Turbulence Generation in High-power Laser-Plasma Interaction Relevant to Astrophysical Scenarios

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ABSTRACT:

Many astrophysical scenarios such as supernova remnant (SNR), Cassiopeia A, the collision of galaxies, turbulent magnetic field amplification in the intergalactic medium, etc., have been imitated by utilizing high-power lasers. A hundred times stronger magnetic field has been observed in Cassiopeia A than in the adjacent interstellar medium. It is presumed that the surrounding clumpy media near supernova remnant Cassiopeia A supports myriads modes, which act as a source for amplifying the turbulent magnetic field. The origin of magnetic field amplification in the clumpy medium is not fully understood yet. The typical model for this amplification is the seed field amplification due to turbulence generation. Such magnetic field amplification and turbulence generation have been reported experimentally in laboratory astrophysics. A model is proposed to study the turbulence generation and magnetic field amplification, which ensues due to the high-power laser interaction with plasma. In this study, we employed computational techniques to solve the coupled system of the model equations.

INTRODUCTION:

In laboratory astrophysics, the amplification of the magnetic field has been observed in the laboratory experiments relevant to the many astrophysical phenomena like supernova remnant (SNR), Cassiopeia A, the collision of galaxies, etc. [1-4]. The present investigation is motivated by the laboratory experiments in which up to megagauss order amplification of the magnetic field is observed [1]. A nonlinear wave-wave coupling model is developed between the x-mode laser and the upper hybrid wave. The relativistic electron mass variation and nonlinear ponderomotive force are considered in this model.

MODEL EQUATIONS FOR THE DYNAMICS:

The expressions for the electric field for the x-mode laser and upper hybrid wave are given by

$$\vec{E}_l = \left|E_{lx}\hat{x}+E_{ly}\hat{y}\right| \exp\left\{-i\left(\omega_l t - k_l x\right)\right\} \tag{1}$$

$$\vec{E}_u = \hat{x}E_{ux} \exp\left\{-i\left(\omega_u t - k_u x\right)\right\} \tag{2}$$

Where, $k_l(k_u)$ and $\omega_l(\omega_u)$ are symbolize the propagation constant and the angular frequency of pump wave (upper hybrid wave), respectively. Now, the wave equation governing the dynamics can be written as

$$\nabla^2\vec{E} - \nabla\left(\nabla.\vec{E}\right)| = \frac{4\pi}{c^2}\frac{\partial J}{\partial t} + \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} \tag{3}$$

The nonlinear coupled dynamical equations for the x-mode laser and upper hybrid wave have been developed. The coupled dynamical equations in the normalized form can be written as

$$i\frac{\partial E_{ly}}{\partial t} + iC_1\frac{\partial E_{ly}}{\partial x} + \frac{\partial^2 E_{ly}}{\partial x^2} + \frac{\partial^2 E_{ly}}{\partial z^2} = nE_{ly} - C_2\left|E_{ly}\right|^2 E_{ly} = 0 \tag{4}$$

$$\frac{\partial^2 n}{\partial t^2} + C_3\frac{\partial^2 n}{\partial x^2} + n = \frac{\partial^2\left|E_{ly}\right|^2}{\partial x^2} + C_4\frac{\partial^2\left|E_{ly}\right|^2}{\partial z^2} \tag{5}$$

Equation (4) is the dynamical equation for the x-mode laser, and equation (5) denotes the dynamical equation for the upper hybrid wave. The normalizing parameters and constants are

$$t_n \approx \omega_l^{-1}\ ,\quad x_n = z_n = \sqrt{\frac{c^2 t_n}{2\omega_l}}\ ,\quad n_n = \frac{2\omega_l n_0(\omega_l^2 - \omega_{ce}^2 - \omega_{pe}^2)}{\omega_{pe}^2 t_n(\omega_l^2 - \omega_{pe}^2)}\ ,\quad E_n = \sqrt{\frac{16\pi m_e x_n^2 n_n(\omega_{ce}^2 + \omega_{pe}^2)}{\omega_{pe}^2 t_n^2}}\ ,$$

$C_1 = \sqrt{\dfrac{2k_l^2 c^2 t_n}{\omega_l}}$, $C_2 = \dfrac{e^2 E_n^2 \omega_{pe}^2 t_n(\omega_l^2 - \omega_{pe}^2)}{4c^2\omega_l^3 m_e^2(\omega_l^2 - \omega_{ce}^2 - \omega_{pe}^2)}$, $C_3 = \dfrac{t_n^2 v_{te}^2}{x_n^2}$, $C_4 = \dfrac{x_n^2}{z_n^2}$, where v_{te} symbolize the electron thermal speed, ω_{ce} and ω_{pe} are the electron cyclotron frequency and electron plasma frequency, respectively.

RESULTS AND DISCUSSIONS:

To solve the normalized equations (4) and (5) the following initial conditions are utilized

$$\vec{E}_k\left(x,z,0\right) = \left|E_0\right|\left\{1+0.1\cos\left(\alpha_x x\right)\right\}\left\{1+0.1\cos\left(\alpha_z z\right)\right\} \tag{6}$$

$$n\left(x,z\right) = -\sum_k\left|E_k(x,z)\right|^2 \tag{7}$$

Where the initial amplitude $E_0 = 1$ and the perturbation wavenumbers α_x, $\alpha_z = 0.2$. A periodic box with periodicity $2\pi/\alpha_x \times 2\pi/\alpha_z$, grid points 256×256, and step size ~10^{-5} are utilized for the computational simulation. For the computational simulation, the finite difference has been employed in time, the pseudo-spectral method is used in space, and all parameters have been taken (not exact parameters) according to the Mondal et al.[1] experiments. The numerical values of normalizing parameters used in computational simulations are B_0=1MG, $\omega_0=5.25\times10^{14}$rad/sec, $n_0=9.75\times10^{17}\text{cm}^{-3}$, T_e=3eV, $n_n\approx0.01n_0$, $t_n\approx$2psec, $x_n=z_n\approx5\mu$m. The accuracy of the algorithm has been verified with the well-known nonlinear Schrodinger equation and modified accordingly for this dynamics. The pump wave exerts a nonlinear ponderomotive force on the upper hybrid wave, resulting in a modification in the background density. When the pump wave propagates in the perturbed background density, the localization of the pump wave takes place, which becomes chaotic with time. The generation of the localized structures of the pump wave in the magnetic field plays an essential role in the turbulence generation in the self-generated magnetic field. From the simulation results, the magnetic field amplification up to 3-4 times has been observed, as shown in the figure. The figures also depict the time-averaged magnetic turbulence generation with power-law scaling ($k^{-1.6}$) observed from the simulation results.

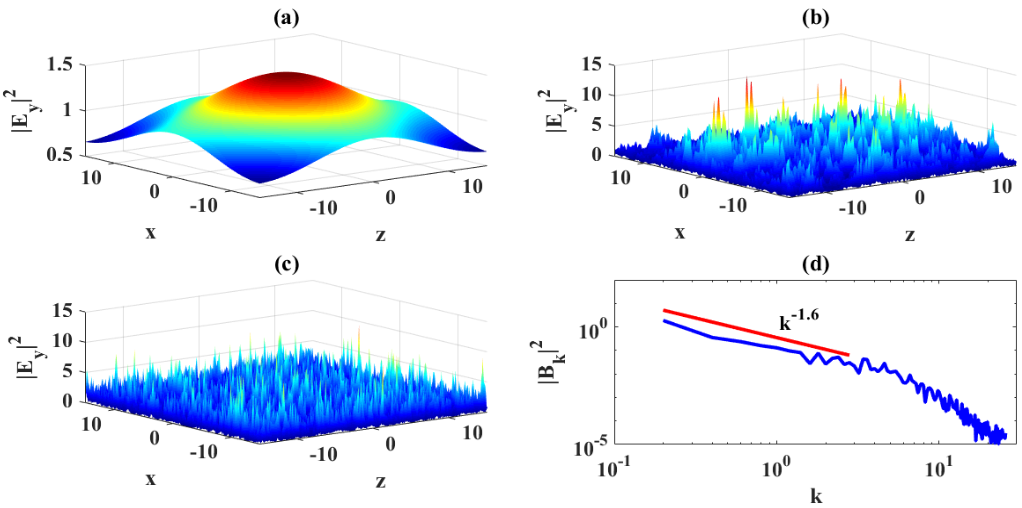

Figure: The normalized field intensity in the z-x plane at the different normalized times (t) (a)0, (b)18, (c)30, and (d) the time-averaged magnetic turbulence between the normalized time 17-24 containing seven spectra.

CONCLUSION:

This investigation describes a nonlinear wave-wave coupling model in the magnetized plasma. The background magnetic field is considered along the perpendicular direction to both the electric field direction and the direction of the propagation constant. A nonlinear wave-wave coupling model is developed by taking into account the relativistic electron mass variation and nonlinear ponderomotive force and solved by computational simulations. The magnetic field amplification and the turbulence generation have been observed from the simulation results.

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