ACCELERATOR SCHEMES BASED ON LASERS AND PLASMAS

Ph.Miné, LPNHE Ecole Polytechnique, IN2P3 & CNRS, 91128 Palaiseau, France

Abstract

The three methods proposed to accelerate particles by laser beams focused into plasmas (beat wave, wakefield and self-modulated wakefield) are now well established by several experiments in the world. The measured electric fields are, as predicted, exceeding by several orders of magnitude those used in conventional accelerators. Two other methods using lasers (inverse Cerenkov effect and inverse free electron laser) have been also experimentally validated in recent years. We present a discussion and comparison of the performances and limitations of these actual "proof of principle" experimental results. Laser channeling by plasma, which has been theoretically and experimentally investigated, can increase significantly the interaction length. Future improvements should include not only high energy gain, but also good emittance and low dispersion in energy. Plans for a 1 GeV single accelerating stage prototype are now under active study for the next generation experiments.

1 INTRODUCTION

Laser intensities have increased in the past years to reach the enormous value of $10^{20}W/cm^2$. Peak power are currently exceeding tens of terawatts, and the petawatt is reached. The most spectacular feature is the compatcness of the TW lasers, which fit a tabletop (T^3 are "table top terawatt") thanks to the advent of chirped pulse amplification [1]. The electric field at the focus of such a laser is 300 GV/cm, given by the formula $eE = 30\sqrt{I}GeV/cm$, when the intensity I is expressed in W/cm^2. This has to be compared with the maximum 100 MeV/m given by conventional microwave accelerators. It is interesting also to compare the density of energy contained in the bunch of electrons used in an accelerator to the same quantity contained in the "bunch of photons" of present day lasers. With 10^{11} electrons of 100 GeV in 1 cm focused into a spot of $200 \times 10\mu m^2$, we have $10^5 J.mm^{-3}$. In a shot of a *single* 100 TW laser lasting 0.3 ps focused into $20 \times 20 \times 100\mu m^3$, we have 10 times more. The compactness of the apparatus needed in the two examples is much in favor of the second one.

However, direct use of this huge electric field is not straighforward, since its direction is perpendicular to the propagation of the wave. More generally, the Lawson-Woodward theorem [2, 3] proves that if the interaction length is infinite, in vacuum, if the particle is relativistic, and neglecting non-linear effects, the net acceleration of a charged particle is nul. When one or more of these assumptions are violated, for example in a design where the particle in vacuum escapes the region of high field before the electric field changes sign, it is possible to obtain a considerable energy gain.

Another alternative is to introduce a material medium such as in the inverse Cerenkov accelerator. In any case an optical structure or a gas is needed, and the material damage can be the limiting factor. A theoretical discussion of laser driven acceleration in vacuum can be found in [4].

Plasmas do not suffer this drawback because they are already ionized. In the following we will review the different schemes of currently investigated acceleration techniques using lasers, with emphasis on those where experimental results are available. An overview of plasma-based accelerator concepts can be found in [5].

2 VACUUM ACCELERATION AND INVERSE FREE ELECTRON LASER

The direct acceleration of particles in the focal spot of a laser has been observed experimentally by several groups. Free electrons have been accelerated in vacuum from few tens of keV to MeV energies by a 80 TW subpicosecond laser pulse ($10^{19}W/cm^2$, 300 fs) [6]. Some other designs have been proposed like an axicon lens geometry, as in the inverse Cerenkov accelerator [7], or an open waveguide structure [8]. To our knowledge, no experimental result have been published yet.

Inverse free electron laser (IFEL) is another acceleration scheme using laser in vacuum [9]. It uses a transverse, periodic, magnetic field (the wiggler) and a coaxial propagating electromagnetic field. A beam of relativistic electrons entering this apparatus can gain energy if the resonance parameters are fulfilled: $\lambda = \lambda_0/2\gamma^2(1+1/2K^2)$ where λ is the laser wavelength, γ the electron relativistic factor, and $K = eB\lambda_0/2\pi mc^2$, B and λ_0 are the wiggler field and period. To maintain resonance it is necessary to vary λ_0, B or K with the distance. Acceleration has been observed at Yerevan, at Columbia and at the BNL Accelerator Test Facility (ATF) [10]. At BNL/ATF a maximum of 2.5% $\delta p/p$ was measured with an 40 MeV incoming electron energy, a 10 kG magnetic field and a 1 GW power CO_2 laser [11]. Developments are foreseen with a 100 GW laser, in order to reach 76 MeV in one stage or 106 MeV in two stages, with the same initial electron energy [11, 12]. As the vacuum acceleration in the focal spot of a laser, this scheme is difficult to scale at higher energies, due to synchrotron radiation associated with the electron trajectories in the wiggler.

3 INVERSE CERENKOV

To obtain ultra-high energies, it is necessary to produce an electric field parallel to the propagation direction of the charged beam and to avoid phase slippage between the particles and the electromagnetic wave. In the inverse Cerenkov accelerator concept (ICA) a gas is used to slow the phase velocity of the laser light to enable matching the electron velocity. This condition is fulfilled by tilting the laser at the Cerenkov angle $\theta = cos^{-1}(1/n\beta)$, where n is the refractive index of the gas and β is the electron velocity in units of c. Due to this angle, the particle feels a longitudinal electric field component $Esin(\theta)$. The perpendicular component can be nearly canceled by using a radially-polarized laser focused by an axicon lens [13]. An ICA experiment has been performed at BNL/ATF using a 580 MW CO_2 laser focussed in hydrogen gas at two atmospheres. 40 MeV injected electrons were accelerated by 3.7 MeV over a 12 cm interaction distance, which corresponds to model predictions [14]. Future plans are to join efforts with the IFEL BNL/ATF group to use the IFEL as an injector of the ICA. The electrons will be prebunched by the first apparatus to fit the 300 ps laser pulse. An IFEL is a better prebuncher than an ICA because it does not suffer from scattering of the slow electrons by the gas molecules. On the other hand an ICA scales in energy more favorably because it does not suffer synchrotron radiation. In the present BNL/ICA experiment the accelerating gradient is 31 MeV/m, of the same order as in conventionnal accelerators. However when the laser power is increased the limitation of the ICA scheme due to the ionization of the gas will appear.

4 PLASMA BEAT WAVE

4.1 Plasma acceleration

In the seminal paper on plasma based accelerators by Tajima and Dawson [15], it is shown that intense laser pulses can generate large amplitude relativistic longitudinal plasma waves. A plasma has a natural oscillation frequency $\omega_p = (4\pi n_0 e^2/m)^{1/2}$ where n_0 is the electron density, m and e are the mass and the charge respectively. The ponderomotive force proportionnal to the gradient of the square of the electric field expels the plasma electrons from the regions where laser is more intense and triggers the plasma oscillation. This transfer of energy is efficient only if the laser pulse length is approximately equal to the plasma wavelength λ_p. The longitudinal electric field generated by the plasma electrons, assuming that the heavier ions are immobile, can be readily calculated by Gauss' theorem to be $E(V/cm) \approx \epsilon\sqrt{n_0}(cm^{-3})$ where ϵ is the amplitude of the wave $\delta n_0/n_0$. The phase velocity of the plasma wave v_ϕ is equal to the group velocity v_g of the laser in the plasma : $v_\phi = v_g = (1 - \omega_p^2/\omega_0^2)^{1/2}$ where ω_0 is the laser frequency. A Lorentz factor is associated to the plasma wave $\gamma = (1 - v_\phi^2/c^2)^{-1/2}$. The maximum energy gain ΔW of a charged particle injected parallel to the longitudinal wave is shown to be : $\Delta W = 2\epsilon\gamma^2 mc^2$.

4.2 Experimental beat wave results

The plasma beat wave accelerator (PBWA) was the first method experimentally demonstrated, because it can be done with moderate intensity lasers. The modulation of the laser envelope is performed by the beating of two lasers with close frequencies ω_1 and ω_2 , such that the following relation is satisfied: $\omega_1 - \omega_2 = \omega_p$. This resonance condition is ensured by carefully tuning the density of the gas in which the plasma is produced. The first evidence of plasma waves generated by this method, detected by optical diagnostics, came from the UCLA group using a two frequencies CO_2 laser [16]. The same group injected 2 MeV electrons from a linac and succeeded to accelerate them up to 30 MeV [17, 18]. The corresponding gradient was 3 GV/m on a length of 1 cm. What was particularly significant about this experiment is it demonstrated that the electrons were trapped by the wave. A similar experiment was reported by N.A. Ebrahim, who accelerated 12.5 MeV injected electrons up to 29 MeV [19]. In this experiment the working gas was argon instead of hydrogen or deuterium, making the comparison somehow difficult. The Osaka group observed 10 MeV electrons with no injection, the particle being extracted from the thermal background [20]. However the existence of detected electrons with only one laser frequency in this experiment is not clearly interpreted. The Ecole Polytechnique group used a YAG laser delivering 1 μm wavelength instead of 10 μm in the other experiments. The electrons were injected at 3 MeV and accelerated to 4.5 MeV [21].
One theoretical limitation of the PBWA mechanism is that the plasma electrons become relativistic when the wave amplitude is high. Then the plasma frequency suffers a small red shift and the wave saturates after a time equal to $8/\omega_p(2/3)^{1/3}(\alpha_1\alpha_2)^{-2/3}$, where $\alpha_{1,2} = eE_{1,2}/mc\omega_{1,2}$ is the normalized oscillatory velocity of the electrons in the laser fields $E_{1,2}$. This limit is reached by the UCLA group whose plasma wave amplitude is close to 30%. Other limitations appeared in the PBWA experiments, such as a mismatch of the Lorentz factor γ of the injected electrons with the plasma wave. The Ecole Polytechnique was also limited by the modulational instability due to the movement of the ions, the result of this effect being that the useful acceleration time is much shorter than the 100 ps effective duration of the laser pulse.

5 LASER WAKE FIELD

The laser wake field accelerator (LWFA) is the simplest concept, where the plasma wave is excited by a single short laser pulse [15, 22, 23]. The optimum energy transfer is obtained when $\omega_p\tau = 4\sqrt{ln2}$, where τ is the laser pulse duration at FWHM, but this resonance condition is much less stringent than for the PBWA. Moreover, LWFA is not affected by relativistic detuning, nor by modulational instability because the pulse is much shorter than the ion plasma period. Experimental demonstration of the effect had to wait for development of high brightness lasers in the TW domain. A subpicosecond pulse length was also necessary to accomodate the plasma frequency, for example τ = 400 fs corresponds to $n_0 = 2.2 \times 10^{16} cm^{-3}$.

The first evidence of the excitation came from optical diagnostics by two-pulse frequency-domain interferometry [24-26]. Accelerated electrons have been observed by the KEK/JAERI/Tokyo group up to 30 MeV [27], and even more recently to 250 MeV [28]. The Ecole Polytechnique group has observed electrons up to 4.5 MeV from a 3 MeV injected beam [29]. Signals higher than 7 MeV are also detected in this experiment but a detailed analysis shows that these electrons do not traverse metallic energy filters. Consequently they are faked accelerated electrons, and the favoured interpretation is that they are deflected by transverse fields and scattered by the walls of the vacuum chamber. Such an effect may explain the surprising high result in the KEK/JAERI/Tokyo data, not to mention the poor energy resolution of the detector in the upper part of the spectrum.

An important feature both of the PBWA and the LWFA is that the transverse electric field E_r may be stronger that the longitudinal one E_z, due to the small waist at focus. Particle in cell simulation [30] shows that it is a cause of saturation of E_z.

6 SELF-MODULATED LASER WAKE FIELD

The easiest experimental route to accelerating electrons with laser-driven plasma wave is a modification of the laser wakefield concept, combining stimulated forward Raman scattering (FRS) and "sausaging" of the laser pulse envelope [31-34]. FRS describes the decay of a light wave at frequency ω_0 into two light waves at frequency $\omega_0 \pm \omega_p$ and the plasma wave ω_p. FRS was identified as an instability in earlier experiments [35], but with the advent of high intensity lasers opening the possibilty of LWFA, it became rapidly a new method of acceleration. The instability can grow from noise and the density perturbations cause local variation in the group velocity $v_g = c(1-\omega_p^2/\omega_0^2)^{1/2}$ of the laser wave. As a result, light that propagates near a density maximum (minimum) slows down (speed up) and the laser energy is bunched longitudinally. This self-modulation forms a train of pulses with approximately $\pi c/\omega_p$ separation, which act as individual short pulses to drive the plasma wave. In order that the FRS can grow, the plasma density must be chosen to be much larger than for the standard LWFA.

Typically this method of self-modulated laser wake field accelerator (SMLWFA) uses a few TW of laser power in a sub-picosecond pulse, and a dense plasma of the order of $10^{19} cm^{-3}$. To avoid ionization-induced refraction which is especially troublesome at high densities, a supersonic gas jet is mandatory in order to limit the amount of matter traversed. Under these conditions it is not necessary to inject relativistic particles, the background electrons from the plasma itself being efficiently accelerated, so that many groups have been able during recent years to perform this type of experiments.

The first demonstration came from a LLNL/UCLA collaboration [36] who observed 2 MeV electrons with a 5 TW laser in correlation with the detection of FRS. Nakajima et al. [37], using a 3 TW Nd:glass laser directed on high density helium, detected no electrons from background gas but accelerated to 17 MeV when 1 MeV were injected. With the highest powerful Vulcan 25 TW laser at Rutherford Appleton Laboratory, a group of Imperial College/UCLA/LLNL/Ecole Polytechnique was able to reach 44 MeV, at the limit of their electron spectrometer [38], and later 100 MeV [39]. At the University of Michigan a flux of electrons was observed and angularly resolved [40]. The measurements suggest that the electron spectrum is rougly independant of direction. Another experiment was performed at NRL with a 2.5 TW laser, background electrons being accelerated to 30 MeV [41]. The same group studied the temporal evolution of the wakefield by an optical diagnostic (coherent Thomson scattering) [42]. A similar characterization was done by a Michigan-Texas collaboration [43], who observed later accelerated electrons to 2 MeV [40]. Both team found time scales around 2 ps, consistent with the FRS theory.

7 PLASMA CHANNELING

The acceleration length is normally limited by twice the Rayleigh length $L_R = \pi\sigma_0^2/\lambda$, where σ_0 is the spot radius and λ the laser wavelength. This is the distance over which the energy is concentrated in the longitudinal direction. A typical value for a spot size is 10 μm, defined by diffraction at the focus of the optical system. With the wavelength of 1 μm of a Nd:glass laser, this corresponds to $2L_R \simeq 0.6$ mm. This limitation is challenged by the attractive property of a plasma consisting in the possibility to extend the acceleration length by channeling the laser pulse over distances much larger than $2L_R$.

When a laser propagates through a plasma, the index of refraction is $n = (1-\omega_p^2/\omega_0^2)^{1/2}$. For high laser power, the index varies with the radius, since ω_p changes with the relativistic mass factor of the plasma electrons. Under these conditions, the plasma acts like a positive lens and focuses the beam (relativistic self-focusing). It has been shown [44] that this effect takes place if the laser power exceeds a threshold given by $P_c = 16.2\omega_0^2/\omega_p^2$ GW. This condition is easily satisfied for many experiments using short pulse lasers described in the previous paragraphs. The effect was observed in a gas chamber [45] and with a gas jet [46]. Chiron et al. [47] calculated relativistic self-guiding over five Rayleigh lengths. The Michigan group [40] found that the

laser was channeled over four times L_R, limited by the size of their gas jet. They found also that the self guiding increases the electron energy and decreases the angular emittance. In another experiment they measured the plasma density distribution by optical interferometry and by guiding a trailing pulse [48]. The NRL group [49] reported an intense trailing pulse guided for about 20 Rayleigh lengths. In a recent analysis, the Imperial College/UCLA/LULI collaboration observed that relativistically propagating plasma waves are excited over the entire length of the channel, up to 12 L_R [50].
Alternative methods have been experimentally demonstrated. The most impressive result was obtained by hydrodynamic expansion of a preformed plasma, the laser light being channeled up to 3 cm, exceeding 90 L_R [51]. In this experiment a two laser pulse technique was used, an axicon lens bringing the channel-forming pulse from the side, with the light injected longitudinally into this channel. The Ecole Polytechnique group measured the temporal evolution of an electron density channel created by a low intensity laser [52]. A subsequent high intensity pulse was guided by the 2.5 mm long plasma. In other experiments light intensities up to $10^{16} W/cm^2$ have been guided using glass capillary waveguides in vacuum [53] or a plasma generated by a discharge [54].

8 PROSPECTS FOR NEXT GENERATION ACCELERATORS

8.1 Vacuum, IFEL and ICA

The direct acceleration of electrons in vacuum is limited by electron slippage, because the phase velocity of the light is always higher than the velocity of the particles. The only way to increase the output energy would be to increase the laser power. However the very short acceleration length is a drawback to obtain ultra-high energies, due to synchrotron radiation losses. This very simple concept could be attractive to make very compact 100 MeV accelerators useful for many applications.
IFEL does not suffer the limitation due to electron slippage, but it is even proner to synchrotron radiation during the non-linear trajectories of the electrons. Its use is considered only as a preinjector, delivering high quality bunches for next accelerator stages.
The ICA scheme can in principle be scaled to any energy. It is even more favorable to accelerate already ultra-relativistic electrons because the effect of scattering by gas is less important. A 100 MeV, 30 cm long demonstration experiment in one stage is proposed [55]. It requires an accelerating gradient of 370 MeV/m, which is possible with a 250 GW laser, although it is a tenfold increase relative to the actual experimental result. In the same reference a conceptual design of a 1 TeV linac is presented, on the basis of 10^{10} electrons per bunch. 100 laser amplifiers synchronised by the same laser signal, each one giving 50 TW pulses at 0.5 ps, deliver 1.6 kJ to the particle beam, corresponding to 50 TW pulses at 0.5 ps. The gradient is 10 GeV/m and the total accelerating length is 100 m, not including the extra space between stages.

8.2 Single stage plasma accelerator

Considering the past two decades, it is clear that the proof of principle of acceleration by lasers and plasmas is now well established by various and independant groups, for the three schemes, beat wave, wakefield and self-modulated wakefield. The interest has now shifted towards the construction of more realistic devices and the ”1 GeV prototype” seems to be the common goal of experimentalists. This is within reach, as far as SMLWFA is concerned, provided the laser power and the gas jet length are slightly increased. The PBWA suffers from its long pulse duration, so that the modulational instability has time to develop and to destroy the accelerating electron plasma wave. This problem could be overcommed by a intermediate scheme between PBWA and LWFA, where two frequencies bring the advantage of several pulses resonant with ω_p inside an envelope few ps long, made by chirped pulse amplification. A 1 GeV LWFA prototype is nevertheless feasible with the actual technology (25 J in 120 fs) as long as the acceleration length is made long enough, of the order of 16 mm [56]. This places conditions on the focal length to be $\simeq 5$ m and on the electron injection energy to be > 15 MeV. The considerable progress made during the past years in plasma channeling experiments enables to think of a 1 GeV accelerator with smaller and cheaper lasers. Repetition rates higher than 10 Hz, which are not accessible to high energy lasers, could be routinely obtained, for a variety of applications.

8.3 Multi-stage plasma accelerator

A multi-stage concept is mandatory to reach multi-TeV final energy. With the LWFA or PBWA it is possible to adjust the timing of each individual laser amplifier by standard optical techniques. This is probably not the case in the SMLWFA, since the bunching is created by an instability growing in the plasma itself. Moreover, the density of the gas used in this method, two orders of magnitude higher than in the others, causes diffusion of the accelerated particles. On the other hand, an attractive characteristics of SMLWFA is that no extra source of electrons is needed for injection. It may become soon a very attractive way to built intense and cheap sources of electrons or gamma rays in the range of several hundred MeV for industry, medecine or academic research.
Future experiments in high energy physics demand linear colliders with pulses of 10^{11} particles in the TeV range. The beam quality, high intensity and low emittance, is also a fundamental parameter to ensure usable luminosities. The challenge for lasers and plasma based accelerators is tremendous but conceptual designs have been worked out by many researchers, triggered by the experimental demonstration that accelerating gradients are far higher than in the

conventional microwave technique. A similar calculation can be done as for the ICA scheme with 100 amplifiers, but here the acceleration length is expected to be shorter especially if channeling in plasma can be used efficiently.

The goal of obtaining high beam intensities is common to all future designs, more conventional like two beam accelerator (CLIC at CERN) or more advanced as in laser based concepts. Photoinjectors, in which electrons are emitted from a photocathode by an intense laser pulse, are actively investigated in many laboratories [57]. It would solve the difficult problem of injecting the electrons in a very short bunch, in phase with the accelerating lasers. As a result, one obtain the very elegant concept of "all optical accelerator" [58].

Last but not least is the economical issue, as far as the price of the accelerating components is concerned, as well as the overall power consumption. The transfer of energy from the electric power line to the light output may reach an efficiency close to 50 %, using diodes for laser pumping. What proportion of the light is used to couple to plasma and then accelerate particles is a more problematic question, which was not studied deeply by experimentalists. Few work was done to optimize the injection of electrons into the plasma and to characterize precisely the accelerated beam. We can expect a rapid advance in this issue, with the completion of the foreseen GeV prototypes, next milestone in the field.

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10 REFERENCES

[1] D. Strickland and G. Mourou, Opt. Commun. **56**, 219 (1985).

[2] J.D. Lawson, IEEE Trans. Nucl. Sci. **NS-26**, 4217 (1979).

[3] P. Woodward, J. IEEE **93**, 1554 (1947).

[4] P. Sprangle et al., Phys. Plasmas **3**, 2183 (1996).

[5] E. Esarey et al., IEEE Trans. Plasma Sci. **24**, 252 (1996).

[6] G. Malka, E. Lefebvre and J.L. Miquel, Phys. Rev. Lett. **78**, 3314, 1997.

[7] L.C. Steinhauer and W.D. Kimura, J. Appl. Phys. **72** (1992).

[8] R.H. Pantell, Nucl. Instrum. Meth. **A393**, 1 (1997).

[9] R. Palmer, J. Appl. Phys. **43**, 3014, 1972.

[10] A. van Steenbergen et al., Phys. Rev. Lett. **77**, 2690 (1996).

[11] A. van Steenbergen and J. C. Gallardo, proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada.

[12] J.C. Gallardo, private communication.

[13] J.R. Fontana and R.H. Pantell, J. Appl. Phys. **54**, 4285 (1983).

[14] W.D. Kimura et al., Phys. Rev. Lett. **74**, 546 (1995).

[15] T. Tajima and J. Dawson, Phys. Rev. Lett. **43**, 267, 1979.

[16] C.E. Clayton et al., Phys. Rev. Lett. **54**, 2243 (1985).

[17] C.E. Clayton et al., Phys. Rev. Lett. **70**, 37 (1993).

[18] M. Everett et al., Nature **368**, 527 (1994).

[19] N.A. Ebrahim, J. Appl. Phys. **76**, 11 (1994).

[20] Y. Kitagawa et al., Phys. Rev. Lett. **68**, 48 (1992).

[21] F. Amiranoff et al., IEEE Trans. on Plasma Sci. **24**, 296 (1996).

[22] L.M. Gorbunov and V.I. Kirsanov, Zh. Eksp. Theor. Fiz. **93** 509 (1987); Sov. Phys. JETP **66** 290 (1987).

[23] P. Sprangle et al., Appl. Phys. Lett. **53**, 2146 (1988).

[24] J.R. Marquès et al., Phys. Rev. Lett. **76**, 3566 (1996).

[25] C.W. Siders et al., Phys. Rev. Lett. **76**, 3570 (1996).

[26] J.R. Marquès et al., Phys. Rev. Lett. **78**, 3463 (1997).

[27] K. Nakajima et al., Phys. Scripta **T52**, 61 (1994).

[28] M. Kando et al., KEK preprint 97-10; proceedings of the 1997 Particle Accelerator Conference, Vancouver, Canada.

[29] F. Amiranoff et al., proceedings of this conference; submitted to Phys. Rev. Lett. (1997).

[30] P. Mora, J. Appl. Phys. **71**, 2087 (1992).

[31] P. Sprangle et al, Phys. rev. Lett. **69**, 2200 (1992).

[32] N.E. Andreev et al., JETP Lett. **55**, 571 (1992).

[33] F.M. Antonsen Jr. and P. Mora, Phys. Rev. Lett. **69**, 2204 (1992).

[34] E. Esarey et al., Phys. Rev. Lett. **72**, 2887 (1994).

[35] C. Joshi et al., Phys. Rev. Lett. **47**,1285 (1981).

[36] C. Coverdale et al., Phys. Rev. Lett. **77**, 4659 (1995).

[37] K. Nakajima et al., Phys. Rev. Lett. **74**, 4428 (1995).

[38] A. Modena et al., Nature **337**, 606 (1995).

[39] D. Gordon et al., Phys. Rev. Lett. **80**, 2133 (1998).

[40] R. Wagner et al., Phys. Rev. Lett. **78**, 3125 (1997).

[41] C.I. Moore et al., Phys. Rev. Lett. **79**, 3939 (1997).

[42] A. Ting et al., Phys. Rev. Lett. **77**, 5377 (1996).

[43] S.P. Le Blanc et al., Phys. Rev. Lett. **77**, 5381 (1996).

[44] G.Z. Sun, E. Ott, Y.C. Lee and P. Guzdar, Phys. Fluids **30**, 526 (1987).

[45] A.B. Borisov et al., J. Opt. Soc. Am. **B11**, 1941 (1994.)

[46] P. Monot et al. Phys. Rev. Lett. **74**, 2953 (1995)

[47] A. Chiron et al., Phys. Plasmas **3**, 1373 (1996).

[48] S.Y. Chen et al., Phys. Rev. Lett. **80**, 2610 (1998).

[49] K. Krushelnick et al., Phys. Rev. Lett. **78**, 4047 (1997).

[50] C.E. Clayton et al., to be published in Phys. Rev. Lett. (1998).

[51] C.G. Durfee III and H.M. Milchberg, Phys. Rev. Lett. **71**, 2409 (1993); H.M. Milchberg et al., Phys. Plasmas **3**, 2149 (1996).

[52] V.Malka et al., Phys. Rev. Lett. **79**, 2979 (1997).

[53] S. Jackel et al., Opt. Lett. **20**, 1086 (1995).

[54] Y. Ehrlich et al., Phys. Rev. Lett **77**, 4186 (1996).

[55] W.D. Kimura, R.D. Romea and L.C. Steinhauer, Particle World **4**, 22 (1995).

[56] F. Amiranoff and A. Migus, private communication.

[57] I. Ben-Zvi, Advanced Accelerator Concepts edited by S. Chattopadhyay, AIP Conf. Proc. **398**, 40 (1997).

[58] E. Dodd, J.K. Kim and D. Umstadter, Advanced Accelerator Concepts edited by S. Chattopadhyay, AIP Conf. Proc. **398**, 106 (1997).