Visualizing Three-Dimensional Reconnection in a Colliding Laser Plasma Experiment

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Abstract—Most processes in nature where magnetic field line reconnection occurs are thought to be 3-D and time dependent. These include solar flares and sites in the Earth's and in Jupiter's magnetotails, as well as astronomical objects such as pulsars and colliding galaxies. We present experimental evidence for a fully 3-D reconnection, which occurs when two dense plasmas collide in a background-magnetized plasma.

Index Terms—Laser ablation, magnetic fields, plasmas, plasma waves, scientific visualization.

EXPERIMENTS on the dense laser-produced plasmas (lpp) expanding into a background magnetoplasma trigger a rich variety of phenomena including the formation of magnetic bubbles [1] and the generation of Alfvén waves [2], [3]. The lpp emit streams of field-aligned electrons, which, in turn, generate return currents in the background plasma. Within several microseconds, these become the current systems of shear Alfvén waves. The currents merge and split in space and time and are peppered with regions in which magnetic fields that point in opposite directions are forced together. The data indicate that they are likely the sites of magnetic field-line reconnection.

The experimental sequence is that a background He plasma ($n = 2 \times 10^{12}$ cm^{-3}, $B_0 = 600$ G) is generated in a dc discharge to make a plasma column that is 18 m in length and 60 cm in diameter. Two 1.5-J Nd-YAG lasers strike two carbon targets [Fig. 1(a)] placed in the center of the column. Plasma jets radially move outward from the target surfaces, which are across the background magnetic field, and collide in the center of the machine. Initially (the first microsecond), when two plasma jets form and collide, they are prone to interchange [4] and two-stream or other instabilities, which are currently under investigation. The second stage (2–30 μs) involves the generation of Alfvén waves, which move along the background magnetic field. Their morphology is complex [5] and must be visualized with the most powerful techniques available.

Wave magnetic field data were acquired by using three-axis (3-mm diameter) differentially wound magnetic field pickup loops connected to digitizers (14 b, 10 ns/sample, 16 384 timesteps). Computer-controlled probe drives moved the probe on 16 transverse planes (29 × 29 cm, 1-cm intervals) that are axially separated by 32 cm. The probe signals were integrated, and the field lines were calculated by using a Runge–Kutta scheme. Fig. 1(b) shows a head-on view of magnetic field lines, showing the position and chamber walls. The circular ports are spaced 32 cm apart along the device axis. The calculation of the magnetic field does not include the constant background field, which would highly elongate the field lines. The field lines in Fig. 1 were started on a transverse plane that is 86.5 cm from the targets and are followed for 1200 spatial steps of 0.2 cm. Fig. 1(c) shows a close-up view of the wave field, which has been slightly tilted to show the morphology. The two "O" structures indicate the position of current channels, and the "X"-type region in the center appears to be a magnetic null point. The wave moves along the device axis at the Alfvén speed $V_A = 3.6 \times 10^7$ cm/s in He. The inspection of the temporal evolution shows the field lines merge and reconnect as the wave goes by. It is clearly shown in Fig. 1(c) that the magnetic field in the null point is not confined to a plane but is fully 3-D. The inductive electric field $\vec{E}_L = -\partial \vec{A}/\partial t$ has been derived from the vector potential which, in turn, is evaluated from the currents. The inductive field that is parallel to B is as large as 2 V/m, which represents the changes in time, and is largest inside both the reconnection region and the current channels. The images of the field lines are best appreciated in 3-D stereo pairs and movies that have been generated in our laboratory. Reconnection sites, such as the one shown in Fig. 1, pepper the volume in which the data was acquired. If streamlines were generated on multiple planes, the resulting figure would be too complicated to interpret. We stress that this is a reconnection mediated by the current systems of Alfvén waves. It is the motion of these currents/waves that force magnetic field lines together and trigger local reconnection.

REFERENCES

[1] M. VanZeeland and W. Gekelman, "Laser–plasma diamagnetism in the presence of an ambient magnetized plasma," *Phys. Plasmas*, vol. 11, no. 1, pp. 320–323, Jan. 2004.

[2] W. Gekelman, M. VanZeeland, S. Vincena, and P. Pribyl, "Experiments and observations of Alfvén waves caused by rapidly expanding plasmas in the laboratory and in space," *J. Geophys. Res.*, vol. 108, no. A7, 2003. 81-8-10.

[3] M. VanZeeland, W. Gekelman, S. Vincena, and J. Maggs, "Currents and shear Alfvén wave radiation generated by an exploding laser-produced plasma-perpendicular incidence," *Phys. Plasmas*, vol. 10, no. 5, pp. 1243–1252, May 2003.

[4] B. H. Ripin *et al.*, "Large Larmor radius interchange instability," *Phys. Rev. Lett.*, vol. 59, no. 20, pp. 2299–2302, Nov. 1987.

[5] W. Gekelman, A. Collette, and S. Vincena, "Three-dimensional current systems generated by plasmas colliding in a background magnetoplasma," *Phys. Plasmas*, vol. 14, no. 6, p. 062 109, Jun. 2007.
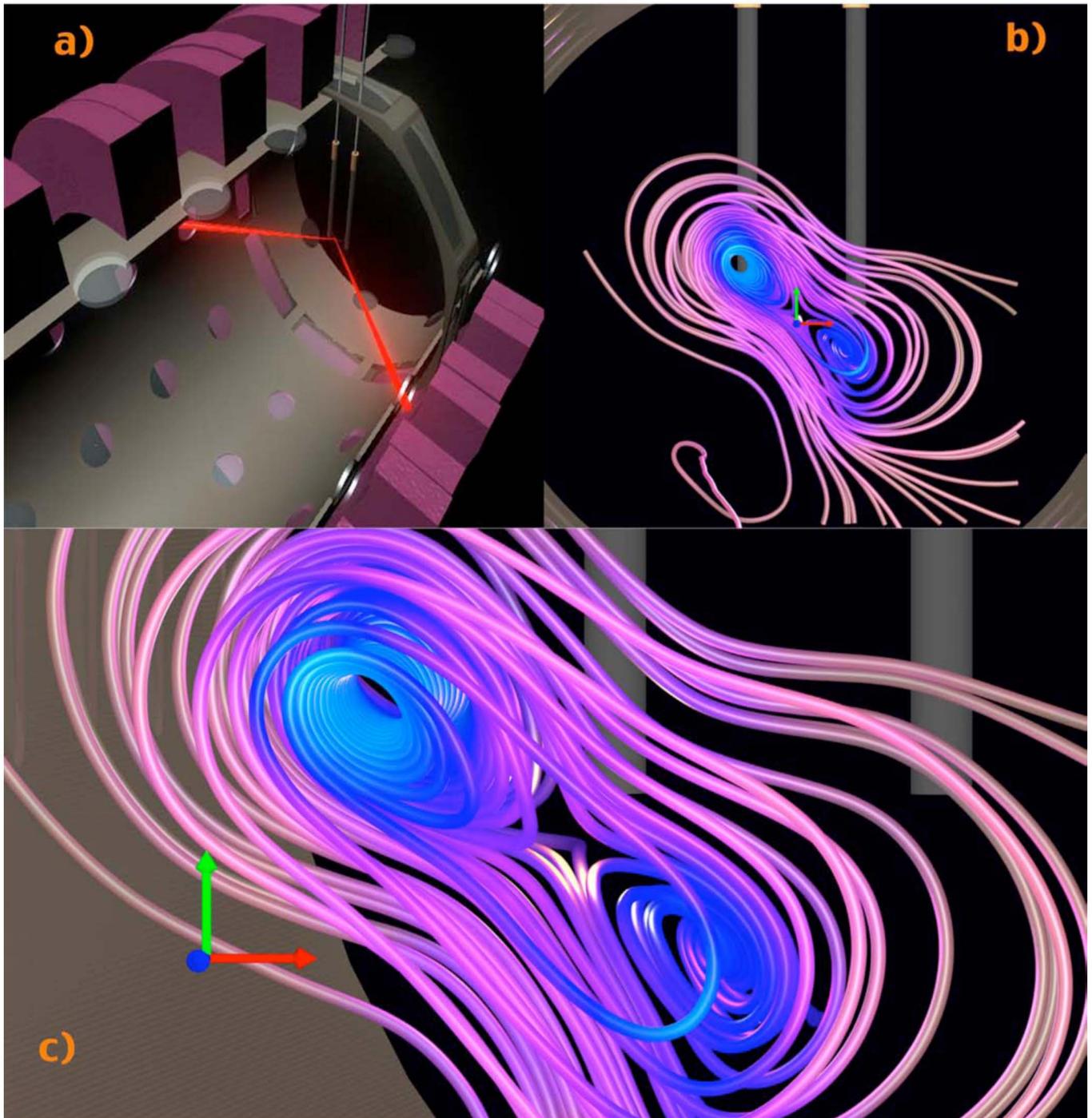
Fig. 1.   (a) Schematic of two targets spaced 6.5 cm apart (center to center), indicating where the (shown in red) laser beams strike them. The laser beams come in from opposite ports on the side of the machine. The axial distance between the round or rectangular ports is 32 cm. The walls of the vacuum chamber are drawn in brown. Everything is to scale. The carbon targets are 12.5 m from the plasma source, which is out of the picture on the lower left. The other end of the plasma device is 4.1 m "above" the targets. The background He plasma is not shown. The axial background magnetic field points "downward." (b) View along the magnetic axis of magnetic field lines at time $\tau = 5.1$ μs after the targets are struck. The field lines are drawn, emanating from 16 positions on a plane, which is 86.5 cm from the targets, and are followed for 1200 steps. The blue arrow on the axis marker points in the z-direction that is of the background magnetic field. (c) Close-up of the magnetic field lines. The reconnection region is illuminated with "white light." The axis marker is located at $\delta z = 192$ cm from the targets which are shown in the rear. The directions that are transverse to the background field are in green (y) and red (x). The background 600-G field is in the (blue marker) z-direction. The (shown in blue) wave magnetic field that is near the current channels is of 0.5-G order.