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Effect of chamber pressure induced space charge potential on ion acceleration in laser produced plasma

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Abstract

The acceleration of ions ($\sim 10^8$ cm/s) has been observed in the laser produced plasma expanding across an uniform magnetic field at low laser irradiance ($\sim 5 \times 10^{12}$ W/cm^2). This acceleration was found correlated with the onset of instabilities in the plasma and decrease in the slope of X-ray emission with laser intensity. A large enhancement in the X-ray emission (E $>$ 2 KeV) from plasma in the presence of magnetic field supports the observation of ion acceleration. An increase in the number of ions was noticed in the pressure range in which enhancement in the self-generated spontaneous magnetic field has already been established. Even scaling of both the variations with chamber pressure during rising part was found in close agreement, which further supports the correlation. The possibility of an external magnetic field in triggering the acceleration and space charge potential in generating a correlation (between ion acceleration and self-generated spontaneous magnetic field) has been discussed.

1. INTRODUCTION

The investigation of fast ions emitted from laser produced plasma is an important topic of interest for laser fusion. It is well known that the energy distribution of ions observed far from a solid target at high laser irradiance can usually be divided into two distinct ion groups, (1) a low energy ion group containing most of the ablated target mass and (2) a small but significant group of higher energy ions (Cairns & Sanderson, 1980; Radziemski & Cramers, 1989). The high energy ions in laser produced plasma are related to the small group of ions transporting a significant fraction of absorbed laser energy (Decoste & Ripin, 1977; Decoste & Ripin, 1978; Cairns & Sanderson, 1980; Tasakiris *et al.*, 1981; Tateyama *et al.*, 1982; Eidman *et al.*, 1984; Radziemski & Cramers, 1989) which is why the study of ion acceleration is useful in various ways in laser plasma interaction, particularly in inertial confinement fusion (ICF). It has been reported (Wagli & Donaldson, 1978; Cairns & Sanderson, 1980) that particularly in the case of steep density gradient ($L_n \sim 2$–$3\,\mu$m) or collisionless resonance absorption, laser energy is deposited into a hot electron distribution at the critical density surface. These electrons distribute their energy in two ways. They can either transport their energy into target interior and form thermal plasma or they can accelerate fast ions through the potential seath formation as a result of ambipolar diffusion of fast electrons. Many sources of fast electrons are available in the literature as resonantly driven electric field (Wagli & Donaldson, 1978), flux limitation (Malone *et al.*, 1975; Max 1982), ponderomotive force in coronal plasma (Hora, 1971), and parametric instabilities (Thompson *et al.*, 1974). Generation of hot electrons from laser produced plasma has been correlated with the emission of hard X-rays and fast ions (Eidman *et al.*, 1984). Various mechanisms have been reported to explain the observation of high energy X-rays emission ($K_\propto$) around the hot focal spot which has been correlated with the emission of fast ion. Many authors have studied the problem of particle acceleration during laser plasma interaction experimentally, theoretically as well as through computer simulation (Forslund *et al.*, 1975; Decoste & Ripin, 1977, 1978; Tasakiris *et al.*, 1981; Eidman *et al.*, 1984). Electrostatic acceleration from a large localized pressure gradient setup by the inhibition of heat transport is the principal mechanism suggested for acceleration of these high energy ions, where self generated magnetic fields play an important role (Decoste & Ripin, 1977; Bell *et al.*, 1993). Formation of dynamic double layer in laser produced plasma is also one of the electrostatic mechanisms to accelerate (Eliezer *et al.*, 1995) the plasma particles at high laser intensity. It has also been shown (Sugihara & Midzuno, 1979) that plasma particles can be heated if an electrostatic wave is propagating perpendicular to a static magnetic field *B*. In this process, energy of the wave is ab-

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sorbed by the particle through Landau damping process. In a somewhat stronger magnetic field, some trapped particles are dynamically accelerated to EXB drift speed due to wave electric field E. After getting energy, particles detrap from the potential well. In this case particle energy becomes much higher than their thermal energy. A similar process known as the VXB acceleration mechanism (Dawson, 1983) produces fast plasma particles if a magnetic field is present in the plasma perpendicular to its density gradient. Mainly all the laser plasma experiments related with ion acceleration were performed at high laser intensity ($>10^{14}$ W/cm^2) irrespective of their time duration as well as in the absence of external magnetic field. Enright and Burnett (1986) have reported the observation of hard X-ray emission along with high energy electrons when a CO_2 laser produced plasma was expanding across the magnetic field. But they did not mention the effect of a magnetic field on ion acceleration. In another experiment, Roger and Schwirzke (1975) reported that an increase in chamber pressure increases the space charge potential which decides the electron current from plasma and as a result induces a self-generated magnetic field. They have further mentioned that an increase in confinement of plasma plume as a result of increased chamber pressure enhances the pressure gradient induced self-generated magnetic field. The role of a self-generated spontaneous magnetic field on ion acceleration through heat flux inhibition is well known. It indicates that any effect generating change in amplitude of the spontaneous magnetic field [chamber pressure induced plasma confinement in the Roger and Schwirzke experiment (1975)] must have a corresponding effect on ion acceleration. Presence of external magnetic field which has already shown confinement of plasma plume in laser produced plasma (Suckewer & Fishman, 1980; Suckewer *et al.*, 1985; Rai *et al.*, 1998) should show a similar effect on ion acceleration. Even, simultaneous presence of both the plasma confining factors (magnetic field and chamber pressure) must show ion acceleration at a comparatively low laser intensity.

The main aim of this experiment was to verify the above discussed points and to better understand the process of ion acceleration. In this paper we are reporting the observation of ion acceleration at low intensity ($\sim 5 \times 10^{12}$ W/cm^2) in a ps laser produced plasma (Low-density scale length plasma) expanding across an external magnetic field. A correlation was found between ion acceleration and density fluctuation as well as enhancement in hard X-ray emissions. An effect of ambient gas pressure on ion acceleration in the presence of an external magnetic field has also been discussed.

2. EXPERIMENT

The experimental set up used in the present study consists of a 35 ps time duration Nd: YAG laser (75 mJ) operating in second harmonic at 0.53 μm wavelength, τ_{SH} ~25 ps and delivering up to 15 mJ energy. A laser beam was focused onto the Cu target using a spherical lens of 30 cm focal length where laser energy was changed using neutral density filters. A thick planar target of Cu was used to form the plasma in a vacuum chamber evacuated at $\sim 10^{-5}$ Torr. The X-rays emitted from laser produced plasma was monitored using a multichannel vacuum photodiode (Rai *et al.*, 1995) having a thin Zapon (~4 μm) and 12-μm-thick Al filters. X-ray detectors were kept at 45° with respect to the target normal where as Langmuir probes were kept at 0° (10° below the laser beam), and 45° with respect to the target normal but at a radial distance of 5 and 17 cm from the target surface to monitor the ion saturation current (time of flight). The signals from X-ray vacuum photodiode and Langmuir probes were recorded using a 100 M Hz L&T Gould Model 7074 digital storage oscilloscope (400 Ms/s). An intensifier based X-ray pinhole camera (Rai *et al.*, 1996) with ~ 50 μm spatial resolution was used to record the pinhole pictures of the X-ray emitting plasma plume. Two bar magnets of 10 × 10 mm cross sectional area kept at 5 mm separation were used to generate uniform external magnetic field of 0.6 T between the poles. Both the targets and the bar magnets were held inside the plasma chamber with the help of two independent manual manipulators such that target was in touch with the magnetic poles as shown in Figure 1. The position of the target was changed without affecting the magnetic field at the location of plasma formation, so as to take each shot at a fresh location. Laser plasma produced in this arrangement expands ~ 10 mm in the uniform magnetic field. However, the small fringing effect may be there at the edge of the magnet where plasma is formed. As the plasma comes out of the magnetic poles it feels the decreasing magnetic field because of increasing distance from the magnetic poles.

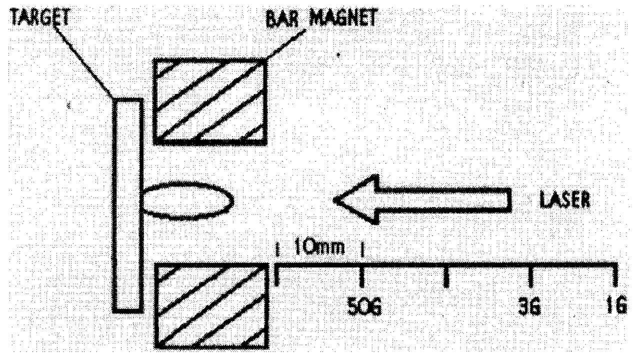

Fig. 1. Arrangement of target and bar magnet during the experiment.

3. RESULTS AND DISCUSSION

3.1. Plasma expansion and ion acceleration

Initially ion saturation current was measured using a Langmuir probe in laser produced plasma expanding in vacuum in the absence and presence of an external magnetic field. The probe was located ~ 5 cm away from the target surface and at 45° from the target normal. The magnet and the target were kept in the chamber as shown in Figure 1. This mea-

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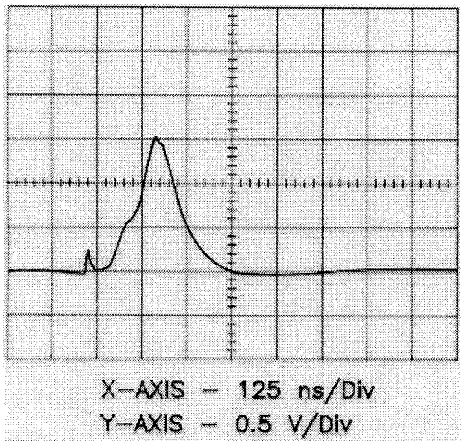

Fig. 2. Oscillogram of the ion current measured using a Langmuir probe kept at $r = 5$ cm. And $\theta = 45°$ in the absence of magnetic field. ($I = 10^{12}$ W/cm^2 and $P = 5 \times 10^{-5}$ Torr).

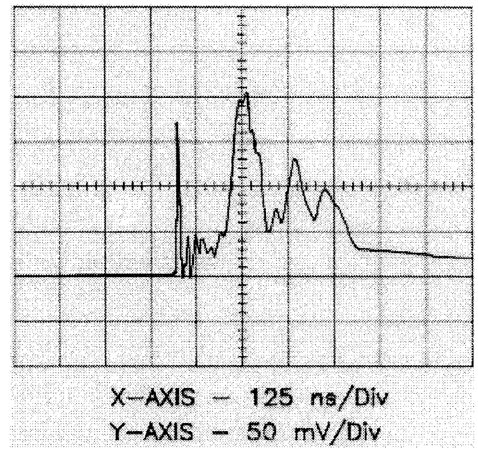

Fig. 3. Oscillogram of the ion current in the presence of magnetic field but in the same condition.

surement was performed at a laser intensity of $\sim 10^{12}$ W/cm^2 and ambient chamber pressure of $\sim 5 \times 10^{-5}$ Torr. Figure 2 shows the oscillogram of ion saturation current in the absence of an external magnetic field. The signal shows a sharp pulse due to X-rays followed by a broad pulse of ions from bulk plasma. The peak of the ion pulse occurs after $\sim$ 206 ns with respect to X-ray pulse and provides the plasma expansion velocity of $\sim 2.4 \times 10^7$ cm/s. Figure 3 shows the oscillogram of ion pulse in the presence of an external magnetic field. It shows a sharp peak due to X-ray followed by a sharp and small ion pulse indicated as "A". The bulk plasma started reaching the probe after the sharp ion peak noted as "A." The measured expansion velocity for this ion pulse ($\sim 1.33 \times 10^8$ cm/s) indicates that a small part of the ions are getting accelerated (Rai *et al.*, 1997). The bulk ion current shows presence of some high frequency oscillations ranging from $\sim$4 MHz to 100 MHz superimposed on it. Similar ion current was recorded by the probe located at $\theta = 0°$ (10° below the laser beam). A comparison of ion current in the absence (Fig. 2) and presence of magnetic field (Fig. 3) shows that a part of the plasma is accelerated whereas the bulk plasma expansion slowed down in the presence of magnetic field which results in an increase in FWHM in temporal profile of ion current. Observation of large amplitude low frequency ($\sim$4 M Hz) oscillations are due to the compression and relaxation of the magnetic line of force, because any charge particle can not cross the magnetic line of force. When a high temperature plasma expands across the magnetic field, it compresses the line of force whereas the magnetic pressure acts as a restoring force and stops the plasma expansion. Initially smooth expansion takes place up to a distance of bounce radius r_b (near $\beta = 1$ surface). This is in agreement with the theory given by Bhadra (1968). Four bounces can be seen in Figure 3 which shows that plasma was not completely stopped under the effect of magnetic pressure and has damping in ion current due to finite temperature of plasma ($kT_e \sim 180$ eV). Even the presence of instabilities in plasma enhances the cross-field diffusion. In the case of perfectly conducting plasma there will not be any damping in the low frequency ($\sim$ 4 MHz) oscillation (Bhadra, 1968). High frequency fluctuations ($\sim$80 MHz) superimposed on ion current may be due to presence of two stream instabilities in the plasma as is reported earlier (Cheung *et al.*, 1973). The main observation in this experiment was the development of small ion pulse (A) before the arrival of bulk plasma at the probe. The velocity of ions corresponding to this peak was found $\sim 1.33 \times 10^8$cm/s, where as velocity of the bulk plasma corresponding to various peaks were ranging from 1.2×10^7–2.67×10^7 cm/s (Figure 3). Expansion velocity of the plasma was found to be $\sim 2.4 \times 10^7$ cm/s in the absence of magnetic field (Figure 2). A simple comparison shows that part of the plasma got accelerated where as bulk of the plasma got decelerated. Figure 4 shows the ion current recorded at chamber pressure of $\sim 10^{-3}$ Torr and a laser intensity of

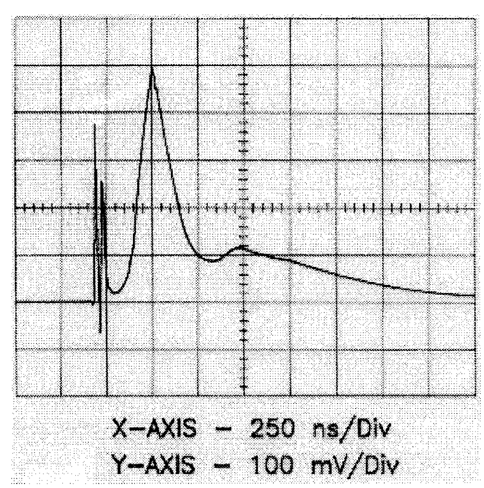

Fig. 4. Oscillogram of the ion current in the presence of a magnetic field ($I = 5 \times 10^{12}$ W/cm^2 and $P = 10^{-3}$ Torr).

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$\sim 5\times10^{12}$ W/cm^2 which shows an increase in the amplitude of fast ion pulse. It was also noted that the amplitude of the first peak due to the first bounce of bulk plasma near $\beta = 1$ surface also increases probably as a result of increased plasma pressure (increase in the number of plasma particles) at higher laser irradiance. In this case only the two bounce has been observed out of which the second one is very small in amplitude. To understand the mechanism of plasma oscillation, it is necessary to solve the energy, momentum, and Ohm's law equations for the expansion of resistive finite temperature plasma across an externally applied magnetic field (Bhadra, 1968; Neogi & Thareja, 1999). One can write the energy integral obtained by solving this equation as

$$\frac{B^2}{3}[r_b^3 - r_0^3] = \frac{3}{2}(N_e + N_i)kT_0 \cdot r_0^2\left(\frac{1}{r_o^2 - r_b^2}\right) + \frac{1}{2}MV_0^2 + 2B^2\left[\int_0^1 F_2(r,\lambda)\frac{dr}{dt}\cdot dt\right] + \int_0^1 (N_e + N_i)k\frac{f_1(t)}{r^3}\frac{dr}{dt}dt, \quad (1)$$

where r_0 and T_0 are the initial radius and temperature of the plasmoid after the end of laser pulse. N_e and N_i are the total number of electron and ions in the plasma, M is the average mass of the plasma, where B is the externally applied magnetic field. In the above equation $f_1(t)$ is proportional to the plasma resistivity η, which is dependent on plasma temperature and

$$F_2(r,\lambda) = \lambda[r - \lambda(1 - e^{-r/\lambda})], \quad (2)$$

where λ is the skin depth. The first and second term in the right hand side of Eq. (1) refers to the thermal and kinetic energy of the plasma respectively. The third and fourth term arise due to finite resistivity of the plasma. During solving this equation, plasma energy loss due to radiation was not taken into account. The above equation explains in a better way the oscillation of plasma under the effect of magnetic field. The r_b in the above equation shows the plasma bouncing radius. One can obtain a simplified form of Eq. (1) by neglecting the plasma resistive and skin depth effects as well as after assigning at an early time

$$\frac{MV_0^2}{2} \ll \frac{3}{2}(N_e + N_i)kT_0 \quad \text{and } r_b \gg r_0.$$

Finally, expression for the bouncing radius can be written as

$$r_b = \left(\frac{9NkT_0}{2B^2}\right)^{1/3} \quad (3)$$

where as the period of oscillation can be given by $\tau = r_b/C_s$, where C_s is the acoustic velocity of the plasma. For finding out the value of r_b and τ, it has been assumed that value of T_0 remains constant during the initial expansion and is not being influenced by the magnetic field. The value of plasma temperature was calculated using an expression for T_0, which is based on asymptotic expansion velocity as

$$T_0 = MV_0^2/5(Z+1) \cong 234 \text{ eV}, \quad (4)$$

where $M = 63\times1.67\times10^{-24}$ is the mean ion mass and $V_0 = 1.4\times10^7$ cm/s. The value of plasma temperature comes out to be $\sim$204 eV based on the calculation of energy absorbed per particle. These values were found in close agreement with the measured plasma temperature $\sim$180 eV. Taking $N \sim 1.36\times10^{14}$, the total number of plasma particles present in the plasmoid and $B \sim 0.6\ T$, the values of bounce radius and time were found as 1698 μm and $(\tau{\sim}r_b/C_s){\sim}30$ ns respectively for $C_s \sim 5.6\times10^6$ cm/s calculated at $T_0 = 180$ eV. This calculation shows that the first bounce will occur after 30 ns and will generate an oscillation of frequency $\sim$3 MHz where as the experimental value of first bounce is $\sim$175 ns (Fig. 2). This difference in measured and calculated values of bouncing times are expected due to variations in the measurement of plasma temperature and r_b calculation. It is clear from Eq. (3) of the bouncing radius and time that the value of r_b decreases as the plasma temperature goes down with time. It shows a successive decrease in bouncing time which is in agreement with the experimental observations (Fig. 2). The damping in the ion current during bouncing occurs as a result of increased resistivity of the plasma due to plasma cooling by radiative recombination as well as due to the presence of magnetohydrodynamic instability which induces cross-field diffusion of plasma particles. If the plasma is perfectly conducting there will not be any damping and the oscillations will have equal amplitude.

A single fluid magnetohydrodynamic equation for generalized form of Ohm's law (Chen, 1974) in a fully ionized plasma can be written as

$$E + VXB = \eta J + (JXB)/en_e, \quad (5)$$

where E and B are the electric and magnetic field in the plasma, J the charge current density, η the resistivity, n_e the electron density, and V the mass flow velocity. During 1D flow in the absence of current, one can write $E_y = Vx \cdot Bz$. It indicates that during the expansion of plasma across the magnetic field, there will be a charge separation due to Lorentz force in the direction perpendicular to V and B. In the presence of this electric field in the plasma, there will be a drift velocity in the direction perpendicular to E as well as B, and as a result there will be a current J in the plasma plume. Direction of this current will be opposite on the front and inside of the plasma. This current will generate a JXB force in the direction of plasma expansion near the front where as it will be in opposite direction inside the plasma. This JXB force will contribute in generating fast particles from the plasma whereas the bulk of the plasma will be decelerated (Neogi & Thareja, 1999). This seems to be one of the ex-

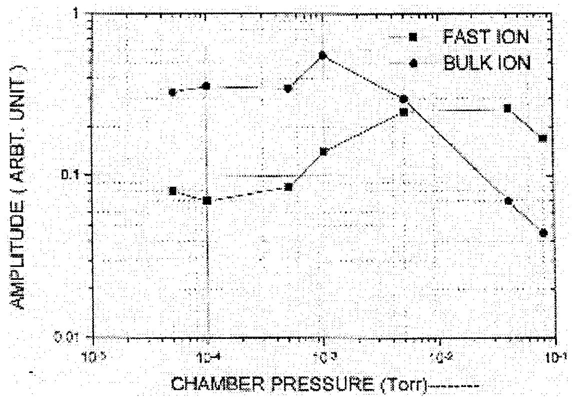

Fig. 5. Variation of fast and bulk ion pulse amplitude with an increase in chamber pressure.

planations for our experimental observation regarding generation of fast as well as slow plasma during expansion across the magnetic field.

Figure 5 shows the variation of amplitude of the fast ion and bulk plasma pulse at first bounce with an increase in chamber pressure (air). Amplitude of the fast ion pulse started increasing after 5×10^{-4} Torr with a peak between 5×10^{-3}–5×10^{-2} Torr where as it started decreasing after 5×10^{-2} Torr. Initially, the increase was fast with a slope $\alpha = 0.9$ between 5×10^{-4}–10^{-3} Torr, where as between 10^{-3}–5×10^{-2} Torr it was $\alpha = 0.44$. The average slope was around ~ 0.67. The amplitude of the bulk ion pulse remains nearly the same with a small increase at 10^{-3} Torr and then shows a gradual decrease. The fast ion expansion velocity (Figure 6) remains same ($\sim 1.33 \times 10^{8}$ cm/s) whereas a small increase in bulk ion velocity was noted with an increase in chamber pressure. Small increase in velocity of bulk plasma may be due to the JXB force acting on the front

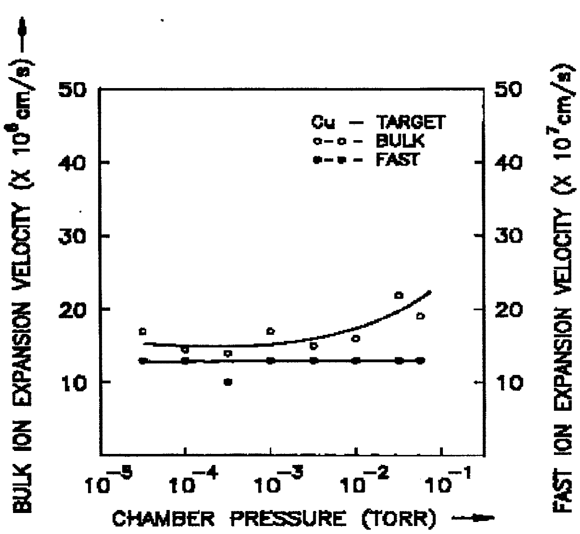

Fig. 6. Variation of expansion velocity of fast and bulk ions with an increase in chamber pressure.

of expanding plasma as has been discussed earlier. Many small amplitude fast ion pulses, but slower than the main pulse (A) were also observed at $\sim 5 \times 10^{-2}$ Torr chamber pressure. The reason for an increase in the amplitude of fast ion pulse at higher chamber pressure is not clearly understood. However, it seems that momentum transfer in laser plasma and background plasma as a result of photoionization (Due to X-rays and UV emission) and charge exchange processes (due to high pressure in chamber) are playing an important role particularly in the presence of magnetic field as is reported earlier (Cheung *et al.*, 1973). The observation of small amplitude peaks along with the main accelerated peak, as discussed above, may be due to the presence of various charge states of light atom ions which are the most probable candidates for acceleration. The effect of ambient chamber pressure on ion acceleration can be understood by considering the evolution of the space charge potential seath and as a result, an electron current from the plasma along with its effect on evolution of spontaneous magnetic field. Because the role of the self-generated spontaneous magnetic field is well known in accelerating the plasma particles. For this purpose a comparison between the variation of self-generated magnetic field with chamber pressure (Roger & Schwirzke, 1975) and the results of Figure 5 was made which shows that the number of ions accelerated increases in the same pressure range in which the spontaneous magnetic field increases. The process of this correlation can be given by the evolution of space charge potential and the self-generated magnetic field in the plasma after considering laser produced plasma as electron emitting cathode (Roger & Schwirzke, 1975). The emission current from such a plasma cathode propagates in the photoionized gas present in the chamber which is another type of electron source. A local potential minimum will be formed near the surface of the plasma. An estimation of the space charge potential, which will be build up in this manner, can be obtained from the knowledge of the temperature and density of the laser plasma. If the plasma is in quasisteady state then a simple analysis provides expression for space charge potential as

$$U_S = \frac{kT_1}{2e} \ln\left(\frac{n_1^2 T_1 m_1}{n_2^2 T_2 m_2}\right). \tag{6}$$

Since the laser produced plasma is expanding outward from the target surface, the final equation for space charge potential gets modified as

$$U_s' = \frac{kT_1}{2e} \ln\left(\frac{n_1^2 T_1 m_1}{n_2^2 T_2 m_2}\right)^{\beta}, \tag{7}$$

where n_1 and T_1 are the density and temperature of laser produced plasma and m_1 is the mass of ions. N_2 and T_2 are the density and temperature of ambient plasma with ion mass m_2. β is a term defined below. This space potential has an important role in the acceleration of ions as well as in gen-

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erating electron current in the plasma which ultimately becomes a source of the self-generated magnetic field. This expression indicates that the ambient plasma density affects the minimum in space potential and decides the net electron current in the plasma, which results an early time self-generated magnetic field. After a simple consideration that the self-generated magnetic field is proportional to net electron current in the plasma and n_2 proportional to ambient pressure, finally a scaling was obtained for early time magnetic field as (Roger & Schwirzke, 1975)

$$B_\theta(ET) \propto P^\beta, \tag{8}$$

where β is a term which defines the effect of plasma motion on the space charge potential as

$$\beta = [V_{th}/(V_{th} + U)]^2 \tag{9}$$

where $V_{th} \sim 10^8$ cm/s is the electron thermal velocity and $U \sim 1.4 \times 10^7$ cm/s is the plasma expansion velocity measured in this experiment, which gives the value of $\beta \sim 0.76$ and provides finally a scaling for the increase of an early time magnetic field as

$$B_\theta(ET) \propto P^{0.76}. \tag{10}$$

Normally the value of β varies between 0.69–0.83 (Roger & Schwirzke, 1975). The pressure gradient based self-generated magnetic field variation with ambient chamber pressure has also been studied earlier. It has been shown (Bird, 1973; Roger & Schwirzke, 1975) that increased background pressure inertially confines the expanding laser produced plasma and increases the normalized axial density gradient $\nabla n_e/n_e$ in proportion to the 1/3 power of the pressure, which is expressed as

$$B_\theta(P.G.) \propto \nabla n_e/n_e \propto P^{1/3}. \tag{11}$$

To confirm the similarity or correlation in both the experimental results (variation in ion current and spontaneous magnetic field with chamber pressure), a further comparison was made between the above discussed scaling with our experimental findings (Fig. 5). The amplitude of the fast ion current follows a scaling during the rising part as $I \propto P^\beta$ where $\beta = 0.9$ was found between 5×10^{-4}–10^{-3} Torr in close agreement with the value of β reported for early time magnetic field as ~ 0.76. The value of $\beta = 0.44$ was found in the pressure range 10^{-3} to 5×10^{-3} Torr which is again in close agreement with the value of slope for pressure gradient induced self-generated magnetic field as ~ 0.33 Eq. (11). This agreement confirms the correlation and indicates that both early time and pressure gradient induced self-generated magnetic fields are playing an important role in ion acceleration. This correlation may not be a coincidence because scaling as well as pressure range are both in correlation. In other words, ambient pressure dependent change in space charge potential and density gradient play an important role in ion acceleration and being reflected in the form of correlation with the self-generated magnetic field, because space charge potential has a common role in both the processes, that is, in ion acceleration and generation of the spontaneous magnetic field. However, it was noticed that the effect of the ambient chamber pressure on ion acceleration becomes prominent only in the presence of the external magnetic field.

3.2. X-ray emission

Some measurement of X-ray emission was performed to find the correlation between ion acceleration and X-ray emission. Figures 7a and 7b show the X-ray pinhole pictures of the plasma recorded in the absence and presence of magnetic field (Rai *et al.*, 1998). A 4 μm Zapon filter was kept before the pinhole to stop the plasma particles from entering into the pinhole camera, whereas it has transmission for X-rays of all energy with a small attenuation at lower energies. It was noted that due to the generation of instabilities (in the presence of magnetic field), the smooth expansion of plasma (in the absence of magnetic field) got distorted at each isointensity contour, even near the hottest portion of the plasma. A decrease in the size of an X-ray emitting plasma plume is due to the confinement of plasma in the presence of an externally applied magnetic field. However, no change in the size of plasma was recorded along the direction of the magnetic field. X-rays emitted from the Cu plasma was recorded using the vacuum photodiode (Rai *et al.*, 1999) at two magnetic fields (0.6 T and 0.01 T) with increasing laser intensity, while keeping all the other plasma parameters constant. Figures 8a and 8b show the variation of the X-ray emission with laser intensity when two of the detectors had a $\sim$4 μm Zapon and 12-μm-thick Al filters. Zapon foil was transparent for X-rays of all energies whereas 12 μm Al transmitted X-rays with energy >2 KeV. Around 2–3 times more enhancement in X-ray emission (Pant *et al.*, 1998; Rai *et al.*, 1998) was noted in the presence of 0.6 T than in the presence of 0.01 T magnetic field (Fig. 8a,8b). No significant change was observed in X-ray emission in the presence of 0.01 T magnetic field or in the absence of magnetic field. However, a significant change was noted in ion current in the presence of magnetic field of 0.01 T. X-ray en-

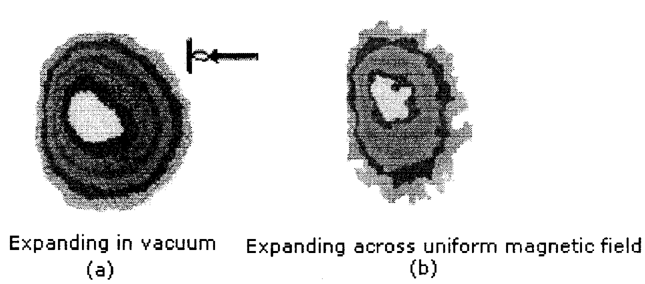

Fig. 7. X-ray pinhole pictures of X-ray emitting plasma plume (a) in the absence of a magnetic field, (b) in the presence of magnetic field.

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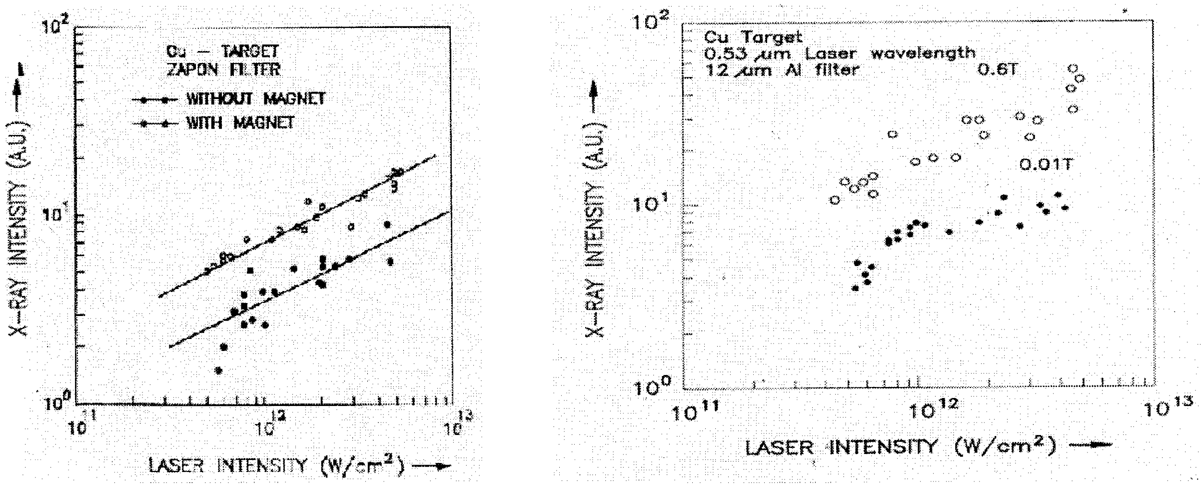

Fig. 8. Variation of X-ray emission with laser intensity (a) With 4 μm Zapon filter (b) With 12 μ m Al filter.

hancement of 4–5 times was recorded towards higher intensity side (5×10^{12}W/cm^2) of laser intensity when a 12 μm Al filter was used as shown in Figure 8b. The scaling of X-ray emission with laser intensity follows the power law variation as $I_x \propto (I_L)^\alpha$ with $\alpha = 0.5$ which is much smaller in comparison to the value $\alpha = 1.5$–2.5 measured in the absence of magnetic field (Bleach & Nagel, 1978; Rai *et al.*, 1995). In fact three types of slopes (value of α) have been observed in X-ray emission v/s laser intensity variation plots obtained experimentally, as ~1.5 in the absence of magnetic field, 0.5 and 1.5 in the presence of 100 G magnetic field and 0.5 in the presence of 0.6 T magnetic field. These observations indicate that as the magnetic field was increased to 100 G then after a certain laser intensity (Threshold), a new decreased slope developed. However, at the higher magnetic field of 0.6 T, only one decreased slope is present for all the experimental range of intensity. It seems that threshold intensity is very small (out of experimental range) in the case of 0.6 T magnetic field. Threshold intensity, where slope changes seems to be dependent on the strength of the magnetic field and it decreases with an increase in the magnetic field strength. This clearly indicates that the absorbed laser energy is being lost through a new channel, which is dependent on the strength of magnetic field and the laser intensity. Similar type of phenomenon of decrease in the slope has been observed whenever high intensity laser interacts with the plasma and generates fast electron as well as comparatively high energy X-rays along with some parametric instabilities (Radziemski & Cramers, 1989). Chang and Hashmi (1977) also have reported the onset of instabilities in ion current in the presence of $B = 170$ G which indicates that change in the slope in case of 100 G magnetic field in the experiment may be due to onset of instabilities in the plasma which may induce loss of energy out of plasma in the form of particle loss (particles having energy) as has been reported by Liewer (1977) in the case of magnetically confined plasma.

3.3. Effect of external and self generated magnetic field

It is well known that generation of toroidal spontaneous magnetic field in laser produced plasma around the focal spot plays an important role in the inhibition of energy transport through fast electrons (Max, 1982; Bell *et al.*, 1993). The self-generated magnetic field in laser produced plasma confines plasma radially and increases the effective plasma density and temperature in the emission zone and generates the fast ions (Bell *et al.*, 1993). In this experiment, both the self-generated as well as an external magnetic fields are acting on the plasma. Amplitude of self-generated magnetic field can be estimated by (Bell *et al.*, 1993)

$$B = 80\,[\tau/2\text{ ps}]\,[\text{kT}_e/100\text{KeV}]\,[L_T/25\mu\text{m}]^{-1}\,[L_n/1\mu\text{m}]^{-1}\text{ MG}. \qquad (12)$$

For this experiment plasma parameters kT_e ~180 eV, L_T ~25 μm and $L_n = Cs\,\tau = 2$ μm provides $B \sim 1.6$ MG self-generated magnetic field, which is sufficient to inhibit the radial energy transport because electron gyro radius

$$r_{ge} = 0.1[kT_e/100\text{ KeV}]^{1/2}\,[B/80\text{ MG}]\,\mu\text{m} \qquad (13)$$

comes out to be ~0.2 μm less than the $Cs\,\tau = 2$ μm, which indicates that this magnetic field is capable of restricting energy transport away from the critical surface and laterally along the target surface. Transport inhibition is supported if the ratio of $\lambda_{mfp}/\rho_L \sim \omega\tau_{ei} > 1$ where

$$\omega\tau_{ei} \sim 8 \times 10^5\,[\tau/2\,ps]\,[kT_e\,/100\text{KeV}]^{5/2}\,[Z/4]^{-1} \times [L_T/25\mu\text{m}]^{-1}\,[[n_e/n_c\,]^{-1}. \qquad (14)$$

Here $\omega\tau_{ei}$ ~63 n_c/n_e for $kT_e = 2$ KeV (high energy electrons), which shows that self-generated spontaneous mag-

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netic field slows down the electron transport across the magnetic field. Since this field was present in both the cases (in the absence and presence of external magnetic field) but all the effects as fast ion generation, change in the slope of X-ray emission and enhancement in X-ray emission (mainly $E > 2$ KeV) are observable only in the presence of external magnetic field in low laser intensity experiments. It seems that the combined effect of both the magnetic field, that is, the self-generated and external magnetic field play an important role in this case. Probably confinement of plasma in this experiment takes place in radial direction mainly due to self-generated magnetic field and in the axial direction due to external transverse magnetic field (Fig. 7). Thus an interaction of laser light with effectively high density plasma (due to confinement) under the combined effect of self-generated poloidal magnetic field (around focal spot) and external magnetic field (perpendicular to the plasma expansion) may be producing similar effects in the plasma at low intensity ($\sim 5 \times 10^{12}$ W/cm^2) as high intensity laser ($>10^{14}$ W/cm^2) is producing in the absence of external magnetic field. This idea has been supported on the basis of two main observations. The first one is the large enhancement in high energy X-ray ($E_x > 2$ KeV) when the laser intensity was in the higher intensity side of the experimental range. Secondly, observation of fast ion pulses in ion saturation current, in the presence of external magnetic field (0.6 T). The possible mechanism of high energy X-ray emission through the generation of hot electrons has been reported (Tateyama *et al.*, 1982) as (1) the JXB force acting on electron as discussed in previous section (2) the reflection of hot electrons from the self-generated potential seath and (3) EXB drifting of electrons. Ion acceleration may be due to the multiple bounce of gyrating ions in the high electric field of potential seath under the combined effect of magnetic fields. The possibility of ions getting more and more energy during each bounce or collision increase (Radziemski & Cramers, 1989) as a result of increased larmor frequency in the presence of external magnetic field at a radial location (away from the target surface) where self-generated magnetic field is either weak or absent. The idea of ion acceleration through multiple bounce may be true only when external magnetic field is playing important role. It seems from the experimental observations that the presence of poloidal self-generated magnetic field alone is not sufficient in generating the above effects in this experiment. And the presence of externally applied magnetic field is playing an important role of triggering the effect, because it extends up to $\sim$10 mm away from the target surface, where as self-generated magnetic field is maximum near the target surface but around the focal spot. Since externally applied magnetic field (0.6 T) is much smaller in comparison to the calculated value of self-generated magnetic field (1.6 MG), thus it is hard to believe that it can generate an effect comparable to the self-generated magnetic field to produce ion acceleration. The role of external magnetic field seems to be coming in the picture as a result of magnetic field amplification due to Nernst advection as has been reported earlier (Yabe *et al.*, 1982; Nishiguchi *et al.*, 1984). Nishiguchi (1984) has shown that any externally applied magnetic field in the laser produced plasma gets convected towards the overdense region due to electron heat flux and becomes amplified by 10–100 times depending on the plasma parameters. The spatially extended and amplified magnetic field can inhibit the energy transport and reduce the preheat in the target. This inhibited energy may be utilized in increasing the energy of plasma particles particularly ions observed in this experiment. The generation of instabilities in the plasma in the presence of externally applied magnetic field (Fig. 7b) may be the reason for convection of plasma, which can help in the amplification of magnetic field. The presence of instabilities in the plasma greatly affects the particle and energy transport (Liewer, 1977). This indicates that magnetic field amplification is possible in the presence of instabilities as a result of convection of magnetic field frozen in the plasma, because it is well known that magnetic field can not penetrate or come out of the conducting fluid (Chen, 1974). The change in the flux depends on the resistivity of the plasma. However the frozen magnetic field can be convected with the plasma before its diffusion. Enright and Burnett (1986) have also mentioned the effect of Nernst advection (Yabe *et al.*, 1982; Nishiguchi *et al.*, 1984) in his experiment where high energy electrons were detected. However, a detailed theoretical analysis of the problem is needed to better understand the process. This Nernst advection seems to be the reason behind the important role (triggering effect) of externally applied magnetic field in ion acceleration. In light of the above discussion one can say that the change in the slope observed in Figures 8a and b is correlated with the loss in absorbed energy *via* ion acceleration and the onset of instabilities in the plasma.

3.4. Wave particle interaction

Normally, effect of VXB acceleration (Dawson, 1983) should not be seen here at such a low intensity. However, the presence of high frequency oscillations in ion current supports the idea of wave particle interaction, which can produce fast plasma particles in the presence of a magnetic field as a result of VXB force acting on the particles. It is a well established fact that in laser plasma interaction electromagnetic wave is converted into an electrostatic plasma wave (resonance absorption or parametric decay instabilities) which travels in the direction of decreasing density gradient. But in the presence of transverse magnetic field, these electrostatic plasma wave travels across the magnetic field lines and accelerates the plasma particles very effectively by the VXB acceleration mechanism, where V is the phase velocity of electron plasma wave and B is the steady magnetic field. The fastest ion pulse observed in this experiment has expansion velocity $\sim 10^8$ cm/s nearly $\sim$10 times the thermal ion velocity, which is expected in the case of VXB acceleration as has been re-

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ported by Dawson (1983). This agreement indicates that the possibility of VXB acceleration in this experiment also can not be ruled out.

If we consider these accelerated ions as copper, its energy comes out to be ~0.7 MeV. During this experiment no diagnostics were available to identify the type of ions accelerated in this experiment. There is a strong possibility that accelerated ions observed are low *Z* impurity ions of hydrogen, Carbon or Oxygen. The evolution of another group of accelerated ions as discussed earlier having less amplitude and expansion velocity ($<1.33 \times 10^8$ cm/s) indicates towards the possible role of charge exchange process which has been reported to be the most probable candidate at high chamber pressure. Increase in amplitude of fast ions (Number of accelerated ions) with chamber pressure support the idea that accelerated ions may be impurity ions of hydrogen, carbon or oxygen and that charge exchange process is playing an important role in producing them. However, the exact role of the charge exchange processes in ion acceleration and the identification of ions accelerated in this experiment are the topics of further investigation. A more detailed investigation of charge states of accelerated ions (using Thompson parabola diagnostic), its energy spectrum and instabilities present in the plasma with a large variation of laser intensity, external magnetic field and ambient chamber pressure may give much more information about the process of ion acceleration.

4. CONCLUSION

In summary we can say that the presence of externally applied transverse magnetic field generates fast ions in laser produced plasma with an expansion velocity $\sim 1.33 \times 10^8$ cm/s at a comparatively low laser intensity of $\sim 5 \times 10^{12}$ W/cm^2, which has been observed in earlier experiments at a higher laser intensity ($>10^{14}$ W/cm^2). Ambient chamber pressure appears to play an important role in ion acceleration in the presence of external magnetic field. The number of ions accelerated increases with an increase in ambient pressure in particular range. It was noted that an increase in number of accelerated ion and increase in self generated magnetic field with an increase in ambient chamber pressure follow nearly same scaling during their rising part. Both of these observations may not be coincidence and indicates a firm correlation in ion acceleration and generation of spontaneous magnetic field. It seems that correlation becomes effective through the generation of the space charge potential seath, which generates a spontaneous magnetic field and plays an important role in ion acceleration. This acceleration process is observable only in the presence of the external magnetic field which indicates that the externally applied magnetic field acts as a triggering factor for ion acceleration in the presence of spontaneous magnetic field. The coupling of externally applied and self-generated magnetic field through the Nernst advection plays an important role in ion acceleration. This coupling and amplification of the magnetic field seems possible through the instabilities in the plasma as a result of the external magnetic field. However, a further detailed experimental and theoretical study is needed to get a clear idea about the coupling of the magnetic field and its effect on ion acceleration. The other acceleration processes such as charge exchange process, VXB acceleration, and stochastic heating as discussed above may also have contribution in ion acceleration. In the present situation it is not possible to quantify the role of each of the different processes. However, it seems that inhibition of energy transport from the plasma due to the combined effect of both the magnetic fields in general and space charge potential along with charge exchange processes in particular during the higher chamber pressure play a dominant role in ion acceleration. However, a further detailed study about the types of ions getting accelerated in various conditions will be helpful in flashing the light on exact physical process taking place during ion acceleration.

The results of this experiment have important implications in inertial confinement fusion particularly in the gas filled hohlraum experiments (Delamater *et al.*, 1996). According to this experiment, the presence of magnetic field and an increase in chamber pressure help in increasing the number of accelerated ion, that is, loss in the content of plasma energy. We have also shown that in similar experimental conditions X-ray emission got enhanced by two to three times, which may be helpful in increasing the pellet gain. Finally, results of both the experiments suggest that an optimum experimental condition have to be obtained to get the benefit of enhanced X-ray emission as well as maintain the loss of energy to a minimum.

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