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Density oscillations in laser produced plasma decelerated by external magnetic field

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Abstract. This paper presents the dynamics as well as the stability of laser produced plasma expanding across the magnetic field. Observation of some high frequency fluctuations superimposed on ion saturation current along with structuring in the pin hole images of x-ray emitting plasma plume indicate the presence of instability in the plasma. Two type of slope in the variation of x-ray emission with laser intensity in the absence and presence of magnetic field shows appearance of different threshold intensity of laser corresponding to each magnetic field at which this instability or density fluctuation sets on. This instability has been identified as a large Larmor radius instability instead of classical Rayleigh-Taylor (R-T) instability.

Keywords. Ion saturation current; large Larmor radius instability.

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1. Introduction

Study of instability in expanding laser produced plasma during acceleration and deceleration phase has wide applicability in various field of research related with plasma physics including inertial confinement fusion [1–4]. The propagation and stability of collimated streams or jets of plasmas in magnetic field is important to a number of other important physical problems, including beam heating of magnetically confined thermonuclear plasma as well as interaction of solar wind with planetary magnetospheres etc. Investigation of laser produced plasma expanding across an external magnetic field is the subject of current interest in many laboratories [4–8]. Various properties of plasma such as x-ray emission, ion acceleration and plasma confinement has already been studied in laser produced plasma expanding across the magnetic field [6]. The presence of magnetic field along the direction of propagation of laser has been proved advantageous in generating a good x-ray laser media, which provided a large enhancement in its gain [7–8]. Generation of high energy ions at comparatively low intensity in the presence of magnetic field has also been observed. It has been discussed earlier that cloud of laser produced plasma is being stopped by the magnetic field B at a distance $R_b \sim B^{-2/3}$. During this process the kinetic energy of the plasma is totally transformed into the energy of magnetic field and plasma becomes unstable. In this situation many instabilities are generated in the plasma. The nature of these instabilities is not very clear now. It is well known that the deceleration force in the plasma induces R-T instabilities, which require the magnetization state of the ions and has been investigated extensively [2]. Streaming and counter streaming plasma flows can dominate the plasma dynamics and the evolution of structures in the plasma. In such a situation presence of various other types of instabilities such as large Larmor radius, lower hybrid drift and Kelvin Helmholtz instabilities can not be ruled out.

In the present experiment we have studied the deceleration and the stability of laser produced plasma expanding across the magnetic field. The instability present in the plasma in the form of density oscillations superimposed on ion saturation current has been analysed in order to get an idea about the process of its generation.

2. Experiment

The experimental setup used in the present study utilizes a picosecond Nd:YAG laser delivering 75 mj energy in 35 ps at $\lambda \sim 1.06$ μm. A second hormonic beam was generated at $\lambda = 0.53$ μm delivering 15 mj energy in $\tau_{\rm sh} \sim 25$ ps for this experiment. The laser beam was focused on the thick copper target kept in the plasma chamber evacuated at $\sim 10^{-5}$ Torr. Various diagnostics systems [9] such as multichannel vacuum photodiode, x-ray pin hole camera based on combination of phosphor screen and image intensifier tube and Langmuir probes were used to record the x-ray emission, two dimensional image of x-ray emitting plasma plume as well as the plasma expansion velocity respectively. The vacuum photodiodes were kept at 45° from the target normal where as Langmuir probes were located at 0° (10° below the laser beam) and 45° at a radial distance of 5 and 17 cm from the target surface. The location of x-ray pinhole camera was at 90° from the direction of laser beam such that it could record the shape of the image (2-dimensional) of expanding plasma plume. The spatial resolution of the pin hole camera was measured as 50 μm which was limited by the spatial resolution of image intensifier tube. The details about pinhole camera having phosphor screen and image intensifier tube have been reported elsewhere. The thick copper plate as the target was kept at one end of the poles of two bar magnets having cross sectional area 10 $\times$ 10 mm. The geometry of locations of magnets and target has already been reported. The bars of magnetic poles were separated by 5 mm, which provided magnetic field of 0.6 T. The magnetic field decays to zero at a distance of 5 to 6 cm from the end of the bar magnet. The target and magnets were moved using different manipulator so that their location can be changed independently according to the requirements of experiment.

3. Results and discussion

Figure 1a and 1b show the ion saturation current measured in the absence and presence of magnetic field. Figure 1a shows a sharp pulse (first one) due to x-ray and ultraviolet emission, which acts as a reference for the measurement of plasma expansion velocity. The second broad pulse is ion saturation current. The expansion velocity of plasma in the absence of magnetic field was found as $\sim 2.4 \times 10^7$ cm/s. In this oscillogram variation of ion saturation current was found smooth. Figure 1b shows the oscillogram of ion saturation current in the presence of magnetic field. In this case ion saturation current shows high

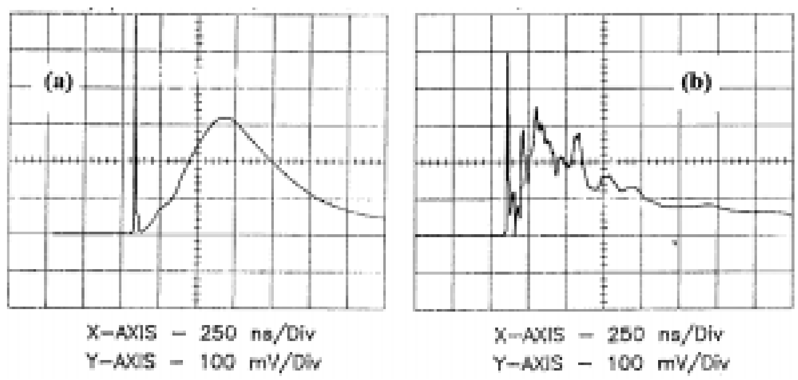

Figure 1. Oscillogram of ion saturation current.

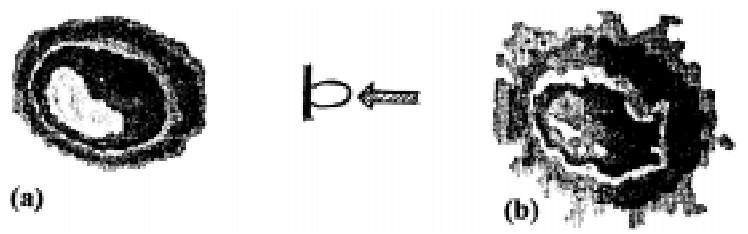

Figure 2. X-ray pinhole pictures of x-ray emitting plasma plume.

frequency fluctuations superimposed on it. Mainly two types of frequencies were observed as ∼4 MHz and ∼100 MHz. The ∼4 MHz oscillations were having large amplitude in comparison to ∼100 MHz oscillations. These oscillations seem to be due to the generation of some kinds of instability in the plasma. The plasma expansion velocity in this case, was calculated as $\sim 1.13 \times 10^7$ cm/s which shows a slight decrease in the value in comparison to the absence of magnetic field. This is due to the deceleration of plasma in the presence of magnetic field. Another observation in the presence of magnetic field was the decrease in the amplitude as well as increase in the pulse width of ion saturation current. The decrease in amplitude is due to broadening of the peaks. However, broadening of peak is due to deceleration of the plasma, which is nothing but the confinement of plasma. Recording the pinhole image of x-ray emitting plume in the absence and the presence of the magnetic field has showed the confinement effect of the magnetic field earlier.

Figure 2a and 2b shows the x-ray pinhole pictures of the laser produced plasma in the absence and presence of magnetic field. It was noticed that plasma expansion is smooth in the absence of magnetic field where as structures develops in the isointensity contour in the presence of magnetic field. These structures occur due to the generation of instabilities in the plasma, which is in agreement with the observation of density fluctuations in the ion saturation current. Similar type of instability generation has been reported in different kinds of experiment. This indicates that free energy of expanding (streaming

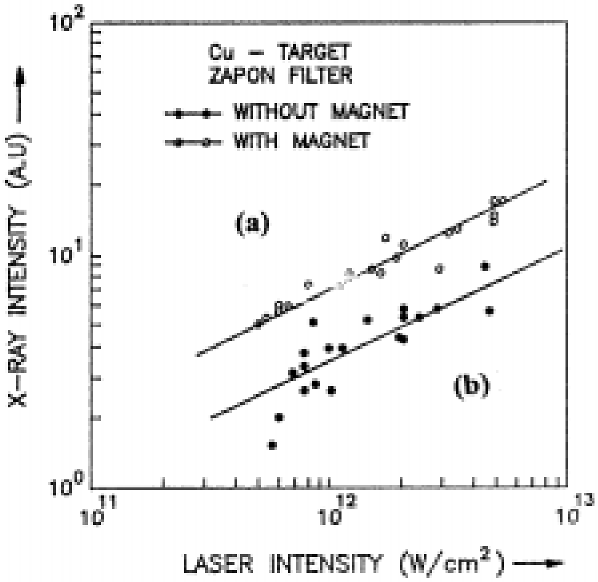

Figure 3. Variation of x-ray emission with laser intensity.

and counter streaming) plasma is being utilized in generation of instability in the plasma during deceleration under the effect of external magnetic field. This has been verified with the help of figure 3, which shows the variation of x-ray intensity emitted from the plasma with laser intensity at 0.01 and 0.6 T magnetic field. Enhancement in the x-ray emission by 2–3 times in the presence of magnetic field has already been reported earlier. Presence of two types of slope as $\alpha = 0.5$ and 1.5 is another observation in figure 3. It is noticed that for low magnetic field (0.01 T) and at low laser intensity $\alpha - 1.5$ where as it reduces to 0.5 as the magnetic field or the laser intensity is increased to 0.6 and 5×10^{11} W/cm^2 respectively. This indicates the presence of threshold laser intensity for the onset of instability corresponding to each value of magnetic field, where the slope changes. In the case of 0.6 T magnetic field threshold intensity may be below our experimental range. This change in slope is due to the relative decrease in x-ray emission. This indicates generation of another channel of energy loss from the plasma, which may be the production of fast particles from the plasma as well as the on set of plasma instability as is clear from the experimental evidences. Similar onset of density fluctuation in laser produced plasma at 170 G magnetic field has already been reported by Chang and Hashmi [10]. But no analysis was presented regarding density fluctuation in terms of instabilities or its process of generation in the plasma. A simple analysis has been presented to better understand the process of instability generation in the following text.

As discussed above mainly two types of oscillations were noted as $\sim$4 MHz and other one at frequency $\sim$100 MHz. The $\sim$4 MHz oscillation seems to be due to oscillation of magnetic field lines under the effect of plasma pressure of expanding plasma and the restoring force due to magnetic field lines. The theoretical model reported earlier [6] can better explain the plasma expansion in the presence of magnetic field. An expression for the expansion of resistive plasmoid in magnetic field can be written on the basis of ohms law, the momentum and energy equation. Neglecting the resistivity and skin depth term one can write the equation as

$$\frac{B^2}{2}(R_b^3 - R_0^3) = \frac{3}{2}(N_e + N_i)kT_0 R_0^2 \left(\frac{1}{R_0^2} - \frac{1}{R_b^2}\right) + \frac{1}{2}M_0 V_E^2. \tag{1}$$

Assuming that at t_0 when the plasma becomes transparent

$$\frac{1}{2}M_0 V_E^2 \ll \frac{3}{2}(N_e + N_i)kT_0 \tag{2}$$

and $R_b \gg R_0$ (plasma radius at t_0). After simplification one can find the expression for bounce radius as

$$R_b = \left[\frac{9}{2} \cdot \frac{NkT_0}{B^2}\right]^{1/3} \approx 1698\,\mu\mathrm{m}, \tag{3}$$

where $kT_0 \approx 180$ eV, $N = 1.36 \times 10^{14}$ is the total number of plasma particles present in the plasmoid. The bounce time of the plasma was calculated as $\tau = R_b/C_s \approx 30$ ns which provides a frequency of ~33 MHz. The variation in measured (~4 MHz) and calculated values of frequency may be due to variation in the estimation of R_b. The second high frequency fluctuation at ~100 MHz seems to be due to Rayleigh–Taylor, large Larmor radius version of Rayleigh–Taylor instability or Kelvin–Helmholtz instability. Because plasma is satisfying nearly all the condition for these instabilities. In order to identify the instability in the present experiment it is necessary to analyse the experimental condition. The driving mechanism for unmagnetized ion Rayleigh–Taylor instability is the deceleration of the expanding plasma shell. This deceleration can be interpreted as an effective gravitational acceleration (g_{eff}). An estimate about the g_{eff} can be obtained by writing the energy balance equation as

$$\frac{1}{2}M_0 V_E^2(t) + \frac{B^2}{8\pi} \cdot \frac{4}{3}\pi R^3(t) = \frac{1}{2}M_0 V_{E0}^2, \tag{4}$$

where the left hand side is the sum of the kinetic energy of the expanding plasma and the swept up magnetic energy at time t and location R. The right hand side is the energy contained in the plasma at time $t = 0$. One can write the expression for effective gravitational acceleration by solving the eq. (2) for $V_E(t)$ and then differentiating it with respect to time.

$$g_{\mathrm{eff}} = -\frac{\mathrm{d}V_E}{\mathrm{d}t} = \frac{B^2}{2M_0}R^2(t) \cong 3.5 \times 10^{14}\ \mathrm{cm/s}, \tag{5}$$

where $B = 6000$ G, $R(t) = R_b \approx 1600\ \mu$m and $M_0 \sim 1.3 \times 10^{-9}$ g is the total mass of the plasma. With the knowledge of effective gravitational acceleration, an expression for the growth rate of classical Rayleigh–Taylor instability in the case of a plasma decelerated by magnetic field can be written in the short wavelength limit $(kL_n > 1)$ as

$$\lambda_{\mathrm{RT}} \sim \left[\frac{g_{\mathrm{eff}}}{L_n}\right]^{1/2} \sim 1.52 \times 10^9, \tag{6}$$

where $L_n \sim 2\,\mu$m is the plasma density scale length. The time for the development of R-T instability can be obtained as

$$\tau_{\mathrm{RT}} \sim 1/\lambda_{\mathrm{RT}} \sim 6.5 \times 10^{-10}\ \mathrm{s}. \tag{7}$$

It is well known that the condition for classical R-T instability to grow is $\tau_{\mathrm{RT}} \cdot \omega_{ci} \gg 1$, whereas in the present case it comes out to be ~ 0.373. This indicates that condition is not satisfied and the instability can not be classical RT instability. Various other plasma parameters were obtained for this experimental condition in order to investigate the conditions for other instabilities. The ion cyclotron frequency was found as $\omega_{ic} \sim 5.74 \times 10^8$ Hz, whereas the ion thermal as well as the plasma expansion velocities were obtained as $V_{Ti} \sim 9.79 \times 10^5 T_i^{1/2} \sim 1.3 \times 10^7$ cm/s and $\sim 2.4 \times 10^7$ cm/s respectively. With the help of ion cyclotron frequency, ion thermal and plasma expansion velocity it is easy to estimate the thermal Larmor radius $r_{\mathrm{LT}} \sim 0.022$ cm and directed Larmor radius $r_{\mathrm{LD}} \sim 0.04$ cm. The large Larmor radius version of the Rayleigh–Taylor instability is predicted theoretically to proceed on faster time scale than the classical Rayleight–Taylor instability. The most important condition for the large Larmor radius instability is that Larmor radius be large compared with the density scale length of the expanding plasma [2]. Here in this experiment the directed Larmor and thermal Larmor radii are found greater than the density scale length of the plasma but is less than the bounce radius of the plasma R_b, which is an important condition for the large Larmor radius instability. This indicates that the high frequency instability being generated in the plasma as a result of deceleration in the presence of magnetic field is a large Larmor radius version of Rayleigh–Taylor instability. The Kelvin–Helmholtz instability depends on the free energy in a velocity shear layer and does not require a transverse deceleration of the plasma. In the present experiment we have streaming and counter streaming (photo ionized background) plasma, but due to lack of experimental data about the velocity shear, it is not possible to say anything about this instability in the present situation. However there is a finite possibility of shear velocity in the plasma even due to coupling of poloidal self generated as well as external magnetic field, which have to be worked out theoretically as well as experimentally.

4. Conclusion

In summary we can say that laser produced expanding plasma develops instabilities when it was decelerated by the external magnetic field. Threshold laser intensity was noticed for the development of instability for different magnetic field. The high frequency instability was identified as large Larmor radius version of Rayleigh–Taylor instability.

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