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Progress on plasma accelerators: from the energy frontier to tabletops

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Abstract

This paper reviews the concepts, recent progress and current challenges for realizing the tremendous electric fields in relativistic plasma waves for applications ranging from tabletop particle accelerators to high-energy physics. Experiments in the 1990s on laser-driven plasma wakefield accelerators at several laboratories around the world demonstrated the potential for plasma wakefields to accelerate intense bunches of self-trapped particles at rates as high as $100\,\mathrm{GeV\,m^{-1}}$ in millimetre-scale gas jets. These early experiments have been followed in the current decade by experiments that are advancing on several fronts—increasing the accelerated charge (to the several nanocoulomb level), producing higher transverse beam quality (to the mm mrad normalized emittance level) and accessing new physics regimes at higher laser power. Several groups are engaged in pursuing two key challenges for laser wakefield accelerators—producing beams with small energy spread and extending the interaction length from millimetres to centimetres and beyond. Major breakthroughs on both fronts have occurred in the past year. In parallel with the progress in laser-driven wakefields, particle-beam driven wakefield accelerators are making large strides. A series of experiments using the 30 GeV beam of the Stanford Linear Accelerator has demonstrated high-gradient acceleration of electrons and positrons in metre-scale plasmas as well as key scaling laws for a 'plasma afterburner', a concept for doubling the energy of a high-energy collider in a few tens of metres of plasma. In addition to wakefield acceleration, these and other experiments have demonstrated the rich physics bounty to be reaped from relativistic beam–plasma interactions. This includes plasma lenses capable of focusing particle beams to the highest energy density ever produced, collective radiation mechanisms capable of generating high-brightness x-ray beams, collective refraction of particles at a plasma interface and acceleration of intense proton beams from laser-irradiated foils.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

This paper is an update to a recent review article in *Physics Today* [1]. After a brief discussion of current particle accelerators, it reviews the concepts and rationale for accelerating particle beams in plasmas. Recent results are used to illustrate the rich plasma physics and current status of research in this emerging field.

Particle accelerators are among the largest and most successful machines built by humans. Since the first cyclotron in the 1930s, the maximum energy of accelerated particles has grown at a Moore's law pace for 50 years. Their success has lead to profound advances in elementary particle and nuclear physics as well as important applications in industry and medicine. Accelerators have verified the Standard Model of particle physics and revealed the character of quarks and gluons, replicated conditions at the early moments of the big bang, including recently a quark–gluon plasma state of matter, and discovered the small asymmetry between matter and anti-matter responsible for what remains of the universe after the big bang. Currently, the 27 km Large Hadron Collider under construction at CERN in Geneva is in pursuit of the Higgs boson, the particle responsible for setting the scale of the mass of all other known particles. At more compact scales, particle accelerators are the principal device in medicine for cancer therapy (both radiation therapy and proton therapy), are used to produce the isotopes used in PET scans, are used in semiconductor lithography and to safeguard mail from possible contamination by anthrax spores.

But the progress on large accelerators has slowed in recent decades (see figure 1) as accelerators have reached tens of kilometres in size and billions of dollars in cost. For both large and small applications, society will derive a great benefit from new accelerator technology that is more compact and less expensive.

To understand the rationale for plasma-based acceleration, consider the limits of conventional particle accelerators based on radio-frequency (rf) waves propagating in corrugated metallic cavities. They are limited first by the availability of high peak power drivers and ultimately by electrical breakdown of the metal structure. These factors correspond to linear accelerating gradients of 20–100 $\mathrm{MeV\,m^{-1}}$. Plasmas, on the other hand, are not limited by breakdown as they are already ionized and indeed support electric fields of the order 10–100 $\mathrm{GeV\,m^{-1}}$, suggesting the potential for creating accelerators three orders of magnitude more compact.

However, accelerating gradient is only one requirement for a practical accelerator. Principal among the other requirements are the luminosity given by

$$L = \frac{fN^2}{4\pi\sigma_x\sigma_y}, \tag{1}$$

where f is the repetition rate, N is the number of particles in a particle bunch and the σ are the spot sizes in the transverse coordinates. For a high-energy collider, this parameter L is proportional to the event rate for the physics processes of interest. Typical linear collider designs have bunches with of the order of 10^{10} particles—a few hundred picocoulumbs to a few nanocoulumbs. In addition to luminosity, the beam must have high beam quality as measured both by its energy spread and its transverse temperature. The energy spread desired ranges from 0.1% to 10% depending on the type of physics event to be studied. The transverse beam quality is characterized by its normalized emittance ε_{N}, proportional to the area of transverse beam phase space and roughly given by the beam spot size times its angular divergence θ times its Lorentz factor γ. A typical value of the normalized emittance from state-of-the-art photocathodes is 1 mm mrad. As will be seen in this article, the field of plasma accelerators has made major strides in the past year on all of these major requirements. Finally, for collider

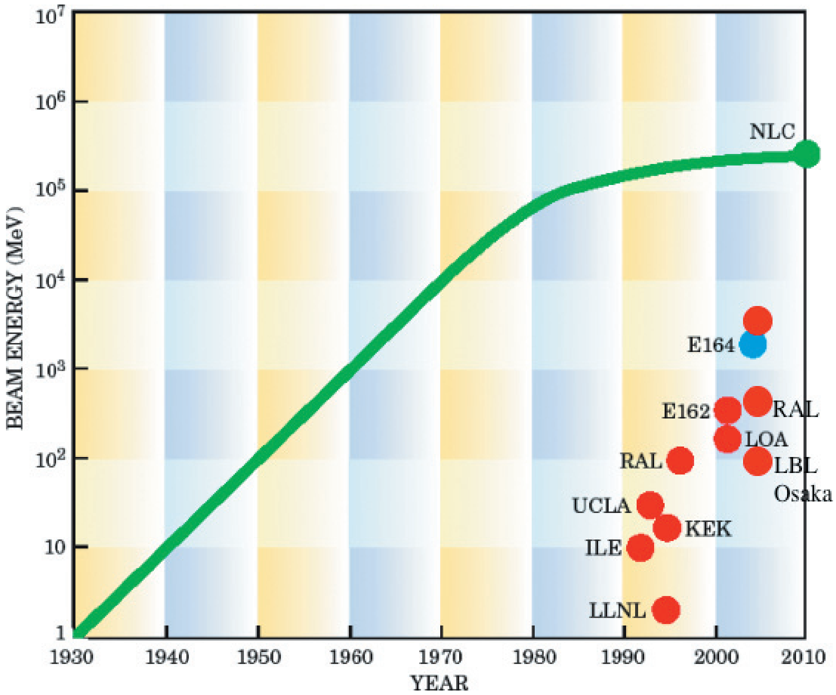

Figure 1. The progress in accelerator energy versus year since the first cyclotron in the 1930s shows exponential progress until recent decades. The progress on acceleration in plasmas is illustrated by representative experiments (circles).

applications, the energy in the beams is considerable, so that reasonable operating cost requires an overall efficiency of a few per cent.

1.1. Concepts for plasma acceleration

Two related concepts for realizing a high-gradient plasma accelerator proposed by the late John Dawson are the beam plasma wakefield accelerator (PWFA) [2] and laser wakefield accelerator (LWFA) [3]. In each case, a short (pulse duration less than half a plasma period) relativistic pulse creates a wake in the plasma by displacing plasma electrons in much the same way that a boat creates an ocean wake by displacing water. In the plasma case, the massive ions are relatively immobile and provide the restoring force to the displaced electrons. In the beam-driven PWFA, it is the space charge force of a beam that displaces the plasma electrons, while in the laser case it is the pondermotive force or radiation pressure that does it. In either case, the wake phase velocity (ω/k) is the speed of the driver—approximately c. Thus, a second group of relativistic particles can surf on the wake and remain in phase with it for some distance.

Analytically, a sense of the amplitude of the wakes can be obtained readily from the linearized cold fluid plasma equations (see [4] and references therein). Substituting Gauss' law and the momentum equation into the time derivative of the continuity equation yields the simple harmonic oscillator equation for the perturbed density wake:

$$(\partial_t^2 + \omega_p^2)\frac{n_1}{n_o} = -\omega_p^2\left(\frac{n_b}{n_o} + k_p^2\nabla^2\sqrt{1+a_o^2}\right), \tag{2}$$

where the terms on the right represent the effect of a drive beam of density $n_b = n_b(t - z/c)$ and a laser of normalized amplitude $a_o = eE/m\omega c$ and frequency ω. a_o is also commonly denoted V_{osc}/c, the non-relativistically defined quiver velocity of an electron in the laser field. From equation (2), it is apparent that large wakes (perturbed density n_1 approaching the plasma density n_o) may result when n_b is of order n_o and/or a_o is of order 1. To see that this results in a large accelerating field, we simply substitute the solution to equation (2) into the one-dimensional Gauss' law ($\mathrm{d}E/\mathrm{d}z = -4\pi e n_1$) and integrate once with the result

$$eE = \frac{n_1}{n_o}\sqrt{\frac{n_o}{10^{16}\,\mathrm{cm}^{-3}}}\,10\,\mathrm{GeV\,m}^{-1}\cos\omega_p\left(\frac{t-z}{c}\right). \tag{3}$$

To estimate the maximum energy of a group of surfing particles (a beam load), we multiply by the acceleration length: $W_{max} = eEL_{acc}$. For lasers there are three principal limits on L_{acc} and energy gain—laser diffraction, particle dephasing and laser depletion. Laser diffraction is typically the shortest, a few times the Rayleigh length given by $\pi w^2/\lambda$ where w is the laser spot size and λ its wavelength. This is often of the order of millimetres or less, but can be overcome with relativistic self-focusing and plasma channels of lower density on axis, the index of refraction being higher in the lower central region (as in an optical fibre).

The second limit on acceleration length is due to the dephasing between the accelerated particles ($v \approx c$) and the laser pulse ($v = v_{gr} = c[1 - \omega_p^2/2\omega^2]$). The distance over which particles slip by a quarter of a plasma wavelength is of the order of 10 cm at a density of $10^{16}\,\mathrm{cm}^{-3}$ and decreases as one over plasma density. Again, this limit can be overcome in principle with a rising plasma density ramp or a magnetic field. However, for $a_o \sim \mathrm{O}(1)$, the third limit—laser energy depletion—is of the same order. This limit is fundamental and in fact desirable to reach as doing so implies that the laser energy has been efficiently converted to the plasma. This limit corresponds to an energy gain in a single stage of the order of $W_{max} \sim 50\,\mathrm{MeV}\ \eta\ (P\ \mathrm{TW})$ for a laser of power P and spot size approximately equal to the plasma wavelength ($\lambda_p = 2\pi c/\omega_p$) and conversion efficiency factor η (<1).

2. Recent results

2.1. Laser wakefield acceleration

Most current experiments do not operate in the classical laser wakefield regime described above in which the pulse length is $\lambda_p/2$. At high enough densities for relativistic focusing and channel production mechanisms to operate, lasers are still not short enough (e.g. 15 fs at $n = 10^{19}\,\mathrm{cm}^{-3}$); thus much recent work has used pulses a couple of λ_p long. These pulses quickly self-modulate due to a combination of effects (e.g. head diffraction causes steepening, increasing the pondermotive force and pump depletion locally, further steepening and shortening the pulse and driving a larger and larger wake). Thus part way through the plasma, the pulse evolves or is 'forced' to the laser wakefield regime described above.

An example of the results of such an experiment was reported by the LOA group in France [5]. Similar results have been reported by groups at RAL in the UK, NRL in the US, U. Michigan and LBNL in the US [6–9]. A two temperature Maxwellian distribution is typical of the accelerated energy spectra—i.e. 100% energy spread. Nevertheless, energy gains above 200 MeV from a millimetre long gas jet ($eE > 200\,\mathrm{GeV\,m}^{-1}$) have been measured. The beam is also shown to be well collimated at high energies. Recent work by the RAL group has shown that the normalized emittance of the higher energy particles is of order 1 mm mrad [10].

2.1.1. Mono-energetic beams. Within the past year, a breakthrough was reported by three laboratories independently: LOA, LBNL and RAL/Imperial College [11–13]. Each obtained

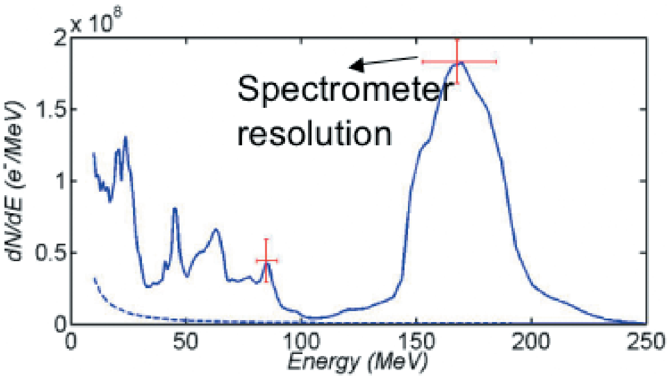

Figure 2. Energy spectrum of accelerated electrons in a recent LWFA experiment showing a mono-energetic beam feature at 170 MeV [11].

a collimated beam with significant energy and charge in a narrow energy band of less than a few per cent—in other words a true beam (see figure 2). The results are consistent and suggest that beams of order 100 MeV with hundreds of picacoulombs of charge can be obtained by properly choosing the length and density of the experiment.

Recent simulations by the OSIRIS and Vorpal consortia and A Pukhov help to make clear the physics leading to this remarkable result. The sequence of events can be described in four stages: (1) the laser self-modulates forming a large enough wake to (2) trap particles from the plasma, (3) the beam load of these particles is sufficient to reduce the wake below the threshold for trapping additional particles, and (4) this single bunch of particles accelerates together and dephases from the wake near the end of the plasma. If the plasma is too long or the density too high for a given length, the particles completely dephase and the mono-energetic beam is lost. This work is described in detail in manuscripts recently submitted by the experimental groups [11–13].

2.1.2. Channelling. A considerable body of work has been devoted to the topic of channel guiding of LWFAs to overcome laser diffraction [14]. The approaches vary from pre-heating the gas on axis with one or more lasers and guiding in the expanding shock structure that results to the use of capillary tubes with and without gas and external discharges. Two groups, LBNL and Osaka, Japan have reported 100 MeV acceleration in gas and a hollow capillary, respectively. The development of lower density channels will likely lead the way to energy gains at GeV levels in the near future.

2.2. Laser acceleration of protons and ions

The phase velocity of wakefields in underdense plasma ($\omega_p < \omega$) is too fast to trap and accelerate protons or ions of modest energy. Instead dense plasmas produced from solid targets are used for accelerating heavy particles. Several mechanisms for accelerating protons and ions can occur in the front, centre and backside of the solid (foil) targets. The backside mechanism is ubiquitous and occurs as follows: the laser first heats electrons to relativistic temperatures. Their expansion off the back surface creates a large positive space change force ($eE \sim kT_e/\lambda_d$) that causes a Coulomb explosion of the ions and a further acceleration of ions in the expanding ambipolar sheath that results. The optimized energy gain is of the order of 1–100 MeV and for a large number of experiments the trend in peak energy can be approximated by $W_{\max} \approx 5\,\mathrm{MeV}\,(\sqrt{I/10^{19}\,\mathrm{W\,cm^{-2}}})\,(\lambda/1\mu)\ln 2\omega_{\mathrm{pi}}\tau_{\mathrm{p}} \sim 3$–$6\,\mathrm{MeV}\,a_{\mathrm{o}}$, where I is the laser intensity and $\omega_{\mathrm{pi}}\tau_{\mathrm{p}}$ is the laser pulse length normalized to the ion plasma frequency [15]. Laser pre-pulse, target preparation and target thickness also play roles in final energy gains obtained.

These experiments with TW–PW (0.1–1000 J) lasers produce prodigious charge 10^{10}–$10^{13}\,e$ (1–1000 nCoul) and recently have been shown to yield very good beam quality. The LULI group in France for example have measured $\varepsilon_{\mathrm{N}} < 0.004$ mm mrad [16]. This is an order of magnitude better than conventional injectors and also is at much higher energy. Although the energy spread is large, the beam longitudinal phase space area (i.e. the longitudinal emittance) is small. That is, the energy spread is correlated with position from front to back and can be undone by appropriate phasing on a subsequent rf accelerator section. Thus the low emittance and high charge offer the possibility of very high-brightness injection for applications. The National Radiological Institute in Japan, for example, has proposed replacing the injector and 10 MeV RFQ accelerator for a proton/ion cancer therapy storage ring with a much smaller (i.e. tabletop) laser–plasma source and small rf stage [17].

2.3. Beam-driven wakefield acceleration

The peak power density available from high-energy accelerators such as the 50 GeV beam at Stanford Linear Accelerator (SLAC) can be as much as 1 PW $\mu\mathrm{m}^{-2}$, exceeding even that of the largest lasers. When such intense sources are directed at matter (invariably becoming a plasma if not already), a host of rich beam plasma physics effects occur that are only recently being revealed. These include wake fields and focusing [18], collective particle beam refraction [19], ionization, hosing and, of course, particle acceleration.

Plasma wakefield experiments with modest beams have been performed at Argonne National Lab and at Fermilab in the USA [20]. However, breakthrough results have been made possible by the development of a sophisticated plasma wakefield lab at the end of the 3 km SLAC (USA) (figure 3). A series of experiments known as E-162, E-164 and E164x by a collaboration of SLAC, UCLA and USC in California has recently demonstrated record high-gradient acceleration of electrons and positrons in plasma wakes as well as strong plasma focusing, high-brightness x-ray generation and other phenomena. Time-resolved measurements of the energy gain and loss of a 4 ps long bunch of electrons [21] as well as positrons [22] have been made in a 1.4 m long Li oven, photo-ionized to $2 \times 10^{14}\,\mathrm{cm}^{-3}$ by a UV laser (E-162). The energy loss increases from zero at the head of the bunch to $150\,\mathrm{MeV\,m}^{-1}$ in the centre (electron case). The tail of the beam surfs on the wake produced by the earlier particles to an energy of 150 MeV with some particles gaining up to 280 MeV. The goal of the E-164 experiments was to extend the acceleration and test a key PWFA scaling law predicting the optimized wake amplitude to be proportional to N/σ_z^2, where N is the number of particles in the beam and σ_z the bunch length.

In E-164 and E-164x the bunch length was reduced by a factor of 20 to approximately $\sigma_z \sim 30\,\mu$ (FWHM ~ 200 fs) by chirping the beam energy in the SLAC linear accelerator (high energy at the tail) and compressing in a magnetic chicane that causes lower energy particles to take a longer path and the higher energy tail particles to catch up to them. The preliminary results of the experiment indicate the acceleration of the tail particles by as much as 4 GeV over 10 cm of the $2 \times 10^{17}\,\mathrm{cm}^{-3}$ density plasma ($40\,\mathrm{GeV\,m}^{-1}$). This was the maximum energy acceptance of the beam line and might have been higher had the beam not begun to clip the collimators in the beam pipe.

This experiment is not only the first to surpass the GeV milestone, but also validates the prediction of detailed three-dimensional PIC simulation models and significantly advances the

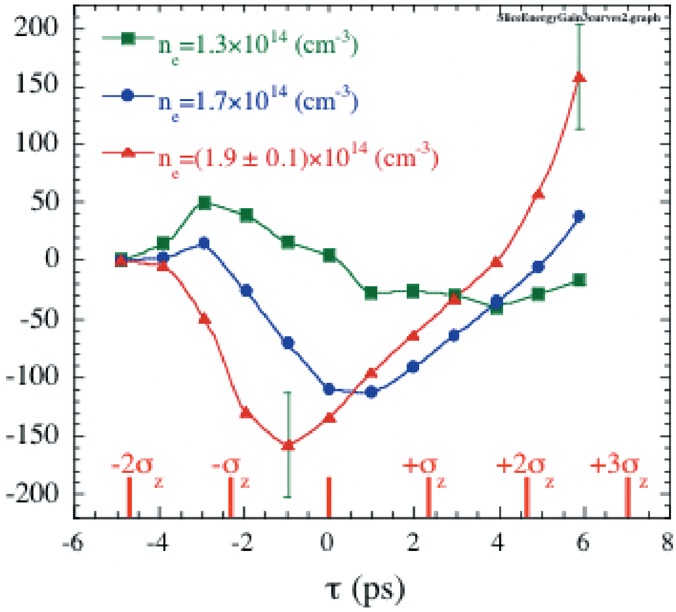

Figure 3. Time-resolved energy change in MeV of 28.5 GeV electrons in the E-162 plasma wakefield acceleration experiment at SLAC/UCLA/USC [20] for three plasma densities. The left part of the figure corresponds to the head of the beam; acceleration of tail particles by 150 MeV is shown. There are approximately 2×10^{10} electrons in a Gaussian pulse of length $\sigma = 0.7$ mm centred at 0 ps.

effort to realize a PWFA at the energy frontier. It is a step toward realizing a concept known as a plasma afterburner [23] to double (or more) the energy of the colliding particles just before the collision point.

In summary, this has been a breakthrough year for plasma-based acceleration with major progress on many fronts. Particularly noteworthy are the first production of mono-energetic beams from LWFAs by groups at LBNL, LOA and RAL/IC, and the acceleration of plasma electrons by more than a GeV in a beam-driven wakefield accelerator at SLAC. With these results and several other innovative ideas for improving beam quality and energy gain described here, plasma accelerators are progressing rapidly toward realization in devices at the energy frontier and on tabletops.

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