Trailmaster: a new driver for fusion and x-ray lasers

Charles B. Stevens reports on the inexpensive and versatile new system under development at Los Alamos National Laboratory.

Los Alamos National Laboratory announced in early 1986 that the first stage of its Trailmaster electrical pulsed-power program had been successfully completed. According to the Trailmaster program manager, Dr. Charles Fenstermacher, this new technology represents a quantum jump in pulsed-power technology and will provide an extremely economical, quickly assembled, and highly versatile means of experimentally exploring a wide range of high-energy-dense processes, such as ignition of thermonuclear fusion reactions, creation of laboratory x-ray lasers, and laboratory-scale simulation of nuclear weapons effects.

Currently, high-energy, pulsed-power systems, such as the 100-trillion-watt Particle Beam Fusion Accelerator II (PBFA-II) light ion facility at Sandia National Laboratories and the 100-trillion-watt Nova laser fusion facility at Lawrence Livermore National Laboratory, cost from $50 to $170 million and take many years to design and construct. Trailmasters, specifically tailored to explore a particular high-energy-density regime, could be designed and built in a few months at a cost of a few tens of thousands of dollars per experiment.

The Trailmaster converts the cheap energy of chemical explosives into compressed, high-power pulses of electrical energy. The key to the system is an electrical circuit "opening switch," which makes it possible to compress an electrical current as much as 500-fold in time and space. In this way a billion-watt electric pulse can be amplified to a 100-trillion-watt power level. The electric pulse can then be tailored to drive myriad types of high-power devices, such as x-ray lasers and nuclear fusion reactors.

The switching science and technology being developed at Los Alamos, however, is applicable to a wide range of other pulsed-power systems. For example, the Trailmaster switching technology could be utilized in more conventional capacitor bank systems to vastly improve the range of high energy accessible to university laboratory facilities working on fusion plasmas, particle accelerators, and lasers. In other words, the Trailmaster program could lead to a general revolution in pulsed-power and high-energy R&D.

The technology of high energy density

Throughout history, high energy density has determined the frontiers of science and economic progress. The higher energy density of steam engines provided the means for reaping the bounty of deep-lying coal and mineral deposits and harnessing of metal-forming machines. And in this century, high energy density has unlocked the limitless energy potentials of the atomic nucleus.

In recent decades, the quest to realize thermonuclear fusion reactions has led to the exploration of plasmas. Plasmas represent a fourth state of matter—solid, liquid, and gas being the first three. When matter is raised to a sufficiently high temperature, its atoms break up into negatively charged electrons and positively charged ions. Because these constituents are electrically charged—unlike the relatively neutral atoms of an ordinary gas—plasmas are dominated by electric forces and the magnetic fields generated by the relative motion of charged particles.

Actually, the conventional states of matter found within the Earth's biosphere are quite rare in the cosmos at large. Most matter in the universe is in the plasma state, like that of the Sun and other stars.

Plasmas and switches

In the quest for higher energy densities, the plasma state offers virtually unlimited possibilities. The reason is that plasmas are held together by macroscopic electric and magnetic fields, while ordinary matter is characterized by limited chemical bonds. Intense electric and magnetic fields that would destroy the chemical bonds—and therefore integrity—of ordinary materials can improve the integrity of plasma configurations.

Besides withstanding much larger concentrations of energy, such as intense electric currents, plasmas can also be rapidly transformed into entirely new types of configurations. For exam ple, a plas
offers virtually no resistance to the flow of electricity, to one in which it suddenly becomes highly resistive.

The plasma focus research of Dr. Winston Bostick of the Stevens Institute of Technology in New Jersey provides an example. In the plasma focus device, large electrical currents are transported between two metal electrodes, via a series of spiral plasmas. The spiral plasmas, or plasma vortices, look like strings and are nested together to form a conducting surface between the metal electrodes. The microstructure of these strings is force free. That is, while extremely large electric currents are flowing through the plasma, and, therefore, large magnetic fields are present together with substantial fluid motion of the plasma itself, all of these different forces or "e nergy flo
do not interact.

This so-called Beltrami-type, force-free plasma configuration is quite similar in geometry to that seen in some superconductors, with the distinction that the plasma must be sustained at millions of degrees Celsius and the superconductor at near absolute zero temperatures. In both cases the force-free Beltrami configuration permits the conduction of electric currents with virtually no resistance.

Under the right boundary conditions, however—such as too high a level of electric current or change in the macroscopic geometry of the plasma vortex sheet—the individual vortices will unravel over extremely short time spans, lasting as little as a billionth of a second. The process is like that of a laser. The unraveling of one vortex can set off the destruction of another, and a chain reaction conflagration results.

With the sudden disappearance of the plasma channels that carried the electric current, the current flow between the two metal electrodes is rudely interrupted. The result is quite similar to that found when one attempts to stop an ocean wave with a simple vertical wall. Upon reaching the wall, the wave will compress and grow greatly in amplitude, concentrating its energy in the process. Similarly, with the disruption of the plasma vortex channels, the electric current pulse will be compressed and grow rapidly in amplitude.

One essential component of the Trailmaster program is to make use of such plasma switches to compress electrical currents many hundred times.

The Trailmaster configuration

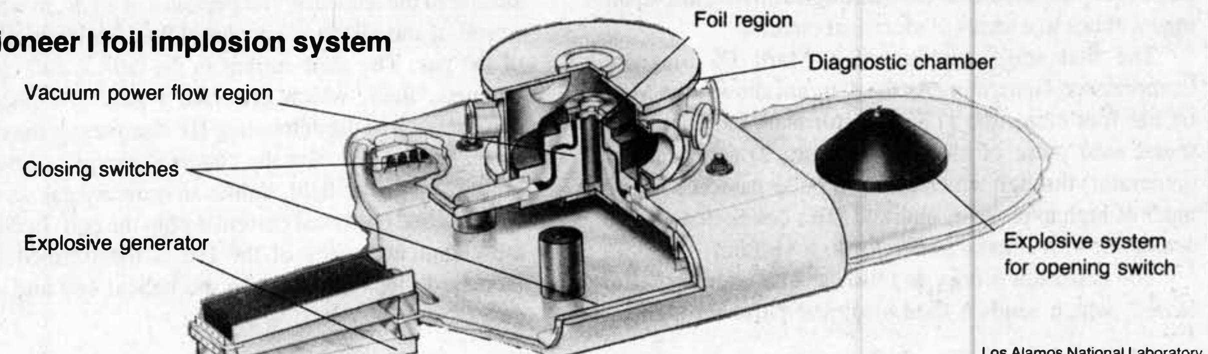
Figure 1 shows the experimental setup of the Trailmaster and **Figure 2** shows a circuit diagram. The process begins by storing an ordinary power level current pulse in the magnetic coil. Chemical explosives surrounding this coil and carefully configured into implosion lenses are then detonated. The implosion lenses compress the coil and its magnetic field. The degree of energy densification is simply given by the volume compression achieved.

This implosion process compresses the electric current that is generating the magnetic field in the coil, and in the process converts the explosive energy into electric energy. The result is a surge of current—a current pulse in the shape of a wave. By opening a switch at the appropriate time, this current surge can be transferred to a new electric circuit. And by properly tuning the elements of the two circuits and having a sufficiently fast opening switch, the current surge can be compressed, in the same manner as an ocean wave hitting a wall.

The dynamics of the chemical explosion and the geometry of the coil configuration limit the speed of compression that can be achieved in this manner. The time-scale characteristic of an efficient conversion of explosive chemical energy to electric current is on the order of 250 microseconds, about one-quarter of a thousandth of a second. The switching out of this current surge into a second circuit provides the means of further compressing the current to a pulse lasting about 500 nanoseconds (1 nanosecond is 1 billionth of a second)—about a 500-fold compression or power amplification.

The final current surge and its wave form—literally, the geometry of the wave—are essential parameters in the end

FIGURE 1
The Pioneer I foil implosion system



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use of the Trailmaster output. Because these characteristics can be readily adjusted by changes in the circuit tuning matchup, the Trailmaster makes an extremely versatile energy driver for a wide variety of devices.

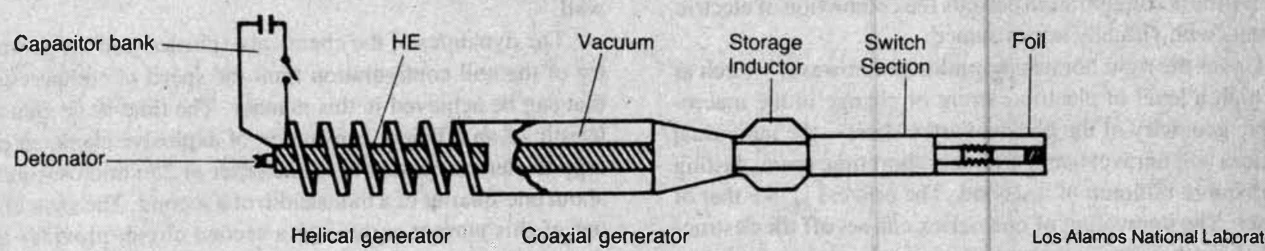
In its most simple form, the Trailmaster could be utilized to produce intense bursts of x-rays. This is accomplished by a second implosion process. The current is passed through a small cylinder made from a thin metal foil. The huge current rapidly transforms the foil into a cylinder of plasma. The intense magnetic fields generated by the current simultaneously exert an inward force on the foil plasma, which leads to its rapid implosion. Because the final compressed metal plasma reaches high densities when the foil implosion arrives at the axis of the cylinder, most of the kinetic energy of the foil implosion and magnetic energy is converted into heating the foil plasma to extremely high temperatures.

The result is a powerful, concentrated burst of x-rays produced by the hot, dense metal plasma. This x-ray source can be utilized to create the conditions for powerful x-ray lasers or for ignition of thermonuclear fusion reactions. The x-rays can also be used directly to simulate the effects of nuclear weapons. When nuclear weapons detonate, the sudden burst of nuclear energy that they release generates a plasma "fireball," whose chief energy output is in the form of intense x-rays.

When these x-rays irradiate satellites, missiles, or other systems, they generate electric currents along metal surfaces. These currents, in turn, generate electromagnetic waves on the interior of the satellite or rocket. This process is called system-generated electromagnetic pulse (SGEMP) and can easily destroy or, at least, disrupt the internal electronic controls of these satellites and missiles. System-generated electromagnetic pulse is among the most difficult threats to predict and protect against. The Defense Department's Defense Nuclear Agency currently must test satellites and rockets against system-generated electromagnetic pulse with expensive underground nuclear tests that cost from $10 to $100 million. Trailmaster would provide a laboratory-
for such tests at costs in the range of tens of thousands of dollars.

The main approach currently being pursued in inertial confinement fusion research, is that of x-ray-driven implosion. Laser pulses are converted into x-rays, which then irradiate a small pellet of fusion fuel. The x-rays are ideal for

FIGURE 2
Schematic of the Trailmaster system



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Trailmaster was conceived as a method to convert the cheap chemical energy of high explosives into compressed, high-power electrical pulses. This is achieved in two distinct stages. First, the chemical explosive energy is transformed into a pulse of electric current. Second, this pulse is compressed 100-fold, through utilizing fast-opening switches in a series of electrical circuits.

The first stage consists of a Mark IX Magnetic Compression Generator. As the diagram shows, the Mark IX has four elements: 1) a capacitor bank to generate an initial seed pulse of electrical current; 2) a helical coil (generator) through which the seed pulse passes; 3) a cylinder of high explosive, marked HE, connected with a detonator; 4) a coaxial generator in a vacuum.

The generator works as follows: The open switch is closed, which sends a seed electrical pulse through the helical coil. Simultaneously, the detonator is set off. As a result, the high explosives begin to explode, from right to left in the diagram. This explosion acts as a piston, compressing the helical coil into the coaxial generator.

The net result of this compression of the helical coil is similar to the adiabatic compression of a gas, in which the action of the piston is converted into the internal energy of the gas. The seed current in the helical coil creates a magnetic field, which acts like a gas. The piston-like compression of the detonating HE compresses the coil and its magnetic field. But the "internal energy" of the compressed magnetic field, unlike an ordinary gas, is seen in an increased elec current within the coil. In this way, the chemical energy of the HE is transformed into an increased electric current in the helical coil and coaxial generator.

symmetrically and efficiently burning off the outer layer of a fusion fuel pellet. This smooth "ablation" of the target surface leads to precisely the type of even compression, or implosion, of the interior of the fuel pellet to extreme densities needed for high-gain inertial fusion. The Trailmaster x-ray burst provides a much cheaper means of producing the same type of smooth pellet implosions, without the need for an expensive laser.

Nonlinear waveforms

These immediate applications of Trailmaster are only the beginning. The Trailmaster converts an acoustic shock wave, generated by the chemical explosive lens, into an electric pulse in a coil. The shape and parameters of the electric pulse can be tuned by both the circuit and the explosive lens design. The geometry and characteristics of the resulting current waveforms are not just those of a simple sinusoidal wave; a properly tailored waveform should be seen as something like a highly nonlinear soliton, or potential soliton. And just as the change in current in a plasma focus can lead to a dramatic change in the geometry and electrical properties of plasma vortices, the final Trailmaster current waveform can be tuned to produce significantly different physical regimes in the front end of the machine. For example, the waveform can be tailored to drive specially designed plasma pinches for fusion, or to generate charged particle acceleration, or to tune the x-ray output of specially designed cylindrical foils.

Energy, as such, is not just simply scalar. Its intensity and geometry determine entirely different physical regimes. This can most immediately be seen in the fact that simply irradiating material with long-wavelength infrared electromagnetic radiation does not directly lead to the generation of nuclear transformation, no matter how intense the irradiation, while short-wavelength gamma-ray electromagnetic radiation will induce nuclear transformations in a wide range of materials, at even extremely low levels of irradiation.

Trailmaster provides an economical, readily accessible and versatile means of exploring the widest range of high-energy, energy-dense physical regimes and will vastly expand the existing frontiers of basic science and applied technologies.

The time-scale for this HE compression process is minimally on the order of one microsecond. This means that the generated current pulse produced by the coaxial generator is at least one microsecond long.

The second stage of the Trailmaster, shown on the right of the diagram, consists of three basic elements: a short-term inductive storage unit; an opening switch section; a cylindrical metal foil.

The microsecond electrical pulse generated by the Mark IX is further compressed more than 100-fold, to an electrical pulse on the order of 10 billionths of a second in this second stage. First the Mark IX output passes into the short-term storage circuit. Then an electrical switch opens and connects this inductive storage circuit to a circuit leading to the cylindrical foil. Because the opening switch opens on a time-scale of billionths of a second, the inductively stored current is released in a pulse lasting billionths of a second.

This energy compression system is analogous to slowly filling a barrel with many buckets of water and then kicking the barrel over the edge.

The passage of the compressed current pulse through the cylindrical foil generates huge magnetic fields which cause the foil cylinder to implode. This self-induced magnetic compression accelerates the foil to hypervelocities. When the sides of the cylinder meet at the central axis, this kinetic energy is transformed into rapid heating of the foil atoms. A high-density, high-temperature plasma results. This in turn generates a powerful burst of x-rays.

Interview: Charles Fenstermacher

The current status of Trailmaster

Dr. Fenstermacher is director of the Los Alamos National Laboratory Trailmaster program. He was interviewed by Charles B. Stevens, director of fusion research for the Fusion Energy Foundation.

Stevens: What are the objectives of the Trailmaster Program, and where does it stand now?

Fenstermacher: The Trailmaster program is an attempt to apply high-explosive-driven flux-compression generators to the problem of converting that high-explosive energy into pulsed power, to drive a foil-initiated plasma implosion to produce an intense x-ray source. The goal of the program is to produce x-ray sources in the megajoule level, within a sub-microsecond time-scale. One of the rationales behind this is that the laboratory enjoys a unique capability in high-explosive-driven flux-compression generators. Once you have demonstrated the feasibility and the performance level of interest using high-explosive generators, then large capacitor banks can be considered for permanent facilities. For example, if we are talking about many megajoules of capacitor banks, the lead time, the construction, and the capital investment are substantial. Currently available high-explosive-driven flux-compression generators can be used to determine the feasibility and explore the limits of the technique. The rationale, therefore, stems from a capability that exists in the lab; the motivation is interest in very intense x-ray sources,