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, and the program is trying to explore the limits of what can be done using those techniques.

Stevens: Where do you stand now, in terms of going to a megajoule?
Fenstermacher: We have just completed the first five major tests—system integration tests. These tests were not designed to demonstrate output performance in terms of x-rays, but as proof-of-principle or shakedown tests to demonstrate that we could integrate the components that we have developed. These components include the generators, the fast-opening switches at high current, the power flow channel, the foil fabrication and handling, the diagnostics, and the modeling and predictive capability results.

These tests were designed to exercise all of these capabilities and bring them all together to demonstrate proof of principle, and to view them as an enabling test to demonstrate the capability in all of those areas, and to provide some design basis for the next step; and the next step is what we call a prototype megajoule system. Now, that doesn't mean that the next system will operate at a megajoule, it's a prototype for a megajoule system. The next step will probably take us up over an order of magnitude over the first series.

Stevens: Is the first series in the 5-10 kilojoule range?
Fenstermacher: The first series, called the Pioneer I, had five shots, fired in the first nine months of 1985. They ran with current in the 5-10 megaamp range; that's not delivered to a load, but what we've developed in the generator. What was delivered to the load was between 1 and 3 megaamps.

Stevens: At what sort of voltage?
Fenstermacher: The voltage isn't the important thing here. What's important is the power of the energy developed. The x-ray energy produced was about 15 kilojoules. So, that's a proof-of-principle test, an enabling test; it's the first integrated system test to put the diagnostics and the whole kit and caboodle together and demonstrate that we can design, predict the performance, field the experiment, and interpret the result. We got interpretable data on all of the tests, and in general, I can say that the systems we designed performed as expected.

Stevens: What is the chief bottleneck in going to the prototype stage?
Fenstermacher: There are a number of problems. In the prototype stage, we're looking for, say, an order of magnitude increase in energy output. Not that an output of that magnitude will be a record-setter; outputs of this magnitude have been achieved with capacitor banks at the Kirtland Air Force Weapons Lab.

Stevens: Do you mean the Shiva system, for example?
Fenstermacher: Yes, the Shiva Quick-Fire series using capacitor banks. Our program is an attempt to develop prototype systems base high-explosive-driven generato perhaps different kinds of opening switches. To come back to your question about what the key issues are here: For the next step, generators are in hand, generators have been developed in this laboratory that are fairly capable of developing the energy of interest on the time-scale of interest.

As for switching that energy out, we're taking three approaches. The first candidate is based on fast-acting fuses, and here our laboratory has made very significant advances. Fast fuses have been around probably for 20 years, and the data on them were more or less empirical, in the sense that people developed so-called handbook curves. These show changes of resistivity as a function of energy deposited in the fuse, without the details of the time-history or phase-space trajectory. By phase space, I mean density and temperature, or you could translate that into conductivity and time. Researchers had not looked into the detailed trajectory through phase space of a fuse. At this laboratory we had developed more detailed physical models of the fuses, using the equation state of the fuse, examining this a little more closely from a more fundamental standpoint. Based on this work, we are optimistic that we can find a region of phase space in which the fuse can be operated, which will do what's necessary to open up switches on the requisite time-scale.

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.

Stevens: Do you mean something on the order of a 500-fold compression?
Fenstermacher: Now we're looking at—and we're still developing this concept—whether we need one switch or two switches in series. In other words, if we want a compression from 100 microseconds (to use round numbers) down to half a microsecond—a factor of 200—we're not sure we can get that in one stage. Therefore,
binations of two-stage systems, to see if we can accomplish that with two stages with reasonable efficiency. The results of that study are not in yet. That's part of the development tests for this next stage, to look at the characteristics of these switches and how they can be used—either alone or in combination—to get compression of 200.

Of the candidates we have, one is a fuse, another is a high-explosive-driven plasma-compression switch, and the third is a rail-gun switch. We are now characterizing and evaluating each of these components, and we hope to make a selection of the most likely one in the next three to six months or so. Then we'll develop, design, and test that selection, and see if we can put a system together, and start its assembly within this next year. We hope to begin testing late this calendar year, if all goes well.

Stevens: What was the second candidate switch?
Fenstermacher: It's a high-explosive-driven plasma-compression switch, of the sort we used in the Pioneer I series. It's a plasma created by beginning with a very thin aluminum foil, about 2,000 angstroms thick, deposited on teflon. This conducts the generator current initially. Then when the time comes to cut that current off and divert it to another path, high explosives are used to compress the plasma and increase its resistivity an order of magnitude or more to close off that channel. Then another closing switch converts that current to the load. We've used that in planar geometry for the prototype megajoule switch.

Stevens: Is the idea to take a relatively long pulse of current and to compress it?
Fenstermacher: The Pioneer I series developed voltages on the order of 100 kilovolts in the power channel, and if you go up a factor of 10, we're talking about voltages in the 300-500 kilovolt range.

Stevens: Are you looking at a system that would be producing megajoule energies in the range of tens of terawatts?
Fenstermacher: Yes, maybe as high as 100 terawatts. That's what we'd certainly like. But the key here is that it isn't necessarily just the power; it's the power with the energy. In other words, with a laser you might produce 10 terawatts, but that's only a joule or two with ultra-short pulse; that's quite different.

Stevens: The Nova laser at Lawrence Livermore is in the range of 100 terawatts and 100 kilojoules in a nanosecond.
Fenstermacher: We're trying to get a source that would be 10 times bigger than that, without the capital investment, and with completely different characteristics from a laser source. It looks like a blackbody source. It's not a coherent radiation field and it's not directed as a laser.

Stevens: There have been a number of papers from Los Alamos on the possibilities of high-energy-dense fusion—such as in Z-pinches—in using intense particle beams, and so forth. Can you say anything about the potential applications?
Fenstermacher: We know that to drive fusion, we're talking about hundreds of terawatts, and this driver looks like a possibility to get into that range. This isn't being developed for commercial power generation, and it's not being developed to make toast 50 years from now. It's a single-shot device developed as a research tool, that will enable you to produce excited states of matter that cannot be produced easily by other means or, in fact, may not be able to be produced by other means in the laboratory.

Stevens: Is it possible to use the soft x-ray blackbody background to drive other types of radiation systems, to produce line radiation?
Fenstermacher: This would represent a laboratory-scale research source and you could use it to study fusion applications, basic physics, and possibly to study the pumping of x-ray lasers and spectroscopy, but in and of itself, it's not a device that would be engineered for applications.

Stevens: Is it a much more economical laboratory source than current methods?
Fenstermacher: It could be. For example, if we say we want to build a 20-megajoule or a 50-megajoule capacitor bank, that requires construction of a building, a long lead time, etc. If we started out today to build a large capacitor bank, we probably wouldn't have that on line for two or three years. We couldn't justify it at this point, because we don't have the results in hand. We do have the high-explosive generator, however. The high-explosive generator system—I'm not talking about the whole system, but just the power supply—might cost in the order of somewhere between $25,000 and $50,000. That's a lot different from a line item construction for a building, including the long lead time.

However, once we demonstrate this, using the high-explosive generators and the numbers turn out right, then we might say, okay, this is a useful laboratory tool and now we want to up the repetition rate. Let's see if we can replace the high-explosive generator with a capacitor bank. At that time, if one had a strong enough application for it, one could justify the capacitor bank, and say, let's start building a permanent installation as a large-scale source.

Stevens: You mentioned that there had been only apparently empirical sorts of relationships in the fuses. Do you think your studies on fuses in general and opening switches in particular will have an impact generally on the science of pulsed power?
Fenstermacher: Yes, I think that if the potential of fuses is realized, it will open the door for all kinds of power amplifications for pulsed power, including use of slow capacitor banks, for example, to provide high-peak power.

Stevens: So you are indirectly aiding university laboratories?
Fenstermacher: For anybody who wants to really develop high-peak power to transfer energy into a load very fast, this will hold great promise for them to get power amplification from a slow power supply.