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MEASUREMENT OF HIGH-ENERGY CHARGED PARTICLES FROM LASER-PRODUCED
PLASMAS*

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High-energy charged particles are copiously produced from the interactions of high power laser beams and matter. These particles may carry with them the bulk of the energy involved as well as the relevant information concerning the mechanisms and the history of the interaction processes.

Two types of high-energy charged particles of very different origin will be discussed here. First, we will discuss briefly some measurement of alpha particles and protons in the MeV region which are products of nuclear fusion reactions. The present level of fusion yield is around 10^7 to 10^8 from the DT-filled microballoon targets. Measurements of these particles could yield valuable information on the degree of compression, fuel temperature, and other relevant data. Second, we will present some recent measurement of very fast ions whose velocity is larger than 5×10^8 cm/s and electrons above 100 keV in energy. The emphasis of this paper will be on the many surprising features of the ultra-fast ion measurement which have until now escaped detection. These measurements are done with glass microballoon targets, flat foils of various thickness, and double foils of different separation. These experiments are carried out using both Nd:glass laser and CO₂ laser. In the case of single and double flat foil targets, both the front and back emission are measured. Angular distribution information is also obtained by tilting the flat targets at different angles with respect to the laser beam direction. These measurements yield much needed information on the general features of laser-target interactions, laser wavelength effects, laser energy absorption, thermal conduction, energy transport, target preheating, etc., which ultimately lead to a clearer understanding of the mechanisms involved in laser-induced fusion.

NUCLEAR FUSION PRODUCTS

Let us begin by summarizing some measurement of protons and alpha particles produced from d-d and d-t reactions, respectively. The detection of these particles was done by using the time-of-flight thin film detector illustrated in Fig. 1. The detail of this detector has been published.¹ These experiments were carried out at KMSF by the LASL group, under an ERDA contract.² A "clam shell" focusing system was employed.³ The laser pulse was composed of a train of one to six pulses with a nominal duration of 30 ps per pulse. The maximum intensity on target was estimated at approximately 3×10^{15} W/cm². The targets used were DT-filled glass microballoons approximately 50 μ m in diameter with a wall thickness of 0.7 μ m. The solid angle subtended by the detector was 9.4×10^{-3} steradian and, typically, 1000 - 5000 alpha particles per shot were collected. A typical alpha-particle spectrum showing the background below 2 MeV is given in Fig. 2(a) and a linear plot of the distribution function above 2 MeV is shown in Fig. 2(b) indicating a maximum at around 2.5 MeV. A maximum energy shift of 1.5 MeV for the alpha particles gives a ρR value of 1.4×10^{-3} g/cm². The measured energy shift for the proton was about 160 ± 40 keV and ρR of $(2 \pm 1) \times 10^{-3}$ g/cm² was obtained. Fuel densities of 0.6 to 2.0 g/cm³ are implied which indicates a compression of 1000 times. The ratio of d-t to d-d reactions was also determined to be 80 ± 20 which implies the fuel ion temperature to be 2 to 6 keV. By comparison with the calculation of Fraley and Mason,⁴ the experiments indicate that optimum conditions are not achieved and effects from radiative and suprathermal electron preheating may be fairly serious. The experimental ρR value is smaller and the fuel temperature is much higher than those predicted.

It is interesting to note that a similar measurement was carried out by the KMSF group.⁵ The results indicate a smaller shift than ours. However, their solid angle of detection is much smaller and an energy cut-off in the spectrum was introduced due to dispersion in the magnetic field. Furthermore, some differences may also be expected since their laser intensities were several times higher. Without the precise knowledge of the electron temperature and the energy loss in plasmas, the estimated values of ρR must at best be considered preliminary. Hence, comparison of data under various conditions of laser-matter interactions must be handled with care. In any case it is obvious that the present fusion yield of 10^7 - 10^8 is very far from the break-even requirement to achieve our energy goal. The necessity of employing megajoules from higher power lasers may compel us to use only those relatively high efficiency laser systems such as CO₂ or HF lasers. It is therefore imperative that the wavelength effects in laser fusion be thoroughly understood. Just as important, the problems of electron preheating the target core must be overcome in order to achieve the desired degree of compression for efficient nuclear fusion. Finally, it is extremely relevant to understand the mechanisms that lead to

Fig. 1.
Thin-film detector assembly employing very fast plastic scintillator and photo multiplier tube and highly efficient light reflector.

Fig. 2.
(a) Typical alpha-particle spectrum showing the background below 2 MeV. (b) Alpha-particle energy distribution above 2 MeV.

those observed fusion reactions even at the present laser intensity level of ≤ 1 TW. Toward these ends, we turn next to the discussions of fast ion and electron measurement.

FAST IONS AND ELECTRONS

The detectors are similar to the TOF detector shown in Fig. 1 with the exception that the light window is a 4000-Å-thick titanium layer coated directly on the 8- μm -thick scintillator. Only one laser beam is used for these experiments.

Figure 3 shows four typical ion spectra emitted from the laser-induced plasmas as observed from the front and back sides of the target. [(a) and (b) are front and back emission from a Nd:glass laser shot, 70 ps and ~ 1 J in a 60 μm diameter; (c) and (d) are front and back emission from a CO₂ laser shot, 1.2 ns, 150 J in ~ 150 μm diameter.] The most striking feature is the steep rise in the leading edge of the ion spectrum. Several important correlations were observed for the front emission alone (front is the laser side of the target).

Fig. 3.

Oscilloscope traces of ion velocity spectrum from a Nd:glass laser shot and a CO₂ laser shot. The first pulse represents a time fiducial marker from x-rays.

1. Its presence implies a steep rising edge in the laser pulse. Adjustment of the quantity of saturable absorber in the laser system severely alters this feature. The presence of any prepulse will wipe out this feature.

2. It is directly dependent on the focused intensity on the target.

3. With the ball-and-disc target, it correlates with implosion observed by x-ray pinhole cameras. A similar co-relation was observed with the number of produced neutrons.

The angular distribution for both the front and the back emission appears to be within a 25° half angle cone, which is similar to the previously reported ion angular distribution for lower energy ions. With the intensity in the neighborhood of $\sim 10^{15}$ W/cm² for Nd:glass and CO₂ lasers, the observed fastest velocity is typically in the range of 0.8 to 1.0×10^9 and 0.8 to 1.5×10^9 cm/s, respectively, for the front emission.

In a given laser energy range (within a factor of 3 or 4), the observed maximum velocity appears to be only weakly dependent on the amount of absorbed energy. However, the number of the fastest ions seems to increase proportionally with laser energy. It is particularly interesting to note that the fast ion components behave very similar to the energy absorption pattern recorded by the calorimeters when targets were illuminated under different angular orientation with respect to the polarization direction of the laser beam. Obviously, these fast ions carried away a great bulk of the total absorbed energy for a given unit of laser energy on focus. The number of the highest energy ions appears to be somewhat larger for the CO₂ shots. However, plasma evolution due to a much larger exposure time to the laser beam is expected to play a role.

We have also observed that the value of the maximum velocity as well as the spectrum shape in the front emission from the single flat foil target is independent of the foil thickness. This feature enables us to make meaningful comparison of front and back emissions as a function of foil thickness while keeping the laser energy fairly constant. The ratio of the ion velocity from the fastest component between the rear and the front emission is plotted in Fig. 4. We see the curve dropping rapidly in the vicinity of a foil thickness of 7 or 8 mg/cm². This foil thickness is much too large for the observed ions to propagate through (ion average energy > 1.5 MeV would be necessary). Unless some extremely large electric fields are set up inside the target to accelerate and decelerate the same particles as it propagates from the region where laser energy is absorbed to the rear surface, it will be more reasonable to assume that ions are accelerated off both faces of the target. Propagation of hot electrons through the target could set up such conditions. Another supporting evidence for this can be derived as follows. We notice that the fastest emitted ions both in the front and the rear are protons. This was done by comparing the observed dE/dx of the ions passing through foils of different thickness with the known table. Shots from plastic foil target (hydrogen intensive) and

platinum foil target (in principle no hydrogen but may acquire some from the pump oil on both surfaces) of the same area density give similar results. In the case of platinum target, the only way the protons at the rear surface can acquire energy is from electrons that stream through the target.

It is obviously of interest to understand the abrupt appearance of the fastest ion component from the plasmas. A model based on an isothermal expansion of a collisionless plasma⁶ appears to provide a reasonable description of such behavior. Furthermore, an electron temperature in the neighborhood of 10 keV can be inferred from our observed maximum velocity of the front emitted protons.

It is again worth pointing out that the rising edge of the fast ions generally appears steeper in the rear side component than those in the front emission. Also, in Fig. 4, it is interesting to note that the velocity of the fastest rear emitted ions is greater than those from the front when the targets are between 0.02 to 0.1 mg/cm² in thickness. When the target becomes thinner, however, the rear side ion velocity seems to slow down. This effect can be explained by considering the momentum given to the entire target by the laser radiation pressure.

The abrupt falling off in the back emission in the double foil data illustrates the insulation property of the vacuum separating the foils. It will be discussed later.

Figure 5 shows the plot of the ratio of the number of fastest ions emitted from the rear surface to those emitted from the front surface vs the target thickness. If we assume that the energy carried by the fastest ions is proportional to the amount of energy remaining in the hot electron distribution after it traverses from the front to the rear of the target then we can compare the electron deposition in the target to the number of ions as a function of that electron temperature. In a simple model, assuming the target material behind the absorption region to be field free and cold, we can use the stopping power of electrons in matter to determine the fraction of a given Maxwellian electron distribution that would not be absorbed in a single pass through the target foil. Curves for energy remaining in the electrons at the rear of the foil for initial temperatures of 5, 10, and 20 keV are plotted on the figure. It is clear that an electron temperature in the neighborhood of 10 keV appears to agree well with the experimental data. It is worth pointing out the agreement with the implied temperature resulted from the isothermal expansion model, as mentioned a while ago. It is also worth noting that previous measurement of high-energy x-ray spectra⁷ from both CO₂ and Nd:glass lasers suggested hot electron temperatures of the order of 15 keV. If not by accident this may shed some light on the mechanisms involved during the energy transport.

So far, we have noted great similarity between the data from both the CO₂ and Nd:glass laser shots. Manifestation of laser wavelength dependence, is weak.⁸

Fig. 4.

Ratio of the fastest rear emitted ion velocity to the fastest front emitted ion velocity plotted against flat target area density.

Fig. 5.

Ratio of the number of the fastest rear emitted ions to the number of the fastest front emitted ions plotted against target area density.

Hot electrons have been observed to leave the target freely.⁹ Figure 6 shows a series of electron spectra with energies greater than 100 keV. For the highest energy components, the electron "temperature" appears to be about 100 keV, the same for both CO₂ and Nd:glass. Understanding of these energetic electrons may be complicated by the absence of any knowledge on the large time-dependent potential. In any case only a small fraction (< 1%) of the absorbed incident laser energy is re-emitted in the form of very energetic electrons. If one could limit the electrons which preheat the target core only to those which escape the absorbing plasma, its effects on subsequent target compression may not be too serious. How these energetic electrons are related to the observed fast ions and the roles they play in plasma evolution can not be ascertained at the present time.

Fig. 6.

Hot electron energy distribution.

Because of their large number and their shorter range, electrons in the tens of keV regime are expected to play a significant role both in thermal conduction and energy transport, as well as preheating the target interior. In the next set of data, we shall address ourselves to the crucially important preheat problems.

If we can prevent the energetic electrons from penetrating the target core by erecting an effective barrier, then we might indeed be able to reduce the amount of target core preheating.¹⁰ Double plastic flat foils separated by a vacuum were used as target as shown in Fig. 7(a). Here F_1 is a foil thin enough to insure the same front and back ion emission while making sure that no laser light is transmitted through. For the Nd:glass laser, 1000-Å-thick foil was found to be suitable for the 70 ps pulse irradiation while 2.5-μm-thick foil is needed for a 1.2 ns pulse. For a 1.2 ns CO₂ laser pulse, a 500 Å or thinner foil can be used. However, we also found 1000 Å to be suitable. The second foil is generally chosen to be 3.75 μm thick so that hydrogen ions of greater than 300 keV in energy can successfully penetrate the foil and still be energetic enough to allow detection. In the same figure, data from CO₂ and Nd:glass experiments are shown. The pulse lengths for both lasers were 1.2 ns FWHM. However, the Nd:glass laser intensity was at least a factor of 2 less than the CO₂ intensity. Both the front and the rear emitted ions were measured as a function of the foil separation. Again, by considering only the fastest ion components, the ratio of the velocity and the ion number are plotted in Figs. 7(b) and 7(c), respectively.

Fig. 7.

(a) Double foil target configuration. (b) and (c) data of the ratio of velocity and ion number, respectively, as a function of foil separation from CO₂ and Nd:glass experiments.

The velocity ratio is expected to be greater than .9 when the foil separation is zero. However, we observed this value to be slightly less as soon as the separations become non-zero and interesting enough it remains fairly constant even as the distance of separation increases. These behaviors seem to imply plasma expansion into the vacuum, but the steady current is maintained by continuous laser irradiation. As the distance of separation approaches 1.0 mm the rear ion velocity drops abruptly and approaches asymptotically to about 0.55 the value of the initial velocity immediately after the ions left the back side of the first thin foil. The corresponding energy of these back emitted ions appears to be equal to or lower than the value that can be accounted for by the simple stopping power of the cold material. The corresponding distribution for the ratio of the rear-front ion number shows the number of ions observed behind the back of the second foil begins to decrease sharply as soon as the separations between the foils is non-zero. Again, this number ratio levels off rapidly as the distance of separation approaches 1.0 mm. These data strongly imply that the vacuum provides fairly effective insulation against the electrons in the 10 keV region.

If we take the effective separation distance to be 1.0 mm, then for a 1.2 ns laser pulse length, the effective electron shorting velocity can be estimated to be about 8×10^7 cm/s. It is worth pointing out that we have previously estimated the electron temperature to be a few keV from the single foil experiments in order to explain the ion measurement. If the ion-temperature is assumed to be equal to the electron temperature, then the implied hydrogen plasma ion velocity agrees with the shorting velocity estimated here.

CONCLUSION

Several important conclusions can be made from the results presented in this paper:

- (1) The sharp rising ion velocity distribution and the distinct cut off velocity are inherent features of high power laser-matter interactions.
- (2) No obvious laser wavelength effects can be detected from the observed interactions.
- (3) The bulk of the energy transported into the interior of the target is probably via the fairly energetic electrons with temperature in the 10 keV region.
- (4) Vacuum insulation may effectively reduce the amount of supra-thermal electron preheating.

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