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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 support 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.

Motivation

- Mondal et al.[1] experimentally reported the magnetic field amplification and turbulence generation in the laser produced.
- The Weibel instability is considered as the primary source for magnetic field amplification and turbulence generation in this nonlinear dynamics.
- First few picoseconds of this nonlinear dynamics is explained by the Weibel instability, but this instability failed to explain the nonlinear cascade at later timescale. Therefor alternating mechanism required.
- A model based on the nonlinear coupling of waves could be a possible mechanism.

Model Equations

The wave equation for the dynamics $\nabla^2\vec{E}-\nabla\left(\nabla.\vec{E}\right)=\frac{4\pi}{c^2}\frac{\partial J}{\partial t}+\frac{1}{c^2}\frac{\partial^2 E}{\partial t^2}$

Model equation for x-mode laser (pump wave)

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

$$i\frac{\partial E_{ly}}{\partial t}+iC_1\frac{\partial E_{ly}}{\partial x}+\frac{\partial^2 E_{ly}}{\partial x^2}+\frac{\partial^2 E_{ly}}{\partial z^2}=nE_{ly}-C_2\left|E_{ly}\right|^2 E_{ly}=0 \qquad (1)$$

Model equation for upper hybrid wave

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

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

Where

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

$$C_1=\sqrt{\frac{2k_l^2c^2t_n}{\omega_l}},\quad C_2=\frac{e^2E_n^2\omega_{pe}^2 t_n(\omega_l^2-\omega_{pe}^2)}{4c^2\omega_l^3 m_e^2(\omega_l^2-\omega_{ce}^2-\omega_{pe}^2)},\quad C_3=\frac{t_n^2 v_{te}^2}{x_n^2},\quad C_4=\frac{x_n^2}{z_n^2},$$

- **Nonlinearity in the nonlinear coupling of waves caused by the relativistic and ponderomotive nonlinearity.**

Initial conditions for the numerical simulation

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

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

Grid size: 256x256, E_0=1
$\alpha_x=\alpha_y$ =0.2, Step size ~10^{-5}

Modes Supported by Plasma

Unmagnetized plasma → Electromagnetic waves; Electron plasma waves; Ion acoustic waves

Magnetized plasma → Electromagnetic waves; Electrostatic waves; Mixed mode

- Electromagnetic waves → X-wave; Whistler waves; Magnetosonic waves; Alfven waves
- Electrostatic waves → Electron plasma waves; Upper Hybrid wave; Ion acoustic waves

Simulation Results

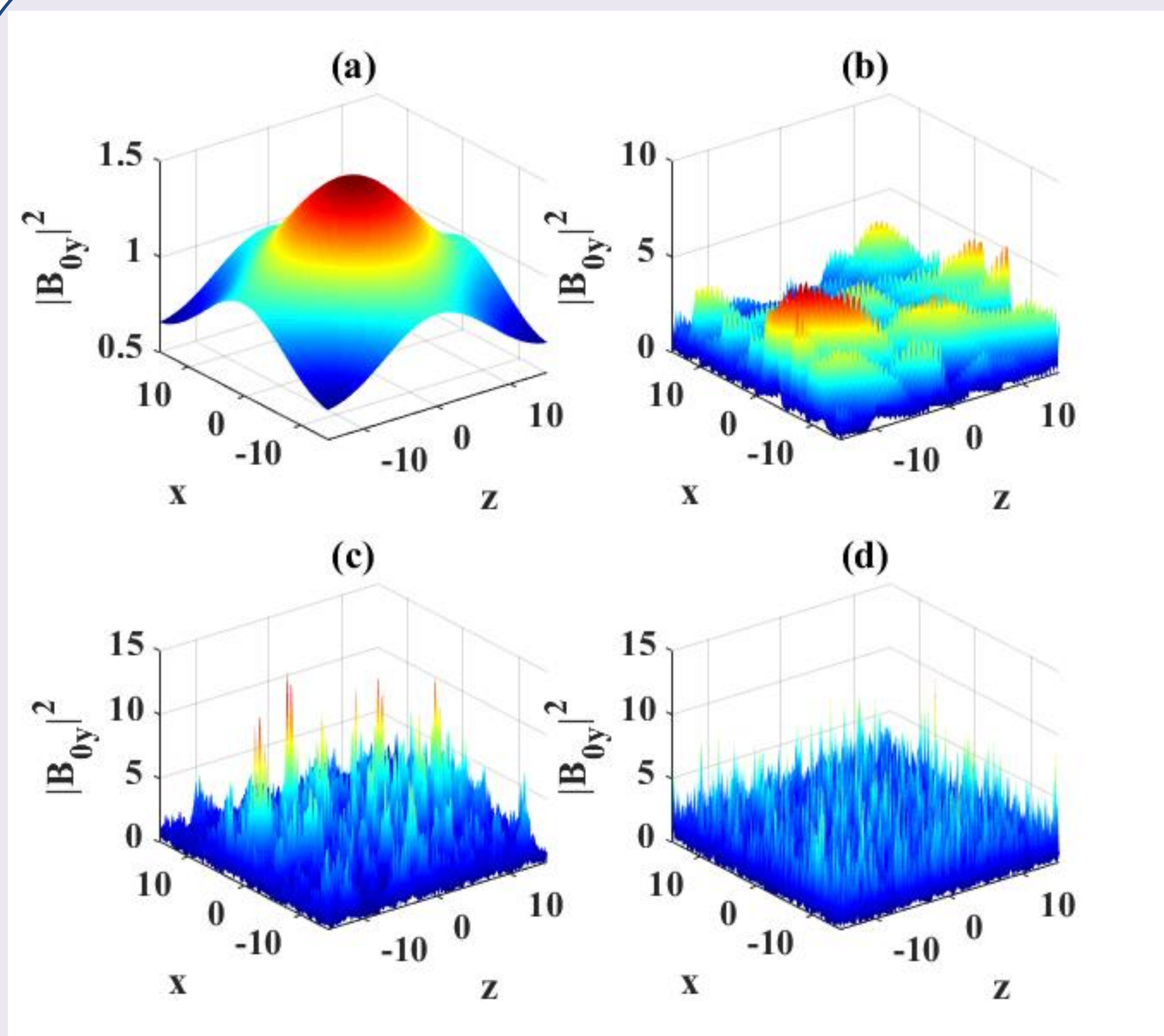

Fig-1: Nonlinear evolution and turbulent magnetic field amplification at different normalised time

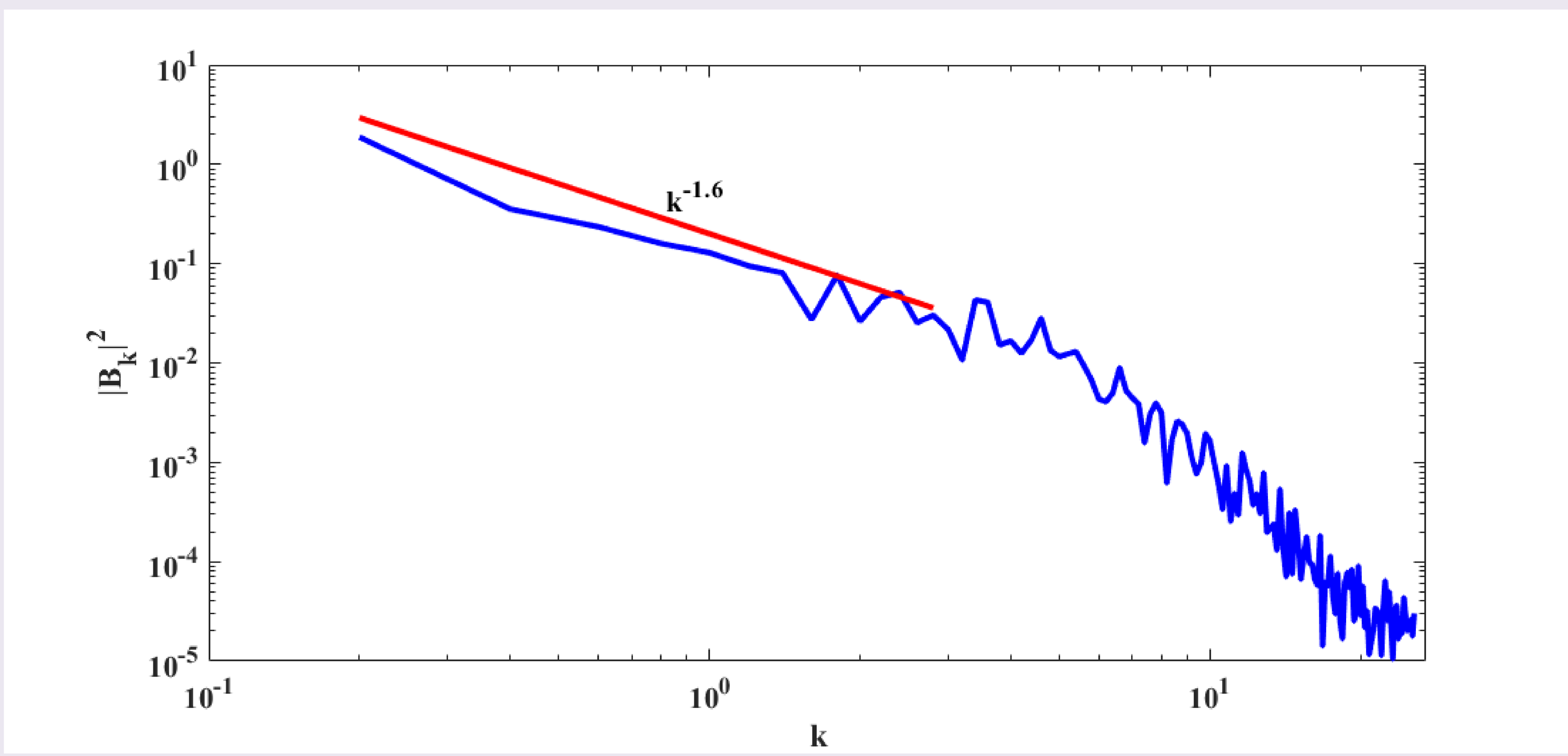

Fig-2: Time-averaged magnetic turbulent power spectrum

Conclusion

- **The coupled system of the dynamical equations of pump wave and upper hybrid wave has been solved numerical simulations.**
- **The amplification of the magnetic field observed from the simulation results.**
- **Turbulence generation associated with the magnetic field amplification has also been observed.**

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4. P. Tzeferacos et al. *Nat. Commun.* **9**, 591 **(2018).**