PERSPECTIVES: PLASMA PHYSICS

Laser-Generated Jets and Megagauss Magnetic Fields

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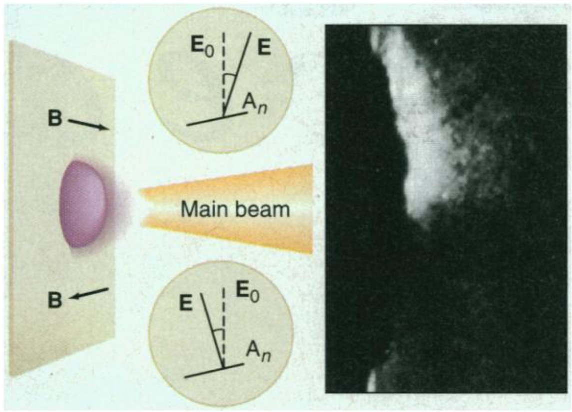
When focused to very high intensities (above 10^{18} W/cm^2), laser pulses possess enormous electric and magnetic fields that can force the electrons of a plasma to oscillate at relativistic velocities. These intense laser-plasma interactions can also produce very high current electron jets. The combination of the relativistic oscillation and the high-current jetting can produce within the plasma magnetic fields of several million gauss. This physics research topic has recently become popular because of its potential use in a laser fusion concept (*1*) called the "fast ignitor."

High-peak laser powers can now be generated with moderate-sized lasers by means of a technique called chirped pulse amplification (*2*), in which a few picoseconds laser pulse from an oscillator is stretched out to a few nanoseconds with a grating. The light is amplified and then recompressed in a second grating. Because the final pulse duration is so short, even a few joules of laser energy can produce a large peak power and focal intensity.

Some recent experiments, reported by Borghesi *et al.* (*3*, *4*) demonstrate that megagauss fields have been produced by laser interactions. The authors used the Vulcan neodymium-glass laser, in the chirped pulse mode, at the Rutherford Appleton Laboratories to produce the intense fields. About 10 J with a 1- to 3-ps duration was focused to a 10- to 15-μm-diameter focal spot, producing an incident intensity of a few times 10^{18} W/cm^2. The light was focused onto both a preionized plasma (*3*) and a solid target (*4*). Solenoidal megagauss magnetic fields, in an azimuthal direction about the laser beam, were observed in both cases.

This is a substantially higher field than observed in the earliest experiments. Large (kilogauss) magnetic fields in laser-produced plasmas were first observed at the Naval Research Laboratory (*5*). The fields are "self-generated" or "spontaneous"—that is, created directly by the laser-plasma interaction. The (thermoelectric) source depends on electron pressure gradients. It is in the direction of the cross product ($\nabla T \times \nabla n$) of the gradients of electron temperature T and density n. Because T normally increases toward the laser axis and n increases into the target, the thermoelectric magnetic fields are azimuthally right handed about the incident laser axis.

These thermoelectrically generated magnetic fields were seen by Borghesi *et al.* for both the solid targets and the preionized plasma targets. However, for the plasma targets (*3*), they also saw magnetic fields with the opposite direction (left handed about the laser axis). This reversed solenoid was the result of time-averaged forces on the electrons due to the intense, high-frequency laser fields.



Big fields. Polarimetry configuration used to measure the magnetic fields (see text for discussion of details). The light pattern shown on the right is due to an azimuthal magnetic field (**B**, into page at top, out of page at bottom) generated by the thermoelectric mechanism. [Adapted from (*5*)]

The ponderomotive electron pressure, which is due to high-frequency electron oscillations in the laser fields (enhanced by relativistic effects), can produce a low-density plasma channel within which the laser pulse can propagate. This phenomenon is discussed in another paper by the Imperial College group (*6*). Inside the channel, the directed laser field momentum is delivered to the electrons and (through resistive drag) to the ions and plasma. A large quasi-steady electron current is then produced into the target, corresponding to a conventional current density **J** back toward the laser. The laser-driven magnetic field **B** produced by this current is right handed about **J** or oppositely directed to the thermoelectric fields. The enormous magnetic fields (hundreds of megagauss) expected to be created by this mechanism will be difficult to observe directly because of the highly localized region, the strong plasma emission, and the refraction of the probing pulse.

The magnetic fields are typically measured with polarimetry, as illustrated in the figure. [This is discussed more fully elsewhere (*5*).] A plane-polarized (probing) laser pulse, propagating along a magnetic field **B**, undergoes a polarization (Faraday) rotation that is right or left handed for waves propagating parallel or antiparallel to **B**, respectively. The magnitude of the rotation is proportional to the electron density times the magnetic field component along the path. The incident polarization $\mathbf{E}_0$ is shown as vertical, with the beam propagating out of the page. The polarization analyzer axis $\mathbf{A}_n$ is a few degrees from cross polarized. A simple polarigram (thermoelectric fields only) is shown at the right. At the top, where the laser propagates antiparallel to **B**, the rotated field **E** is closer than $\mathbf{E}_0$ to the analyzer axis and lets more probe light through. At the bottom, with propagation parallel to **B**, **E** is closer to the analyzer normal, and less probing light is transmitted.

The laser-driven magnetic field exerts a force on the current-carrying plasma, which is in the $\mathbf{J} \times \mathbf{B}$ direction. It is thus directed inward and has a confining or pinching effect on the plasma. The high-density jet that was observed in self-emission and interferometry with solid targets (*4*) is likely due to this effect.

To evaluate ultraintense laser applications, such as the fast ignitor scheme (*1*) for laser fusion, it will be necessary to understand and control unusual laser-plasma interactions. The experiments carried out at Rutherford (*3*, *4*, *6*) are an important step in understanding such phenomena as the magnetic fields, laser channeling, and jet formation, which will be part of these applications.

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