Chapter 6

Second harmonic generation by an obliquely incident s-polarized laser from a magnetized plasma

---

An expression for the relativistic factor in presence of magnetic field has been obtained. The dependence of second harmonic conversion efficiency on the angle of incidence, electron plasma density, laser electric field amplitude and magnetic field has been calculated. An increase in magnetic field increases the value of the modified relativistic factor which in turn, reduces the conversion efficiency. The presence of magnetic field affects the conversion efficiency due to the modification observed in the relativistic factor. In absence of magnetic field, the second harmonic conversion efficiency increases with an increase in the laser electric field amplitude and angle of incidence. However, in presence of magnetic field, the conversion efficiency starts decreasing as the magnetic field is increased.

6.1 Background of the study

Interaction of ultrahigh intensity lasers with plasmas induce transverse currents due to quiver motion of the electrons. Laser intensities upto 10^{20} W/cm^2 has been achieved, which while propagating through the plasma makes the electrons move with relativistic velocities and the electron motion becomes non-linear and thus leads to the generation of harmonics. In presence of high power laser fields, the relativistic change in mass of the electron may affect dielectric property of the plasma medium. On the other hand, there may be depletion in plasma density from the higher field region due to expeltion of electrons in a radial direction from the axis, resulting in density gradient in the transverse direction. Both of these effects may be a source of second harmonic emission. Generation of second harmonics is one of the most important aspects of research in laser-plasma interactions due to its promising applications in the study of material properties, biological samples etc. and also in coherent extreme ultraviolet (EUV) radiation [1–3]. It can also serve as a diagnostic tool for warm and dense plasmas [4–6]. Engers et al. [7] have measured the time dependence of second harmonics from plasmas produced by femtosecond laser pulses. Dromey et al. [8] have observed the generation of higher order harmonics with photon energy $h\nu >$1keV from petawatt class laser-solid interactions and have presented the harmonic efficiency scaling in the relativistic limit. Linearly polarized intense laser beams on interaction with a homogeneous plasma produces transverse nonlinear plasma currents and thus lead to the generation of coherent harmonic radiation in the forward direction [9]. Esarey et al. [10] have shown that the presence of transverse gradients in the initial plasma density profile favours the generation of even harmonics. Meyer and Zhu [11] and Malka et al. [12] have shown the relativistic second harmonic generation under the condition of beam filamentation. Krushelnick et al. [13] have experimentally observed second harmonic generation of stimulated Raman scattered light from a plasma. Jha and Agrawal [14] have studied analytically the second harmonic generation by a p-polarized obliquely incident laser propagating in an underdense plasma. Second harmonic generation in the reflected component of the beam by an obliquely incident, relativistically intense laser polarized perpendicular to the plane of incidence has been reported [15].

Presence of a magnetic field may play a very important role in increasing the efficiency of such second harmonic current from a plasma. The magnetic field gets coupled with the relativistic and ponderomotive effects and drastically affects the efficiency of second harmonic generation. Rax et al. [16] have analyzed relativistic harmonic generation with ultrahigh intensity laser pulses in a weakly magnetized plasma. They have considered both permanent magnet and laser-driven wigglers and have addressed and solved important issues of phase matching, pump depletion, and relativistic tapering. Salih et al. [17] have investigated the second-harmonic generation of an intense self-guided right circularly polarized laser beam in a self created magnetized plasma channel. Generation of second harmonics by a linearly polarized laser beam propagating through an underdense plasma embedded in a transverse magnetic field has been analyzed [18]. Verma and Sharma [19] have investigated second harmonic generation by a laser produced plasma having a density ripple in presence of an azimuthal magnetic field.

Here, we present an analytical study of relativistic second harmonic generation in the reflected component by an obliquely incident s-polarized laser from a cold underdense plasma in presence of a magnetic field. Moreover, the effect of magnetic field on relativistic factor has been properly taken into consideration in this work. Thus, the presence of magnetic field not only affects the motion of electrons, but it also modifies its relativistic mass. Correct understanding of the behaviour of relativistic electrons in presence of magnetic field is essential for the study of any phenomena related to the interaction of lasers with magnetized plasmas. In presence of magnetic field, the relativistic factor is modified and this might have a direct impact on the interaction of plasma electrons and laser field. Here, we have found an analytical expression for modified relativistic factor [20] in presence of magnetic field and hence analyzed the effect on the efficiency of second harmonic generation.

6.2 Theoretical Formulation

The electrons acquire an oscillatory velocity under the influence of laser electric field and a ponderomotive force is thus exerted on the electrons at twice the incident laser frequency. The ponderomotive force thus give rise to oscillatory electron velocities at second harmonic and produces a non-linear second harmonic current which drives the emission of second harmonic radiation. We consider an s-polarized laser beam incident obliquely on a vacuum-plasma interface at $z = 0$ with $z < 0$ as vacuum and $z > 0$ as a uniform plasma of density n_0^0 embedded in a magnetic field, $\vec{b} = b\hat{z}$. The laser beam is propagating along the $x - z$ plane at an angle θ with the z-axis as shown in Fig. 6.1. The fundamental laser beam propagating through vacuum can be

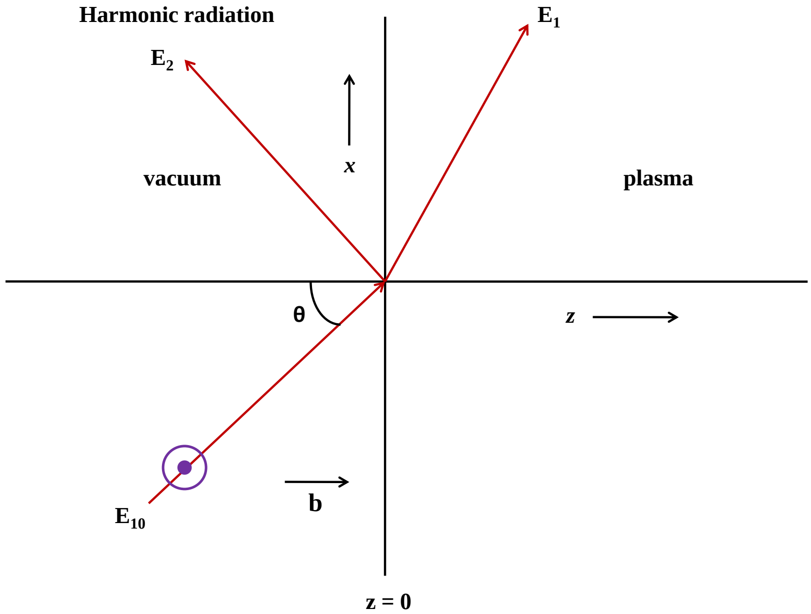


Fig. 6.1: Schematic of second harmonic generation process by an obliquely incident s-polarized laser.

represented as

$$\vec{E}_{1i} = \hat{y}E_{10}exp[-i(\omega t - k_x x - k_{0z}z)] \tag{6.1}$$

where $k_x = (\omega/c)sin\theta$ and $k_{0z} = (\omega/c)cos\theta$. The electric and magnetic fields of the laser transmitted inside the plasma can be written as

$$\vec{E}_1 = \hat{y}E_1 exp[-i(\omega t - k_x x - k_z z)] \tag{6.2}$$

$$\vec{B}_1 = c\frac{\vec{k} \times \vec{E}_1}{\omega} \tag{6.3}$$

where $k_z = [(\omega^2/c^2)(1 - \omega_p^2/\omega^2) - k_x^2]^{1/2}$ and $a_1 = 2a_0/(1 + k_z/k_{0z})$. $a_0 = eE_{10}/m_0\omega c$ and $a_1 = eE_1/m_0\omega c$ are the normalized electric field parameters, $\omega_p^2 = 4\pi n_0^0 e^2/\gamma m_0$ is the relativistic plasma frequency, $\epsilon_1 = 1 - \omega_p^2/\omega^2$ is the dielectric constant where e, m_0 and γ are the electronic charge, rest mass and time averaged value of relativistic factor respectively.

6.3 Relativistic factor in presence of magnetic field

At high intensities, the laser electric field make the electrons quiver with velocities close to the velocity of light and hence the electrons become relativistic. An increase in intensity will increase the value of the relativistic factor $\gamma = 1/\sqrt{1 - v^2/c^2} = \sqrt{1 + a_0^2/2}$ and hence will increase the relativistic mass of the electron. This will decrease the effective plasma frequency which in turn will affect the plasma dielectric constant and increase the transparency of plasma. The cyclotron effects induced due to the presence of magnetic field can severely affect the dynamics of the relativistic electrons. The relativistic factor can thus get modified in presence of magnetic field and can significantly effect the second harmonic generation.

The equation governing electron momentum is given as

$$\frac{dp}{dt} = -eE_1 - \frac{e}{c}\vec{v} \times (\vec{B} + \vec{b}) \tag{6.4}$$

The components of the above eqn. can be written as

$$\frac{dp_x}{dt} = -eE_1 \frac{k_x}{\omega} v_y cos(\omega t - k_x x - k_z z) - \frac{e}{c} v_y b \tag{6.5}$$

$$\frac{dp_y}{dt} = \frac{-eE_1}{\omega}(\omega - k_x v_x - k_z v_z) cos(\omega t - k_x x - k_z z) + \frac{e}{c} v_x b \tag{6.6}$$

$$\frac{dp_z}{dt} = -eE_1 \frac{k_z}{\omega} v_y cos(\omega t - k_x x - k_z z) \tag{6.7}$$

The equation governing electron energy is given as

$$m_0 c^2 \frac{d\gamma_t}{dt} = -eE_1 v_y cos(\omega t - k_x x - k_z z) \tag{6.8}$$

Using Eqs. 6.7 and 6.8, we get

$$\frac{d}{dt}\left\{p_z - m_0 c \gamma_t (\epsilon_1 - sin^2\theta)^{1/2}\right\} = 0 \tag{6.9}$$

Thus, we can write

$$p_z - m_0 c \gamma_t (\epsilon_1 - sin^2\theta)^{1/2} = p_{z0} - m_0 c \gamma_0 \tag{6.10}$$

where $p_{z0} (= m_0 \gamma_0 v_{z0})$ and γ_0 are the initial values of electron momentum along z direction and relativistic factor respectively.

Using Eqn. 6.8 in Eqn. 6.5 and integrating it using the initial values of electron momentum along x as $p_{x0} (= m_0 \gamma_0 v_{x0})$ and integrating Eqn. 6.6 using the initial values of electron momentum along y as $p_{y0}(= m_0\gamma_0 v_{y0})$ we obtain

$$p_x = mc\gamma_t sin\theta - \frac{e}{c}(y - y_0)b + p_{x0} \tag{6.11}$$

$$p_y = p_{y0} + \frac{e}{c}(x - x_0)b - \frac{eE_1}{\omega} sin(\omega t - k_x x - k_z z) \tag{6.12}$$

Using Eqn. 6.10 we get

$$\frac{p_z}{m_0 c} = \gamma_t(\epsilon_1 - sin^2\theta)^{1/2} + \frac{p_{z0}}{m_0 c} - \gamma_0 \tag{6.13}$$

Here we define a variable τ such that

$$\tau = \frac{z}{c} - t \tag{6.14}$$

Using Eqn. 6.10 one can obtain

$$\frac{dx}{d\tau} = -\frac{p_x}{m_0\gamma_0(1 - \beta_{z0})} \tag{6.15}$$

and

$$\frac{dy}{d\tau} = -\frac{p_y}{m_0\gamma_0(1 - \beta_{z0})} \tag{6.16}$$

where $\beta_{z0} = v_{z0}/c$. Using Eqs. 6.11 and 6.12 in Eqs. 6.15 and 6.16 we obtain

$$x - x_0 = \frac{1}{m_0\gamma_0(1 - \beta_{z0})}\left\{mc\gamma_t sin\theta - \frac{e}{c}(y - y_0)b\tau - p_{x0}\tau\right\} \tag{6.17}$$

and

$$y - y_0 = \frac{-1}{m_0\gamma_0(1 - \beta_{z0})}\left\{p_{y0}\tau + \frac{e}{c}(x - x_0)b\tau + \frac{eE_1}{\omega^2} cos\left[\omega\left(\frac{z}{c} - \tau\right) - k_x x - k_z z\right]\right\} \tag{6.18}$$

Solving Eqns. 6.17 and 6.18 we obtain

$$x - x_0 = \frac{-mc\tau\gamma_t sin\theta - p_{x0}\tau - \omega_c\tau\left\{\frac{eE_1}{\omega^2} cos\left[\omega\left(\frac{z}{c} - \tau\right) - k_x x - k_z z\right] + \tau p_{y0}\right\}}{m_0\gamma_0(1 - \beta_{z0})\left\{1 + \omega_c^2\tau^2\right\}} \tag{6.19}$$

and

$$y - y_0 = \frac{\omega_c mc\gamma_t \tau^2 sin\theta - p_{y0}\tau + \omega_c p_{x0}\tau^2 - \frac{eE_1}{\omega^2} cos\left[\omega\left(\frac{z}{c} - \tau\right) - k_x x - k_z z\right]}{m_0\gamma_0(1-\beta_{z0})\left\{1+\omega_c^2\tau^2\right\}} \tag{6.20}$$

Using Eqs. 6.19 and 6.20 in 6.11 and 6.12 we obtain

$$\frac{p_x}{m_0 c} = \frac{\gamma_0(\beta_{x0} + \beta_{y0}\omega_c\tau)}{1+\omega_c^2\tau^2} + \frac{\gamma_t sin\theta}{1+\omega_c^2\tau^2} + \frac{a_1\omega_c cos\left[\omega\left(\frac{z}{c}-\tau\right) - k_x x - k_z z\right]}{\omega(1+\omega_c^2\tau^2)} \tag{6.21}$$

and

$$\frac{p_y}{m_0 c} = \frac{\gamma_0(\beta_{y0} - \beta_{x0}\omega_c\tau)}{1+\omega_c^2\tau^2} - \frac{\omega_c\tau\gamma_t sin\theta}{1+\omega_c^2\tau^2} - a_1 sin\left[\omega\left(\frac{z}{c}-\tau\right) - k_x x - k_z z\right] - \frac{a_1\omega_c^2\tau cos\left[\omega\left(\frac{z}{c}-\tau\right) - k_x x - k_z z\right]}{\omega(1+\omega_c^2\tau^2)} \tag{6.22}$$

where $\beta_{x0} = v_{x0}/c$, $\beta_{y0} = v_{y0}/c$ and $\omega_c = eb/m_0 c\gamma_0(1-\beta_{z0})$ is the electron cyclotron frequency. Using Eqn. 6.13, 6.21 and 6.22 with $\gamma_t^2 = 1 + (p_x^2 + p_y^2 + p_z^2)/m_0^2c^2$ and applying initial conditions, $\beta_{x0} = \beta_{y0} = \beta_{z0} = 0$, $\gamma_0 = 1$, the time averaged value of the relativistic factor is obtained as

$$\gamma = \frac{1}{2\left[1-\epsilon_1 + sin^2\theta\left\{1+\frac{1}{\left(1+4\pi^2\left(\frac{\omega_c}{\omega}\right)^2\right)^2}\right\}\right]}\left\{-2(\epsilon_1 - sin^2\theta)^{1/2} + \left[4(\epsilon_1 - sin^2\theta) + 4(1-\epsilon_1+sin^2\theta)\left\{2+\frac{a_1^2}{2}\left(1+\frac{\left(\frac{\omega_c}{\omega}\right)^2\left(1+4\pi^2 a_1^2\left(\frac{\omega_c}{\omega}\right)^2\right.}{\left(1+4\pi^2\left(\frac{\omega_c}{\omega}\right)^2\right)^2}\right)\right\}\right]^{1/2}\right\} \tag{6.23}$$

6.4 Second harmonic conversion efficiency

The electrons under the influence of an intense laser electric field of frequency ω and wave vector $\vec{k}$ acquire an oscillatory velocity $\vec{v_1}$ at $(\omega, \vec{k})$ and the laser exterts a ponderomotive force $\vec{v_1} \times \vec{B_1}$ on electrons at $(2\omega, 2\vec{k})$. The ponderomotive force gives rise to ocillatory electron velocities at $(2\omega, 2\vec{k})$ and produces a second harmonic current $\vec{J_2}$ at $(2\omega, 2\vec{k})$ which gives rise to second harmonic radiation.

The wave equation governing second harmonic generation is given as

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right)\vec{E_2} = \frac{4\pi}{c^2}\frac{\partial \vec{J_2}}{\partial t} \tag{6.24}$$

The solution of Eqn. 6.24 can be written as

$$\vec{E_2} = \vec{A_2} exp[-i(2\omega t - 2k_x x + 2k_{0z} z)] \tag{6.25}$$

The laser imparts an oscillatory electron velocity at $(\omega, \vec{k})$

$$\vec{v_1} = \frac{e\vec{E_1}}{\gamma m_0 i\omega} \tag{6.26}$$

which produces an oscillating current at $(\omega, \vec{k})$

$$\vec{J_1} = -n_0^0 e\vec{v_1} = -\frac{n_0^0 e^2 \vec{E_1}}{\gamma m_0 i\omega} \tag{6.27}$$

$\vec{v_1}$ beats with $\vec{B_1}$ to produce the ponderomotive force $\vec{F_2}$ at $(2\omega, 2\vec{k})$

$$\vec{F_2} = \frac{i\vec{k}c\epsilon_1 e}{2\gamma\omega} a_1 E_1 exp[-i(2\omega t - 2k_x x - 2k_z z)] \tag{6.28}$$

The electron velocity due to $\vec{F_2}$, self-consistent field $\vec{E_2}$ and the external magnetic field $\vec{b}$ at $(2\omega, 2\vec{k})$ is

$$\vec{v_2} = \frac{1}{2\gamma m_0 i\omega}\left\{e\vec{E_2} - \vec{F_2} + \frac{e}{c}(\vec{v_2}\times\vec{b})\right\} \tag{6.29}$$

The x, y and z components of the electron velocities are obtained as

$$v_{2x} = \frac{e}{2\gamma m_0 i\omega\left(1 - \frac{\omega_c^2}{4\omega^2}\right)}\left\{\left(E_{2x} + \frac{\omega_c}{2i\omega}E_{2y}\right) - \frac{ik_x c\epsilon_1}{2\gamma\omega}a_1 E_1 exp\left[-i(2\omega t - 2k_x x - 2k_z z)\right]\right\} \tag{6.30}$$

$$v_{2y} = \frac{e}{2\gamma m_0 i\omega\left(1-\frac{\omega_c^2}{4\omega^2}\right)}\left\{\left(E_{2y}-\frac{\omega_c}{2i\omega}E_{2x}\right)+\left(\frac{\omega_c}{2i\omega}\right)\frac{ik_x c\epsilon_1}{2\gamma\omega}a_1E_1exp\left[-i(2\omega t\right.\right.$$
$$\left.\left.-2k_xx-2k_zz)\right]\right\} \tag{6.31}$$

and

$$v_{2z} = \frac{e}{2\gamma m_0 i\omega}\left\{E_{2z}-\frac{ik_zc\epsilon_1}{2\gamma\omega}a_1E_1exp[-i(2\omega t-2k_xx-2k_zz)]\right\} \tag{6.32}$$

Using Eqn. 6.30, 6.31 and 6.32, the current densities along x, y and z directions are obtained as

$$J_{2x} = \frac{1}{\left(1-\frac{\omega_c^2}{4\omega^2}\right)}\left\{-\frac{\omega_p^2}{8\pi i\omega}\left(E_{2x}+\frac{\omega_c}{2i\omega}E_{2y}\right)+\frac{\omega_p^2k_xc\epsilon_1}{16\pi\omega^2\gamma}a_1E_1exp\left[-i(2\omega t\right.\right.$$
$$\left.\left.-2k_xx-2k_zz)\right]\right\} \tag{6.33}$$

$$J_{2y} = \frac{1}{\left(1-\frac{\omega_c^2}{4\omega^2}\right)}\left\{-\frac{\omega_p^2}{8\pi i\omega}\left(E_{2y}-\frac{\omega_c}{2i\omega}E_{2x}\right)-\left(\frac{\omega_c}{2i\omega}\right)\frac{\omega_p^2k_xc\epsilon_1}{16\pi\omega^2\gamma}a_1E_1exp\left[-i(2\omega t\right.\right.$$
$$\left.\left.-2k_xx-2k_zz)\right]\right\} \tag{6.34}$$

and

$$J_{2z} = -\frac{\omega_p^2}{8\pi i\omega}E_{2z}+\frac{\omega_p^2k_zc\epsilon_1}{16\pi\omega^2\gamma}a_1E_1exp[-i(2\omega t-2k_xx-2k_zz)] \tag{6.35}$$

Substituting Eqs. 6.33, 6.34 and 6.35 into the x, y and z components of wave Eqn. 6.24, and solving for A_{2x}, A_{2y} and A_{2z} by assuming $\partial^2/\partial z^2 << \partial^2/\partial x^2$ we obtain

$$A_{2x} = \frac{-i\epsilon_1a_1E_1sin\theta\omega_p^2}{2\gamma\omega^2\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}\left\{1-\frac{\omega_p^4\omega_c^2}{4\omega^6\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}^2}\right\}}$$
$$\times\left\{1+\frac{\omega_p^2\omega_c^2}{4\omega^4\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}}\right\} \tag{6.36}$$

$$A_{2y} = \frac{\epsilon_1 a_1 E_1 sin\theta \omega_p^2 \omega_c}{4\gamma\omega^3 \left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}\left\{1-\frac{\omega_p^4\omega_c^2}{4\omega^6\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}^2}\right\}} \times\left\{1+\frac{\omega_p^2}{\omega^2\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}}\right\} \quad (6.37)$$

and

$$A_{2z} = \frac{-i\epsilon_1\omega_p^2(\epsilon_1 - sin^2\theta)^{1/2}}{2\gamma\omega^2\left(4cos^2\theta - \frac{\omega_p^2}{\omega^2}\right)} a_1 E_1 \quad (6.38)$$

The resultant amplitude ($|A_2^2| = |A_{2x}^2| + |A_{2y}^2| + |A_{2z}^2|$) of the second harmonic wave is calculated and the ratio of the reflected second harmonic power density, $P_2 = c|A_2|^2/8\pi$ to that of the fundamental power density, $P_0 = c|E_{10}|^2/8\pi$ is obtained to calculate the second harmonic conversion efficiency, $\eta(= P_2/P_0)$ as

$$\eta = \left[\left[\frac{\epsilon_1^2 sin^2\theta\omega_p^4}{4\gamma^2\omega^4\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}^2\left\{1-\frac{\omega_p^4\omega_c^2}{4\omega^6\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}^2}\right\}^2}\right. \times\left[\left\{1+\frac{\omega_p^2\omega_c^2}{4\omega^4\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}}\right\}^2+\left(\frac{\omega_c}{2\omega}\right)^2\left\{1+\frac{\omega_p^2}{\omega^2\left\{4cos^2\theta\left(1-\frac{\omega_c^2}{4\omega^2}\right)-\frac{\omega_p^2}{\omega^2}\right\}}\right\}^2\right] \left.+\frac{\epsilon_1^2\omega_p^4(\epsilon_1 - sin^2\theta)}{4\gamma^2\omega^4\left(4cos^2\theta-\frac{\omega_p^2}{\omega^2}\right)^2}\right]\left\{\frac{4a_0}{\left\{1+\frac{(\epsilon_1-sin^2\theta)^{1/2}}{cos\theta}\right\}^2}\right\}^2 \quad (6.39)$$

It can be seen from Eqn. 6.39 that in absence of magnetic field, the second harmonic electric field has only x and z components. Thus, second harmonic emission is p-polarized in absence of magnetic field and is dependent on the incident angle θ.

6.5 Results and Discussion

Second harmonic generation from plasmas by an obliquely incident s-polarized laser in presence of magnetic field has been studied analytically in this work. Considering relativistic mass variation, the expression for modified relativistic factor in presence of magnetic field has been derived and the second harmonic conversion efficiency η has been calculated for relativistic laser intensities. Fig. 6.2 represents the variation

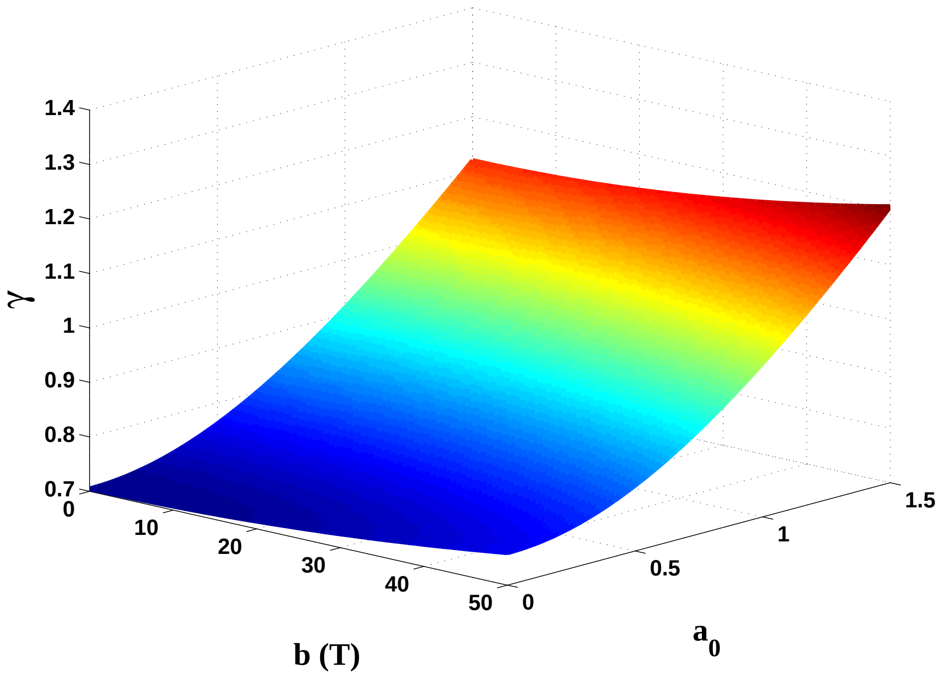


Fig. 6.2: Modified relativstic factor γ as a function of normalized electric field amplitude a_0 and applied magnetic field b at $\omega_p^2/\omega^2 = 0.1$, $\theta = 70^0$ and $\omega = 1.88 \times 10^{14}$ Hz.

of the modified relativistic factor γ with normalized electric field amplitude a_0 and magnetic field b. It is observed that γ increases both with a_0 as well as b. This behaviour of γ is reflected in almost all the results having the variation of η which is obtained as a function of b. Fig. 6.3 shows the variation of η with b and the angle of incidence θ at $a_0 = 1$. For normalized electron density $\omega_p^2/\omega^2 = 0.1$, it is found that η increases with θ. However, θ can be varied upto a maximum of 70^0 (critical angle) as beyond the critical angle the laser propagation vector becomes imaginary and the laser propagation becomes evanescent. Hence, the second harmonic conversion efficiency is maximum at the critical angle. It is observed that η decreases with an increase in magnetic field. The dependence of η on b is found to be same in Fig. 6.4 as in Fig. 6.3 which depicts the variation of η with b and ω_p^2/ω^2. Fig. 6.5 (a) displays the variation of η as a function of a_0 and b. Fig. 6.5 (b) displays the same variation for unmodified relativistic factor γ' [15]. The efficiency increases with a_0 as expected. Second harmonic conversion efficiency in case of an unmagnetized

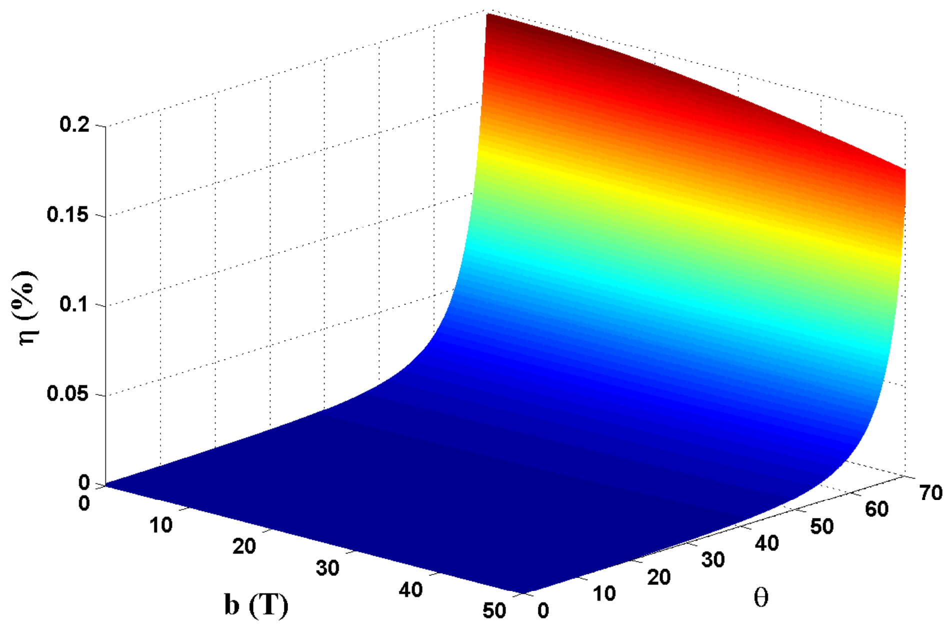


Fig. 6.3: Conversion efficiency η as a function of applied magnetic field b and angle of incidence θ at $a_0 = 1$, $\omega_p^2/\omega^2 = 0.1$ and $\omega = 1.88 \times 10^{14}$ Hz.

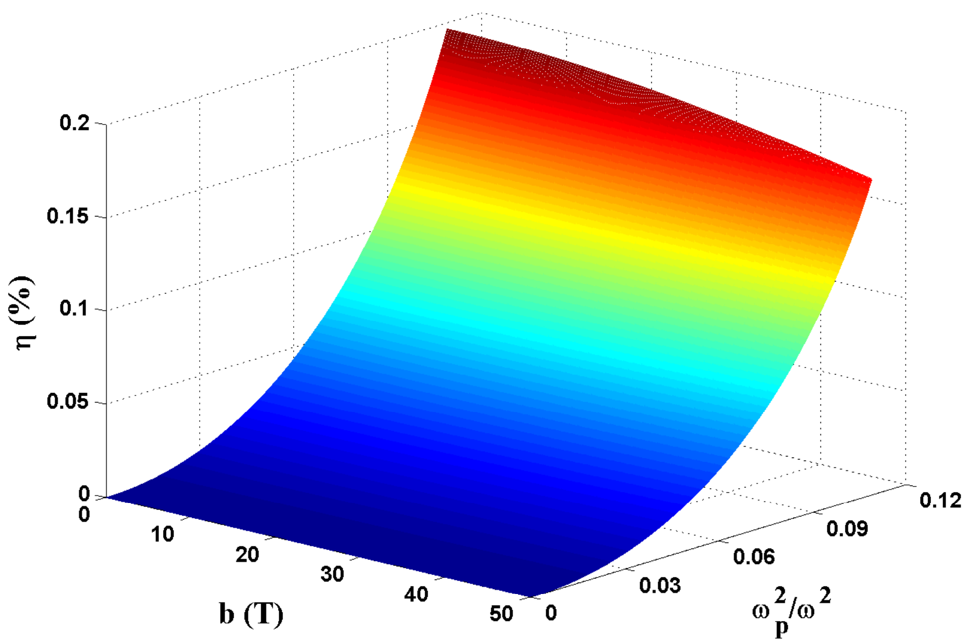
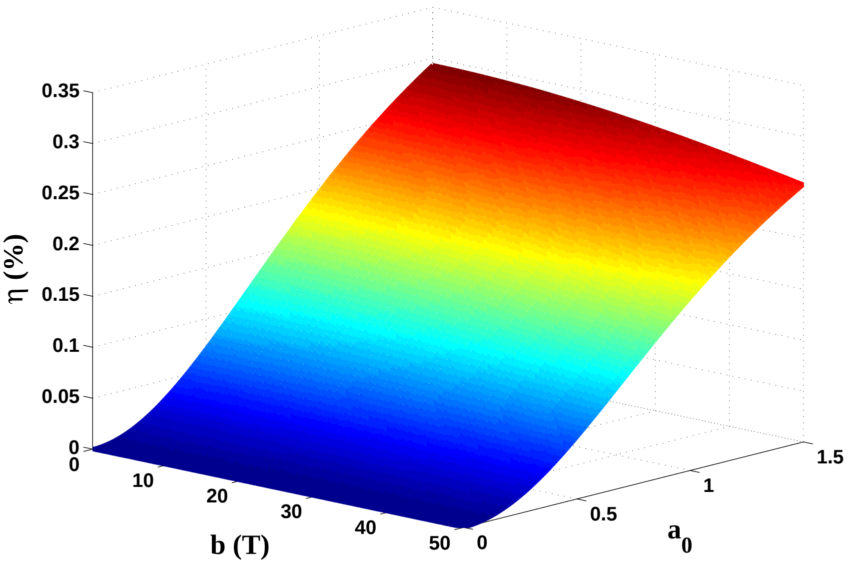
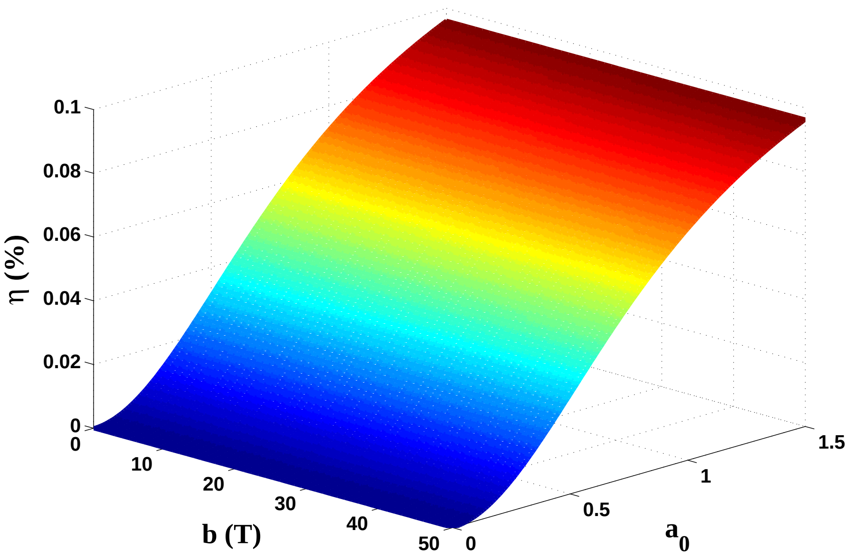


Fig. 6.4: Conversion efficiency η as a function of applied magnetic field b and normalized electron density ω_p^2/ω^2 at $a_0 = 1$, $\theta = 70^0$ and $\omega = 1.88 \times 10^{14}$ Hz.

plasma as shown in Fig. 4 [15] for $a_0 \approx 1$ at the critical angle is about ≈ 0.2 % which agrees with our result in Fig. 6.5 (a) when the magnetic field is zero ($b = 0$ T). A comparison of the results shown in Fig. 4 [15] with our results as depicted in Fig.



(a)



(b)

Fig. 6.5: Conversion efficiency η as a function of applied magnetic field b and normalized electric field amplitude a_0 at $\omega_p^2/\omega^2 = 0.1$, $\theta = 70^0$ and $\omega = 1.88 \times 10^{14}$ Hz with (a) modified γ (b) unmodified γ'.

6.5 (a) shows that the second harmonic conversion efficiency increases up to $a_0 \approx 1$ and then gets saturated. However, our results show that the conversion efficiency decreases with an increase in magnetic field. When the effect of magnetic field on the relativistic factor is ignored, then it is found from Fig. 6.5 (b) that the second harmonic conversion efficiency increases slightly with the increase in magnetic field. This may be due to the contribution of the magnetic field to the transverse motion of the electrons which is favourable for the generation of the second harmonic current. However, the introduction of the modified relativistic factor results in a decrease of the efficiency with the magnetic field. This may be attributed to the increase in the value of the relativistic factor γ with an increase in magnetic field.

6.6 Conclusion

We have investigated the effect of magnetic field on the efficiency of second harmonic generation in a plasma subjected to an intense obliquely incident s-polarized laser beam. In presence of magnetic field, the relativistic factor gets modified and this has been duly taken into consideration in this work. The conclusions drawn from the above discussions can be summarized as follows:

i) The efficiency is found to increase with the angle of incidence upto the critical angle.

ii) Second harmonic conversion efficiency increases with a_0 which is also revealed in the literature [15]. However, in the presence of magnetic field, the conversion efficiency starts decreasing as the magnetic field is increased.

iii) The presence of magnetic field enhances the value of the modified relativistic factor γ, which results in the reduction of the second harmonic conversion efficiency.

Bibliography

[1] Schnürer, M., Cheng, Z., Hentschel, M., Tempea, G., Kálmán, P., Brabec, T., and Krausz, F. Absorption-limited generation of coherent ultrashort soft-x-ray pulses. *Phys. Rev. Lett.*, 83:722–725, 1999.

[2] Sekikawa, T., Kosuge, A., Kanai, T., and Watanabe, S. Nonlinear optics in the extreme ultraviolet. *Nature*, 432(7017):605, 2004.

[3] Tzallas, P., Witte, K., Tsakiris, G., Papadogiannis, N., and Charalambidis, D. Extending optical fs metrology to xuv attosecond pulses. *Applied Physics A*, 79 (7):1673–1677, 2004.

[4] Theobald, W., Häßner, R., Wülker, C., and Sauerbrey, R. Temporally resolved measurement of electron densities ($> 10^{23}$ cm^{-3}) with high harmonics. *Phys. Rev. Lett.*, 77:298–301, 1996.

[5] Merdji, H., Salieres, P., Le Deroff, L., Hergott, J.-F., Carre, B., Joyeux, D., Descamps, D., Norin, J., Lynga, C., L'huillier, A., Wahlstrom, C.-G., Bellini, M., and Huller, S. Coherence properties of high-order harmonics: Application to high-density laserplasma diagnostic. *Laser and Particle Beams*, 18(3):495502, 2000.

[6] Dobosz, S., Doumy, G., Stabile, H., D'Oliveira, P., Monot, P., Réau, F., Hüller, S., and Martin, P. Probing hot and dense laser-induced plasmas with ultrafast xuv pulses. *Phys. Rev. Lett.*, 95:025001, 2005.

[7] Engers, T., Fendel, W., Schüler, H., Schulz, H., and von der Linde, D. Second-harmonic generation in plasmas produced by femtosecond laser pulses. *Phys. Rev. A*, 43:4564–4567, 1991.

[8] Dromey, B., Kar, S., Bellei, C., Carroll, D. C., Clarke, R. J., Green, J. S., Kneip, S., Markey, K., Nagel, S. R., Simpson, P. T., Willingale, L., McKenna, P., Neely, D., Najmudin, Z., Krushelnick, K., Norreys, P. A., and Zepf, M. Bright multi-kev harmonic generation from relativistically oscillating plasma surfaces. *Phys. Rev. Lett.*, 99:085001, 2007.

[9] Mori, W. B., Decker, C. D., and Leemans, W. P. Relativistic harmonic content of nonlinear electromagnetic waves in underdense plasmas. *IEEE Transactions on Plasma Science*, 21(1):110–119, 1993.

[10] Esarey, E., Ting, A., Sprangle, P., Umstadter, D., and Liu, X. Nonlinear analysis of relativistic harmonic generation by intense lasers in plasmas. *IEEE Transactions on Plasma Science*, 21(1):95–104, 1993.

[11] Meyer, J. and Zhu, Y. Second harmonic emission from an underdense laserproduced plasma and filamentation. *The Physics of Fluids*, 30(3):890–895, 1987.

[12] Malka, V., Modena, A., Najmudin, Z., Dangor, A. E., Clayton, C. E., Marsh, K. A., Joshi, C., Danson, C., Neely, D., and Walsh, F. N. Second harmonic generation and its interaction with relativistic plasma waves driven by forward raman instability in underdense plasmas. *Physics of Plasmas*, 4(4):1127–1131, 1997.

[13] Krushelnick, K., Ting, A., Burris, H. R., Fisher, A., Manka, C., and Esarey, E. Second harmonic generation of stimulated raman scattered light in underdense plasmas. *Phys. Rev. Lett.*, 75:3681–3684, 1995.

[14] Jha, P. and Agrawal, E. Second harmonic generation by propagation of a p-polarized obliquely incident laser beam in underdense plasma. *Physics of Plasmas*, 21(5):053107, 2014.

[15] Singh, K. P., Gupta, D. N., Yadav, S., and Tripathi, V. K. Relativistic second-harmonic generation of a laser from underdense plasmas. *Physics of Plasmas*, 12(1):013101–013101–4, 2005.

[16] Rax, J. M., Robiche, J., and Kostyukov, I. Relativistic second-harmonic generation and conversion in a weakly magnetized plasma. *Physics of Plasmas*, 7(3): 1026–1034, 2000.

[17] Salih, H. A., Tripathi, V. K., and Pandey, B. K. Second-harmonic generation of a gaussian laser beam in a self created magnetized plasma channel. *IEEE Transactions on Plasma Science*, 31(3):324–328, 2003.

[18] Jha, P., Mishra, R. K., Raj, G., and Upadhyay, A. K. Second harmonic generation in laser magnetizedplasma interaction. *Physics of Plasmas*, 14(5):053107, 2007.

[19] Verma, U. and Sharma, A. Laser second harmonic generation in a rippled density plasma in the presence of azimuthal magnetic field. *Laser and Particle Beams*, 27(4):719724, 2009.

[20] Qian, B.-L. Relativistic motion of a charged particle in a superposition of circularly polarized plane electromagnetic waves and a uniform magnetic field. *Physics of Plasmas*, 7(2):537–543, 2000.