

ADVANCED ACCELERATION SCHEMES

P. A. Naik[#], B. S. Rao, and P. D. Gupta

Raja Ramanna Centre for Advanced Technology, Indore-452013, India

Abstract

In pursuit of significant reduction in the size and the cost of high energy electron accelerators, many advanced accelerator schemes have been proposed over the years and some of them are being actively pursued. We present here a review of the basic concepts involved in some of the promising schemes and the corresponding experimental results. As there has been a significant progress in the field of plasma based acceleration over the past decade, there has been a growing interest in these accelerators for various applications. Therefore, we will present some of the potential applications of these accelerators and future outlook.

INTRODUCTION

High energy particle accelerator is one of the most important inventions of the twentieth century which has led to enormous advances in scientific understanding of the world around us. The particle accelerators have also played and still play a fundamental role in the different fields of light sources, neutron sources, transmutation of nuclear waste, medical diagnosis and medical therapy, and numerous other industrial applications. The accelerating gradients in conventional radio-frequency (rf) linear accelerators are currently limited to <50 MV/m, due to the breakdown that occurs on the walls of the accelerating structure. Therefore, despite their success, the present day high energy accelerators are hitting practical limits due to their large size and the cost. This poses grave threat to the future of research activity dependent on accelerators. To address this major issue, many advanced accelerator techniques have been proposed and some of them are being actively pursued. Most of the advanced techniques were inspired by the continuous progress in the laser technology over past 30 years. The availability of powerful lasers and particle beams, has made it possible to generate extremely high electric fields and drive particle acceleration with high acceleration gradient > 100 GV/m. Presently, laser or particle beam driven plasma based acceleration techniques are known to be the most promising methods for compact size high energy accelerators. In this paper, we briefly review the basic concepts and present the experimental results of the schemes based on direct laser acceleration. There has been significant progress particularly in the field of laser-driven plasma based acceleration over the past decade. This has attracted lot of attention in the scientific community for applications of these accelerators in wide ranging fields due to the unique characteristics of particle beams produced. In view of

this, we will present some of the potential applications of these accelerators.

LAWSON-WOODWARD THEOREM

It can be shown from Maxwell equations in vacuum that energy gain from optical fields is not possible. This is known as the Lawson–Woodward (LW) theorem [1, 2]. The theorem assumes that : (i) the region of interaction is infinite, (ii) the laser fields are in vacuum with no walls or boundaries present, (iii) the electron is highly relativistic ($v \approx c$) along the acceleration path, (iv) no static electric or magnetic fields are present, and (v) nonlinear effects due to ponderomotive, $v \times B$, and radiation reaction forces are neglected. One or more of the assumptions of LW theorem must be violated in order to achieve a nonzero net energy gain. For example, finite energy gain can be achieved by introducing a background of gas into the interaction region, as in the inverse Cherenkov accelerator. Energy gain can also result from the introduction of a periodic magnetic wiggler field, as in the inverse free electron laser accelerator. In vacuum, a nonzero energy gain can be achieved by the introduction of boundaries that limit the interaction distance, like in an inverse transition radiation accelerator. Introduction of plasma medium gives rise to several other plasma based electron accelerators, like the plasma beat wave accelerator, laser wake-field accelerator, plasma wake-field accelerator etc. We shall examine them one by one.

INVERSE CERENKOV ACCELERATION

In the inverse Cherenkov acceleration (ICA) scheme, a background gas is used reduce the phase velocity of the laser light to match with the electron beam velocity. Phase matching is achieved by intersecting the laser beam with the e-beam on its propagation axis at the Cherenkov angle defined by $\theta_c = \cos^{-1}(1/n\beta)$, where n is the index of refraction of the gas and β is the electron velocity divided by the velocity of light. Satisfying the Cherenkov phase matching condition enables electrons to stay in phase with the light wave over a long distance, resulting in acceleration. Also, due to the wave-front inclination, a longitudinal component of the electric field will be developed. The injected electron bunch propagates in phase with the optical field and experiences acceleration. As this process is opposite to that of Cherenkov radiation, process, it is designated as "inverse" Cherenkov acceleration. The ICA was first demonstrated at Stanford University in 1981 [3]. Subsequently, Fontana and Pantell [4] used a radially polarized laser beam focused onto the e-beam using an axicon. Using this geometry, Kimura *et al* experimentally demonstrated a 3.7 MeV modulation on

[#]Corresponding author
Email: panaik@rrcat.gov.in

a 40 MeV electron beam using a 580 MW CO₂ laser pulse interacting with a 12 cm gas filled cell [5].

INVERSE FREE ELECTRON LASER ACCELERATION

In an inverse free electron laser accelerator (IFELA) [6], co-propagating electron and laser beams pass through an undulator which causes the electron trajectory to oscillate in the same plane as the laser beam electric field. There is energy exchange between the laser (wave) and the electrons (particles) near the resonant condition $\gamma^2 = (\lambda_u / 2\lambda)(1 + K^2 / 2)$, where γ is the Lorentz factor, λ_u is the undulator wavelength, λ is the laser wavelength, $K = eB_0\lambda_u / 2\pi mc$, e is the electron charge, B_0 is the peak magnetic field, and m is the electron rest mass. When the electrons have slightly lower energy than that required for resonance, they will gain energy from the laser (they lose energy when they have energy slightly higher than that required for resonance, as in an FEL). As the electron gains energy, it reached the resonance energy. Its energy cannot increase anymore as it will now start losing the energy to the wave (dephasing). Higher energy exchange is possible if the undulator is tapered (e.g. either gap is decreased or the period λ_u is increased along the magnet array) so that the energy of the electrons remains slightly below the resonance value all along the undulator. Expectedly, the tapering in an IFELA is exactly opposite to that in an FEL.

The acceleration of electrons through IFELA was first demonstrated in 1992 [7]. There are two notable recent experiments on the IFELA scheme. In the first experiment at BNL, known as STELLA [8] for Staged Electron Laser Acceleration, an electron beam of 45 MeV energy from Advanced Test Facility (ATF) was sent through an IFELA pre-buncher undulator magnet. This magnet was followed by a chicane compressor and then a second tapered undulator. A CO₂ laser was sent collinearly with the electron beam. The laser was focused at the centre of the tapered undulator to give a peak intensity of $\sim 2 \times 10^{12}$ W/cm². The chicane delivered a bunched beam at the entrance of the tapered undulator. Since here the same CO₂ laser beam is used to microbunch the beam and accelerate the pre-bunched beam, phasing between the two is preserved. The energy measurement of the electron beam after the tapered undulator showed acceleration of the pre-bunched beam with an average gradient of 27 MeV/m. This experiment demonstrated first staged acceleration and showed good capture efficiency (> 80%) of the pre-bunched beam and < 1% energy spread [9]. In a second experiment at UCLA's Neptune laboratory, a more powerful (400 GW) CO₂ laser was used in conjunction with a strongly tapered undulator. In this experiment, 14.5 MeV electron beam was accelerated upto 30 MeV, with a peak gradient of 70 MeV/m [10].

VACUUM LASER ACCELERATION

The spot size and the intensity of a Gaussian (TEM₀₀) laser beam propagating along the z direction are given by

$w(z) = w_0 [1 + (z/z_R)^2]^{1/2}$ and $I(z) = I_0 [w_0/w(z)]^2 \exp[-2(w(z)/w_0)^2]$ respectively, where $z_R = \pi w_0^2/\lambda$ is the Rayleigh length. The finite spot size of the laser gives rise to axial electric field $E_z \sim (\lambda/2\pi w_0)E_\perp$ through $\nabla \cdot E = 0$. The axial electric field can be > 1 GV/m with the currently available table-top TW lasers. However, the phase velocity of the electric field along the z-axis is $v_\phi/c \approx 1 + \lambda/(2\pi z_R) > c$ near the focus. Therefore, even highly relativistic electrons with $v_z \approx c$ will dephase with respect to the accelerating field over a length $\sim z_R$ [11]. Electron acceleration and net energy gain can be achieved through interaction with laser in vacuum by limiting the laser-electron interaction to approximately a region of length $2z_R$. The interaction length can be limited by introducing optics close to the focus, such that minimal phase slippage occurs. In case of the first-order Laguerre-Gaussian mode, the maximum energy gain due to vacuum laser acceleration by the E_z field is given by $W(\text{MeV}) = 31P(\text{TW})$ [12]. Recent experiments by Plettner *et al.* demonstrated a 30 keV energy modulation on a 30 MeV electron beam from the interaction with a 0.5 mJ, 4 ps laser pulse. Here, the interaction was terminated by an 8 μm thick gold-coated Kapton tape kept near focus [13]. This was a case of inverse transition radiation acceleration. Non-linear ponderomotive force can also result in net energy gain. The acceleration due to ponderomotive force mechanism is most efficient at low electron energies and high laser intensities since $F_p \sim \gamma^1 \nabla I$. Simulations [14, 15] indicated that when a moderate energy electron bunch intersects with a very intense laser pulse at a small angle, a significant fraction of the electrons can be accelerated to energies in excess of 100 MeV for laser strength parameter $a_0 = 10$ through a combination of direct and ponderomotive acceleration. A major limitation to these schemes is the $1/\gamma$ dependence of the ponderomotive force. A fundamental limitation to all concepts that rely on electron acceleration through the direct laser acceleration through linear or nonlinear process is the shorter ($\sim 1 \mu\text{m}$) wavelength of the lasers. Therefore, it is desirable that a high-quality bunch be injected into the both accelerating and focusing phase region of the laser field with a bunch length less than $\lambda/4$ (duration < 0.8 fs for $\lambda = 1 \mu\text{m}$). Such extremely short electron bunches can be produced by pre-bunching of electron beam from conventional accelerator using IFEL interaction. This has been experimentally demonstrated [16], and used as an injector into a second stage of a laser accelerator [9].

PLASMA BASED ACCELERATION

Plasma based accelerators are of great interest because of their ability to sustain extremely large acceleration gradients. The accelerating gradients in conventional radio-frequency (rf) linear accelerators are currently limited to < 50 MV/m, due to breakdown that occurs on the walls of the accelerating structure. Since plasma is ionized state of matter, where the gas has broken down into ions and electrons, no further electrical breakdown is

possible and hence accelerating electric field of 100 GV/m, or greater can be produced in plasma using intense laser or charged particle beams. In these schemes, electron beam is accelerated by the Coulomb field of the electrostatic plasma wave excited by the laser (or particle) beam in its wake.

LASER DRIVEN PLASMA BASED ACCELERATION

The laser-driven plasma based electron acceleration was proposed in 1979 by Tajima and Dawson [17]. In this scheme, when an ultra-short, ultra-intense laser pulse propagates in plasma, it pushes the plasma electrons from the high intensity region to the lower intensity region of the beam (or pulse) due to the ponderomotive force, F_p , which is proportional to the negative gradient of laser intensity, $-\nabla I_L$. The ions of the plasma are not affected by the ponderomotive force due to their large mass and ultra-short duration of the laser. Due to this, a space charge is developed resulting in a restoring force which pulls the electrons back to their equilibrium position. While trying to regain the equilibrium position, the electrons set up travelling longitudinal plasma density oscillations or plasma wave in the wake of the laser pulse, similar to the water waves generated in the wake of a moving boat. The plasma wave in the wake of laser pulse consists of travelling longitudinal electric field, therefore the electric field is known as laser wake-field. The wake-field in the plasma travels with a phase velocity equal to the group velocity of the laser pulse, which is close to c (speed of light in vacuum). The laser wake-field, therefore, is most suitable for accelerating particles to relativistic energies. It can be driven most efficiently when the laser pulse duration is approximately equal to that of the plasma wave period. When driven resonantly, a wake-field of amplitude ~ 100 GV/m or greater can be generated. When electrons with appropriate energy are injected in front of the plasma wave, they will be trapped in the wake-field and get accelerated. This method of electron acceleration is known as laser wake-field acceleration (LWFA). A recent excellent review article provides detailed understanding of this field [18]. In the LWFA experiments, the plasma wavelength is on the order of 10 μm or wave-period on the order of 30 fs for plasma density of $\sim 10^{19}$ cm^{-3} . Therefore, injection of electrons from external accelerator poses extreme challenge. Different methods for triggering injection of electrons from the plasma wave itself have been proposed. If one can manage to inject electrons into a single period of the wake-field, it will lead to electron bunches with length shorter than the plasma wavelength. Experimentally, major breakthrough in terms of generation of low divergence quasi-monoenergetic electron beams has been achieved in the year 2004 [19-21] using self-injection. In these experiments, a single laser pulse is used to drive the wake-field to sufficiently large amplitude such that electrons are injected into the rear of the first wake period through transverse breaking of the plasma wave. The

electrons then surf the wake and after outrunning the wave, they form a monoenergetic electron bunch. This is referred to as the ‘bubble’ regime [22]. Most of the experimental studies reported have been unable to access this regime directly but they depended on the modulation of the laser pulse as it propagated in plasma, eventually reaching the conditions for transverse wave breaking. For example, this regime was accessed even though initial laser pulse is much longer than required for acceleration in bubble regime [23, 24] due to strong self-modulation of the laser. With current laser technology, quasi-monoenergetic electron beams in the range of 100 MeV have been produced over millimetre distances, with maximum charge of hundreds of picocoulombs. GeV electron beam has also been reported in recent experiments from discharge plasma wave-guiding or self-guiding over cm-scale lengths [25-30]. One important aspect for LWFA to become practical accelerator is to produce stable and controllable electron beam. Towards this goal, injection mechanism based on the use of two laser pulses has shown to produce stable and controllable electron beam [31]. In this scheme, two counter propagating ultrashort pulses with the same wavelength and polarization are made to collide at desired location in the plasma. The interference of the two pulses at the location of collision forms beat wave pattern that heats plasma electrons locally. A fraction of these hot electrons are trapped in the wake-field driven by the one of the two laser pulses called “pump pulse” and therefore gets accelerated to relativistic energies. This scheme is complicated experimentally, but it offers more control on acceleration and experiments have shown that the electron beam energy can be tuned continuously from 10 to 250 MeV. Remarkable reduction of electron beam divergence and stable pointing has been demonstrated with the use of an external magnetic field surrounding the plasma [32]. There has been significant progress over the last few years in the field of LWFA towards producing stable and controllable electron beam. Recent experiments on LWFA using different schemes showed improvements in pointing and energy stability through precise control on the laser and target parameters [25, 27, 33-39]. In addition, control of the laser pulse front tilt has shown to steer the direction of the electron beam pointing [40]. The duration of electron bunch produced from LWFA has been measured recently to be less than 10 fs [41-42].

PARTICLE BEAM DRIVEN PLASMA BASED ACCELERATION

Particle beam driven plasma based electron acceleration is also known as plasma wake-field acceleration (PWFA) was proposed by Chen *et al* in the year 1985 [43]. PWFA is one of the most actively pursued advanced acceleration scheme. In this scheme the wake-field is driven by an intense, high-energy charged particle beam when it passes through the plasma. Electron or positron beam can be used to excite the wake-field. In the case of an electron beam, the space-charge of the electron bunch blows out

the plasma electrons which while trying to regain equilibrium position overshoot it and set up plasma oscillations. When a second bunch containing fewer particles than the drive beam injected in the wake at appropriate phase, they can be trapped and accelerated. In the case of a positron beam, the plasma electrons are “pulled in” instead of being expelled as in the case of an electron beam driver. The PWFA scheme is very attractive because of its potential to double the beam energy of a high energy accelerator beam in a single stage of acceleration that is only tens of meters long using existing state-of-the-art driver beams.

The first demonstration of the excitation of a wake-field by a relativistic beam was shown at Argonne National Laboratory, USA 1987 with acceleration gradient ~ 2 MeV/m [44]. By 1995, numerous laser-driven electron acceleration experiments had confirmed that plasmas could support gradients of tens of GeV/m. According to linear wake-field theory, for a fixed number of particles in the bunch, the accelerating gradient scales as the inverse square of the electron pulse length [45]. Simulations showed that this scaling held even in the extremely nonlinear blowout region in which the Stanford Linear Accelerator (SLAC) experiments operated and that accelerating fields on the order of 40 GeV/m were possible by using 50 fs long electron bunches. Early PWFA experiments with the 28.5 GeV, 10 ps (FWHM) electron beam from SLAC used pre-ionized Li plasma column with densities in the 10^{14} cm⁻³ range [46]. The bulk of the drive electron beam excited the wake and therefore lost energy, however the electrons in the back of the same beam overlapped with the accelerating portion of the wake-field and thus gained energy. In these early experiments, energy gains of up to 350 MeV were observed in a 1.4 m long plasma. As much shorter electron bunches in the 50 fs (FWHM) range became available, the prospects of obtaining multi-GeV energy gains using a higher density plasma seemed possible. In recent breakthrough Final Focus Test Beam experiments (FFTB) at SLAC by using a 42 GeV beam, electrons with a maximum energy of up to 85 GeV and an energy gain of 43 GeV were obtained in an 85 cm long plasma [47]. In this experiment, head of the electron bunch drives the plasma wave while the tail of the electron bunch witnesses the plasma wave and gets accelerated. This method of acceleration results in accelerated electrons with continuous energy spectrum. To realize practical high energy accelerator, the issues related to energy spread and transverse emittance need to be addressed. Future PWFA experiments at Facilities for Accelerator Science and Experimental Test (FACET) using SLAC are aimed at producing high gradient electron and positron beam in a single stage with small energy spread, transverse emittance, and high energy transfer efficiency [48] by injecting an ultra-short (~ 30 fs) witness bunch with finite energy spread 400 fs behind the drive bunch of 100 fs duration. Both drive and witness bunch will have 25 GeV energy. The FACET experiments are expected to

advance the frontier of PWFA and allow exploration of new phenomena.

APPLICATIONS

Synchrotron facilities in which electron bunches of few GeV energy are bent by magnetic field to produce x-rays for applications in biological, medical or materials science. Therefore, if table-top multi-GeV beams could be generated and manipulated in a small scale laboratories, this would potentially widen access to such experimental techniques and potentially enable a huge range of additional applications. Some laboratories are already pursuing this area of investigation [49-51]. Recently undulator radiation in soft x-ray region has been demonstrated by passing a laser produced monoenergetic electron beam of 210 MeV energy through an undulator [52]. Also, recent results from JAEA in Japan have shown that soft x-ray radiation can be produced by reflecting a counter propagating laser beam from the curved density structures in the plasma wake-field [50]. Similarly there has been a significant amount of work recently in the measurements of harder x-ray radiation due to the betatron motion of electrons undergoing acceleration in these experiments [53]. Source compactness, broad spectral range, and perfect synchronization of particle and radiation bursts are unique properties that could extend the breadth of applications. The ultrashort and the high peak current of laser-plasma electron beams could lead to compact XFEL facilities, on a size affordable by small-scale laboratories. Implementation in existing hospitals of phase-contrast imaging techniques developed at synchrotrons to provide high-resolution images with micrometre resolution could enable significant advancement in clinical diagnostics. Finally, time-resolved experiments, where the particle burst or the x-ray flash can act indifferently as a pump or a probe, would significantly extend the field of investigation in the dynamics of matter, compared with currently available techniques using a visible pump and x-ray or visible probes.

Fundamental phenomena of condensed matter and plasma dynamics can also be probed with these unique particle beams generated from laser-driven plasma based accelerators. For example, energetic, low emittance proton beams are a powerful probe for quasi-static magnetic and electric fields that develop in laser-produced plasmas and are also good candidates for injection into conventional accelerators. Proof-of-principle experiments have also demonstrated the applicability of electron or proton-based radiography to the probing of dense materials [54-55]. Light and flexible devices for non-destructive material inspection would also be interesting, with potential applications in automobile engineering, aircraft inspection and security.

CONCLUSIONS

Due to the use of the extreme accelerating fields available in plasmas, typically ~ 100 GV/m, this approach

has the potential to transform the technology of particle acceleration among the other techniques discussed. While accelerator grade high quality electron beam production has to be demonstrated from PWFA, it has been already shown that the high-quality, low-emittance particle beams can be produced from laser-driven plasma based experiments. The continued efforts in the field may soon lead to the production of high rep rate, sub-10 fs, high quality electron beams in the GeV range. Further work to reduce the energy spread of these beams will be necessary for the production of compact XFEL radiation. For high energy physics applications in which very high luminosity electron beam having TeV energies are required, significant further work to develop this technology is necessary - and conceptual designs of such laser based accelerators would require many high energy lasers and would be far from compact. The dramatic improvement in the energy and beam quality of laser based plasma accelerators seems promising for this approach for the generation of very high energy for high energy physics research. However, electron energy is not the only important parameter and it is also necessary to consider the extremely high luminosity value required for such applications. It is expected that this field will become even more exciting as understanding of how to control and optimize the beam parameters develops and many applications become reality.

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