Chapter 7: Summary and Future outlook

In this thesis work, experimental investigations on laser wakefield acceleration of self-injected electrons were carried out under wide ranging laser pulse and target conditions using a table-top 45 fs, 10 TW laser system. The investigations showed that precise control of interaction parameters is crucial for producing stable relativistic electron beams with low divergence and small energy spread. Studies on fast electrons and x-rays generation from laser solid interaction at oblique incidence were also carried out. The summary of these studies and outline of future work that can be carried out in this field, are discussed in this chapter.

7.1 Summary of the important results

The study on laser wakefield acceleration of electrons in the self-modulation regime using helium gas jet showed generation of low divergence (< 10 mrad), and quasi-monoenergetic (ΔE/E < 10%) electron beam, with energy up to about 20 MeV, at a high plasma density of 8.5×10^{19} cm^{-3}, in contrast to the poor quality beams reported in many earlier experiments in this regime. Simultaneous observation of forward Raman scattering (FRS) confirms strong modulation of the laser pulse and excitation of large amplitude plasma wave. The results clearly suggest that even if the initial laser pulse length cτ₀ is much longer than the plasma wavelength λ_p, strong self-modulation of the laser pulse supported by a high plasma density produces intense pulse-lets of longitudinal size of ~λ_p/2 and transverse size and interpulse separation ~ λ_p, which eventually leads to acceleration in “bubble” like wakefield and generates quasi-mono-enerygetic electron beam. We have shown that the self-modulation and consequently the accelerated electron charge and energy could be controlled by introducing frequency chirp in the laser pulse. We have also shown that an optimum value of positive
chirp generates a laser pulse with faster rise time which produces intense seed for stronger
modulation of the laser pulse and consequently a stronger wakefield excitation, leading to
higher electron beam charge and energy. Although SM-LWFA relies on FRS instability, the
plasma wave amplitude could be controlled by controlling the seed. Since the
ponderomotively excited wake dominates over other noise sources in this parameter regime,
pulse shaping through laser chirp provides a handle to control the seed for the instability. This
offers a method for minimizing shot-to-shot output fluctuations in the beam properties in the
SM-LWFA.

The effect of interaction parameters viz., pre-pulse and gas media has also been
studied. We have shown that the ASE pre-pulse pedestal associated with the CPA based high
power laser pulses can be used advantageously to form pre-plasma in helium gas jet suitable
for intense laser pulse guiding. Guiding of intense fs laser pulses over few times Rayleigh
length in the ASE pre-pulse formed plasma channel was observed under optimum conditions.
It has been shown that the laser beam guiding could facilitate generation of high energy
electrons due to the longer interaction length and lower plasma density on the axis. It was
further demonstrated that accelerated electron beam with low divergence and quasi-mono-
energetic distribution with peak energy more than 50 MeV could be produced. However, the
stability of the electron beam produced from these pre-plasma channels is affected by the
shot-to-shot fluctuations of the ASE pre-pulse. We have shown that with reduction in pre-
pulse intensity below the ionization threshold, the stability and the quality of the quasi-mono-
energetic electron beam could be improved significantly, although the peak energy is limited
to a smaller value ~ 35 MeV. The results agree with the scaling laws of the “blowout”
regime, clearly suggesting that this regime could be accessed even at higher density to
produce high quality electron beams. Investigation of LWFA in nitrogen (N₂) gas jet under
same experimental conditions showed comparable stability and quality of the accelerated
electron beam. However, the mean electron energy (25 MeV) is less than that observed from He gas jet target. Electron acceleration in Ar gas jet was unstable and collimated electron beams of 40 – 50 mrad were observed once in a while at plasma density > 10^{20} \text{ cm}^{-3}. Highly stable, quasi-mono-energetic electron beams from He and N\textsubscript{2} are extremely attractive for application of the accelerator in future, especially due to the wide spread availability of ≤ 10 TW class lasers with a number of laser plasma laboratories around the world.

A study on the novel technique of laser-driven electron acceleration in solid plasma plumes showed fs laser pulse self-guiding and quasi-mono-energetic electron beam (∼ 10 MeV) generation from wakefield acceleration in solid Nylon plasma plume target. The nanosecond laser pulse for plasma plume formation and the fs laser pulse for wakefield acceleration of electrons, were derived from the same Ti:sapphire laser system. This scheme is simple, low cost, and has the capability for high repetition rate operation. This scheme is therefore highly attractive for future investigations.

Collimated relativistic electron beams were also observed when the fs laser pulse interacted at grazing incidence with a pre-formed under-dense plasma on the solid target generated by the inherent ASE pre-pulse. The level of ns laser pre-pulse is found to be critical for the generation of the electron beam along the target surface. By optimal choice of pre-pulse, highly collimated electron beam with angular divergence ∼ 3° and quasi-mono-energetic peak at 3 MeV was achieved. The electron beam produced from this technique is a potential candidate for applications which require high repetetion rate. This can also be used as an injector for high energy conventional accelerators or laser-plasma wakefield accelerators and also for many other possible applications.

Further, measurement of the angular distribution of the hard x-ray bremsstrahlung radiation (> 40 keV) generated due to the fast electrons produced from the solid copper target from the interaction of the Ti:sapphire laser pulses with planar copper target at 45° incidence
angle was carried out. The secondary sources of x-rays and the direction of fast electrons emission were identified from the angular and distance dependence of x-ray dose distribution measurements. Next, the fast electrons were characterized under different laser irradiation conditions. The measurements on the angular spread showed that the fast electron jet along the target normal direction with a half cone angle < 20°. The energy spectrum of the fast electrons for both p- and s-polarized laser irradiation at intensities in the range 4×10^{16} - 4×10^{17} W/cm² (for a fixed pulse duration of 45 fs) and for pulse duration in the range 45 fs – 1.2 ps (for a fixed laser fluence of 1.8×10^4 J/cm²) were investigated. The fast electron temperature showed a power law scaling with laser intensity of the form I^{2/3} and exponential scaling of the form exp (-τ / 540 fs) with the pulse duration. The results clearly suggested that the fast electrons were generated from the resonance absorption mechanism.

### 7.2 Future outlook

Demonstration of stable electron beams from laser wakefield accelerator is an important outcome of the present thesis work. However, controlling the electron beam parameters (e.g. energy and charge) is another important requirement for any practical accelerator. In this context, other controlled injection schemes e.g. those using density transitions [154-158] or colliding pulses [159-162] could also be investigated. Laser produced solid plasma plumes can be further investigated for different target and laser interaction condition, for producing controlled and stable electron beams. The effect of controlled pre-pulse in presence of external magnetic field can be explored for extended laser guiding and enhanced energy gain of electrons in the wakefield [110]. There is also a need to further increase the electron energy to near-GeV and above, which invariably requires use of higher power lasers. It would be interesting to perform similar investigations on laser wakefield acceleration using the 150 TW laser which has recently been installed in our laboratory, for
beyond 100 MeV to near-GeV acceleration in different gas jets and plasma plumes. The use of capillary plasma wave-guides can also be investigated for longer interaction lengths and further high energies.

Investigation of collimated quasi-mono-energetic electron beam generation from solid surface pre-plasma by laser grazing incidence can be extended to study the role of target material, angle of incidence, and laser parameters (e.g. intensity, polarization and chirp/pulse duration) for higher energy and higher quality electron beams, which will be interesting for number of applications including the fast ignition concept of inertial confinement fusion. Further, the study of fast electron generation from laser-solid interaction at oblique incidence can be extended to study in detail the role of angle of incidence on the efficiency of fast electron generation, their angular distribution and energy spectrum. The fast electrons can be used to generate hard x-ray bremsstrahlung which can be explored for applications like transmutation of nuclear isotopes through $(\gamma, n)$ reactions.