Laser Plasma Accelerator (LPA) – Literature Review

N. N. Gosai

Associate Professor, Department of Nanoscience and Advanced Materials, Saurashtra University, Rajkot 360 005, Gujarat, India

**E Mail: nitin_gosai86@yahoo.com*

ABSTRACT: This review describes about particle accelerators and laser, especially a generation of intense laser pulses. For present-day light sources they are used to drive photo cathodes in high-brightness electron guns; to control and measure beam properties; and to seed the amplification process in the latest generation of light sources that rely on electron-beam-based free-electron lasers. Designs and considerations had been discussed. The electron beams generated today from laser plasma accelerators are approaching parameters that make their usage interesting for new applications. The use of advanced electron accelerators for linear colliders is most important. In this paper author discussed the possible use of an advanced LPA as injector for the LHeC. The application for the ring-ring option of the LHeC is indeed not fully excluded and could be used to demonstrate gains in size and cost with the new technologies, while developing them to full maturity for linear collider applications. Required R&D studies would involve the study of injection with ultra-short bunches into a storage ring.

Key words: LPA, Plasma, Beam – beam interaction and electron positron collider.

1 Introduction

Particle accelerators and lasers have made fundamental contributions to science and society, and are poised to continue making great strides in the 21st century. Lasers are essential to modern high performance accelerator facilities that support fundamental science and applications, and to the development of advanced accelerators. In accelerator and radiation science, which aims at developing advanced acceleration and radiation source concepts, lasers provide the power for laser plasma accelerators or dielectric-structure-based direct-laser accelerators. For present-day light sources they are used to drive photo cathodes in high-brightness electron guns; to control and measure beam properties; and to seed the amplification process in the latest generation of light sources that rely on electron-beam-based free-electron lasers. (At the user beam lines of light sources, they are also widely used in pump-probe experiments.) Lasers are also used in radiation sources, such as those producing high harmonics in gases, or those producing intense gamma-ray beams via inverse Compton or Thomson scattering against relativistic electron beams. Medical applications are emerging that rely on laser produced particle and radiation beams that offer the potential to be compact and cost effective.

1.1 Power: Improvements in average and peak power are needed for all of the application areas under consideration, especially colliders for high-energy physics. Advances in these parameters made on behalf of the accelerator community will have spinoff benefits for other uses. In turn, accelerators should benefit from laser advancements made for other purposes, though unique requirements indicate that the accelerator group would benefit from a dedicated R&D effort.

1.2 Efficiency: To deploy and continue to advance accelerators and radiation sources, the accelerator field will need not only high average power and high peak power lasers, but also high ―wall-plug efficiency.

1.3 High Power Optics: Laser components and optics that can withstand high-average-power operation will be crucial to these advances.

1.4 Multi-way, interactive R&D cooperation: Engagement of the national labs, universities and industry will be essential for comprehensive R&D of new materials and new architectures for lasers, as well as for novel concepts in acceleration and radiation generation.

Generation of intense laser pulses

The application of CPA techniques to generate high power laser pulses originated from the work of Mourou and co-workers. Previously this technique was used in microwave (radar) applications. The basic concept behind CPA is to increase the power of pulsed laser beams during the amplification process in such a way that at any step the beam power lies below the damage threshold of the optical materials in the laser. This is achieved first by lengthening the pulse in time, thus reducing the energy density in the pulse which then can be amplified without reaching the damage threshold. At the end of the amplification processes the pulse is compressed back in time to reach its original temporal width resulting in a high peak power, ultra short laser pulse.

The working of CPA scheme is explained in Fig. (1) The ultra short (» 10^{-13} – 10^{-14} sec) low energy (» 10^{-9} J) laser pulse is generated using a mode locked laser at high repetition rate (» 10^{8} Hz.). These optical pulses are then stretched in time (» 10^{-10} sec) to decrease its peak power by orders of magnitude. One such pulse is then fed to one or more amplifying stages to increase the pulse energy density thus by increasing the energy of the pulse by six to nine orders of magnitude.

Advanced acceleration techniques are actively being pursued to expand the energy frontier of future colliders. Although the minimum energy of interest for the next lepton collider will be determined by high-energy physics experiments presently underway, it is anticipated that 1 TeV energy, will be required. The laser-plasma accelerator (LPA) is one promising technique for reducing the size and cost of future colliders—if the needed laser technology is developed. LPAs are of great interest because of their ability to sustain extremely large acceleration gradients, resulting in compact accelerating structures [1-3].

Laser-plasma acceleration is realized by using a short-pulse, high-intensity laser to drive a large electron plasma wave (or Wakefield) in an under dense plasma (see Figure 1). The electron plasma wave has relativistic phase velocity – approximately the group velocity of the laser – and can support large electric fields in the direction of propagation of the laser.

Design Considerations for Laser-Plasma Colliders

The beam-beam interaction at the interaction point (IP) of a collider produces radiation (beamstrahlung) that generates background for the detectors and increases the beam energy spread, resulting in loss of measurement precision. The beam-beam interaction is characterized by the Lorentz-invariant beamstrahlung parameter Υ (mean field strength in the beam rest frame normalized to the Schwinger critical field). The current generation of linear collider designs based on conventional technology operate in the classical beamstrahlung regime $\Upsilon << 1$. Next generation linear colliders (1 TeV) will most likely operate in the quantum beamstrahlung regime with $\Upsilon >> 1$.

Of particular interest is how the various laser and electron beam parameters characterizing a LPA-based collider scale with respect to plasma density and laser wavelength. These scaling laws, originally derived in Ref. [5], are summarized in Table 2.

A class of more-futuristic accelerators for particle physics, driven entirely by lasers, would require average laser power far exceeding today‘s state of the art. The performance of lasers has grown in dramatic ways, due to inventions such as chirped pulse amplification. Today, lasers can achieve peta watt-level peak power operating at 1 Hz; lower-energy systems (10 mJ) can operate at tens of kHz. These performance improvements have enabled a vast range of scientific opportunities, including proof-of-principle experiments on the most advanced accelerator concepts. As these laser-based techniques mature, the need for higher average power has come to the fore. Higher average power enables laboratory-tested concepts to be turned into facilities: light sources that serve a broad range of users; industrial and medical applications; or the most demanding of all, particle colliders. Developing high average power (tens to hundreds of kilowatts), high peak power (peta watt) lasers is an extremely challenging task that will take several decades of aggressive R&D and, most likely, revolutionary new concepts and ideas. The following general issues for laser development are under establishment:

Researchers have high hopes for the benefits of 10 petawatt lasers—they could improve cancer treatment as part of new ion acceleration systems, and they could provide atto-second pulses for metrology with unprecedented precision. But designers must account for the newly modelled QED(quantum electro-dynamic) effects as they work toward these applications [4].

An intense laser pulse drives a plasma wave (wake) in a plasma channel, which also guides the laser pulse and prevents diffraction. Plasma background electrons injected with the proper phase can be accelerated and focused by the wake [1].

Rapid progress in laser-plasma accelerator research, and in particular the demonstration of high-quality GeV electron beams over cm-scale plasmas in 2006 at Lawrence Berkeley National Laboratory [4], has increased interest in laser-plasma acceleration as a path toward a compact TeV-class linear collider [5]. A conceptual diagram of an LPA-based collider [1] is shown in Figure 1.

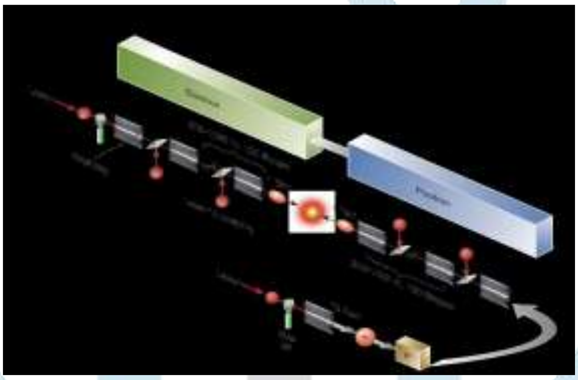

Figure 1: Concept for an LPA-based electron-positron collider.

Both the electron and positron arms start with a plasma-based injection-acceleration module where controlled injection techniques are applied to produce a high quality ~10 GeV electron beam. Electrons are then accelerated to 1 TeV using 100 laser-plasma modules, each consisting of a 1-m long preformed plasma channel (10^{17} cm^{-3}) driven by a 30 J laser pulse giving a 10 GeV energy gain. A fresh laser pulse is injected into each module. Similarly, positrons are produced from a 10 GeV electron beam through pair creation and then trapped and accelerated in a LPA module to ~10 GeV. Subsequent LPA modules would accelerate positrons to 1 TeV. A luminosity of 1034 $cm^{-2}s^{-1}$ requires 4×10^{9} particles/bunch at a 13 kHz repetition rate [1].

In the standard laser wakefield acceleration configuration, the electron plasma wave is driven by a nearly resonant laser (pulse duration on the order of the plasma period) propagating in a neutral, under dense ($\lambda p >> l$, where l is the laser wavelength) plasma. There are several regimes of plasma acceleration that can be accessed with a laser driver. Two regimes observed that have attracted attention for collider applications are the quasi-linear regime [3] and the bubble [6] (or blow-out [7]) regime. In the quasi-linear regime, the accelerating and focusing phase regions for electrons and positrons are symmetric, since the wake field is approximately sinusoidal.

Long term future of High-Energy physics requires the need for new high-gradient technology Gradients from 1GeV/m to 100 TeV/m are possible from relativistic plasma waves.

1. The **beam energy** of the electron beam must be increased by a factor of 10, to about 10 GeV. The ongoing BELLA project [36] at LBNL is targeted to demonstrate the generation of 10 GeV electron beams from a laser plasma accelerator. Its goal should be achieved within the next 2 years.

2. The **bunch population** should be increased by a factor of 10-20 beyond present achievements. Alternatively, accumulation of 10 injections per RF bucket would be required, resulting in a 10× increase in the required repetition rate. Lasers can be operated at high repetition rates.

3. The **bunch length** of the generated bunches is much shorter than required. This is, *a priori*, no problem, as the electron beam will approach its equilibrium distribution once stored. However, fast instabilities must be controlled. In particular, the transverse mode coupled instability could be a problem, as it is worsened by short bunch length.

The first two items are expected to impose no fundamental feasibility issue for a possible use in the RR option of the LHeC. The third item is an interesting problem for further accelerator physics studies that explore the injection and control of ultra-short bunches in storage rings. There is no experimental experience with such bunches and theoretical studies would be required before assessing feasibility limits in this new regime.

It is noted that only one example application has been considered in this short note, namely, the LHeC. However, other applications for high energy physics and photon science ring facilities can be envisaged—for example, top-up of electron storage rings during operation.

Tools and techniques for laser plasma accelerators

Plasmas exhibit a rich variety of oscillatory and wave-like phenomena in which charged particle motion gives rise to fields and fields result in particle motion. These wave-particle effects are employed in many particle acceleration and plasma heating methods as well as in wave generation mechanisms. Wave-particle and field-particle interactions also play a key role in particle acceleration mechanisms believed to be operating in the auroral acceleration region of the earth's magnetosphere and more generally, in the domain of space plasmas. Yet even though plasmas are often manipulated with EM waves, deriving a self-consistent model of plasma wave-particle interaction is still an outstanding fundamental problem in plasma physics, particularly when large amplitude fields are involved.

The experimental description of plasma properties under varying circumstances is a major part of the effort to develop such a treatment. This description may proceed on two different levels. On the macroscopic level, one may sometimes treat the plasma as a fluid described by the parameters of temperature, pressure, density, and flow velocity. A microscopic (or kinetic) description employs a more fundamental quantity in a plasma, the one-particle velocity distribution function f(v;x,t) of each particle species. Velocity moment integrals of the distributions connect the microscopic properties with the fluid parameters.

One approach seeing increasing application today in plasma diagnostics is laser-induced fluorescence (LIF) spectroscopy, which is based on laser excitation of transitions between quantum states of particles in plasmas. LIF has been used to measure quantities as diverse as atomic and ionic densities, ion velocities and temperatures, electron temperatures, as well as electric and magnetic fields, in both fusion and basic research plasmas. Scanning the frequency of a narrowband laser across the Doppler broadened absorption line of an ionic transition yields a direct measure of the ion velocity distribution function. The power of LIF lies in the non-perturbative nature of this diagnostic and also in the superb velocity (spectral), spatial, and temporal resolution.

Of particular relevance to this proposal is the application of LIF to the study of plasma wave-particle interactions, with significant participation and contributions by T.N. Good. A large body of research has been conducted in quiescent magnetized plasmas (in Q -machines). Researchers employing LIF have concentrated their efforts on discovering the properties of electrostatic ion cyclotron, ion acoustic, lower hybrid, and drift waves. Ion waves constitute a subset of the assortment of electrostatic and electromagnetic waves that may be supported by the plasma medium. Because ions contribute in a significant way to the dynamics of these waves, they are good candidates for an experimental inquiry of wave-particle interaction that utilizes the LIF diagnostic technique. Time scales for ion processes are slower than for those involving primarily electrons, adding advantage by making them easier to follow.

As ions respond to the wave fields via modifications of their trajectories, the ion distribution is perturbed. The ion response takes the form of a coherent oscillation and, in cases of significant absorption of wave energy, an incoherent (non-adiabatic) alteration of the ion distribution. Through the use of phase-lock techniques, or spatially localized measurements of the ion distribution synchronous with the wave field, a component of the perturbed distribution can be observed oscillating coherently with the wave. Single point detection of the phase-coherent, perturbed distribution, or spatial scanning of the velocity moments of this distribution yield measurements of wave vector and fluctuation amplitude is important. Ion heating and acceleration, typical forms of the incoherent response to ion waves, are readily detected by measurements of the ion distribution function[2]. Test-particle diagnostics, utilizing ions selectively placed into metastable or spin polarized states by optical pumping, provide a means of investigating the behavior of particle orbits.

Rapid progress in laser-plasma accelerator research has been made over the past decade (see [3] for a review). In particular, the production of high-quality GeV electron beams over cm-scale plasmas was demonstrated in 2006 at Lawrence Berkeley National Laboratory [4]. Since that time, LPA research at many facilities worldwide has demonstrated GeV-level energies. This has been enabled by guiding of the laser pulse over cm distances (tens of times the natural diffraction range of the laser) using tailored plasma density channels, which act like optical fibers and which perform self-focusing. The beams have percent level energy spread and estimates of normalized emittance are at the mm-mrad level. To further improve performance, particle injection into the micron-scale accelerator structure is being controlled via several mechanisms including wake phase velocity control using plasma density tailoring, the beat between colliding laser pulses, and ionization of high-Z species to produce electrons near the peak of the laser intensity.

This has recently produced beams which are both stable and can be tuned in energy. Continued injector and accelerator structure (guiding, laser mode, etc.) control work is in progress to further reduce energy spread and emittance. A critical technology for a LPA based collider will be staging of several modules in series. Experiments are expected to begin addressing this issue in the coming year, including the use of plasma mirrors or other techniques to minimize distance between stages and maintain geometric gradient. Also in progress are experiments to extend LPAs to 10 GeV using PW laser drivers in meter-scale plasmas.

Using the scaling laws presented in Table 1, the baseline example of a LPA collider presented in [5] can be scaled to different plasma densities and laser wavelengths. Tables show estimates of parameters for electron-positron colliders for four cases: a 1 TeV center-of-mass (CoM) collider with a plasma density of $n_0 = 10^{17}$ cm^{-3}, a 1 TeV CoM collider using a single-LPA stage with a plasma density of n0 = 2 x 10^{15} cm^{-3}, a 10 TeV CoM collider with a plasma density of $n_0 = 10^{17}$ cm^{-3}, and a 10 TeV CoM collider with a plasma density of n_0 = 2 x 10^{15} cm^{-3}. In all these cases a laser wavelength of Using the scaling laws presented in Table 2, the baseline example of a LPA collider presented in Ref. [5] can be scaled to different plasma densities and laser wavelengths. Tables 1-3 and 1-4 show estimates of parameters for electron-positron colliders for four cases: a 1 TeV center-of-mass (CoM) collider with a plasma density of $n_0 = 10^{17}$ cm^{-3}, a 1 TeV CoM collider using a single-LPA stage with a plasma density of n_0 = 2 x 10^{15} cm^{-3}, a 10 TeV CoM collider with a plasma density of n0 = 10^{17} cm^{-3}, and a 10 TeV CoM collider with a plasma density of n_0 = 2 x 10^{15} cm^{-3}. In all these cases a laser wavelength of 1 micro-meter and a laser intensity of 3 x10^{18} W/cm^2 ($a_0 = 1.5$) are assumed.

The laser-plasma accelerator parameters are based on scaling laws for the quasi-linear regime obtained from simulation codes. A mild plasma density taper is assumed. The length of one linac is of order of 0.1 km for the 1 TeV CoM, $n_0 = 10^{17}$ cm^{-3} case, and of order 1 km for the 10 TeV CoM, n0 = 10^{17} cm^{-3} case. Using a lower plasma density with a lower accelerating gradient requires a one-linac length of 0.5 km for a 1 TeV CoM collider and 5 km for a 10 TeV CoM collider = 1 m and a laser intensity of 10^{18} W/cm^2 ($a_0 = 1.5$) are assumed. The laser-plasma accelerator parameters are based on scaling laws for the quasi-linear regime obtained from simulation codes. A mild plasma density taper is assumed. The length of one linac is of order of 0.1 km for the 1 TeV CoM, $n_0 = 10^{17}$ cm^{-3} case, and of order 1 km for the 10 TeV CoM, $n_0 = 10^{17}$ cm^{-3} case. Using a lower plasma density with a lower accelerating gradient requires a one linac length of 0.5 km for a 1 TeV CoM collider and 5 km for a 10 TeV CoM collider.

Table 1: Beam parameters of 1 TeV and 10 TeV e+e– colliders based on LPA technology.

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Energy per beam (TeV)	0.5	0.5	5	5
Luminosity (10^{34} $cm^{-2}s^{-1}$)	2	2	200	200
Electrons per bunch ($\times10^{10}$)	0.4	2.8	0.4	2.8
Bunch repetition rate (kHz)	15	0.3	15	0.3
Horizontal emittance □εx (nm-rad)	100	100	50	50
Vertical emittance □εy (nm-rad)	100	100	50	50
□* (mm)	1	1	0.2	0.2
Horizontal beam size at IP ζ*x (nm)	10	10	1	1
Vertical beam size at IP ζ*y (nm)	10	10	1	1
Disruption parameter	0.12	5.6	1.2	56
Bunch length ζz (μm)	1	7	1	7
Beamstrahlung parameter ϒ	180	180	18,000	18,000
Beamstrahlung photons per e, nγ	1.4	10	3.2	22
Beamstrahlung energy loss δE (%)	42	100	95	100
Accelerating gradient (GV/m)	10	1.4	10	1.4
Average beam power (MW)	5	0.7	50	7
Wall plug to beam efficiency(%)	6	6	10	10
One linac length (km)	0.1	0.5	1.0	5

The conversion efficiencies assumed are 50% for laser to plasma wave and 40% for plasma wave to beam (laser to beam efficiency is 20%). A high laser wall plug efficiency of 50% is also assumed, giving an overall efficiency, wall plug to beam, of 10%. Notice that the laser energy per stage per bunch is on the order of tens of J (for $n_0 = 10^{17}$ cm^{-3}) and the required rep rates are of the order of tens of kHz (for $n_0=10^{17}$ cm^{-3}), clearly indicating the need for the development of laser systems with high average power (hundreds of kW) and high peak power (hundreds of TW). Another set of LPA collider parameters, using a different baseline example, can be found in Ref. [8].

As the plasma density scalings shown in Table 2 indicate, operating at lower density reduces the required wall plug power for fixed luminosity. This is achieved by using more charge/bunch at a lower repetition rate. As discussed in Ref. [5], operating at higher charge/bunch implies more severe beam-beam effects at the IP. Table 2 shows that at $n_0 = 2 \times 10^{15}$ cm^{-3} the beamstrahlung induced energy loss is prohibitively high.

Table 2: Laser and plasma parameters of 1-10 TeV e+e– colliders based on LPA technology.

Case: CoM Energy (Plasma density)	1 TeV (10^{17} cm^{-3})	1 TeV (2×10^{15} cm^{-3})	10 TeV (10^{17} cm^{-3})	10 TeV (2×10^{15} cm^{-3})
Wavelength (μm)	1	1	1	1
Pulse energy/stage (kJ)	0.032	11	0.032	11
Pulse length (ps)	0.056	0.4	0.056	0.4
Repetition rate (kHz)	15	0.3	15	0.3
Peak power (PW)	0.24	12	0.24	12
Average laser power/stage (MW)	0.48	3.4	0.48	3.4
Energy gain/stage (GeV)	10	500	10	500
Stage length [LPA + in-coupling] (m)	2	500	2	500
Number of stages (one linac)	50	1	500	10
Total laser power (MW)	48	3.4	480	34
Total wall power (MW)	160	23	960	138
Laser to beam efficiency (%)	20	20	20	20
[laser to wake 50% + wake to beam 40%]				
Wall plug to laser efficiency (%)	30	30	50	50
Laser spot rms radius (μm)	69	490	69	490
Laser intensity (W/cm^2)	3×10^{18}	3×10^{18}	3×10^{18}	3×10^{18}
Laser strength parameter a0	1.5	1.5	1.5	1.5
Plasma density (cm^{-3}), with tapering	10^{17}	2×10^{15}	10^{17}	2×10^{15}
Plasma wavelength (mm)	0.1	0.75	0.1	0.75

A process that extracts the energy of the remaining wakefields in the plasma as well as in bunches has been suggested [9]. Inserting circuitry in the plasma as a passive feedback system extracts the wakefield energy, converts this energy into electricity, and feeds it into an external circuit. The conversion efficiency is on the order of unity. Thus, it would enhance the coupling efficiency of the laser pulse to the wakefield 12 energy by at least a factor of 2 (or even more). Other energy extraction methods may be envisioned, such as using a trailing anti-resonant laser pulse (or a low energy e-beam) to gain energy from the remaining plasma wave and to transport that energy out of the plasma [5].

Conclusion

Here author describes about especially a generation of intense laser pulses. Designs and considerations had been discussed. Beam, Laser as well as collider parameters based on LPA technique have been mentioned. The electron beams generated today from laser plasma accelerators are approaching parameters that make their usage interesting for new applications. Possible applications of an advanced LPA as injector for the LHeC have been reported.

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