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EDITORIAL • OPEN ACCESS

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To cite this article: Chan Joshi and Victor Malka 2010 *New J. Phys.* **12** 045003

New Journal of Physics
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EDITORIAL

Focus on laser- and beam-driven plasma accelerators

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New Journal of Physics **12** (2010) 045003 (5pp)
Received 19 March 2010
Published 30 April 2010
Online at http://www.njp.org/
doi:10.1088/1367-2630/12/4/045003

Abstract. The ability of short but intense laser pulses to generate high-energy electrons and ions from gaseous and solid targets has been well known since the early days of the laser fusion program. However, during the past decade there has been an explosion of experimental and theoretical activity in this area of laser–matter interaction, driven by the prospect of realizing table-top plasma accelerators for research, medical and industrial uses, and also relatively small and inexpensive plasma accelerators for high-energy physics at the frontier of particle physics. In this focus issue on laser- and beam-driven plasma accelerators, the latest advances in this field are described.

Contents

1. Plasma acceleration of electrons

The idea of using collective fields in a plasma to accelerate charged particles is over six decades old and can be traced to G I Budker and V I Veksler of the (then) USSR. They independently proposed to use the fields generated in a plasma by the passage of a medium-energy electron beam to accelerate ions to high energy [1]. However, a conceptual breakthrough in this field was achieved exactly 30 years ago when Toshi Tajima and John Dawson of UCLA proposed using a relativistically propagating disturbance or a wake created in a plasma by the passage of a short laser pulse to accelerate electrons to ultrahigh energies in a short distance [2]. Shortly thereafter, P Chen *et al* [3] showed that instead of a laser pulse, one can use a high-current bunch of electrons to generate very high electric fields in a plasma that can be used to accelerate particles extremely rapidly . The concepts came to be known as the laser wakefield accelerator (LWFA) and the plasma wakefield accelerator (PWFA) [4], respectively.

The current excitement in this field stems from the fact that the optimal laser pulses and electron bunches that are needed to produce such wakefields over many diffraction lengths have become available to experimentalists only in this decade. Simultaneously, there has been a revolution in plasma simulation capability, leading to the discovery of the blowout or bubble regime of wakefield acceleration [5, 6]. In this extremely nonlinear regime, a short laser or electron pulse completely blows out all the plasma electrons, creating a bubble-like wakefield structure that is robust and has some very desirable properties for generating high-quality and high-energy beams (figure 1) [7]. The first is that the accelerating field is independent of the transverse position in the wake so all the particles at a given longitudinal position gain energy at the same rate, which helps minimize the energy spread of the accelerated beam. The second is that the focusing field increases linearly with transverse position, which helps minimize the transverse emittance growth of the beam. Thirdly, the electron density depression caused by the disturbance (the wakefield) is able to guide a matched drive beam over many diffraction lengths, thus increasing the energy gain. This is important because this self-guiding obviates the need to provide external guiding, simplifying the concept for practical applications.

2. Plasma acceleration of ions

In contrast to Budker and Veksler's early idea of using an external medium-energy electron beam to create collective fields in a plasma to accelerate ions, the current focus is on firing a powerful laser pulse on a solid target to generate such an electron beam. The ponderomotive force (of the laser pulse) forces the electrons through the thin target. As the electrons exit the target they generate a large space charge electric field that can drag the ions either through the target or from the rear surface of the target. This latter effect is often referred to as the target normal sheath acceleration (TNSA) mechanism [8]. The conversion efficiency of transferring laser pulse energy into that of high-energy ions can be very high. Also, while being accelerated the space charge repulsive force that would transversely blow the ions apart is at least partially compensated for by the co-propagating plasma electrons. Combined with the small source size, the transverse emittance of the ions can thus be rather small. There are several practical applications that could utilize laser-produced ion beams, such as hadron therapy in oncology, injectors for proton accelerators, isotope generation for nuclear medicine and proton radiography [9].

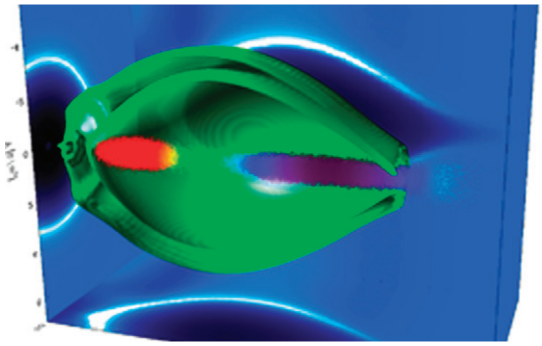

Figure 1. Three-dimensional PIC code simulation of the excitation of a wakefield (green) in the so-called bubble regime by an optimal high-current electron bunch. A trailing bunch of electrons (red) is accelerated by the wakefield. Figure used with the kind permission of C Huang and S Martins, and also FACET.

In many laser–solid target interaction experiments, high-energy ions are often seen in both forward and backward directions with a broad energy spectrum and often comprise protons and carbon ions irrespective of the target composition. The ion emission is dominated by hydrocarbon contamination of the target surfaces unless extreme care is taken in preparing the targets. The mechanisms that accelerate the ions can be more complex than the one described above, making this area productive and inviting for research. Among the new ideas that have been proposed for efficiently generating high-energy, monoenergetic ions is the so-called radiation pressure acceleration [10]. Here, the ponderomotive force of a high-contrast, circularly polarized laser pulse adiabatically pushes both the electrons and ions comprising an ultrathin target. Conclusive experimental verification of this idea is awaited with much interest.

3. Recent developments: laser wakefield accelerators (LWFA)

The rapid progress witnessed in LWFA development has to do with more and more groups worldwide having access to tens of TW, tens of femtosecond titanium–sapphire lasers. This pulse duration is of the order of the wavelength of the wake at a plasma density of $8 \times 10^{18}\,\mathrm{cm}^{-3}$. This density is high enough to readily observe self-trapped electrons from an LWFA. Many groups have reported forward-directed, small divergence electron beams with a relatively narrow energy spread using such lasers [11]. Understanding of how the plasma electrons are trapped in the wake and ideas as to how to optimize the trapped charge and the energy spread are still evolving and are the subject of several papers in this focus issue [12–15]. The use of two laser pulses, which collide in the plasma, allows very nice control of the electron beam parameters (charge, energy and relative energy spread) and very good understanding of the electron beam dynamics in the accelerating plasma medium (beam loading effects). If electron energies beyond 1 GeV are needed, it is necessary to propagate short laser pulses many centimeters through a lower-density plasma. Self-guiding is not likely to sustain wakes over 10 cm because continuous diffraction of the front of the laser pulse erodes the laser pulse. The laser pulse has to be externally confined using a capillary tube or a separately created plasma channel [16–18]. Such plasma waveguides also reduce the laser power requirement for achieving a certain energy gain from an LWFA.

Until recently, there was no direct and single-shot diagnostic for observing the wakefield. This is because the wakefield is highly transient, propagating at the speed of light with a lifetime of only a few picoseconds. A frequency domain holographic technique has enabled these structures to be visualized, confirming many aspects of the nonlinear theory of LWFA [19]. Another new diagnostic that has been demonstrated is the characteristic conical pattern of the second harmonic emission in the near-forward direction by currents driven by the laser pulse in the electron sheath that envelops the ion bubble [20].

4. Recent developments: plasma wakefield accelerators (PWFA)

There are far fewer PWFA than LWFA experiments being performed worldwide. This is because there are far fewer facilities that can provide the high-current, highly relativistic charged particle beams that are needed for such experiments [21]. The two main facilities are at the SLAC National Accelerator Laboratory and the Brookhaven National Laboratory, both in the United States. PWFA development is driven by its application in high-energy physics. A very systematic study of the dependence of the wakefield amplitude as a function of plasma density and its linear scaling with length has now been carried out [22]. Theoretical models have been verified in experiments and this has led to an understanding of beam hosing [23], radiation loss [24], head erosion [25] and optimum density for a given bunch length [26]. Beam-driven PWFA experiments have now shown greater than 40 GeV energy gain in a meter-scale plasma accelerator [27]. These advances have prompted the US Department of Energy to announce a substantial increase in funding for this area of research through the establishment of a new facility called FACET at SLAC. The main goals of the PWFA experiments on FACET are to demonstrate significant energy gain by electron and positron bunches in a single, high-gradient PWFA stage while preserving the beam emittance and small energy spread and demonstrating a reasonable energy transfer efficiency [28]. Another facility for LWFA experiments, BELLA, at Lawrence Berkeley National Laboratory, has also been recently approved.

5. Recent developments: ion acceleration in laser plasmas

There is currently much activity in the area of radiation pressure acceleration. The goal of this work is to optimize the target thickness, shape and composition for given laser pulse parameters [29]. Researchers are still trying to understand the details of the TNSA mechanism, such as the divergence angle of the ions and the effect of the laser focusing conditions on ion emission [30, 31]. One-, two- and three-dimensional particle-in-cell (PIC) code simulations are being carried out to estimate the effect of laser pre-pulse, polarization and pulse length on the ion energy and momentum spread [32]. What is a little surprising is that recently published reports on the observation of quasi-monoenergetic emission of ions from structured targets [33, 34] have not been extended/repeated by other groups, given the importance of obtaining a monoenergetic ion beam for future applications.

6. Conclusion

Laser- and beam-driven plasma acceleration is a very vibrant field, as evidenced by the many new developments reported in this focus issue of *New Journal of Physics*.

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