Click here for Full Issue of EIR Volume 25, Number 40, October 9, 1998

Petawatt laser creates machine-tool revolution

Scientists have designed a tabletop laser so powerful and precise that it will revolutionize the machine-tool-design sector. Charles B. Stevens reports.

The fall of 1998 may be marked as the dawn of the Third Industrial Revolution, which will be further advanced early in the next millennium with the launch of the first interstellar, relativistic rocketship, and the demonstration of laser fusion. But, this fall, at the Y12 plant at Oak Ridge National Laboratory in Tennessee, the first true laser machine tool will go into industrial operation.

Not coincidentally, all three events will have been produced by the same group of scientists and engineers who are primarily working on the perfection of inertial confinement fusion at Lawrence Livermore National Laboratory, the University of Rochester, and other laboratories throughout the world.

The tabletop petawatt laser provides an exemplary case of the machine-tool-design principle enunciated by Lyndon H. LaRouche. The original application for which the petawatt laser (*peta* means 10^{15} or 1,000 trillion) was designed, was for aiding research and development of inertial confinement fusion energy (ICF). The petawatt laser is a new type of laser technology, and a new type of laser system. For ICF, the extremely powerful, though ultrashort pulse is designed to help ignite fusion fuel pellets.

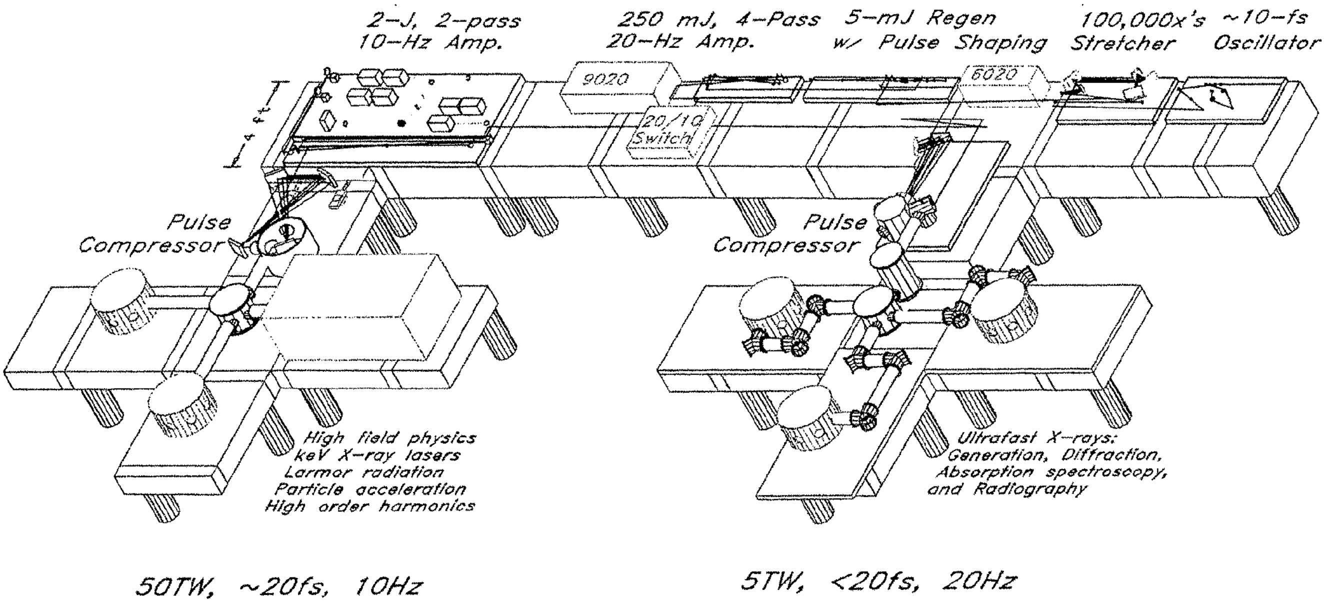
The tabletop petawatt laser (**Figure 1**) was already 10 times more powerful than the gargantuan NOVA laser system which generates a very high-energy pulse for compressing spherical pellets of fusion fuel: The idea is to have the petawatt pulse be delivered after the maximum compression of the fusion fuel pellet has been achieved. The high-power pulse would interact with the surface of the compressed pellet and generate high-energy electrons, or what are called "hot" electrons. The "hot" electrons could then penetrate to the center of the compressed pellet and ignite the cold, compressed fusion fuel to above the 100 million degrees centrigrade temperatures, which are required to sustain nuclear fusion of the hydrogen isotopes, deuterium and tritium. The energy output from the core region would spread outward and ignite the remaining fusion fuel in the pellet before the pellet blows apart. In this manner, a high-energy gain—that is, a much greater fusion energy output than the total energy input of the original laser pulses—could be achieved. In short, the tabletop petawatt laser was developed as a tool to take the National Ignition Facility (NIF), under construction with a completion date of 2003, well beyond its original gain specification. (The contrast in scale is remarkable: The existing Livermore NOVA laser system is on the scale of a modest arena, while the NIF, under construction, is on the scale of a large arena. The petawatt laser fits on the top of a few tables.)

Thus, this new tool would demonstrate a new scientific concept: fast ignition with hot electrons.

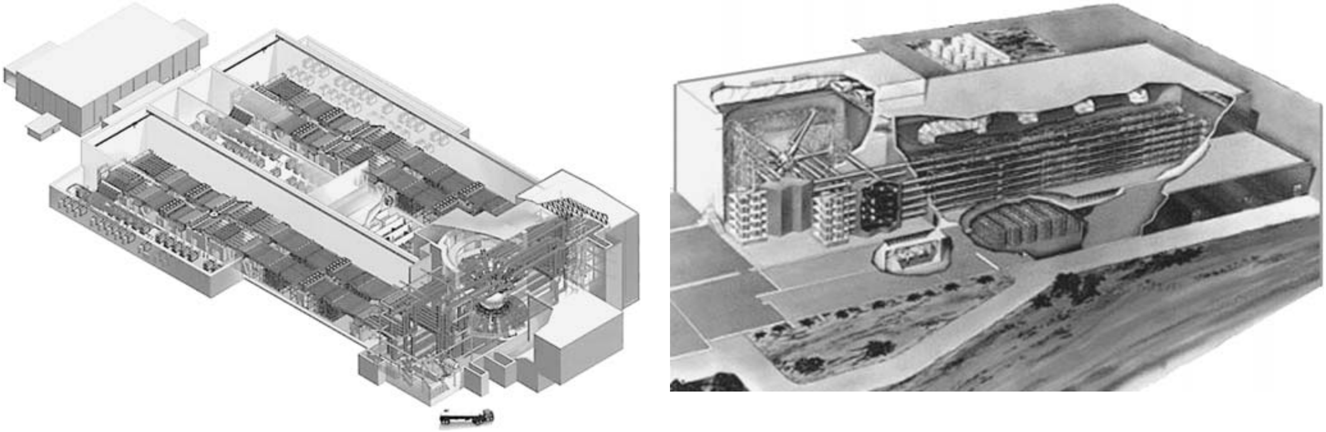
However, the petawatt laser has now demonstrated a new type of interaction with matter, leading to the development of an entirely new type of machine tool for industry, allowing that technology to proliferate throughout the economy. Because the petawatt laser manifests new interactions between light and matter, it is already revolutionizing many fields of scientific research other than inertial confinement fusion, and its use is spreading rapidly, primarily because of its small size and relatively small cost, which makes it accessible to a wider range of researchers. Already the petawatt laser has produced novel physical conditions in combination with high-energy particle accelerators. Last year, scientists working on the

FIGURE 1

Comparison of laser facilities



The diagram (above) shows the petawatt laser system, which can fit across a few table tops. By comparison, the National Ignition Facility laser (bottom left), under construction, is the size of a large arena. The artist's conception shows a truck parked next to the NIF to indicate the scale. The existing Livermore laser system, also shown as an artist's rendition, is about the scale of a modest arena.



Stanford Linear Accelerator (SLAC) were able to "spark" the vacuum and generate matter directly from the vacuum—that is, pairs of electrons and antimatter positrons—when the SLAC beam was combined with a powerful pulse from the petawatt laser. It is already projected that the ultrashort-pulse petawatt laser can be combined with an upgraded SLAC to generate energies in excess of 10 trillion electron volts. This will create conditions for entirely new types of physical interaction at the frontiers of science.

Over the last decade, laser intensities have been increased by more than a factor of 10,000 to attain power densities of greater than 10^{20} watts per square centimeter (see **Figure 2**). The electric field strength at these intensities is on the order of a trillion volts per centimeter. This is 100 times the electric field that binds electrons into their orbits within the atom. And at these intensities the light pressure is up to 1 trillion times that of one atmosphere. The physical conditions generated are either found only in the interior of stars or even denser astronomical singularities.

How the petawatt laser works

The petawatt laser was first realized through the work of D. Strickland and G. Mourou, who were then working at the University of Rochester Laboratory for Laser Energetics, the

FIGURE 2

Peak power reached by lasers, 1974-2002

(in terawatts)

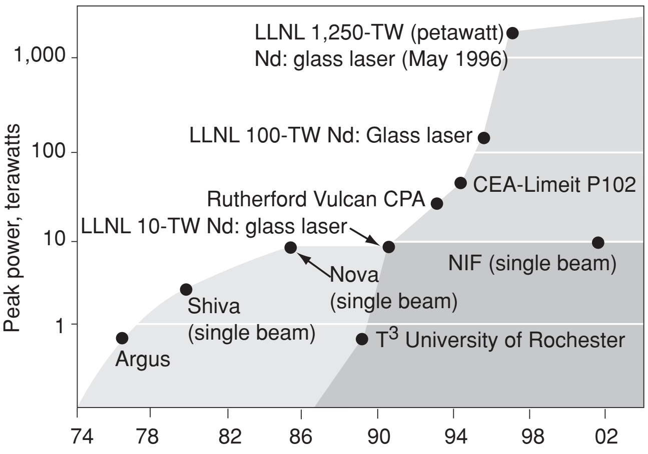
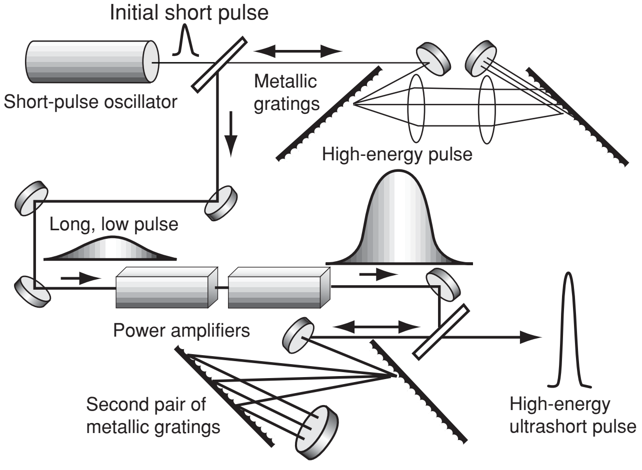


FIGURE 3

How the short-pulse petawatt laser works



The short pulse originates from a titanium-sapphire laser oscillator that produces a broadband initial short pulse. Mirrors deflect this initial pulse to metallic diffraction gratings which stretch it out into a long, low-energy pulse. One set of mirrors deflects this stretched pulse into broadband power amplifiers, which produce the high-energy pulse. A second set of mirrors deflects this pulse into a second pair of metallic diffraction gratings, which compress the high-energy pulse into a high-energy ultrashort pulse. A plasma mirror is then utilized to focus this final pulse onto a target.

second major laser fusion laboratory in the United States, located in New York. Strickland and Mourou applied a technique that had been originally utilized in pulse amplification of radar outputs and in compression of telecommunication transmissions: chirped-pulse amplification (CPA). In May 1996, scientists working under Michael Perry at Lawrence Livermore National Laboratory succeeded in perfecting this CPA proceedure to produce the first petawatt laser pulse. This was 10 times greater than the output of the giant Livermore NOVA laser fusion system.

As shown in **Figure 3,** the first step is to generate a low-energy, broad-band ultra-short laser pulse from a solid-state titanium sapphire laser. This pulse is as coherent as ordinary monochromatic laser pulses, but it consists of many different wavelengths—that is, many colors. This is what makes the pulse broadband. The pulse is then passed through a diffraction grating, which breaks the pulse up into its various colors, just as a prism does with white light. Each of the colors of the pulse then travels a separate path of varying length. The pulse is reflected off a second grating and an elongated version of the original pulse is thereby generated. The "stretcher" action increases the pulse length by a factor of roughly 10,000. The elongated pulse is then passed through a broadband solid-state series of amplifiers, in which process the energy of the pulse is increased by as much as 100 billion times. The pulse is then passed through a second series of gratings in which the colors are recombined in space and time to regenerate the original length pulse, but at 100 billion times greater energy.

Once this new level of power density was achieved by the petawatt laser development team, they faced a major hurdle with respect to how to generate optical materials that could withstand the new power density, so that the beam could be focussed. This problem was solved by the development of a radical new approach developed by Michael Perry and Livermore Associate Director at Large John H. Nuckolls. (Dr. Nuckolls is the father of laser pellet fusion. Beginning in the 1950s, he pioneered the work upon which today's inertial confinement research is based.)

Dr. John H. Nuckolls

The new approach to optical mirrors was based on utilizing a plasma for the mirror. The plasma could withstand the 700 billion watts per square centimeter of the petawatt laser beam. In practice, the first part of the petawatt laser pulse generates a short-lived dense plasma, when it encounters the surface of a polished glass mirror. And just as the Earth's ionospheric plasma will reflect radio waves of the right wavelength range, the petawatt laser's short-lived plasma has sufficient density to reflect the laser pulse. Because the pulse is so short, the plasma does not have time to expand during the remainder of the main body of the pulse which is reflected. (Besides reflecting this higher power density, the short-lived plasma protects the remaining mirror surface and other delicate optical and diagnostic instruments down the line, which could be damaged by radiation generated when the petawatt laser pulse hits a target.)

This breakthrough in optics indicates that those who criticized the original Strategic Defense Initiative in the 1980s, may have underestimated the potential for plasma "optics" in the case of the X-ray laser.

Using lasers in machining

Machining with conventional lathes and machine tools is limited to cuts down to 100 microns width at depths on the order of one millimeter. Below this level, laser and

LaRouche explained 'tuning' lasers in 1983

The following are excerpts from a presentation by Lyndon H. LaRouche, Jr. to a Washington, D.C. conference of the Fusion Energy Foundation, on April 13, 1983. The full text appeared in EIR, *April 26, 1983.*

It is true that many voices, such as the *New York Times,* insist that this is all unworkable "star wars" technology; it should be remembered that the *New York Times* said the electric-light bulb should not be developed, and that people of the same views said such silly things as that it would be ten years after World War II before the Soviet Union could develop a fission-weapon, and that thermonuclear fusion was impossible. Others say this is all music of the future, no earlier than 20 years ahead. In some cases, they could know the facts, but refuse to discover those facts; in other cases, even among some professionals, they are sincerely ignorant of some basic principles of Riemannian physics. We limit our brief discussion of the point here to the case of lasers and both the military and civilian-economy feasibilities involved.

There are two broadest relevant features of lasers and laser-like systems. First, if we concentrate even a fairly small quantity of wattage on a sufficiently small area, the concentration of energy, which we call its energy-flux density, can be made sufficient to "boil," so to speak, any material. This much seems to be explainable in terms of widely acceptable theory of heat; the second principle can not be so explained. Second, lasers have a property which is sometimes called "self-focusing." This is described more accurately by reporting that each range of the upper electromagnetic spectrum has very distinct qualities of harmonic resonance. In one case, this focuses the energy on the molecular scale, in another the atomic scale, in another the nuclear scale, and in higher ranges, the subnuclear scale. To cause a laser to work as desired, one must tune the laser to monochromatic frequencies such that very little of the laser's beam is absorbed by the medium through which it is transmitted, and the beam is tuned at the same time to the part of the spectrum of matter of the target selected. Thus, what is called "self-focusing" of lasers at the point of contact with targets, is actually a reflection of the indicated harmonic-resonance principles.

There is a precise analogy for this from *bel canto* methods of singing. A master of *bel canto* methods should be able to break a glass, but at the same time, the singer's breath will not disturb the flame of a candle in front of his mouth.

By aid of these self-focusing properties of lasers and laser-like particle-beams, we are able, in effect, to concentrate the wattage of a beam into areas measurable, in some instances, in fractions of Angstrom units. No material can withstand such impact for even microseconds. . . .

The principles governing the way in which a coherent, directed beam does work on its target, are, most immediately, the principles defined by Bernhard Riemann's 1859 paper, "On the Propagation of Plane Air Waves of Finite Magnitude," Riemann's proof of Leonardo da Vinci's earlier definition of the hydrodynamic generation of acoustical shock-waves. The principles of this 1859 paper apply not only to such things as the "sonic boom" of a supersonic projectile; they are a universal principle of action in our universe, a principle which the Soviet literature terms "Riemann waves.". . .

If we examine the kinds of processes which lasers and laser-like beams involve from any standpoint but Riemann's, progress in this field is not altogether impossible, but is very cumbersome, and is a succession of fits and starts, as one attempts to interpret the phenomena by varieties of mathematical-physics doctrines which are not the most appropriate for this work. From Riemann's standpoint, the whole domain is wonderfully simple to understand. . . .

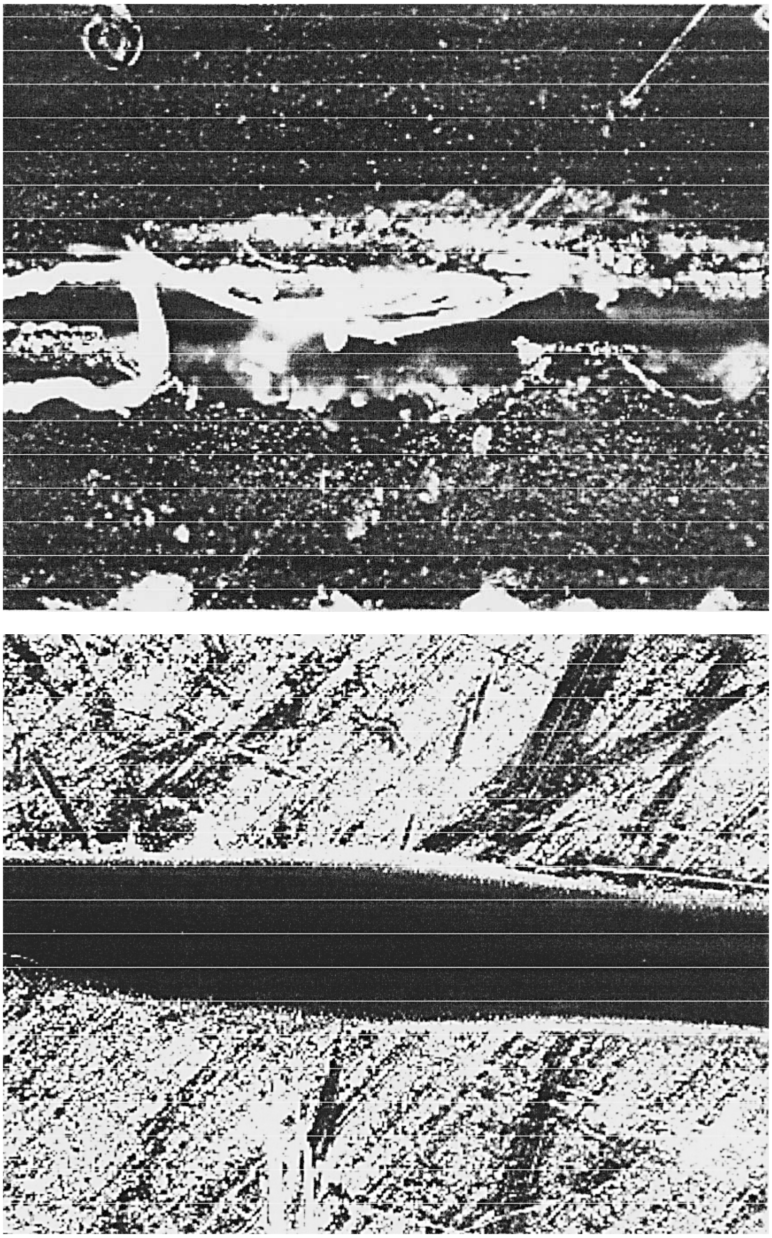
electron beam tools are utilized for high precision work. Electron beam and laser industrial technologies now in use remove material by a thermal process, where the material to be removed is heated to the melting or boiling point. With a few specialized materials, more efficient molecular dissociation of materials can be achieved with excimer lasers, but this photodissociation mechanism does not work with metals.

With conventional lasers, i.e., with longer pulses, energy is deposited from the incident beam in the material in the form of heat, that is, lattice vibrations. The absorbed laser energy therefore generates a rise in temperature at and near the absorption site, resulting in melting or boiling as temperature increases. Material is then removed by conventional melting or vaporization. In some materials, this temperature rise can be very fast, which results in the generation of ablation and shock waves passing through the material. The thermal and shock effects result in an actual change in the grain structure or even in the composition of the material in the area of the cut. The affected zone can range from a few microns to several millimeters. A concomitant drawback to conventional laser machining is that material is redeposited or resolidified on the workpiece. In most high-precision work, the presence of slag is unacceptable.

With the development of even shorter pulse systems, down to the femtosecond level (10^{-15} seconds), a new interaction with matter was observed. This new type of "cold" ablation offers a major advance over conventional machining. With these ultra-short pulses, absorption of the laser energy occurs with virtually no heat transfer to the surrounding material, which generates a "cold" laser-cutting process, as distinct from the thermal processes generated by laser pulses longer than 10^{-11} seconds, in which the cutting process first melts and then vaporizes the material, with significant transfer of heat to the material outside the cutting region. And unlike the chips and flakes generated by ordinary machine tools and long-pulse laser cutting, the short-pulse laser method, for the most part, generates only solid carbon or benign gases, which can either be released into the air or captured.

FIGURE 4

Comparison of 'hot' versus 'cold' laser machining



Shown here are top views of "hot cut" (top) and "cold cut" (bottom) stainless steel. The "hot cut" stainless steel was cut with a conventional 1.053 micron laser, operating at a pulse length greater than 1 nanosecond. The presence of resolidified molten material, which is called slag, and poor single-pass cut quality, indicative of laser cutting by conventional methods, is readily apparent. The "cold cut" stainless steel was cut with a 350-femtosecond pulse laser, and the edges are obviously clean.

Livermore experiments showed that as one proceeds to shorter and shorter laser pulses, there is a transition from the thermal mode of energy transfer to a new mode of energy transfer, which is characterized by collisional and multiphoton ionization and the formation of a highly organized plasma. Once formed, the plasma protects the remaining material at the site of the laser cut, because it reflects any further incident laser light during the short pulse. (The plasma dissipates very rapidly and thus allows further pulses to act on the material.) Heat transfer to the lattice of the material being cut does not occur, since the laser pulse is less than or equal to the shortest period of the highest frequency lattice vibrations.

In experiments with metal, it was found that the short laser pulse does initially produce joule heating as the electromagnetic fields of the laser pulse diffuse into the metal up to the "skin" depth expected. But the formation of the short-lived plasma sheath above the material stops this diffusion and reverses it. For pulses in the range of 100 to 150 femtoseconds, there is virtually no heat energy transferred to the metal.

The Livermore experiments report that, typically, each laser pulse removes a few microns of material. The pulses can be readily generated in rapid fire, thousands of times per second. This means that the cutting process is fairly rapid, while at the same time being "cold": There is no significant transfer of heat to the material being worked (**Figure 4**).

A wide range of materials has been tested with this new laser machine tool. Diamond, for example, does not absorb light at the wavelength of the petawatt laser, 0.82 microns. But the beam intensity is sufficient to produce charge carriers by multiphoton processes, which leads to the generation of other carriers by an avalanche breakdown process in the strong electric fields of the laser pulse, and thus a plasma is formed. The result is efficient and accurate cutting of diamonds. A range of metals were successfully cut, as were semiconductor materials.

Many biological materials, such as tissue, bone, cartilage, and teeth have also been successfully machined. The laser machine tool holds great promise for some medical procedures, such as painless removal of dental cavities, and laser angioplasty. (Previous attempts to use lasers in angioplasty have led to pieces of plaque being broken off, threatening to cause clots in blood vessels.)

The first industrial-scale application of the new Livermore femtosecond laser machine tool will be to disassemble weapons containing high explosive materials—old nuclear weapons, and biological and chemical warheads and shells. With more conventional laser cutting and machine tools, these materials are very unsafe, and can easily be ignited by subsidiary heat and shock. The new femtosecond laser machine tool ideally solves these problems. And, because of its accuracy, in many cases, parts that have not suffered wear and tear can be reutilized.

Another immediate application of the femtosecond laser is for generation of cooling ducts in turbine blades. Whereas current machining methods introduce damage and imperfections into the turbine blades, thereby decreasing their strength and limiting the temperatures and speeds at which they can operate, the new Livermore laser system could revolutionize turbine blade design and manufacture.

LaRouche-Riemann model vindicated

Livermore's success with the first effective laser machine tool is a resounding confirmation of the LaRouche-Riemann method for physical economy, which was the basis for Lyndon LaRouche's concept of a ballistic missile defense system, and which underlay the strategic doctrine announced by President Ronald Reagan, the Strategic Defense Initiative (SDI).

In 1982-83, when LaRouche was organizing for the Reagan administration to implement his missile defense strategic policy, even LaRouche's closest scientific and technical allies in the government objected to LaRouche's projections that a technological revolution would be engendered by the development of the same laser, directed-energy beams, and "new physical principles" designed to make nuclear missiles "impotent and obsolete."

During this period, 1982 and early 1983, many meetings were held with National Security Council staff in the Old Executive Office Building, during which a major topic of debate was LaRouche's specification that an SDI would constitute a science-driver for the entire U.S. economy. By sparking new technologies and new production methods based on new physical principles, the military SDI program would more than pay for itself, through spin-offs in the civilian economy, according to LaRouche. A major example put forward by LaRouche was the utilization of the laser as a machine tool.

For example, Dr. Ray Pollock, a National Security Council specialist on missile defense and a former Los Alamos National Laboratory scientist, joined other government scientists in taking the role of devil's advocate, and strongly objected that all of the extant technical facts indicated that such diffusion into the civilian economy—such as with laser machining—was "unrealistic." In the case of the laser, they argued, the primary means of energy transfer was heat. This meant that, while the laser could possibly be useful as a spot welder or rough cutter of metal sheet, it could not compete with the efficient and accurate removal of material that was achieved with existing machine tools. The scientists putting forward this pessimistic analysis were the world's leading laser scientists.

Yet, now with the realization of the Livermore short-pulse laser machine tool, LaRouche has been fully vindicated. And he would have been vindicated far more quickly, had his SDI science-driver policy been fully implemented in the 1980s. Instead, the Fusion Energy Foundation, which LaRouche had founded in 1974 and which had worked on the strategic policy for ballistic missile defense since 1979, was illegally shut down—along with several other LaRouche-associated groups—by the Justice Department "permanent bureaucracy" in 1987. LaRouche's enemies then had him sent to prison for five years in 1989.

The Livermore breakthrough with ultrashort-pulse petawatt lasers demonstrates LaRouche's machine tool principle in practice and will hopefully open the minds of researchers to LaRouche's unique comprehension of Riemannian physics.