ULTRA-HIGH GRADIENT COMPACT ACCELERATOR DEVELOPMENT

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Abstract

Continued development of lasers with peak powers as high as 100 TW has enabled laser-plasma based acceleration experiments with tremendous gradients of up to 1 TV/m. In order to usefully apply such gradients to 'controlled' acceleration, various hurdles still need to be overcome. This paper describes the statee-of-the-art experiments that have led to acceleration of electrons using TW lasers in plasmas. Progress in plasma waveguiding of TW lasers and injection of electrons is presented. Finally, different routes towards integrated experiments that could lead to controlled laser wakefield acceleration in the foreseeable future are discussed.

INTRODUCTION

After an amazingly successful history of more than half a century, RF accelerator technology seems to approach its limits, the main one being that of the maximum achievable gradient. Development of new concepts for significantly higher gradients has been ongoing for more than a decade. This paper focuses on the main thrust in this area, i.e. the use of plasma waves driven by lasers for the acceleration of electrons. Alternative concepts of plasma waves driven by electron bunches, or direct laser acceleration are not considered.

The basic concept of Laser Wakefield Acceleration (LWA) is straightforward: interaction of the laser field with plasma electrons causes the generation of a plasma wave, i.e. an electron density modulation with accompanying longitudinal and transverse electric field gradient, in which electrons can be accelerated [1]. The magnitude of the gradient is not limited by breakdown on cavity walls, as in RF-technology, but by 'wave-breaking', when the amplitude of the (longitudinal) wave becomes larger than the wavelength. This occurs at very much higher gradients than in RF accelerators: fields of up to a TV/m have been reported in recent experiments. To be able to use these plasma waves for controlled acceleration, three issues have to be solved simultaneously:

1. Wave excitation: A relativistic plasma wave has to be driven to large amplitude.
2. Guiding: The plasma wave must extend over sufficient length to allow acceleration to high energies.
3. Injection: Electrons must be injected into and trapped by the plasma wave.

In this paper we will review three experiments that have produced high energy electrons (50-200 MeV) through laser driven plasma waves. In subsequent sections we will discuss the progress on the separate issues of guiding and injection and the possibilities to accomplish controlled laser wakefield acceleration. This is not meant to be a complete overview of all activities (for a recent review, see for example Bingham et al. [2]), but rather a selection of highlights to illustrate developments in this field.

HIGHLIGHTS

Plasma Beatwave Acceleration

In Plasma Beatwave Acceleration (PBWA) two collinear laser beams are used to drive the plasma wave. The two beams differ in frequency to produce a beat pattern. If the frequency difference exactly matches the local plasma frequency, a plasma wave is resonantly excited (by the ponderomotive force of the beat pattern) and can be driven to large amplitudes. The advantage of PBWA over Self Modulated and Forced Wakefield Acceleration (discussed later) is the ability to drive a large wave with a relatively low laser intensity and relatively long pulses, which in turn simplifies synchronization with an external injector. The most impressive results for this type of LWA have been reported recently by the Neptune Laboratory at UCLA [3]. In the experiment a TW, two-wavelength CO_2 laser system is used. The pulses are 100-400 ps long at wavelengths of 10.6 μm and 10.3 μm. The laser beams are focused in a hydrogen filled low-pressure chamber, where they produce a fully ionized plasma at the focus. By changing the pressure, the plasma density is varied so that the plasma frequency matches the frequency difference of the laser beams. In the experiments discussed here, the plasma density is 10^{16} cm^{-3}, resulting in a plasma wavelength of 340 μm, or ≈ 1 ps.

Because the plasma is created by the laser itself, the length of the plasma (and the extent of the plasma wave) is limited by ion induced refraction, rather than the Rayleigh range of the laser focus. This effect is compensated through the use of longer laser pulses (400 ps). During the presence of the laser pulse in the plasma, the ponderomotive force creates a small radial electron density gradient. When the laser pulse is long enough, the ions will move to compensate this gradient and a density minimum on axis results. This density channel guides the laser pulses and extends the plasma and the acceleration distance, resulting in a higher energy gain. Using 400 ps laser pulses in the latest experiments increased the interaction length between the plasma wave and (externally injected) electrons to ≈ 30 mm, from 17 mm when using shorter (135 ps) laser pulses.

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In the UCLA experiments, a 50-pC, 12-MeV, 10-ps electron bunch from an RF photoinjector was injected into the plasma. Approximately 1 % (3×10^6 electrons) of these electrons was accelerated by the plasma wave. The energy spectrum shows a rapid drop above 12 MeV to a level of 100 electrons/MeV at 20 MeV. Above 20 MeV the spectrum is nearly flat and extends to 50 MeV. The maximum energy gain of the electrons (38 MeV) shows that the field gradient in the plasma wave is approximately 1 GV/m.

Self Modulated and Forced Wakefield Acceleration

If higher laser power is available (30 TW), a large amplitude plasma wave can be driven using a single laser pulse.

In the Self Modulated Wakefield (SMWF) regime a laser pulse is used, which is much longer than the plasma wavelength. Laser light is scattered in the plasma to produce sidebands at $\omega_0 \pm \omega_p$ (with ω_0 the original laser frequency and ω_p the plasma frequency). The beat pattern between these sidebands and the unperturbed laser is naturally resonant with the plasma frequency. The ponderomotive force of this beat pattern can efficiently drive a plasma wave to large amplitudes. Some very successful experiments in the self-modulated regime were done at the Rutherford-Appleton Laboratory with the Vulcan:CPA laser [4, 5]. The laser pulse (50 TW, 1 ps) is focused into a hydrogen gasjet where it produces a fully ionized plasma with electron density up to 1.5×10^{19} cm^{-3} (plasma wavelength ≈ 9 μm, or 30 fs). At lower plasma densities (0.4×10^{19} cm^{-3}) the electron spectrum of accelerated electrons shows a Maxwellian-like distribution from 0 to 13 MeV, where the distribution falls below the detection threshold. These electrons come from the tail of the temperature distribution in the plasma, heated by interaction with the laser beam and the plasma wave. Some of these hot electrons have the right direction and energy to be trapped by the plasma wave and are accelerated. At higher plasma densities, the number of accelerated electrons increases and the tail of the energy distribution of electrons extends to 100 MeV. In this regime, wave breaking (the amplitude of the longitudinal plasma wave becoming larger than the wavelength) causes plasma electrons to be trapped.

An improvement from SMWF is the so-called Forced Laser Wakefield (FLW) Acceleration. In a FLW, the laser pulse length is of the order of the plasma wavelength. A plasma wave is driven purely by the ponderomotive force associated with the laser pulse. Interactions between the front of the laser pulse and the plasma results in a steepening of the front edge of the laser pulse. This effect increases the efficiency with which a large amplitude plasma wave is generated. At the Laboratoire d'Optique Appliquée a 30 TW, 30 fs laser pulse was focused into a hydrogen or helium gas jet, producing a plasma with a density of 2.5×10^{19} cm^{-3} [5, 6]. The wakefield was driven to wavebreaking to trap background electrons. The spectrum of accelerated electrons shows a Maxwellian-like distribution from 0 to 120 MeV with an effective temperature of 18 MeV. Above 120 MeV the distribution is effectively flat up to the highest measured energy of 200 MeV. To reach these high energies, the accelerating gradient in the plasma wave must have been close to 1 TV/m.

DEVELOPMENTS

Guiding

To increase the interaction length between the drive laser and the plasma, and thus lengthen the acceleration distance beyond the Rayleigh range, the drive laser needs to be guided. Successful experiments have been carried out using gas-filled capillaries [7]. The high power laser ionizes the gas and creates the plasma. The laser is guided by internal reflection inside the capillary. The biggest disadvantage of this method of guiding is that if the (high power) drive laser does not have a very good profile higher order modes will hit the face of the of the capillary at the entrance plane and the experiment is likely to be single shot.

A medium that can withstand these very high powers is of course plasma. To guide a high intensity laser in a plasma a fully ionized (to prevent ionization induced diffraction) cylindrical plasma needs to be created with a density minimum on axis. A lower plasma density means a higher refractive index on axis, so that the plasma acts as an optical fiber. Ideally the plasma profile should be parabolic so that a matched Gaussian laser pulse will be guided without deformation.

Basically, two ways of generating such a plasma have been pursued, either using lasers or using an electrical discharge to ionize the plasma. In a laser produced plasma channel, a high intensity laser pulse ionizes the plasma. The same pulse or a subsequent pulse must then heat the plasma so that the hydrodynamic expansion that follows will at some point in time create the desired profile. Nikitin et al. [8] used an axicon lens to produce a 0-order Bessel beam at the focus and create a long cylindrical plasma. They used a relatively long (100 ps) laser pulse so that the tail of the pulse heats the plasma electrons through inverse Bremsstrahlung. The expansion of the plasma causes a hydrodynamic shock wave expanding radially outward. They were able to guide laser pulses with 5×10^{16} W/cm^2 over 8-9 Rayleigh lengths (1.5 cm) at plasma densities around 10^{19} cm^{-3}, with an efficiency of slightly more than 50%. Volfbeyn et al. [9] used a similar scheme, but with two separate laser pulses: A short (75 fs) laser pulse to ignite the plasma and a second, longer (160 ps) laser pulse to heat the plasma. They achieved similar guiding results.

Using a discharge plasma for guiding has great appeal from the point of view that these plasmas can be produced over a relatively long distance. This is especially interesting for lower plasma densities (10^{17}-10^{18} cm^{-3}), where the dephasing length is of the order of cm, rather than mm. The greatest challenge is to produce a stable, straight plasma channel. The most promising channels have been produced by Butler et al. [10]. They used a pulsed discharge in hydrogen in a ceramic capillary with a diameter of 400 μm. In these capillaries, a current pulse fully ionizes and heats the plasma. Cooling of the plasma on the capillary walls creates a plasma profile with a density minimum at the center of the plasma. With this plasma they were able to guide more than 80% of the energy of a high intensity laser pulse ($>10^{17}$ W/cm^2) over 3 cm (70% in a 5 cm channel) at a plasma density of 2×10^{18} cm^{-3}. However the intensity at the exit of the channel was only 40% of the intensity at the entrance, possibly due to local mismatch in the channel or ionization induced diffraction of residual neutrals.

Injection

The third challenge towards controlled LWA is injection of electrons in the plasma wave. Two general approaches can be distinguished depending on the origin of the electrons: Injection of background plasma electrons (as in SMLWA and FLWA) or external injection of pre-accelerated electrons (as in the PBWA experiment described above).

Injection through wavebreaking such as in the experiments described earlier, will not lead to controlled LWA. Not only is the injected phase nearly impossible to control, but also, since injection takes place continuously along the plasma, the energy spectrum of the electrons will be flat at best. A scheme for controlled injection of background electrons was proposed by Eseray et al. [11]. In this scheme, currently being pursued at Berkeley National Lab, two additional, counter propagating, high intensity laser pulses are focused into the plasma. If they are timed exactly right, they will produce a low phase velocity beatwave. The ponderomotive force of the localized beatwave pattern will accelerate some of the background electrons in the propagation direction of the passing plasma wave, by which they will be trapped and accelerated further. Simulations show that bunches of approximately 1 fs, with a charge of 1 pC can be injected this way.

Pre-accelerated electrons from an external source were used in the PBWA experiments at UCLA and some other LWA experiments elsewhere. In all cases the electron bunch was much longer than the plasma wavelength. This means that there is no control over the injection phase. Furthermore, the transverse size of the wakefield is determined by the width of the laser focus and only a small fraction (1 % in the UCLA experiments) of the pre-accelerated electrons could be injected into the wakefield.

State-of-the-art in RF-photoguns is bunch length and synchronization on the order of 1 ps. This is clearly insufficient for controlled acceleration in a laser wakefield. There is an effort at Eindhoven University of Technology (TUE) to explore the limits of photo-injectors. At TUE, it has been shown that for modest charge per bunch (10 pC), using a metal photocathode and fs-laser, bunch lengths of 50 – 100 fs are feasible. At the same time, synchronization down to 80 fs has been demonstrated, while a straightforward route to 10 fs has been identified [12]. In the same group, a solution for bunches with higher charge is being pursued, using MV, ns pulses for GV/m pulsed DC acceleration [13]. Simulations predict that photoemission with a 30-fs UV laser will generate 100 pC bunches at lengths well below 100 fs. Specs of this order will allow controlled acceleration of kA peak currents in a wakefield, provided a plasma channel with ps wave period is available (density $\approx 10^{17}$ cm^{-3}).

The claims made above about fs, kA bunches are substantiated by the recent development of a physics picture of the ‘pancake’ bunch regime, i.e. the regime in which the aspect ratio of the bunch, R/d, is larger than 1 *in its restframe.* This regime is relevant in all photoguns. In a typical RF-photogun using a few-ps laser pulse, it extends up to an accelerated energy of γ = 2-3, and to γ = 10-20 when using a fs-laser pulse. In this regime, the Coulomb expansion of the bunch is determined not by space charge, but by surface charge only. This leads to quite counter-intuitive behavior: in particular, for a given charge, peak current and brightness increase for decreasing laser pulse length. Even more importantly, the pancake regime provides a route towards the creation of “waterbag” bunches, i.e. homogeneously-filled ellipsoids with purely linear self-fields [14]. Such ideal bunches are known to conserve their initial ‘thermal’ brightness. What is required, is shaping of the radial laser profile to a half-circle instead of the usual Gaussian. Use of this method will lead to very short bunches with unprecedented brightness. The relevance of this novel idea obviously goes well beyond that of the application to injection in a laser wakefield accelerator.

To finish this section on injection, we mention the compression/acceleration scheme proposed by Khachatryan [15]. It makes use of external injection of a bunch from an electron gun, but with significantly relaxed requirements on bunch length and synchronization. The basic idea is to inject a sub-relativistic bunch into a plasma and then have an intense laser pulse catch up with the electrons. The highly non-linear wakefield trailing the laser pulse can trap and compress the electron bunch, both longitudinally and radially, into a very much shorter and automatically synchronized bunch. The scheme requires a strongly non-linear wakefield, and thus laser power in the 10 – 20 TW range, in addition to a still non-trivial photo-injector.

CONCLUSIONS AND OUTLOOK

The results obtained in LWA experiments are impressive. The gradients achieved are astounding and a large charge with good emittance is ejected. However, taking an energy slice out of the broad spectrum produces a beam with specs still below those of RF accelerators. There is a clear need for progress, since no experiment has yet been performed that controls all aspects of LWA (wave excitation, guiding and injection). Here we will present three different approaches that may lead to controlled laser wakefield acceleration in the foreseeable future.

Classical Laser Wakefield Accelerator

In the 'classical' scheme, an external electron source injects pre-accelerated electrons into a pre-ionized plasma channel. A moderate intensity laser pulse sets up a linear wakefield to accelerate the electron bunch. In fact, all ingredients exist for a controlled laser wakefield experiment in this regime. The TUE photogun can produce 10 pC, 100 fs electron bunches at 7.5 MeV and the discharge plasma channel from the group of Hooker [10] guides well at a plasma density of 2×10^{18} cm^{-3}. 1D estimates shows that a (modest) 2 TW laser pulse focused into a 1 cm long plasma channel of this type, with a matched diameter of 40 μm can accelerate these bunches from 7.5 MeV to 50±20 MeV. The plasma wavelength at these densities is 80 fs, so the electrons would still be injected into all phases of the plasma wave. However, a big improvement from present experiments is the fact that the acceleration distance is the same for the entire bunch. Better control over the energy spread can be obtained if the plasma channel can be operated at lower density and/or if the injected electron bunch can be improved. Injection of a 75 fs bunch in a 5 cm long, 2×10^{17} cm^{-3} plasma channel, still with only a 2 TW laser will produce bunches of 50±5 MeV.

Two consortia of research groups are actively pursuing this approach: one in the Netherlands (including TU Eindhoven) and one in the UK (led by the University of Strathclyde). This approach constitutes a comprehensive route towards the development of a truly 'table-top' controlled laser wakefield accelerator.

Two-stage Accelerator

Reitsma et al. [16] have proposed and simulated a two-stage accelerator scheme. In these simulations they inject a high charge (2 nC), low average energy (1-3 MeV) bunch from a self-modulated LWA into a channel-guided, resonant LWA. They find that up to 40% of the electrons is trapped and accelerated by a 10-100 TW laser to 50 MeV with an energy spread of 60%. Taking this approach further, it seems possible to take an energy slice from a forced-wakefield accelerator. The charge in these bunches will be much lower, of the order of a few pC, but the bunch length is of the order of the plasma wavelength of the FLWA. This bunch can then be injected into a second (resonant) LWA with a lower plasma density and accelerated in a controlled fashion.

All-optical Laser Wakefield Accelerator

An all-optical scheme is being pursued at Lawrence Berkeley National Lab. In this scheme no less than five high power laser pulses are used to generate the plasma, drive the plasma wave and inject electrons at a specific phase in the plasma wave. The first two pulses create a guiding plasma channel using the ignitor-heater method described above. A third laser pulse then drives a large amplitude plasma wave. Combined with the colliding pulse injection, this will produce kA, fs bunches.

REFERENCES

[1] T. Tajima, et al. Phys. Rev. Lett. **43** (4), 267 (1979).

[2] R. Bingham et al. Plasma Phys. Control. Fusion **46** R1, (2004).

[3] S.Ya. Tochitsky, et al. Phys. Plasmas **11** (5), 2875 (2004).

[4] D. Gordon, et al. Phys. Rev. Lett. **80** (10), 2133 (1998).

[5] Z. Najmudin et al., Phys. Plasmas **10** (5), 2071 (2003).

[6] V. Malka, et al. Science **298** 1596 (2002)

[7] F. Dorchies, et al. Phys. Rev. Lett. **82** (23) 4655 (1999).

[8] S.P. Nikitin, et al. Phys. Rev. E **59** (4) R3839 (1999).

[9] P. Volfbeyn, et al. Phys. Plasmas **6** (5) 2269 (1999).

[10] A. Butler, et al. Phys. Rev. Lett. **89** (18) 185003 (2002).

[11] E. Esarey, et al. Phys. Rev. Lett **79** (14) 2682 (1997)

[12] F.B. Kiewiet et al. Nucl. Instr. Methods A **484** (1-3) 619 (2002).

[13] G.J.H. Brussaard, et al. accepted for publication in IEEE Trans. Plasma Sci., (2004).

[14] O.J. Luiten, et al. accepted for publication in Phys. Rev. Lett. (2004).

[15] A.G. Khachatryan, Phys. Rev. E, **65** 046504 (2002)

[16] A.J.W. Reitsma, et al. Phys. Rev. ST-AB, **5** (5) 051301 (2002).