Observation of ion acceleration in nanosecond laser generated plasma on a nickel thin film under forward ablation geometry

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One of the striking observations in this research is the enhancement of neutral velocity with the increase in background pressure. The earlier observations were mostly looking the effect of background gas as a medium to drag the motion of plasma species and the shock wave and drag models were very effectively used to describe the dynamics of plasma plume constituents. However, we observed that the neutrals closer to the sample (up to 5 mm), gain significant acceleration. In this chapter, a detailed study is performed with varying pressure and slightly higher laser energy so as to record the TOF spectra of ionic species and other neutral transitions from plasma. The results show that TOF spectra recorded for different neutral transitions show different dynamics and the slower peak of the neutral emission becomes faster with background pressure. A similar observation is seen for the ionic species as well. The TLP records significant electron current towards the very early stage of evolution suggesting the plasma plume loses fast electrons and due to this the charge neutrality within plasma is disturbed. This makes a double-layer like situation as reported elsewhere. The acceleration of ionic peak in 20 mbar background pressure is very large and the calculations show an extremely high accelerating field in the plasma generated in rear ablation geometry in a lower fluence range than the reported DL observations. One of the lines (712.2 nm) of neutral nickel shows an extremely large asymmetry in spectral broadening with the increase in background pressure. This large asymmetry may be due to the presence of micro electric fields present inside the laser produced plasma plume. Interestingly, this asymmetry in spectral broadening exhibits temporal and spatial dependence which suggests that electric field is present in the plasma plume for much longer duration and also over a significant distance. Hence, it can be anticipated that the acceleration of ions continuously takes place for significantly longer distances. Because of this continuous acceleration, the estimation of electric field considering double layer separation a few Debye lengths probably gets overestimated.

I. INTRODUCTION

In the last chapter, a striking observation about the multi-component nature of emission spectrum of neutral nickel lines as well as the ion current recorded using TLP for 1064 nm generated plasma plume in rear ablation geometry was noticed. At one such instance it was also noticed that the neutral emission of nickel shows a faster peak, which is against the common expectation that the background pressure acts against the propagation of plasma plume. Hence a detailed study regarding this phenomena was required to understand the underlying physics behind this observation. Earlier studies with similar laser intensities on solid targets also observed the splitting of peaks at longer distances as the background gas pressure increases. However, the interpretation of this splitting was based on scattering of species from heavy atoms. In this chapter TOF spectra from ionic species are also studied as the emission from ionic species is significantly weak at higher fluence than used in the earlier chapter. It was also observed that the TOF profiles of neutrals, as well as ion saturation current, do not fit well with the SMB distribution but a multiple distribution is essential to get a fit of experimental data, indicating some other phenomenon other than thermal expansion e.g. acceleration reported elsewhere shall be present in this experimental geometry. Interaction of intense laser pulse with ultra thin film resulting in acceleration of protons and ions has been experimentally demonstrated and simulated effectively by different groups. Various acceleration mechanisms like the target normal sheath acceleration (TNSA) and radiation pressure acceleration (RPA) are currently attracting a substantial amount of experimental and theoretical attention. Interaction of high power laser with a foil resulting in collimated plasma ejection from the rear of thin foil targets was reported by Kar et al. All these acceleration mechanism of ions on laser interaction on thin films were reported for high laser intensities ($\geq 10^{19} W/cm^2$) for few cycle laser pulses. In this chapter, an attempt is made to establish such an acceleration for the plume constituents with TOF spectroscopy and TLP. In addition to these diagnostis a high resolution spectrometer with ICCD and bandpass filters for neutral nickel lines with high gain PMT are also used to measure the plasma emission spectrum. By using higher fluence, emission from ionic species of nickel lines can also be observed.

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II. EXPERIMENTAL SETUP

The experimental set up is similar to the one described in earlier reported work. The laser used for this experiment is 1064 nm Nd:YAG laser with 10 ns pulse width. The laser beam, sample manipulator, vacuum system and gas feed, etc. are the same. In this experiment, in place of ICCD, an imaging system is used to image the plasma plume into an optical fiber array with 10 branches fibers having core diameter of 400 microns. The array is placed in a manner so that individual fibers collect light from various distances from the sample along the axis of the laser beam. Four of the optical fibers from this array are coupled to four different PMT’s so that simultaneous recording of emission from different positions within the plasma is possible. Narrowband interference band-pass filters with pass band for prominent neutral nickel lines are used to allow the desired spectral lines to the PMT. PMT records the temporal emission of respective neutral lines from four different locations simultaneously. Another remaining fiber from the fiber array is coupled to another half meter spectrometer with PMT. This spectrometer and PMT is used to detect ionic spectral lines from the plasma. The spectral resolution of this spectrometer with PMT is better than 0.1 nm. The spectrometer is arranged with an F number matching optics for SMA fiber and hence any of the remaining fibers can be used to measure emission from any of the desired locations inside the plasma.

The 1 meter spectrometer is also coupled with another fiber array with 10 fibers using f number matching optics. The fiber array is placed at the image plane of another imaging system aligned diametrically opposite to the earlier mentioned fiber array so that emission from plasma along the propagation axis can be imaged to the spectrometer. The slit of the spectrometer is fixed at 50 microns so that an effective spectral resolution of 0.12 nm is achieved. The spectrometer with fiber array and ICCD enables acquire spectra from different locations inside plasma simultaneously and at different time delays on a shot to shot basis.

TLP mounted at a distance of 10 mm onwards records the ion saturation current and floating potential. The emission spectrum from ions and neutrals is recorded at the locations closer to the sample whereas ion saturation and floating potential from 10 mm onwards. The spectral information with the spectrograph can provide significant insight into the accelerated ions.

III. ACCELERATION OF NEUTRALS AND IONS

As observed earlier experiments the peak position of the neutral line (361.9 nm) shifts to shorter time as the background pressure increases for 1064 nm ablation at \( \approx 5 \) mm from the sample. The present attempt is to confirm the consistency of this observation for different laser energies as well as from different locations within the plasma and also for other transitions of neutral lines. Hence an attempt is done to see this effect using interference filter and PMT at a distance very close to (1-2 mm) sample. Figure shows the TOF spectra for three different neutral lines (361.9 nm, 508.0 nm and 712.2 nm) using the same optical fiber and PMT for different background pressures. Figure (a) is the TOF emission at 1 mm from the sample for 361.9 nm, which shows that the peaks are observed at shorter times as compared to 5 mm distance as discussed in the previous chapter. As can be seen from the figure, for all the three pressures, the TOF spectra show two well-resolved peaks. Similar to the observation described in previous chapter for 5 mm, the slower peak becomes faster(observed at shorter time) as marked in the figure and the faster peak gets slightly

![Graph showing temporal evolution of neutral lines of nickel at different pressures.](image_url)
slowed down. For instance, the slower peak at 305 ns for 0.1 mbar background pressure advances to 265 ns by increasing the background pressure to 10 mbar. At the same time, the faster peak trails from 140 ns to nearly 160 ns. Although 20 ns deviation is rather small and may be argued as uncertainty, it should be noted here that triggering of acquisition is done by a fast PD of 1 ns rise time and every component used in this experiments like PMT, filter, cables and triggering mechanism are exactly the same.

IV. SUMMERY

This chapter is an extended study on the acceleration of neutral species observed with an increase in background pressure for 1064 nm generated plasma plume. Experimentally, using TOF optical emission spectroscopy, it is observed that similar acceleration is present for ionic species also. However, the acceleration of neutrals species is not observed for neutrals for certain excited state (specific transitions) near the sample as observed for the neutrals emitting at 361.9 nm. Also, the nature of fast and slow peaks exhibited by different neutral species is distinctly different in its temporal dynamics. This suggests that the formation mechanisms of these different neutral species should be different. The species which show an acceleration of slower peak also show a slight deceleration for the faster peak. At higher laser fluences, the fast and slow peaks observed for the species, which show acceleration, appear merged due to peculiar nature (slowing of fast peak and faster slow peak) exhibited by this species. However, the increase of laser fluence does not affect the evolution pattern significantly as the neutral species do not show the acceleration.

The study on ionic species with varying background pressures shows a consistent evolution of the slower peak and advancement in peaking time with an increase in background pressure. As the background pressure increases, the temporal separation between fast and slow peaks of the ionic line decreases considerably. This indicates, that there is a significant acceleration in the case of the slower peak. The acceleration seen for the neutrals at closer distances eventually vanishes at moderate distances. However, for ionic species, the acceleration can be observed for a little longer distances. An interplay between the drag of background medium and acceleration is observed for different atomic species. In the case of neutrals at medium distance, the drag force dominates, however, for ionic species the acceleration is dominant. As the distance further increases, the drag of background medium for neutrals and ionic almost varies in a similar fashion. At low background pressure, the TLP measurements at longer distances show a matching between temporal responses for the fast peak observed for ionic TOF emission.

The significant acceleration witnessed for ionic species at a closer distance can be attributed to the double layer formation within the plasma plume. The escape of the hot electrons from the plasma plume is recorded on TLP. The acceleration shown by the ionic species is modeled to a double layer concept with an assumption of layer thickness and shows a very large electric field. The reason for such a large field for such a low laser fluence is can be attributed to the present experimental configuration of rear ablation.

However, the observed asymmetry of neutral line and its possible connection with the presence of micro fields indicates the possibility of continuous acceleration of ionic species within the plasma plume over longer distances and extended time as the asymmetry itself shows such a trend. Hence, the large acceleration seen for ionic species appears to be continuous process in contrast to the DL concept, where the acceleration can take place within few Debye lengths. More detailed study and analysis are required to quantitatively establish the actual cause of the observed acceleration of ionic species in this configuration and laser power density used.

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