Advanced Particle Acceleration Concepts

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Abstract A survey and critique of the many different "Advanced Particle Acceleration Concepts" is presented in this paper.

Key words laser, plasma, accelerator, acceleration, particle

1 Introduction

In this talk I will attempt to present in a conceptually logical and systematic manner the work and accomplishments to date in the futuristic field of Advanced Particle Acceleration Concepts. This field of R& D is made easy to follow through a series of biennial Advanced Accelerator Concepts Workshops and publication of the workshop papers in the American Institute of Physics Conference Proceedings. These workshops were started for U.S. workers but quickly became the premier international vehicle for communication; they are listed in Table 1. No details or mathematics are included in this talk. For these, reader is referred to the AIPConference Proceedings.

The principal concentration of the AAC research is to produce an ultrahigh electric field in a medium that is transparent to particles, which can then be accelerated in a short distance. To this end, the media considered are either the vacuum or the plasma, and the high field is to be excited in these media by either an electron beam or a laser beam, these being capable of carrying the highest spatial density of energy.

Table 1. Advanced accelerator concepts workshops.

workshop name	location	year	AIP Conf. Proc. No.
laser accelerator of particles	Los Alamos, New Mexico	1982	91
laser accelerator of particles	Malibu, California	1985	130
advanced accelerator concepts	Madison, Wisconsin	1986	156
advanced accelerator concepts	Lake Arrowhead, California	1989	193
advanced accelerator concepts	Port Jefferson, New York	1992	279
advanced accelerator concepts	Lake Geneva, Wisconsin	1994	335
advanced accelerator concepts	Lake Tahoe, Nevada	1996	398
advanced accelerator concepts	Baltimore, Maryland	1998	472
advanced accelerator concepts	Sante Fe, New Mexico	2000	569
advanced accelerator concepts	Mandalay Beach, California	2002	647
advanced accelerator concepts	Stony Brook, New York	2004	737
advanced accelerator concepts	Lake Geneva, Wisconsin	2006	

2 Vacuum as medium

The electric field at the surface of a charge Q (e-bunch) with dimension R is of the order $E \sim \frac{1}{4\pi\varepsilon_0}\frac{Q}{R^2} \sim 1\text{GV/m}$ for $Q=1\text{nC}$ and $R=0.1\text{mm}$. At the diffraction-limited focus of a laser, the power density is $\sim \frac{P}{\lambda^2} = \frac{\varepsilon_0 c}{2}E^2$, which gives $E=\sqrt{\frac{2}{\varepsilon_0 c}}\sqrt{\frac{P}{\lambda^2}}$. For a laser of wavelength $\lambda = 10\mu\text{m}$ and power P=10GW, we get $E \sim 300\text{GV/m}$. It is these tantali-

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zingly high electric field strengths that goad people to pursue these possibilities.

However, in an infinite vacuum, the field of a traveling electron bunch is a relativistically flattened disk of Coulomb field, and that of a laser beam is the transverse field of a plane wave. Neither is appropriate for accelerating charged particles. Thus, we need conductive structures (waveguides) to shape the fields so that they are useful for acceleration.

3 Electron bunch in waveguide (WG)

Traveling in a WG, a charge bunch induces a longitudinal wakefield that may be used for acceleration. A typical wakefield potential $V(z)$ induced by a charge distribution $\rho(z)$ traveling along $+z$ looks like (Fig. 1).

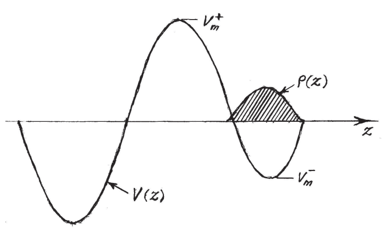

Fig. 1. Longitudinal wake-potential of a symmetric charge bunch.

We define a transformer ratio $R \equiv V_{m^+} - V_{m^-}$. A particle located at V_m^+ is maximally accelerated and the negative potential over the bunch decelerates the bunch electrons. Thus we have (max. accelerated electron energy) $\tilde{<} R$ (bunch-electron energy). It is easy to show that for a fore-and-aft symmetric bunch $R \tilde{<} 2$. Thus the acceleration is limited. It is possible to get $R > 2$ with an asymmetric beam bunch, but it is difficult to obtain R larger than a single digit. A simple engineering ploy that overcomes this dilemma is to couple the wakefield from the WG where it is induced to a second WG where a particle beam is to be accelerated. Depending on the design of the coupler and the WG, very large values of R can be obtained. This 2-waveguide (or 2-beam) system simply follows the common concept and practice of exciting the accelerating WG by a separate rf supply-the klystron-and is employed in the design of the Compact Linear Collider (CLIC) at CERN.

4 Laser beam in waveguide

A closed WG that will support a laser beam with the appropriate longitudinal electric field for particle acceleration could be just a miniature iris-loaded linac structure except now the transverse dimensions are of the order of the laser wavelength-some 10μm or less. For this we encounter several difficulties:

1) The heat capacity of these miniature structures is so low that they are easily damaged by wall heating due to the high-intensity beams passing through.

2) It is difficult to excite only the fundamental mode leaving all higher-order modes (HOMs) unexcited.

3) The beam-coupling impedance of the miniature structure is high, hence the accelerated beam current is limited by instabilities to a low value.

A slightly more promising structure, which eases at least the first two difficulties, is the photonic band gap (PBG) structure. In this structure a regular pattern of holes are drilled in a dielectric rod (fiber). The 2-D lattice formed by the holes support a series of transverse modes clustered in bands separated by wide gaps (2-D Brillouin zones). The fundamental propagating mode having the lowest wave number is confined in the lowest band. All HOMs can bridge the band gap. Thus, only the fundamental mode is trapped and can propagate freely along the length of the guide.

There has also been a great deal of effort devoted to forming and using channels in plasma as waveguides. We shall discuss this further after we have introduced plasma as medium.

5 Laser beam in infinite vacuum

There are proposals to use lasers to accelerate particles without a waveguide structure. One can superpose two identical plane-wave laser beams traveling at angles $\pm\theta$ in the polarization plane. Properly phased, the transverse components of the electric field cancel and the longitudinal components add to give $2E\sin\theta$. But, of course, for rather narrow beams θ

must be small and the overlapping region cannot be very long. Acceleration must be carried out in stages. Such arrangements have not yet been demonstrated by experiments.

Another scheme is the Inverse Free-Electron Laser (IFEL). In a free-electron laser (FEL), a transversely undulated e-beam interacts resonantly with an injected plane-wave laser beam. The longitudinal dynamics of a beam particle interacting with the laser beam is similar to that of a particle in a traveling-wave linac. A particle riding on the "decelerating phase" of the laser wave imparts energy to the field as the stimulated radiation-the free-electron laser process. On the other hand, a particle riding on the "accelerating phase" takes energy from the field and is accelerated, hence the name "inverse FEL". The experimental setup STELLA used at BNL-ATF is shown diagrammatically in Fig. 2. A beam of electrons was accelerated from 14MeV to 55MeV. Simulations show that with optimal design it should be possible to obtain an energy gain of >300MeV per stage. As an exercise during AAC 2004, a conceptual design was made of a four-stage IFEL accelerator with a total energy gain of >1GeV.

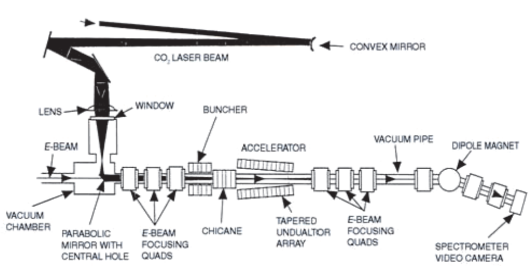

Fig. 2. Schematic layout of the STELLA experiment.

The trouble with the IFEL is that an undulated electron beam emits spontaneous radiation at an intensity $\propto \gamma^2$. This clearly will limit the top energy attainable.

6 Plasma as medium

A conventional two-component plasma consists of a distribution of electrons with average density $\bar{n}$ overlaid on a static distribution of much heavier ions with uniform density $\bar{n}/Z$ where Z=charge No. of the ions. The light electron distribution can be excited to a density oscillation (longitudinal oscillation) with frequency $\omega_{\rm p} = \sqrt{\frac{e^2\bar{n}}{\varepsilon_0 m}}$ where m=electron mass. If the exciter travels at velocity c, the oscillations will string out to form a plasma wave with phase velocity c. At the wave-breaking limit (density amplitude $=\bar{n}$) the amplitude of the electric field is $\hat{E} = \sqrt{\frac{e\bar{n}}{\varepsilon_0\omega_{\rm p}}}$. For $\bar{n}=10^{24}{\rm m}^{-3}$, we get $\omega_{\rm p} = 5.6\times10^{13}{\rm s}^{-1}\lambda_{\rm p}\cong 34\mu{\rm m}$, $f_{\rm p}\cong 9$THz and $\hat{E}=96$GV/m. Again this high field is tantalizing.

7 Excitation of plasma wave

The plasma wave can be excited by either an electron beam or a laser beam. There are several modes of excitation.

a. Shock excitation. Here one shoots a short electron bunch or laser wave packet through the plasma. For best efficiency the length of the exciter should be $\sim \lambda_{\rm p}/4$. The amplitude of the plasma wave is generally limited by the intensity of the single-bunch exciter.

b. Beat wave resonant excitation. Here one shoots into the plasma two laser beams of frequencies ω_1 and ω_2 such that $\omega_1-\omega_2=\omega_{\rm p}$. The superposed laser beam looks like a carrier wave of frequency $\omega_1+\omega_2$ with amplitude modulated at frequency $\omega_1-\omega_2$, which excites the plasma wave resonantly. By increasing the pulse length of the "beat wave" exciter beams, one can generally reach the wave-breaking limit or beyond. Always having to set up the resonant condition $\omega_1-\omega_2=\omega_{\rm p}$ is obviously a nuisance. The discovery described below offers a much simpler alternative.

c. Self-modulated resonant excitation. Due to nonlinear coupling, a single laser beam traveling in the plasma will, after a short initial lethargy time, automatically develop an amplitude modulation at frequency $\omega_{\rm p}$, which in turn will excite a plasma wave. The laser modulation and the plasma wave will grow together exponentially. The discovery of the self-modulated excitation of a plasma wave by a single laser beam gave the laser-plasma acceleration concept a substantial boost toward reality. To prepare the plasma and excite a wave all one needs to do is to shoot a long laser pulse into a neutral gas. The front of the laser pulse will ionize the gas to form the plasma (or the plasma channel, as will be discussed later), and the remainder of the pulse will excite the plasma wave (even to over-breaking) by the self-modulated resonant excitation mechanism. This procedure is so simple and direct as to make excitation of plasma wave by an electron bunch much less attractive.

8 Sources of electron for acceleration

There are two alternative sources of electrons that can be used for acceleration.

a) A separate accelerator can be used as an injector to inject a high-energy electron beam.

The best work of high-energy injection is represented by a series of experiments (Exp 157, 162, 164, 164X) carried out from 1999 to 2003 using the SLAC 28.5GeV beam. The experimental setup is shown in the diagram in Fig. 3. The best result obtained is an energy gain of ~4GeV over 10cm of plasma with density $\sim 2\times10^{20}\text{m}^{-3}$. This corresponds to an accelerating field of ~40GV/m, rather high indeed.

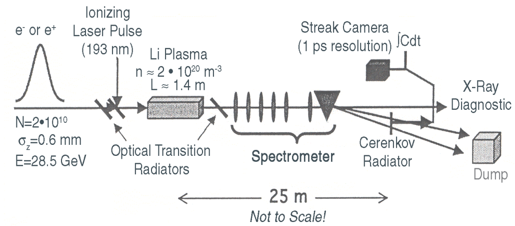

Fig. 3. Experimental layout of the laser-plasma acceleration experiments at the SLAC FFTB.

Adding energy to the already high-energy beam suggests the application as "after-burners" for accelerators or colliders. The results of the SLAC experiments show that a laser-plasma accelerator with a total plasma length of 12.5m will add 500GeV to the beam. This could be added at the ends of the 500GeV e^- and e^+ superconducting linacs of the International Linear Collider (ILC) to double the collision energy to 2TeV. The total length of, say, 10×12.5m=125m of each afterburner can easily be accommodated in the present ILC design.

b) Electrons at essentially zero energy are abundant in the plasma.

Table 2. Laser-plasma acceleration experiments reported in AAC 2004.

	scheme	laser power /TW	laser wavelength /μm	pulse duration /fs	spot size /μm	plasma density /cm^{-3}	energy gain /MeV
LOA	SM-LWFA*	30	0.8	33	18	6×10^{18}	$170\pm15^{\dagger}$
LBNL	SM-LWFA‡	8	0.8	55	7	10^{19}	$86\pm2^{\S}$
RAL	SM-LWFA	16	0.8	40	25	2×10^{18}	$78\pm2^{\P}$
AIST	SM-LWFA	2	0.8	50	5	1.5×10^{20}	$7\pm1^{\Vert}$
Tokyo	SM-LWFA	6	0.8	50	6	1.8×10^{19}	40
UCLA	PBWA††	1	10.3, 10.6	$4\times10^{5\ddagger\ddagger}$	200	10^{16}	38
NRL	SM-LWFA§§	10	1.06	500	12	10^{19}	20
JAERI	SM-LWFA	20	0.8	23	5	1.4×10^{20}	40
Osaka	LWFA¶¶	30	1.06	500	25	6×10^{16}	100
KERI	SM-LWFA	2	0.8	700	5	10^{19}	10

SM-LWFA = Self-Modulated-Laser Wake Field Acceleration (laser-plasma acceleration), PBWA=Plasma Beat Wave Acceleration, *acceleration attributed to "forced" LWFA, † narrow energy spread beam contained 500pC, ‡ acceleration in preformed plasma channel, §narrow energy spread beam contained 200pC, ¶narrow energy spread beam contained 20pC, ‖narrow energy spread beam contained 2fC, averaged over 90 shots, ††electrons externally injected, ‡‡ponderomotive ion-channel formation, §§ optical injection using LIPA, ¶¶acceleration in glass capillary.

A large number of laboratories all over the world are carrying out laser-plasma acceleration of plasma-background electrons. Some of these experiments are listed in Table 2. Earlier results gave accelerated beams with 100% energy spread from zero to maximum. However, recent experiments (e.g., the first four listed in Table 2) produced beams with relatively narrow energy spreads. This is presumably due to the fact that in the over-breaking plasma wave regime the electrons are captured during a short time when they are still non-relativistic, and the main acceleration is derived after they have gained relativistic energy and at near-constant phase along near-identical vertical phase trajectories. This effect is borne out also in simulations and makes the acceleration much more useful. The layout of such an experiment can be extremely simple as shown in Fig. 4 minus the quad triplets for high-energy injection.

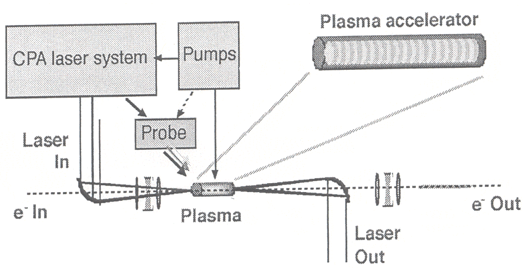

Fig. 4. Schematic layout of a laser-plasma acceleration laboratory.

9 Plasma channel for laser guiding

Finally, the efforts of creating a narrow plasma channel and using it as an indestructible waveguide for laser guiding have led to interesting successes.

A simple plasma channel would have a parabolic density profile $n(r) = n_0[1+\alpha(r^2/r_0^2)]$. The matched laser beam width w is given by $w^4 = (1/\pi r_e)(r_0^2/n_0)(1/\alpha)$ where r_e=classical electron radius. This is the width at which a laser beam will be guided to propagate at fixed width. Taking $n_0=10^{24}\mathrm{m}^{-3}$, $w=r_0$, and $\alpha=1$(plasma density doubles at laser-beam edge), we get $w\cong 10\mu\mathrm{m}$. Such a plasma channel can be formed by ionizing the gas inside a conducting capillary tube along a wall that is heated by a current pulse. Or it can be formed by the inverse process of first forming a plasma core that is then heated along the center-line by a laser pulse to expand radially outward. Using a plasma channel, high-intensity laser beams have been guided to travel at uniform width for more than 10 Rayleigh range. With such an arrangement, electrons can be accelerated by the longitudinal field of the guided laser beam, or by the field of the plasma wave in the channel, or both.

The understanding and the sophistication of the advanced particle acceleration concepts have come a long way since the first efforts in the 1970s, but there is still a long way to go before any of these concepts will mature into a realistic accelerator.

先进粒子加速法概念

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摘要　列举了全部“先进粒子加速法概念”，并分别对其进行回顾及评述.

关键词　激光　等离子体　加速器　加速方法　粒子

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