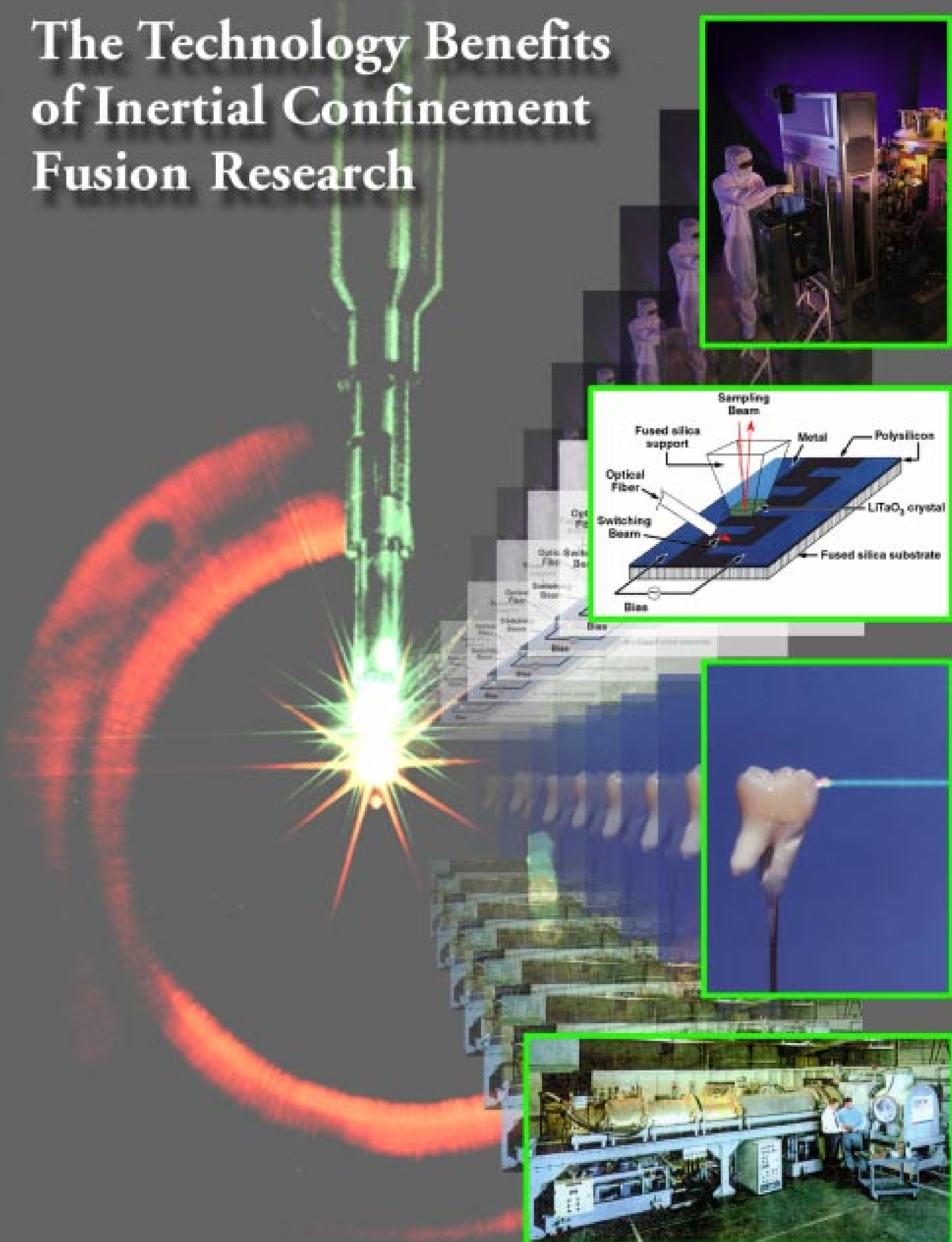
The Technology Benefits of Inertial Confinement Fusion Research



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On the cover

Photograph of a laser-irradiated target with overlain examples of spin-off technology.

From top to bottom: The ICF program has a long history of providing spin-off technologies to other fields. The prototype system shown here will be used in extreme ultraviolet lithography development for the manufacture of semiconductor circuits; electro-optic sampling circuit used to measure subpicosecond electrical pulses; short-pulse laser removal of dental caries; and repetitive pulsed power drivers for commercial ion-beam surface treatment.

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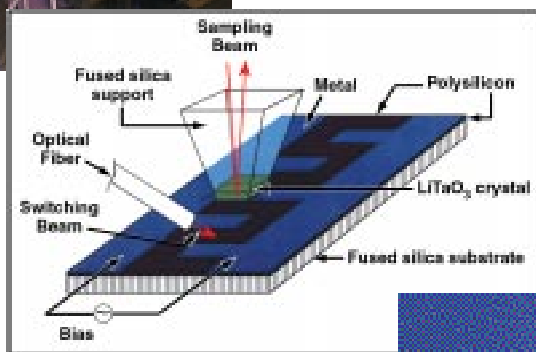

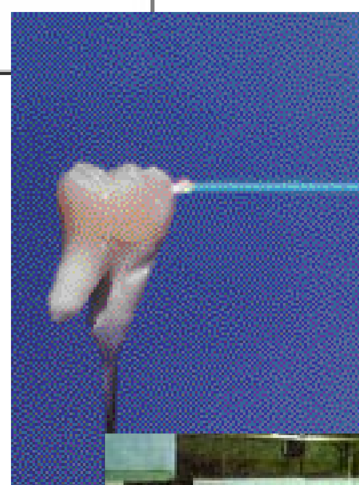

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Inertial Fusion Technology Spin-Offs—History Provides A Glimpse of the Future

Introduction

The development and demonstration of inertial fusion is incredibly challenging because it requires simultaneously controlling and precisely measuring parameters at extreme values in energy, space, and time. The challenges range from building megajoule (10^6 J) drivers that perform with percent-level precision to fabricating targets with submicron specifications to measuring target performance at micron scale (10^{-6} m) with picosecond (10^{-12} s) time resolution. Over the past 30 years in attempting to meet this challenge, the inertial fusion community around the world has invented new technologies in lasers, particle beams, pulse power drivers, diagnostics, target fabrication, and other areas. These technologies have found applications in diverse fields of industry and science. Moreover, simply assembling the teams with the background, experience, and personal drive to meet the challenging requirements of inertial fusion has led to spin-offs in unexpected directions, for example, in laser isotope separation, extreme ultraviolet lithography for microelectronics, compact and inexpensive radars, advanced laser materials processing, and medical technology. The experience of inertial fusion research and development of spinning off technologies has not been unique to any one laboratory or country but has been similar in main research centers in the United States, Europe, and Japan.

Strengthening and broadening the inertial fusion effort to focus on creating a new source of electrical power (inertial fusion energy [IFE]) that is economically competitive and environmentally benign will yield rich rewards in technology spin-offs. The additional challenges presented by IFE are to make drivers affordable, efficient, and long-lived while operating at a repetition rate of a few Hertz; to make fusion targets that perform consistently at high-fusion yield; and to create target chambers that can repetitvely handle greater than 100-MJ yields while producing minimal radioactive by-products. Meeting these challenges will produce spin-off value of enormous magnitude. By exploring the technology spin-offs of the inertial fusion community to date, we can glimpse the expected future rewards from an IFE program as well as the DOE Defense Program's ongoing inertial fusion efforts.

The information in this document has been collected from inertial fusion colleagues around the world, including various individuals at the University of Rochester—Laboratory of Laser Energetics (LLE), Lawrence Livermore National Laboratory (LLNL), Osaka University—Institute of Laser Engineering (ILE), Rutherford Appleton Laboratory—Central Laser Facility (CLF), Sandia National Laboratories (SNL), Lawrence Berkeley National Laboratory (LBNL), and Los Alamos National Laboratory (LANL).

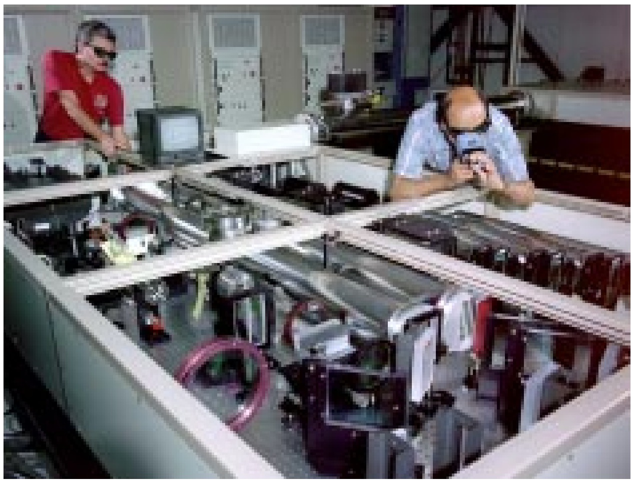
The technological spin-offs are divided into the following categories: laser and pulsed power engineering; optics, materials, and manufacturing; diagnostics and instrumentation; semiconductor manufacturing; and medical technology. Laser and pulse power engineering spin-offs flow directly from inertial fusion driver developments. Materials and materials processing spin-offs have naturally occurred because improved materials are fundamentally enabling for inertial fusion as well as for many other fields. Including optics in this group recognizes the fact that optical materials and manufacturing are increasingly becoming enabling technologies of the 21st century. Spin-offs in diagnostics and instrumentation largely derive from the challenging measurement of target phenomenon. Spin-offs in semi-conductor and medical technology have arisen from numerous areas and simply from the creativity and breadth of view of individuals working in target and driver technology.

One measure of industrial spin-off value in the United States is the R&D 100 Awards, which some have called the "Oscars of applied research." Members of the inertial fusion community have been highly successful in winning these awards presented for the most technologically significant products each year. A table at the end of the document describes more than 40 R&D 100 Awards that have been received by members of this community over the past 30 years. Another measure of spin-off value, and arguably the most important, are companies that were founded or were greatly enhanced based on inertial fusion technology developments as described throughout this paper.

Laser and Pulse Power Engineering

Since the early 1970s the primary lasers used for inertial fusion research have been based on flashlamp-pumped Nd:glass. Megajoule-class fusion ignition facilities utilizing this technology are now under construction in Livermore, CA (National Ignition Facility) and in Bordeaux, France (Laser MegaJoule). Laser design improvements and simulations to increase the output energy, power, precision, beam quality, and flexibility of solid-state lasers has been a focus of the inertial fusion laser community for many years. The community has made fundamental contributions to the laser field with improvements in the laser-damage threshold of optics, spatial filtering and optical relaying to minimize beam modulation, methods for nonlinear frequency conversion to produce ultraviolet laser beams, diffractive optics to sample and manipulate beams on target, and beam smoothing to reduce laser speckle in a time-integrated sense. The fusion community has driven the physics understanding of high-power laser beam propagation, which has had applications in fields ranging from military lasers to fiber-based telecommunications.

Gas lasers, particularly KrF excimer lasers, have also been used for inertial fusion research. KrF, which operates directly at 0.25 μm in the ultraviolet, has had the advantage of readily producing a broad-bandwidth, smooth beam on target as developed at the Naval Research Laboratory for inertial fusion research. High-energy versions of this laser require improvements in pulse power technology, discussed below, as well as in the damage threshold of ultraviolet optics, which have broad applications. It is notable that the direct output of smaller-scale KrF lasers based on discharges (manufactured by Cymer Lasers in the United States) are currently being used in state-of-the-art semiconductor lithography via short-wavelength, high-resolution imaging of masks.



A zig-zag slab Nd:glass laser producing 60-J green output at <2x diffraction limited at 3 Hz for Advanced Imaging Testbed experiments by the Air Force. This technology is also used for laser peening.

Two major solid-state laser design innovations coming directly from or greatly enhanced by inertial fusion laboratories have been zig-zag and short-pulse lasers based on chirped pulse amplification (CPA) lasers. The parentage and early development of zig-zag and CPA lasers have been strongly connected with both LLE's and LLNL's inertial fusion programs.

Solid-state zig-zag lasers, invented at General Electric Corporation, are designed to increase the average power of solid-state lasers by using thin slabs of gain media rather than rods to provide effective cooling while providing large beam area to produce high-output power. They utilize a totally internally-reflecting zig-zag beam path to average out phase distortions and produce a high-quality beam. Both LLNL's and LLE's laser teams have developed zig-zag lasers for kilowatt-class industry and military applications (x-ray lithography and laser peening are discussed below). The LLNL group added the important feature of stimulated Brillouin scattering phase conjugation to produce diffraction-limited high-power beams. The former director of LLE and several staff formed Hampshire Instruments, which attempted to develop an industrial tool for contact x-ray lithography of microcircuits by specifically applying phase-conjugated zig-zag laser technology to produce x-rays. The use of laser-produced plasmas to produce keV x-rays capable of producing extremely fine feature sizes was itself an invention coming directly from LLE in 1983. LLNL's laser program has recently delivered a multibeam laser based on flashlamp-pumped zig-zag laser technology that is being used by the Air Force Research Laboratory for advanced imaging of satellites. Interestingly, zig-zag laser technology is now spinning back into the inertial fusion field where such lasers are finding application at LLNL for damage testing of National Ignition Facility (NIF) optics and at ILE in Japan where they are being pursued as a possible high-power laser drivers for inertial fusion energy based on laser diode pumping.

The technique of CPA, originally used for the generation of intense microwaves pulses, was first developed for solid-state lasers by Mourou and coworkers at LLE in 1985. It is now used in nearly all high-power ultra-short pulse lasers and has revolutionized the ultrafast science field. The general concept is first to stretch a short pulse in time by dispersing its frequency components, to amplify this much-longer "chirped" pulse to high power avoiding undesired nonlinear effects, and finally to recompress the pulse in time at the output using a pair of gratings. The CPA technique has allowed "tabletop terawatt (T^3)" laser systems that produce relevant power densities for inertial fusion research without investing in large laser systems. The largest-scale application of CPA technology was the demonstration of a Petawatt laser by Perry and colleagues at LLNL in 1996 for applications ranging from making MeV x rays for dense object radiography to researching new approaches to inertial fusion. By using the broadband laser material, Ti:sapphire, relatively simple femtosecond lasers can be used to create and probe ultrashort events with femtosecond resolution for diverse scientific applications. A recent application of a high-power Ti:sapphire CPA technology is the generation of deuterium-deuterium fusion neutrons on a tabletop by Ditmire and coworkers at LLNL. To satisfy the scientific user community, high-power CPA lasers are now being sold by several companies in the United States and Europe (Positive Light, Clark, and Thompson). Several efforts are underway to increase the average power of CPA lasers specifically for femtosecond materials processing as discussed in the next section.

Scientist inside the Petawatt vacuum compression chamber at LLNL, which is used to compress a nanosecond-duration spectrally chirped pulse to less than one picosecond in duration. This temporal compression is performed by a pair of meter-scale gratings, one of which is seen on the right. The development of chirped-pulse-amplification laser technology has led to several industrially important spin-offs.

Recently the solid-state laser driver community for inertial fusion has been turning toward diode-pumped solid-state lasers (DPSSLs) as the preferred technology choice of the future. DPSSLs offer compactness, efficiency, and long life by using high-power semiconductor laser diodes. The present price of laser diodes limits the scale of the systems in which they can be practically used. Nonetheless, the regenerative amplifiers of the NIF, which provide the preponderance of beamline gain (from nanojoules up to millijoules), utilize this technology. DPSSLs are a spin-back into inertial fusion from Department of Defense (DoD) and commercial developments, which have their roots in inertial fusion in the 1980s. For example, the NIF utilizes lens ducts for delivering laser diode power, which were invented at LLNL originally for non-ICF uses and later commercialized by VLOC, a division of II-VI Corporation. Similarly in Japan, the inertial fusion effort at ILE has developed laser diodes and microlens delivery systems for welding, cutting, and drilling that have been transferred to Nalux Corp. and Hamamatsu Photonics. Hamamatsu and ILE are now working closely together on the development of DPSSLs as eventual drivers for fusion energy.

The large-scale applications that will drive the price of high-power laser diodes into a commodity market have yet to be established. Such military or industrial applications, when they occur, will also be enabling for DPSSLs as fusion energy drivers. It is worthwhile noting that diode lasers are a backbone component of the 1.5-μm wavelength fiber telecommunication industry in which they are currently more than a $1 billion dollar annual market. DPSSLs are currently used for materials processing lasers operating at kilowatt power levels being marketed by TRW in the United States and Rofin Sinar in Germany. Similar DPSSL systems are now in development at Mitsubishi, Toshiba, and several other companies in Japan. However, the first very large-scale application of high-power DPSSLs is likely to be for military use. LLNL, under U.S. Army support, is now beginning development of DPSSLs for point defense against tactical missiles. DPSSL development for defense against strategic missile attack is now being actively discussed by the Air Force and others. It is relevant that the $1.2 billion Airborne Laser now under construction for the Air Force utilizes DPSSLs for illuminating and tracking missiles, which are then engaged by more highly developed chemical gas lasers.

A heat capacity laser testbed using flashlamps as a surrogate pump source operated to investigate beam quality limits. A 100-kW diode-pumped prototype is being developed for the Army's High Energy Laser Strategic Test Facility.

The development of pulse power drivers for inertial fusion has had an equally strong effect within its broad community. The development of pulsed power capability for inertial fusion applies to the DoD where hardening military electronics against the radiation produced by nuclear blasts has been a major concern. This technology also applies to National Aeronautics and Space Administration and the space community where hardening of space probes and satellites against solar and cosmic radiation is also a strong concern. Broadening beyond their ICF developments, SNL has developed Repetitively Pulsed High-Energy Pulse Power (RHEPP) systems in which large time-integrated x-ray doses can be generated. RHEPP technology has been applied to food sterilization, demilitarization, decontamination of chemical and biological weapons, elastomer processing, and for adding enthalpy to simulate hypersonic flow in wind tunnels. Quantum Manufacturing Technologies, Alameda Applied Sciences, and Megapulse, Inc. have all benefitted directly from SNL's work. This technology is now spinning back into the inertial fusion community where the Naval Research Laboratory (NRL) is applying the RHEPP developments to the Electra electron-beam-pumped KrF laser now under development specifically for application to IFE.

Repetitive pulsed power drivers for commercial ion beam surface treatment at SNL.

As in the laser community, small, compact pulse power sources have also been developed having industrial applications such as x-ray sources for microelectronics lithography and generating ion beams that provide surface treatment of metals and ceramics. The pulse power codes developed at Sandia within the inertial fusion program have found various industrial applications. The code QUICKSILVER has been used for commercial microelectronics packaging design of high-speed network chip packages and for cell phone memory interconnects. It is currently licensed to the Centre D'Etudes, Gramat (CEG), France; NRL; and the Universities of Arizona and Illinois. The codes SCREAMER and ATHETA have been licensed commercially for the design of repetitive pulse power accelerators to Quantum Manufacturing, NRL, CEG, and several other corporations. The three-dimensional hydro code ALEGRA is now being used for shock physics and structural response calculations for high-stress radiation environments and high-velocity impact environments (such as satellites encountering space debris).

Lawrence Berkeley National Laboratory (LBNL) has developed induction accelerators over the past twenty years, and specifically over the past several years for heavy-ion accelerators for IFE. The LBNL heavy-ion fusion (HIF) effort has recently been integrated with LLNL's Beam Research Group. Their induction accelerator developments have had application within the defense community, for example at the Dual Axis Hydro Test Facility (DARHT) now under construction at Los Alamos, where a pair of electron induction linacs are used to generate intense x rays, which in turn are used to image the implosion process created by conventional explosives. Also, solid-state modulator technology originally designed for HIF recirculators has been applied to the design of the proposed Advanced Radiography Machine, which requires a similarly high repetition rate (to image the implosion at several points in time). This work has also benefited the high-energy physics and light-source communities through the development of injectors for relativisitic klystrons, improving our understanding of space charge physics, and developments for high-power free electron lasers. The use of induction accelerators for food sterilization has also been investigated. The HIF group has also been prolific in generating codes such as WARP and GYMNOS, which have applied to the modeling of space-charge-dominated beams with applications in high-energy physics, atomic vapor laser isotope separation, and plasma processing. An accelerator for Boron Neutron Capture Therapy for medical treatment uses an injector modeled after heavy-ion fusion developments. See the table below for further examples of heavy-ion fusion and pulsed power spin-off technologies coming from LBNL and SNL.

Scaled experiments being completed on all systems of a heavy ion driver at LBNL. Experiments, theory, and simulation agreed.

Spin-offs and Cross Disciplinary Connections to Pulsed Power and Heavy Ion Fusion

Categories	ICF/IFE Technology Spin-off	Where and How Used
Induction accelerators	Dual Axis Hydro Test Facility (DAHRT)	For stockpile stewardship (injector, linac, and final focus areas benefited from HIF staff and experience)
Induction accelerators	Advanced Radiography Machine	*(Proposed) for stockpile stewardship. (High repetition- rate flexible format FET pulse modulators originally developed for HIF recirculator)*
Induction accelerators	Injector for Relativistic Klystrons	For high energy physics research
Induction accelerators	University of Maryland Electron Ring (UMER)	At U. Md. for studies of space-charge physics (highly influenced by HIF recirculator design)
Induction accelerators	High-power free-electron lasers	common beam research personnel involved in both FEL and HIF research (both with high peak power, low-emittance beam requirements)
Induction accelerators	Composite curing using induction linac	material fabrication of polymer composites using electron beams. Science Research Laboratory outgrowth of Beam Research program
Induction accelerators	Other potential applications	Spallation neutron source for materials research, tritium production, waste transmutation, subcritical nuclear power generation, and/or fusion materials research
Computer Software	Space-charge dominated beam codes	WARP-used for many accelerators (AVLIS (laser isotope separation) electron beam injector (GSI bunch compression in rings, UMER (electron ring experiments) GYMNOS used in DARHT simulations and plasma processing applications
Computer Software	Interactive User Interface	The linkage of Fortran to the scripting language Python, developed for the HIF code WARP, is being used by the MFE code UEDGE, and likely other tools soon

Categories	ICF/IFE Technology Spin-off	Where and How Used
Beam Transport	Transport of space-charge dominated beams	Demonstrated first in HIF theory and later in HIF experiments. Now applicable to many LINAC injectors; Applied directly to design of the Fermilab Tevatron main injector upgrade
Beam Transport	Space charge effects in bends	LEP curvature aberration effects deduced by HIF theorists
Beam Transport	Space-charge and neutralization effects	Imitron, medical accelerator design aided by knowledge of neutralization physics deduced by HIF theory
Beam Transport	Theory of beam modes and beam stability	Longitudinal instability, temperature anisotropy instability, kinetic and fluid beam modes
Beam Transport	Theory of beam halo	HIF theorists have contributed to longitudinal halo theory applied to high average power accelerators such as APT and NSNS
General Accelerator	Medical accelerators	Accelerator for Boron Neutron Capture Therapy (BNCT) - medical accelerator (injector modeled after HIF ESQ injector)
General Accelerator	Beam cooling	Electron cooling at Fermilab (HIF scientists contributed to beam dynamics studies of low-emittance and space-charge dominated beams)
General Accelerator	Plasma lens	Plasma lens for high energy physics (SLAC, LBNL) and high energy density physics (GSI)
Accelerator Components	Long pulse induction cores	Pioneered the use of Allied Signal Metglas amorphous iron tape for long pulse length, low power loss induction cores
Accelerator Components	Superconducting magnet arrays	Extension of superconducting magnet technology to low aspect ratio, multiple beam arrays, which may have applications to other high power accelerator applications
Pulsed power components	Radiation Effects Testing	The short pulse technology developed for the ICF program has been used to build pulsed-power accelerators that drive z-pinch loads for soft x-ray radiation effects testing
Pulsed power components	Repetitive Pulsed Power	High average power repetitive pulsed power systems have been developed to drive many loads, ranging from soft x-ray to electron beam to ion beam diodes
Pulsed power components	Low power repetitive ion diodes	Low power ion beams have been developed for several industrial applications, including surface treatment of metals and ceramics
Pulsed power components	Repetitive electron beam diodes	Repetitive electron beam diodes have been developed for several industrial applications, including electron beam welding, as a source of high energy x-rays for use in food sterilization, for demilitarization and decontamination of chemical and biological weapons, for elastomer processing, and for adding enthalpy to simulate hypersonic flow in windtunnels
Pulsed power components	Repetitive soft x-ray sources	Low power repetitive soft x-ray sources have been developed for such applications as x-ray microlithography
Pulsed power components	Radiation-hardening	Diagnostics and electronics used in pulsed power must be protected from the harsh environment that is present. The methods of protection have applications to the space industry.
Pulsed power diagnostics	Radiography	Inductive Voltage Accelerators are used to generate high-current, small-spot-size, intense bremsstrahlung source for use as backlighters of large samples

Optics, Materials, and Manufacturing

Improving laser damage has been an important area of inertial fusion driver research that has had broad applications within the laser community. For example, multilayer coating techniques based on the research conducted with the inertial fusion programs at LLNL and LLE in the United States and at ILE in Japan for increasing optical laser damage resistance and monitoring the fabrication of of multilayer reflectors and polarizer coatings have appeared in the product lines of both U.S. companies (Spectra Physics and OCLI) and Japanese companies (Showa Optronics). The phosphate laser glass utilized in the NIF and Laser MegaJoule was originally developed by LLE working with Hoya Corp. and later refined to eliminate damaging platinum particle inclusions by LLNL working in concert with both Schott Glass Technology and Hoya. LLNL also worked with Schott Glass Technology to develop high-strength phophate laser glass (APG-1 and APG-2) for high-average-power laser applications. LLE, working with Kigre Corp. and GE/Binghamton, N.Y., demonstrated the first surface strengthening of phosphate glass, again specifically for high-average-power laser operation.

NIF Large-aperture phosphate laser glass blank as cut from a continuously melted glass strip.

The growth of crystals for laser media and for nonlinear conversion has been an important specialty of the ICF community. LLNL invented the broadband lamp-pumped laser material, Cr:LiSAF, and transferred the technology to VLOC, a division of II-VI Corp. Following its original exploration in Russia, LLNL has perfected the rapid growth of KDP conversion crystals and transferred that technology to Cleveland Crystals Inc. and Inrad in the United States, and through the French Commissariat a L'Energie Atomique, to Crismatek in France. This new crystal growth method will make possible producing the large quantity of near-perfect crystals needed for both the NIF and Laser MegaJoule.

Potassium dihydrogen phosphate (KDP) crystal created with rapid-growth method.

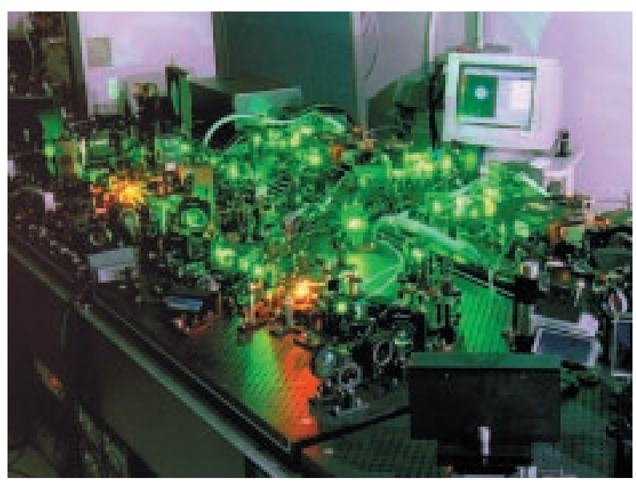
Fabrication of optical components has been another area in which ICF has made important contributions to industry. The aspheric lens polishing methods developed at Tinsley for the Nova laser contributed to the fabrication of the corrector employed in the Hubble Space Telescope. Rapid deterministic polishing methods are now being developed for the NIF at Zygo Corp., Kodak, and Tinsley. The most advanced polishing method under investigation is magnetorheological finishing in which an externally applied magnetic field is used to control the local material removal rate by over four orders of magnitude. This process, developed at LLE in collaboration with Byelcorp Scientific Inc. with government support, is the basis of the company QED Technology, Inc., founded in Rochester, N.Y. To date, QED has sold seven such optical finishing machines to industry. Improvements to the polishing of ultra-smooth surfaces was also invented at LLE and is used by Norton, Inc. in their polishing products.

Diffractive optics consist of surface structures of order of a wavelength in depth on large optics for accomplishing specific functions. The ICF community has been a leader in the fabrication of such optics, which are used extensively in current ICF systems and will be part of the megajoule systems under construction. Both LLE and LLNL have developed special methods for controllably etching desired patterns into fused silica such as gratings and phase plates. Industrial companies in the diffractive optics field such as Rochester Photonics and Digital Optics are appraised of the ICF work although no formal technology transfer has yet occurred.

Colleagues at ILE in Japan report that laser ablative shaping technology originally developed for controlling ICF beam shapes on target is being used in the development of single-mode fiber connectors by Sumitomo Electric Industries specifically to produce reasonably priced connectors for use in Fiber to the Home high bandwidth telecommunications.

LLE has been a pioneer in the development of liquid crystal optical components for laser systems. In 1989, LLE received an R&D 100 award for their development of a liquid crystal polarizers used in the Omega laser. This technology was transferred to Meadowlark Optics of Longmont, CO. LLE researchers found the relationship between molecular structure and laser damage in liquid crystals, which has been a key for identifying appropriate materials for high-power laser use. More than 300 liquid crystal components have now been incorporated into the upgraded Omega laser for polarization control since 1995. Under support from Reveo, Inc., LLE also developed a pigment from polymer liquid crystal flakes, which produces printed patterns that are sensitive to the color and polarization of the illuminating light. Applications are envisioned in personnel security, anticounterfeiting, and printing of 3D pictures.

Materials processing with high-power lasers is an important industrial area with strong connection to inertial fusion. DPSSLs are being developed for cutting and welding in the United States, Japan, and Europe based on research conducted in the ICF community. The application of short-pulse CPA lasers for materials processing is believed by some to be an industrial break-through, a major component of the femtosecond revolution. ICF laser development work at LLNL led to the realization that pulse lengths shorter than 1–10 ps remove material so rapidly that there is effectively no heat transfer to the remaining material. This so-called “cold cutting” is being applied to the dissassembly of nuclear weapons within the Department of Defense’s (DOE’s) Defense Programs in a manner that will allow their reuse. It is also being explored for producing precision holes in aircraft engine turbine blades, for fuel injectors in diesel engines, and for tissue ablation for medical applications. Another application is laser peening in which a light pulse of ~20 ns operating an ~100 J/cm^2 produces shock compression to harden the surface of critical components, such as turbine blades, gears, and medical implants. Using zig-zag slab laser technology mentioned earlier, LLNL is working with Metal Improvement Corp. to commercialize this technology.
Pulsed power component developments by the



A 15-W CPA laser developed for laser cutting, employed at the Y-12 plant.

ICF community have been similarly enabling for industry. High-energy storage density capacitors based on metalized dielectrics have been developed for the NIF at Aerovox and Maxwell Technologies in the United States and by three companies in Europe, while very high-current switches have also been developed at Maxwell. In Japan, high-average-power thyratron switches at Nisshin Electric Company and minaturized high-energy-density capacitors at Matsushita have derived from ICF researchers. For future heavy-ion fusion drivers, developments are underway for low-loss amorphous magnetic cores, castable lower-cost large insulators, cheaper regulated pulsers with solid-state switching, and robotically wound low-cost superconducting quadrapoles lenses.

Finally, the fabrication of ICF targets is worth noting as a unique manufacturing technology having niche applications. General Atomic is leading the U.S. ICF program in this regard, although it depends heavily of developments originating mainly from LLNL, LANL, and LLE. Highly spherical, extremely smooth capsules to contain the deuterium-tritium fuel are needed, with ablators that range from polymers doped with various elements for diagnostics purposes to ultra-smooth layers of beryllium. The interior hydrogen fuel is contained both in a smooth inner layer and in the residual gas that eventually provides a fusion sparkplug. The ICF community has developed high strength polyimide shells to contain the fuel, as well as thin metal permeation layers to control permeability of hydrogen. Developing the cryogenic systems to deploy such targets on the Omega laser and eventually the NIF has extended the cryogenic field for example in tritium compatible valves being developed at Ontario Hydro, which work at cryogenic temperatures. Interferometric techniques to measure the internal surface roughness have also been developed at LLE and LLNL. In England, the need to produce ICF targets with specific small-scale features at the Central Laser Facility led to the creation of Exitech, a company who now has wide business area.

Diagnostics and Instrumentation

The ultra-high speed diagnostics used for measuring inertial fusion implosions have found application in many other fields. Streak cameras which can measure light or x-rays with picosecond time resolution have been developed largely because of the needs of inertial fusion. The company Kentech was founded in England specifically for meeting the needs of the inertial fusion programs at Rutherford Laboratory, Imperial College, and elsewhere around the world. Kentech now specializes in high-speed electronics for a variety of applications and users. The inertial fusion programs at LLNL and LLE have also been active in developing high-dynamic-range high-speed streak cameras as well as framing cameras which can even capture x-ray images with a temporal resolution of a few tens of picoseconds. To handle the very large information-content images generated by inertial fusion experiments, the company Oxford Framestore Applications was also founded in England.

LANL has been active in developing ultrasound methods to characterize ICF targets. Their non-contact diagnostic techniques, developed in part with Lasson Technology, will find application in corrosive or volatile environments and potentially at cryogenic temperatures.

Micropower impulse radar (MIR) is a LLNL spin-off invention from laser fusion diagnostics work in transient digitizers, itself an R&D 100 winner in 1993. Since the first award, MIR has been applied to numerous uses, ranging from an electronic dipstick to measure fluid levels in automobiles (winning another R&D 100 Award in 1996) to a land-mine detection system.

Based on emitting and detecting very low-amplitude voltage impulses, MIR has a sensitive detection window for accurate ranging that can be varied over time to provide radar return information at various ranges. The hardware package is very small (hand-held), made of inexpensive electronics, and has extremely low power requirements. Average emissions are well below 10 mV and are spread over several gigahertz bandwidth, virtually eliminating unwanted reception.

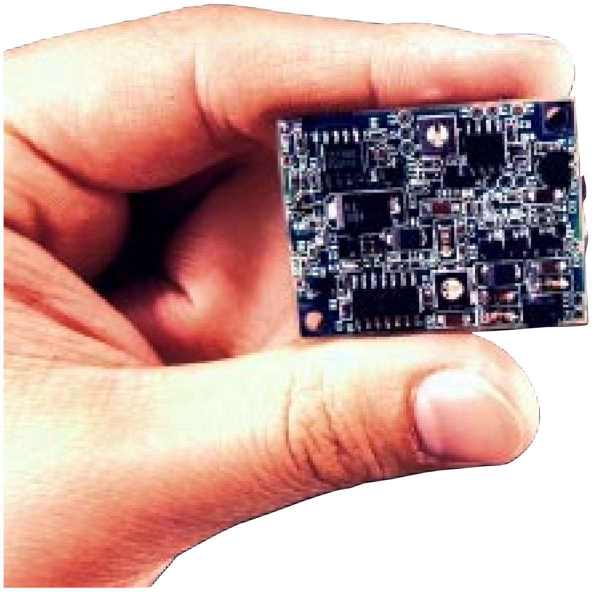


Photo of a complete MIR motion sensor system (minus antennas and standard 9-volt battery).

The MIR technology has over 30 associated patents. It has also won numerous awards and is licensed to over 20 companies. Several MIR products are now on the market.

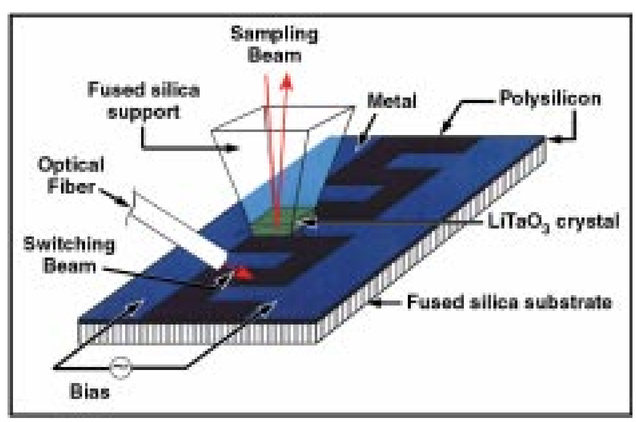
Experiments using MIR to image concrete slabs showed vast improvements over the higher-powered, lower-frequency systems tested earlier. At the same time, Laboratory engineers were developing unique three-dimensional reconstructive imaging software, using diffraction tomography that was refined to "see" through layers of material. A system for inspecting bridges for cracks called HERMES is shown on the cover.

In contrast to conventional radar, which uses continuous microwave energy to detect objects over many miles, impulse radar transmits ultrashort electromagnetic pulses that allow the detection of objects at very short ranges. The MIR's pulses, producing a wide band of frequencies, generate a great deal of information about detected objects at high resolution and accuracy. The echoes of these pulses are measured by an extremely sensitive receiver that is set for a detection range of a few centimeters to many tens of meters. MIR system components also include timing circuitry, a signal processor, and antennas. Together, they determine system range, directionality, and how well materials such as concrete, wood and other non-metallic materials can be penetrated.

An MIR system is compact and lightweight and has low power requirements; it is less expensive to produce than a conventional radar system and is amenable to many more applications. Furthermore, MIR modules can be grouped into arrays to increase system speed and area of coverage.

As described in the recent popular press (e.g., *Technology Access Report*, May 1999), the U.S. Patent and Trademark Office is reexamining one MIR patent (per LLNL's request) against a 1987 patent from an inventor at an Alabama company. The final office action is expected in the near term.

Another important ICF diagnostic spin-off is the electrooptic sampling system developed at LLE for measuring repetitive voltage pulses in electronic circuits with subpicosecond time resolution and microvolt sensitivity. In this device a femtosecond laser is used to trigger a high speed electrical sampling switch. More recently LLE has developed fast photodetectors and switches based on illuminating superconductors with optical pulses. In collaboratorion with Hypress Inc., LLE has shown the first detection of single flux quantum logic pulses (1 mV-ps) based on a Josephson logic circuit.



Electro-optic sampling circuit used to measure subpicosecond electrical pulses (courtesy of LLE).

Semiconductor Manufacturing

The inertial fusion program has a long history of providing spin-offs to the semiconductor manufacturing. Attempts to develop proximity print lithography at Hampshire Instruments, an LLE spin-off, were mentioned earlier. Inertial fusion work at ILE in Japan has benefited the Japanese semiconductor industry such as the development of laser interferometry for the precision positioning of optical steppers employed by Canon Inc.

Microelectronic circuits are built-up layer-by-layer with very intricate patterns. The patterns today have details of about 250 nanometers in lateral dimension. The process of putting images of the circuit patterns on the silicon chips is called lithography. The vitality and robust growth of the semiconductor industry dictates that they follow a roadmap to make the circuit features smaller. Therefore, they need to continually develop more sophisticated lithographic processes. The resolution of images as limited by diffraction of light is directly related to the wavelength. EUVL is a method of lithography that uses very short wavelength light, about 13 nanometers, which can make very high-resolution images and, therefore, very high-resolution microelectronic circuits. In fact, the 13-nanometer light can make images with 25-nanometer features, a capability that will support the microelectronics industry until at least 2015.

Extreme ultraviolet lithography (EUVL) is a new technology being developed by a consortium of three Bay Area national laboratories: Lawrence Livermore, Sandia-California, and Lawrence Berkeley. Work at these laboratories is funded by a consortium of Intel, Motorola, and Advanced Micro Devices under a three-year, $250M CRADA agreement. Much of the technology for optical systems at EUVL wavelengths grew out of work on diagnostics for ICF. The EUVL project will directly impact the semiconductor manufacturing industry that is approaching $200 B/yr. The United States accounts for half of the total semiconductor sales while Japan, Europe, and Asia account for the remainder. There are also EUVL programs in Europe and Japan, which are new and growing quickly.

The problem has been that no one has ever made a short-wavelength lithographic system with the performance and precision necessary for EUVL. The laboratories, however, have developed new types of interferometry, required to make the precision optical elements, that has an absolute accuracy many times that of prior techniques. They have developed optical coatings that reflect 10-nanometer light; these coatings are far more uniform than ever before. They have assembled an imaging camera that has surface accuracy well beyond that used in the Hubble Space Telescope which has been used to produce images with 50 nanometer circuit features. They have built diode-pumped solid state laser-produced plasma sources to generate light for the camera. These laboratory contributions are being transferred directly into the commercial sector to allow commercialization of EUVL technology.

Ultra Clean Ion-Beam Sputter Deposition System that will be used in EUVL development to deposit thin films in integrated circuits

In December, 1998 an international panel of experts assembled by Sematech selected EUVL as the technology of choice for the mass production of integrated circuits for the next decade.

Some of the most important technology developments for EUVL are discussed below. It takes little imagination to see how these developments could also spin-back into filling future technology needs of inertial fusion energy.

EUV Optics and System

The application of 11- to 13-nm EUV light to lithography tools that print critical dimensions in the 30- to 100-nm range requires high-precision reflective optics. These optics are used in the condenser to collect the EUV radiation from the source and to focus the radiation onto the reflective reticle in the camera to reproduce an image of the mask pattern onto the wafer. Each of the mirrors must be manufactured and assembled in the lithography subsystem to maximize the imaging efficiency and reduce distortion.

EUVL Masks

EUVL uses a reflective mask, and reflectivity at EUV wavelengths is obtained by coating a mask substrate with multilayers. The challenges include detection of sparse submicron defects on large fields. The identification and minimization of defects which can cause optical damage is of similar importance for inertial fusion.

EUVL Thin Films/Coatings

The multilayer coatings for EUV lithography systems typically consist of alternating layers of molybdenum and silicon (Mo/Si) or molybdenum and beryllium (Mo/Be). The primary materials-dependent characteristics of EUV multilayer mirrors are reflectance, stress, and stability. Using an a thermal buffer-layer technique with amorphous silicon and Mo/Be buffer-layers, it has been possible to obtain Mo/Be and Mo/Si multilayers with a near-zero net film stress and less than a 1% loss in reflectance. Disposition technology challenges include thickness control and repeatability.

Metrology at Near-atomic Dimensions

High-accuracy metrology tools are prerequisites for fabricating the precision optics for EUVL. Improvements in figure metrology have been made that will enable the absolute measurement of surfaces to the accuracy required.

Medical Technologies

In 1994, researchers at LLNL began applying ICF technology and expertise developed over decades of ICF work to a new area—medical technologies. The goal was to apply ICF research and expertise to solve specific medical problems. The expertise of ICF senior scientists in lasers, optics, plasma and x-ray diagnostics and computational models was matched with physician-identified medical needs to form a roadmap for development of key medical devices. The initial focus was treatment of stroke. Five years later several of these stroke treatment systems are being commercialized by the medical industry, and two are in early stage human trials.

The connection between ICF development and medical technologies is partially a direct adaptation of ICF technologies, but even more so, it is the use of ICF-driven expertise that can be readily applied to developing medical solutions. Below is a table of medical technologies that are being developed, or have been commercialized, using ICF-derived expertise and technology. In addition, three key technologies are featured in more detail.

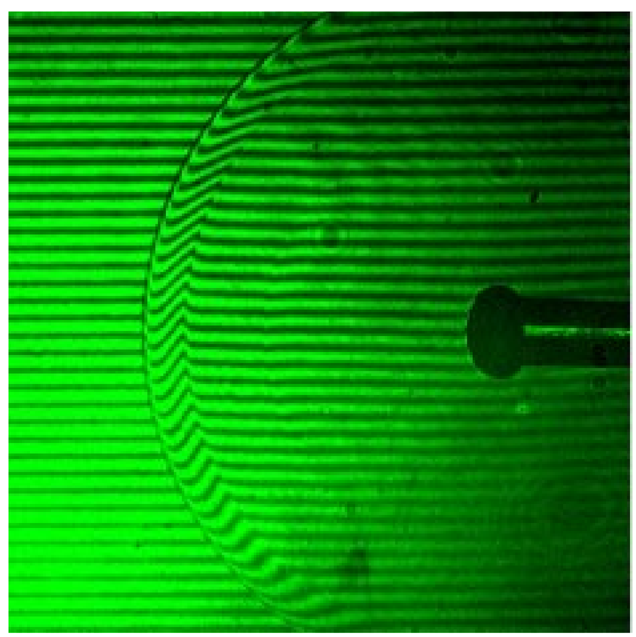
ICF Core competencies	ICF core technologies	Medical applications
Plasma diagnostics	X-ray sources	X-ray catheter for prevention of restenosis
Plasma Diagnostics	X-ray Characterization	System for clinician dose measurement during angiography
Optical Florescence	Chemical sensors	Continuous glucose monitor for diabetics

(table continued next page)

ICF Core competencies	ICF core technologies	Medical applications
Laser/matter interaction modeling	LASNEX code	Characterization of treatment system for Benign Prostate Hyperplasia
Laser/matter interaction modeling Lasers and Optics	LASNEX code Diode-pumped lasers and fiber optic delivery	Opto-acoustic laser system for blood clot emulsification during stroke
Optical Design	optical systems for ultra-short pulse lasers	Two photon photodynamic therapy for eye disease
Precision plasma temperature measurements	Interferometric temperature and shock measurements	Measurement of laser tweezer heating for in vitro fertilization
Advanced laser systems	Optical parametric oscillators	Tissue characterization from UV to mid-IR
Precision temperature measurement	Optical pyrometry	Temperature measurement and feedback system for Tissue Welding
Advanced optical systems	Optical Coherence Tomography	OCT system for dental imaging
Advanced Laser systems	Ultra short Pulse Lasers	USPL surgery system
Plasma diagnostics	Laser-based plasma diagnostics	USPL plasma luminescence system for discriminating between bone and soft tissue
Radiation transport modeling	Monte Carlo codes for radiation transport	Peregrine radiation treatment planning system
Complex Optical systems	Optics and spectroscopy systems	Cancer detection with an optical biopsy
Optical Diagnostics	Optical Instrumentation	Ultra fast Spectrometer
Laser optical systems	Specialized laser systems	Laser Tweezers for manipulating single cells

Opto-acoustic thrombolysis stroke treatment system

Stroke is the third leading cause of death (155,000/year) and the leading cause of disability in the United States, costing over $40 billion/year for treatment and rehabilitation. ICF-derived research at LLNL has lead to a unique technology to aid in the disruption of stroke-causing thrombus occlusions (blood clots). This minimally invasive technique involves guiding a catheter to the site of the occlusion and introducing an optical fiber delivery system into the catheter. Laser light is coupled into the optical fiber and delivered to the occlusion, causing mechanical disruption of the occlusion and re-establishing blood flow to the brain. The light creates a vapor bubble and an acoustic wave, which is transmitted into the clot aiding in the emulsification of the clot.



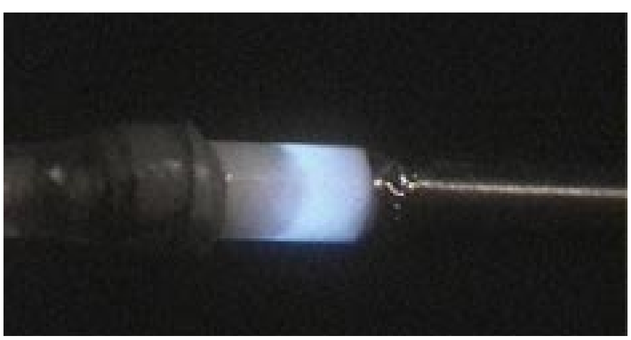
The stress wave and vapor bubble created by the deposition of laser energy through an optical fiber.

Initial development of the laser and delivery system was performed at LLNL, incorporating computer modeling and experimentation, a derivative of laser and optical technologies developed within ICF. Additionally, laser-tissue interaction models, originally developed as laser-matter simulations for ICF, were crucial in optimizing the laser parameters for optimal acoustic wave effectiveness, optimizing irradiation parameters, and predicting thrombus-material failure modes. The technology was licensed to EndoVasix, Inc., which began human trails in 1998.

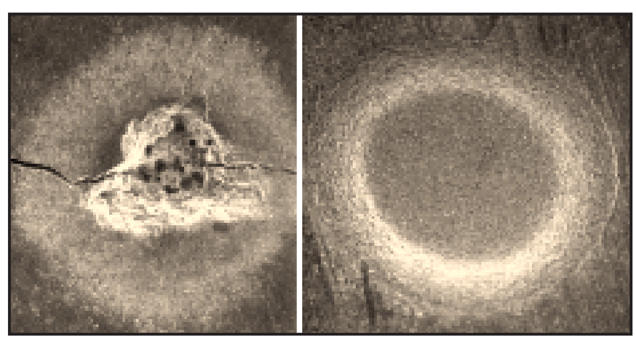
Heart Disease Treatment with the X-Ray Catheter
Heart disease caused by blockage of a coronary artery is a common medical problem, affecting over 1,000,000 Americans annually. LLNL, in conjunction with Interventional International Corporation, has developed an x-ray catheter system to address a key element of heart disease treatment. Following balloon angioplasty to reopen occluded cardiac arteries, scar tissue often forms in the artery during the natural healing process, blocking blood flow. Known as restenosis, this clogging requires repeated surgery. Research has shown that treatment of the arterial wall with ionizing radiation immediately after angioplasty can prevent restenosis. The x-ray catheter is a safe, cost-effective means of delivering this ionizing radiation in the form of x-rays. The technical basis for the x-ray catheter originated in the x-ray diagnostics research that has been an ongoing, fundamental part of the overall ICF effort. This technical excellence in x-ray diagnostics includes both diagnostics and sources.

The Ultra-Short Pulse Laser Surgical System
Researchers at LLNL have developed a surgical system that is an outgrowth from ICF research into ultra-short pulse lasers and the Petawatt laser for ICF experiments. The system uses an ultra-short pulse laser to create high-precision cuts without damaging surrounding tissue. The laser produces such short duration bursts of laser energy that ablation occurs without collateral damage to surrounding tissues. Combining miniaturized commercial sources of ultra-short pulse lasers with newly developed delivery systems and diagnostics have created a powerful new surgical tool that creates tiny cuts with amazingly small kerf (<100 um). It can also drill tiny holes (<150 um diameter) all without thermal or mechanical damage to surrounding areas.

The application of this technology for corneal sculpting is under investigation at the University of Michigan and at the company Intralase. Another area for medical applications of ultra-short pulse lasers is dentistry. A big advantage for dentistry is the minimized energy transfer from the beam to the material that is being drilled. The minimized heat transfer by the laser means the heating of the tooth, which causes patient discomfort, does not occur.



LLNL's x-ray catheter prototype, emitting a therapeutic x-ray dose (>6gy/minute).



(Left) Extensive thermal damage and cracking to tooth enamel caused by 1-ns laser ablation. (Right) Smooth hole with no thermal damage after drilling with a ultra-short pulse laser.

R&D 100 Awards

Each year *R&D Magazine* selects the 100 most technologically significant products and processes submitted for consideration and honors them with an R&D 100 Award. Winners are chosen by the editors of the magazine and a panel of 75 experts in a variety of disciplines. Corporations, government laboratories, private research institutes, and universities throughout the world vie for this "Oscar" of applied research. The R&D 100 judges look for products or processes that promise to change people's lives by significantly improving the environment, health care, or security. Researchers from the inertial fusion community have been frequent recipients of these awards as noted in the table below.

Year	Research Area	Institution	Technology Description
1998	High-performance Electromagnetic Roadway Mapping and Evaluation System (HERMES)	LLNL, Federal Highway Administration	A high-resolution, radar-based mobile inspection system for detecting and mapping defects in bridge decks, highways, tunnels and rapid transit systems, based on micropower impulse radar.
1998	Laser peening system	LLNL, Metal Improvement Co. Inc.	A high-average-power, pulsed laser-peening system that instills deep compressive stress into metal components to extend service lifetime. Applications include surface treatment of aircraft fan blades, disks, and rotors; helicopter drive gears and bearings; hip replacement joints in the medical industry; oil drilling tools; and enhancing corrosion fatigue resistance for DOE's nuclear waste storage containers.
1998	Optical dental imaging system	LLNL, University of Connecticut Health Center	A hand-held, noninvasive, high-resolution, optical dental imaging system that can diagnose periodontal disease and detect cavities. Applications include diagnosis of periodontal diseases, detection of cavities, and evaluation of dental restorations.
1998	Fiber optic infrared temperature system	LLNL	A fast, accurate, high-resolution optical sensor that measures temperature for medical and industrial applications such as temperature-based laser controls for tissue welding of skin grafts, laser-based surgery and nerve repair, and temperature control of silicon wafer surfaces during the dry-etching process.
1997	Absolute interferometer	LLNL	A device that can measure the surface curvature of optics with ultra-high accuracy—nearly 1/1,000 of a visible light wavelength. This special capability greatly expands the frontiers of the semiconductor and optical-manufacturing industries.
1997	Ultra clean ion beam sputter deposition system	LLNL, Veeco Instruments, Inc.	A system that can produce defect-free reflective coatings on masks used to transfer patterns onto silicon wafers or microchips. The new system yields only two defects in 100 cm^2, more than a 300,000-fold improvement over the current method. An enabling technology for extreme ultraviolet (EUV) lithography to mass produce images or patterns on integrated circuits.
1997	Femtosecond laser materials processing	LLNL	A high-repetition-rate, ultra-short pulse Ti-sapphire laser system that can cut and drill materials with high precision and high speed, with a minimal heat-affected zone. Applications include chemical weapons dismantlement, machining of electronic materials, drilling of high-precision holes, and hard-tissue cutting of bones and teeth.

1997	Ultra-high gradient insulator (UHGI)	LLNL, AlliedSignal Federal Manufacturing & Technology Plant	An ultra-high gradient device that can sustain four times higher electrical voltage than of conventional insulators of similar size. When applied to silicas or glass insulators, it can support 175,000 volts per centimeter, about five times the limit of today's insulators. Applications include equipment size reduction for accelerators, x-ray machines, and semiconductor production tools.
1996	Ce:LiSAF, first tunable ultraviolet solid-state laser product	LLNL, VLOC (formerly Lightning Optical Corporation)	A cerium-doped lithium-strontium-aluminum flouride optical crystal used as laser gain media to generate tunable laser output in the UV region. Applications include remote sensing and optical communications between infantry units over short distances.
1996	Six degrees of freedom sensor	LLNL	A small, noncontact optical sensor that can accurately monitor its position in six degrees of freedom. This sensor can be used to guide robotic machining tools to follow a pre-described machining path and shorten the manufacturing process change-out time.
1996	Ultrahigh-density magnetic sensors	LLNL, Read-Rite Corporation	A critical component in magnetic storage devices such as computer hard-disk drives. The new sensor using alternating layers of thin magnetic and nonmagnetic materials offers greater sensitivity and 100 times greater storage densities than current commercial products, approaching the projected limit of magnetic disk drive technology of 100 gigabit/1 in.^{2} (6.4 cm^2).
1996	Electronic dipstick	LLNL	A low-power. low-cost (<10 $) device that can measure the fluid level in a container to better than 0.1% accuracy by measuring the time it takes for an electrical impulse to reflect from the liquid surface. Applications include measuring fluid levels in cars, supertankers, and grain elevators.
1996	Lithography system for flat-panel displays	LLNL	A cost-effective laser interference lithography that can precisely produce regular arrays of extremely small (less than 100 atoms wide) electron-generating field-emission tips. This will advance the production of field-emission display flat panels, which are thinner, brighter, larger, and have a wider field of view than matrix liquid crystal displays. Applications range from more efficient portable computers to virtual-reality headsets and wall-hugging TV sets.
1995	High-average-power solid-state laser with high-pulse energy and low beam divergence	LLNL	A flashlamp-pumped Nd:glass zig-zag slab laser that can deliver output power of 150 W (25-to 30-J per pulse at 6 Hz) with near-perfect beam quality and narrow spectral line width. The performance of this system is 10 times that of any current commercial product. Applications include advanced integrated circuit production and coherent laser radar.
1995	All solid-state laser with diode irradiance conditioning	LLNL	A new diode-pumped solid-state laser architecture that integrates all key components (laser diode pump array, lens duct optic, and laser gain medium) in a compact configuration.

			It offers a relatively inexpensive yet robust and reliable means of generating coherent laser light for applications in medical surgery, pollutant detection, and laser welding.
1995	Sealed-tube Electron Beam Gun for Material Processing	LLNL, American International Technologies	A low-cost, durable, compact sealed-tube electron-beam gun that can deliver 2 ma of 65 kV electrons (130 W) into the air. The sealed tube uses a thin-film material as a vacuum window that passes electrons of lower energy, eliminating the need for costly high-vacuum systems. The major application is in polymer curing.
1994	Multilayer dielectric gratings	LLNL	High-efficiency and high-damage-threshold gratings made of multi-layer dielectric materials. The new gratings are attractive for commercial high-power laser systems that employ gratings for pulse compression.
1994	A process for rapid growth of KDP crystals	LLNL	A method of growing high-quality potassium dihydrogen phosphate (KDP) crystals about 10 to 40 times more quickly than conventional methods, thus promising great savings in laser technology and all other fields requiring high-quality crystals.
1994	Ytterbium-doped apartite laser crystals	LLNL, University of Central Florida	Ytterbium-doped apatite laser crystals, which have 2.5-to-5 times more energy storage capacity than other laser crystals. The apatites provide a means for attaining high-energy storage with low loss in laser amplifiers and Q-switched oscillators.
1993	Modular high-power laser diode array	LLNL	A modular, high-power, laser-diode array packaged with LLNL's cooling system for high-power operation that enables lasers to operate at five times greater power than previously possible and about seven times lower cost.
1993	Single-shot transient digitizer	LLNL	A system that can electronically record electrical signals as short as 30 trillionths of a second. Applications include high-speed physics, telecommunications, and testing of high-speed digital computer ships. With low-cost, off-the-shelf components, it is an inexpensive replacement for oscilloscopes.
1991	High-voltage, solid-state switch for power conditioning circuits	LLNL	A solid-state switch assembly that combines the high reliability of solid-state electronics with the high-voltage standoff and high-current switching capabilities of thyratrons. This switch assembly is more reliable and cost effective than thyratrons. Applications include thyratron-replacements in the power-conditioning circuitry for lasers, radars, accelerators, and other devices.
1991	Cr:LiCAF and Cf:LiSAF lasers	LLNL	Crystals with versatile optical and physical properties that could be used as gain media in tunable solid-sate lasers. These crystalline lasers offer longer energy-storage lifetime, higher efficiency, more flexibility in harmonic generation, and good beam quality at high-average-power. They can be used in a broad range of scientific, industrial, and defense applications.

1990	Ultra-thin diffractive lens	LLNL, University of California at San Francisco	An ultra-thin, flexible, diffractive lens that can image a broad spectrum of wavelengths to a common focal point. It can replace the artificial intraocular lens implants now used to restore vision to cataract patients. This lens may be implanted through a sutureless incision or placed directly on the cornea to correct aphakia (absence of the natural lens), myopia (nearsightedness), and hyperopia (farsightedness).
1990	Ultra-low-density silica aerogel	LLNL	An inorganic polymer foam in which the solid portion occupies only 0.2% of the total volume, yet no pore is larger than a few hundred angstroms across. The foam is highly compressible, elastic, and transparent with acoustic impedance and thermal conductivity lowest of any known inorganic material. The principal application of this aerogel is for Cherenkov effect detection.
1989	Liquid crystal polarizer	UR/LLE	The concept for using liquid crystals in high-power lasers was originated at LLE in 1979.
1989	Reflective x-ray mask for lithography	LLNL	A reflective x-ray mask for lithography to eliminate the problems of fragility and radiation sensitivity of conventional x-ray masks. It is an optically flat, multi-layer x-ray mirror onto which the metallization for an integrated circuit pattern is deposited. It has applications for reproducing next-generation high-density integrated circuit devices and allows the production of 400-Mbit DRAM devices on a 1.5-cm^2 chip that usually would hold 4-Mbit devices.
1988	Composite polymer-glass edge cladding	LLNL	An optically absorbing edge cladding material applied to large laser disks to reduce the undesired internal reflections in disks that deplete the excited state populations and gains of optical amplifiers. This method provides less index inhomogeneity and stress-induced birefrengence near disk edges and costs a fifth that of conventional fused-glass edge claddings. It can be applied to all types of laser glass and crystals.
1988	Neutron penumbral-aperture microscope	LLNL, University of Melbourne	A high-resolution, high-sensitivity neutron microscope that uses a two-step coded aperture-imaging technique to produce images of small 14-MeV neutron sources. The device uses the 14-MeV neutrons emitted by the deuterium-tritium fusion reaction to present an image of the core of a laser-fusion target.
1988	X-ray laser cavity	LLNL	A resonant optical feedback device that can increase output power and efficiency of x-ray lasers by a factor of 200, beam divergence by an order of magnitude, and output brightness by a factor of 1600. It uses multi-layer mirrors and beamsplitters to provide feedback and amplification to the gain medium.
1987	Planar triode pulser	LLNL, Grant Applied Physics, Inc.	A high-power ultra-high-speed electrical pulser system that can be used to drive fast-framing cameras for investigating subnanosecond phenomena. The pulser is about 100 times more powerful and 10 times faster than existing pulsers. The principal application is in high-speed photography.

1987	Zone-plate coded microscope	LLNL	A broad-spectral-bandwidth microscope that uses a two-step imaging technique to produce high-resolution (≥1 μm) x-ray images of small objects. The principal application is to provide high-resolution, multi-spectral images of laser fusion experiments and to image high-energy particle emissions, such as neutron, proton, and alpha particles from radioactive sources.
1987	Highly dispersive x-ray mirror	LLNL	A generalized x-ray optical component that combines lithography and multi-layer thin-film deposition to manipulate x-ray beams and produce a three-dimensional x-ray diffraction element. The mirror was developed for use in soft x-ray cavities. Other applications include materials micro-analysis and scanning x-ray spectroscopy of microbiological and solid-state devices.
1987	Platinum-free phosphate laser glass	LLNL, Hoya Optics, Schott Glass Technologies	A special process that can reduce the Pt inclusion concentrations in phosphate laser glass by a factor of 1000 to less than 0.1 per liter. The principal application is in high-power laser systems as damage-resistant optical media.
1986	Particle beam fusion accelerator II	SNL	A device capable of igniting thermonuclear fuel in the lab and the only inertial fusion approach with sufficient cost- and energy-efficiency for commercial power production.
1986	Photonic high-speed multichannel data recorder	SNL	A device that records multi-GHz, multihcannel photonic data, facilitating the study of high-speed, single-shot, transient phenomena over distances of several kilometers.
1986	Precision engineering research lathe	LLNL	A research lathe that has an overall contouring accuracy of 0.1 μm in its 100 × 100-mm work zone. This small two-axis computer-controlled turning machine can be used both for production of optical quality contoured parts and for research in precision metal cutting. Other applications include the manufacture of infrared and visible-light metallic optics, astronomical telescopes, and x-ray microscopes.
1986	Beamsplitter for low energy x rays	LLNL	An x-ray beamsplitter made of a thin multilayer film supported by a thin x-ray-transparent silicon nitride membrane. It is an x-ray analog of the optical two-way mirror, which divides an x-ray beam into a reflected and a transmitted beam, which permits manipulation of x rays. The principal application is the development of x-ray optical devices for micro-mechanics, microbiology, and surface science.
1985	Time-resolved imaging x-ray spectrometer	LLNL	A spectrometer using grazing incidence reflection from a large ellipsoidal mirror to direct the x-ray emission image onto the slit of an x-ray streak camera. It has a sensitivity three-to-four orders of magnitude greater and a time resolution three orders of magnitude higher than comparable instruments. The principal application is in x-ray laser research.

1979	Nd-doped fluorophosphate laser glass	LLNL, Owens Illinois	The glass to be used in the Nova Laser facility to determine the feasibility of producing thermonuclear fusion energy from fuel pellets implosively driven by laser light. The glass amplifies 1052-nm laser light with little spatial distortion, providing roughly twice the performance per unit cost in large laser systems like Nova.
1978	Diamond machining process	LLNL, Union Carbide	Process that allows direct fabrication of optical components using a single-point diamond tool and a specially constructed machine tool, which produces a variety of optical components, such as aspherical surfaces, conical surfaces, and flats with discontinuous surfaces, in a shorter time and at less expense than conventional processes. Applications include the manufacture of reflective metal optics for high-energy lasers and optical components for infrared and x-ray imaging.

Conclusions

There can be little doubt that the community of scientists and engineers working on inertial fusion around the world has provided broad technology spin-offs in a variety of fields and industries. This has been driven by the extremely challenging technical problems that the community faces and the technical strengths of individual inertial fusion researchers. We are confident that investmentsin the NIF, the ongoing ICF Program, and the development of inertial fusion energy will reap similar benefits in the future.

For further information or to gain contact with individuals knowledgeable about the spin-offs cited, please contact Howard Powell at Lawrence Livermore National Laboratory (e-mail: powell4@llnl.gov or phone: 925-422-6149.