Trident

Playing in the X-Games

Major Player in the "X-Games"

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If you're thinking of competing in the "X-Games of Contemporary Science," you might want to talk to David Montgomery, director of Los Alamos' Trident high-power-laser facility. He and other Trident scientists have cooked up some winning strategies for the events in the last 10 years or so.

In these X-Games, as the National Academy of Sciences calls them, scientists create and study, in the laboratory, the "extreme" matter usually found inside the sun, other stars, and gas giants such as Jupiter—or in even more exotic places such as near the edges of black holes and within gamma-ray bursts and the atmospheres of neutron stars. The conditions needed to sustain this matter are truly extreme; phrases like "millions of atmospheres," "millions of degrees," "many times the density of lead" are typically used to describe them.

More precisely, extreme matter is matter with an internal pressure of at least 1 million atmospheres, that is, 1 million times the pressure of Earth's atmosphere at sea level, and falls under the purview of "high-energy-density physics" (pressure can be expressed as an "energy density," or energy per unit volume).

Scientists can create extreme matter in the laboratory only briefly. But doing so lets them study it up close and personal, rather than through a telescope from millions or billions of light-years away. Such studies are already benefiting research on fusion energy and nuclear weapons, where these extremes also prevail.

Cooking Up Extreme Matter

Extreme matter is usually a hot, dense plasma, ordinary matter broken down by extreme heat into a swirling soup of positively charged atomic nuclei (ions) and negatively charged electrons.

"One way to create extreme matter is to shine intense light—just a pulse of it—onto a solid target, usually a metal foil or wire, to quickly heat it up," says Montgomery. "Trident makes some of the most-intense light pulses on Earth."

In addition to being intense, the pulse must be extremely brief. Because hot plasmas disperse rapidly and lose energy quickly, mainly radiating it as ultraviolet light or even x-rays, the pulse must heat the matter much faster than the plasma disperses and cools through radiation. In a typical Trident experiment, a light pulse will turn a tiny bit of target material into a microplasma with a volume of 1 cubic millimeter (about the size of a large grain of salt) or less.

The light energy required to do that and the time in which the energy must be deposited in the target determine the light pulse's power, which is the energy of the pulse divided by its duration.

To produce 1 cubic millimeter of extreme matter requires about 1 trillion watts (a terawatt), equal to the combined power output of all the electrical plants in the United States. But don't worry about the lights dimming each time Trident spits out a light pulse. Trident packs the terawatts into the pulse by cramming a small amount of energy—about what's needed to light a 100-watt light bulb for a few seconds or so—into a very brief time. The longest pulse produced at the facility lasts for only a few tens of microseconds. Trident also produces pulses that pack 200 terawatts of power, more than enough to create some very extreme matter, but those pulses are even shorter—only half a trillionth of a second.

Moreover, Trident can provide its short pulses and long pulses simultaneously. "For example," Montgomery says, "a long pulse can be used to create extreme matter while a series of short pulses acts as a fast strobe light to photograph how the matter behaves. With two long-pulse beams and one short-pulse beam, as well as great versatility in being able to change the pulses' shapes in time, Trident is probably the most-flexible high-power-laser system in the world."

When focused onto a target, a Trident short pulse is also very small, with a diameter of 9.6 millionths of a meter (9.6 micrometers)—that's about the diameter of a red blood cell—and a length about equal to the thickness of a sheet of paper (about 150 micrometers). Squeezed into this tiny volume, the light can exert a pressure of billions of atmospheres. This "radiation pressure" can very effectively push a plasma's electrons around, a phenomenon scientists can exploit to spectacular effect.

The power, duration, and size of a Trident short pulse are typical of the short pulses produced at the handful of high-power-laser facilities that exist around the world. But Trident's short pulses contain more of the available light energy than other lasers in its class. The method used to generate powerful short pulses also produces a preceding jolt of light, a "prepulse," which hits a target before the short pulse does. However, because the short pulses at Trident and other high-power-laser facilities contain so much energy for their size, the premature arrival of even a tiny fraction of that energy can blast a target to smithereens before the short pulse arrives. For this reason, experiments with metal-foil targets thinner than 1 micrometer require as small a prepulse as possible.

At Trident, the prepulse value of the short pulses is less than one 10-billionth of the available light energy. That leaves nearly all of the energy—at least 99.99999999%—to be packed into the Trident short pulse. To put that in perspective, if the prepulse were a wave an eighth of an inch high, the short pulse would be at least 20,000 miles high. Trident's prepulse value is about 10,000 times smaller than those of the four other operational short-pulse lasers in Trident's energy class. No wonder Trident researchers can do experiments that cannot be done elsewhere!

Stunts with Short Pulses

In the mid-1960s, scientists realized that intense laser light could compress and heat matter enough to produce significant amounts of fusion energy, which powers the sun and other stars and could one day provide an inexhaustible source of terrestrial energy. The nuclei in a plasma are all positively charged, so they strongly repel each other when they're close together. But in a hot, dense plasma, they approach each other at such high speeds and so often that many pairs of them can overcome their repulsion and fuse—releasing enormous amounts of nuclear energy.

In the last decade or so, the pursuit of laser-induced fusion has spurred the development of several swimming-pool-size laser systems that produce short pulses with powers well over a trillion watts. In 1996, one beam line of the Nova laser—which was built for fusion research at Lawrence Livermore National Laboratory (LLNL) in 1984—was converted to short-pulse operation. The result was the first petawatt (1,000 trillion watts) laser. The appropriately named "Petawatt" was used to study laser-induced fusion, among other things, before being dismantled in 1999 to make way for LLNL's National Ignition Facility (NIF). The size of three football fields, NIF will house the world's largest laser, which many hope will sustain fusion reactions for a few billionths of a second—an event that could occur as soon as 2010.

With NIF fusion on the horizon, scientists at Trident and other high-power-laser facilities are gearing up to support NIF efforts by exploiting a key discovery made with the Petawatt—that ultraintense short pulses can produce intense beams of electrons, protons, and other ions, as well as intense bursts of high-energy x-rays. The proton beams could be used to ignite fusion plasmas, while the x-rays will be used to take pictures of them.

Plasma Portraiture

Capturing images of fusion plasmas is no easy task because such plasmas can be 100 times denser than lead. However, x-rays that are bright enough and energetic enough can shine through the densest plasma to produce a "shadowgraph," just like a medical x-ray. Trident researchers recently implemented the Petawatt's x-ray-production technique to do just that—in order to take pictures of fusion plasmas; fusion-fuel compression, leading to the fuel's "ignition"; and hot, dense plasmas in general.

The researchers aim a short pulse at a metal wire with a diameter of 12 micrometers. The intense light quickly frees some of the electrons in the wire and accelerates them to energies of 100,000 or so electron volts. These energetic electrons then strike other electrons in close orbit around the metal's nuclei, "exciting" the orbiting electrons to move in larger orbits. The excited electrons quickly drop back to their original orbits, but they emit high-energy x-rays as they do.

The resulting x-ray burst can produce good x-ray photos of hot, dense plasmas. The burst is also brief enough—about as short as the light pulse—to freeze a swirling plasma's motion. Moreover, the x-rays are emitted from the end of the wire, so the source of the x-rays is about the size of the wire's diameter. This source size can capture details as small as 10 micrometers in an x-ray shadowgraph.

Other facilities around the world, including the University of Rochester's Omega-EP and the Z-R, a "z-pinch" plasma facility at Albuquerque's Sandia National Laboratories, are also using this technique to take pictures of hot, dense plasmas. NIF will use this same type of source.

Potent Proton Acceleration

Trident was built in 1992, about 10 years before the National Academy of Sciences came up with the X-Games theme, but Trident's original mission—to support an earlier, never fully realized, national laser-induced-fusion program (ICF, for inertial confinement fusion)—was well aligned with the pursuits of many present-day X-Gamers. An upgrade completed in 2007 boosted Trident's maximum power from 30 terawatts to over 200 terawatts through the addition of the short-pulse capability. This was all Trident needed to seriously compete with other short-pulse, high-power-laser facilities.

In addition to a super-low prepulse value, the intensity of a Trident short pulse can be higher than those of more-powerful short pulses produced at other facilities. This feature has contributed to a major improvement in the method of proton-beam generation discovered with the Petawatt.

The intensity of a pulse is its power divided by the area on the target illuminated by the pulse. Trident achieves high intensity by focusing a larger fraction of a short pulse's power into a small area than can some higher-power lasers. Since the radiation pressure of a pulse is proportional to its intensity, a Trident short pulse can more effectively push a target's electrons around—the first step in accelerating protons with a light pulse (see "Proton Acceleration" box).

In addition to igniting fusion plasmas, the proton beams could also be used to treat cancerous tumors. Many different types of cancer have been successfully treated by blasting tumors with protons accelerated to about 200 million electron volts (MeV) in a circular accelerator called a cyclotron. Cyclotrons typically 12 feet in diameter are now offered commercially for proton-radiation treatment. But they could be replaced one day with much smaller and cheaper systems based on laser acceleration—in part because ultraintense short laser pulses can accelerate protons in about 1 millionth the distance required by existing accelerators to reach the same energy.

A few months ago, Trident researchers led by Kirk Flippo produced protons with an energy of 58.5 MeV—surpassing by 0.5 MeV the record set by the Petawatt but using only about one-sixth the power that the Petawatt needed. This is a significant step toward developing compact proton accelerators.

When Trident protons reached 58.5 MeV, the energy of the Trident prepulse was less than one 10-millionth that of the short pulse. However, the best proton acceleration requires a foil target that is very thin but still intact and cold when the short pulse hits it. To permit ideal conditions for proton-acceleration experiments, the Trident researchers thought about how they could reduce the prepulse energy even further.

"Randy Johnson, another of our staff members, came up with a highly effective remedy," Flippo says. The Trident "crew" successfully implemented Johnson's idea this year in early September, reducing the prepulse energy to less than one 10-billionth that of the short pulse—a thousandfold improvement that has already permitted proton-acceleration experiments with metal-foil targets as thin as 5 billionths of a meter. Other high-power lasers can use targets no thinner than 10 to 20 micrometers without destroying them (prematurely). Trident's super-low prepulse value promises to be one more significant step toward developing compact proton accelerators.

Proton Acceleration

Going for the Gold

Lawrence Livermore's National Ignition Facility will be the site of renewed efforts to try for the first time to sustain fusion reactions in the laboratory. If all goes well, the facility's intense laser beams will compress and heat to fusion a mixture of two hydrogen isotopes—deuterium and tritium—contained in a hollow, BB-size sphere of beryllium or plastic.

The beams will compress the fusion fuel indirectly, as shown in the figure below. (A) They will strike the inner walls of a hollow gold cylinder about the size of a pencil eraser, producing a hot gold plasma. (B) The gold plasma will then radiate x-rays that compress the sphere, which will be positioned at the cylinder's center. (C) The compressed and heated fuel will "ignite" to produce sustained fusion reactions. However, earlier experiments with the Nova laser showed the beams might fail to reach the gold walls because of another plasma that the beams will form first by ionizing the sphere supports, the helium gas that surrounds the sphere, and plastic windows at the ends of the cylinder.

The problem is that large periodic density variations, or waves, could develop in the first plasma. Such waves Going for the Goldreflect light, and although small waves are always present in a plasma, laser light can pump energy into them so they grow large enough to reflect all the laser light away from its original path.

Normally, a laser beam contains hundreds of bright points called "speckles" caused by the beam's constituent light waves interfering with each other. (The overlapping of the crests of two waves produces a speckle.) The ideal way to study how a laser beam interacts with a plasma is to first study how one of those speckles interacts with a plasma. Montgomery headed a small team from 1999 to 2007 to do just that. The more-realistic situation was later addressed by applying what was learned for one speckle to the hundreds of speckles in an actual laser beam.

In Montgomery's experiments, one Trident beam produced a single speckle, and a second beam produced a well-characterized plasma.

Before these studies, no one really knew, despite various theories, exactly how laser light can cause plasma waves to grow and how their growth can be stopped. These experiments have provided that understanding.

Want to Play?

Trident is ideal for exploring—on a smaller but scientifically useful scale—proton acceleration; laser-plasma interactions (see "Going for the Gold"); small, intense pulsed x-ray sources; and other concepts useful to X-Gamers, says Montgomery. Although larger facilities have more than enough power to pursue such studies, they lack Trident's beam quality and flexibility, which allow Trident to perform some high-energy-density physics experiments not presently possible at larger facilities. Larger facilities are also much more expensive to use. So it's productive and cost effective to explore interesting possibilities at Trident, even if the work eventually moves to another facility.

Trident is no secret in the scientific community. Researchers from around the world bring their experiments to the Los Alamos facility to take advantage of its quality and versatility, the hands-on research that can done there, and the opportunity to interact with Trident's resident scientists. This past summer, 27 proposals were received for access to Trident beam time during the first half of 2009, and more proposals were submitted in October.

So, if you're thinking about the X-Games, David Montgomery could be the guy to call.