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A BRIEF HISTORY OF THE LOS ALAMOS LASER PROGRAMS

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Abstract

The laser programs at Los Alamos began in 1969 to investigate the feasibility of laser-induced fusion. However, within a year they had been expanded to include a number of other applications including laser isotope separation. These programs now compose a substantial part of the Laboratory's research programs.

Introduction

This paper is a brief history of the principal laser activities at Los Alamos, all of which were interrelated. The paper emphasizes why the activities were started rather than what was done and who did it.

The laser programs at Los Alamos originated in work in two apparently unrelated fields: fusion research and nuclear rocket propulsion. Both studies were pursued actively at Los Alamos for a number of years before the invention of the laser in 1960, but another eight years passed before the laser was developed enough to be useful in our areas of interests.

Foundations

Thermonuclear or fusion research developed along two very different paths: one championed by Edward Teller was the development of thermonuclear weapons, and the other espoused by Jim Tuck was the development of controlled thermonuclear reactions (CTRs) for utility electric power generation. Accomplishments in both fields were essential to developing what is known today as laser fusion, a somewhat ambiguous term. Weapons physics provided the mathematical tools and understanding for the creation of the very small thermonuclear explosions basic to this process. On the other hand, CTR research developed the field of plasma physics, which provided the tools and understanding for pursuing laser matter interaction physics.

Conventional CTR deals with low-density plasmas of thermonuclear fuel, generally a mixture of deuterium and tritium (DT), contained and insulated from the surrounding environment by carefully constructed magnetic fields. If one assumes an optimum temperature in the fuel (about 100 million K for DT), the energy released is proportional to the product of the particle density and the containment time $N\tau$. To pay for the energy supplied to heat the plasma and supply the radiation losses (scientific breakeven) the Lawson criteria must be met: $N\tau \sim 10^{14}$.

In contrast, inertial containment fusion burns a high-density fuel in an explosive manner. The containment time is proportional to the distance an expansion wave has to move at the speed of sound in the hot fuel (or the radius R of a spherical system). The speed of sound in hot fuel provides a criterion for breakeven in engineering units of $\rho R = 0.2 \text{ g/cm}^2$. In both cases the criterion for efficient fuel burnup with satisfactory net energy gain is almost a factor of 10 higher than the criterion for breakeven. In the case of inertial containment, this criterion shows that the amount of fuel needed and therefore the energy invested decreases inversely with ρ^2 . A very high power density is needed for the absorbed energy to create an ablation pressure sufficient to compress the fuel to high density. Also, at a high enough fuel density, the alpha particles released in the fusion reaction are stopped in a thin layer of fuel. Thus, the fuel is heated to ignition temperatures so that a burning or deflagration wave can propagate into relatively cold fuel. Calculations based on codes developed in the weapons programs, but suitably modified for this process, were used to arrive at the laser power density focused on the pellet surface of approximately 100 TW/cm^2 . The laser energy required was first estimated to lie in the few hundred kilojoule range. Then the energy dropped to values below 1 kJ as compressions of 10,000 times solid density were contemplated. As experiments exposed the hard facts dictated by nature, this estimate has risen again to values higher than originally estimated, now a few megajoules. Proposed compressions are now limited to 1000 times solid density. To meet both the power and energy requirements, the laser pulse length has lengthened from 1 to $\geq 10 \text{ ns}$.

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Program Development

At Los Alamos, interest in using laser-initiated fusion as the basis for advanced propulsion systems for interplanetary missions started in 1968 within the nuclear rocket propulsion program (Project Rover, later Merva). Of course as work progressed, we realize that generating utility electric power by this technique would be easier than by using traditional methods. Stan Ulan had proposed the explosion of atomic bombs or even hydrogen bombs at the rate of several per second some distance below an oscillating pusher plate (momentum smoother) spring mounted to a space ship. This concept was explored in simulation experiments at General Atomics by Ted Taylor and coworkers (Project Orion). In principle, this technique could boost a space-ship weighing several thousands tons into orbit and beyond from the Earth's surface. A certain lack of aesthetic appeal in riding on top of exploding nuclear bombs and the objection to dispersing radioactive debris into the atmosphere terminated Project Orion. Our engineering studies indicated that if the propulsion system weight could be kept low enough, many small thermonuclear explosions used in a similar system, started up in orbit began might produce a very attractive driver for manned interplanetary missions. We began with a study on how to use a small Rover reactor to drive a gas dynamic CO₂ laser (GDL) for military applications and extended this study to a high-energy, short-pulse system for laser-initiated fusion. To generate nanosecond pulses, a much higher operating pressure (several atmospheres) was needed than pressure than GDLs require to operate satisfactorily. In addition, the magnetic field used to optimize the pusher plate performance could supply electrical energy to drive the CO₂ laser. So we turned our attention to electrical pumping schemes.

At that time (June 1969), glass lasers of a few joules output were being developed, and mode-locking techniques had produced 10 PS pulses with some degree of consistency. Electric-discharge-pumped CO₂ lasers were restricted to low-pressure, longitudinally pumped devices for a long pulse or cw operation. However, medium-pressure, flow-stabilized CO₂ lasers being under investigated at the Air Force Weapons Laboratory.

We calculated that we would need to develop lasers with outputs of several hundred kilojoules of energy delivered in a nanosecond or less to burn pellets with a satisfactory energy gain. The only laser that might produce such an output with a repetition rate of at least 1 pps was a large-volume CO₂ laser operating at a pressure of at least 3 atm. To produce a stable glow discharge for pumping such large volumes of gas at high pressures, we developed the electron-beam-controlled discharge technique in which all the electrons needed to carry the desired pumping current were produced by the electron beam. This technique was demonstrated in January 1970 almost simultaneously with a similar, but independent, development at AVCO that they were considering for low-pressure operation.

The calculations and pellet design criteria were established using modified hydrodynamic and radiation transport computer codes developed for the weapons programs, whereas the laser absorption and transport physics was based on the understanding of plasma physics developed in the CTR programs. Thus, the previous statement that both types of thermonuclear research provided the basis for laser fusion is justified.

We recognized that extensive research and development in four areas would be necessary if laser fusion were to become a reality. These areas were (1) developing suitable lasers; (2) establishing an understanding of absorption and energy transport by experiments; (3) developing better pellet design codes; and (4) developing fabrication techniques for complex pellets.

Soon after serious work started in Los Alamos, we contacted numerous groups both in the United States and in the Soviet Union, France, Germany, Japan, and England. In general the work in these countries was at about the same stage of experimental development or at a lower level. However, the theoretical work at Livermore, which had been in progress for a number of years, was further advanced than ours.

In early 1970 a major program was initiated at Los Alamos in each of the four areas. Although the primary effort in laser development was on the CO₂ laser, we recognized that the interaction physics might prove to be optimum for a different wavelength. Therefore, the program plans included the development of a picosecond glass laser with harmonic generation crystals to obtain interaction data at wavelengths of 1, 1/2, 1/3 and 1/4 μ m. We also started a HF chemical laser program to give data at the 2.7 μ m wavelength and to explore the possibility that HF might result in a lower cost laser than would CO₂. A short-wavelength gas laser of the excimer variety was studied to provide a backup for CO₂ in case short wavelengths were needed. A 10 J output in the ultraviolet region had been obtained from a xenon laser in a cooperative program between Maxwell Labs and Los Alamos.

Early in the program we decided to establish a broadly based laser development and applications program that would include military uses, laser photochemistry and isotope separation, and nonlinear optics applied to spectroscopy and biology.

By the mid 70s a single-beam CO₂ laser chain was operating at the level of a few hundred joules, and a dual-beam CO₂ laser (Gemini) was operating at 1 kJ (with a 1-ns pulse). Both lasers were providing interaction and implosion data; the six-beam kilojoule Helios laser was being built and a 100-kJ CO₂ laser was being designed. In addition, considerable data had been obtained on interaction physics at 1 μ m using two glass lasers. By 1976 we used one of these lasers to produce a second-harmonic green light of sufficient intensity to start experiments. We had obtained 1-ns operation of an HF oscillator and had used it to extract energy from an HF amplifier. A program on excimer lasers produced a number of promising laser candidates. Unfortunately, the HF and excimer programs were cancelled soon after because of budgetary limitations.

Early measurements indicated that hot electrons and high-energy ions were being produced in substantial quantities by both 10.6- and 1.06- μ m radiation. The dominant absorption process appeared to be resonance absorption rather than a combination of inverse bremsstrahlung and plasma instabilities as had been previously believed. Both the theoretical prediction and experimental measurements for this mechanism indicated that although troublesome (more so for 10.6- μ m than for 1.06- μ m radiation) hot-electron energy would lie within acceptable bounds for optimized targets. It did, however, push the required laser energy into the megajoule region for a useful energy multiplication because hot electrons preheat the core making compression difficult.

Current Status

Subsequent careful experiments with Helios at energies up to 8 kJ showed substantial increases in fuel density and neutron production in ablatively driven pellets. But, they also indicated a hotter electron component than was previously measured. To increase the absorption of the longer wavelength radiation and to improve symmetry, we have explored hollow targets. Although they increased the absorption to an acceptable level, they created other problems. Experiments at 0.53- and 0.35- μ m wavelengths have indicated an acceptable hot-electron temperature and good absorption of the light. As a consequence, we are studying the use of KrF as an alternative to CO₂. Present estimates indicate that between two and four times as much energy would be needed for 10.6- μ m as for 0.35- μ m wavelengths--a large penalty to pay at present energy requirement levels.

The Antares Laser is now in its check-out phase with operation expected by the end of FY 1983 at 40 kJ. This laser will permit experiments that determine the hot-electron temperature and amount of absorption at a more representative scale size. These might well be different from current extrapolations. It is also essential to extend the short-wavelength experiments to higher laser energies and varied larger targets as this performance is also open to question.

The very high laser output energy now predicted to be necessary (5 to 10 MJ) to give satisfactory energy multiplication either may require a different drive such as a heavy-ion accelerator, or may make magnetic containment concepts more attractive than inertial containment for utility power generation.

Parallel Laser Programs

As mentioned earlier, work was also started in other areas of laser applications at Los Alamos. In 1972 we began investigating the use of lasers in separating the isotopes of uranium. We expected to extend this use to other elements of interest throughout the periodic table. Because of expected material problems in handling uranium vapor and molten uranium, we decided to investigate the use of uranium hexafluoride (UF₆), the compound used in diffusion plants with a well-established materials technology. Early experiments showed that UF₆ was readily dissociated to UF₄ (a white powder) + F by ultraviolet radiation. To obtain isotopic selectivity it was speculated that infrared radiation might be used by tuning the wavelength to an absorption line of a particular isotopic species of UF₆. We soon discovered that an extremely large "hot band" population that prevented selectivity existed at room temperature or at any temperature where satisfactory vapor density existed. To remove this restriction, we developed a technique for dynamic expansion of UF₆ in a carrier gas. Spectroscopy conducted on flow-cooled UF₆ indeed demonstrated that isotopic selectivity could be achieved, but the infrared wavelength fell in the 16- μ m band where no satisfactory lasers existed. The proposed system exposed a cold stream of UF₆ in a carrier gas to infrared and ultraviolet light down stream of a nozzle throat followed by a collector for the UF₆ precipitate.

Subsequent work demonstrated useful separation factors, and development of lasers and flow systems for an engineering demonstration system were in the check-out phase when a decision was made by Washington to stop work on the molecular process in favor of continuing work on the atomic vapor process developed at Livermore. In spite of this setback, work is proceeding on other isotopic species of interest to DOE or to industry.

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Much of the work in spectroscopy and laser photochemistry undertaken as part of this program continues in a number of promising areas, including process analysis and control in coal gasification and detection techniques for chemical warfare agents and other toxic substances.

As work on Directed Energy Weapons became an acceptable area for Los Alamos participation, we began to develop a free electron laser program in 1978. New techniques for improving the efficiency and power output of such devices and amplifier tests conducted in 1982 were highly successful. The oscillator tests scheduled for this fiscal year, if successful, should establish the program on a sound technical basis. We are very optimistic about the potential of the free electron laser because of its high efficiency, high power capability and wide tunability. It would be useful for military applications and as a potential source of low-cost photons for industrial photochemical processing.