Simultaneous Measurements of Fuel Areal Density, Shell Areal Density, and Fuel Temperature in D^3He-Filled Imploding Capsules

Measurements of the charged-particle products of the fusion reactions from an imploding inertial fusion capsule can provide a direct means of characterizing key aspects of the implosion dynamics. Parameters such as the fusion yield, fuel ion temperature, capsule convergence, fuel and shell areal densities, and implosion asymmetry can be inferred by these measurements and can complement and augment similar measurements made using fusion neutrons or x-ray techniques. In addition, such measurements provide unique information on charging up the target and on charged-particle acceleration. In collaboration with MIT and LLNL, LLE has developed two charged-particle magnetic spectrometers that have been implemented on OMEGA.

An initial application of these spectrometers to characterize the compressed capsule parameters involved the compression of capsules containing a mixture of deuterium (D_2) and helium-three (^3He). The fusion reactions arising from such a fuel include three primary and four secondary reactions:

Primary:

$$\begin{aligned} \mathrm{D+D} \quad (50\%) &\rightarrow {}^3\mathrm{He}\,(0.82\ \mathrm{MeV}) + n(2.45\ \mathrm{MeV}) \\ (50\%) &\rightarrow \mathrm{T}\,(1.01\ \mathrm{MeV}) + p(3.02\ \mathrm{MeV}) \\ \mathrm{D} + {}^3\mathrm{He} &\rightarrow {}^4\mathrm{He}\,(3.6\ \mathrm{MeV}) + p(14.7\ \mathrm{MeV}) \end{aligned}$$

Secondary:

$$\begin{aligned} \mathrm{D+T} &\rightarrow {}^4\mathrm{He}\,(3.5\ \mathrm{MeV}) + n(14.1\ \mathrm{MeV}) \\ {}^3\mathrm{He} + \mathrm{T}(51\%) &\rightarrow {}^4\mathrm{He} + p + n\ 12.1\ \mathrm{MeV} \\ (43\%) &\rightarrow {}^4\mathrm{He}\,(4.8\ \mathrm{MeV}) + \mathrm{D}(9.5\ \mathrm{MeV}) \\ (6\%) &\rightarrow {}^5\mathrm{He}\,(2.4\ \mathrm{MeV}) + p(11.9\ \mathrm{MeV}) \end{aligned}$$

The richness of particles and energies produced by the fusion of D^3He provides the opportunity for simultaneous measurement of several key capsule parameters. First, by measuring the ratio of D-D protons (or neutrons) to D^3He protons, the temperature of the fuel ions at burn time can be inferred. Figure 78.36(a) plots the ratio of the D-D to D-^{3}He reaction rate as a function of ion temperature. Second, the spectrum of the emergent fusion-produced protons will be affected by energy loss upon escape from the capsule. The 3-MeV D-D protons, for example, have a range of approximately 40 mg/cm^2, whereas the 14.7-MeV D-^{3}He protons have a range greater than 300 mg/cm^2 [see Fig. 78.36(b)]. Measurements of the slowing down of the charged particles therefore indicate the capsule's total areal density at burn time. In addition, the yield of neutron secondaries from the D-D reaction provides an independent measure of the fuel areal density. Thus, it is possible, in principle, to obtain simultaneous characterization of yield, fuel temperature, shell areal density, and fuel areal density by measuring the spectrum of fusion particles emerging from the implosion and burn of a D^3He–filled capsule. A series of such measurements carried out on OMEGA with the newly implemented charged-particle spectrometers (CPS) in conjunction with the single-hit neutron detector array (MEDUSA) provided information on the secondary reaction product yield for these experiments.

Spectrometer Description

The charged-particle spectrometer[1] consists of a 7.6-kG permanent magnet with CR-39 track-etch detectors.[2] A schematic of the magnet and sample particle trajectories is shown in Fig. 78.37. Constructed of a neodymium–iron–boron alloy with a steel yoke, this dipole magnet weighs 160 lb and has a long dimension of 28 cm and a 2-cm gap between pole faces. CR-39 pieces are positioned throughout the dispersed beam, normal to the particle directions, using the mounting structure shown in Figs. 78.38(a) and 78.38(b), which allows greater than 80% coverage between the proton-equivalent energies of 0.1 to 57 MeV. Accurate, and calibrated, particle trajectory calculations determine the energy of particles arriving at each position on the detectors. The presence of multiple particle species is conveniently managed since, at any given detector position, the track diameters from each species are clustered into discrete diameter groups—the heavier particles (such as alphas) having larger diameters than the lighter particles (such as protons)—and thus may be easily distinguished. Identifica-

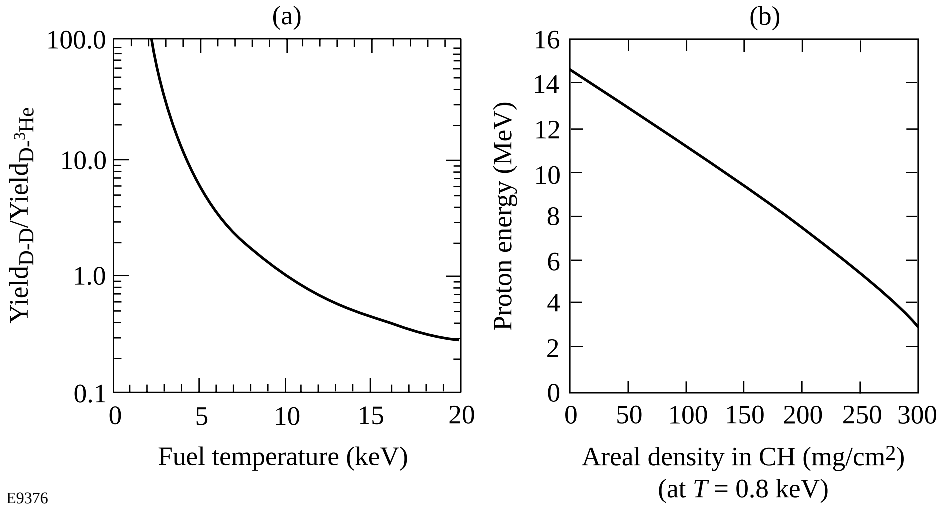

Figure 78.36
(a) Plot of the temperature dependence of the ratio of D-D fusion reactions to D-^{3}He reactions; (b) plot of the energy reduction as a function of areal density of 14.7-MeV protons traversing CH at a temperature of 800 keV.

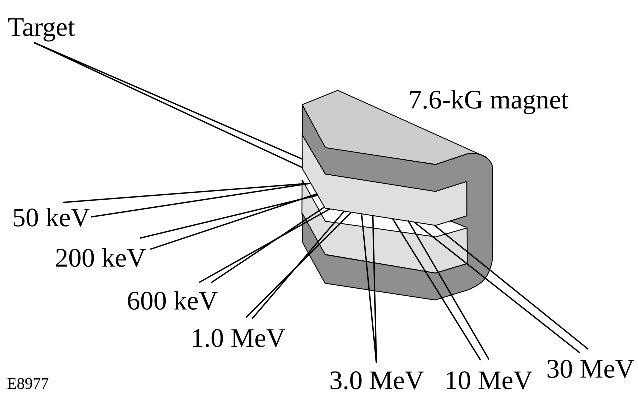

Figure 78.37
Schematic of the spectrometer and sample particle trajectories. A 7.6-kG pentagonal dipole magnet, 28 cm at its longest dimension, disperses protons in the range of 0.1 to 57 MeV. A linear array of CR-39 nuclear track detectors is placed normal to the dispersed beam. The large dynamic range of these detectors allows measurement of particle yields from 10^8 to 10^{17}.

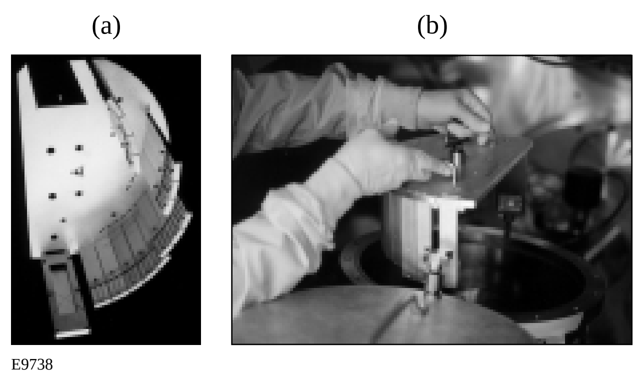

Figure 78.38
The mounting plate assembly that accurately positions pieces of CR-39 in the dispersion arc of the magnet. (a) The mounting plate assembly viewed from the perspective of the magnet. Pieces of CR-39 are positioned in each of the finger structures; these fingers are arranged in arcs that cover the dispersion region of the magnet. The finger at the bottom of the photo is positioned to view the target directly. X-ray film is placed at this position to ascertain the alignment of the spectrometer. The collimator slit is shown at the top of the photo. (b) The loaded mounting plate assembly being lowered onto the magnet (which is obscured) inside the vacuum chamber of CPS-1. After every shot, the mounting plate must be removed, and the CR-39 must be unloaded. A new, freshly loaded plate must then replace it in preparation for the next shot.

tion of each particle species is aided by using a track growth prediction model, calibrated to known particles and energies.

To assess the symmetry of all measurements, two virtually identical spectrometers are operating, one positioned inside the OMEGA chamber, at 100 cm from the target, and the other positioned outside, at 235 cm. The spectrometer inside the chamber is surrounded by a polyethylene-lead shielding structure designed to minimize the neutron noise levels on the CR-39. Incoming particles are collimated by a slit that can be varied from 1 to 10 mm wide, depending on the expected flux levels, giving solid angles between 10^{-6} and 10^{-5}. The measurement range of the instruments covers yields of 10^8 to more than 10^{17}, while the energy resolution is better than 4% over all energies. After every shot, the CR-39 detectors are removed from the spectrometer and replaced by a new set. The exposed detectors are then etched in sodium hydroxide and examined under a microscope. A rapid, automated scanning system has been developed that allows up to 10^6 tracks to be counted per shot.

Demonstration Experiments

Polymer ablator capsules, as illustrated in Fig. 78.39, were used to test the concept of simultaneous density and temperature measurements with D^3He–filled capsules. The principal diagnostics used for these experiments were the two charged-particle spectrometers, MEDUSA (to measure the fuel areal density via secondary reaction products[3]), and In activation (to measure the DD neutron yield).

In one series of shots, capsules of CH filled with a mixture of deuterium and ^{3}He were irradiated with up to 28.5 kJ in 1-ns near-square-top pulses with 2-D SSD beam smoothing. The capsule wall thickness ranged from 14.5 to 18.5 μm. Computer simulations of these implosions were performed using the one-dimensional hydrodynamic code *LILAC*,[4] and the spectra were calculated using the particle-tracking code *IRIS*.[5] The assumption of ideal performance (i.e., no mix, one-dimensional performance) in these simulations indicated that fuel ion temperatures in the range of 3.5 to 5.0 keV and capsule convergence ratios (ratio of initial target radius to compressed target radius) up to 28 could be achieved.

Figure 78.40 shows the measured proton spectrum obtained on one of these experiments. Table 78.V is a summary of the predicted and measured target parameters for this shot. The measured spectrum generally shows a greater slowing down for the thicker CH shells compared to thinner CH shells. This increased slowing down is apparent in the simulation results. The simulations, however, predict much larger areal densities, corresponding to an increased slowing down in the target, than are observed experimentally (Table 78.V), indicating departures from one-dimensional, unmixed implosions.

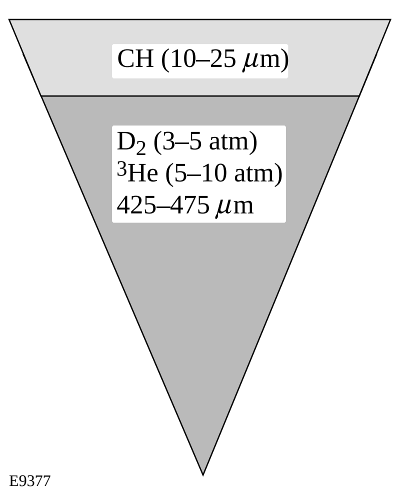

Figure 78.39
Polymer shell capsules filled with D^3He were used to test the CPS.

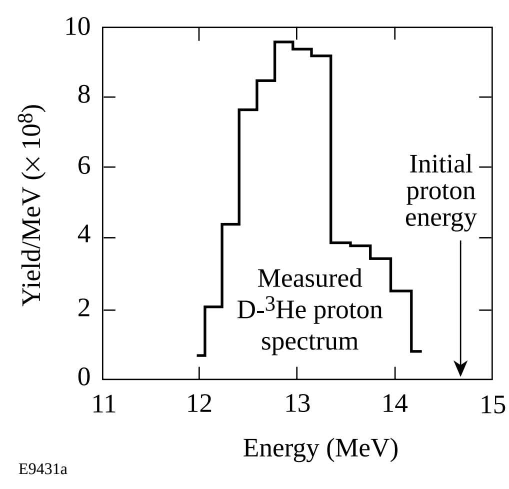

Figure 78.40
D-^3He proton spectrum measured on shot 13799. For this shot the laser energy was 28.3 kJ (1-ns square pulse), and the CH ablator was 18.4 μm thick. The capsule was filled with 2.8 atm of D_2 and 4.9 atm of ^{3}He.

Table 78.V: Predicted and Measured Parameters—Shot 13799.

Parameter	Predicted	Measured/Inferred
D-D neutron yield	5.4×10^{10}	2.1×10^{10}
$D\text{-}^3He$ proton yield	3.1×10^{9}	1.3×10^{9}
Fuel temperature	3.6 KeV	3.9 keV
Proton downshift	4.2 MeV	1.9 MeV
Shell areal density	120 mg/cm^2	60 mg/cm^2
Fuel areal density	32 mg/cm^2	13 to 17 mg/cm^2
Convergence ratio	28	16 to 18

The simulated fuel temperature in Table 78.V is well reproduced by the experiment. This is probably due to the fact that higher temperatures occur earlier in the implosion history of the target when capsule conditions are closer to one-dimensional predictions. The difference between the measured and calculated areal densities is probably due to the fact that the areal density is predicted to increase later in the implosion. In this later phase, the mixing of the fuel and the shell due to hydrodynamic instabilities can cause significant departures from one-dimensional behavior and can reduce the fusion burn significantly. This may be the principal cause of the observed discrepancy between simulation and experiment. More detailed modeling using either mix models or multidimensional hydrodynamic simulations is necessary to correlate the measured spectra with conditions in the target. This analysis is presently being carried on.

In conclusion, simultaneous measurements of the fuel areal density, shell areal density, and fuel temperature have been carried out on OMEGA using D^3He–filled imploding capsules and the recently installed charged-particle spectrometers. The initial experiments demonstrated the ability to carry out these measurements at fuel ion temperatures of 3 to 6 keV, fuel areal densities in the range of 10 to 20 mg/cm^2, and shell areal densities in the range of 40 to 60 mg/cm^2. Measurements such as these can be applied to the parameter region characteristic of cryogenic-fuel capsules on OMEGA: total areal density of several hundred mg/cm^2 and fuel temperature of several keV. In future experiments, we will extend such measurements to higher fuel and shell areal densities and attempt to validate these techniques on cryogenic-fuel targets.

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