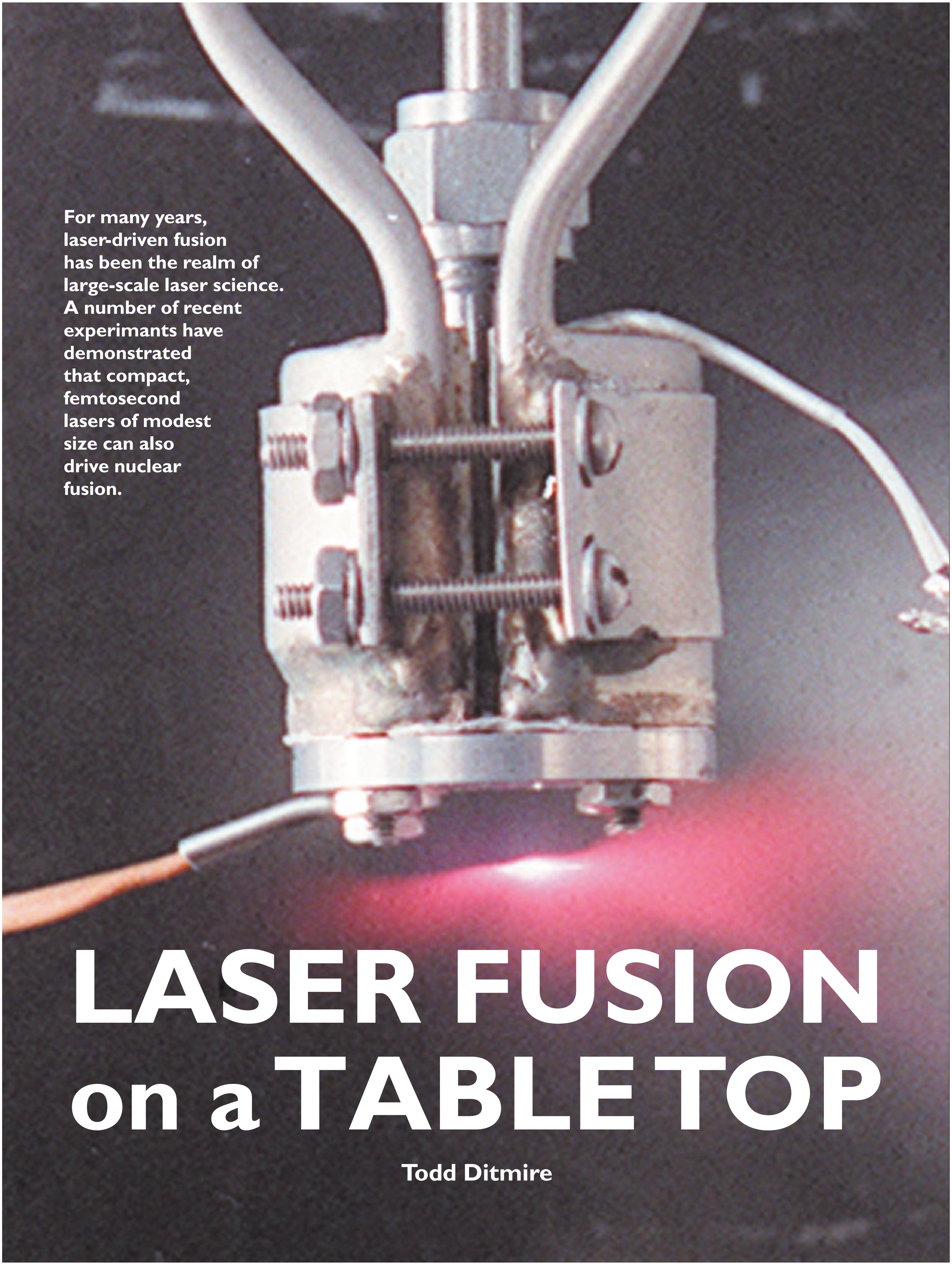

LASER FUSION on a TABLE TOP

Todd Ditmire

For many years, laser-driven fusion has been the realm of large-scale laser science. A number of recent experimants have demonstrated that compact, femtosecond lasers of modest size can also drive nuclear fusion.

The development of ultrahigh-intensity, ultrashort-pulse lasers in the late 1980s and 1990s has led to a revolution in the study of laser interactions with matter. Lasers of this class, which use chirped-pulse amplification (CPA)[1] and now routinely produce laser pulses with peak powers of many terawatts (10^{12} W) in pulse durations of a few tens of femtoseconds, yield unprecedented light intensity. When focused to spot sizes of a few micrometers, these lasers achieve intensity ranging from 10^{18} W/cm^2 to over 10^{20} W/cm^2. Even more remarkable is the fact that the latest generation of lasers that can produce such extreme brightness are tabletop in scale.

Only in recent years have researchers begun to explore the wealth of science rendered accessible with this ultraintense light. Under irradiation at such extreme intensities, exotic forms of matter result. These states include plasmas with pressures exceeding 1 Gbar and electron beams accelerated to highly relativistic energies of many MeV. Another fascinating finding that has come to light in a number of recent experiments is the fact that tabletop lasers can drive nuclear fusion.

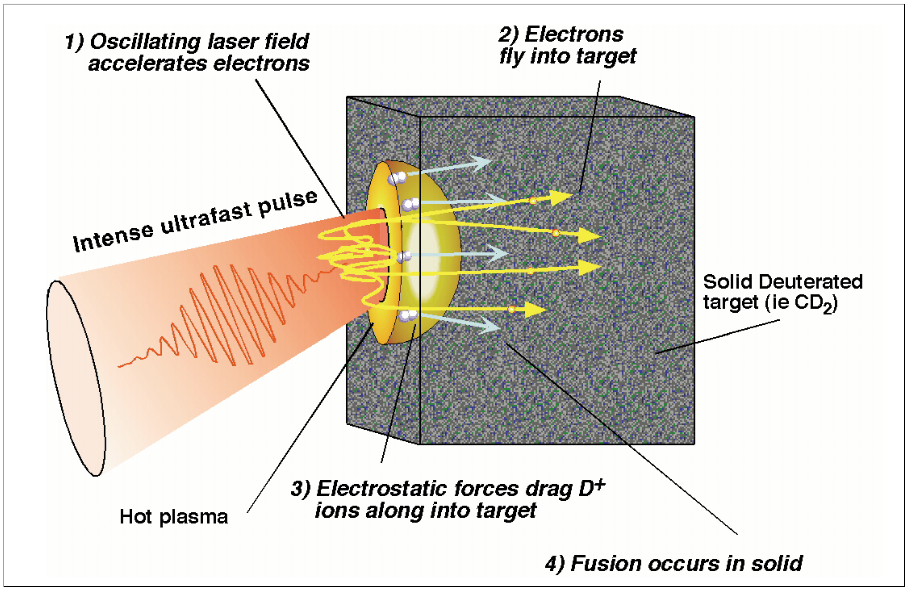

Figure 1. Events that lead to DD fusion in a solid target irradiated by an intense short-pulse laser. First, the laser accelerates electrons in plasma at the surface. These electrons then race into the target, setting up an electrostatic potential which propels the deuterium ions behind them. The accelerated ions then fuse with cold ions in the bulk material.

Nuclear fusion in laser-produced plasmas

For many years, laser-driven fusion has been the realm of large-scale laser science. In particular, fusion research with intense lasers has centered on the study of the technique known as inertial confinement fusion (ICF).[2] In this approach, a release of nuclear energy is sought from nuclear reactions between deuterium and/or tritium ions through the nuclear reactions $D + D \rightarrow He^3 + n$ (+ 3.3 MeV of excess energy), $D + D \rightarrow T + p$ (+ 4.0 MeV), or $D + T \rightarrow He^4 + n$ (+17.6 MeV). These nuclear reactions will only occur with any significant probability if the plasma is heated to high temperatures ($>10^7$ K or many keV). In the ICF experiments, a large, multibeam laser irradiates a pellet containing deuterium or a deuterium/tritium mixture. The pellet implodes under pressure from the ablation of material by the laser. The ablation pressure of the laser compresses and heats the fuel to a condition in which nuclear fusion occurs. In these experiments, nanosecond-duration lasers with ten or more beams are used, and pulse energy of many kilojoules is usually necessary. Such lasers—like the recently deactivated Nova laser at Lawrence Livermore National Laboratory, or the operating Omega laser at the University of Rochester—are quite large in scale.

This approach holds the greatest promise of attaining ignition, the state at which the nuclear fuel burns on its own and, ultimately, releases more energy than was injected to implode and heat it in the first place. Any real hope of using laser-driven fusion to drive a power plant still rests with the ICF approach, which is why ICF research is being pursued in a number of laboratories around the world. The construction at Lawrence Livermore of the enormous National Ignition Facility laser (which, when it is completed, will deliver 1.8 megajoules of ultraviolet laser energy) represents the culmination of many years of successful ICF research in the U.S.

Nuclear fusion with large lasers has been achieved in a number of other ways as well. Although the experiments differ from one another, generally they all rely on colliding plasmas produced from the explosion of a nanosecond-laser-heated target containing deuterium.[3] A large laser heats a target with nuclear fuel and the explosion of the hot plasma gas generates the hot ions necessary to drive the fusion. The principal product of such experiments is the release of neutrons from the nuclear fusion reactions (through the $D + D \rightarrow He^3 + n$ reaction). Such experiments often produce quite a lot of neutrons, although achieving this result still requires facility-scale, ~kilojoule-class lasers that fire in single-shot mode.

Recent experiments using compact, femtosecond lasers have now demonstrated laser-driven fusion on a much more modest scale. In these experiments, scientists have observed nuclear fusion, and the resultant release of energetic neutrons, from lasers with pulse energy of less than 1 J and repetition rate of 10 Hz. Such experiments have leveraged the advantage of CPA lasers, which allow high pulse intensity to be achieved with modest pulse energy. Deuterium fusion (DD fusion) by means of compact, tabletop-scale lasers represents a different class of experiments from the large-scale fusion research described above: the physical mechanisms for creating the hot ions to drive the fusion are different. Furthermore, the high-repetition-rate capabilities of modern, femtosecond multiterawatt lasers enables study on a level of detail not possible with large-scale systems. Experiments with terawatt, femtosecond lasers are interesting not only because of the insights they yield into the study of high-intensity laser interactions, but also because they offer the promise of a unique, high-repetition-rate source of (pulsed) high-energy neutrons.

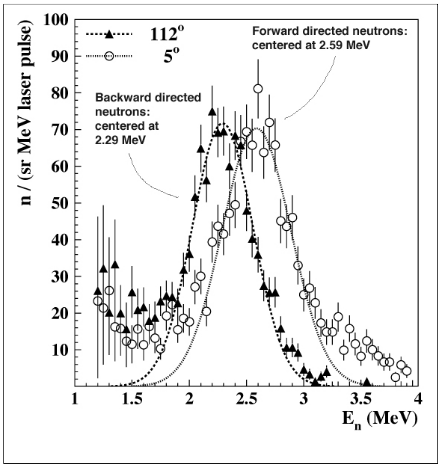

Figure 2. Neutron-energy spectrum data recorded from fusion in a solid-target interaction. The neutrons emitted forward are shifted to slightly higher energy while neutrons emitted backward (i.e., back toward the laser pulse) are shifted to a slightly lower energy. Reproduced from Ref. 5 with permission.

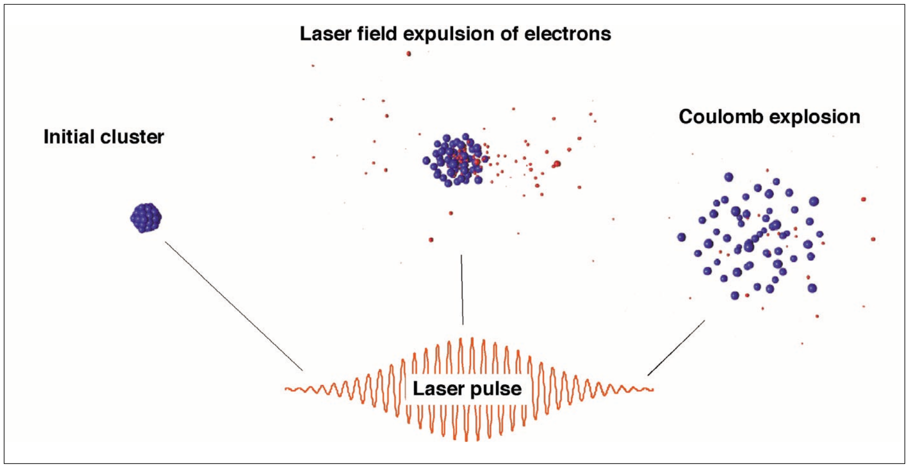

Figure 3. Illustration of how an intense laser pulse creates fast ions from a cluster. The short pulse first ionizes the atoms in the cluster (on the rising edge of the pulse). The intense part of the pulse quickly strips the free electrons from the cluster, the ions of which then repel each other, leading to an energetic Coulomb explosion.

Fusion in solid targets: the laser ion accelerator

The first class of experiments in which DD fusion has been observed using tabletop lasers is in interactions of terawatt-laser pulses with solid targets. A number of groups have observed DD fusion from plasmas created when these pulses are focused onto the surface of a deuterated target, most often a deuterated plastic target (i.e., $[CD_2]_n$).

For example, Pretzler *et al.* observed fusion neutrons when a 200 mJ, 160 fs Ti:sapphire laser was focused on the surface of a slab composed of deuterated polyethylene powder.[4] The laser was focused to an intensity of about 10^{18} W/cm^2 on the surface of these targets at 10 Hz, resulting in roughly 10^2 n/shot being emitted in all directions. Similar experiments were performed by Hilsher *et al.*, who focused 300 mJ, 50 fs pulses on deuterated polyethelene, also at an intensity of ~ 10^{18} W/cm^2[Ref 5]. In these experiments, the scientists observed around 10^4 neutrons per shot. The neutrons, which arise from the $D + D \rightarrow He^3 + n$ reaction, have well-defined energy near 2.45 MeV.

Although a number of explanations have been offered for the appearance in these interactions of fusion neutrons, it is generally accepted that the neutrons arise from the acceleration of deuterons by the laser into the target, a physical mechanism illustrated in Fig. 1. The accelerated deuterons then collide with other (cold) deuterons in the target, and fuse.

As shown in Fig. 1, when the laser pulse impinges on the target at high intensity, the light ionizes the solid and creates a plasma. Some expansion of this plasma during the pulse gives rise to the formation of a cloud of plasma in front of the target (although this cloud may only be a fraction of a laser wavelength thick, i.e., $<< 1\ \mu$m). As the intense laser pulse propagates into the plasma, it accelerates electrons. The complex mechanisms leading to this acceleration are an active topic of study. However, one simple mechanism for this acceleration, the mechanism which dominates for very-short-laser pulses, can be understood by examining the trajectories of electrons of the plasma in the laser field. The oscillating electric field of the laser accelerates electrons of the plasma back and forth, in and out of the interface between plasma and vacuum. During this field-driven motion, some of the electrons get launched into the solid during a phase of the laser-field oscillation in such a way that the electron escapes the forces of the field before the laser can reverse the direction of the electron. In this way, electrons with energies of well over 1 MeV are possible (when the laser intensity is $>10^{18}$ W/cm^2, as it was in the experiments described in Refs. 4 and 5.)

These accelerated electrons set up an electric field in the target, which then accelerates the ions behind them. In a sense, the electrons pull the ions along with them. If the target contains deuterium, the deuterons get accelerated into the target with energies ranging from a few keV up to over 1 MeV. These energetic deuterons will travel into the bulk of the target and fuse with other deuterons deep inside the material. One signature of this process is a shift in the neutron energy. If the deuteron travels into the target with high energy, then the energy of the neutrons that get emitted along its path will be shifted up to a higher level. (The shift occurs when the energy of the incoming deuteron becomes significant when compared to the total energy release from the fusion event. In a sense, the energetic deuteron gives an additional “kick” to the outgoing neutron along the direction of the incoming deuteron.)

Such a shift of neutron energy from a directed beam of deuterons into the solid target was observed recently in the experiments of Hilscher *et al.*[5] The effect is shown in the data of Fig. 2 [from Ref. 5], in which the observed spectrum of neutrons emitted into the target was centered at 2.59 MeV, shifted up from an energy of 2.45 MeV, the energy expected from fusion of near-stationary deuterons. The neutrons observed in the backward direction (i.e., up from the surface of the target, back toward the incoming laser beam) exhibit an energy which is shifted down, to 2.29 MeV. (This occurs because the neutron receives a momentum kick in a direction away from the observer.)

Though the experiments are larger than traditional tabletop experiments, this approach to driving DD fusion with short-pulse lasers has been scaled to much higher neutron yields, using much higher laser-pulse energy. For example, Disdier *et al.* observed as many as 10^7 neutrons from a solid target irradiated with a much higher energy laser that emitted a 20-J, 400-fs laser pulse.[6] Even higher yields have been observed at Lawrence Livermore National Lab by users of the 500-J, 500-fs Petawatt laser.[7] These experiments, performed on large-scale, "single-shot" machines, suggest the tantalizing possibility that much higher neutron yields may be achieved from solid-target experiments.

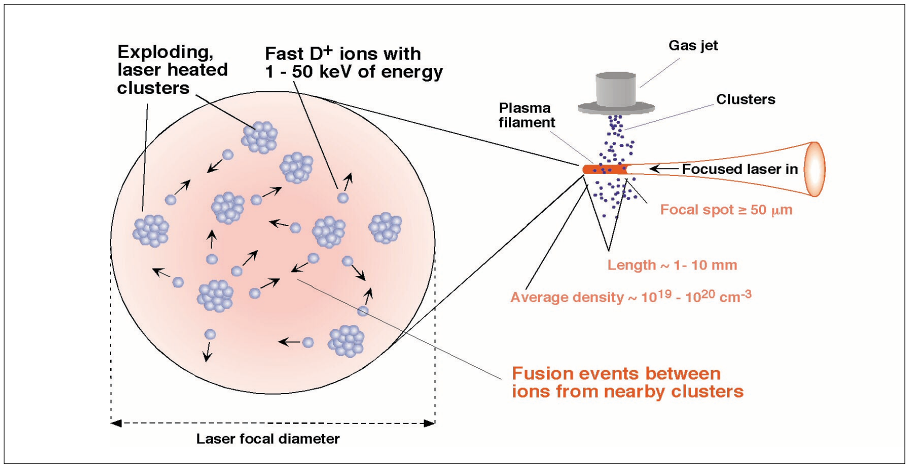

Figure 4. Schematic of the fusion process in a gas of clusters.

Fusion from clusters: a laser driven "nanoexplosion"

Another class of tabletop laser-fusion experiments revolve around the use of a very different kind of target. In these experiments, the laser is not focused onto a solid; instead, the pulse is focused into a gas target composed of small clusters of atoms. The clusters, which can range in size from a few atoms to many thousands of atoms each (i.e., a few nanometers in size), are a widely studied form of matter. Interest in the interaction of high-intensity-laser light with clusters has blossomed in recent years because clusters are seen as a bridge between molecules and solids.[8]

Although clusters themselves can be produced in a number of ways, the experiments conducted to observe DD fusion use van der Waals bonded clusters of deuterium or deuterated methane. When a gas of atoms or molecules is allowed to expand into vacuum through a gas jet, the gas cools and clusters form; these clusters are, in a sense, nanometer ice particles in a cold gas. This process is a relatively straightforward method for making clusters of a variety of species, including hydrogen and deuterium.

DD fusion has been observed in experiments in which an intense laser pulse is focused into a gas containing these clusters. For example, Ditmire *et al.* observed DD-fusion neutrons when a gas of pure D_2 clusters, with average sizes around 5 nm, was irradiated with 35 fs, 150 mJ laser pulses focused to an intensity of up to 5 x 10^{17} W/cm^2.[Ref. 9] In this experiment, approximately 10^4 neutrons per shot were observed. More recently, Balcou *et al.* observed DD fusion from a gas of deuterated methane (CD4) clusters.[10] They observed about 10^3 neutrons per shot using a 35-fs laser focused to > 10^{17} W/cm^2.

To understand the origin of fusion in these experiments, it is necessary to look in more detail at the dynamics of laser interaction with individual clusters on a microscopic scale. Although the specific nature of the laser-cluster interaction depends to a large degree on the size of the cluster and on the species, (we know that clusters of atoms with lots of electrons, like Xe, behave quite differently from clusters of small atoms, like deuterium), it is simple to summarize the nature of the interaction with deuterium clusters. The steps of the interaction are illustrated schematically in Fig. 3. When the laser irradiates the cluster, it optically ionizes the constituent atoms. If the laser pulse is short (a few tens of femtoseconds in the case of deuterium clusters) the ions produced in the cluster are largely stationary: they cannot move on the fast time scale of the laser pulse. The electric field then drives oscillations of the liberated electrons in the cluster. If the laser field is strong enough, it can extract some (or all) of the electrons from the cluster, leaving a sphere of positively charged ions. The electrostatic repulsive forces between the ions lead to a "Coulomb explosion" of the cluster.

The powerful electrostatic forces in the cluster will eject ions with substantial kinetic energy. For example, energy of up to 1 MeV has been observed for ions from the explosion of Xe clusters.[11] In the fusion experiments described above, the kinetic energy release of these explosions in deuterium-bearing clusters is exploited. A schematic of the fusion process is illustrated in Fig. 4. In these experiments, a gas of clusters is formed by a puff of deuterium (or deuterated methane) gas into vacuum via a pulsed gas jet, backed with high pressure gas. In the case of the deuterium experiments, the gas is also cryogenically cooled. The laser pulse is focused to a spot in the middle of the gas among the clusters. In the focal volume where the laser is intense, clusters explode from irradiation by the passing laser pulse. This leads to the formation of a cigar-shaped filament of plasma. After passage of the laser pulse along the "cigar," energetic deuterons can collide with other fast deuterons in the cigar itself or with deuterium atoms in the surrounding gas. The collisions give rise to fusion events. Figure 5 shows a picture of this fusion plasma from the experiment of Ref. 9. Although neutron yield from these cluster-fusion plasmas is similar to those seen in the solid-target experiments (10^4 - 10^5 n/shot with 100 mJ laser pulses), the neutron energy spectrum (shown in Fig. 6 [from Ref. 12]) is sharper in energy and centered at 2.45 MeV. These data indicate that the fusion observed in this experiment arises from a slightly cooler plasma with an isotropic velocity distribution.

This laser irradiation of a cluster gas leads, in a sense, to a plasma with very hot ions, since each of the clusters will tend to explode isotropically. The result is a short-lived, high ion temperature of sorts. One particularly intriguing aspect of this interaction is that virtually all the laser light is absorbed by the clustering gas, a remark-

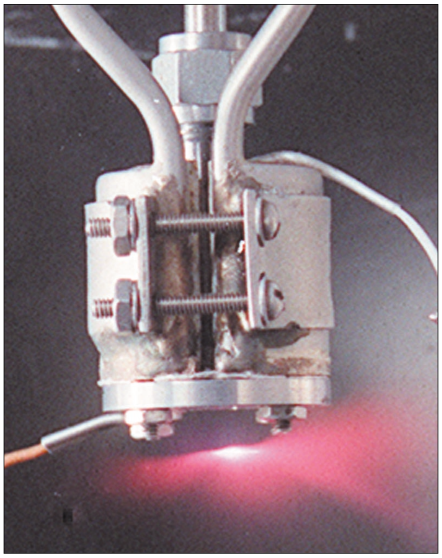

Figure 5. Picture of fusion plasma from the experiment of Ref. 9. The laser enters the gas from the right. The stainless steel gas jet pulses gas down from the top into the path of the laser. Clusters form in this gas jet, scattering the near IR laser light as it enters the plume. A white fusion plasma spark is created directly underneath the nozzle of the gas jet.

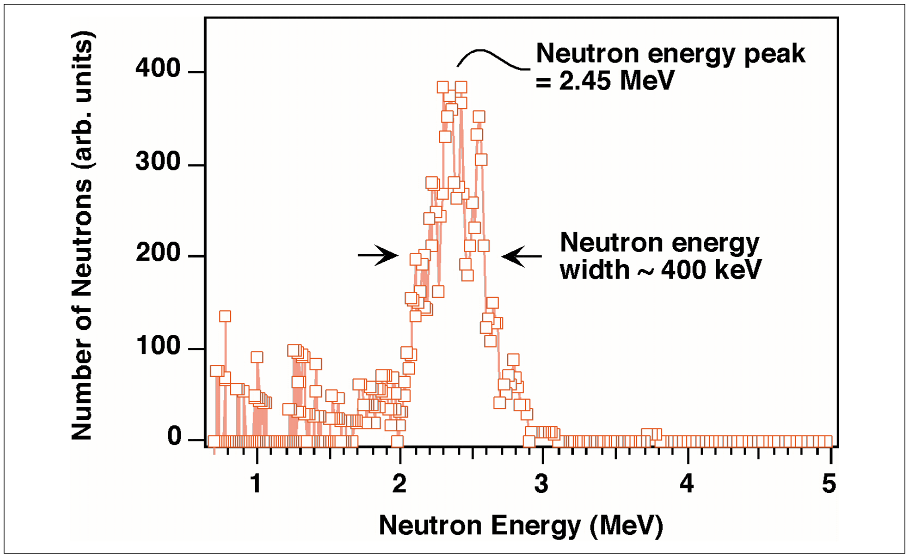

Figure 6. Neutron energy spectrum data recorded from fusion in a deuterium cluster jet. These data are from the experiments reported in Ref. 12. Unlike the data of Fig. 2, this spectrum is centered at 2.45 MeV and exhibits a relatively narrow energy spread.

able occurrence given that the *average* density of the gas itself is only equal to about that of one atmosphere (~10^{19} atoms/cm^3) and is, of course, completely transparent to low-intensity light. Most of the absorbed laser light is converted to fast-ion kinetic energy in the exploding clusters. Another interesting feature of this phenomenon is that the emission time of neutrons from these plasmas is fast. The neutron pulse duration will be determined by the time it takes the hot plasma to disassemble. The disassembly time has been measured, and it appears that the emission time is on the order of 100 ps or less.[12]

Future prospects and conclusion

Where these tabletop fusion experiments will lead is an open question. The principal line of research today involves increasing fusion yield. As mentioned, neither of these approaches to short-pulse laser fusion will likely lead to a viable means of energy production: achievement of such a goal will still rely on the ICF approach. However, because of the high repetition rate of these fusion experiments, the prospect of using them as a compact source of neutrons is being investigated.

Clearly, if these approaches are to be useful as sources of neutrons, the total neutron yield per shot will have to be increased dramatically. It is not clear at present whether the yields necessary for realistic applications are achievable with compact lasers. Yet these fusion experiments do offer some rather unique features as a potential neutron source. For example, in the case of both solid and cluster targets, the source of the neutrons is small (much smaller than 1 mm). No equivalent point-like source of neutrons can be generated through conventional means, such as accelerator-based sources or nuclear reactors. This characteristic may yield advantages in imaging or in generating very high fluxes over small regions.

The energy spectrum of the neutrons is unique: it is largely a pure "fusion" spectrum peaked at 2.45 MeV (unlike the broad neutron spectrum from a fission reactor). This may be of some interest in the study of neutron damage of materials destined to be used in a future fusion reactor. Materials damage by neutron irradiation is a very active area of study because of the need to develop materials that will be able to withstand the insult of high neutron irradiation in future fusion machines. Today there is no way to exactly replicate the neutron spectrum produced from a reactor fusion plasma at the high fluxes expected. A high-repetition-rate laser fusion source may permit this in the future.

Finally, these laser-driven fusion neutron pulses have another unique facet: they are emitted in a short-duration pulse. This has been confirmed in the case of the cluster targets. Although yet to be measured in the solid targets, a short neutron burst is likely there as well. The short-pulse nature suggests some interesting future applications inaccessible by use of conventional neutron sources. For example, these neutrons might be used in fast-neutron radiography combined with gated imaging. Even more exciting, they might be used as a "pump" pulse in time-resolved pump-probe experiments. Neutron-radiation-damage dynamics in materials are predicted, through various simulations, to occur on time scales of a few tens to a few hundreds of picoseconds. These neutron pulses might be fast enough to allow us, for the first time, to create and watch neutron-damage dynamics in a material in real time. Estimates of the neutron yields necessary to perform such an experiment suggest that improvements of three to four orders of magnitude will be necessary. Though no small task, improvements of our understanding of these laser-induced fusion processes coupled with advances in high-energy compact laser development might make such experiments possible in the near future.

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