Magnetized plasma structures in laser-irradiated curved targets

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Abstract. This work presents an extensive theoretical study of magnetic field generation effect in hollow targets with curved internal surface, known as “snail” or “escargot” targets [1]. They were recently proposed as a robust setup for generating intense spontaneous quasi-stationary magnetic fields frozen in laser-produced plasmas. The results of such studies are indispensable for planning experimental investigations and for possible applications of the curved targets, including, but not limited to, laboratory astrophysics, fast ignition, and particle acceleration.

1. Introduction
Laboratory-produced magnetic fields attract particular interest both as a special physical phenomenon and as a necessary part of astrophysical studies in laboratory, magnetized solutions of Inertial Confinement Fusion (ICF), particle guiding, atomic physics in magnetic fields, and many other applications. Laser-based (optical) approaches to strong magnetic field generation are compact, precise, and thus looking very promising. By now, the highest quasi-static magnetic fields produced with the use of lasers, reach the values of $10^7$ Gauss [2, 3, 4, 5]. More intense magnetic fields have been measured in laser-plasma interaction with high-intensity lasers (see, i.e. [6]), but the time of life of those fields is strictly limited by the laser pulse duration. One way to increase the magnetic field value was proposed in 2015 [1]. It was shown on the base of large-scale 2D particle-in-cell (PIC) simulations that an intense laser pulse, caught in the internal volume of a hollow snail-shaped target, may generate a very strong magnetic field, decoupled from the pulse and frozen in the ablated plasma. The generated magnetized plasma then carries the field over the hydrodynamic time scale, so that the magnetized structures may exist for tens of picoseconds and more, becoming extremely interesting for a vast variety of applications.

Most of the conventional laboratory generators of quasi-static magnetic fields, both coil-based, and laser-based (optical) are working within a discharging scenario, where strong currents are released either from a capacitor bank or from a laser-irradiated capacitor-like target. The currents excite and support magnetic fields in a surrounding space. Because of their generation process, these are vacuum magnetic fields. They may be used to magnetize secondary targets or guide particles. Usually, the vacuum magnetic field is a convenient laboratory instrument, though magnetization process becomes sometimes challenging, i.e. for laboratory astrophysical studies, where plasmas usually are both magnetized and collisionless.

The novel approach [1], based on special geometrical design of the targets, allow to produce rather magnetized plasmas than vacuum magnetic fields, so that finally not currents of conducting...
electrons but the laser plasmas themselves carry the magnetic field. This scheme possesses the advantages of intense laser pulses, which may produce very strong magnetic fields, and the conservation of spontaneous magnetic fields by means of plasma magnetization during the ablation process. Compactness of the target internal volume allows saving the high values of generated fields in magnetized structures over the hydrodynamic time scales. The astrophysical applications of this scheme are straightforward, since many interesting phenomena take place in the target itself. The magnetization of plasmas (one of the most important astrophysical parameters, defined as a relation between the magnetic and the plasma pressure) observed in PIC simulations, reaches the order of unity, and may be controlled by the target size and laser parameters. Many more applications that demand strong magnetic fields as particle guiding or laser-driven magnetized ICF [7] may also follow.

To remind briefly the considered scheme of magnetic field generation, a special target geometry is presented in Fig. 1. On the left panel there are two simplest realizations, a “snail”, or “escargot” geometry, and a cylinder geometry. In both cases, the laser pulse reflects multiple times on the internal target volume. To make this possible, in the case of the cylinder, the pulse should enter through a side open edge. Strictly speaking, the reflection geometry is rather complicated and the interaction process may be fully reproduced only by 3D simulations. But for the incidence angles, as shown in Fig. 1, which are close to the right angle with the cylinder axis, interaction process is expected to be similar to that in the “snail” target. The latter allows description by means of 2D PIC simulations, since it has an entrance in the interaction plane. In the presented work this shape is generally used.

The physics of the magnetic field generation in the “snail” target is defined mainly by electron currents excited by laser radiation, shown in Fig. 1 (right panel) with black arrows. The surface current (dashed arrow) is generated by the directly laser-accelerated electrons, which go along the internal curved target surface because of surface electric and magnetic fields and is supported by multiple laser pulse reflections. The return discharge current raises on the femtosecond time scale in order to neutralize the surface charge in the region of laser-surface interaction. Its propagation is also defined by the target internal surface geometry. During the action of the laser pulse, these currents create the strong magnetic fields in the internal target volume, which is filled at the same time with the plasma. When the pulse ends, the value of these currents drop down, and only the magnetic field frozen in the ablated plasmas survives. The magnetized structure inside the target hollow evolves then on the hydrodynamic time scale. It comes to equilibrium between the plasma pressure and the magnetic field pressure. At this stage, the magnetic field may be increased once more by the compression with a flow of hot plasma, coming from the target internal walls [1]. Later in time, the hot target walls expand, thus leading...
to the loss of confinement. Because of the large spatial scale and high plasma density in PIC simulations, the simulation time was limited to 30–40 ps, when the magnetic field intensity drops down to values approximately half of the maximum values. This lifetime scaling is suitable for many applications and diagnostics. In this work in the simulations the laser wavelength was chosen to be 1 μm, target material was aluminum with the ion density \( \approx 10^{22} \text{ cm}^{-3} \). Earlier it was found [1], that the target density is not a critical parameter if it is much higher than the critical density. Simulations were presented with the code PICLS [8], the simulation box was 9496 × 9216 cells, spatial resolution was \( \approx 20 \text{ nm} \), temporal resolution was \( \approx 0.07 \text{ fs} \).

2. Intensity, polarization and size dependence

As theoretically proved in this work, the described process of magnetic field generation by intense laser pulse interaction with curved-surface targets is an effective and robust mechanism in a wide range of parameters. The first example, presented in [1], correspond to a target diameter \( \approx 100 \mu \text{m} \), a 1.5 ps laser pulse of intensity \( 5 \times 10^{19} \text{ W/cm}^2 \) and demonstrate the characteristic values of the generated fields of the order of 2 × 10^8 Gauss. To understand the scaling of these values with laser pulse intensity, simulations for the same target but various laser intensities were carried out, see Fig. 2. The use of relativistic laser intensities allows to increase strongly the magnetic field amplitude by generation of a direct current of laser-accelerated electrons. While further increase of the laser intensity, as shown in Fig. 2 (laser intensity \( 10^{22} \text{ W/cm}^2 \)), the relativistic transparency and hole-boring effects inhibits the process of current generation and only a relatively small part of the laser energy may be converted to the magnetic field.

Other important parameter is the target size. For the same laser parameters, but different target sizes, the maximum magnetic field values are increasing for smaller targets. Several results of the simulations are presented in Fig. 3, where three target diameters 50, 100, and 200 μm were examined at the fixed laser intensity \( 10^{19} \text{ W/cm}^2 \). The highest magnetic field value was obtained for the smallest diameter of 100 μm (\( \approx 3 \times 10^8 \) Gauss). For this case the low density magnetized plasma is compressed by high density unmagnetized ablated plasma, imploding from the walls [1]. For less energetic laser pulses, operating in mild relativistic regime, like that on PHELIX facility at GSI, with intensity \( I \approx 10^{18} \text{ W/cm}^2 \), the scaling in Fig. 2 predicts magnetic fields of the order of \( 2 – 3 \times 10^7 \text{Gauss} \). In this case decreasing of the target size becomes even more important, since an available for the ablated plasma volume is much less. In Fig. 4 simulation results are presented for the laser pulse intensity \( I = 10^{18} \text{ W/cm}^2 \) and the snail target diameters \( \approx 50 \mu \text{m} \) and \( \approx 100 \mu \text{m} \). The maximum magnetic field at 6.1 ps is \( \approx 3 \times 10^7 \text{ Gauss} \) and \( \approx 1.5 \times 10^7 \text{ Gauss} \) respectively. Note, that the geometry of the magnetized structure becomes more regular for the smaller target sizes. For the smallest targets, the magnetized structure was almost homogeneous inside the target volume, see Fig. 3 and Fig. 4.
Figure 3. Results of 2D PIC simulations for different diameters of the “snail” targets, for a 1.5 ps laser pulse with the intensity $1 \times 10^{19}$ W/cm$^2$, at 7 ps after the beginning of interaction. On the left column – electron density, in the critical densities $n_c = 10^{21}$ cm$^{-3}$, on the right column – $B_z$ component of the magnetic field. One of the main effects which contribute to the magnetic field value is compression of the produced low-density magnetized plasma by high-density ablated plasma at late times. On the presented results for the smallest target diameter 100 $\mu$m compression plays the most important role, so that the magnetic field value reaches $|B_z| \sim 3 \times 10^8$ Gauss. For the diameter 150 $\mu$m and 200 $\mu$m magnetic field has similar values of $|B_z| \sim 2\ldots2.5 \times 10^8$ Gauss.

As the main driver for the magnetic field generation are electron currents, excited during the laser interaction with the internal target surface, the interaction mechanism should put an imprint on the magnetic field value and structure. Indeed, for the case of s- and p- polarizations of the incident laser pulse, the magnetic field structures are quite different, see Fig. 5. The analysis of energy redistribution and the effectiveness of the current generation is not evident because of the changing interaction condition in time and during the propagation. It may up to some point correspond to the Brunel-type mechanism, with the complications because of magnetic fields, stochasticity, plasma resonances etc. The corresponded analysis and the more detailed studies of the interaction mechanisms and the dependence on polarization and incident angles are to be presented elsewhere.
3. Deviations from “snail” geometry

3.1. Non-ideal reflection

The simulation results presented in Fig. 3 and Fig. 4 were carried out for the ideal targets with sharp idealized surfaces, and the geometrical shape defined by an analytical expression from the work [1]. After multiple simulations it was generally found, that a small preplasma of few tens of microns width does not considerably change neither in the magnetic field value, nor in its structure, and by this reason these results are not presented here. However, the important point may be the target production technique. It may be possible, that the surface would not be ideal. In this case, the laser pulse reflection may become less effective, and the current values may drop down. To classify the effect of the non-ideal surface, a test simulation was done with an artificial noise (saw-shaped) in the main reflection region, see Fig. 6. A saw on the surface was composed from seven equilateral triangles with 5 µm side. Surprisingly, the magnetic field structure remained almost the same, but the magnetic field value appeared to be about two times less. This results proves again the robustness of the proposed scheme for the magnetic field generation.

3.2. Modified curved targets

The geometrical properties of the magnetized structure obtained as a result of the interaction process is an important parameter for possible applications. Magnetic field lines are closed, either inside the structure near the target or at infinity. When the lines are closed at far distances from the target area, plasma is promoted to expand in the direction along the lines and locked in...
the transverse direction. Closing of magnetic lines in the target internal volume may help to create a confined magnetized plasma, expanding on slow hydrodynamical time scales. For many magnetized applications, such a confined magnetic structure may be a very interesting solution. Probably, the simplest way is to follow toroidal-like geometry, which may be realized with a spherical target with an entrance hole and a conical tip on the opposite side. The tip may have a different geometry, its mission is to reflect the laser beam and not allow it to escape. The cross-section of an example of such a target is shown in Fig. 7 (left panel) with black color. Laser pulse on both upper and lower sides of the target propagates according to the target shape, rising up correspondent currents. In case of spherical symmetry, the geometry of the currents acquires quasi-toroidal shape, and the magnetic lines close in the target internal volume. On the right panel of Fig. 7 the tip is replaced by the diffusive degraded surface, similar to the saw in Fig. 6 (right panel). In this case directly accelerated by the laser pulse electrons do not propagate along the target surface, and only the return currents survive (solid black line in Fig. 1). As a result, the magnetic field value is less pronounced, though it is still clearly visible. This may be useful for understanding of the roles of two main electron currents during laser-target interaction and may become a good point for experimental “yes or no” confirmation.

4. Conclusion
The presented extensive numerical studies show a very robust character of the magnetic field generation, which works in a wide range of laser pulse intensities and in different curved targets.
The predicted amplitudes of the magnetic fields reach values of the order of $\sim 1 - 3 \times 10^7$ Gauss ($\sim 1 - 3 \text{kT}$), even for moderate mild relativistic intensities. These values are already greater than the modern achievements for the highest optically generated magnetic fields with the capacitor-coil targets [4, 5]. Even higher magnetic fields, up to giga-gauss level, are expected to be generated with more intense laser pulses, according to the scaling in Fig. 2. The limits are defined by the relativistic transparency and the hole-boring effects, preventing further reflection of intense pulse inside the target volume. This limitation may probably be removed by the use of targets with special internal geometries [9].

In conclusion, a novel promising setup for manipulation of spontaneous laser-produced magnetic fields of the order of several kT and higher is numerically studied. This approach may become a flexible and convenient tool for a wide range of applications, from laboratory astrophysical studies to particle acceleration schemes. The proposed study opens a new page in the engineering of laser-driven devices for strong B-field production, operating with the target geometry to direct laser propagation and matter response.

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