Multi-MeV Ion Production from High-Intensity Laser Interactions with Underdense Plasmas

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Experiments were performed using high-power laser pulses (greater than 50 TW) focused into underdense helium, neon, or deuterium plasmas ($n_e \sim 5 \times 10^{19}$ cm^{-3}). Ions having energies greater than 300 keV were measured to be produced primarily at 90° to the axis of laser propagation. Ion energies greater than 6 MeV were recorded from interactions with neon. Images of the ion emission were also obtained, and it is possible that spatially resolved measurements of the ion energy spectrum can provide a method to estimate the intensity of the focused radiation in the interaction region.

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Over the past several years, there have been rapid advances in the use of high-power, short pulse lasers [1]. In particular, the potential of such lasers for applications in particle acceleration [2], x-ray generation, and inertial confinement fusion [3] seems promising. Because of the complexity of interactions at ultrahigh intensity and the short temporal and spatial scales, direct observations of the properties of the laser-produced plasma as well as measurements of the laser pulse itself during the interaction are difficult. As a very high intensity laser pulse interacts with underdense plasma the pulse can undergo severe propagation instabilities [4] and will also lose energy through inverse bremsstrahlung absorption, ionization, and plasma scattering instabilities. These phenomena are often interrelated, which consequently complicates diagnosis of the interaction.

In this paper, we discuss measurements of accelerated ions produced by the "Coulomb explosion" of a high-intensity laser-produced plasma [5]. In this situation ions are accelerated by electrostatic forces caused by charge separation induced by the laser ponderomotive pressure. It is found that a spatially resolved measurement of the high energy ions can provide a direct and simple estimate of the laser intensity in the plasma. By imaging ion emission it may be possible to estimate how the intensity of the laser pulse changes as it propagates through the underdense plasma. In these experiments, we have measured peak ion energies of 1.0 MeV for deuterium gas interactions, 3.6 MeV for helium interactions, and greater than 6 MeV for interactions with neon.

Such measurements indicate that the peak laser intensity achieved during these experiments was greater than approximately 6×10^{19} W/cm^2. This provides evidence that in our experiments significant relativistic, charge-displacement self-focusing of the laser pulse occurs as it propagates through the plasma. Previous computer modeling of such interactions have inferred that intense laser pulses can be self-focused to such intensities [6]. This is the first measurement of such high energy ion emission from underdense plasmas ($n_e < 0.05 n_{\rm crit}$), the first measurement of the angular emission of such ions, as well as the first measurement of the spectrum of fast ions. Previous measurements of MeV ion emission have been obtained only from laser plasma interactions at high density ($n_e \sim n_{\rm crit}$) [7], where the ions are accelerated in the ablated plasma due to space charge forces generated by escaping hot electrons. Earlier experiments using underdense plasmas were performed at much lower intensities and have measured ions accelerated by the laser ponderomotive force up to energies of 50 keV [8].

The production of energetic ions has also been inferred previously from observations of a plasma channel left trailing the high intensity laser pulse as it propagates through the underdense plasma [9]. The generation of this channel is due to the expansion of energetic ions via the momentum given to them during a Coulomb explosion. As a very high intensity laser pulse propagates through an underdense plasma the strong ponderomotive force of the laser pulse forces some of the electrons from the region of highest intensity. Ions are affected much less by the ponderomotive force due to their larger mass. However, as the laser pulse passes, these ions will be given an impulse perpendicular to the laser axis which is produced by the large space charge forces caused by charge separation. After the laser pulse passes, electrons will return to their original positions on a time scale of about $1/\omega_{\rm pe}$ (where $\omega_{\rm pe}$ is the plasma frequency); however, the lateral momentum given to the ions will be retained and they will continue moving out of the plasma, carrying low energy electrons with them. The energy of these ions is thus directly related to the intensity of the focused laser pulse, and the maximum energy that can be gained by an ion during these interactions is simply given as the relativistic ponderomotive energy [$U = Zm_e c^2(\gamma - 1)$, where Z is the ion charge and γ is the relativistic factor of the electron quiver motion in the laser field].

Our experiments were performed using the VULCAN laser at Rutherford Appleton Laboratory. This system produces laser pulses having an energy of up to 50 J and a duration of 0.9 psec at a wavelength of 1.054 μm (Nd:glass). The laser pulse was focused into a gas jet target (4 mm nozzle diameter) using an $f/4$ off axis parabolic mirror. When helium was used as the target gas the plasma had an electron density up to about 5×10^{19} cm^{-3}. The plasma electron density during the interaction was determined by the wavelength shift of laser light scattered by the forward Raman scattering instability. Deuterium and neon were also used as target gases.

In our experiments, the angular distribution of ions emitted during such high intensity laser plasma interactions was recorded using CR-39 nuclear track detectors placed at various positions surrounding the interaction region and which are sensitive to helium ions greater than about 300 keV [10]. As an energetic ion collides with the detector it causes structural damage in the material so that an observable track can be recorded for each ion. In this way, the total number of ions can be counted. It was found that there was no significant variation in ion emission in the azimuthal direction (i.e., changing the laser polarization had little effect). However, a distinct peak was observed in the emission of ions with energies greater than 300 keV at 90° to the axis of propagation. Measurements of the ion emission at higher energies were also obtained by using CR-39 track detectors covered with thin aluminum filters (2 μm) which will block all signal from helium ions below about 2 MeV in energy.

Averaged measurements over four shots are shown in Fig. 1. It is clear that the majority of ion emission occurs in the 90° direction, although the emission lobe also extends in the backward direction somewhat. Emission at energies greater than 2 MeV shows a narrower lobe in the 90° direction. Simultaneous measurements over a wide range of angles indicated that there was some spatial structure in the ion emission pattern—which seemingly corresponds to bursts of ions emitted at certain narrow angles and which change from shot to shot (although within the indicated error bars). During these experiments, simultaneous measurements of very energetic electrons (up to 100 MeV) were measured in the directly forward direction—however, there was no measurable energetic ion emission in the forward direction (i.e., no corresponding beam of ions). Presumably, the highest energy electrons leave the plasma before the ions can respond to any space charge forces produced. It should also be noted that the total number of electrons lost in this way is relatively small and their contribution to the energy of ions ejected in the transverse direction should be negligible.

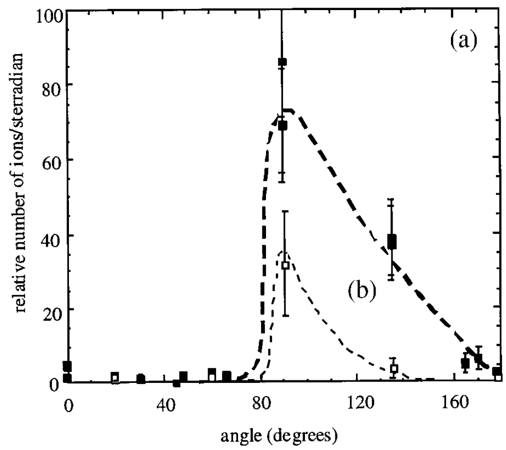

FIG. 1. Angular emission of energetic ions. (*A*) distribution of helium ions with energy greater than 400 keV. (*B*) distribution of helium ions with energy greater than 2 MeV (shown ×10). (Note that dashed lines are drawn as a visual aid only.)

A calculated ion energy spectrum resulting from a Coulomb explosion is shown in Fig. 2 for a value of $a = 5$ [where $a =$ dimensionless amplitude of the laser electric field $= p_{\mathrm{osc}}/mc = (I_{\mathrm{laser}}/1.25 \times 10^{18}\ \mathrm{W/cm^2})^{1/2}$]. This spectrum was calculated by simply balancing the force due to charge separation ($\nabla \cdot \boldsymbol{E} = -4\pi e \delta n_e$) with the ponderomotive force of the laser on the electrons [$\boldsymbol{F} = -mc^2 \nabla(1 + a^2/2)^{1/2}$]. The momentum imparted to an ion by the resulting space charge force acting over

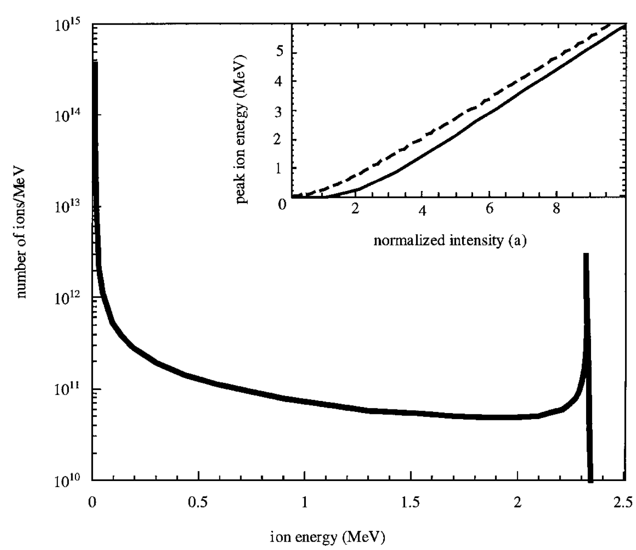

FIG. 2. Calculated ion spectrum for Coulomb explosion in helium where $a = 5$, $\tau = 1$ psec, and the laser focal spot radius is 5 μm (150 μm interaction length, $n_e = 10^{19}$ cm^{-3}). The scaling of peak ion energy vs laser intensity is shown in the inset, where the solid line is the calculated value and the dashed line is the ponderomotive energy, $U = Zm_e c^2(\gamma - 1)$.

the duration of the laser pulse is then calculated. In this example, the laser pulse ($\tau = 1$ psec) was assumed to have a 5 μm radius Gaussian focal spot. The calculated spectrum indicates that the maximum ion energy is directly dependent on the intensity of the focused laser pulse and that this energy is well defined. An experimentally obtained ion spectrum will be the result of interactions over a wide range of laser intensities—however, the peak ion energy observed in the spectrum should correspond approximately to the maximum laser intensity in the plasma. In these experiments, the laser intensity was unlikely to be sufficiently large to force all of the plasma electrons from the focal region (cavitation), so it may be possible to use this simple theoretical model for interpretation of our experiments. Large amounts of stimulated Raman side scatter were also observed in these experiments—which is theoretically expected to suppress cavitation [11].

The spectrum of the energetic ions was measured using a Thomson parabola, which spatially separates ion species having different charge to mass ratios through the use of parallel electric and magnetic fields. CR-39 was used as the detector. The spectrometer was positioned at 42 cm from the laser interaction at 90° from the axis of propagation and used a 250 μm diameter pinhole as the aperture. A typical experimentally measured spectrum is shown in Fig. 3 for helium interactions. The spectrum in Fig. 3 also shows good qualitative agreement with a recently published ion spectrum from particle-in-cell calculations ($I = 2 \times 10^{18}$ W/cm^2) [12], which also shows the "plateau" structure evident in our measurements.

For the helium spectrum shown, it is estimated that 0.25% of the incident laser energy is transferred to ions having greater than 300 keV of energy by using the previously measured ion angular emission profiles. It is interesting to note that in helium plasmas both He^{1+} and He^{2+} ions were observed with very high energy. In the interaction region helium ions are completely ionized since the intensity required to directly field ionize He^{1+} is about 10^{16} W/cm^2. This implies that the He^{1+} is generated by charge-exchange/recombination of ions as they travel out of the gas jet to the detector. The classical charge exchange cross section is given approximately by $\sigma \cong \pi(Z_1 Z_2 e^2)^2/\Delta E^3$ (where Z_1 and Z_2 are the charge states of the two species and ΔE is the difference in kinetic energy) [13]. This indicates that lower energy ions will have a significantly enhanced probability of charge exchange with the neutral atoms in the surrounding gas—agreeing with our observations of the ion spectra that higher ionization states had a higher peak energy. Note that the charge-exchange process does not affect the ion energies significantly.

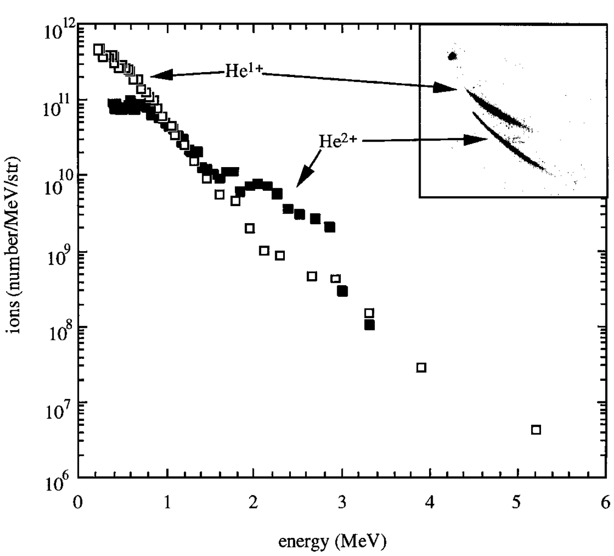

FIG. 3. Typical ion spectrum from helium interaction (90°) (Thomson parabola tracks are shown in the inset).

The process of relativistic, charge-displacement self-focusing is not exactly reproducible from shot to shot since it is sensitive to small changes in density gradients in the gas jet, as well as fluctuations in the initial beam profile of the incident laser. The maximum ion energy, such that there were more than 10^8 (ions/MeV)/sr, was found to be 3.6 MeV for helium, 1.0 MeV for deuterium, and greater than 6 MeV for neon. It is possible to use these measured energies as a diagnostic of the peak laser intensity during the laser plasma interaction. These interactions are well above the critical power threshold for relativistic self-focusing [$P_{\mathrm{crit}} = 17\ (n_e/n_{\mathrm{crit}})$ GW $=$ 1.7 TW for plasmas of densities 10^{19} cm^{-3}] so that it is expected that there will be a significant enhancement of the peak laser intensity during the interaction. This is precisely what is observed if we calculate the necessary laser intensity to produce the observed ion spectra. In Fig. 4, a plot of the estimated peak laser intensity in the plasma (obtained from the peak ion energy) versus the "expected" laser intensity from the measured laser parameters (pulse length, energy, far field focal spot) is presented. It is clear that the effect of the plasma is typically to increase the laser intensity in the interaction region. All of the data from our measurements are presented here, and it should be noted that there is a significant shot-to-shot variation in these results—probably due to the nonlinear nature of the self-focusing processes. However, it should be stressed that accurate diagnosis of the interaction will require comparison to sophisticated computer simulations [12]. The estimates of the laser intensity during the interactions with neon gas (less than the "vacuum" intensity) suggest that the effects of ionization induced diffraction can also counteract any self-focusing processes and cause a reduction in intensity.

Ion emission was also spatially resolved using pinhole imaging. A large diameter pinhole (250 μm diameter) was used for measurement of the ion images onto CR-39. The magnification used ($\sim$2:1) was such that it was possible to obtain a rough image of the regions of most intense ion emission from the laser-produced

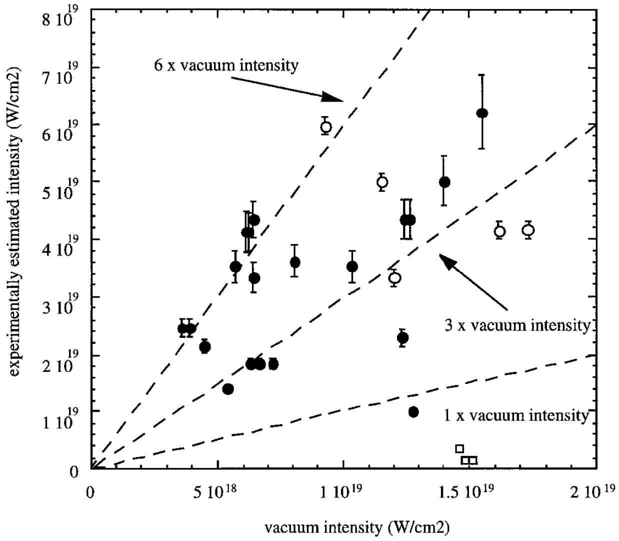

FIG. 4. Experimentally estimated laser intensity in plasma (from peak ion energy) vs expected vacuum intensity (from simultaneous measurements of laser parameters); black circles—helium; white circles—deuterium; squares—neon. Dashed lines are drawn as a visual aid only.

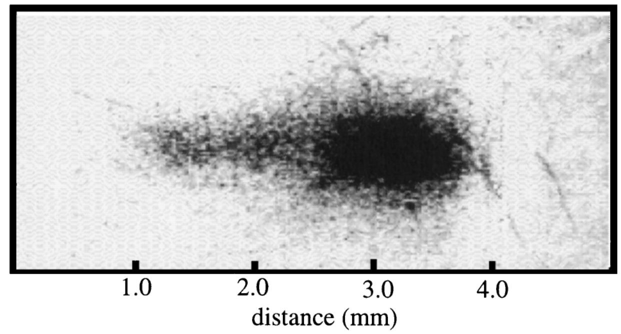

FIG. 5. Pinhole image of typical helium interaction recorded on CR-39. Laser propagates from right to left.

plasma. Images were obtained for helium and deuterium gas interactions. An example ion image of a helium interaction having multiple foci is shown in Fig. 5. Since there was typically a significant number of energetic neutrals—it was also possible to create an image of the interaction region using the neutral particles and then to add a magnetic field to determine the maximum ion energy. In this way it may be possible to determine the peak laser intensity throughout the interaction region. Multiple focal spots in the ion images were also found to be correlated with optical images of the Thomson scattered light during these interactions.

In conclusion, these experiments have shown that energetic ions are produced primarily in the 90° direction during these interactions and that the generation mechanism can be understood as a result of Coulomb explosion processes. We have shown that neon ions greater than 6 MeV and helium ions up to 4 MeV can be generated. From these measurements it is likely that during our experiments the laser pulse undergoes significant self-focusing as a result of relativistic and charge-displacement effects throughout the interaction region.

These results are important since they may lead to the use of a new and potentially powerful diagnostic for direct measurement of the intensity of very high power laser pulses inside an underdense plasma. This phenomenon may also be useful as a point source of energetic neutrons—if high repetition rate laser interactions with a deuterium gas jet can induce a significant number of thermonuclear fusion reactions between laser-accelerated ions and those in the surrounding gas [14].

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