Self-generated magnetic fields during nanosecond laser-target interaction

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Abstract

The interaction of a nanosecond laser pulse with a solid target is one of the most common scenarios appearing in many disciplines, like inertial confinement fusion, X-ray plasma sources, laboratory astrophysics and others. The detailed understanding of the involved physical phenomena is crucial for increasing predictive capabilities of the simulations and achieving a better agreement with the experimental results. One of the challenging parts of the physical modelling is description of the self-generated magnetic fields and their role in the process of interaction. The classical approach to their generation relies on the crossed gradients of density and temperature [1]. However, these conditions can occur also on the fronts of propagating shock waves, where the modelling of the magnetic fields has proved to be challenging and numerical instabilities may arise [2]. We propose a stable high-order numerical method, which is integrated to our recently developed multi-dimensional magneto-hydrodynamic code [3].

Introduction

The mechanism of spontaneous magnetic fields generation in a quasi-neutral plasma posed a major question in the astrophysical context, until the effect of Biermann battery was revealed [1]. Later, its importance was also recognised for laser–target interaction with increasing laser intensities available [4]. In essence, a misalignment of the density and temperature gradients leads to an self-consistent electric field, which in turn generates a strong magnetic field. Importance of the effect was recognized in inertial confinement fusion (ICF) [5] and galactic formation processes [6, 7], for example.

The processes of interaction of a laser with a solid target are described within the magneto-hydrodynamic framework. In particular, the newly developed resistive Lagrangian

MHD code PETE2 is used [3]. The computational mesh follows the flow of the ablated material, where high-order curvilinear finite elements are advantageously employed for tracking the rapidly expanding plasma. However, integration of the Biermann term to the numerical MHD is a non-trivial problem due to its inherent non-linearity and sensitivity to the geometric effects. Inability to sufficiently resolve the quantities, especially at the fronts of propagating shock waves, leads to the artificial self-amplification of the generated field known as the Biermann catastrophe [2]. We investigated this effect on the problem of an elliptical shock previously [8]. Here, the model is improved for realistic simulations of laser–target interaction.

Numerical model

The Biermann term is integrated to the numerical MHD model trough the fluid-frame electric field. This approach conserves the total energy, magnetic flux and divergence-free magnetic field [3]. One of the cornerstones of the method is to rewrite the source term from the initial formulation (designated as the *naive model*) to the *dual form* [8, 7, 2]:

$$\vec{E}_B = -\frac{\nabla p_e}{e n_e} = -\frac{k_B T_e}{e p_e}\nabla p_e = \cancel{-\frac{k_B}{e}\nabla(T_e \ln p_e)} + \frac{k_B \ln p_e}{e}\nabla T_e. \quad (1)$$

The reason for this reformulation is discontinuity of the electron pressure p_e and density n_e at the shock fronts, while the temperature T_e remains approximately continuous due to various transport mechanism typically (e is the elementary charge, k_B Boltzmann constant).

The second important part of the proposed method is the Helmholtz decomposition to the solenoidal part $\vec{E}_B^{sol}$ and the gradient part ∇A, which reads:

$$\nabla \times \nabla \times \vec{E}_B^{sol} = \frac{k_B}{e}\nabla \times (\nabla \ln n_e \times \nabla T_e)$$
$$\Delta A = -\frac{1}{e}\nabla \cdot (k_B T_e \nabla \ln n_e + k_B \nabla T_e).$$

This procedure tackles the problem of the significantly smaller solenoidal part of the electric field, which only contributes to the magnetic field generation. It is solved separately with reconstructed gradients similarly to the methods directly calculating the magnetic field [9, 10]. Though, the gradient part is still important for the Joule heating. A consistent approach is preferred also here and this part is recovered from the scalar potential A.

The aforementioned high-order finite elements are used for discretization of the quantities [3]. The newly appearing potential A is chosen from the H^1-conforming elements and the gradients are constructed in the weak sense in a H_{div}-conforming finite element space.

Simulations

The spontaneous magnetic field generation is demonstrated on a simulation of laser–target interaction under typical conditions. The laser with the peak intensity 10^{12} W/cm^2

and central wavelength 1 μm irradiates a solid aluminium target wide 20 μm and thick 2 μm. The Gaussian profiles of the laser pulse is assumed with the temporal full-width-half-maximum $t_{\mathrm{FWHM}} = 500$ ps and spatial $d_{\mathrm{FWHM}} = 7.5\,\mu\mathrm{m}$. Only the upper half-plane is simulated with 120×75 constant/linear elements distributed with the geometric factor 0.99×1.01. The Wentzel–Kramers–Brillouin model of collisional laser absorption is applied with the flux-limited heat diffusion (the flux limiting factor is $f_{lim} = 0.1$).

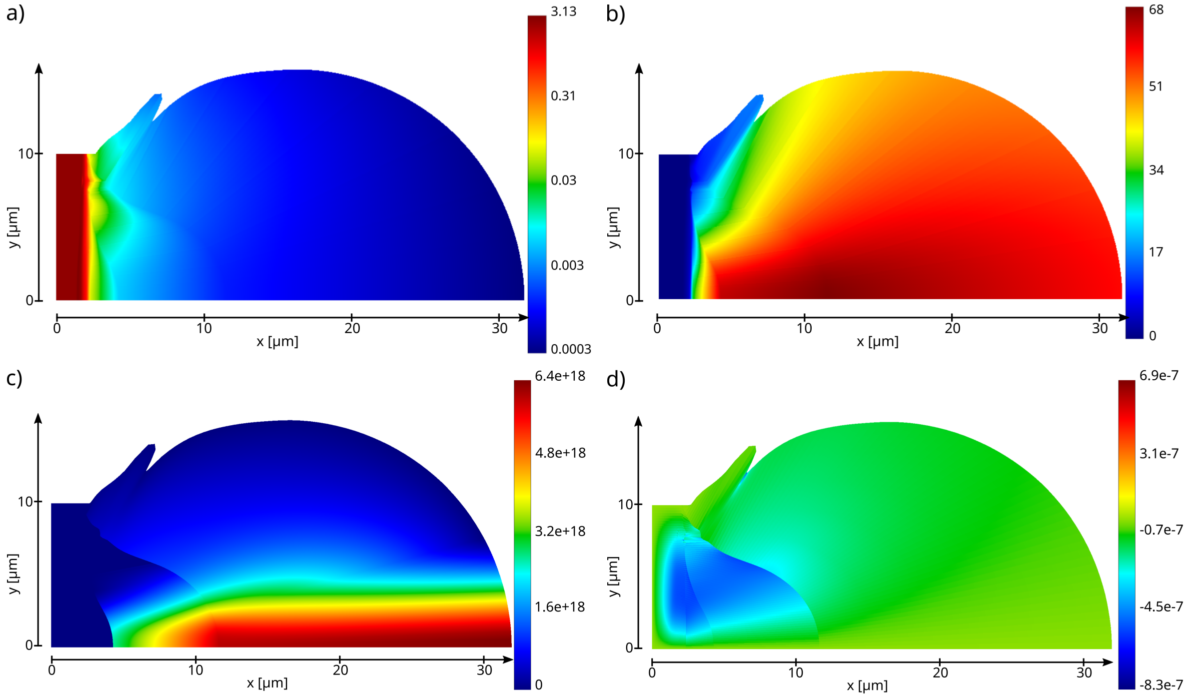

Figure 1: *Simulation of the laser–target interaction with spontaneous magnetic field generation: a) mass density* $[\mathrm{g/cm^3}]$*, b) electron temperature* $[\mathrm{eV}]$*, c) laser intensity* $[\mathrm{W/cm^2}]$*, d) magnetic field* $[\mathrm{statT}]$*. See the accompanying text for details.*

The results at time $t = 300$ ps are presented in Figure 1. It can be recognized the density predominantly drops in the direction along the laser axis, while the temperature involves also a strong transversal gradient. This configuration then leads to generation of the magnetic field through the Biermann battery effect, reaching the considerable values of ≈ 25 kG in the cusp of the plasma plume.

Conclusions

The Biermann battery mechanism is an important source of the spontaneous magnetic field during nanosecond laser–target interaction with a strong relevance to ICF [5] or astrophysics [6]. The proposed method based on high-order finite elements consistently models this phenomenon within a resistive Lagrangian MHD code, where the detrimental effect known as the Biermann catastrophe is prevented. The simulation of a typical scenario of a laser interacting with a solid target confirms generation of strong magnetic fields even for the relatively low intensity of the laser pulse. With increasing intensity, the magnetic fields of megagauss levels are reported [4] and the hot electrons generated by a direct laser–plasma interaction start to significantly contribute [11, 12]. Investigation of these effects remains a topic of the future research.

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