T.2: Laser Wake-field Acceleration: An Advanced Technique for Compact Electron Accelerators

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Introduction

High energy particle (electron/proton/ion) accelerators are required for addressing various fundamental questions e.g. particle physics research, search for new particles, origin of mass, identity of dark matter, extra dimension of space, and many other applications. During last 50 years or so, many high energy particle accelerators have been built worldwide for exploring above mentioned fundamental scientific issues, and have led to many important scientific discoveries. These accelerators have been built using radio-frequency (RF) based acceleration technique where the acceleration gradient is limited to <100 MV/m,due to the material breakdown on the walls of the RF accelerating cavities. Therefore, such accelerators are quite big in size e.g. Stanford Linear Accelerator (SLAC), USA and Large Hadron Collider (LHC), CERN, Geneva. The quest for higher and higher energy of the particles to go deeper into the fundamental questions is driving the scientific community to build even bigger accelerators e.g. the proposed International Linear Collider (ILC).

With the current RF based acceleration techniques, the only way to increase the energy of the particles is to increase the size (length) of the accelerators, leading to tremendous rise in the cost and therefore requires multinational collaboration, and several years to construct such accelerators. The scientific community needs less expensive and compact accelerators for variety of applications e.g. developing compact x-ray/γ-ray sources, medical applications e.g. in cancer therapy, sterilizing food, treating materials used in industry, and disposing of nuclear waste etc. Therefore, more advanced and efficient means of accelerating the particles are required. It is in this context, it was realized that 'plasma' can be used to accelerate particles. Plasma as a medium for particle acceleration has an advantage that it has no electrical breakdown limit, like conventional accelerating structures, and therefore can support large accelerating field and hence compact and cheaper accelerators can be developed.

Although, the concept of using collective fields in a plasma to accelerate charged particles was proposed several decades back, a major development towards using 'plasma' as an accelerating medium for electrons happened in 1979 when Tajima and Dawson proposed to use highpower, ultra-short laser pulses to generate collective fields (electron plasma wave) in a plasma and use it for electron acceleration [1]. This scheme is known as "Laser Wake-field Electron Acceleration (LWFA)" [2]. Soon thereafter, it was also shown that a high-current, short-duration charged particle beam can also be used to generate electron plasma wave and hence to accelerate electrons [3]. This scheme is known as "Plasma Wake-field Acceleration (PWFA)".

In PWFA,the plasma wave is excited by a relativistic electron / positron or proton beam. The Coloumb force due to charged particles space charge expels the plasma electrons (for electron beam) / pulls them (for positron/proton beam). The displaced electrons snap back to restore charge neutrality and overshoot their original position, setting up a plasma wave. SLAC is working on this scheme of acceleration. In the year 2007, they demonstrated doubling the energy of SLAC's high-energy electron beam in less than one meter of plasma [4]. A bunch of electrons with energy 42GeV from SLAC linac was fired into an 84 centimetre long chamber full of lithium vapour which immediately transformed into a plasma. The electrons at the back side of the bunch rode the wake-field created by the front side of the beam and got accelerated to energies of up to 85 GeV i.e. more than double the energy of the driving beam. However, the fraction of electrons accelerated was quite small. A new project, the Facility for Advanced Accelerator Experimental Tests (FACET) is being pursued at SLAC for further improvements in this scheme. This concept of doubling the energy of an electron beam is known as "Energy Doubler" or "Plasma Afterburner".

In this theme article, however, plasma based acceleration using lasers i.e. LWFA technique will be described in detail.

Laser Wake-field Acceleration (LWFA)

LWFA technique is based on the concept of utilizing collective fields induced by an intense, ultra-short laser pulse as it propagates inside an underdense plasma (a plasma with electron density below the corresponding critical density for a given laser wavelength, e.g. for Ti:sapphire laser operating at a wavelength of 800nm, the critical plasma density is ~2×10^{21} cm^{-3}). A laser pulse of appropriate duration (few tens of fs) and intensity (>10^{18} W/cm^2) when injected into underdense plasma (of appropriate density, typically in the range of 10^{17}–10^{20} cm^{-3}) excites electron plasma wave behind it. When the short, intense laser pulse enters inside the plasma, the electrons are pushed forward at the leading edge of the laser pulse and again backward at the trailing edge of the laser pulse due to "ponderomotive force", a force which is proportional to the intensity gradient ($F_p \propto -\nabla I_L$) of the laser pulse and arises due to non-linear part of the Lorentz force of the laser field on the electrons. The ponderomotive force pushes electrons from the region of high laser intensity to the low intensity region. As the laser pulse propagates in the plasma, the displaced electrons try to snap back to their equilibrium position to maintain charge neutrality. However, while doing so they overshoot the equilibrium position which sets up electron oscillations behind the laser pulse. This electron oscillation moves behind the laser pulse with a phase velocity (v_ϕ) equal to the group velocity (v_g) of the laser in the plasma which is given by:

$$v_\phi = v_g = c\sqrt{1-\frac{\omega_p^2}{\omega^2}}$$

where 'c' is the speed of light in vacuum, ω is the laser frequency, and ω_p is the plasma frequency given by:

$$\omega_p = \sqrt{n_0 e^2/m_0\varepsilon_0}$$

$$\omega_p \simeq 5.64\times 10^4\sqrt{n_0(cm^{-3})}\ \text{rad/s}$$

where n_o is the ambient electron density, m_o and e are the electron rest mass and charge respectively, and ε_o is permittivity of free space. These moving plasma oscillations are called 'electron plasma wave' or simply 'plasma wave'. The corresponding plasma wavelength is given by :

$$\lambda_p(\mu m) \simeq 3.3\times 10^{10}/\sqrt{n_0(cm^{-3})}$$

For $\omega_p << \omega$, the phase velocity of the plasma wave is close to the speed of light (~c).The maximum longitudinal electrostatic field associated with such a plasma wave (wave-breaking field) is given by:

$$E_{wb} = m_0\omega_p c/e$$

which is referred to as the cold non-relativistic wave breaking field [5]. Wave-breaking can be understood as a phenomenon similar to the breaking of the ocean waves on a beach. As this field is generated in the wake of the laser pulse, it is termed as 'Laser Wake-field' as shown in Fig.T.2.1. It could be understood as similar to the water waves generated in the wake of a moving speed boat in water.

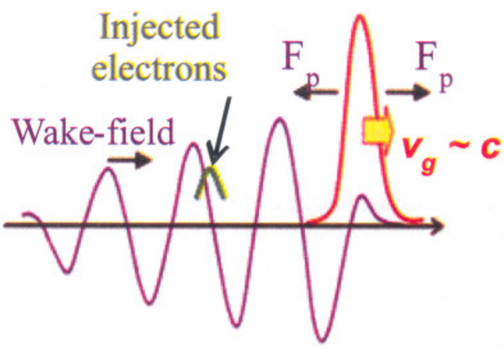

Fig.T.2.1:Laser wake-field generation in a plasma and electron acceleration.

In a simpler form cold non-relativistic wave-breaking field is given by:

$$E_{wb}\left(\frac{V}{m}\right) \simeq 96\sqrt{n_0(cm^{-3})},$$

which for an electron density in the plasma of say $10^{18}cm^{-3}$, corresponds to ~96GV/m. This acceleration field is approximately three orders of magnitude higher than that available with conventional RF based accelerators.

In the linear regime, the plasma wave is a simple sinusoidal oscillation with $E<E_{wb}$. However, in the non-linear regime,the electric field departs from a simple sinusoidal form. In particular, the electric field exhibits the characteristic "saw-tooth" profile associated with wave steepening and the density oscillations become highly peaked. Furthermore, the period of the non-linear plasma wave increases as the amplitude increases. It is possible for the maximum amplitude of a non-linear plasma wave to exceed the cold nonrelativistic wave breaking field. The maximum electric field amplitude in the case of non-linear, relativistic plasma wave is given by:

$$E_{wb}(NL) \simeq \sqrt{2}(\gamma_p - 1)^{1/2}E_{wb}$$

which is referred to as the cold relativistic wave-breaking field, where

$$\gamma_p = (1-\frac{v_\phi^2}{c^2})^{-1/2}$$

is the relativistic Lorentz factor associated with the phase velocity (v_ϕ) of the plasma wave, which in the 1D low intensity limit is $\sim\omega/\omega_p$. This is because the relativistic wake-field resists the wave breaking. In such a case, the electrons cannot easily overtake those with lesser momentum, as the wave is propagating at a relativistic speed and it becomes difficult for electrons to overtake this speed because they cannot exceed the speed of light. Instead they pile up at the particular wave phase to form a cusp singularity. In such a case, the plasma wave structure does not remain perfect sinusoidal and is therefore called non-linear plasma wave. Thus relativity facilitates matter to form robust structures and also enhances the maximum ('wave breaking') field above which they break, leading to much greater accelerating gradient in the non-linear regime. Owing to this high acceleration field, compact accelerators can be developed using laser-driven plasma based acceleration technique.

In order to excite high amplitude plasma waves, it is necessary that the laser pulse duration is short so that the corresponding ponderomotive force is stronger due to higher intensity gradient. Also, when the laser pulse length (L = cτ, where τ is laser pulse duration defined as FWHM: full width at half-maximum) matches with half the plasma wavelength (λ_p) i.e. $L\approx\lambda_p/2$, the plasma wave is resonantly excited and produces large amplitude wake-field. For typical plasma densities suitable for LWFA in the range of 10^{17}–10^{19} cm^{-3}, this corresponds to drive laser beams with pulse lengths in the range of ~150–15 fs, i.e. in the ultra-short regime.Later it was also proposed that in place of a single laser pulse, a train of laser pulses (with appropriate pulse width and spacing between the pulses) can be used to generate a large amplitude wake-field.

When Tajima and Dawson proposed the idea of LWFA in 1979, laser systems with ultra-short pulse duration and sufficient power were not available. However, high-power lasers with longer duration pulses (sub-ns regime) were available for fusion related studies and such systems were used to demonstrate a technique of electron acceleration known as Plasma Beat Wave Acceleration (PBWA). Subsequent to the invention of Chirped Pulse Amplification (CPA) technique [6] in 1985, Ti:sapphirelaser systems of several TW power and pulse duration of several tens of fs became available in the early 1990s. Such systems were used to demonstrate yet another version of LWFA known as Self-Modulated Laser Wake-field Acceleration (SM-LWFA). Only during last decade it has been possible to demonstrate true LWFA with the availability of laser systems with few tens of TW and higher power and few tens of fs duration. In fact now PW class laser systems are available and are being used for this purpose.

Plasma Beat Wave Acceleration (PBWA)

The PBWA was proposed by Tajima and Dawson as an alternative to the LWFA since compact, ultra-shortpulse, ultra-high power laser technology was not available in 1979. In this scheme two laser pulses (in the ps regime) are collinearly injected into a low density plasma, such that the plasma frequency equals the difference frequency of the two lasers, i.e. $\omega_p = \Delta\omega = \omega_1 - \omega_2$.Two laser beams of frequency ω_1 and ω_2 will beat at a frequency $\Delta\omega = \omega_1 - \omega_2$.The beat pattern can be viewed as a series of short light pulses, each $\pi c/\omega_p$ long, moving through the plasma at the group velocity of the laser. Plasma electrons feel the periodic ponderomotive force of these pulses. Since $\omega_p = \Delta\omega = \omega_1 - \omega_2$ the plasma responds resonantly to the ponderomotive force and large amplitude plasma waves are generated, with a phase velocity equal to the group velocity of the laser beam, which is close to speed of light 'c'. PBWA uses conventional long pulse (~100 ps) and modest intensity lasers ($I \sim 10^{14} - 10^{16}$ W / cm^2). For example, two CO_2 lasers operating at 10.6 µm and 9.6 µm; or Nd:YAG laser (1.064 µm) and Nd:glass laser (1.054 µm).For both, CO_2 as well as Nd:glass laser, the required plasma electron density is ~10^{17} cm^{-3}.

PBWA scheme has many limitations. Pre-formed plasma of uniform density is required as the excitation process is highly resonant. As the plasma wave amplitude increases, its period also increases. Since the period of the beat wave is fixed, the plasma wave will eventually become out of phase. So, the plasma wave amplitude saturates much before the wave breaking limit. Moreover, since the laser pulse length L exceeds λ_p, the laser beam gets subjected to various instabilities.

Self-Modulated Laser Wake-field Acceleration (SM-LWFA)

Earlier it was mentioned that in place of a single laser pulse, a train of laser pulses can be used to generate a large amplitude wake-field. Under appropriate conditions, it is possible for a single long laser pulse to break up into a train of short pulses, with each of these short pulses having a width of the order of λ_p. The process by which this happens inside plasma is referredto as self-modulation.

SM-LWFA uses a single ultra-short duration (few tens of fs), ultra-high intensity ($\geq 10^{18}$ W / cm^2) laser pulse as in the standard LWFA. However, SM-LWFA operates at comparatively higher density such that laser pulse length L $>\lambda_p$. Moreover, laser power (P) is larger than the critical power for relativistic guiding (P_c), i.e. $P > P_c$ ($= 17\,\omega^2/\omega_p^2$ GW). In the high density regime, the laser pulse undergoes a self-modulation instability which causes the pulse to become axially modulated at the plasma period. This effectively works as a train of short pulses and hence large amplitude plasma wave is generated. The break-up of a long laser pulse can occur via forward Raman scattering in the 1-D limit or via envelope self-modulation instability in the 2-D limit. Physically, the envelope self-modulation occurs from the plasma wave producing periodic regions of enhanced focusing and diffraction.

The advantage of the SM-LWFA over the LWFA is the enhanced acceleration. SM-LWFA operates at higher density, hence a large wake-field will be generated, since $E \sim n_0^{1/2}$. Further, as the wake-field is resonantly excited by a series of beamlets and at $P > P_c$, the laser pulse will tend to focus to a higher intensity, and the wake-field generated is large. Relativistic optical guiding allows the laser to propagate over a longer distance.

Disadvantages of the SM-LWFA are: at higher densities the laser pulse group velocity (plasma wave phase velocity) decreases and hence electron dephasing may limit the acceleration length. Also, the modulated pulse structure eventually diffracts.

Blow-out or Bubble Regime

The high intensity 3D regime of LWFA has been referred to as the bubble, blow-out, or cavitation regime [7,8]. In this extremely non-linear regime, a short laser or electron pulse (in case of PWFA) completely blows out all the plasma electrons, creating a bubble-like wake-field structure. In addition to electron cavitation, a fraction of the plasma electrons can become self-trapped in the ion cavity and can be accelerated to high energies. The robust bubble structure has some very desirable properties for generating high quality, high energy electron beams. The first is that the accelerating field is independent of the transverse position in the wake so all the particles at a given longitudinal position gain energy at the same rate, which helps minimize the energy spread of the accelerated beam. The second is that the focusing field increases linearly with transverse position, which helps minimize the transverse emittance growth of the beam. Thirdly, the electron density depression caused by the disturbance (the wake-field) is able to guide a matched drive laser beam over many diffraction lengths, thus increasing the energy gain. This is important because this self-guiding obviates the need to provide external guiding, simplifying the concept for practical applications. It may be noted that plasma blowout can occur in the SM-LWFA regime also after evolution of the laser pulse during the initial phase of its interaction with plasma.

To summarize, the excitation of large plasma wake-fields by laser pulses can be divided roughly in two categories. The "standard" regime (LWFA) in which the laser intensity is sufficiently high and the laser pulse is sufficiently short ($L\sim\lambda_p$) or the gradients in the axial intensity profile are sufficiently short, such that the initial laser pulse profile immediately drives a large plasma wave leading to blow-out or bubble regime. In the standard regime, pulse evolution is not required to excite a large wake-field. The other category is "self-modulated"regime (SM-LWFA), where initially longer pulses ($L>\lambda_p$) of relatively lower intensities are used. In this second regime, the initial laser profile does not immediately drive a sufficiently large wake-field, and evolution of the laser pulse is necessary to excite a large plasma wave. The pulse evolution is a result of the initial plasma density perturbation acting back on the laser pulse leading to self-focusing and pulse break-up in small pulse lets generating suitable condition for strong wake-field generation and bubble formation.

Electron Injection in Wake-field

In principle, the electrons can be externally injected in the laser wake-field. However, as very small time (several fs) and space (several μms) scales are involved, this puts very stringent requirements on the external electron source and its synchronization with the ultra-short laser pulse. However, as mentioned earlier, electrons could also be self-injected (from the plasma itself) into the wake-field thanks to the phenomenon of wave-breaking which occurs for plasma waves of large amplitudes in the non-linear regime. However, due to highly non-linear process, in order to have control over self-injection of the electrons to generate high quality electron beams, precise control over laser and plasma parameters is required. Therefore, other controlled methods of electron injection have also been investigated viz. density gradient injection (by creating a localized sharp density variation in the gas-jet target), ionization induced injection (by mixing high-Z gases with the low-Z gas-jet targets), and optical injection (by using a second laser pulse and colliding it with the main laser pulse).

Limitations of LWFA

Several mechanisms can limit the energy gain in an LWFA: laser diffraction, electron dephasing, pump depletion, and laser-plasma instabilities. Some of these limitations are discussed below.

Laser beam diffraction

A laser pulse propagating in vacuum undergoes Rayleigh diffraction, i.e., the laser spot size evolves according to

$$\omega(z) = \omega_0\sqrt{1+\frac{z^2}{z_R^2}}$$

where$_0$ is the minimum spot size at the focal point (z=0) and $Z_R=\pi\omega_O^2/\lambda$ is the Rayleigh length, which is typically in the range of sub-mm to few mm. Without some form of optical guiding, the acceleration length in LWFA will be limited to $\sim Z_R$. However, relativistic self-focusing of the laser beam inside plasma prevents laser diffraction and hence the laser pulse can propagate several Rayleigh lengths inside the plasma. As mentioned earlier also, in the bubble regime, for matched conditions, the bubble structure helps in guiding the laser pulse over a longer distance. Pre-formed plasma channels with parabolic density profile e.g. capillary discharge, can also be used to guide the laser pulse to longer distances. Hence, channeling coupled with guiding can increase the laser propagation length inside the plasma to cm scale, and hence facilitating production of GeV electron beams on a 'table-top'.

Dephasing

As the electron is accelerated along laser-propagation axis by electrostatic plasma wave, its velocity increases and approaches the speed of light. If the phase velocity of the plasma wave is constant with $v_p<c$, the electron will eventually outrun the plasma wave and move into a phase region of the plasma wave that is decelerating. The dephasing length (L_d) is defined as the length over which the wake-field slips from the electron over half the wavelength so that no longer able to continue acceleration. Dephasing length is given by:

$$L_d = \lambda_p\gamma_p^2$$

where $\gamma_p=\omega/\omega_p$, is the relativistic Lorentz factor associated with the plasma wave. For typical plasma densities used in LWFA, this could be in the range of sub-mm to several mms.

Pump Depletion

As the laser excites plasma wave, it loses energy, i.e. it (pump) gets depleted. The pump depletion length (L_{pd}) is given by:

$$L_{pd} = (\lambda_p^3 / \lambda^2) a_0^{-2}$$

Where a_0 is laser strength parameter determined by laser intensity (for Ti:Sapphire laser operating at a wavelength of 800nm, $a_0 \sim 1$ for I ~ 2x10^{18} W/cm^2, when relativistic effects become important).In the linear ($a_0^2 \ll 1$) wake-field regime,$Z_R \ll L_d \ll L_{pd}$. Furthermore, since $L_d \propto n_0^{-3/2}$ and$L_{pd} \propto n_0^{-3/2}$, the dephasing length and pump depletionlengths can be increased by operating at lower densities.Since $L \sim \lambda_p$in the standard LWFA, lower densities correspondto longer laser pulse durations $L \propto n_0^{-1/2}$.

In the linear regime, dephasing limits the energy gain of the electron in the plasma wave. Over the dephasing length electrons gain energy by:

$$\Delta\varepsilon = 2\gamma_p^2 m_0 c^2 a_0^2$$

However, by appropriately tapering the axial plasma density profile, dephasing limitations can be overcome, resulting in a larger single-stage energy gain. Appropriate tapering may mitigate dephasing such that acceleration will be limited by pump depletion. However, in the non-linear regime (a_0^2>1) $L_d \sim L_{pd}$ and no density tapering is needed since the electron energy gain is limited by pump depletion, not dephasing. In particular, the regime, $a_0^2 \sim 1$ such that $L_d \sim L_{pd}$, has advantages over the linear regime.

LWFA: Progress in Experimental Work

Initial experiments on laser-driven plasma based electron acceleration using PBWA and SM-LWFA schemes produced electron beams of several MeV to few hundred MeV energy but of poor quality and with 100% energy spread. It was only in year 2004 that three groups simultaneously reported generation of quasi-monoenergetic electron beams [9-11]. The generation of high quality electron beams could be achieved in these experiments by precise tuning of the plasma density and a higher degree of control of the laser parameters, and more importantly matching the acceleration length to the dephasing length. Subsequently, various other laboratories also reported generation of quasi-monoenergetic electron beams[2]. All these experiments basically demonstrated the bubble regime of acceleration although in most of these experiments initial laser pulse parameters (pulse duration, power and focal spot) were not matching for the bubble regime considering the plasma densities used. This could only be possible because of laser pulse evolution (pulse shortening or pulse break-up,and self-focusing) during the initial phase of the laser plasma interaction.

After successful demonstration of high quality, quasi-monoenergetic electron beams, a major break-through was reported in year 2006 by generation of GeV electron beams by LWFA in a capillary discharge channel [12]. Later on, generation of GeV electron beams was also reported in gas-jet targets relying on relativistic self-focusing and guiding of the laser beam in the plasma [13,14]. Generation of high-quality electron beams of few hundreds of MeV energies by using other controlled electron injection schemes viz. optical injection [15], density gradient injection [16], and ionization induced injection [17] has also been reported. In summary, during the last decade worldwide efforts have led to generation of high quality, quasi-monoenergetic electron beams of energy upto GeV level on a table-top using LWFA.

Applications of LWFA

The electron beams generated by laser wake-field accelerators possess a number of unique properties, such as ultra-short pulse duration of the order of the laser pulse (few fs), high peak currents and excellent emittance values with an energy spread of about a few percent. This makes them attractive for a variety of applications [18] viz.for development of compact x-ray and γ-ray sources (by betatron radiation and inverse Compton scattering process), x-ray free electron laser injector, ultrafast (fs) radiolysis, cancer therapy, compact radio-activation machines such as PET sources, etc. The laser wake-field is also a source of coherent THz radiation, which in turn, maybe employed for various applications. Furthermore, the electron bunches generated by LWFA are synchronized to the laser pulses, enabling variety of pump-probe applications.

Experiments on LWFA at Laser Plasma Division, RRCAT, Indore

At Laser Plasma Division, we are pursuing a programme on experimental investigations on LWFA. Experiments have been carried out using a CPA based 10 TW, 45 fs Ti:sapphire laser system providing > 10^{18} W/cm^2 of intensity on He gasjet target having electron density in the range of 1-10x10^{19} cm^{-3}. While working in the SM-LWFA regime, we have been able to generate quasi-monoenergetic electron beams with energy in the range of 20-50 MeV and a beam divergence of <10 mrad, at specific values of electron density [19-22]. The effect of the laser pulse chirp and laser pre-pulse on the electron beam generation was also studied [20,21]. With the proper choice of focusing optics (focal length of the off axis parabola) and controlling the ASE pre-pulse intensity below the pre-plasma formation threshold, high quality, stable electron beams with almost no background have been generated using He gas-jet target [22]. A comparative study with different gases (He, N_2, and Ar) was also performed. Recently, we have demonstrated generation of high quality quasi-monoenergetic electron beam with peak energy ~12 MeV, from self-guided LWFA in a plasma plume produced by laser ablation of solid Nylon $(C_{12}H_{22}N_2O_2)_n$ target [23]. Further experiments are also planned for near-GeV electron beam generation using a 150 TW, 25 fs Ti:sapphire laser system which will be operational soon in our laboratory.

Experiments with gas-jet targets

A schematic of the experimental setup used for LWFA in plasma plume target is shown in Fig. T.2.2. The 10 TW Ti:sapphire laser system delivers horizontally polarized laser pulses of τ~45fs, having central wavelength $\lambda_0 \cong 800$ nm. The contrast ratio of the replica fs duration pre-pulse arriving 8 ns before the main pulse was better than 10^6, and the contrast ratio of ASE pre-pulse was about 10^6. The ps pre-pulse contrast ratio was 10^3 and 10^4 at 1 ps and 5 ps (respectively) before the main pulse.

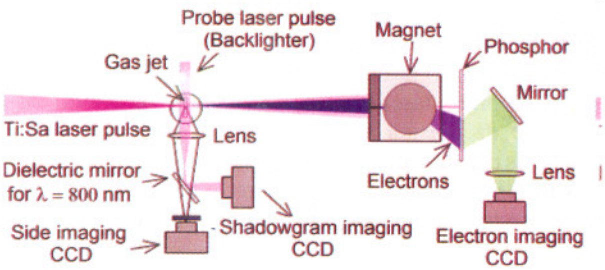

Fig.T.2.2: Schematic of the experimental setup

The laser beam was focused using an off-axis parabolic mirror (OAPM). In the initial studies OAPM of focal length ~40cms providing focal spot of FWHM ~18μm was used, and in later studies of 30 and 27 cms providing focal spot of FWHM ~11-12μm. Gas-jet was produced by a supersonic nozzle with an orifice of 10mm length and 1.2 mm width, and laser pulse was focused at a height of 1 mm above the nozzle orifice. The gas-jet density was obtained from interferometry and it was further confirmed from the forward Raman scattering measurements [19]. The longitudinal profile of the gas-jet was flat-topped, with scale length about 100 μm at the edges. Backing pressure of the gas-jet was varied to adjust the plasma electron density (n_e) in the range of 10^{19}–10^{20}cm^{-3}.

For measuring the energy spectrum, a single-shot electron spectrograph consisting of two circular permanent magnets with 50 mm diameter, 9 mm pole gap, and effective magnetic field B_{eff} = 0.46 T, was used to deflect the electrons onto a DRZ-High (Gd_2O_2S:Tb) phosphor screen which was imaged with a 16-bit CCD camera. A slit was used at the entrance of the magnet to allow in only the electrons within 8 mrad acceptance angle in the plane of the electron dispersion. The low energy cut-off of the electron spectrometer was 10 MeV.

The electron beam charge was estimated using an integrating current transformer (ICT, Bergoz:ICT-082–070-5:1)) and also using the available absolute calibration data of the phosphor screen. The electron beam profile and the pointing variation were measured by moving the magnet out from the path of the electron beam.

The laser-plasma interaction was imaged from the non-linear Thomson side-scattering radiation at second harmonic (400 nm) of the laser, with 5X magnification using a 12-bit CCD camera. A narrow band-pass filter at 400 ± 20 nm was kept in front of the CCD camera for transmitting the second harmonic radiation. A small fraction of the drive laser beam, with variable delay relative to the main laser beam, was used as a probe beam (back-lighter) to record the shadowgram images of the interaction region with 2ps time resolution. The probe beam was sent perpendicular to the incident laser axis and the gas-jet flow direction and was in the direction of the side-imaging setup.

A multilayered dielectric mirror, with high reflectivity at 800 nm radiation, was placed in front of the side imaging CCD camera to reflect the probe beam onto a separate 12-bit CCD camera, while allowing the 400 nm radiation to reach the side imaging CCD camera, as shown in Fig.T.2.2. A narrow band-pass filter at 800± 20 nm was kept in front of the shadowgram imaging CCD camera.

In the initial experiments with He gas-jet target and OAPM of focal length ~40cms, highly collimated, quasi-monoenergetic electron beams of energy in the range of 10-21 MeV was observed at a plasma density of ~8.5×10^{19}cm^{-3}, but only in 20% of the laser shots [19]. Generation of high-energy electron beams with 100% energy spread was observed in every laser shot with energy integrated total charge in excess of 2 nC which was found to depend strongly and asymmetrically on the magnitude and sign of the laser pulse chirp [21]. In a later experiment with OAPM of focal length ~30 cms, we could generate electron beams with energy upto ~50 MeV, having low divergence in the range of 3-6 mrad, and bunch charge up to 100 pC, at a plasma density of ~6.4×10^{18} cm^{-3}, as shown in Fig.T.2.3 [20].

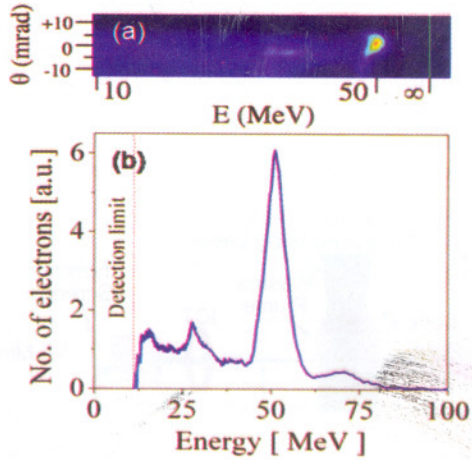

Fig.T.2.3: Energy spectrum of the quasi-monoenergetic electron beam of energy ~50 MeV.

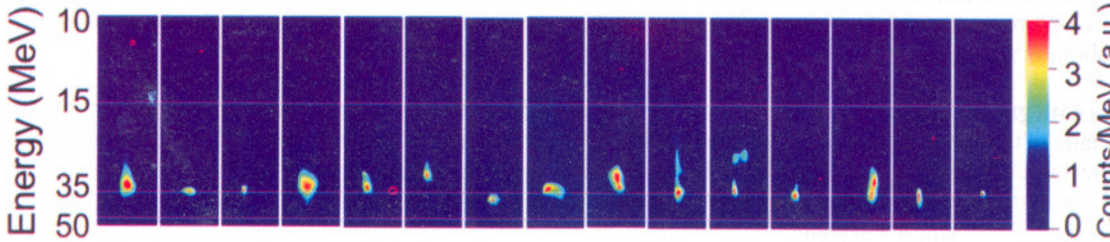

Fig. T.2.4: Energy spectrum of the quasi monoenergetic electron beam from He gas jet target recorded in 15 consecutive shots.

In our recent experiments with OAPM of focal length ~27cms, high quality, stable, quasi-monoenergetic electron beams were produced (in best conditions reproducibility was almost 100%) at a plasma density of $\sim 5.8\times10^{19}$ cm^{-3} with He gas-jet.

A series of images of the electron beam energy spectra recorded during one of the experimental runs is shown in Fig.T.2.4.The electron beam has virtually background free quasi-mono-energetic distribution with peak energy of ~35 MeV, charge of several pC, divergence ~10mrad, and pointing variation ~10 mrad. High stability of the electron beam was achieved by having low laser pre-pulse intensity below pre-plasma formation threshold, and a high quality of the beam was obtained by operating near self-injection threshold [22].

A comparative study with different gases has also been performed, which showed similar kinds of beams with N_2 gas-jet (although with comparatively larger background and energy fluctuation), and highly divergent electron beams with very poor reproducibility with Ar gas-jet .

Experiments with plasma plume targets:

Gas-jet is the most commonly used target medium for LWFA experiments. However, operation of the gas- jet at high repetition rate > 1 Hz (required for many applications of the electron beam) is limited by the requirement of high vacuum before each gas-jet pulse. As an alternative, we have investigated a novel scheme wherein laser ablated solid plasma plume is used as a target for LWFA. The laser ablation of the solid target releases negligible amount of material in the vacuum chamber in comparison to a gas-jet and therefore allows operation at high repetition rate of ~ 1 kHz or more.

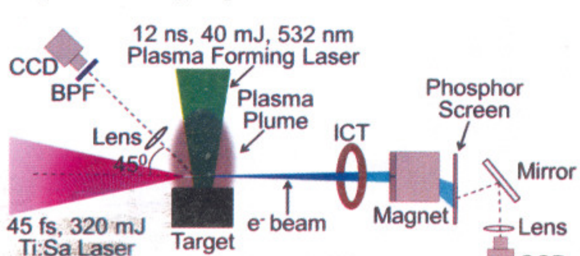

Fig.T.2.5: Schematic of the experimental setup for LWFA in plasma plume target

A schematic of the experimental setup used for demonstration of LWFA in plasma plume target is shown in Fig.T.2.5.Ti:sapphire laser pulse (λ = 800 nm) of 45 fs duration and focused intensity $\sim 5\times10^{18}$ W/cm^2(using OAPM of focal length ~17cms) was used as a drive beam for LWFA. To produce plasma plume, a part of the second harmonic converted Nd:YAG laser pulse that pumps the final amplifier of the Ti:sapphire laser system, was focused on a solid target to produce its plasma with appropriate density and scale length 90 ns before the arrival of the 45 fs laser pulse.

Various target materials, target distances and delay between the two laser pulses, were investigated to identify the appropriate conditions for accelerating electrons and to produce a high quality electron beam. After optimization, high-quality quasi-monoenergetic electron beam with divergence ~10 mrad, energy ~12 MeV, and charge ~50 pC was produced as shown in Fig.T.2.6 [23].

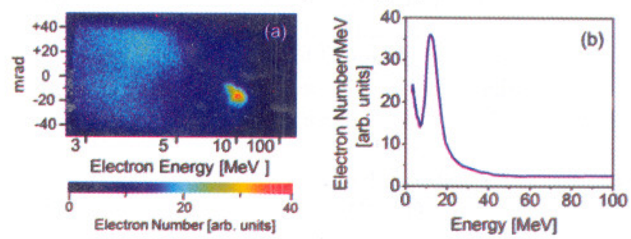

Fig.T.2.6: (a) Image of the energy dispersed electron beam showing well collimated quasi-monoenergetic electron beam, and (b) Energy spectrum of the quasi-monoenergetic electron beam shown in (a).

Conclusion and Future Prospects

Laser wake-field electron acceleration technique is a vibrant field of research due to possibility of developing compact accelerators and unique electron beam properties with potential new applications in the fundamental and applied physics. The research on LWFA is progressing very rapidly. Using LWFA, GeV electron energy has already been produced and may soon energies of 10 GeV could be demonstrated [24]. In future large accelerators (colliders) may also be based on plasma acceleration technique [25]. Another advantage of LWFA accelerators is due to ultra-short duration of the generated electron beams which allow unprecedented advantage in stopping such beams using collective deceleration mechanism [26] in a plasma after the usage, which is not possible with conventional accelerators where electron beam duration are longer and beam dump after use is a serious issue.

The issue for matching the performance of LWFA with conventional accelerators, laser systems providing ultra-short pulses with high peak and average powers (repetition rate of tens of kHz) with high efficiency are required. Such characteristics are not available with today's laser technology. Although semiconductor diode lasers can provide very high average laser powers, they have poor beam quality. New technologies based on fibre lasers are being explored [27]. The key technology for achieving this is coherent beam combining in which pulses from many fibre lasers are coherently combined on very large scales [27].

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