Large intensities of MeV particles and strong charge ejections from laser-induced fusion in ultra-dense deuterium

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Nanosecond-pulsed lasers have been used previously in the energy range < 0.9 J and at intensities up to 10^{14} W cm^{-2} to observe D+D fusion in ultra-dense deuterium D(-1). Protons and neutrons have been detected with a temperature of 100 MK, indicating a thermal fusion plasma. The energy of the laser pulse is more important for the fusion process than the intensity or wavelength, and extrapolation from the results obtained has indicated break-even at an approximate pulse energy of 1 J, in rough agreement with theory. We now use a pico-second pulsed laser with up to 1 J pulse energy to further investigate the processes taking place. With the short 80 ps pulse length, the MeV particles are not collisionally quenched in the ultra-dense layer of D(-1) as easily as with a ns pulse, and much stronger charge oscillations are observed. Thus, the plasma formed with ps pulses penetrates more easily through the quenching and shielding D(-1) layer on the target.

Ultra-dense deuterium D(-1) is a quantum fluid which is superfluid [1] and probably also superconductive (Meissner effect observed) [2] at room temperature. Laser-induced nuclear fusion D+D in D(-1) has been reported [3-5]. Previous studies have used 0.2-0.9 J, 7 ns long laser pulses. Due to the large density of D(-1) at 10^{35} m^{-3} [6], most MeV particles released are collisionally quenched. Even neutrons with 14 MeV from the fusion processes have a calculated mean free path in D(-1) of only 150 nm [5]. Detection of neutrons is thus not generally useful to study the rate of fusion in D(-1) at energy levels below ignition. High-energy particles initiating the fusion are released in the D(-1) layer by laser-induced Coulomb explosions (keV particles) [7] and laser-initiated self-compression (MeV particles) [8].

We now describe the results found employing a laser with 1 J, 80 ps pulses at 1064 nm (Ekspla PL2143C with APL 70-1100). The vacuum chamber used is pumped by a fore-vacuum pump to < 10^{-2} mbar before gas admission. The apparatus is shown schematically in Fig. 1. The laser beam is focused to a spot size of nominally 4 μm by a movable lens with

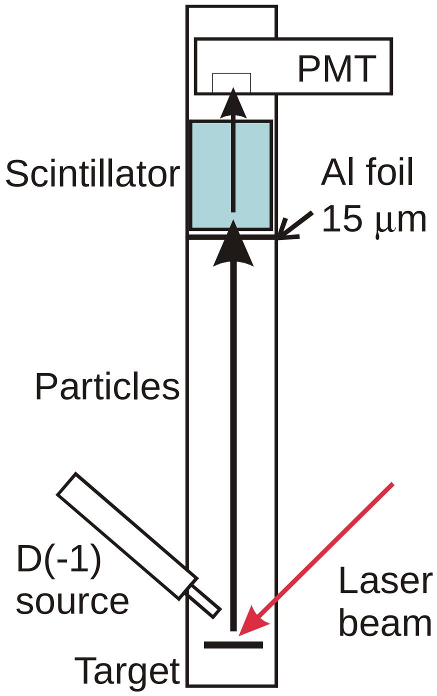

Fig. 1. Apparatus

focal length 50 mm onto a movable horizontal target plate which is covered by a layer of ultra-dense deuterium D(-1). This material is produced in a source similar to a published construction [9], but able to work at higher pressure (up to 10 mbar in the chamber) and higher flow rates of D_2 gas. An iron oxide catalyst forms D(-1) from deuterium gas (99.8%) in the source. On the target plate, the superfluid D(-1) forms a thick enough layer on the surface before it creeps over the edge of the plate. The laser pulses give rise to intense visible plasma blobs of several mm diameter from D(-1). At a distance of 56 cm above the target plate, a 10 cm long fast plastic scintillator is mounted as a vacuum window behind a 15 μm thick, light tight Al foil. A photo-multiplier (PMT) behind blue-violet glass filters observes the scintillations due to energetic particles passing through the Al foil, giving a time-of-flight (TOF) spectrum on a fast (300 MHz) digital oscilloscope. Only particles with energy above 1 MeV will penetrate the Al foil with any large probability [5]. An IR diode (Hamamatsu G8376-03, 400 MHz) observes the emission from the target through a glass window and a long-pass filter (T at 1120-1650 nm). A straight wire antenna outside the metal chamber provides the trigger signal.

With D(-1) on the target, a signal is observed by the PMT due to fast particles penetrating into

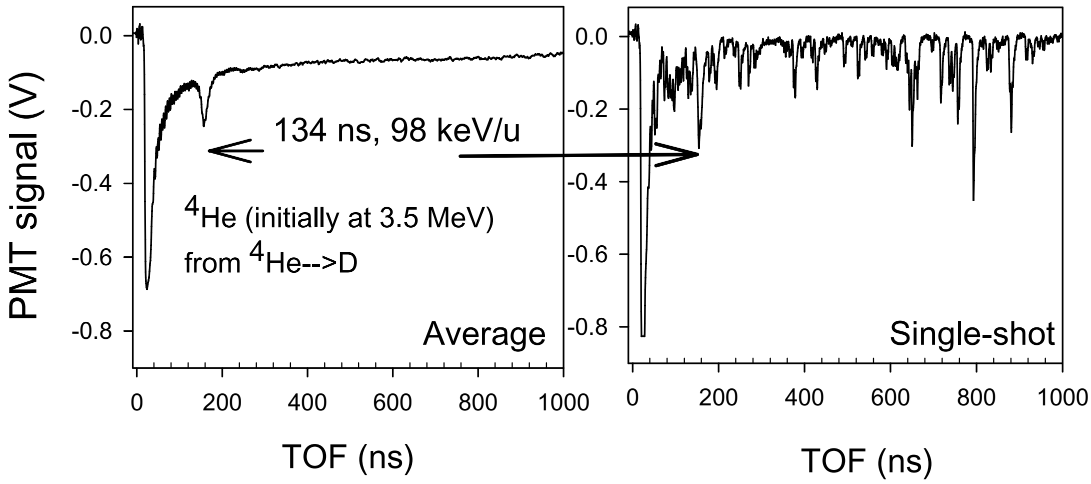

Fig. 2. Signal due to MeV particles in the PMT

the scintillator. Examples of the results are shown in Fig. 2. The left-hand panel shows an averaged spectrum in the oscilloscope, while the right-hand panel shows a single-shot spectrum. The number of particles observed is much larger (factor 10-100) than with a ns-pulsed laser onto the same type of target. A 3 MeV proton or neutron from the fusion process will arrive after 23 ns, thus within the first peak of the signal. The rise-times of the PMT and the oscilloscope are both in the 2-3 ns range, and a clear structure will thus not be observed in this first peak. The ions ejected from the fusion plasma are also collisionally delayed, which decreases resolution. However, a clear TOF peak is observed at 132 ns. In pulse-counting experiments with ns-pulsed lasers (to be published) several other peaks have also been detected. Most of them can be explained as due to collisional delay of ^{4}He, initially with 3.5 and 3.6 MeV energy from the fusion process. A collision of ^{4}He with D leaves 98 keV u^{-1} on the ^{4}He particle, giving a calculated time-of-flight of 129 ns. This agrees well with the observed peak in Fig. 2.

When the laser samples the same spot on the target for more than a minute, the signal deceases strongly. This is due to removal of the D(-1) layer by the laser at this spot with maybe 10-20 µm diameter. If the laser beam or the target is moved slightly, the signal is observed again. Since D(-1) is superfluid, it is expected that the layer at the laser spot will be renewed quickly. It is concluded that in this case the heating due to the fusion process and the laser is so large that D(-1) is no longer superfluid around this spot. By slightly knocking on the chamber, the signal is observed again transiently. This process can be repeated for a long time. It may be due to the D(-1) superfluid layer sliding on top of the vibrating target. It is not observed with a ns-pulsed laser, probably due to the more efficient D(-1) removal by the ps laser.

The signal of MeV particles observed has been calibrated absolutely by measuring similar intense spectra with a ns-pulsed laser on another type of target. It is also possible to measure the total ion signal by a metal collector in such experiments with ns resolution, which means that the number of ions observed and their total kinetic energy can be calculated. The signal in Fig. 2 corresponds to approximately 2×10^{10} ions to the collector per laser shot, or to 1×10^{13} ions per laser shot released isotropically (if isotropic emission from the fusion process is valid). Assuming an average ion energy of 1 MeV, this corresponds to > 1 J in energy for the ions released.

The IR diode outside the window in the chamber observes the IR emission due to the laser pulse and the fusion plasma, and also detects the RF charge oscillations due to the plasma and the ejected charges. For these results, an oscilloscope LeCroy 8300 with risetime 150 ps was used. In Fig. 3, panel (a) shows the (fixed laser position) light signal from the target, with almost total absorption of the laser energy in the target plate. With fusion taking place, the longer signal indicating further energy release from fusion on the target is shown in panel (b). By moving the diode so that it does not see the plasma, only the RF oscillatory signal remains (c). Moving the focusing lens out of the laser beam thus using unfocused laser light, the oscillations disappear completely and the IR peak length is halved relative to that in (a). The 1.6 ns period of the oscillations corresponds to a plasma electron density of 5×10^{15} m^{-3}. This indicates an oscillation in the plasma ejected from the target.

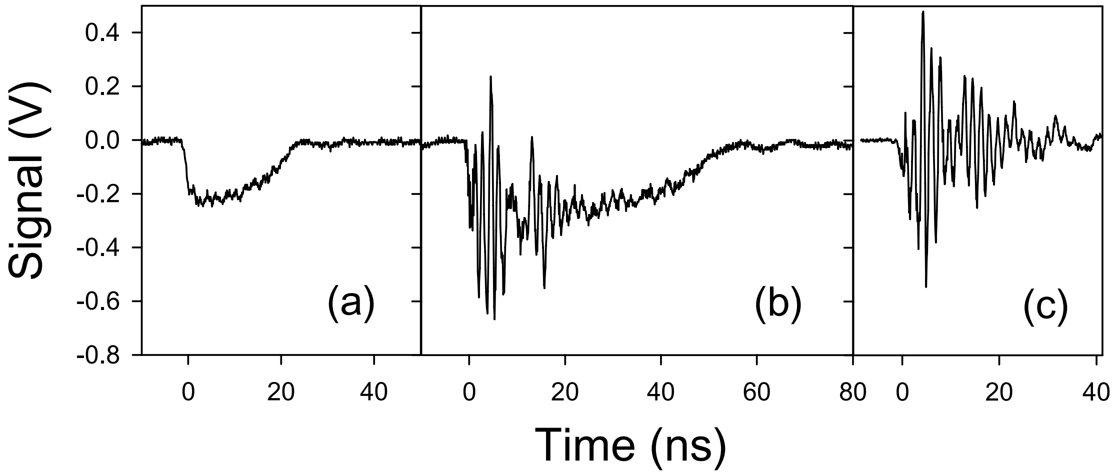

Fig. 3. IR emission and RF signal at the IR diode

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