SYNOPSIS

The advancements in laser technology over the years have led to the generation of femto-second duration laser pulses of terawatt to petawatt power from table-top systems, which has opened up new research areas. The ultra-short, high power laser pulses can be easily focused to a spot size of the order of 10 µm resulting in intensity exceeding $\sim 1 \times 10^{18}$ W/cm$^2$. Matter subjected to such ultra-high intensities gets instantly ionized by the leading edge of the laser pulse due to the extremely strong electric field and turns into a plasma. The oscillatory velocity of the free electrons in such intense laser fields becomes relativistic. This relativistic regime of laser-plasma interactions has attracted great interest of the scientific community due to the potential of these interactions in generating high energy electrons, ions, and neutrons, as well as x-rays, with unique properties. The duration of the emission of both high energy particles and the short wavelength radiation is expected to be ultra-short. This has many applications in basic science, medicine, and technology. In addition, ultra-short laser pulses with a few fs duration allow experimentalists to study highly transient processes in a time resolved manner.

Electron acceleration by the large amplitude relativistic plasma waves driven by a high intensity, ultra-short laser pulse propagating in the plasma, created mostly from a gaseous medium, is interesting due to the extremely strong accelerating fields of $\sim 100$ GV/m of the plasma wave. This method of acceleration, referred to as laser wakefield acceleration (LWFA), was proposed in the year 1979 by Tajima and Dawson. The strong accelerating field of the plasma wave enables generation of high energy electrons from a compact and low cost accelerator setup. Therefore, this method is being actively pursued as an alternative to the present day high energy accelerators, whose size and consequently the cost becomes huge, mainly due to the accelerating field in the conventional radio-frequency technology being
limited to less than 100 MV/m. Generation of hundreds of MeV electrons from laser driven acceleration in millimeter long plasmas was demonstrated several years ago. However, the electron beams were typically characterized by large divergence and exponentially decreasing energy distribution. With more controlled experiments and advancement in understanding of the processes involved, high quality electron bunches characterized by quasi-mono-energetic peak and low divergence (< 10 mrad) were produced under widely different laser pulse and plasma density parameters. While the generation of high quality electron beam is a big step forward towards the usability of the laser wakefield accelerator for applications, there are several key issues related to further improvement in quality, stability, and repetition rate of the electron beam. Currently active research is going on at major laboratories around the world including at Laser Plasma Division, RRCAT in India, to improve these parameters for realizing a practical laser wakefield accelerator which can be installed in a small scale setup for wide ranging applications. In parallel, demonstration experiments of electron beams produced from laser wakefield accelerators for applications in soft x-ray undulator, radiography, transmutation etc. have been performed and further applications in free-electron lasers are being explored.

While laser wakefield acceleration is of interest for generation of high energy electrons with several tens of MeV to GeV from a compact accelerator setup, multi-MeV energy electrons generation from intense laser - solid interactions through various mechanisms, such as resonance absorption, vxB acceleration, etc., are being investigated actively over the years to understand the interaction processes under wide ranging laser and target parameters and also due to their application in the fast ignition concept of inertial confinement fusion. The energetic electrons produced from interaction of laser with solid targets are generally referred to as “hot” or “fast” electrons. The fast electrons when retarded in the target material produce a bright source of hard x-rays, which can be useful for a variety
of research and technological applications. For instance, such sources have been used for activation of short-lived isotopes which can be used in radiological diagnostics for positron emission tomography, transmutation of elements by neutron capture to deactivate long-lived fission fragments, and for nuclear fission of actinides. Again, many of these applications require collimated energetic electrons in a well-defined direction. Therefore, careful control of the laser and plasma conditions is required to generate collimated electron beams from solid target.

In the present thesis work, several experimental studies have been carried out on laser wakefield acceleration using different laser interaction parameters and gas jet target media, with an objective to generate high energy and high quality electron beams and the optimum conditions for the same have been identified. Laser driven acceleration in solid plasma plume target was studied as an alternative to the conventional gas jet targets, due to its ability to be operated at high repetition rate. Quasi-mono-energetic electron beams were demonstrated from the solid plasma target through optimization of pre-pulse and target conditions. Generation and characterization of fast electrons from high intensity laser - solid interactions were also carried out under different laser irradiation conditions to understand the interaction process. Angular distribution of the bremsstrahlung x-ray emission produced by the fast electrons was studied. The chapter-wise summary of these studies is given below.

**Chapter 1** gives theoretical foundations of various ultra-high intensity laser matter interaction processes relevant to the present thesis work. Starting with basics of electromagnetic waves and plasma, electromagnetic wave propagation in plasma, laser induced ionization of atoms, motion of a free electron in laser field, ponderomotive acceleration, self-focussing etc. are discussed. Laser wakefield acceleration and related concepts viz. electron self-injection, dephasing, pump depletion along with various regimes of
electron acceleration are presented. Finally, energetic electrons and bremsstrahlung x-ray generation in resonance absorption, vacuum heating, and $J \times B$ heating are described.

All the experiments presented in the thesis were carried out using a table-top 10 TW, 45 fs Ti:sapphire laser system at Laser Plasma Division, RRCAT. Chapter 2 gives the overall description of the Ti:sapphire laser system. Next, measurements of various laser pulse parameters viz., laser pulse duration, spectrum, focal spot, and pre-pulse intensity contrast are described and the results are presented. Experiments on laser wakefield acceleration require relatively low density plasmas which are mostly generated from supersonic gas jet targets. The supersonic gas jet system used in the present thesis work is described. The detection and measurement of high energy electrons was done using various diagnostics. Magnetic spectrometer is an important diagnostic for measuring the energy of the high energy electrons. The magnetic spectrometer used in the experiments is described in detail.

Chapter 3 describes the experimental setup for electron acceleration. In achieving electron generation and acceleration, alignment of the setup and finding the right parameters is very crucial. Unless these are adjusted properly, no electrons are generated/accelerated. This chapter also presents the results on generation of high quality electron beam from self-modulated laser wakefield acceleration. In this chapter, the dependence of electron beam parameters viz. charge, divergence, and the electron spectrum, on the plasma density is also discussed. The electron energy spectrum typically showed 100% spread at lower plasma density but at a relatively high density $\sim 8.5 \times 10^{19}$ cm$^{-3}$, high quality electron beam having divergence $<10$ mrad, and quasi-mono-energetic distribution with energy spread ($\Delta E/E < 10$ %) was produced with a peak energy of $\sim 20$ MeV. These results, along with simultaneous detection of Raman peak in the forward laser scattering measurements, are described in detail. The results suggest strong self-modulation of the laser pulse. The underlying physics of high
quality beam generation based on self-modulation is discussed. The effect of positively/negatively chirped laser pulses on self-modulation and electron acceleration was also investigated. Asymmetric dependence of laser self-modulation, electron beam charge and energy on the magnitude and sign of the chirp is presented.

The effect of various interaction parameters viz. laser pre-pulse and gas medium on laser wakefield acceleration has been investigated to find optimum laser pre-pulse parameters and target gas medium for generating higher energy and stable electron beam. Chapter 4 presents the results of the study on the role of nanosecond duration pre-pulse pedestal in the propagation of 45 fs Ti:sapphire laser pulses and on the wakefield acceleration in a helium gas jet. Guiding of the fs laser pulses over few Rayleigh lengths in a pre-formed plasma channel, created by optimum pre-pulse level is described. Generation of electrons with higher energy (~ 50 MeV) due to laser guiding is discussed. The results of investigation on laser-driven electron acceleration in different gas jet targets viz. helium (He), nitrogen (N₂), and argon (Ar), with reduced pre-pulse pedestal intensity are presented. The parameters of the electron beam produced from all the 3 gas jets are compared in detail and explanation for the observed results is given.

Although the relativistic electron beams produced from laser wakefield acceleration in gas jet plasma targets have high peak current of ~ kA, the average current is limited mainly due to low repetition rate operation of pulsed gas jet targets. Laser driven acceleration in plasma produced from solid targets is investigated to find the possibility of quasi-mono-energetic electron beam generation at high repetition rate. Chapter 5 describes the experimental set-up and the results of quasi-mono-energetic electron beam generation from laser produced plasma plume. The results of low divergence, quasi-mono-energetic electron beam generation from Nylon target plasma plume, along with the target and target surface
distance from the fs laser axis, are presented and the physics behind the electron acceleration is discussed. Relativistic electrons were also observed, without the use of separate laser pulse for plasma formation, when the femtosecond laser beam interacted with the solid target at grazing incidence. However, the beam quality was found to depend critically on the level of ASE pre-pulse and consequently on the scale length of the pre-plasma produced in front of the solid target surface. The optimization procedure for generating quasi-mono-energetic electron beam in this case will also be discussed.

Ultra-intense laser interaction with solid target at oblique incidence results in absorption of laser energy through various mechanisms and generates fast electrons. The angular and energy distribution of these electrons is critically dependent on various laser and target interaction parameters. **Chapter 6** presents the study of fast electrons generated from the interaction of the Ti:sapphire laser pulses with planar copper target at 45° incidence angle, under different irradiation conditions. The measurements on the angular spread and the energy spectrum of the fast electrons for both p- and s-polarized laser irradiation at intensities in the range $4 \times 10^{16} - 4 \times 10^{17}$ 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 $1.8 \times 10^9$ J/cm²) is described and scaling laws for temperature of fast electrons with laser intensity and pulse duration are presented. 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, is also presented. A physical explanation for fast electron generation and observed x-ray dose distribution is also given.

In **Chapter 7**, a summary and conclusions derived from the presented work are given. Finally, an outlook for extension of the present work in future is also outlined.