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Matter Radiat. Extremes 11, 017602 (2026)

<https://doi.org/10.1063/5.0272622>



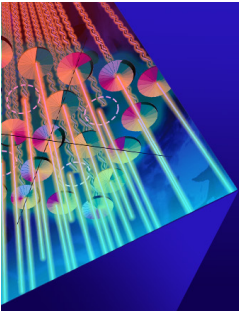
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Cite as: Matter Radiat. Extremes 11, 017602 (2026); doi: 10.1063/5.0272622

Submitted: 25 March 2025 • Accepted: 9 October 2025 •

Published Online: 31 October 2025



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ABSTRACT

Experiments with interacting high-velocity flows in a laser plasma can help answer fundamental questions in plasma physics and improve understanding of the mechanisms behind some astrophysical phenomena, such as the formation of collisionless shock waves, deceleration of accretion flows, and evolution of solar and stellar flares. This work presents the first direct experimental observations of stagnation and redirection of counterstreaming flows (jets) of laser plasma induced by intense laser pulses with intensity $I \sim 2 \times 10^{18} \text{ W/cm}^2$. Hybrid particle-in-cell–fluid modeling, which takes into account the kinetic effects of ion motion and the evolution of the pressure tensor for electrons, demonstrates the compression of counterdirected toroidal self-generated magnetic fields embedded in counterstreaming plasma flows. The enhancement of the toroidal magnetic field in the interaction region results in plasma flow stagnation and redirection of the jets across the line of their initial propagation.

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I. INTRODUCTION

Counterstreaming plasma flows are observed in astrophysical objects and in some cases lead to the formation of highly inhomogeneous nonequilibrium plasma structures. Well-known examples include solar wind interaction with planetary magnetospheres, colliding stellar winds,^{1–4} supernova remnants (see, e.g., Ref. 5 for a review), pulsar wind nebulae (see, e.g., Ref. 6 for a review), gamma-ray burst afterglows,⁷ radiolobes of active galactic nuclei,^{8,9} and decelerating accretion flows.^{10,11} While the global hydrodynamics of these shocks is relatively well understood, the details of their microphysics are still an open issue.¹² The notable unsolved problems are properties of small-scale magnetic fields (magnetic turbulence) and the process of initial particle injection into a nonthermal distribution, which further undergoes diffusive shock acceleration. Recent X-ray polarization measurements^{13,14} provide a glimpse into the first problem, whereas the second can only be studied by means of either numerical models or laboratory modeling. Microphysics of collisionless shocks is a complex problem involving plenty of plasma

instabilities and various elementary processes. It is not trivial even to list all the relevant physical phenomena, much less to implement them in numerical models. Laboratory experiments with plasma flows complement numerical simulations in revealing the details of collisionless-shock microphysics.

In addition, the role of the large-scale magnetic field in the microphysics of collisionless shock waves is still not fully understood. Investigation of this topic and interpretation of the results are complicated by the fact that in addition to the external magnetic field, the dynamics of plasma flows can also be influenced by the self-induced large-scale magnetic field. It is known that without any seed, a magnetic field can be generated through several mechanisms, such as the Biermann battery¹⁵ or as a result of the development of Weibel-type instabilities in the plasma.¹⁶ Counterstreaming plasma flows in which a self-generated toroidal magnetic field is embedded can exhibit entirely new effects, such as redirection of plasma flows, magnetic reconnection,^{17–19} and plasma stagnation.^{20–22}

The large distances to the astrophysical objects with counterstreaming jets under consideration complicates direct observation

of flow redirection and testing of theoretical models. However, laboratory approaches offer the possibility of creating controlled experimental conditions that allow detailed investigation of the evolution of plasma structures. Experiments enable the control of key parameters that are difficult or impossible to measure in astronomical observations, thereby contributing to a deeper understanding of the physical mechanisms behind the observed phenomena. Thus, laboratory experiments are a crucial companion to astronomical observations.²³

Modern laser systems allow the creation of plasma flows with fairly high directed velocities (of the order of and exceeding 100 km/s), which enables ions in counterpropagating flows to be collisionless, while electrons and ions in each flow remain collisional.²⁴ Therefore, a magnetohydrodynamic approach can be used for an approximate description of the evolution of the individual plasma flows,²² but for an accurate description of the interaction between the two flows, the kinetics of the ions must be taken into account. In this context, experimental studies can be divided into two classes, investigating collisionless and collisional ion interactions, respectively. For collisionless interactions, characterized by high relative ion velocities between streams and consequently low collisional dissipation, astrophysically relevant phenomena have been observed, such as collisionless shocks^{21,25–28} and Weibel instability.^{29–32} Particularly important in the astrophysical context are studies of magnetized collisionless shocks.^{33,34} There have been a number of investigations of the interaction of high-velocity laser-driven plasma flows with magnetized ambient media.^{35–38}

Collisional interactions and plasma stagnation resulting from the conversion of directed flow energy into thermal energy in counterstreaming plasma flows have been extensively investigated.^{39–42} Transitions from collisionless to collisional interaction regimes have been observed.^{24,42} There have been some studies^{43,44} focusing on oblique collisional interactions of plasma flows, examining collimation and stability of plasma flows in the context of scaled astrophysical jets and demonstrating the existence of density-dependent morphologies and radiative cooling effects. Magnetic reconnection during tilted plasma flow interactions in external magnetic fields has also been investigated.^{17,18} These studies observed collisional stagnation of plasma flows, manifested through enhanced self-emission between targets.

Several experimental studies^{20,21,45,46} have investigated magnetic stagnation of counter-propagating plasma flows and are therefore closely related to our work. All of these experiments were conducted on the Omega EP Laser System using kilojoule-class nanosecond laser beams. In one study,²⁰ counterstreaming plasma flows expanded into an ambient plasma containing an external magnetic field with strengths up to 8 T. The external magnetic field had an X-type null-point geometry frozen into the background plasma. When the counterstreaming laser plasma flows propagated into this magnetized medium, magnetic reconnection and magnetic stagnation of plasma flows were observed. Critically, in that experiment, in the absence of an ambient plasma and/or an external magnetic field, stagnation of counterstreaming nanosecond-laser-produced plasmas was not observed, but, instead, mutual plasma interpenetration dominated the interaction dynamics.

In Refs. 45 and 46, diverging (noncollimated) plasma flows generated by ~ 2 kJ nanosecond laser pulses with velocities $V \sim 1000$ km/s were collided head-on. In Ref. 21, collimated plasma

flows (produced using V-shaped targets) with velocities exceeding $V \sim 1700$ km/s were collided at various angles, including a counterstreaming geometry. Proton radiography measurements in all these studies revealed large-scale stable electromagnetic field structures. Through the use of an analytical model similar to that in Ref. 22, these studies demonstrated the formation of a magnetic stagnation surface in the collision region. The analytical model shows that magnetic fields generated by the Biermann battery mechanism are advected from the target, compressed and amplified to 10–30 T in the interaction region.

Our investigation of magnetic stagnation of plasma flows generated by relativistic-intensity femtosecond laser pulses complements the above studies, but explores a different physical regime owing to the distinct nature of intense laser–matter interaction. The key difference, as will be discussed in detail later, lies in the ratio between the plasma ram pressure $\rho V^2/2$ and the self-generated magnetic field pressure $B^2/8\pi$, which is characterized by a dimensionless parameter $M_A = V/V_A$, where $V_A = B/\sqrt{4\pi\rho}$ is the Alfvén speed calculated from the flow density ρ . While all the studies mentioned above operated in the regime $M_A \gg 1$, our work deals with a fundamentally different regime $M_A \sim 1$ (see Table II).

All the abovementioned laser–plasma experiments investigating the collision of quasi-counterstreaming flows have primarily been conducted using energetic (up to several kJ) and moderately intense $I < 10^{15}$ W/cm² nanosecond laser pulses. Experiments like ours where counterstreaming plasma flows are created by irradiating solid targets with intense short (a few tens of femtoseconds to a few picoseconds) laser pulses with peak intensities exceeding 10^{18} W/cm² have been absent until now. This significant new approach was proposed in a theoretical study⁴⁷ of the generation of collisionless shock waves. When a plasma is heated with short intense pulses, there are several significant differences compared with nanosecond plasma heating. Under femtosecond intense irradiation of the target, a substantial fraction of accelerated electrons is generated, with oscillatory energies up to few MeV.⁴⁸ Energetic electrons can escape and move away from the heating region,⁴⁹ resulting in an huge electric field that returns electrons and accelerates ions in some cases to 10 and even 100 MeV.^{50,51} In this process, the direct and reverse oscillating electron flows contribute to the generation of magnetic fields, such as large-scale fountain magnetic fields^{52–56} and small-scale filamentation fields arising from the development of Weibel-type current instabilities.^{16,57–59} Fountain toroidal self-generated magnetic fields in a plasma can exceed Biermann fields and reach several hundred tesla,^{54–56} and more than 30 000 T has even been reported in some cases.^{60,61} These magnetic fields can exert a constraining influence on the radial expansion of the plasma,⁵² leading to a collimated plasma flow, which we call a jet.

Our present work is dedicated to an experimental investigation of the interaction of counterstreaming plasma jets generated by intense laser pulses ($I \sim 2 \times 10^{18}$ W/cm²). We have developed and implemented an original scheme that allows us to split the impact of the intense laser pulse across several targets and generate counterstreaming plasma jets. All experiments are conducted on the single-channel petawatt PEARL laser facility.^{62–64} A detailed study of the topology and evolution of the interacting plasma flows and magnetic fields is carried out using two-dimensional interferometric plasma density measurements, shadowgraphy, and Faraday

polarimetry measurements with femtosecond temporal resolution. Numerical computations performed using a hybrid particle-in-cell (PIC)–fluid approach confirm the mechanism of plasma stagnation and redirection by the toroidal self-generated magnetic field, which is advected and amplified in the interaction region of the flows.

This work does not aim to elucidate the mechanism responsible for generating the toroidal large-scale magnetic field, which may be related to the Biermann mechanism or the fountain effect. Instead, we focus on describing the experimentally observed phenomenon of stagnation of counterstreaming plasma jets and their radial redirection, in which the advection of the toroidal magnetic field plays a significant role. To the best of our knowledge, such studies have not previously been conducted, primarily owing to the lack of multichannel petawatt laser systems.

The remainder of the paper is organized as follows. Section II describes the setup and experimental scheme. Section III presents the experimental results. Section IV presents the results of numerical modeling using the AKA52 hybrid code. Section V presents a discussion of the results obtained and an interpretation of the numerical computations. In Secs. V and VI, we discuss the overall results and draw conclusions.

II. METHODS

The experiments were conducted at the petawatt PEARL laser facility.^{62,63} Details of the capabilities of the laser facility can be found in our review⁶⁴ and elsewhere.^{65–69} In the experiment, a laser pulse with an energy of 10–15 J, a duration of 60–80 fs, and a wavelength of 910 nm was used to generate plasma. The laser pulse was focused using an $F/40$ spherical mirror into a spot with a diameter $\sim 100 \mu\text{m}$. As a result, an intensity of about $2 \times 10^{18} \text{ W/cm}^2$ was achieved on the target. The intensity of the prepulse did not exceed 10^{-7} relative to the main pulse.

Optical methods were used for plasma diagnostics. The diagnostic pulse was a weakened replica of the main laser pulse, with an energy of about $1 \mu\text{J}$, a duration of 60–80 fs, and an aperture of more than 3 cm, allowing nearly instantaneous snapshots of the entire expanding plasma. A Mach–Zehnder interferometer was used to measure the plasma density (as shown schematically in Fig. 1 in the [supplementary material](#)). Faraday polarimetry⁷⁰ was employed to diagnose the magnetic field generated in the plasma (see Fig. 1 in the [supplementary material](#)). A detailed description of the diagnostic methods is provided in our review⁶⁴ and in the [supplementary material](#). Snapshots of the plasma were taken from 0.5 to 50 ns after the target irradiation. Plasma probing was conducted simultaneously in two directions using two probe laser beams, one of which is marked in the scheme in Fig. 1.

A. Experimental setup

The experimental setup for generating counterstreaming plasma flows is shown in Fig. 1. A laser pulse with s-polarization (E was in the plane of the target surface) was incident at a small angle θ of about 5° to the target normal, interacted with the target surface pre-ionized by the prepulse, and was reflected toward the second target located at a distance of about 2 mm. Both targets were made of the same material, polymethyl methacrylate ($\text{C}_5\text{O}_2\text{H}_8$)_n. The interaction of the laser pulse with the targets resulted in the generation

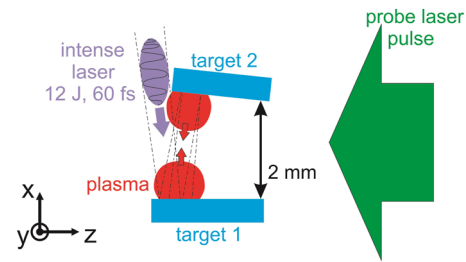


FIG. 1. Experimental setup. An intense laser pulse with energy $\sim 12 \text{ J}$ and duration 60 fs irradiates the first target (polymethyl methacrylate) at an angle of $\sim 5^\circ$ with s-polarization. Approximately 30% of the pulse energy is absorbed, while the remaining $\sim 70\%$ is reflected and scattered. This reflected light subsequently irradiates the second polymethyl methacrylate target, positioned 2 mm from the first target. The second target is tilted by $\sim 5^\circ$ relative to the first target's orientation to achieve quasi-counterpropagating collision of the two plasma flows. The Rayleigh length of the pump beam ($\sim 10 \text{ mm}$) ensures comparable laser spot sizes on both targets. Plasma dynamics are diagnosed using a 60 fs optical probe beam (green arrow), employed for shadowgraphy, interferometry, and Faraday polarimetry measurements.

of laser plasma flows propagating in the directions of the target normals. The angle between the target normals was taken to be about $\theta = 5^\circ$, thereby ensuring a quasi-counter collision of the two flows.

It is experimentally observed that the second plasma flow has characteristics similar to the first flow, such as density, expansion velocity, temperature, and total number of particles. This is because of the low absorption of intense and short laser pulses when they irradiate a solid target. Direct measurements show that a significant portion, about 70%, of the energy of the intense pulse is reflected from the solid target under our parameters. Such values agree well with those found in previous studies,^{71,72} where absorption has been measured and numerically estimated for similar laser pulse parameters, yielding 20%–30%. Notably, at our intensities of $\sim 10^{18} \text{ W/cm}^2$, the absorbed laser energy fraction shows little dependence on the target material composition.^{71,72} Thus, in our experiment, the laser pulse arriving at the second target has an energy of $\sim 70\% \times 12 \text{ J} = 8.2 \text{ J}$. Consequently, the energy contribution to each flow can be approximated as 3.6 J (primary target) and 2.5 J (secondary target). The Rayleigh length is about 10 mm, which significantly exceeds the 2-mm distance between the targets. Therefore, the size of the laser spot on the second target is of the same order of magnitude as the size of the spot on the first target.

B. Description of a single laser plasma flow

To better understand the interaction of two plasma flows, let us first consider the characteristics of a single flow when a single target is irradiated. In the first few picoseconds after irradiation, the plasma electrons have a very high temperature, reaching several hundred keV.^{48–50} As the plasma is expanding, it rapidly cools down and isotropizes, resulting in a characteristic temperature of $T_e \sim T_i \sim 50 \text{ eV}$ after a few nanoseconds.^{48,49} These temperature estimates are consistent with measurements under similar conditions^{50,73,74} made using a focusing spectrometer with spatial resolution (FSSR).^{75,76}

Figure 2 shows a two-dimensional profile of the linear plasma density obtained using femtosecond optical interferometry 8 ns

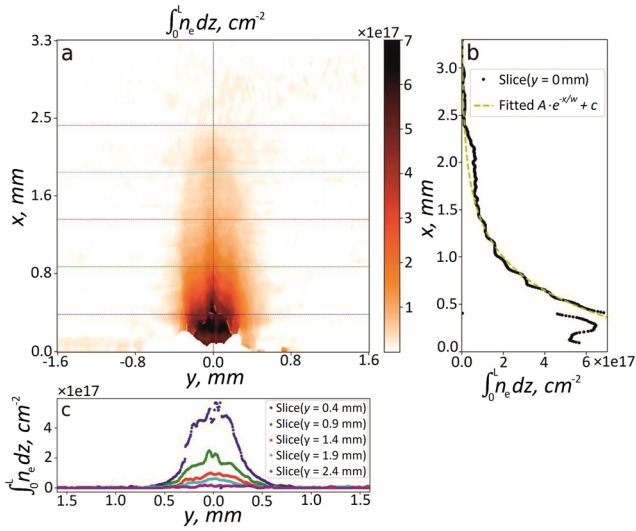


FIG. 2. Snapshot of plasma flow, obtained 8 ns after irradiating a single target with pulse intensity 2×10^{18} W/cm² (no second target and second flow). (a) Two-dimensional distribution of integrated plasma density along the beam, obtained after analyzing the interferogram. (b) Plasma density slice along x axis directed normally to target. (c) Plasma density slices along target surface.

after irradiation. For the details of the reconstruction of the plasma density, see Refs. 64 and 77. The plasma flow generated by an intense laser and expanding into a vacuum has a collimated structure with an expansion angle no more than a few degrees, which is significantly different from the quasi-spherical expansion of a “nanosecond” laser plasma.^{67,78}

The dotted lines in Fig. 2(a) mark the slices presented in Figs. 2(b) and 2(c). The one-dimensional profile of the plasma density [Fig. 2(b)] along the normal to the target (x axis) is well approximated by the dependence $N_e = Ae^{-x/w}$, where $w = 0.5$ mm, $A = 7 \times 10^{18}$ cm⁻². This experimental profile should be treated as empirical. However, it shows good agreement with the scaling $N_e = Ae^{-x/C_s t}$,⁷⁹ where $t = 8$ ns and $C_s = 60$ km/s represents the ion sound speed corresponding to an electron temperature of $T_e \sim 50$ eV. The speed of the plasma flow front is estimated to be 100 km/s.

To obtain approximate estimates of the main parameters (Table I), it is reasonable to assume that the plasma consists of individual ions H⁺, C⁺, and O⁺. The plasma density at a distance of 1 mm (see Table II) of 2.5×10^{18} cm⁻³ was obtained from the linear concentration (Fig. 2) under the assumption of an axially

TABLE II. Calculated values of some parameters.

Parameter ^a	Value
ρ (g/cm ³)	5.9×10^{-5}
C_s (km/s)	58
V_A (km/s)	110
l_{ee} (cm)	1.25×10^{-4}
$\tau_{col ee}$ (ns)	1.65×10^{-3}
R_{Le} (cm)	5.6×10^{-5}
f_{ce} (Hz)	8.4×10^{11}
l_{ei} (cm)	5×10^{-6}
$\tau_{col ei}$ (ns)	1.9×10^{-3}
l_{ii} (cm)	8.7×10^{-5}
$\tau_{col ii}$ (ns)	3.3×10^{-3}
l_i (directed) (cm)	5×10^{-2}
R_{Li} (directed) (cm)	1.2×10^{-2}
f_{ci} (Hz)	1.3×10^8
τ_{ff} (ns)	9×10^3
M	1.7
M_A	0.9
η (cm ² /s)	3.4×10^4
Re_M	30
Re	20
Eu	2.2
β	3×10^{-2}

^a ρ , mass density; C_s , sound speed; $V_A = B/\sqrt{4\pi n_i m_i}$, Alfvén speed (where n_i is the ion density and m_i is the ion mass); l_{ee} , mean free path for e - e collisions; $\tau_{col ee}$, time between electron collisions; R_{Le} , electron Larmor radius; f_{ce} , electron gyrofrequency; l_{ii} , mean free path for i - i collisions; $\tau_{col ii}$, ion collision time; R_{Li} , ion Larmor radius; f_{ci} , ion gyrofrequency; τ_{ff} , bremsstrahlung cooling time; M , Mach number; $M_A = V/V_A$, Alfvén Mach number; $Re_M = LV/\eta$, magnetic Reynolds number; η , magnetic diffusivity; $Re = LV/\nu$, Reynolds number (where ν is the kinematic viscosity); $Eu = \sqrt{\rho V^2/p}$, Euler number; $\beta = p/(B^2/8\pi)$, plasma beta.

symmetric flow. According to the FLYCHK database,⁸⁰ for a temperature $T_e \sim 50$ eV and a characteristic density of 2.5×10^{18} cm⁻³, the plasma in equilibrium has an average charge number $\langle Z \rangle = 2$. The average mass number is approximately estimated as $\langle A \rangle = 7$ under the assumption that the plasma composition is determined by the target composition. The initial numerical characteristics of the studied plasma are presented in Table I and are used to estimate some parameters characterizing the behavior of the plasma in Table II. Estimates for the mean free path of electrons and ions within the flow, as well as ions from different flows, are provided. The mean free path of ions from different flows $l_i(\text{directed}) = 0.5$ mm is

TABLE I. The values of the initial parameters for each of the two flows.

Parameter	Electron density n_e (cm ⁻³)	Charge state Z	Mass number A	Flow velocity V (km/s)	Ion temperature T_i (eV)	Electron temperature T_e (eV)	Spatial scale L (cm)	Magnetic field B (Tcy)
Value	5×10^{18}	2	7	100	50	50	0.1	30*

calculated using the expression in Eq. (2) of Ref. 31 and is of the same order of magnitude as the interaction scale L . At the same time, the electron collisions within and between the two flows are significant, as are ion collisions within the flows. Table II presents the values of the Reynolds number $Re = LV/\nu$ and the magnetic Reynolds number $Re_M = LV/\eta$, where L is the characteristic spatial scale, V is the flow velocity, ν is the kinematic viscosity calculated using the expression from Ref. 81 (p. 825), and η is the magnetic diffusion coefficient calculated using the formula from Ref. 82 (p. 467).

The bremsstrahlung cooling time (see Table II), $\tau_{ff} \approx 9 \times 10^{-6}$ s, is estimated using the expression in Eq. (5.15b) of Ref. 83 for bremsstrahlung radiative losses per unit volume for a thermalized plasma. Therefore, radiative cooling has a negligible effect on the evolution of the plasma on the tens of nanoseconds timescale that we discuss in this paper.

III. RESULTS

Shadowgraphy images and two-dimensional plasma density profiles are shown for a single flow in Figs. 3(a)–3(d) and for two counterstreaming flows in Figs. 3(e)–3(h). The plasma snapshots were obtained 1 ns [Figs. 3(a) and 3(e)], 4 ns [Figs. 3(b) and 3(f)], 8 ns [Figs. 3(c) and 3(g)], and 16 or 17 ns [Figs. 3(d) and 3(h)] after target irradiation. The plasma expansion is axially symmetric, and the plasma density profiles in the (z, x) plane do not differ from those in the (y, x) plane and are therefore not presented here. Clearly, the structure of the plasma during the counterstreaming flow interaction differs significantly from the structure of a single flow starting from the very first recorded images ($\tau = 1$ ns) in Figs. 3(a) and 3(e). The characteristic transverse scale of the plasma at $\tau = 1$ ns, which is 1 mm for a single flow, increases to 2 mm for the counterpropagating flows [see Figs. 3(a) and 3(e) and the slice at $x = 0.4$ mm in Fig. 4(a)]. At the same time, the measured plasma density in the

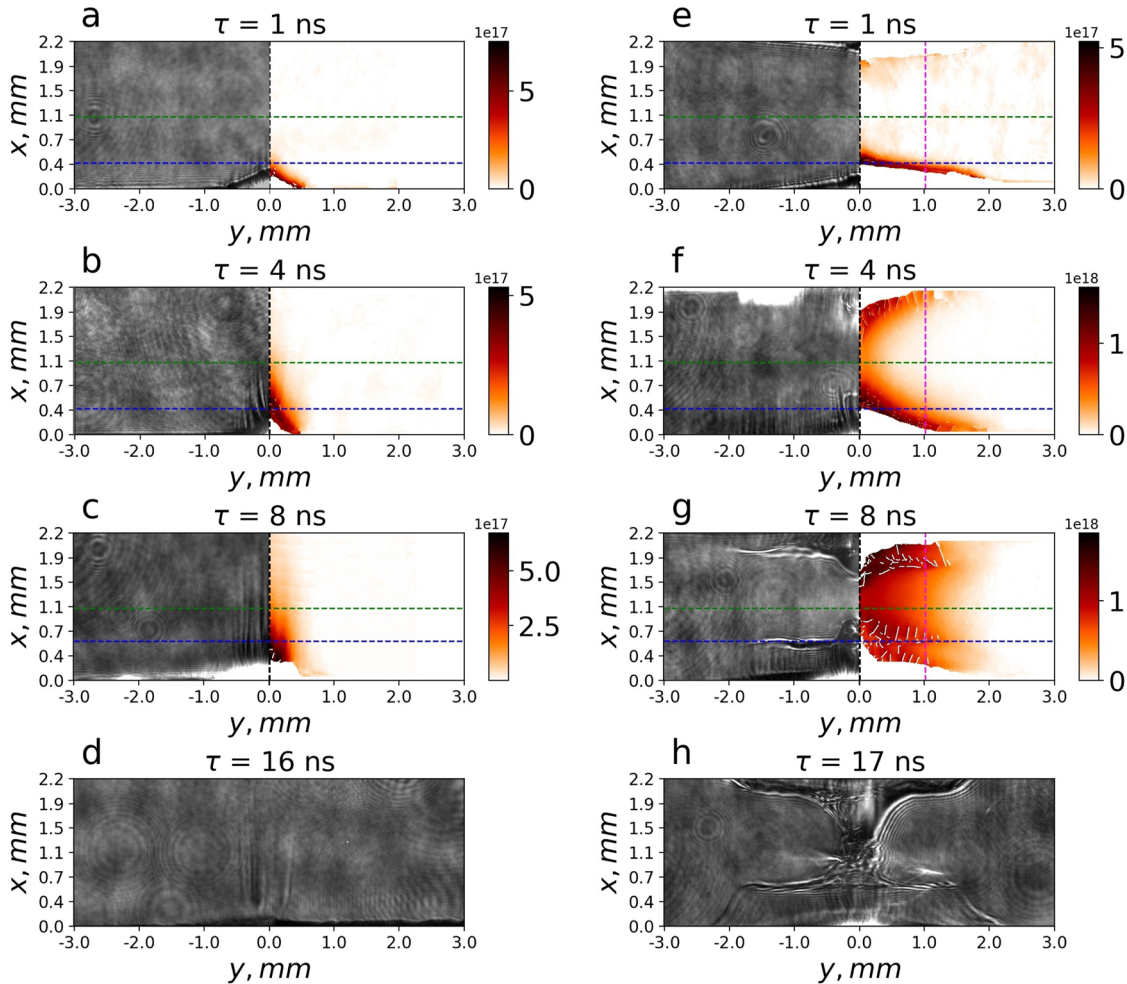


FIG. 3. Two-dimensional profiles of linear plasma density: (a)–(d) images of a single flow (no second target and second flow) obtained at 1, 4, 8, and 16 ns, respectively; (e)–(h) counterpropagating flows of plasma obtained at 1, 4, 8, and 17 ns, respectively.

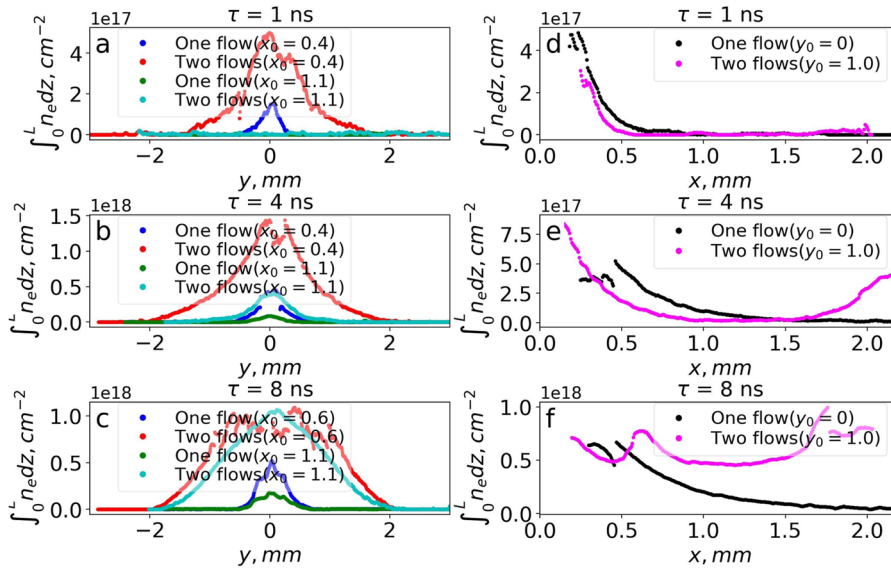


FIG. 4. One-dimensional profiles (slices) of linear plasma density. The positions of the slices in the two-dimensional profiles are marked by dashed lines in Fig. 3.

center of the interaction region is below the detectable threshold of our interferometer ($N_{\text{thd}} \sim 10^{16} \text{ cm}^{-2}$). We assume that the increase in the transverse scale of the plasma flow at this stage ($\tau < 1 \text{ ns}$) may be most likely due to additional ionization by X rays from the opposite targets, although inelastic scattering of accelerated electrons could also contribute to this effect.

In the next stage ($\tau = 4 \text{ ns}$), as seen in Figs. 3(b) and 3(f), plasma is detected in the $x = 1.1 \text{ mm}$ plane, i.e., in the middle of the interaction region. Density slices at $x = 1.1$ and 0.4 mm are presented in Fig. 4(b), while the slice at $y = 0$ is shown in Fig. 4(e). It can be seen that the transverse size (at $x = 0.4 \text{ mm}$) for the counterpropagating flows has increased to 3 mm , while the transverse size of the single flow has not changed significantly and has remained $\sim 1 \text{ mm}$.

At $\tau = 8 \text{ ns}$ [Figs. 3(c) and 3(g)], two local density compression layers are detected in the counterstreaming plasma flows, with centers located at approximately $x \approx 0.6$ and 1.8 mm . In the region between these compressions and the targets, a less dense plasma is observed. This is demonstrated by the slice for $y = 1 \text{ mm}$ [Fig. 4(f)], where a double-humped plasma density profile for the two flows is detected, along with an exponentially decaying profile for the single flow. In the density slice for $x = 0.6 \text{ mm}$, the characteristic transverse scale of two colliding plasma flows reaches 3.8 mm . This topology indicates stagnation and radial redirection of the plasma flows.

We conjecture that these plasma compressions are caused by the deceleration of the plasma by the compressed and enhanced toroidal magnetic field (see the simulation in Sec. IV). The existence of a strong magnetic field is tested by our polarimetric measurements. The details of the polarimetric diagnostic setup and the methods for recovering the depolarization angle are described in the supplementary material and in our review.⁶⁴ In addition, Fig. 2 in the supplementary material presents a characteristic distribution of the depolarization angle, representing the rotation of polarization of the laser probe beam passing through the plasma. It captures the initial stage of counterstreaming plasma flow interaction at 4 ns after target irradiation, before stagnation onset. The

supplementary material also provides a description of the patterns, including identification of reliable regions and potential measurement artifacts. Overall, the depolarization angle distribution (Fig. 2 in the supplementary material) clearly demonstrates the presence of large-scale toroidal field structures localized near the plasma flows with alternating polarity (a chessboard-like pattern across different quadrants). Without taking into account parasitic artifacts, we determine that depolarization in the toroidal magnetic field regions shows a characteristic angle of $\sim 1^\circ - 2^\circ$. With a characteristic linear density of about $2 \times 10^{18} \text{ cm}^{-2}$ (Fig. 3), the scale of the region occupied by magnetic toroids is $L = 2 \text{ mm}$. Such Faraday depolarization indicates magnetic fields in this region with amplitudes of $20 - 40 \text{ T}$, estimated using expressions from Refs. 84 and 85. The value of 30 T given in Table I is adopted for the following calculations. We note in advance that these experimental results show qualitative agreement with the simulations from Sec. IV.

In the next stage $\tau = 16 - 17 \text{ ns}$, as shown in the shadowgraphy image in Fig. 3(h), the central cores (“head”) of the counterstreaming plasma flows collide in the vicinity of the $y = 0$ axis. Meanwhile at the periphery, where $r = \sqrt{y^2 + z^2} > 0.5 \text{ mm}$, the compressed front of the plasma flow has not practically shifted over 9 ns with respect to Fig. 3(g), indicating the stagnation of the plasma flow in this region.

IV. SIMULATIONS

To explain the nature of the observed phenomenon, we present numerical simulations of the plasma using a hybrid PIC–fluid approach. We did not aim to perform a one-to-one simulation of the experiment, owing to computational resource limitations. However, our simulations are capable of reproducing important energy relationships (temperatures and kinetic energy) stored in the plasma and the self-generated magnetic field.

We use the arbitrary kinetic algorithm (AKA) hybrid code⁸⁶ based on the common and well-accepted principles of previous codes, such as Heckle,⁸⁷ with advanced features such as an

ablation operator and a six-component electron pressure tensor. In the numerical model, ions are described according to the PIC formalism, while electrons are described by a ten-moment fluid model: density (n_e equal to the total ion density, owing to neutrality), mass velocity (V_{ex}, V_{ey}, V_{ez}), and a six-component electron pressure tensor ($\hat{P}_{exx}, \hat{P}_{eyy}, \hat{P}_{ezz}, \hat{P}_{exy}, \hat{P}_{eyz}, \hat{P}_{ezx}$). Electromagnetic fields are considered in the low-frequency approximation (Darwin approximation), neglecting the displacement current. The generalized Ohm's law contains three terms: (i) $\mathbf{V}_i \times \mathbf{B}$, where $\mathbf{V}_i$ is the mass velocity of ions; (ii) the Hall effect term $(\mathbf{J} \times \mathbf{B})/en$ (where $\mathbf{J}$ is the total current density, which is equal to the curl of $\mathbf{B}$), which describes the decoupling of ions from the magnetic field; and (iii) $(\nabla \cdot \mathbf{P}_e)/en$, the divergence of the electron pressure tensor, representing the contribution of the electron fluid.⁸⁸ Ion collisions are accounted for using the Takizuka–Abe binary collision model.⁸⁹

The magnetic field and density in the model are normalized to $B_0 = 100$ T and $n_0 = 2.5 \times 10^{20} \text{ cm}^{-3}$, respectively, from which follows the normalization of the other quantities. The density determines the ion inertial length $d_0 \sim 19 \mu\text{m}$, which sets the lengthscale. The box has a 2D rectangular shape with dimensions $30 \times 60 \times 1d_0$. The magnetic field determines the time normalization, since the time is normalized to the inverse ion cyclotron frequency $t_0 = \Omega_0^{-1}$, which is ~ 2.3 ns. The velocities are normalized to the Alfvén speed V_0 calculated from the normalized quantities B_0 and n_0 . In the simulation, the target density is initialized and maintained at a level of $8n_0$ (i.e., $2 \times 10^{21} \text{ cm}^{-3}$). The pixel size is chosen to resolve the ion inertial length in the interaction region.

Continuous plasma production resulting from the laser–target interaction is simulated using an ablation operator,⁹⁰ which accounts for the heating of ions and electrons. The operator of

particle production maintains constant target density, simulating a reservoir for a target with solid-state density. This approach is adequate, as we observe in the experiment that after irradiation the target serves as a prolonged (several tens of nanoseconds) source of plasma. The heating operator linearly increases the electron pressure in a thin layer near the target surface, creating a pressure gradient along the normal to the target surface; this generates an electric field and accelerates ions, giving rise to plasma expansion. The magnitude of the heating operator is fitted to achieve the desired temperature for electrons ($T_{\text{spot}}^{e,i} = 10T_0$, where $T_0 \approx 50$ eV for the chosen parameters). The ablation operator is activated when $t\Omega_0 < 20$, after which pressure pumping is turned off, and particles are loaded with a cold temperature; the diameter of the heated area is $15d_0$.

Figure 5 illustrates the evolution of a single plasma flow. We see that the simulation reproduces the experimentally observed flow quite well. As is clearly found in the experiment, it is collimated along the x axis, which is a result of the action of self-generated toroidal magnetic fields. In addition, similarly to the experiment, filamentation of the magnetic field B_z and consequently of the currents (not shown here) is observed in the plasma flow. This filamentation does not have a significant impact on the stagnation phenomenon under discussion. The mechanisms behind the emergence of this filamentation were partially discussed in Ref. 64 and will be discussed in detail in our upcoming paper.

Figure 6 illustrates the evolution of the interaction between two counterstreaming plasma flows. Already at the first stage $t = 3.75t_0$ presented here, the electron fluid advects the toroidal magnetic field (B_z in 2D), initially generated near the target, into the interaction region [Fig. 6(b)]. At $t = 8.75t_0$, the bulk plasma from both targets reaches the central plane $x = 10d_0$ [Fig. 6(c)]; as a result of the

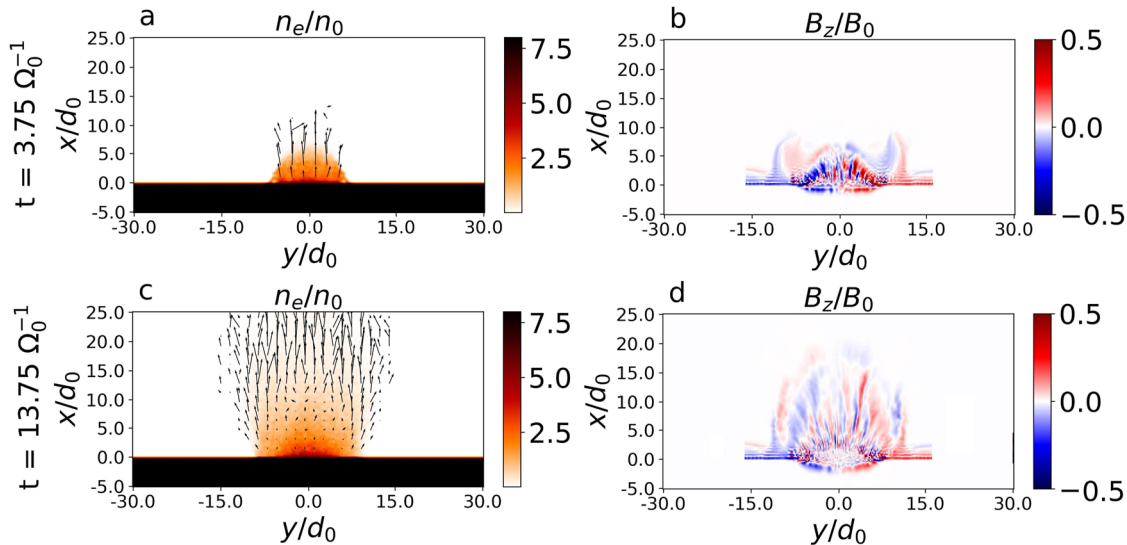


FIG. 5. Results of hybrid code AKA52 2D3V simulations for a single plasma flow. Panels (a) and (c) show two-dimensional profiles of electron density of plasma at times $3.75t_0$ and $13.75t_0$, respectively. Arrows indicate directions of ion motion, and arrow length demonstrates relative magnitude of ion velocity. Panels (b) and (d) present two-dimensional profiles of azimuthal magnetic field (for 2D modeling B_z) at times $3.75t_0$ and $13.75t_0$, respectively. Spatial scales are normalized to ion inertial length $d_0 = c/\omega_{pi} = 19 \mu\text{m}$, magnetic field is normalized to $B_0 \sim 100$ T, density is set to $n_0 = 2.5 \times 10^{20} \text{ cm}^{-3}$, and timescales are normalized to inverse ion cyclotron frequency $t_0 = \Omega_0^{-1} = cM_i/q_i B_0 \sim 2.3$ ns.

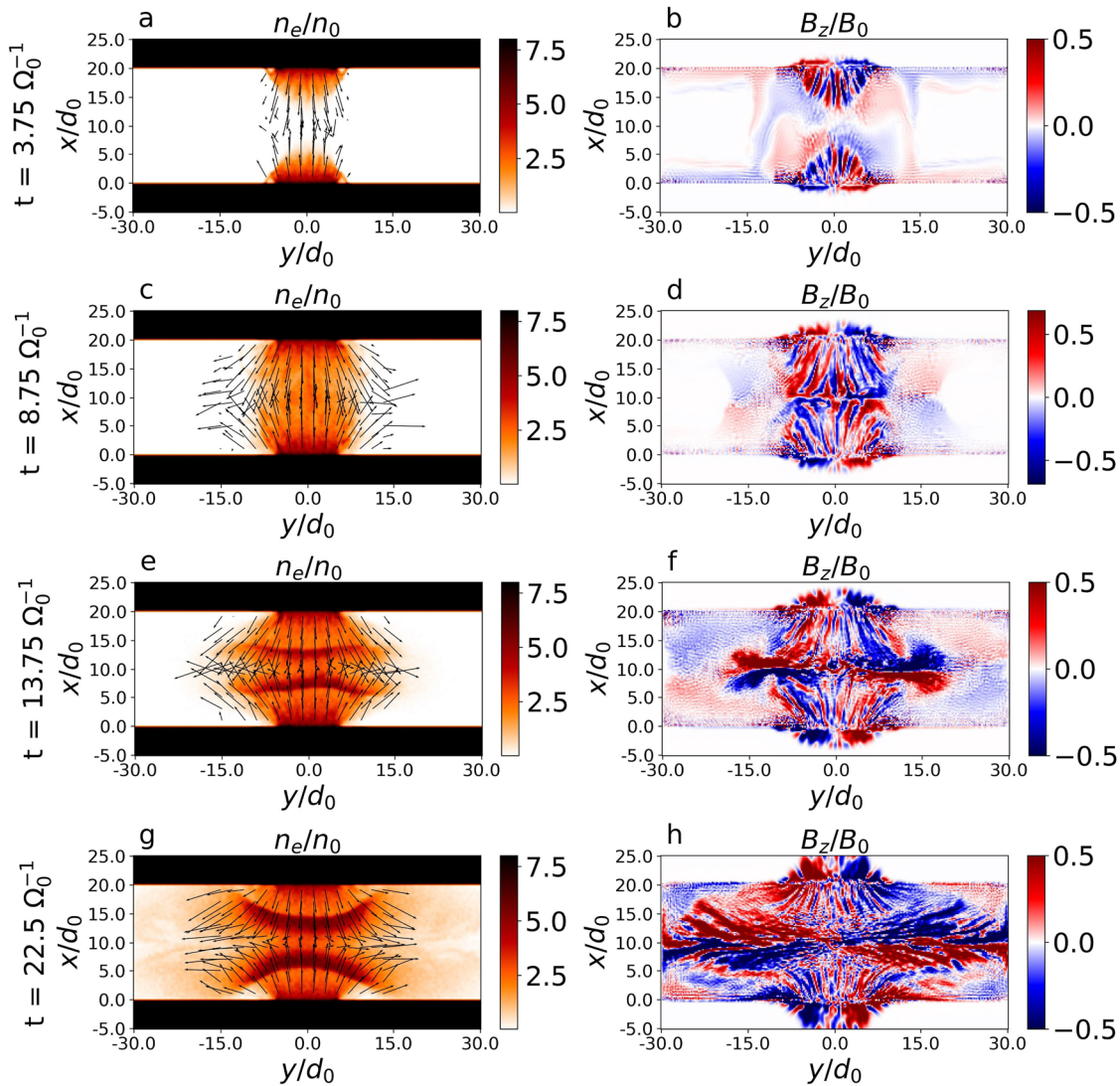


FIG. 6. Results of hybrid code AKA52 2D3V simulations for two counterstreaming plasma flows. Panels (a), (c), (e), and (g) show two-dimensional profiles of electron density of plasma at times $3.75t_0$, $8.75t_0$, $13.75t_0$, and $22.5t_0$, respectively. Arrows indicate directions of ion motion, and arrow length demonstrates relative magnitude of ion velocity. Panels (b), (d), (f), and (h) present two-dimensional profiles of azimuthal magnetic field (for 2D modeling B_z) at times $3.75t_0$, $8.75t_0$, $13.75t_0$, and $22.5t_0$, respectively. Spatial scales are normalized to ion inertial length $d_0 = c/\omega_{pi} = 19 \mu\text{m}$, magnetic field is normalized to $B_0 \sim 100 \text{ T}$, density is set to $n_0 = 2.5 \times 10^{20} \text{ cm}^{-3}$, and timescales are normalized to the inverse ion cyclotron frequency $t_0 = \Omega_0^{-1} = cM_i/q_iB_0 \sim 2.3 \text{ ns}$.

advection, the toroidal magnetic field in this region is compressed and increased [Fig. 6(d)]. Further strengthening of the field [see Fig. 6(f) at $t = 13.75t_0$] leads to redirection of the plasma in the radial direction, as demonstrated by the arrows indicating the ion particle motion in Fig. 6(e). Current layers maintaining such a magnetic field structure are formed in the central plane (not shown). In Fig. 6(g), stagnation of the plasma flows and their subsequent redirection in the radial (y in 2D) direction is observed. Since the magnetic field frozen into the plasma is advected with the flows, the magnetic layer also expands in the radial direction [Fig. 6(h)]. As in the

experiment, regions with density jumps are observed [Fig. 6(g)], and the topology of the flows and magnetic fields matches the topology of the experimentally observed plasma [Figs. 3(g) and 3(h)].

The results of these numerical simulations of the experiment demonstrate that the self-generated toroidal magnetic field is a crucial component of the interaction of the counterstreaming plasma flows. In hybrid numerical calculations, the magnetic field is generated by the electron fluid according to the Biermann battery mechanism $\sim \nabla T_e \times \nabla n_e$.^{15,91} The temperature and density gradients are largest in the plasma generation region; therefore, the magnetic

field is predominantly generated in the vicinity of the target and is advected into the interaction region by two counterstreaming flows. The Reynolds number $Re = LV/\nu$ and the magnetic Reynolds number $Re_M = LV/\eta$ significantly exceed unity (see Table II), indicating that the magnetic field is substantially frozen in the plasma flows.

V. DISCUSSION

As mentioned in Sec. I, magnetic stagnation of counterpropagating plasma flows generated by nanosecond laser beams has been investigated in Refs. 20, 21, 45, and 46. Here, we discuss in detail how our approach using femtosecond relativistic-intensity pulses differs from these previous investigations. In Ref. 20, the plasma flows expanded into an ambient medium magnetized by an 8 T external magnetic field with an X-point geometry in the interaction region. Crucially, no magnetic stagnation occurred without the ambient plasma, which served to confine the external magnetic field within the interaction zone. In its absence, the plasma flows simply expelled the magnetic field and interpenetrated each other. While our experiment exhibits a somewhat different field topology from the X-type configuration in Ref. 20, the fundamental distinction lies in the origin of the magnetic stagnation: our magnetic fields are entirely self-generated and therefore frozen into the plasma flows, being advected into the interaction region by the counterstreaming plasmas.

In Ref. 45, magnetic stagnation of the electron component was observed under the influence of self-generated toroidal magnetic fields. Using a model identical to the analytical approach from Ref. 22, it was demonstrated in Ref. 45 that the self-generated Biermann magnetic field is advected by plasma flows and amplified in the collision region to values of about 10 T, which led to the observation of caustics in the proton images. However, it was also indicated that the observed amplified magnetic field was completely insufficient to magnetize and confine ions with characteristic velocities of $V \sim 1000$ km/s. In other words, the magnetic field pressure in the interaction region was significantly lower than the plasma ram pressure, and thus could not restrain the energetic plasma flows, which penetrated through each other. The same interaction regime ($M_A \gg 1$) was investigated in Ref. 21.

Herein lies the distinctive advantage provided by the use of relativistic-intensity femtosecond laser pulses in our study. These pulses produce fountain-type magnetic fields embedded in the plasma flows, which our Faraday measurements confirm reach strengths exceeding 30 T on nanosecond timescales. In contrast to previous studies, the plasma flow in our case has a lower velocity of about 100 km/s. Simple estimates show that a magnetic field capable of affecting the directed ion motion of the plasma ($B^2/8\pi \sim \rho V^2/2$) must have a magnitude of the order of 20–30 T. In our hybrid simulations, such a strong magnetic field is predominantly observed in the narrow layer located in the central plane between the two targets. However, our experimental Faraday polarimetry data indicate that the area containing a strong magnetic field of ~ 30 T occupies a larger volume (see Fig. 2 in the [supplementary material](#)). Such conditions, where the pressure of self-generated magnetic fields can dominate the plasma's dynamic pressure ($M_A \sim 1$) and thus globally redirect flow dynamics, are exceptionally difficult to achieve with nanosecond laser systems.

It is worth noting that in the simulations, the total (integrated over the box) energy of the magnetic field throughout the plasma region is significantly lower than the kinetic energy of the plasma flows. The simulations indicate that the Biermann magnetic field generated in the vicinity of the target and subsequently advected and intensified in the interaction region is sufficient to redirect the plasma. Thus, the effect of stagnation and redirection of the plasma flows is based on the redistribution of the energy density of the magnetic field in a thin layer, where the magnetic field is intensified and compressed by the two counterpropagating flows. Certainly, the conditions and processes in the experiment differ somewhat from those implemented in the numerical simulation. First, the modeling does not account for the extremely complex ablation processes occurring during relativistic-intensity laser irradiation, such as ionization, acceleration of electrons to relativistic velocities, or the intricate dynamics and relaxation of the nonthermal electron fraction. A proper description of these processes would require a comprehensive and computationally intensive approach. Some attempts to model ablation and target heating on timescales of several tens of picoseconds under similar conditions have been made in Refs. 48 and 49, but extension of these models to the nanosecond timescales relevant to our study remains unachievable today to the best of our knowledge. In our work, we have not aimed to accurately describe the ablation process. Instead, we have configured the ablation operator in the hybrid code to generate, on nanosecond timescales, a plasma flow whose energy characteristics and spatial structure match experimental observations—an approach that adequately captures the post-ablation interaction physics that is central to our study.

Another key difference between experiment and simulation concerns the mechanism of self-generated magnetic field production. In our experiment, where plasma is generated by the action of intense laser radiation, the toroidal magnetic fields can be generated not only by the Biermann battery, but also by the fountain non-thermal energetic electrons. A significant portion of the laser energy during intense femtosecond laser heating is transferred to those energetic electrons.^{48–50} Consequently, fountain fields—as reported in Refs. 54–56—can reach several hundred teslas, substantially exceeding Biermann-generated fields. In the simulation, electrons are treated as a fluid, and self-generated magnetic fields arise solely through the Biermann mechanism, but stronger fountain-origin toroidal fields will undoubtedly not disrupt the effect observed in the simulations; instead, they will lead to a more significant and rapid stagnation of the plasma. We suppose that this is the reason for some discrepancy in the spacing (scales) and timing of plasma stagnation between the experiment and the simulation. It is not feasible to take the fountain magnetic field into account in numerical modeling with a hybrid code. The influence of the fountain magnetic field on stagnation may be determined by PIC modeling, but this would require significantly more computational resources and will be addressed in our future studies.

VI. CONCLUSION

Experiments with counterstreaming flows of laser plasma are of great importance for understanding the nature of many phenomena in astrophysics and plasma physics. We have experimentally observed the stagnation of counterstreaming laser plasma flows

induced by short laser pulses with an intensity $I \sim 2 \times 10^{18}$ W/cm². We have shown by hybrid modeling that the stagnation of the plasma is associated with the advection of a toroidal magnetic field generated by the plasma near the target. The advection of the magnetic field by the plasma into the central region leads to compression and intensification of the magnetic field in the interaction area of the counterstreaming flows. Simulations have demonstrated an enhancement of the magnetic field in the central region by more than ten times compared with the field observed during the expansion of a single flow, which is in good agreement with the analytical model presented in Ref. 22. The intensified magnetic field results in redirection of the plasma flow in the radial direction, which is confirmed by the topology of the plasma, observed both in the experiment and the simulations.

SUPPLEMENTARY MATERIAL

See the [supplementary material](#) for a detailed setup of the interferometry and Faraday rotation diagnostics, as well as for a characteristic distribution of the depolarization angle obtained in the plasma.

ACKNOWLEDGMENTS

The research is supported by Russian Science Foundation Grant No. 24-62-00032.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

R. S. Zemskov: Conceptualization (equal); Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Software (equal); Validation (equal); Visualization (equal); Writing – original draft (equal); Writing – review & editing (equal). **S. E. Perevalov:** Conceptualization (equal); Formal analysis (equal); Investigation (equal); Methodology (equal). **A. V. Kotov:** Formal analysis (equal); Investigation (equal); Methodology (equal); Validation (equal). **A. A. Murzanev:** Data curation (equal); Formal analysis (equal); Investigation (equal); Methodology (equal); Visualization (equal). **A. I. Korytin:** Formal analysis (equal); Investigation (equal); Methodology (equal). **K. F. Burdonov:** Formal analysis (equal). **V. N. Ginzburg:** Resources (supporting). **A. A. Kochetkov:** Resources (supporting). **S. E. Stukachev:** Resources (supporting). **I. V. Yakovlev:** Resources (supporting). **I. A. Shaikin:** Resources (supporting). **A. A. Kuzmin:** Resources (supporting). **E. V. Derishev:** Conceptualization (equal); Validation (equal); Writing – review & editing (equal). **A. V. Korzhimanov:** Conceptualization (equal); Methodology (equal); Writing – review & editing (equal). **A. A. Soloviev:** Conceptualization (equal); Investigation (equal); Methodology (equal); Project administration (equal); Supervision (equal). **A. A. Shaykin:** Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal). **A. N. Stepanov:** Conceptualization (equal); Formal analysis

(equal); Investigation (equal); Methodology (equal); Project administration (equal); Supervision (equal); Writing – review & editing (equal). **M. V. Starodubtsev:** Conceptualization (equal); Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal); Writing – review & editing (equal). **E. A. Khazanov:** Funding acquisition (equal); Project administration (equal); Resources (equal); Supervision (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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