LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

UCRL-BOOK-222681

Laser Fusion: The First Ten Years 1962-1972

R. E. Kidder

July 7, 2006

Inertial Confinement Nuclear Fusion: A Historical Approach by its Pioneers

LASER FUSION:
THE FIRST TEN YEARS
1962-1972

Ray E. Kidder

Introduction

This account of the beginning of the program on laser fusion at Livermore in 1962, and its subsequent development during the decade ending in 1972, was originally prepared as a contribution to the January 1991 symposium “Achievements in Physics” honoring Professor Keith Brueckner upon his retirement from the University of San Diego at La Jolla. It is a personal recollection of work at Livermore from my vantage point as its scientific leader, and of events elsewhere that I thought significant. This period was one of rapid growth in which the technology of high-power short-pulse lasers needed to drive the implosion of thermonuclear fuel to the temperature and density needed for ignition was developed, and in which the physics of the interaction of intense light with plasmas was explored both theoretically and experimentally.

Prologue

In August of 1956, I accepted an offer of employment in the Theoretical Division (T-Division) of the University of California Radiation Laboratory in Livermore California, popularly known as the “rad lab.” I had arrived in Livermore with an MS in mathematics, a PhD in mathematical physics, six years experience at the California Research Corporation (mostly in fluid mechanics), and no knowledge of nuclear weapons. I soon discovered that the physics of nuclear weapons was indeed as fascinating as I had hoped it would be. As a late-comer to the field (I was 33) I decided to focus my attention on the simplest thermonuclear system; a mixture of the two heavy isotopes of hydrogen, deuterium and tritium, that also had the virtue of being the easiest to ignite.

Easiest, but far from easy. No thermonuclear fusion explosion has ever been created without being ignited by means of a nuclear fission explosion - an atomic bomb! The goal of a ‘pure-fusion’ explosion, ‘pure’ because it did not employ fission, seemed unachievable at the time, but perhaps not impossible. A way might be found.

After a long period of studying the process of the ignition and burn of deuterium-tritium (DT) I concluded that the process could be described, approximately, in terms of a three-temperature model. The next task was to formulate a numerical method for solving the three-temperature system of equations, and finally to write a computer program to do the arithmetic. The latter was rapidly accomplished by Alex Cecil, an expert programmer and personal friend, and was ready for use in the late summer of 1960, four years after my arrival in Livermore.

Meanwhile, a small group under the leadership of Jim Wilson in B-Division[1] had begun design work on a ‘pure fusion’ device intended to produce a thermonuclear explosion of a small amount of DT. I was happy to collaborate with this group, having great respect for Jim’s remarkable technical ability and ingenuity. Maybe ‘pure fusion’ was possible after all.

At the same time, the late summer of 1960, Ted Maiman at the Hughes Malibu Research Laboratory reported the successful operation the first solid state (ruby) laser. The news of this event was received with great interest by a number of people at Livermore who recognized its potential application to the pure fusion problem. Those that I particularly recall were Stirling Colgate (M-Div), John Nuckolls (A-Div), Thomas Wainwright (T-Div), Jim Wilson (B-Div), and Ron Zabowski (A-Div). Further progress in the development and performance of the laser at Hughes was closely watched, with particular attention to the possibility, necessary to its application to pure fusion, that the laser could be controlled to produce powerful, short-duration, pulses of laser light.

In the Summer of 1961, one year after Maiman's discovery of the ruby laser, Hellwarth and McClung, also at Hughes, discovered and successfully applied the technique of cavity "Q-spoiling" as a means of producing the desired short pulses. In the same year, Snitzer, at the American Optical Company, showed that a laser could be made with any one of a number of rare-earth oxides disolved in glass, instead of the ruby crystal used by Maiman. This made it possible to use relatively inexpensive material in the form of large rods or disks of excellent optical quality as the laser medium, and offered the prospect of building pulsed lasers of greatly increased size and power.

The Beginning

As a result of the promising outlook for the development of high power lasers at this time, I carried out what might be termed "back-of-the-envelope" calculations in the fall of 1961 which suggested that a short-duration (less than 10 nanoseconds) very energetic (at least 100 kilojoules) laser pulse might be sufficient to compress to high density and to ignite a small quantity of thermonuclear (DT) fuel.

I informed John Foster, the Laboratory Director, of my calculations and conclusions, and expressed the view that LRL should initiate a laser-fusion project unless planned discussions with Maiman and Hellwarth at Hughes disclosed difficulties I had not anticipated.

I visited Maiman and Hellwarth on April 14, 1962, accompanied by Ken Trigger of LRL, a personal friend of Ted Maiman. These discussions disclosed no basic reason that the required very large laser-pulse energy could not be produced, while at the same time preserving adequate beam quality (brightness). I reported this affirmative conclusion to Foster promptly upon my return to the Laboratory and recommended that an exploratory laser fusion project be created.

---

(1) B-Division was responsible for the design of nuclear weapon "primaries," the 'primary' being the first stage of a two stage nuclear weapon. A-Division was responsible for the second stage, or 'secondary.'

The Physics Department, a new Laboratory Department led by Associate Director Ted Merkle, was formed in May of 1962. Shortly thereafter, Q Division (initially Q "Project") was created under my leadership as a Division of the Physics Department. It was both a theoretical and experimental Division largely concerned with the interaction of electromagnetic radiation (including laser radiation) with matter, and applications to thermonuclear fusion. This was the beginning of the LRL laser-fusion program described in 1963 to General Betts, director of the AEC's Division of Military Applications. Q Division's scientific staff grew rapidly, leveling off at a total of fifteen theorists and eight experimentalists (see list of personnel in Appendix C).

To summarize, the four physics developments preceding the commencement of the laser fusion program at Livermore that were of the greatest importance were:

EARLY STEPS TOWARD HIGH-POWER
SHORT-PULSE LASERS (PRE-1962)

LASER CONCEPT	Schawlow & Townes, *Phys. Rev.* **112**, 1940 (1958)
RUBY LASER	Maiman, *Nature* **187**, 493 (1960)
Nd-GLASS LASER	Snitzer, *Phys. Rev. Lett.* **7**, 444 (1961)
Q-SWITCHING	Hellwarth & McClung, *J. Appl. Phys.* **33**, 828 (1962)

STATUS: 300 Kw Peak Power
120 nsec Pulse

Shortly after we decided to launch a modest laser fusion effort at Livermore, it seemed desirable to let the then-existing laser community know of our interest in high-power laser development, and to seek its help. At the time, Keith Brueckner held the post of Vice President and Director of Research of the Institute for Defense Analyses (IDA) which had been looking into possible military applications of lasers for the Department of Defense. There were none better qualified than he to turn to in this regard, and on May 22, 1962, Johnny Foster wrote a letter to Keith outlining our interest and requesting his assistance (see Appendix A).

One result of this request was an invitation from Keith that I participate in the IDA Laser Summer Study on high power lasers and possible military applications that took place at the facility of the National Academy of Sciences, Woods Hole, Massachusetts, from June 17 to July 31, 1963. This was my introduction to the world of high power lasers and its practitioners.

After the laser project had been in existence at Livermore for approximately one year and had begun to assume noticeable proportions, it was deemed advisable to inform the AEC in Washington formally of its existence and purpose. As a result, the first official written disclosure of the existence and nature of the Laser Research Program at Livermore was sent in October of 1963 to Maj. General A. W. Betts, then head of the Division of Military Applications, with a letter of transmittal (see Appendix B) by my boss, Dr. Ted Merkle, Associate Director for Physics. An excerpt from this program letter that indicates the high power laser characteristics then thought to be required is given below:

LRL LASER RESEARCH PROGRAM

"I. INTRODUCTION

...Further progress in the development of high power lasers was watched closely by the Laboratory. Interest was considerably increased when the giant-pulse mode of operation was successfully demonstrated in 1961. As a result of the promising outlook for the development of high power lasers at this time, calculations were carried out to estimate the requirements which would need to be met by a laser in order that a small amount of thermonuclear fuel (DT) could be ignited by focusing the laser light upon it. These calculations indicated that a laser producing 10^5 joules of light in 10^{-8} seconds with an unfocused power density of 10^9 watts/cm^2 and a beam divergence of 10^{-3} radians would probably be required. Although these requirements were then far beyond the state of the art, there appeared to be no reason that they could not ultimately be met, and in early 1962 LRL began an exploratory research program to evaluate the feasibility of constructing the required high-power laser unit and to investigate suitable implosion and ignition configurations."

An Early Computer Calculation

The first computer calculations of laser-driven implosions at Livermore utilized a computer program that I had designed, and modified for this purpose. It was a one-dimensional, three-temperature (ion, electron, and radiation temperature), hydrodynamic code with provision for the heating of an ablator by the absorption of laser light to drive a spherical implosion of a metal shell (gold) containing gaseous deuterium-tritium (DT). (A modified version of this computer program was eventually declassified and published in the report: WAZER: A One-Dimensional, Two-Temperature Hydrodynamic Code, Ray E. Kidder and William S. Barnes, UCRL-50583, January 31, 1969).

A calculation done in August of 1964 with an ablator of frozen deuterium indicated that a laser pulse having an energy of at least 500 kilojoules, and a width no greater than 4 nanoseconds, would be required to achieve ignition of the DT and a modest gain of five (ratio of thermonuclear yield to laser pulse energy). This estimate was revised upward to 3 Megajoules (in 5 nanoseconds) by a Wazer computer simulation in 1966. The minimum pulse-energy required to achieve ignition had increased thirty-fold from the initial rough estimate made in 1962.

This estimate of the required energy, unsophisticated as it was, clearly showed that a very large increase in laser power and energy beyond the few joules then available would be needed, and that single pulses of shorter duration than ten nanoseconds would also be needed. We shall turn to the matter of short pulses first, and then describe the approach taken at Livermore to build more-powerful lasers.

Short Pulses

The first step in the generation of the short pulses needed for the laser-driven implosion of small targets and, more immediately for studying high-intensity light-plasma interaction physics, was to generate a train of short pulses by locking together in phase a large number of intra-cavity modes of laser oscillation. The cavity modes of slightly different frequencies would then periodically come into phase and reinforce each other at intervals equal to the cavity round-trip time and produce a train of short pulses.

This concept was first successfully applied at the Bell Telephone Laboratories in 1964 to mode-locking the Helium-Neon gas laser by means of synchronous intracavity modulation, and subsequently at the United Aircraft Research Laboratories in 1966 to mode-locking the Nd^{3+}-doped glass laser, the kind to be used at Livermore for fusion, by means of an intracavity saturable absorber.

Shortly thereafter, a method employing the nonlinear process of 2nd harmonic generation at the surface of a GaAs crystal was devised at the IBM Watson Research Center to measure the shape of the pulses from a mode-locked Nd-glass laser, and capable of measuring pulse widths of a picosecond (10^{-12} seconds) or less. The selection and amplification of a single mode-locked laser pulse needed for laser-plasma interaction experiments was successfully accomplished in 1968 at Livermore.

ULTRA-SHORT PULSE DEVELOPMENT (1964 - 1968)

MODE-LOCK	He-Ne	Hargrove, Fork, Pollock, APL 5, 4 (1964)
MODE-LOCK	Nd-Glass	De Maria, Stetser, Heynau, APL 8, 174 (1966)
PULSE-WIDTH MEASURED (4 - 6 ps)		Armstrong, APL 10, 16 (1967)
SINGLE-PULSE SELECTION		Kachen, Steinmetz, Kysilka, APL 13, 229 (1968)

The short pulses needed and their means of measurement were now available.

Powerful Lasers

The formidable laser pulse energy expected to be required to achieve ignition of DT made it clear that not only would many individual laser beams be needed to drive the implosion of the fusion target, but also that the energy delivered by each beam must be large to keep the number of separate beam-lines within reason. This latter requirement implied that the laser amplifiers and other necessary optical components comprising a beam-line must be of large aperture to insure that the light intensity to which they would be exposed did not attain values that would damage them.

At the time, there were only two lasers considered at Livermore to be candidates as possible laser fusion drivers; the Neodymium-doped glass laser (at 1.06 microns wavelength) and the atomic Iodine gas laser (at 1.3 microns), both radiating in the near infrared region of the spectrum. After gaining some experience in operating a small Iodine laser oscillator-amplifier system (in which the amplifier gain was reduced by means of the Zeeman effect in an inhomogeneous magnetic field to prevent parasitic oscillation), a choice was made in favor of the glass laser. We concluded that the glass laser and the Iodine laser had similar long-range potential as a fusion driver, but we found the glass laser to be easier to work with, so we decided in its favor.

The glass itself was an obstacle to maintaining good beam quality because its index of refraction was significantly intensity-dependent. This nonlinear optical effect could result in beam-degradation and ultimately optical damage to the glass due to self-focusing and filamentation of the beam. It followed that the less glass through which the beam had to pass, the better. Minimizing the glass in the beam of a large aperture laser required that the laser medium be configured in the form of relatively thin disks, and then tilted at such an angle (Brewster’s angle) with respect to the direction of the polarized beam being amplified that no light was lost by reflection at the surfaces of the disks. This tilt permitted the laser disks to be pumped through their faces rather than their edges by tubular flashlamps that surrounded them. A photo of the first glass disk laser amplifier at Livermore is shown in Figure 1. A sketch of the laser amplifier components and their orientation is shown in Figure 2 below.

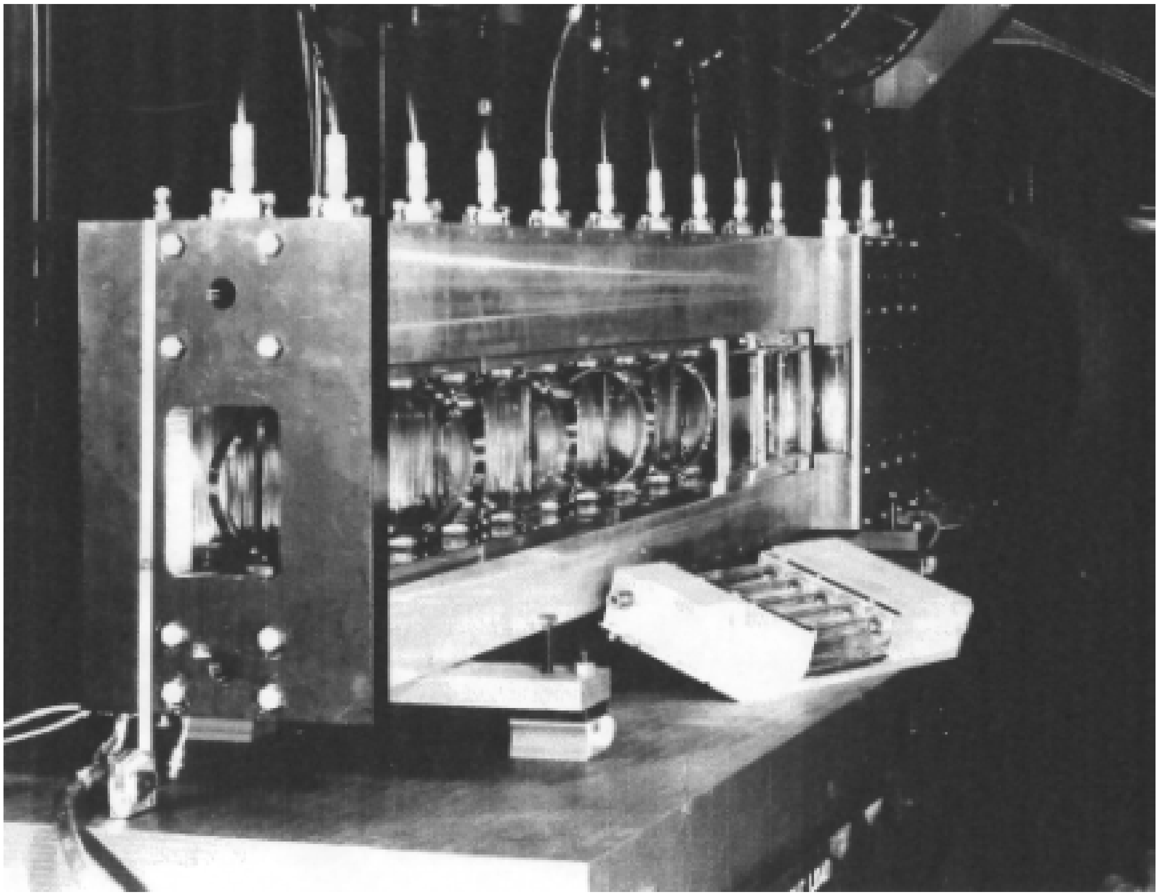


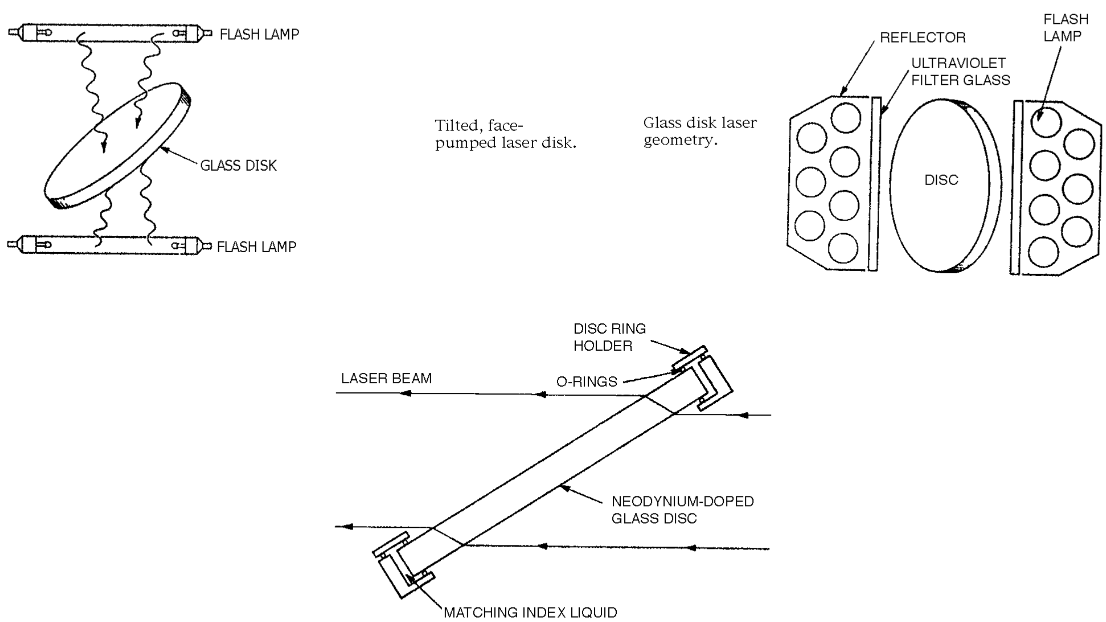
Figure 1

PHOTOGRAPH OF NEODYMIUM GLASS DISK AMPLIFIER

The disk amplifier head contains 16 Neodymium-doped glass disks, each 14 centimeters in diameter and 2.5 centimeters thick. The disks are pumped by 20 modules, each containing five series-coupled flashlamps. Each flashlamp module utilizes a maximum of 18 kilojoules delivered in 1 millisecond. A glass shield is placed between the flashlamps and the disks, both to filter out damaging ultraviolet light and to protect the disks from exploding flashlamps.

Figure 2

LARGE-APERTURE GLASS DISK LASER CONFIGURATION

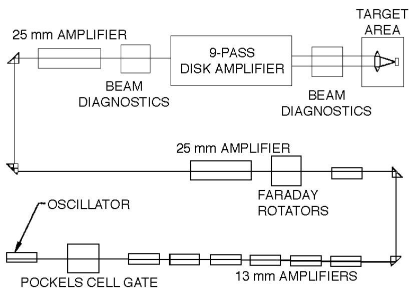


Cross section of glass laser disk.

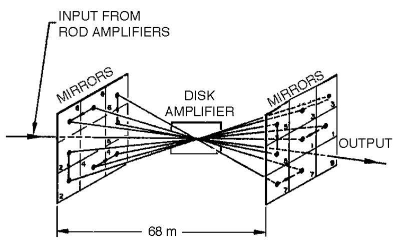
At the time the Nd-glass disk laser system was being designed, delivery schedules and the availability of funds limited us to one disk amplifier consisting of sixteen glass disks 14 cm in diameter. In order to efficiently extract the energy stored in the amplifier with a minimum input of energy, we elected to make it appear as though we had nine amplifiers in a row by reflecting the laser beam back and forth through the single amplifier nine times, the reflection being accomplished by means of quartz retroreflecting prisms as illustrated in Figure 3. To accomplish this, the two sets of reflecting prisms had to be placed a considerable distance apart (68 meters), and the laser system therefore came to be known as the “long-path” laser.

Figure 3

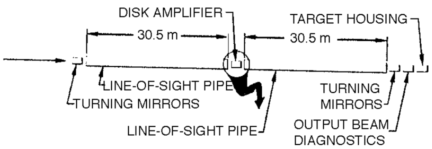
THE "LONG-PATH" LASER SYSTEM

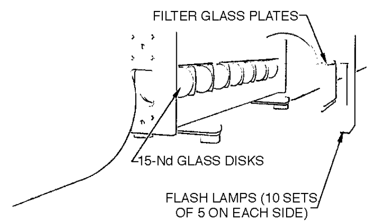


The long path laser system. A series of rod amplifiers provides input to the disk amplifier, which consists of fifteen Nd-glass disks 14 cm in diameter.



Laser beam paths through the disk amplifier. Most of the mirros have been replaced with prisms, as called for in the original design.





The disk amplifier portion of the long path laser system. A laser pulse from the rod-laser section enters the disk system and makes a series of nine distinct passes through the glass disks, the line-of-sight pipes reduce air turbulence and can be filled with helium, if necessary, to reduce noninear effects.

Although single pulses with up to 400 joules of energy had been produced with this laser, it was routinely used to produce pulses of several tens of joules in a few nanoseconds with a beam divergence of approximately 50 micro-radians. The output beam could be focused to intensities in excess of 10^{14} watts/cm^2, intensities in the range needed for our studies of the light-plasma interaction, with an optically slow (f/7) focusing lens.

The laser also demonstrated, on a small scale, those design features that were expected to be employed in a future large laser system capable of achieving thermonuclear ignition: Large aperture, face-pumped, Neodymium-doped glass disks tilted at Brewster's angle, with multipassing for efficient energy extraction.

Application to Producing Hot Plasma

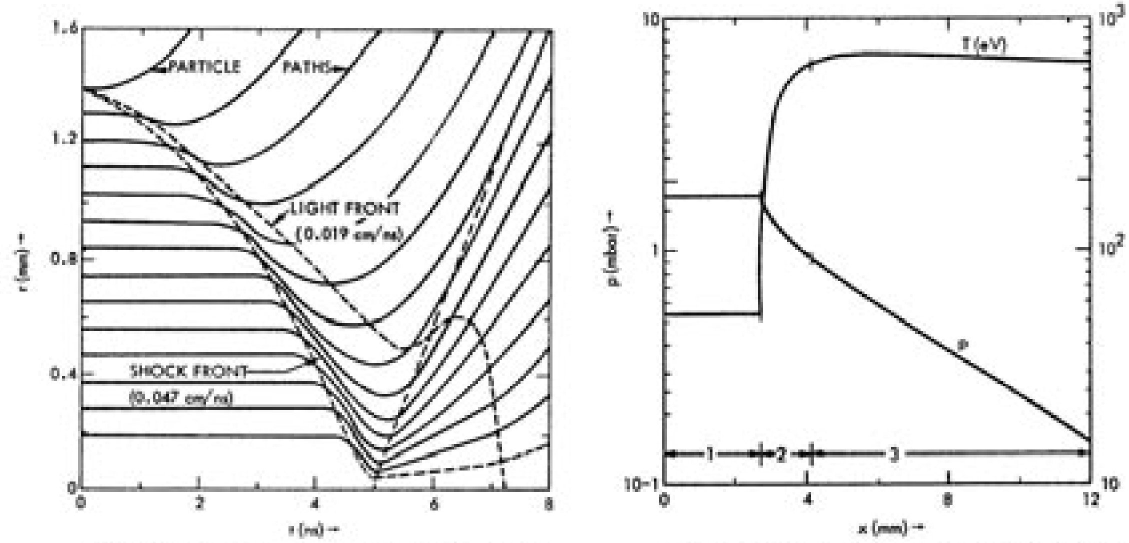
Although one-dimensional, three-temperature computer calculations of laser-driven implosions of spherical capsules containing DT fuel had been carried out as early as 1964, it was not until after September of 1971, seven years later, that we at Livermore were allowed to discuss the importance of high fuel-compression or how it might be achieved by means of lasers. Classification rules forbade it.

During that time, we were permitted to describe the possible use of lasers to heat plasmas to high temperature and pressure, provided the conditions were <u>not</u> such as to produce high compression. I published a paper in 1968, for example, describing the results of a one-dimensional computer calculation of the subsonic heating of a bare sphere of deuterium gas, and the structure of the ablation-driven convergent shock that was produced as shown in

Figure 4 below. The number of thermonuclear neutrons to be expected from the $D(d,n)^3He$ reaction was also presented.

Figure 4

ABLATION-DRIVEN SHOCK IN DEUTERIUM GAS



Subsonic heating of deuterium gas sphere. Radius r versus time t plot of particle paths, shock front and light front. (10 kJ in 5 ns, D_2 : v_s = 385 cm³/g).

Light-induced shock in deuterium. Pressure p and temperature T versus distance x. Indicated regions are the pre-compression shock (1), Chapman-Jouguet deflagration (2), and isothermal expansion (3). (I = 10⁴ GW/cm², v_s = 300 cm³/g, t = 16 ns).

The prohibition against discussing the importance of high fuel-compression was lifted in late 1971, following the disclosure by N.G. Basov of the Lebedev Physical Institute, Moscow, that high compression may be achieved by laser-driven implosion. He stated in a paper presented at the European Physical Society Meeting on "Laser-Plasma Interaction," September 1971, Hull, England:

> "It is estimated that values of compression between 100 and 1000 can be achieved by means of spherical hydrodynamic plasma implosions."

The significance of being able to achieve high fuel compression can be appreciated from the fact that the least amount of laser-pulse energy required to achieve ignition scales as the *inverse square of the fuel density.* Compressing the fuel to high density is indeed essential to reduce the laser-pulse energy requirement to an achievable level, and it must have seemed very odd to others working on laser fusion at the time that we at Livermore appeared to disregard this basic fact.

Light-Plasma Interactions

The interaction of intense laser light with a plasma resulted in the excitation of a variety of interesting nonlinear effects, most of them bad from the standpoint of laser fusion. These effects were extensively studied both theoretically and experimentally during the ten-year period ending in 1972 that we are considering. An idea of the influence they had on the opinion of one observer of the laser fusion work at Livermore can be seen from the following recollection.

I believe it was in 1967 when Edward Teller attended a meeting of a small group of us who were working on laser fusion. One of the group was at the blackboard explaining the unstable growth of plasma waves driven by laser light. Teller listened to the explanation with a deepening scowl (it is well-known that he can muster a formidable scowl), and finally could restrain himself no longer. Interrupting the speaker in mid-sentence he held up his hands and said:

"Wait a minute. Wait a minute! Are you telling me that laser fusion involves REAL plasma physics?"

"Yes, sir, it does", said the speaker.

To which Teller replied with profound conviction and disappointment,

"Well, (long pause), it will never work."

We list below a number of light-plasma interaction processes that are of importance to laser fusion (that involve "real" plasma physics).

INSTABILITY & HOT ELECTRONS

Decay	Du Bois & Goldman, Phys. Rev. Lett. 14, 544, (1965)
Stimulated Raman Scattering	Bloembergen & Shen, Phys Rev. 141, 298 (1966)
Decay & Oscillating Two-stream	Nishikawa, J. Phys. Soc. Japan 24, 1152 (1968)
Superthermal Tail	Kruer & Dawson, Phys. Rev. Lett. 25, 1174 (1970)
Self-focusing	Palmer, Phys. Fluids 14, 2714 (1971)
Stimulated Brillouin Scattering & Hot Electrons	Shearer et al, Phys. Rev. 6A, 764 (1972)

ENERGY & MOMENTUM

Resonant Absorption	Friedberg et al, PRL 28, 795 (1972)
Density-profile steepening	Kidder, U.S. - Japan Seminar (1972)

The instabilities listed produce anomalously energetic or "hot" electrons in the laser-heated ablating plasma that drives the convergent implosion of the DT fuel. These hot electrons can, by virtue of their higher energy, penetrate into the fuel, heat it, and thus make it more difficult to compress to the high density needed.

The first indication of the production of hot electrons was found in numerical computer simulations of the light-plasma interaction by Kruer and Dawson at the Princeton Plasma Physics Laboratory in 1970. They found a "super-thermal tail" added on to the main energy distribution of the plasma electrons. The existence of these hot electrons was observed, somewhat by accident, in experiments by Shearer and co-workers at Livermore in 1971, and also by the Lebedev group in Moscow.

The Livermore experimenters were observing the interaction of a focused laser beam ($\sim 2 \times 10^{14}$ watts/cm^2) with a target of deuterated polyethylene (CD_x) plastic, and measuring the number of neutrons produced by deuterium fusion. As a control, they repeated the experiment with ordinary polyethylene that contained no deuterium, expecting that the neutrons would disappear. When the detectors continued to detect scintillation pulses, it became clear that penetrating radiation other than fusion neutrons was responsible. Further experiments identified the penetrating radiation to consist of hard x-rays that could only have been produced by anomalously energetic plasma electrons. Hot electrons were an unfortunate reality.

In addition to producing hot electrons, stimulated Brillouin scattering (SBS) and stimulated Raman scattering (SRS) can cause laser light to be reflected rather than absorbed by the plasma, and thus wasted. (It is interesting to note that the effect known as "phase-conjugate reflection," in which light obliquely incident upon a surface is reflected directly back in the direction from whence it came, was first observed in 1971 in light-plasma interaction experiments by the laser-plasma group at the Max-Planck-Institute for Plasma Physics in Garching, Germany, and attributed to SBS.)

The undesirable propensity of the light-plasma interaction to produce hot electrons and reflect laser light is the result of intense light interacting with a nearly collisionless plasma. Light with a wavelength as long as that of Nd-doped glass (1.06 mm) cannot penetrate a plasma whose electron density exceeds 10^{21} electrons/cm^3, a density at which the plasma is essentially collisionless at the necessarily high temperatures that exist in the interaction region. At shorter wavelengths, the laser light can penetrate into denser, more collisional plasma, the density increasing strongly (as ω^2) with the frequency ω of the laser light, and the undesirable light-plasma interaction effects are reduced or eliminated.

Collisional absorption of penetrating, short wavelength light in a relatively dense plasma would avoid the "real plasma physics" difficulties that worried Edward Teller, but powerful lasers producing shorter wavelength radiation than that of the Nd-doped glass laser were not then available.

Status of Laser Fusion - 1972

By the Spring of 1972, ten years after the start of the laser fusion program at Livermore, much had been learned. Ultra-short light pulses had become available. The face-pumped, Nd-doped glass disk laser that would be the leading contender as a laser-fusion driver for the next two decades had been developed and put into service. The nature and effects of the plasma and fluid instabilities that appeared in the light-plasma interaction region had been explored (and deplored) both theoretically and experimentally. The status of laser fusion at this time is briefly outlined below.

STATUS OF LASER FUSION - 1972

LASERS:	Nd-Glass Disk	TARGETS*:	D_2 Ice
	CO_2 TEA		CD_2 Plastic
	Ultra-short Pulse		

THEORY:	Plasma & Fluid Instabilities	EXPTL.:	Hard X-rays
	Hot Electrons (esp. CO_2)		Hot Electrons
	Coupling Problems		Instabilities

* DT-filled Glass Microballoons did not appear until 1974.

As indicated in the outline, a laser had entered the picture that we have as yet not considered. This is a laser in which carbon dioxide gas (CO_2) at atmospheric pressure is made to 'lase' by means of a transverse (to the direction of light propagation through the laser) electric discharge, 'TEA' being the acronym for Transverse Electric Atmospheric. The CO_2 TEA laser radiates infra-red light at a wavelength of 10.6 μm, ten times as long a wavelength as that of the Nd glass laser, a property that would exacerbate the hot electron and light-plasma coupling difficulties that have been described.

This type of laser attracted considerable interest because it gave promise of high power at relatively low cost, and because it had the potential of being pulsed at a repetition rate of a few pulses per second that would be needed if laser fusion were to be useful for the production of electric power. As a result, a serious effort was made at the Los Alamos National Laboratory to develop the pulsed CO_2 laser as a laser fusion driver. Light-plasma interaction and coupling difficulties were not satisfactorily overcome, however, and the development was finally abandoned.

In the meanwhile, computer codes that were specially designed for the purpose of simulating laser-driven implosions were being developed by George Zimmerman and co-workers at Livermore, and independently by Keith Brueckner and co-workers at KMS Fusion, Inc., in Ann Arbor, Michigan. These simulations suggested to both groups that it might be possible to achieve "breakeven" with as little as one kilojoule of laser light; that is, produce as much fusion energy out as laser energy in.

Shortly after the declassification of compression, a landmark paper was presented in May of 1972 at the International Quantum Electronics Conference in Montreal by John Nuckolls, Lowell Wood, Albert Thiessen, and George Zimmerman from Livermore, and subsequently published in the international science weekly Nature, September 15, 1972. Their computer simulations of a direct-drive implosion of a droplet of liquid DT suggested that central "hot spot" fuel ignition, together with 10,000-fold fuel compression, could be achieved by properly programming the time-dependence of the laser power driving the implosion, and that "one kilojoule of laser energy may be sufficient to generate an equal thermonuclear energy;" sixty kilojoules being sufficient to generate a 30-fold energy gain. The method and results described were viewed as a "break-through," and prompted a major increase in laser fusion interest both in the U.S. and abroad.

Breakeven at a Kilojoule?

The basic challenge in igniting thermonuclear fuel with lasers lies in achieving extremely high fuel-compression by means of a strongly convergent, highly symmetric, spherical implosion. If the implosion symmetry is poor, the amount of laser energy needed to ignite the fuel becomes excessive.

Obstacles to the achievement of strongly convergent, highly symmetrical spherical implosions are presented by fluid instabilities (Rayleigh-Taylor, Richtmeyer-Meshkov), and the fact that high power laser beams are notably nonuniform in intensity and inherently ill-suited to the task of uniformly illuminating a spherical surface. At the time, however, the proponents of 'breakeven at a kilojoule' believed that these obstacles to implosion symmetry were likely to be quickly overcome, as indicated by the following chronology:

NEWSWEEK (1/31/72):

According to Lowell Wood and John Nuckolls of the Lawrence Livermore Laboratory, The Basov [Soviet] team is likely to reach this so-called "break-even point" within the next year, slightly ahead of the Americans.

IQEC CONFERENCE (Montreal, 5/7-11/72):

As if to give proof to the disclosure by Edward Teller during the 1972 IQEC in Montreal that current U.S. policy concerning fusion research enabled the first major declassification in the nuclear energy field in 15 years, various AEC-supported research papers were delivered by J. Nuckolls, L. Wood, A. Thiessen, and G. Zimmerman of the Lawrence Livermore Laboratory dealing with the current superhigh-density approach to laser fusion and the LASNIX computer program used to simulate the implosion-thermonuclear burn of spherical DT pellets. (IEEE Spectrum, January 1973, emphasis added)

NUCKOLLS, WOOD, THIESSEN & ZIMMERMAN (Nature, 9/15/72):

> Also < 1 kJ of light energy is sufficient to generate an equal quantity of thermonuclear energy, if optimally employed.

KMS INDUSTRIES INC. SHAREHOLDERS REPORT (AUGUST 1973):

> Your company predicted to the U.S. Atomic Energy Commission that it would reach breakeven in energy before December 31, 1973.

These predictions of 'breakeven' in 1973 failed to materialize. The problem of achieving adequately symmetric laser-driven implosions, while combating the "real plasma physics" deplored by Edward Teller, would engage the attention of the laser fusion community for the next thirty years, and continues to do so.

The declassification referred to by Edward Teller was possible because the computer calculations of Nuckolls, et al., referred to the implosion of a bare droplet of liquid DT, a featureless configuration not thought to reveal anything of nuclear weapons significance.

Epilogue

The first ten years of laser fusion was a period in which much of the basic science and technology that would support the future program was developed.

- High-power short-pulse lasers capable of being scaled up to much larger size had become available.

- The physics of the high-intensity light-plasma interaction had been elucidated both theoretically and experimentally.

• Sophisticated computer models and programs had been developed to study the details of the process of implosion to high density, ignition, and propagating thermonuclear burn.

An excellent analytical and computational study of the status and prospects of laser-driven fusion as of 1973 was published the following year by Keith Brueckner and his collaborator Siebe Jorna in the Reviews of Modern Physics.(**Laser-driven Fusion**, Rev. Mod. Phys. 46, 325, April 1974). Much work remained to be done, but the basics were largely in place.

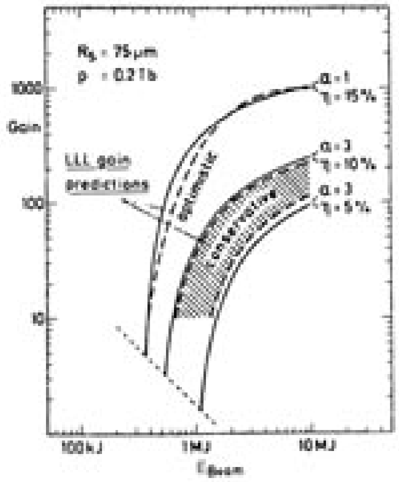
In addition to the impetus provided by the relaxation of classification and the predictions of the possibility of breakeven at a kilojoule, the laser fusion concept was given a powerful boost by the Arab oil embargo in the Fall of 1973. During its first ten years of existence, Livermore's laser fusion program had been entirely supported as a nuclear weapons-related research program, but now there was serious talk of utilizing laser fusion to breed fissile fuels for fission reactors and/or to generate electric power. (It continues to be funded by the Department of Energy as a Defense Program, however, rather than as an Energy Program.)

In 1976 a simple model of a fusion target was devised by the author (and later significantly improved by J. Meyer-ter-Vehn at the Max-Planck Institute of Quantum Optics in Germany) that provided a straightforward physical interpretation of the factors that govern the energy gain of fusion targets (an interpretation not readily discernable from complicated computer simulations) and yields useful, quantitative results. More specifically, it provides a relationship between the Energy Gain (G) (ratio of thermonuclear yield to laser pulse energy) that can be achieved by means of a laser-driven implosion of a target containing DT fuel, and the amount of laser pulse energy (E_{beam}) needed to drive the implosion.

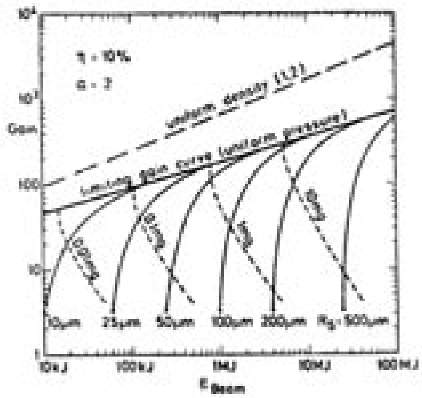
The model considers a spherical mass of DT fuel divided into two concentric, adjoining regions: A central region or 'spark' that is hot enough and large enough to ignite (T = 5 keV, $\rho R = 0.4\ g/cm^2$), and a surrounding region that is highly compressed and as cold as can be managed. The two regions are assumed to have the same pressure. The central 'spark' ignites, and initiates a thermonuclear burning wave that propagates outward through the surrounding highly compressed fuel. Burning is halted by disassembly of the exploding fuel. Curves of Gain versus laser-beam energy are shown in Figure 5 below.

Figure 5

THERMONUCLEAR ENERGY GAIN VS. LASER-BEAM ENERGY



Fit of the present gain model to the 'conservative' and 'optimistic' gain predictions obtained at Livermore on the basis of extensive code simulations. The LLL results correspond to a spark radius R_s = 75 µm and a central pressure p = 0.2 Tbar; the 'conservative' band is well reproduced with an isentrope α = 3 and an hydroefficiency ranging between 5% < η < 10%, whereas the 'optimistic' curve corresponds to α = 1 and η = 15%.



Gain curves for fixed isentrope α and hydroefficiency η and increasing spark radius R_s. Lines of equal fuel mass M_F (short dashes) are labelled by the mass value. Limiting gain curves are shown for the present model assuming uniform pressure (fat solid line) as well as for the Kidder-Bodner model assuming uniform density (long dashed line).

The three free parameters of the model are: The implosion efficiency (h) (the energy delivered to the uniform-pressure DT fuel, divided by the output energy of the laser driver); the pressure (p) of the compressed DT fuel (or, alternatively, the 'spark' radius R_S), and the isentrope (a) (the energy delivered to the compressed fuel surrounding the 'spark', divided by the lesser amount of energy that would be required to achieve the same compression isentropically).

Assuming a spark radius (R_S) of 75 mm, an isentrope (α) equal to 3, and the efficiency (h) to lie between 5 and 10 %, all being physically reasonable values, the left-hand figure of Figure 5 shows that the Gain vs. Energy curves of the model bracket the results (then believed be conservative) of a series of detailed LASNEX computer simulations that were conducted at Livermore. These three parameter values are seen to characterize the results of the computer simulations very well. (For purposes of illustration, the figure to the right shows Gain vs. Energy curves for a wide range of values of the spark radius between 10 µm and 500 µm, assuming that α=2 and η=10%.)

In the twenty years since 1972, the output of pulsed lasers for laser fusion has increased a thousand-fold, from 100 joules to 100 kilojoules in the case of the Nova laser at Livermore. Harmonic generation (2ω, 3ω, 4ω) in a nonlinear optical medium such as a KDP crystal has been used to produce shorter wavelength light to improve the beam-plasma coupling and minimize the production of 'hot' electrons. An efficiency of more than 50% has been achieved in generating the third harmonic of the light from a Nd-glass laser.

The difficult problem of obtaining uniform illumination of a capsule containing DT, in order to drive a spherically-symmetric implosion, has been addressed by first converting the laser light into soft x-rays within a spherical cavity or 'hohlraum,' and then using these x-rays to drive the implosion of a capsule suspended within the cavity. This approach to beam-smoothing is referred to as ‘indirect drive’, as opposed to ‘direct drive’ in which the capsule is directly illuminated by the laser, and was considered to be classified by the U.S. government until the Fall of 1980.

The declassification of the technique of indirect drive was the result of events surrounding the case of the *United States of America vs. The Progressive, Inc. et al*, *March 19, 1979*, concerning the publication of an article by Howard Morland in the Progressive magazine that was alleged to contain H-bomb secrets. The following general statements were declassified in 1980.

> In thermonuclear weapons, radiation from a fission explosive can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel.
>
> In some ICF [Inertial Confinement Fusion] targets radiation from the conversion of focused energy (e.g., laser or particle beam) can be contained and used to transfer energy to compress and ignite a physically separate component containing thermonuclear fuel.

Since that time, optical beam-smoothing techniques (Induced Spatial Incoherence, Smoothing by Spectral Dispersion, etc.) that are applicable to direct drive, i.e., not involving the conversion of light into x-rays, have been proposed and are being explored. The purpose of these techniques is to reduce the spatial coherence of the laser light so that spatial intensity variations in the focused light used to drive the implosion are minimized.

It is currently predicted at Livermore that DT ignition and modest (ten-fold) energy-gain can be achieved using indirect drive with one-to-two megajoules of 3rd harmonic (3ω) Nd-glass laser-pulse energy. This is the goal of the National Ignition Facility (NIF) being built at Livermore. A laser of similar capability, Laser Megajoule (LMJ), is being constructed at Bordeaux, France. To succeed will require careful attention to proper pulse-shaping, target designs that minimize the growth of fluid and plasma instabilities, and the achievement of highly symmetrical spherical implosions.

If the proposal is carried out and is successful, the hydrogen bomb will have been finally ‘tamed’ and brought into the laboratory, first for purposes of scientific research, and perhaps later for commercial applications such as the breeding of fissile fuels and the generation of electric power.

The story of Laser Fusion or, more generally the story of Inertial Confinement Fusion, is by no means over, but my narrative must end here. It has been written from my personal perspective at Livermore, and of course does not do justice to the many important contributions made by workers at other laboratories both in the United States and abroad, or indeed to much of the work of my colleagues at Livermore itself. For this I apologize.

This work was performed under the auspices of the U.S. Department of Energy by University of California, Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

List of Figure References

Figure 2.

J.E. Swain, R.E. Kidder, K. Pettipiece, F. Rainer, E.D. Baird, and B. Loth, **Journal of Applied Physics** 40, 3973 (1969).

Figure 3.

S.W. Mead, R.E. Kidder, J.E. Swain, F. Rainer, and J. Petruzzi, **Applied Optics** 11, 345, (1972).

Figure 4.

R. E. Kidder, **Nuclear Fusion** 8, 3, (1968).

Figure 5.

J. Meyer-ter-Vehn, **Nuclear Fusion** 22, 561 (1982).

Appendix A

Copy

Dr. Keith A. Brueckner May 22, 1962
Vice President and Director of Research
Institute for Defense Analyses
1710 H Street NW
Washington 6, D.C.

Dear Keith:

During your recent visit to the Livermore Laboratory on May 16, we discussed with you our interest in high-power lasers. We believe that the laser may have some important applications to the work of this Laboratory, depending on the output power and energy that can be achieved, and have at present a small group of our people looking into these applications and the associated laser requirements.

In view of the potentialities of the high-power laser, we feel that it is important that we be kept fully informed as to developments in this area on a continuing basis. In particular, we believe that the results of the recently completed proposals for the development of high power lasers and the investigation of the interaction of laser beams with surfaces should be made available to us This information in some cases will be of a "Company Confidential" nature, and of course we will comply with whatever restrictions are imposed on its handling. In turn, it is possible that some of the special skills available at LRL may be helpful in the development of a high-power laser.

I would appreciate your bringing to the attention of the appropriate people our interest in the development of a high-power laser. Please let me know how we may keep informed about the progress of this work.

Sincerely,

John S. Foster, Jr.
Director
LRL, Livermore

JF/hb
Bc R. Kidder
T. Merkle

Appendix B

Copy

University of California October 23, 1963
Lawrence Radiation Laboratory
Livermore, California

Major General A. W. Betts
Director, Division of Military Applications
U.S. Atomic Energy Commission
Washington, D.C.

Dear Sy:

For some time now we have been investigating possible applications of Lasers to weapons physics. This work, though modest in extent, is progressing rapidly and shows promise of making some unique contributions. . . .

Knowing your strong interest in new developments of this sort, we enclose a brief review of our Laser program.

Sincerely,

T.C. Merkle
Associate Director

TCM: gp

Cc: Maj. General A. W. Betts
Dr. J. S. Foster
Dr. R. E. Kidder
File (2)

Appendix C

GENRAL JOB DESCRIPTION OF
Q DIVISION PERSONNEL

QUANTUM MANY-BODY PHYSICS

Conway, John
DeWitt, Hugh
Garrison, John
Morrison, Harry
Wong, Jack

THEORETICAL LASER PHYSICS

Barnes, William (50%)
Fleck, Joseph
Harrach, Robert
Kidder, Ray
Scofield, James
Shearer, James (50%)

RADIATIVE TRANSFER & OPACITY

Grasberger, William
Zink, William

CODE DEVELOPMENT & PROGRAMMING

Barnes, William
Cecil, Alex

EXPERIMENTAL LASER PHYSICS

Gregg, David
Kachen, George
Mead, Warren
Petruzzi, Joseph
Pettipeice, Kenneth
Rainer, Frank
Shearer, James (50%)
Swain, Jams

EQUATTION OF STATE-THEORY

Einwohner, T.
Ree, Francis