Surfing Plasma Waves: A New Paradigm for Particle Accelerators*)

Chandrashekhar JOSHI

UCLA, Electrical Engineering Department, Los Angeles, CA 90095-1594, USA

(Received 26 August 2008 / Accepted 6 February 2009)

Accelerator-based experiments have produced key breakthroughs in our understanding of the physical world. New accelerators, to explore the frontiers of Tera-scale Physics, appear possible, based on concepts developed over the last three decades in multi-disciplinary endeavors. The Plasma-Based Particle Accelerator is one concept that has made spectacular advances in the last few years. In this scheme, electrons or positrons gain energy by surfing the electric field of a plasma wave that is produced by the passage of an intense laser pulse or an electron beam through the plasma. This talk reviews the principles of this new technique and prognosticates how it is likely to impact science and technology in the future.

Keywords: plasma wakefield accelerator, laser, relativistic electron beam, tera-scale physics

DOI: 10.1585/pfr.4.045

1. Introduction

More than a decade before Moore's law, depicting the number of transistors on an integrated circuit versus time was postulated, Livingston had graphed a similar relationship for maximum energies produced by high-energy particle accelerators. The updated version of the plot depicted in Fig. 1 came to be known as the Livingston curve. Since its first appearance in 1954, the Livingston curve has been the barometer of the future vitality of the field of high-energy physics much in the same way as Moore's law has been for the semiconductor industry. As did Moore's law, the Livingston curve showed that between 1930 and 1980 the maximum energy of electron accelerators roughly increased by a factor 10 per decade while the cost of increasing the energy dramatically went down roughly the same factor. The exponential increase depicted by the Livingston curve was possible because of continuous technological innovations for acceleration and focusing of charged particles as the existing technologies showed signs of maturity.

Now it appears that we are once more facing a dead-end. Unless an entirely new paradigm is successfully introduced very soon, International Linear Collider (ILC), the largest and arguably the most expensive accelerator based on the mature radio-frequency technology, will perhaps be the last of these gargantuan machines ever built. And yet it is ironic that according to the National Research Council's decadal survey of Elementary Particle Physics [1], accelerator-based experiments that require particle energies even beyond the reach of the ILC will be needed to answer some of the most intriguing questions of our time

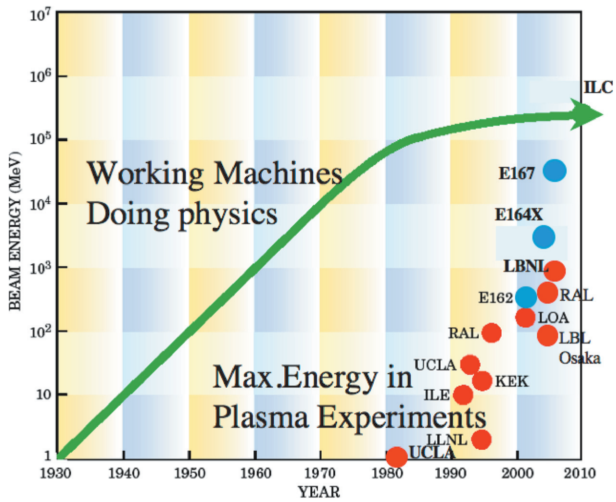

Fig. 1 Accelerator Moore's law. The exponential growth of electron beam energy, first noted by Livingston (green curve), began tapering off around 1980 as conventional radio-frequency technology approached its limits. The extrapolation beyond 2010 shown with the arrow is the proposed 250 GeV beam of the International Linear Collider. Progress toward a more radical solution offered by Plasma Accelerators, that might eventually exceed the current energy frontier of high energy physics defined by the ILC, is indicated by red dots (laser experiments) and blue dots (electron beam-driven experiments). The green line represents the maximum beam energy achieved by accelerators doing high energy physics whereas the circles show the maximum energy of electrons observed in laboratory scale experiments.

such as: Do space and time have extra dimensions? And what is the nature of dark matter and can it be produced in the laboratory? This new regime for experiments at the en-

author's e-mail: joshi@ee.ucla.edu

*) This article is based on the invited talk at the 14th International Congress on Plasma Physics (ICPP2008).

ergy frontier of particle physics is called terra-scale physics because the total energy at the center of mass of collision of two charged particles is greater than one trillion electron volts (10^{12} eV).

The end of the roadmap for high-energy accelerators depicted in Fig. 1 was anticipated as early as in the 1980s. The U.S. Department of Energy began a bold initiative to revisit the fundamental principles of particle acceleration. It is intuitively obvious that any method that leads to emission of radiation by electrons must also accelerate electrons if run in reverse order. However, not all processes that emit radiation are equally or indeed sufficiently efficient. On the other hand Gauss' law tells us that separation of high concentrations of opposite charges will produce extremely large electric fields, a necessary condition for accelerating charged particles. There has been major progress in the last few years in generating and controlling such "extreme collective fields" produced by space-charge density waves in plasmas and using them to accelerate electrons [2]. These breakthroughs give hope that an alternative technology needed to keep the Livingston curve back on track may be in the offing.

The simplest example of a collective accelerator is capacitor with an electric field E_z caused by separation of positive and negative charges by a distance d. This electric field exerts a force on a stationary electron that is injected just inside the negatively charged plate. The electron is attracted and therefore accelerated to the positive plate and gains energy $W_{\max} = -eE_z d = V$ electron volts. In this case the energy gain is limited by the separation distance d of the charges.

If one were to move the capacitor plates synchronously with the accelerating electron then the electron can never catch up with the positive plate and continues to gain energy. Now the energy gain $W_{\max} = -\int_0^L eE_z \mathrm{d}z$ where L is the length the electron interacts with the field. As the electron energy increases, its velocity very quickly approaches c, the speed of light. For example even a 50-kilovolt electron has a velocity of $0.3c$. Clearly, it is unfeasible to move a physical object such as a capacitor at such high velocities in order to produce synchronous electric fields to accelerate electrons.

2. Plasma Wakefield Acceleration (PWFA)

This is where space-charge density waves in an ionized gas or plasma come in [3]. Normally plasma is charge neutral with equal densities of electrons and ions. Now imagine that the density of plasma electrons is forced to vary sinusoidally along z but the more massive ions form a uniform density background as shown in Fig. 2. This charge separation of electrons and ions can be viewed as the creation of multiple capacitors. These capacitors however have microscopic dimensions because the wavelength and transverse size of such a wave is typically one mm or less. The ions exert a space-charge restoring force on the electrons causing them to oscillate around their equilibrium position with a characteristic frequency ω_{p} which is called the plasma frequency. This space-charge density wave, also called a plasma wave, has a phase velocity which has the usual definition, $v_{\mathrm{ph}} = \omega_{\mathrm{p}}/k_{\mathrm{p}}$ where k_{p} is the wavenumber of the plasma wave given by $2\pi/\lambda_{\mathrm{p}}$ where λ_{p} is the wavelength of the wave. Now if we can make λ_{p} such that $v_{\mathrm{ph}} \cong c$ then we have a wave which has a relativistic phase velocity. To "catch" this wave and gain energy from it, the injected electrons have to be moving close to the speed of light to begin with, much in the same way as a surfer has to be moving with a speed close to that of an ocean wave to catch the wave. According to Einstein's special theory of relativity, once the particle's velocity approaches c, further increase in its energy is due to an increase in its mass. Therefore once the particle catches the relativistic plasma wave, the particle's velocity asymptotes to c which means that it remains synchronous with its electric field for a very long distance and therefore gains a very significant amount of energy from it.

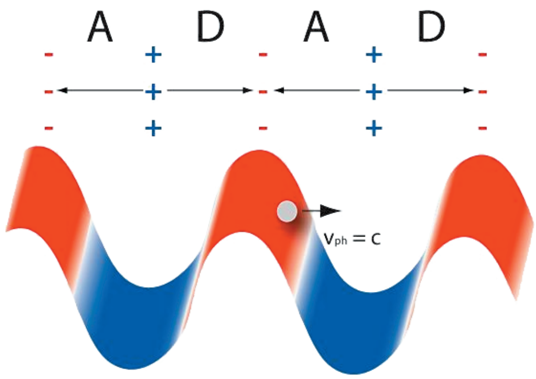

Fig. 2 A space charge density wave in a plasma is a sinusoidal variation of plasma electron density. Such a wave looks like a series of capacitors with electric fields that are accelerating(A) and decelerating(D) for an externally injected electron (white ball) in the wave. For a large gain in energy the wave must have a phase velocity close to the speed of light.

It is easy to see why the electric field E_z of such a plasma wave is extremely high in the first place. One can use Poisson's equation $\underline{\nabla} \cdot \underline{D} = \rho$ to estimate the maximum electric field that can be generated if the charge density ρ is equal to the plasma electron density n_{e}. This means that in the crest of the wave the electron density is twice its value in the initially charge neutral plasma and in the trough of the wave there are only plasma ions left. If such a wave can be made to have a phase velocity of c we find that $E_{z,\max} \cong \sqrt{n_{\mathrm{e}}}$ V/cm. Using a typical value of $n_{\mathrm{e}} = 10^{17}$ electrons per cm^3, one obtains $E_{z,\max} \cong 30$ GeV/m. This electric field is approximately one thousand times larger than that produced by a moving radio-frequency electromagnetic wave in a conventional accelerator. If one could create such a plasma wave over a distance of a few tens of meters, one could obtain particle energies needed to do terra-scale physics. This then is the principal motivation for intense research in plasma-wave accelerators.

Toshiki Tajima and the late John M. Dawson of UCLA first suggested how such relativistic waves might be excited in a plasma [4, 5]. In an extremely nonlinear avatar of their original idea shown in Fig. 3, an intense but short pulse of relativistic electrons or photons is sent through a plasma. It pushes away plasma electrons because of the space charge repulsion force of the electrons or the radiation force of the photons [6, 7]. This leaves a column of positively charged ions behind. The plasma ions however, attract the plasma electrons back toward the axis where they overshoot and form a structure that resembles a series of bubbles strung together. The sheath of the bubble is formed by the flow of plasma electrons and the space within the bubble is filled with plasma ions. Although the resulting structure is three dimensional, it can be thought of as a series of capacitors. The phase velocity of this structure is tied to the velocity of the drive beam pulse, rather like the wake of a motorboat that is tied to the boat. This is why the electric field of such a wave in plasma is often referred to as the wakefield and the acceleration scheme is known as the Plasma Wakefield Accelerator (PWFA) [8].

Experiments using lasers to excite the plasma wakefields have produced very impressive results. These have shown that electron beams with low divergence angles and narrow energy spreads can be generated with energies in the 1 GeV [9–11] range from plasma in a distance of about one centimeter. The titanium-sapphire lasers needed to produce such beams have tens of terawatts of power but the accelerator itself is extremely compact. The beam parameters are well suited for many applications that require "table-top" accelerators including in nuclear medicine, cancer therapy, structural biology and material science [12].

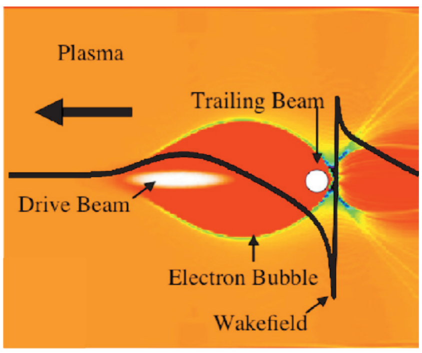

Fig. 3 Three dimensional computer simulation of an extremely nonlinear wakefield (black curve) excited in plasma by either an electron or a photon drive beam. The plasma electrons have been completely blown out of the red region by the drive beam. A second distinct trailing beam is placed where the wakefield is negative and is accelerated by it. The arrow shows the direction of the drive beam.

3. Recent Results on PWFA

There has been spectacular recent progress in electron beam-driven plasma accelerators [13]. A collaboration of scientists from UCLA, University of Southern California and Stanford Linear Accelerator Center (SLAC) have demonstrated what most scientists in the field thought was just a dream only a couple of years ago. They doubled the energy of 42 billion volt electrons using the Plasma Wakefield Accelerator (PWFA) that was only about one meter in length [14].

In this demonstration of a "plasma energy doubler" the experimenters sent a dense, ultra short pulse of electrons produced by the SLAC linac through a one-meter long column of lithium vapor. The space-charge force of the leading edge of the beam is intense enough to ionize the outermost electron of the lithium atom, creating fully an ionized plasma. The bulk of the electrons in the drive beam lost energy in expelling the plasma electrons and exciting the wakefield depicted in Fig. 3. The positive electric field acts to slow down most of the beam electrons however, the electric field changes sign towards the back of the bubble as the plasma electrons return back toward the beam axis. The beam electrons toward the end of the drive beam pulse experience the negative field and are accelerated by it. Since the beam particles are all ultra-relativistic there is no relative motion between the accelerating beam electrons (their mass is increased) and those that loose energy (their mass is reduced).

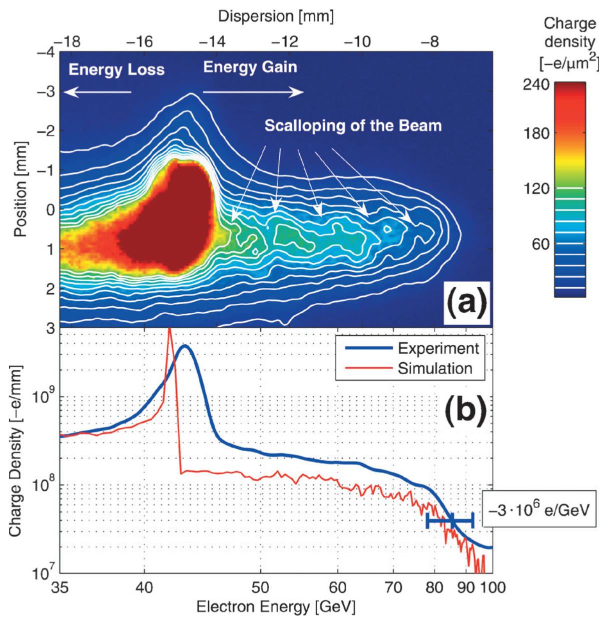

Fig. 4 (a) The energy spectrum of the initially 42 GeV electrons after passing through an approximately one meter long plasma observed in recent experiments at SLAC (b) A comparison between the measured spectrum and the simulated spectrum showing that some electrons are accelerated out to 85 GeV energy. (Blumenfeld *et al.*, Nature vol.445, p.741, 2007)

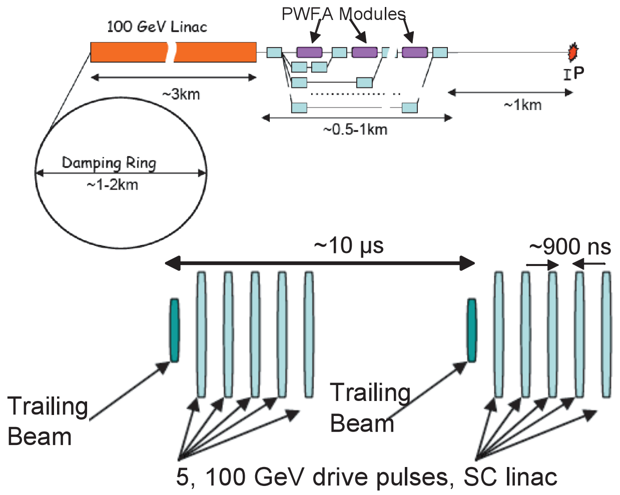

Fig. 5 One arm of a 500 GeV (1 TeV center of mass), multi-stage plasma wakefield accelerator (top). A 100 GeV superconducting (SC) linac is used to generate the multi-bunch pulse structure needed to drive each 100 GeV energy gain PWFA module (bottom).

The energy spectrum of the beam measured after the plasma is shown in Fig. 4. In this spectrum the electrons that lost energy in driving the wake are mostly dispersed out of the field of view of the spectrometer camera and thus are not seen. However, accelerated electrons in the back of the same pulse are seen to reach energies of up to 85 GeV. This is a truly remarkable result when one remembers that it takes the full 3 km length of the SLAC linac to accelerate electrons to 42 GeV but some of these electrons can be made to double their energy in less than one meter. This is the first time a plasma accelerator is shown to give energy gains of interest for particle physics.

There is much to do before one can declare that we have a viable alternate technology for building future particle accelerators. It is generally accepted that all future machines beyond the Large Hadron Collider, now under construction at CERN in Switzerland, will be linear electron-positron colliders. Plasma accelerators therefore need to demonstrate that plasmas can accelerate positrons as rapidly as it can electrons [15]. It is also imperative to demonstrate that plasmas can accelerate a sufficient number of electrons and positrons with a sufficiently small angular and energy spread so that they can be focused to sub-micron spot sizes at the collision point of the device.

The next key development is the "staging" of two plasma-accelerator modules. For high-energy physics applications each module should be designed to add on the order of 100 GeV energy to the accelerating beam. Given the microscopic physical size of the accelerating structure, it is probably a wise strategy to minimize the number of plasma acceleration stages. For 1 TeV center of mass energy, one can envision a superconducting linac producing a train of 5, 100 GeV drive pulses at a system repetition rate of 100 kHz. The individual pulses are separated by about 1 μs, but contain three times the charge of the trailing beam pulse that is being accelerated. As shown in Fig. 5 the drive pulses are first separated from one another and subsequently brought back where they are collinear with the accelerating beam [16]. Each pulse drives one stage of the PWFA from which the accelerating beam gains 100 GeV energy. The ten meter long PWFA module acts as a transformer. It increases the voltage (energy) of the accelerating beam by a factor of two each time at the expense of the current. Both electrons and positrons are accelerated in this manner. This scheme is called a Plasma Afterburner, in analogy to the afterburners used on jet engines to provide the added thrust.

Theory shows that there are no showstoppers, only extreme practical challenges in attaining the needed milestones to realize the full potential of plasma accelerators. It would not be an exaggeration to say that success in meeting these challenges would mean continued progress in our understanding of the nature of the physical world in the 21st century.

[1] *Revealing the Hidden Nature of Space and Time* (The National Academy Press, 2000).
[2] C. Joshi, Phys. Plasmas **14**, 055501 (2007).
[3] C. Joshi, Nature **311**, 525 (1984).
[4] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979).
[5] P. Chen *et al.*, Phys. Rev. Lett. **54**, 693 (1985).
[6] J.B. Rosenzweig, Phys. Rev. A **44**, R6189 (1991).
[7] A. Pukhov and J. Meyertervehn, Appl. Phys. B: Lasers and Optics **74**, 355 (2002).
[8] C. Joshi, Sci. Am. **294**, 40 (2006).
[9] C.G.R. Geddes *et al.*, Nature **431**, 538 (2004).
[10] J. Faure *et al.*, Nature **431**, 541 (2004).
[11] S. Mangles *et al.*, Nature **431**, 535 (2004).
[12] C. DesRosiers *et al.*, Phys. Med. Biol. **45**, 1781 (2000).
[13] C. Joshi, Cern Courier **47**, 28 (2007).
[14] I. Blumenfeld *et al.*, Nature **445**, 741 (2007).
[15] B. Blue *et al.*, Phys. Rev. Lett. **90**, 214801 (2003).
[16] V. Yakimenko and R. Ischebeck in *"Advanced Accelerator Concepts,"* AIP Conf. Proc. **877**, 158 (2006).