

The effect of high intensity laser propagation instabilities on channel formation in underdense plasmas

Z. Najmudin, K. Krushelnick,^{a)} and M. Tatarakis

The Blackett Laboratory, Imperial College of Science, Technology & Medicine, London SW7 2BZ, United Kingdom

E. L. Clark

*The Blackett Laboratory, Imperial College of Science, Technology & Medicine, London SW7 2BZ, United Kingdom
and Radiation Physics Department, AWE plc, Aldermaston, Reading RG7 4PR, United Kingdom*

C. N. Danson

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, United Kingdom

V. Malka

Laboratoire pour l'Utilisation des Lasers Intenses (LULI) Unité mixte n7605 CNRS - CEA, Ecole Polytechnique, Université Pierre et Marie Curie, Palaiseau, France

D. Neely

*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, United Kingdom
and Radiation Physics Department, AWE plc, Aldermaston, Reading RG7 4PR, United Kingdom*

M. I. K. Santala

*The Blackett Laboratory, Imperial College of Science, Technology & Medicine, London SW7 2BZ, United Kingdom
and Department of Engineering Physics and Mathematics, Helsinki University of Technology, P.O. Box 2200, 02015 HUT, Finland*

A. E. Dangor

The Blackett Laboratory, Imperial College of Science, Technology & Medicine, London SW7 2BZ, United Kingdom

(Received 17 December 2001; accepted 6 November 2002)

Experiments have been performed using high power laser pulses (up to 50 TW) focused into underdense helium plasmas ($n_e \leq 5 \times 10^{19} \text{ cm}^{-3}$). Using shadowgraphy, it is observed that the laser pulse can produce irregular density channels, which exhibit features such as long wavelength hosing and “sausage-like” self-focusing instabilities. This phenomenon is a high intensity effect and the characteristic period of oscillation of these instabilities is typically found to correspond to the time required for ions to move radially out of the region of highest intensity. © 2003 American Institute of Physics. [DOI: 10.1063/1.1534585]

I. INTRODUCTION

The interaction of intense laser pulses with plasmas has recently received much attention both theoretically and experimentally not only because of the inherently interesting physics¹ but also because of the many exciting applications that have been proposed for such beams. These applications include plasma based particle acceleration,^{2–5} and “fast-ignition” of inertially confined fusion pellets.⁶ In these applications it is envisaged that the beam must propagate through long distances of underdense plasma, either in a self-formed or preformed guiding channel. Clearly, the uniformity and stability of the plasma density channel is important for the success of these concepts. Instabilities of these channels, such as “sausaging” (which results in an excessive focusing and defocusing of the laser) and “hosing” (a transverse motion of the channel), would be detrimental to the guiding.

Indeed, the hosing of a laser beam, though conjectured by several authors,^{7–9} has never previously been observed (not only in plasmas but in any nonlinear medium). In this paper, we report observations of the propagation of high intensity laser pulses through underdense plasmas, which may have similarities to the corona of ablated plasma that surrounds the compressed pellet in the fast ignitor scheme. In particular, we observe plasma structures which can only be explained by the presence of these propagation instabilities.

It is well known that in high intensity laser plasma interactions, a laser beam can overcome natural diffractive defocusing and can remain focused via its own nonlinear interaction with the plasma. In particular, the relativistic quiver velocity of electrons in an intense laser field can lead to an increased on-axis index of refraction. This, in conjunction with the reduction of on-axis electron density due to the ponderomotive force of the intense pulse,¹⁰ can give rise to the formation of a self-focusing structure. This allows the propagation distance of the beam to be extended and enables

^{a)}Electronic mail: kmkr@ic.ac.uk

the production of much higher peak intensities than could be achieved by focusing in vacuum.¹¹ A simple treatment, for an idealized Gaussian beam, gives a critical power at which natural diffraction is exactly balanced by self-focusing. This critical power is given by $P_{cr} = 17(n_{cr}/n_e)$ GW, where n_e is the initial plasma density and n_{cr} is the critical density (i.e., $n_{cr} = \epsilon_0 m_e \omega_0^2 / e^2$, for a laser of frequency ω_0). There have been several previous experimental studies which have observed the effects of high intensity self-guiding and the onset of self-focusing at about this power.¹¹⁻¹⁶

Here we present results from experiments which examine the propagation of much higher power laser pulses in underdense plasmas ($P > 10P_{cr}$). Using a transversely propagating probe beam we have used shadowgraphy to study the plasma generated by the passage of a high intensity laser. In these experiments we have observed both laser-hosing and “sausaging”-like propagation instabilities. These measurements were temporally integrated over the duration of a transversely propagating probe pulse (≈ 10 ps), so the formation of such structures must be related to the motion of ions in the laser-produced plasma. The spatial wavelength of the plasma density structures resulting from these propagation instabilities was found to correspond approximately to the time which ions require to leave the focal region of the laser multiplied by the speed of light c . The measurements presented here thus suggest that there is a positive feedback mechanism between such laser propagation instabilities and the ponderomotive expulsion of ions from the region of high laser intensity.

II. SHADOWGRAPHY OF THE INTERACTION

A. Experimental setup and principles of shadowgraphy

These experiments were performed using the chirped pulse amplification beam of the VULCAN laser system at the Rutherford Appleton Laboratory. This laser produces pulses having an energy of up to 40 J and a duration of 0.9–2.0 ps at a wavelength of 1.054 μm (Nd:glass). The laser pulse was focused into a gas jet target (4 mm nozzle diameter) using an $f4$ off-axis parabolic mirror. In vacuum, the laser pulse could be focused to a 10- μm -diam spot (Rayleigh length $< 100 \mu\text{m}$). The peak intensity was consequently up to about $1 \times 10^{19} \text{ W cm}^{-2}$. When helium was used as the target gas the plasma was completely ionized and had an electron density which could be varied up to $5 \times 10^{19} \text{ cm}^{-3}$ by adjusting the backing gas pressure for the valve.

In such high intensity laser-plasma interactions, it is found that shortly after the passage of the laser pulse a density depleted channel is generated in the plasma.^{12,13} The generation of this channel can be explained by the “Coulomb explosion” mechanism.¹⁷ Essentially the space charge force generated by the radial displacement of electrons balances the ponderomotive pressure of the laser pulse and ions within the radius of expulsion of electrons are accelerated by this space charge force for the duration of the laser pulse. These ions retain their momentum and continue to travel radially away from the axis, even after the laser pulse passes,

leaving behind a column of plasma which is depleted in density. The depleted density channel, is found to be remarkably stable over time, being formed only a few picoseconds after the passage of the intense laser pulse, but remaining for tens of picoseconds afterwards. Hence the detection of such a deeply depleted density dip is clear proof of the passage of an intense laser pulse. By studying this density channel, it is possible to make quantitative measurements, not only of the longitudinal extent of the laser propagation, but also of any nonuniformities in its propagation. To study the channel formation, we used shadowgraphy of the laser produced plasma.

For this, a second short-pulse low energy frequency-doubled laser beam was directed orthogonally to the direction of propagation of the channel-forming beam as a probe. The refractive index of a plasma is given by $\eta = (1 - n_e/\gamma n_{cr})^{1/2}$, where n_e/n_{cr} is the ratio of plasma electron density to the critical density and γ is the Lorentz factor of plasma electrons quivering in the electric field of the laser. For a beam traveling in the x direction, the total angular deflection due to gradients in the y direction is given by $\theta \approx \int (\partial \eta / \partial y) \partial x$. Hence the probe beam is deflected away from areas of high density. However, reimaging this deflected light will give an intensity minimum in the image from areas of high density gradients. Since the gradients formed by the plasma channel formation are much steeper than those generated by the plasma creation, it is found that the images obtained using shadowgraphy, which are proportional to the second derivative of the density, are dominated by the channel formed on axis. In these experiments we have found that shadowgrams are particularly well-suited for diagnosing channel formation.

Part of this probe beam was also split after passing through the plasma and used for Moiré deflectometry measurements of the plasma density. Other diagnostics were simultaneously implemented. In particular, the self-emitted light due to Thomson self-scattering was imaged. Forward Raman scattering was also measured and used to diagnose the electron density in the plasma. In addition, the spectra and divergence of electrons accelerated during the interaction by the generation of relativistic plasma waves were also measured.

B. Typical shadowgraphic images

Figure 1 is typical of shadowgrams taken during the experiment, and demonstrates the channel formation observed previously.^{12,13} The focused laser beam forms a wide column of plasma which has a density minimum on axis, produced by expansion of the plasma in response to the ponderomotive force of the high-intensity beam. This density dip is confirmed by Moiré deflectometry. The channel created by the majority of the laser energy is clearly identifiable, by the darkened part of the image. It is noticeable that the channel is more than 1 mm in length, or over 10 Rayleigh lengths. Undoubtedly the majority of the laser energy has been self-focused. This is found to be the typical behavior of the laser pulse whenever the laser power exceeds $10 \times P_{cr}$. The plasma generated by the laser pulse eventually expands out,

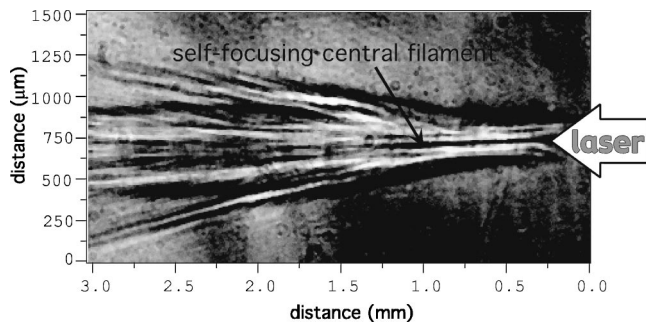


FIG. 1. Shadowgraph taken with $n_e = 2.9 \times 10^{19} \text{ cm}^{-3}$, $\tau_L \approx 0.9 \text{ ps}$, $P/P_{cr} \approx 19$ (image taken approximately 30 ps after main interaction).

and many filaments are observed within this expanding cone of plasma. At lower powers this filamentation is found to be even greater and sometimes filaments are observed to exit the channel at large angles. Such filamentation is due to side-scattering instabilities (ionization induced scattering instabilities¹⁸ and stimulated Raman side scattering¹⁹)—which is evident from our simultaneous measurements of the frequency shift of the side scattered light.

C. Anomalous propagation

Significant shot-to-shot fluctuations are also observed in the characteristics in these density channels. This may be due to variations in the beam profile or phase front, which is typical with such ultrahigh power laser pulses and which may affect filamentation.²⁰ An example of an irregular structure is shown in Fig. 2. In this case, instead of a single straight channel, the width of the plasma and the interior darkened region is found to be modulated. Indeed the whole beam after expanding away from focus, appears to be refocused at a second point about $300 \mu\text{m}$ into the gas jet. After this, the characteristic filamentation of the beam occurs. Modulations of the focus of high intensity laser beam have been inferred with other diagnostics such as imaging of

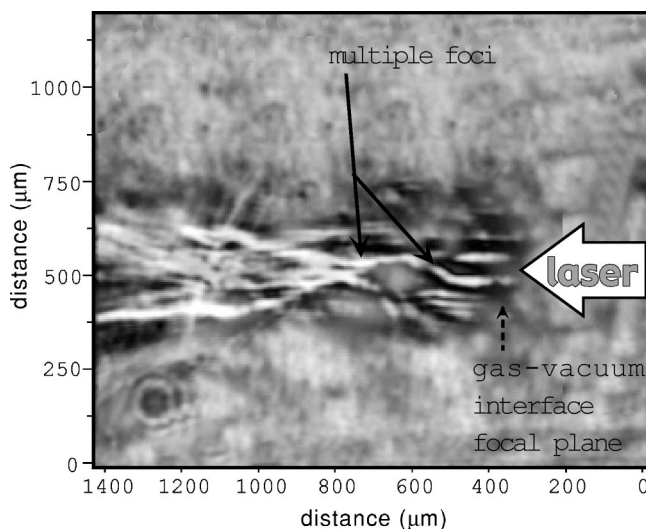


FIG. 2. Shadowgraph taken with $n_e = 3.7 \times 10^{19} \text{ cm}^{-3}$, $\tau_L \approx 2.0 \text{ ps}$, $P/P_{cr} \approx 38$ (image taken approximately 30 ps after main interaction).

Thomson self-scattering.^{21,22} The spatial wavelength of these modulations was observed to be comparable in all of these experiments. Such behavior is attributed to a combination of nonlinear self-focusing and diffractive defocusing.

The “sausaging” density channels observed in Fig. 2 however must be produced by the motion of ions during the passage of the high-intensity laser. This ion motion is generated by the large ponderomotive force of the laser, which expels electrons from the region of high intensity. The resulting space charge force can consequently accelerate ions in the radial direction away from the axis of propagation. After the laser pulse has passed, the electrons return to the focal region on a time scale of $\approx \omega_{pe}^{-1}$ (about 10 fs in these experiments) but the ions retain their initial momentum and continue to move out of the plasma. Hence the observed channel size is indicative of laser waist size at that point. This description¹³ is supported by direct imaging of the expelled high-energy ions.¹¹ Clearly, the critical time scale for ion motion to affect the propagation of the intense laser pulse is that required for an ion to leave the focal region (dependent on the laser intensity via the ponderomotive force) rather than the ion plasma period (where the ion plasma frequency is given by: $\omega_{pi} = \sqrt{m_e/m_i} \omega_{pe}$). The ponderomotive force on these ions in the relativistic case is just given by $F_p = Zm_e c^2 \nabla(1 + a^2/2)^{1/2}$.¹¹ So the time taken for nonrelativistic ions to leave the focus (of radius r_0) is given approximately by the time,

$$\tau \approx \left[2Z \frac{m_e}{M_i} \frac{c^2}{r_0^2} \left(1 + \frac{a^2}{2} \right)^{1/2} \right]^{-1/2}, \quad (1)$$

where a is the normalized vector potential and r_0 is the laser focal spot radius. Since these ions move relatively slowly in response to the ponderomotive force of the laser, the intrinsic spatial scale length of this motion will likely provide positive feedback to laser propagation instabilities which have a similar length scale. Thus, when considering the dynamics of the interaction of the laser pulse with the plasma a spatial scale length for ion motion of $l = \tau c$ becomes important. For the parameters of our experiment this scale length is on the order of $250 \mu\text{m}$, which is similar to the scale length of the sausaging observed in Fig. 2. Note that this distance does not necessarily correspond to the self-focusing distance of the laser pulse but rather to the minimum length at which non-uniformities in the channel will tend to occur because of such self-focusing, i.e., the minimum time which ions can respond to changes in laser intensity. The effects of higher frequency intensity variations would be “washed-out” or time-averaged to zero because of the slow ion response. At lower intensity the effects of low frequency nonuniformities would also be time-averaged to zero since the ions would remain in the focal region throughout the duration of the laser pulse—and not respond to laser propagation instabilities.

D. Long wavelength hosing and ion motion

Figure 3 shows another shadowgraph exhibiting a long propagating central filament (again over 10 Rayleigh lengths). Before entering the gas jet the plasma density chan-

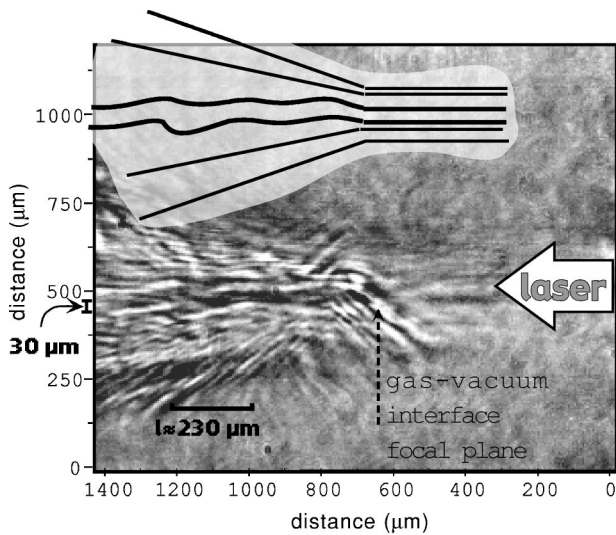


FIG. 3. Shadowgraph taken with $n_e = 2.3 \times 10^{19} \text{ cm}^{-3}$, $\tau_L \approx 2.0 \text{ ps}$, $P/P_{cr} \approx 14$. Above is a delineated schematic which shows extent of plasma due to untrapped filaments (thin lines) and the central channel generated by the high-intensity laser (thick lines), which exhibits hosing (image taken approximately 30 ps after main interaction).

nel generated in the low-density gas outside the supersonic jet of the gas-jet has straight walls. However, after crossing the boundary into the high-density region, the plasma channel forms a transverse structure which oscillates either side of the direction of propagation, and which has a wavelength of about $230 \mu\text{m}$. The ‘‘hosing’’ motion grows slightly as the pulse propagates.

Laser hosing in a plasma has been predicted⁷ however, these theories have only considered the interaction of a laser pulse with the large amplitude plasma wave generated by the pulse (via forward Raman scattering and the self-modulation instability), as well as the motion of the laser pulse in a precreated guiding channel. In all cases, the primary wavelength of the oscillation is predicted to be that of the plasma wave, $k_p \approx k_0(\omega_p/\omega_0)$, which in our experiments corresponds to $\lambda_p \approx 7 \mu\text{m}$. This is about the resolution of our diagnostics in this experiment, and it should be noted that no self-focusing or hosing structures were observed at spatial wavelengths shorter than about $200 \mu\text{m}$.

However recently, Duda *et al.*⁹ have considered a fully relativistic treatment of the electron response to a laser pulse, and find that hosing at longer wavelengths also has a finite growth rate and may be important in some circumstances. In their simulations, it was found that at later times, the propagation of the laser pulse can in fact become dominated by this long wavelength hosing. The dispersion relation for this instability is given by⁹

$$\bar{\omega}^2(\bar{\omega} - \bar{k})^2 - (\bar{\omega}^2(P/P_{cr})/\bar{x}_R^2) - (\bar{\omega} - \bar{k})^2 = 0, \quad (2)$$

where $\bar{k} = k/k_{pe}$, $\bar{\omega} = \omega/\omega_{pe}$, and $\bar{x}_R = x_R * k_{pe}$ is the normalized Rayleigh length x_R . The solutions for $\omega(k)$ of this equation consist of a real oscillatory term and an imaginary term which constitutes the growth rate of the instability. This growth rate is plotted versus wavelength of the hosing instability for $P = P_{cr}$ and $P = 30P_{cr}$ in Fig. 4(a). The peak of

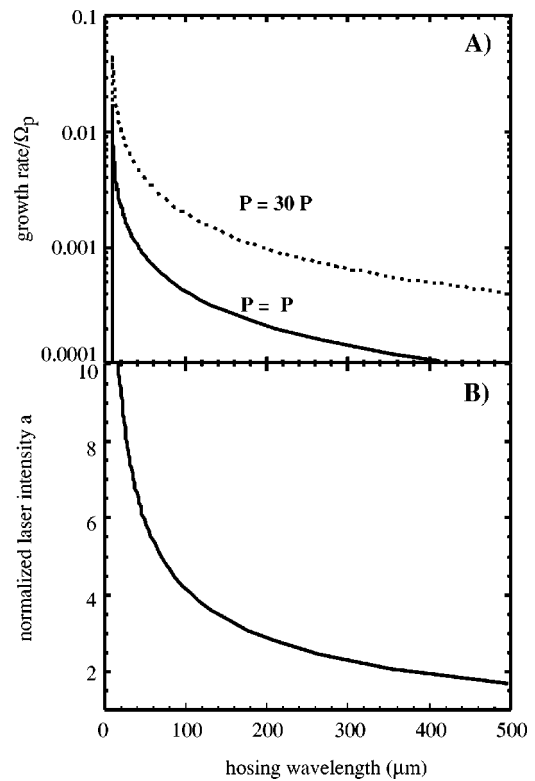


FIG. 4. (a) Plot of growth rate of hosing instability vs wavelength (at $n_e = 10^{19} \text{ cm}^{-3}$ for two different laser powers). (b) Plot of intensity required for ion ejection time to be equivalent to the hosing wavelength.

the growth rate occurs at the plasma wavelength ($2\pi c/\omega_{pe}$), but is clearly significant at longer wavelengths as well. The transverse amplitude of the wave packet displacement should be easily observable for the resolution of the diagnostics in these experiments and grows like $\sim \exp[(P/P_{cr})^{1/2}(k/k_p)^{1/2}(\tau/\tau_R)]$.⁹

It remains unclear theoretically why the long-wavelength modes dominate in the particle-in-cell (PIC) simulation (i.e., why the shorter wavelength hosing with higher growth rates saturates).

This long wavelength instability is difficult to directly observe experimentally, since the hosing motion occurs within the laser pulse, which is traveling through the plasma at about the speed of light. But because of the oscillatory motion of the laser pulse centroid, the generation of plasma waves will be affected and this results in the production of accelerated electrons at large angles to the axis of laser propagation. This can explain recent results which have shown a rapid increase in divergence of the generated electron beam with increasing electron density.²³

However, if ion motion is considered, this instability can also account for the spatially oscillating plasma density channel observed in our experiments. In Ref. 9 the motion of ions was considered for the high density situation and it was suggested that the presence of ions may contribute a stabilizing force on this instability at low laser intensities but might in fact enhance hosing at very high intensities.

Observation of this hosing instability in our experiment, i.e., in the density depression left in the wake of the high

intensity laser pulse, requires that the wavelength of the hosing instability is greater than the average time necessary for an ion to move out of the focal region, as given by (1), times c (in our case $\approx 250 \mu\text{m}$). If this criterion is satisfied, the trailing part of the laser pulse will then see both an electron and an ion density perturbation in the plasma which could reinforce any transverse displacement of the laser light. This would consequently produce a disturbed "track" in the plasma after passage of the laser pulse at a spatial wavelength corresponding to the temporal motion of the tail of the laser divided by the propagation speed of the laser through the plasma. Obviously the average time for ion motion in the frame of the laser must also be less than the duration of the laser pulse. This implies a maximum spatial wavelength of $\approx 300 \mu\text{m}$ for a 1 ps duration laser pulse.

The normalized laser intensity, which will eject an ion from the region of the laser for a given hosing wavelength at $n_e = 10^{19} \text{ cm}^{-3}$, is plotted in Fig. 4(b). This constitutes the minimum intensity required for spatial structures of a particular wavelength to be observed in the plasma channel. This criterion is also equivalent to the condition that the period of the oscillatory motion of laser hosing during the laser pulse be less than the average ion ejection time. This is necessary since the spatial wavelength of the observed density perturbations in the plasma is just given by $2\pi c / \text{Re}(\omega_{\text{hose}}(k))$. This condition can therefore also be expressed as $\tau_{\text{ejection}} \cdot \text{Re}(\omega_{\text{hose}}(k)) < 1$.

For the intensities encountered in our experiments, in which a is between 2 and 4, this criterion is met for the observed hosing wavelengths. Hence, at these high intensities it is very likely that ion motion is significant to the development of this long wavelength hosing instability. The minimum hosing wavelength recorded in our experiments was about $200 \mu\text{m}$. This is reasonable as Fig. 4(b) shows that increasing the intensity would not significantly decrease the hosing wavelength.

It is clear however that there is considerable theoretical work to do to clarify the effect of ion motion on the propagation of intense laser pulses in these plasmas.

III. SUMMARY

In conclusion, these measurements constitute the first observations of a self-imposed transverse motion of a laser beam or laser hosing instability in a plasma or, in fact, in any nonlinear medium. It appears that by considering the effect of ion motion with previously published theory on long wavelength hosing instabilities, the observed density perturbations in the laser-produced plasma channels can be ex-

plained. At the higher powers and longer pulse durations required for fast ignitor experiments this instability may clearly have detrimental effects, and it may also increase the emittance of electron beams accelerated in high density laser-produced plasmas. However in fast ignition experiments the use of external guiding techniques for the high intensity ignition pulse (cone-guided ignition²⁴) may be able to avoid such problems.

ACKNOWLEDGMENTS

The authors would like to acknowledge useful discussions with Professor W. Mori and the technical assistance of the VULCAN operations team.

- ¹M. Tatarakis, I. Watts, F. N. Beg *et al.*, *Nature (London)* **415**, 280 (2002).
- ²T. Tajima and J. Dawson, *Phys. Rev. Lett.* **43**, 267 (1979).
- ³P. Sprangle, E. Esarey, A. Ting, and G. Joyce, *Appl. Phys. Lett.* **53**, 2146 (1988).
- ⁴A. Modena, Z. Najmudin, A. E. Dangor *et al.*, *Nature (London)* **377**, 606 (1995).
- ⁵E. Esarey, P. Sprangle, J. Krall, and A. Ting, *IEEE Trans. Plasma Sci.* **24**, 252 (1996), and references therein.
- ⁶M. Tabak, J. Hammer, M. E. Glinsky *et al.*, *Phys. Plasmas* **1**, 1626 (1994).
- ⁷G. Shvets and J. S. Wurtele, *Phys. Rev. Lett.* **73**, 3540 (1994).
- ⁸P. Sprangle, J. Krall, and E. Esarey, *Phys. Rev. Lett.* **73**, 3544 (1994).
- ⁹B. J. Duda, R. G. Hemker, K. C. Tzeng, and W. B. Mori, *Phys. Rev. Lett.* **83**, 1978 (1999).
- ¹⁰G. Sun, E. Ott, Y. C. Lee, and P. Guzdar, *Phys. Fluids* **30**, 526 (1987); A. B. Borisov, A. V. Borovskiy, O. B. Shiryayev *et al.*, *Phys. Rev. A* **45**, 5830 (1992).
- ¹¹K. Krushelnick, E. L. Clark, Z. Najmudin *et al.*, *Phys. Rev. Lett.* **83**, 737 (1999).
- ¹²K. Krushelnick, A. Ting, C. I. Moore, H. R. Burris, E. Esarey, P. Sprangle, and M. Baine, *Phys. Rev. Lett.* **78**, 4047 (1997).
- ¹³G. S. Sarkisov, V. Y. Bychenkov, V. N. Novikov *et al.*, *Phys. Rev. E* **59**, 7042 (1999).
- ¹⁴C. E. Clayton, K. C. Tzeng, D. Gordon *et al.*, *Phys. Rev. Lett.* **81**, 100 (1998).
- ¹⁵P. E. Young, G. Guethlein, S. C. Wilks, J. H. Hammer, W. L. Kruer, and K. G. Estabrook, *Phys. Rev. Lett.* **76**, 3128 (1996).
- ¹⁶R. Kodama, K. Mima, and K. A. Tanaka, *Phys. Plasmas* **8**, 2268 (2001).
- ¹⁷N. H. Burnett and G. D. Enright, *IEEE J. Quantum Electron.* **26**, 1797 (1990).
- ¹⁸T. M. Antonsen and Z. Bian, *Phys. Rev. Lett.* **82**, 3617 (1999).
- ¹⁹C. D. Decker, W. B. Mori, T. Katsouleas, and D. E. Hinkel, *Phys. Plasmas* **3**, 2047 (1996).
- ²⁰D. E. Hinkel, E. A. Williams, R. L. Berger, L. V. Powers, A. B. Langdon, and C. H. Still, *Phys. Plasmas* **5**, 1887 (1998).
- ²¹P. Monot, T. Auguste, P. Gibbon *et al.*, *Phys. Rev. Lett.* **74**, 2953 (1995).
- ²²Z. Najmudin, A. E. Dangor, A. Modena *et al.*, *IEEE Trans. Plasma Sci.* **28**, 1057 (2000); Z. Najmudin, R. Allott, F. Amiranoff *et al.*, *ibid.* **28**, 1084 (2000).
- ²³M. I. K. Santala, Z. Najmudin, E. L. Clark *et al.*, *Phys. Rev. Lett.* **86**, 1227 (2001).
- ²⁴R. Kodama, P. A. Norreys, K. Mima *et al.*, *Nature (London)* **412**, 798 (2001).