Ultra-intense Laser Plasma Interaction Studies at RRCAT, Indore

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The Laser Plasma Division at the Raja Ramanna Centre for Advanced Technology (RRCAT), Indore has been engaged in research and development activities on laser plasma interaction using 10 TW, 45 fs, Ti:sapphire laser and a variety of in-house developed diagnostic systems for ultrashort laser pulses, plasma and x-ray radiation. Our recent studies include laser wakefield electron acceleration, high order harmonic generation, resonance enhancement of single harmonics, MeV energy bremsstrahlung radiation, absorption of ultrashort laser pulses in in-situ produced metal clusters, and ultrashort pulse K-shell x-ray line emission. This paper briefly describes these studies and important results obtained.

Key Words: Laser-plasma interaction, Electron acceleration, High order harmonics, Bremsstrahlung

1. Introduction

Recent advances in compact ultra-intense lasers providing peak powers of several tens of terawatt (TW) to petawatt have opened up many possibilities of enormous application interests. Ultra-intense laser plasma interaction in the high field regime have led to acceleration of electrons to GeV energy, production of ultra-intense coherent soft x-ray radiation, high energy protons, ions, x-rays, γ rays, neutrons with many potential applications. At the Laser Plasma Division of RRCAT, Indore, we have been involved in studies of laser plasma interaction both in the high energy density and high field regimes. In this paper, we briefly describe some of our recent experiments performed using a 10 TW, 45 fs Ti:sapphire laser up to an intensity of 2.4 x 10^18 W/cm². These include 1) Initial studies in laser wakefield electron acceleration, 2) High order harmonic generation from pre-formed plasma plumes, 3) MeV energy bremsstrahlung radiation, 4) Absorption of laser radiation and intense x-ray emission from laser irradiated in-situ produced metal clusters, and 5) Ultrashort pulse K-shell x-ray line emission.

2. Initial Studies on Laser Based Electron Acceleration

Conventional accelerators are large size systems because the accelerating electric field has to be kept below ~50 MV/m to avoid electrical breakdown in the accelerating structures. On the other hand, laser wake-field generated inside a plasma can give extremely high accelerating field ~100 GV/m, and this may pave way for developing very compact accelerators in future. Laser Plasma Division of RRCAT has recently initiated experimental investigations in laser wake-field electron acceleration, in collaboration with scientists from High Energy Research Laboratory (KEK), Japan, and observed acceleration of electrons.

The Ti:sapphire laser beam was focused on a helium gas jet using an f/6.6 off-axis parabolic mirror. The gas jet was produced by a shock wave-free slit type (10 mm x 1.2 mm) supersonic Laval nozzle. Helium gas was puffed using a fast solenoid valve and its density was varied by changing the backing pressure of the gas. The Ti:sapphire laser beam was focused at the entrance edge of the gas jet, about 1mm above the nozzle entrance. The focal spot diameter of the beam was 18 μm (FWHM) and the corresponding peak laser intensity was ~2.4x10^18 W/cm². A scintillator (NE102) - photomultiplier combination with the face of the scintillator covered with a 2-mm thick aluminum disc was placed along the axis to serve as a detector for the accelerated electron beam.

The experiments were performed at different laser intensities and backing pressures of the gas jet. The electron density was estimated from interferometric measurements to be ~ 10^20 cm^{-3} at a backing pressure of 67 bar of the gas jet. Figure 1 shows the detected signals corresponding to the accelerated electrons impinging on the detector. When the laser was fired in the absence of the gas jet, no measurable signal was observed. The signal amplitude varied in different laser shots. In few shots, a very large amplitude of the detected signal was observed indicating occurrence of appropriate matching of various laser and gas jet parameters for efficient excitation of the laser wake-field in the plasma. A magnet based electron spectrograph with DRZ phosphor screen and a CCD camera is under construction for detailed energy measurements.

The plasma wavelength (λ_p) corresponding to a density of 10^{20} cm^{-3} is calculated to be 3.3 μm and the laser pulse length corresponding to 45 fs laser pulse duration is 13.5 μm. This implies that there are about four plasma wavelengths under the laser pulse envelope and the experimental regime is self-modulated wake-field acceleration. The strong excitation of plasma waves can lead to wave breaking resulting in injection

![Fig.1 Detected signals corresponding to laser accelerated electrons.](image-url)
of MeV electrons into the accelerating phase of the electric field of the plasma wave. For $\lambda_0 = 795$ nm, the amplitude of the plasma wave ($E_{wb}$) for wave breaking is estimated to be $2.4T_e V/m$. The dephasing length $L_{dp} \approx \lambda_p (n_c/n_e) \approx 56 \mu m$. Hence the maximum energy gain at $n_e = 10^{20} cm^{-3}$ will be $\sim 17$ MeV.

Despite large accelerating field, the dephasing of the electrons from the plasma wave limits the electrons energy to about $2(n_c/n_e) \times m_0 c^2$. Hence the maximum energy gain at $n_e = 10^{20} cm^{-3}$ will be $\sim 17$ MeV.

The spatial profile of the electron beam has been measured using DRZ phosphor and CCD camera combination. Figure 2 shows electron beam profile at a gas jet pressure of 37 bar and laser intensity of $2 \times 10^{18}$ W/cm$^2$ indicating divergence of $\sim 10$ mrad (half cone angle). However there was shot to shot variation observed. In future experiments our emphasis will be on producing stable monoenergetic electron beam. We are also setting up a capillary discharge plasma system to serve as a waveguide for propagation of focused ultra-intense laser beam over several mm to achieve electron beam of higher energy and smaller divergence.

3. High Order Harmonic Generation

High order harmonic generation using ultrashort pulse lasers is an attractive means of producing coherent radiation in the extreme ultraviolet (XUV) spectral range, which may serve as a much simpler alternative to the soft x-ray lasers. It also has the additional advantage of having ultrashort sub-femtosecond duration pulses. Mostly gas jets are used for high order harmonic generation. However, these harmonics have a low conversion efficiency. Alternatively, one can use plasma plumes produced from low intensity laser pulse irradiation of solid targets as the medium for harmonic generation. This may be advantageous compared to the use of gas jets since the availability of a much wider range of target materials for plasma production increases the possibility of resonant enhancement.

The plasma plume was produced by uncompressed 300 ps pulse from the Ti:sapphire laser and high order harmonics of the 45 fs laser beam were observed using a flat-field grating XUV spectrograph. The details of the experimental setup and parameters for the preparation of optimal plasma for efficient harmonic conversion are given elsewhere.$^{6,7}$ A typical spectrum of high order harmonics generated by passing the femtosecond laser beam through silver plasma plume is shown in Fig. 3. Up to 61$^{\text{st}}$ harmonic order$^{8}$ was observed providing coherent soft x-ray radiation down to $\sim 13$ nm.

Next, the harmonic spectrum was studied as a function of the laser pulse chirp.$^{9}$ The latter was varied by simply enhancing some particular harmonic orders. We have studied high order harmonic generation$^{6-9}$ in plasma plumes and observed resonant enhancement$^{10,11}$ and extinction$^{11}$ of some single harmonics simply by changing the separation between the two compressor gratings. It was observed that the harmonic spectrum shifts towards shorter frequencies if we introduce negative chirp in the laser pulse and vice versa. Tuning of the 47$^{\text{th}}$ harmonic of laser radiation with variation in the laser chirp is shown in Fig. 4. In this figure, the positive sign indicates positively chirped and negative sign shows negatively chirped laser pulse. Tuning of up to 0.8 nm (for the 47$^{\text{th}}$ harmonic) is observed by changing the pulse duration from -165 fs to 260 fs. The shift in frequency is explained from the generation of harmonics in the initial part of the laser pulse.$^{9}$

Interesting features were observed in harmonic spectrum from plasma plumes of some target materials. Figure 5 shows the harmonic spectrum of indium$^{10}$. It can be clearly seen that the 13$^{\text{th}}$ harmonic of indium is very strong ($\sim 200$ times) compared to its neighbors. When laser pulse duration was...
varied from unchirped 48 fs to negatively chirped 250 fs, intensity of 13th harmonic became comparable to that of its neighbors. These observations indicate that intensity enhancement occurs due to resonance of the harmonic wavelength with one of the transitions in the atoms/ions of the plasma. Similarly extinction was also seen in plasma plumes from other targets.

4. MeV Energy Bremsstrahlung Radiation

Ultrahigh intensity ($I > 10^{18}$ W cm$^{-2}$) laser interaction with matter can produce electrons with energy up to several MeV. These fast electrons produce multi-keV to MeV x-rays through bremsstrahlung process in solid targets. This radiation can be used for many nuclear applications ranging from waste disposal to production of radio isotopes for industrial and medical usage. Measurements of the x-ray dose rate and its angular distribution are necessary for optimum utilization of these sources for the above applications. On the other hand, the x-ray radiation with significant dose rate levels may be harmful to the users. The fast electrons leaving the target may result in production of x-ray sources other than at the target itself. From the safety point of view, it is desirable to identify and characterize all sources of such radiation to take necessary precautionary measures. We have performed measurements of hard x-ray dose rate produced in the interaction of Ti:sapphire laser pulses focused on a solid planar copper target and observed multiple locations of this x-ray source.

Angular distribution of x-ray dose (hv > 40 keV) measured outside the plasma chamber at a distance of 500 mm from the target at a laser intensity of $\sim 1.3 \times 10^{18}$ W/cm$^2$ with a laser repetition rate 2 Hz is shown in Fig. 6. The angular distribution is strongly peaked along the target normal direction with a dose rate of 40 $\mu$/s/h. Analysis of the data indicates that this bremsstrahlung radiation is emitted by the jet of fast electrons emanated along the target normal produced through resonance absorption.

To investigate the reason for this occurrence, we measured the variation of the dose rate outside the plasma chamber with distance from the target along the direction of target normal. This dependence was of the form: dose rate $\propto (r-220)^{-2}$. This functional form indicates as if a hard x-ray point source is located at a distance of ~220 mm from the target surface. The reason for this virtual shift is the occurrence of another source of x-rays at the glass window located at a distance of ~430 mm from the target, along the target normal direction in addition to the one located at the target. A combination of these two sources, one at the laser irradiated target surface and the other at the glass window at the chamber wall, can give rise to the experimentally observed distance dependence.

5. Laser Absorption in Metal Clusters

Efficient coupling of high intensity ultrashort laser pulses with matter and resulting x-ray emission has been a topic of great interest for practical applications. Although metal clusters and grating microstructures have been used for achieving high absorption and enhanced x-ray emission, such targets are produced separately. Recently, ablation driven by intense laser pulses has emerged as an alternate route for production of nanometer sized clusters. It is interesting to explore the use of such clusters as targets for efficient absorption of high intensity ultrashort laser pulses, and intense x-ray generation. We have carried out an experimental study on energy absorption and x-ray emission from ultrashort laser pulse irradiation of such in-situ produced silver clusters.

In our experiment, clusters were formed by irradiation of planar silver target by a 30 mJ, 300 ps uncompressed Ti:sapphire laser pulse, and they were irradiated by ultrashort laser pulse of 70 mJ, 45 fs. The absorption measurement of the femtosecond pulse by the in situ produced silver clusters was carried out for two different time delays. First, a delay of 10 ns was kept between the cluster forming pre-pulse and the irradiating main pulse. A low absorption of <10% was observed in this condition as the clusters cannot reach the interaction region in this short time. At 75 ns delay, the clusters are expected to reach the interaction volume to interact with the main beam which propagated at a distance of ~30 μm parallel to the target. The pre-pulse beam intensity was varied between 10$^{10}$- 4x10$^{12}$ W/cm$^2$. Figure 7 shows variation of the femtosecond laser pulse absorption at an intensity of 3x10$^{12}$ W/cm$^2$ with pre-pulse laser intensity. The absorption increases with increase in pre-pulse intensity reaching a maximum of ~70% at the maximum pre-pulse intensity of 4x10$^{12}$ W/cm$^2$.

High absorption of the laser light is expected to result in higher x-ray conversion. The integrated x-ray (hv > 1 keV) yield was measured to be 60 μJ giving a high percentage conversion efficiency of the laser energy into x-rays of 8.5x10$^{-3}$%. Thus this method of in-situ cluster formation offers a simple way of intense x-ray generation which may be applicable to a wide range of solid materials.
6. Ultrashort Pulse K-Shell X-ray Line Radiation

Ultra-short duration intense x-ray emission from plasma produced by femtosecond laser pulses from solid targets has important application in time resolved measurement of x-ray diffraction, x-ray absorption spectroscopy, study of phase transitions etc. The efficiency and brightness of the x-ray source can be maximized by changing the laser parameters for highest absorption of laser light into the plasma. We have carried out a spectroscopic study\(^ {16} \) of K-shell x-ray line emission from magnesium plasma produced at an intensity of \(\approx 10^{18}\) W cm\(^{-2}\). High-resolution x-ray spectrum was recorded in the wavelength range of 9Å to 10Å using an x-ray crystal spectrograph\(^ {16} \) with a spectral resolution of 0.013Å. The x-ray spectrum was recorded on a 16 bit, back illuminated, x-ray CCD camera.

Figure 8 shows the variation of K-\(\alpha\) line (\(\lambda = 9.82\) Å) intensity with the laser pulse duration at a constant fluence of 5.9x10\(^7\) J cm\(^{-2}\). The laser pulse duration was varied by the adjustment of the separation between the two gratings in the pulse compressor. Intensity of the K-\(\alpha\) radiation increases with pulse duration up to 450 fs and shows a scaling of \(\tau_{\alpha}^{0.56}\). It remains nearly constant thereafter up to \(\approx 800\) fs. The increase in pulse duration increases the density scale length, which in turn increases the absorption of the laser light into the plasma resulting in the increase of the K-\(\alpha\) yield. The yield does not increase after 450 fs as the continued increase in pulse duration decreases the laser intensity. The K-shell x-ray yield per unit solid angle was estimated using known value of quantum efficiency of CCD camera. The K-\(\alpha\) line (\(\lambda = 9.82\) Å) yield per shot assuming an isotropic emission comes to \(\approx 8.4 \times 10^7\) photons/sr and its peak photon brightness is estimated to be \(\approx 1.7 \times 10^{23}\) photons/cm\(^2\)-sec-sr assuming pulse duration of K-\(\alpha\) radiation of the order of laser pulse duration.

\[ \text{K-}\alpha \]

Fig. 8 Variation of K-\(\alpha\) intensity as a function of laser pulse duration

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