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Creation of magnetized jet using a ring of laser beams

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ABSTRACT

We propose a new way of generating magnetized supersonic jets using a ring laser to irradiate a flat surface target. Using 2D FLASH code simulations which include the Biermann Battery term, we demonstrate that strong toroidal fields can be generated and sustained downstream in the collimated jet outflow far from the target surface. The field strength can be controlled by varying the ring laser separation, thereby providing a versatile laboratory platform for studying the effects of magnetic field in a variety of astrophysical settings.

1. Introduction

Using FLASH code [2] simulations, we have recently demonstrated that a bundle of laser beams of given individual intensity, duration and focal spot size, produces a supersonic jet of higher density, temperature, velocity and collimation, if the beams are focused to form a circular ring pattern at the target instead of a single focal spot [3]. The increased density, temperature and velocity provide a more versatile platform for a variety of laboratory astrophysics experiments [12,11,10,4] with larger dynamic range. In this paper we investigate the effects of the ring pattern laser configuration on magnetic field generation, using a new version of the FLASH code, which includes the Biermann Battery (BB) or ($\nabla P_e \times \nabla n_e$) term [1,5] for magnetic field creation, where P_e and n_e are electron pressure and density, respectively. Because of the 2D nature of our simulations, only the azimuthal B_ϕ field is created. However, it is well known that for quasi-axisymmetric laser-driven blowoffs, B_ϕ is the dominant field component generated by the BB effect, so that our 2D results should be valid to first order. In follow-up simulations, we will use the 3D FLASH code (without the BB term) to check that the (r,z) components of the BB term remain small compared to the ϕ-component throughout, so that our 2D approximation if self-consistent. Further down the road, we will explore inclusion of the (r,z) components of the BB term into fully 3D FLASH simulations to study various non-axisymmetric effects.

In the current 2D (r,z) version of the FLASH code, the magnetic field evolution terms included are [5]:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (u \times \mathbf{B}) - c\nabla \times (\eta \mathbf{j}) + c\frac{\nabla P_e \times \nabla n_e}{e n_e^2}. \quad (1)$$

In the limit of low plasma resistivity η (e.g. low density, high temperature plasma), the last term (so called "Biermann battery" term) dominates field creation. In 2D, P_e, n_e are functions of only (r,z). Hence the $\nabla P_e \times \nabla n_e$ term has only a ϕ-component. The code also adopts a shock detection scheme to suppress artificial creation of unphysical BB fields at the shock front. Laser absorption is computed using ray-tracing in the geometric optics approximation.

2. Numerical simulations

We use a (r,z) grid with (512×2048) zones. The electron-ion plasma has zero initial magnetic field. The laser target is modeled as a 2 mm wide by 0.5 mm thick CH foil. We simulate the laser-driven blowoffs using laser parameters equivalent to 10 Omega laser beams of 250 μm focal spot diameter. The total laser energy equals 5 kJ in a 1 ns square pulse. The laser incident angle is 30° from target normal.

Fig. 1 illustrates the geometry setup of the different runs. "Separation" is here defined to be the distance from the midpoint

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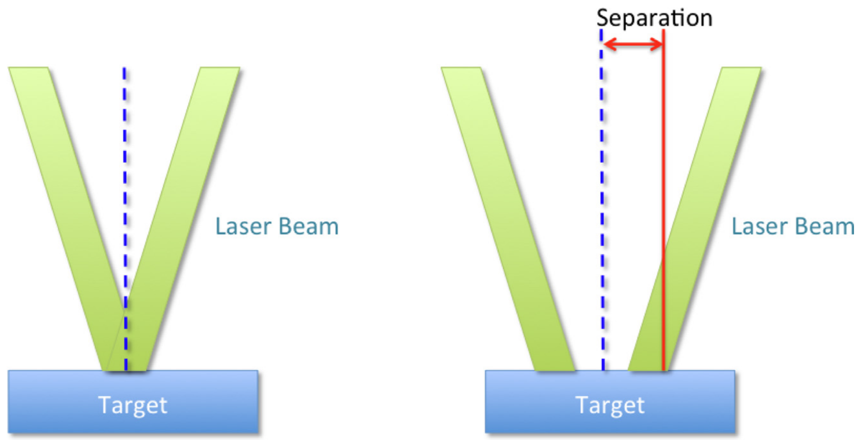

Fig. 1. Sketch illustrating the geometry used in our FLASH simulations.

of the circular ring to the target center. Fig. 2 compares the BB-generated field at 0.3 ns, for three different runs: single focal spot (left), 400 μm separation (middle), and 800 μm separation (right). The maximum BB-generated field at this early time is around 50 kG. While the field for the single-spot laser blowoff has a simple toroidal geometry, the ring-laser blowoff creates toroidal B fields of opposite polarity on the inside and outside of the ring, as expected. Fig. 3 compares the B field at 3 ns, after the laser has turned off. By this time the blowoff of the zero separation case has diverged to the point that the density and pressure gradients are too weak to sustain significant magnetic field except near the target surface. In contrast, the 800 μm separation case shows strong toroidal field far downstream along the axis due to the compression and heating of the convergent flow from the ring towards the axis. Even at a distance of $z = 0.3$ cm, the BB-generated field exceeds 20 kG, which would be useful for a variety of magnetized jet experiments. At the jet base, the field is more complicated due to multiple shock formation from the plasma collisions, with multiple polarity reversals due to idealization of the MHD approximation. In a real physical experiment, finite resistivity, either due to collisions or anomalous effects, will lead to reconnection and decay of the magnetic field near the base. Fig. 4 compares the electron and ion densities at 3 ns, showing strong collimation and density enhancement for the ring cases. Fig. 5 compares the electron and ion temperatures at 3 ns, which mirror the density enhancement. These increased density and temperature gradients are responsible for sustaining the BB-generated field downstream far from the target surface (Fig. 2).

Magnetic field generation via the Biermann battery term has been investigated before in various laser-plasma experiments [6–8]. In these studies, hot electron transport (e.g. Nernst effect leading to electron advection of magnetic fields) played an important role. However, hot electron transport is not turned on in our simulations. We are mainly interested in outflow conditions at distances >1 mm from laser target and times >1 ns. Hence transient effects at early times (<ns) and near the target surface (<1 mm), which can be very complicated, will not be modeled in details as a first approximation. The FLASH code does have the option of incorporating electron transport using both the Branginski conductivity as well as flux limiters and we plan to include

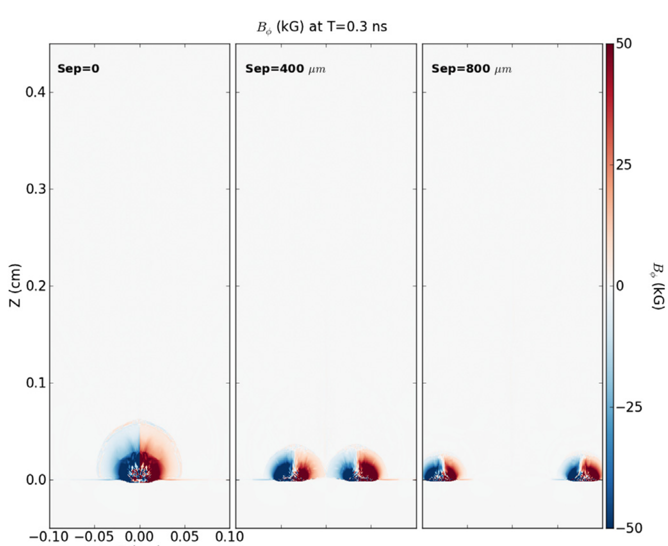

Fig. 2. B_ϕ profiles at $t = 0.3$ ns for the three runs with different ring laser separations. Color scales denote field strength into and out of the plane. The toroidal fields inside and outside of the ring have opposite polarity. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

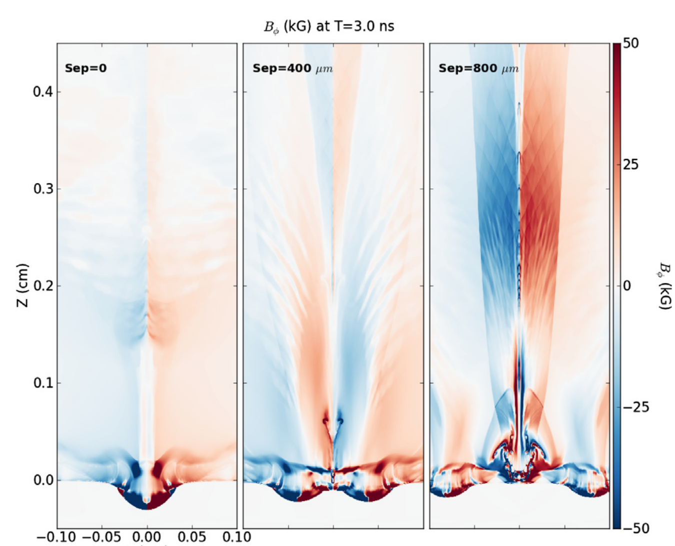

Fig. 3. Same as Fig. 2 at $t = 3.0$ ns. The field for the 800 μm separation case is much stronger far from the target, due to sustained BB effects along the axis, exceeding 20 kG even at $z = 0.3$ cm. In contrast, the field for the zero separation case is negligible by this time except near the target surface.