially when the driving pump pulse is short enough to leave a wakefield behind, it is called the Cerenkov wake.[8] In the case of RBS, however, $\beta_{\phi,b} \ll 1$, so A in Eq. (5) approaches to zero yielding

$$\omega_b \simeq \omega_h = \sqrt{\omega_p^2 + \omega_c^2}. \tag{7}$$

Then from Eqs. (6) and (7), and the resonance conditions aforementioned, the plasma wave frequency can be represented as a function of the magnetic field both for RFS and RBS as in Fig. 1, where it is shown that the plasma wave frequency for the RBS case is more strongly influenced by the magnetic field than that for the RFS. As a consequence, it is expected that the RBS shows more frequency shift by the magnetic field effect than the RFS. Since there is almost no magnetic field information contained in RFS signal, it can be used as a reference to measure the plasma density. Then the

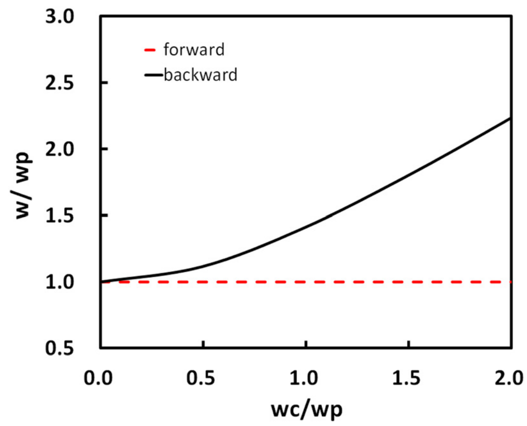

FIG. 1. Plasma wave frequency depending on magnetic field obtained from Eqs. (4) and (7).

magnetic field information can be extracted by measuring the additional frequency shift of RBS. Experimentally, the intensity and direction of the magnetic field as well as the plasma density can probably be measured by irradiating the pump pulse in various different angles, and detecting simultaneously the for- and back-scattered signals.

As a test of such an idea, we performed a series of one-dimensional PIC simulations of the Raman scattering in a magnetized plasma. For separation of the backscattered and forward-scattered signals, we employed the directional field split method for the field solver.[15] In the simulations, the external magnetic field was perpendicular to the propagation of the pump laser pulse. Then a longitudinally Gaussian pump laser pulse with the wavelength $\lambda = 10\ \mu$m and pulse duration $\tau = 10$ ps was launched. The peak value of the normalized vector potential of the pump pulse was $a_0 = eE_{0y}/m_e\omega_0c = 0.3$. We also loaded a cold, magnetized plasma with densities $n_0 = 1.0 \times 10^{15}$ cm^{-3} and 1.0×10^{17} cm^{-3}, which corresponded to $\omega_p/\omega_0 = 0.0095$ and 0.095, respectively. Here, we used a linearly polarized laser field in y direction. The plasma was magnetized by a z-directional various DC external magnetic fields. The laser pulse propagated to the right x-direction in the simulation window, so the right going and left-going fields contained the RFS and RBS signals, respectively.

Figure 2 is the simulation result for the magnetic field 20 T measured at $t = 43.3$ ps. Figures 2(a)–2(c) show the right going field, the left going field, and the k-spectra of the RFS and RBS signals, respectively. In the case of RFS spectrum, only the lower sideband is presented for comparison with the downshifted RBS frequency. From Fig. 2(c), it is clearly seen that the additional frequency shift by the magnetic field in RBS is large enough compared to the bandwidth of each peak, so it can be readily utilized to get the magnetic field strength. Note that the RFS signal is superposed by the original pump wave, so it is not distinguishable in the figure, while the backscattered signal can be separately observed as in Fig. 2(b).

In Fig. 3, it is shown that the Raman peak shift for different magnetic fields measured from the simulations agree well with the theory. Because of the low growth rate of RFS in low plasma density, we could not detect the RFS in the case $n_0 = 1.0 \times 10^{15}$ cm^{-3}. However in real experiments,

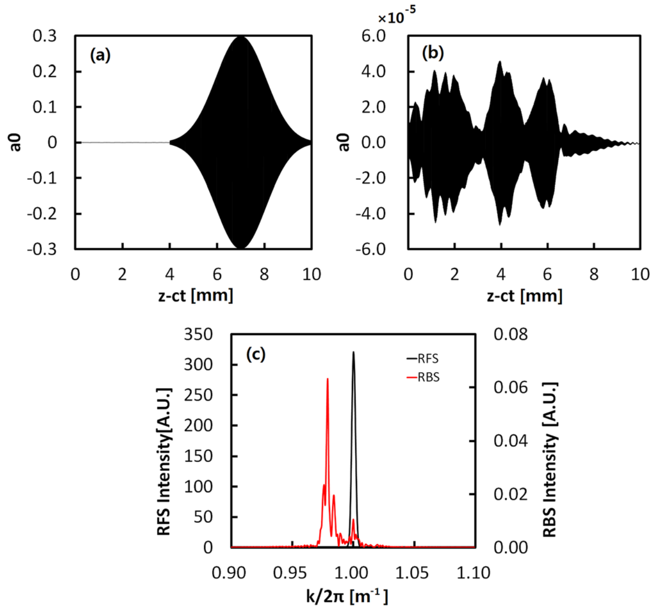

FIG. 2. Measured (a) right going field and (b) left going field at $t = 43.3$ ps and for magnetic field $B = 20$ T using a directional field splitting method. (c) The frequency spectra for RFS (black) and RBS (red) are also shown.

the RFS signal might be detected more easily by using a longer pump pulse. In the case of higher plasma density of $n_0 = 1.0 \times 10^{17}$ cm^{-3}, Fig. 3(b) shows a good agreement between the theory and the simulations even in extremely high magnetic field.

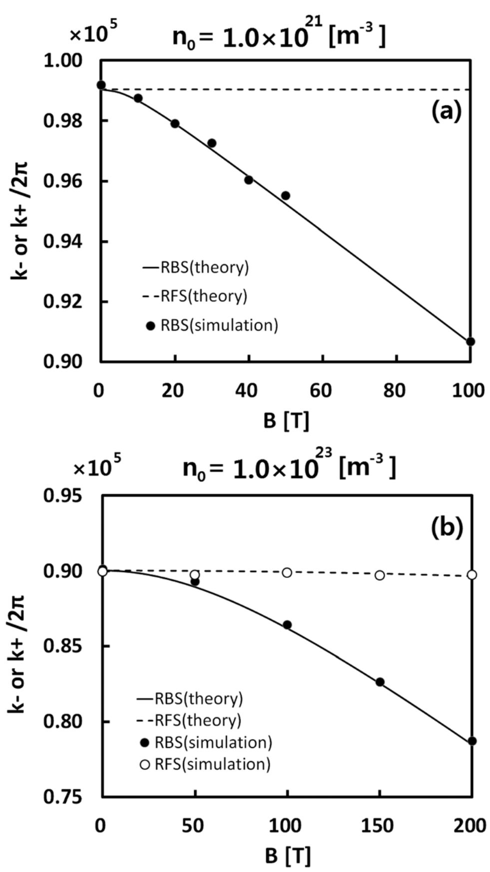

FIG. 3. Frequency shifts of RBS and RFS depending on the external magnetic field for (a) the plasma density $n_0 = 1.0 \times 10^{15}$ cm^{-3}, where the RFS was too weak to be detectable in the given simulation range, and (b) $n_0 = 1.0 \times 10^{17}$ cm^{-3}, where both RBS and RFS could be measured.

To get more confidence in the simulation results, we measured the growth rate of the backscattering and compared it with the theory. The previous theoretical study of RBS growth rate in a cold, magnetized plasma[10] shows

$$\gamma = \frac{1}{2} k_0 V_0 \sqrt{\frac{\omega_p^2}{\omega_0 \omega_h}}. \tag{8}$$

To compare the growth rates from Eq. (8) and simulations, we used the fact that the intensity of the scattered wave is proportional to $\exp[\gamma_{eff}\tau_{eff}]$. Here, we approximated the Gaussian pulse duration τ and peak amplitude a_0 used in the simulations to the square shape with $\tau_{eff} = \tau/2$ and $a_{0_{eff}} = a_0/\sqrt{\pi}$. Because Eq. (8) is valid for an infinitely long homogeneous laser pulse, the simulation results can directly compared to it only after such averaging and approximating the Gaussian shape to the square shape. It is shown in Fig. 4 that the ratio of the spectral peak intensity of the scattered wave to that for $B = 0$ is matched well with the theoretical expectation.

Here, we discuss a potential experimental application of the suggested idea. The proposed diagnostic method, along with the previous one to measure the plasma temperature,[4] can be realized in the experiments by simultaneously detecting RBS and RFS spectra of the pump laser pulse irradiated in various angles. Though the plasma diagnostics by Raman scattering is usually applied to a relatively high-density plasma above 10^{18} cm^{-3}, we showed the suggested idea can also be used even in a low density plasma such as 10^{15} cm^{-3} or below. In that sense, one of the good applications of the proposed method might be the diagnostics of Tokamak plasma density and magnetic field, where the density is in the range of 10^{13}–10^{15} cm^{-3} and the magnetic field at the core can reach up to a few or more than 10 T depending on the operating regime. In that case the electron temperature can be as high as $T \lesssim 10$ keV,[16] so the currently proposed method probably should be combined with the previous method[4] of temperature measurement. To get a high enough growth rate in such a low density plasma, a longer duration of the laser pulse may be required. However, the pulse duration and focal spot are still very small compared to the length scale of the Tokamak plasma. Furthermore, the scattered

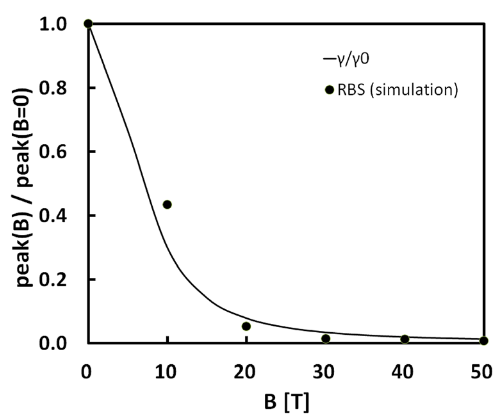

FIG. 4. The RBS peak intensity and the theoretical growth rate depending on the external magnetic field. The solid line indicates γ/γ_0 and the dot indicates measured peak intensity, where γ_0 is the growth rate for $B = 0$.

signals may come dominantly from the focal spot of the pump pulse, where the laser intensity is the maximum. Since the spot size is also small compared to the plasma, any boundary effects can be neglected. So our method may provide a good way of *pin-pointing* the local plasma parameters. In that sense, though our method can be applied to homogeneous plasmas most effectively, such a limitation does *not* seem to diminish much the applicability of the suggested method. Note that when the dimensions of the plasma and the pump pulse are similar to each other, the plasma inhomogeneity may result in the bandwidth broadening of the scattered signals. On the other hand, the studies about the effects of density gradient on the growth of RBS can be found in Refs. 17 and 18.

Before we summarize the works, it may be inspiring to compare the proposed idea with the Faraday rotation,[19,20] which is a well-known, robust method of measuring the magnetic field of a magnetized plasma. The rotation angle of the electric field polarization induced by the phase velocity difference of right-handed- and left-handed circularly polarized waves is described by $\phi[rad] = 2.62 \times 10^{-17} \lambda^2 n_e B d$ in cgs unit, where λ and d are the wave length and propagation distance of the pump pulse, respectively. Then, to obtain the rotation by 1° under the parameters of Fig. 3(a), the pulse propagation length should be at least 3 cm, which is larger than the Raman growth length by an order of magnitude: the RBS growth length is $\tau_{eff} \simeq 5$ ps, corresponding to 1.5 mm.

In conclusion, we proposed and studied a method to measure the density and the magnetic field of a magnetized plasma utilizing the different frequency shifts of RFS and RBS for a given magnetic field. The idea was verified theoretically and also by one-dimensional PIC simulations. To clearly separate the back- and forward scattered signals, we employed the directional field splitting method for the field solver in the PIC simulations. We showed that the additional frequency shift of RBS by the magnetic field was large enough to distinguish the magnetic field effect. Furthermore, the growth rate of RBS measured from the simulations agreed well with theoretical predictions. And finally a potential experimental application regarding Tokamak plasma diagnostics was discussed.

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