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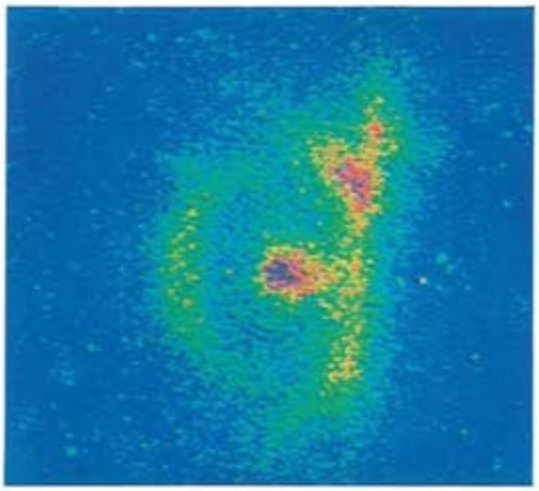
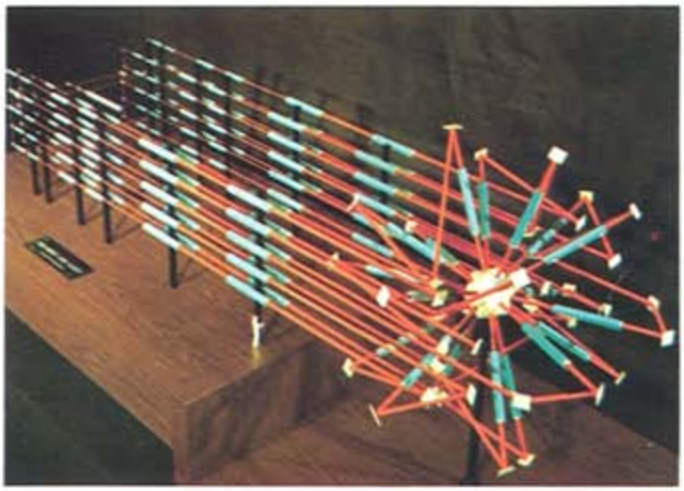
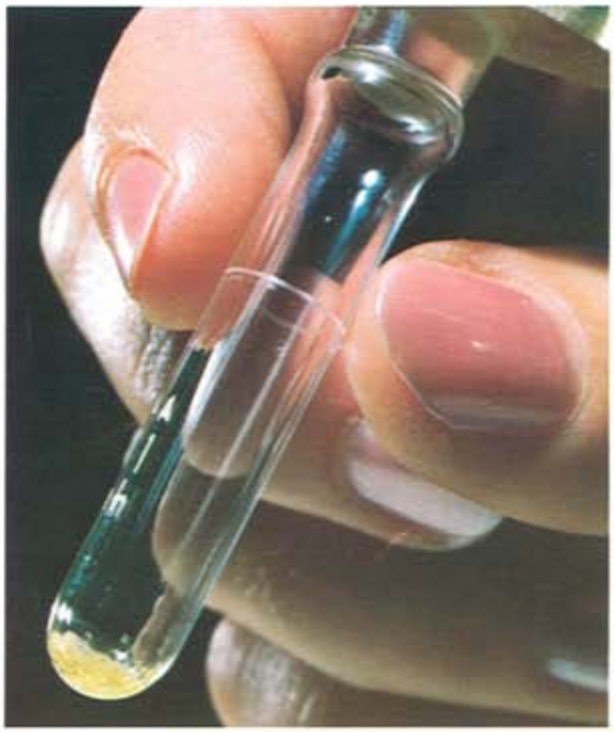






LAWRENCE
LIVERMORE
LABORATORY

LLL LASER PROGRAM

LASERS AND LASER APPLICATIONS

LLL LASER PROGRAM OVERVIEW

During the past year, substantial progress has been made toward laser fusion, laser isotope separation, and the development of advanced laser media, the three main thrusts of the LLL laser program.

Our accomplishments in laser fusion have included:

- **Firing and diagnosing more than 650 individual experiments on the 0.4-TW Janus laser system (including many experiments with neutron yields in the 10^7 range).**
- **Producing 1 TW of on-target irradiation with Cyclops, presently the world's most powerful single-beam laser.**
- **Completing the design for the 25-TW Shiva laser system and ordering the long-lead-time components. (The building to house this laser system is on schedule and nearly complete.)**
- **Demonstrating new laser media and new pumping techniques.**

We have experienced breakthroughs in new materials, coatings, and components that enable Nd:glass laser-amplifier chains four to eight times more powerful than those under construction. Also, we have completed calculations for high-gain targets to be driven by a 100- to 300-TW upgraded Shiva laser.

Our accomplishments in laser isotope separation have included:

- **Demonstrating laser enrichment of 3 mg of uranium from 0.7 to 3% uranium-235 (from natural uranium to reactor grade).**
- **Demonstrating a four-photon uranium enrichment process with significantly greater single-stage enrichment than ever before achieved.**
- **Cataloging extensive basic data on long-lived energy levels in atomic uranium, which allow efficient laser isotope separation with available laser technology.**
- **Demonstrating deuterium enrichment with lasers.**
- **Investigating both atomic and molecular processes for laser isotope separation of plutonium.**
- **Studying and characterizing candidate lasers for isotope-separation applications.**

This Laboratory is conducting a program to assess the scientific feasibility of laser-driven implosion and thermonuclear burn of microscopic targets containing deuterium and tritium. Experiments are being run on a single-pulse basis, the emphasis being on fast diagnostics of neutron, x-ray, α-particle, and scattered laser-light fluxes from the target. Our laser source for this work is the neodymium-doped-glass (Nd:glass) laser operating in a master-oscillator, power-amplifier configuration, where a well-characterized, mode-locked pulse is shaped and amplified by successive stages to a peak power of 1 TW in a 20-cm-diam beam.

Thermonuclear burn has been demonstrated. With successively larger Nd:glass laser systems, we now expect sequentially to demonstrate significant burn, light energy breakeven (equal input and output energies) and, finally, net energy gain. Beyond these demonstrations of scientific feasibility lie the practical proofs of laser fusion (demonstration facilities and, eventually, a full-scale operating pilot plant).

A second major laser program at LLL is proving the scientific feasibility of laser isotope separation: that is, the ability of lasers to change the isotopic ratios of elements. Thus far we have concentrated on uranium enrichment because of the potential for this technology to dramatically reduce these enrichment costs. Experiments are well under way, with impressive results. A timetable has been established leading to a full-scale operating pilot plant. Near-term planning also calls for expanding our studies, on a modest scale, to plutonium and other elements of interest.

The third major component of our laser effort – research and development – concerns the development of efficient, low-cost lasers for the fusion and isotope-separation programs. Many difficult technical and theoretical laser-development problems must be solved before either program can be considered commercially viable. For example, the lasers for future power reactors will likely be high-efficiency, high-pulse-rate, short-wavelength gas lasers. Those for future uranium-enrichment plants may well be copper-vapor-pumped dye lasers. Neither exists on any scale today. We are actively pursuing these and other candidate laser systems.

In our 1974 annual report, we published a comprehensive overview of the LLL laser program directions and accomplishments through 1974.[1] This article updates that information to reflect our work throughout the past year.

Contact John L. Emmett (Ext. 4211) for further information on this article.

LLL AND THE NATIONAL LASER PROGRAM

LLL's involvement with laser technology dates back to the early 1960's, soon after the laser was invented. Of chief interest to us has been the ability of lasers to produce a spatial and temporal concentration of energy that is comparable to that in the heart of a nuclear explosion. We have regarded lasers, from their inception, as an interesting and potentially valuable tool for energy conversion that might someday compete with, and supplement, other schemes such as nuclear fission and magnetic-confinement fusion.

Our early studies, sponsored by the U.S. Atomic Energy Commission, were aimed at understanding fundamental laser science and technology. These modest efforts were directed mostly to the LLL nuclear explosives and military applications programs, but they suggested certain nonmilitary uses – such as laser fusion and laser isotope separation – that grew in national importance with the passing years. Our work contributed heavily to an AEC decision, in the early 1970's, to expand the laser program and increase its emphasis on nonmilitary applications. The LLL effort became the cornerstone of a new national laser program (now administered by ERDA) whose major goals are:

- Laser fusion – to demonstrate the scientific feasibility of initiating thermonuclear burn in a fuel pellet by irradiating the pellet with a laser pulse of high power and short duration.
- Laser isotope separation – to demonstrate the scientific feasibility of using laser-induced processes to alter the isotopic ratios of chemical elements of significant economic value.
- Laser research and development – to support the above, identify fruitful areas for new laser research, and provide the scientific data base for evaluating new laser applications in the context of major national problems.

Many agencies, both public and private, are now participating in the national program. At LLL, the volume of laser work has grown from a $1 million project to a full-fledged $30 million program involving more than 300 scientists, engineers, and support people. Goals (milestones) have been set, leading to a feasibility demonstration of laser fusion in the next decade. The time schedule for laser isotope separation calls for a feasibility demonstration at the end of this decade.

Experiments and theoretical studies are proceeding concurrently. What we are emphasizing are solid foundations for future work, well-predicted experiments, and prompt technology transfer (i.e., effective communication of techniques and results to industry and other participating agencies). In the long run, we view predictable computer simulations as crucial to the upward scaling of experiments, which could significantly reduce future research and development costs. Technology transfer, likewise, could have a significant impact by hastening applications of our research. Our first laser technology transfer symposium and other technology transfer activities at LLL will be discussed in next month's *Energy and Technology Review*.

The accompanying article is an overview of current LLL research in laser technology, with a glimpse of our future plans. Other articles in this issue discuss, in more detail, certain aspects of this research: the space frame for our forthcoming Shiva system, beam-propagation problems, and our laser spectroscopy studies in conjunction with the development of laser isotope separation.

Laser Fusion Program

The conceptual basis of this Laboratory's laser fusion program is laser-driven implosion of inertially confined deuterium-tritium (D-T) fuel. The program currently represents about 40% of ERDA's laser fusion effort.

Our efforts during the past three years have centered on developing the analytical and experimental tools needed for D-T implosion experiments on a continuously increasing scale. We now have target-design codes that encompass radiation transport, thermonuclear-burn physics, laser-plasma coupling, and the fluid dynamics of high-density, high-temperature plasmas. Sophisticated techniques have been devised for making microtargets for our present experiments. Finally, we have achieved unmatched developments in high-peak-power, high-brightness, solid-state laser technology and fully integrated laser test facilities. The future of laser fusion requires predictive capabilities such as the above, as well as developments in experimental hardware.

We are working toward five milestones for achieving laser-induced fusion:

- Reaching an adequate understanding of the physics of the interaction between laser light and plasma.

• Demonstrating a high-density laser-induced implosion (defined as occurring when compressions of 100 to 1000 times liquid density are attained).

• Achieving significant thermonuclear burn (defined as occurring when a fusion energy output greater than 1% of the laser light energy is attained).

• Achieving light energy breakeven by raising the pellet burn efficiency such that the fusion energy produced is of the same magnitude as the light energy in the laser pulse.

• Achieving net energy gain by raising system efficiency such that the fusion-energy output substantially exceeds the energy input to the whole laser system.

These are *scientific* milestones as compared with *applications* milestones (e.g., prototype reactors) described later. Figure 1 gives our present estimates of the laser technology needed to reach these scientific milestones.

In achieving the first and second milestones, we had to determine the kind of laser output pulse — in terms of energy, duration and shape, wavelength, coherence properties, and symmetry — that is required to compress a D-T pellet to burn conditions. Then we had to design and build a laser to produce this output pulse. Last May, with a microtarget of the exploding-pusher type first developed at Livermore in 1970, we first achieved a 10^7-neutron yield from laser-fusion implosion.[2] In this and other experiments, the target yield has been well predicted by our implosion codes, suggesting that the observed neutrons are from D-T compression and genuine thermonuclear burn rather than from reactions of accelerated, non-Maxwellian fuel ions. Alpha-particle measurements have confirmed the thermonuclear nature of these neutrons.

We are continuing our basic laser/matter experiments with well-characterized Nd:glass lasers of moderate size. Pulse energies will range from tens of joules to about 1 kJ, and pulse lengths will range from the low-nanosecond region to tens of picoseconds. The main purpose of these experiments is to provide a data base for comparison with theoretical calculations.

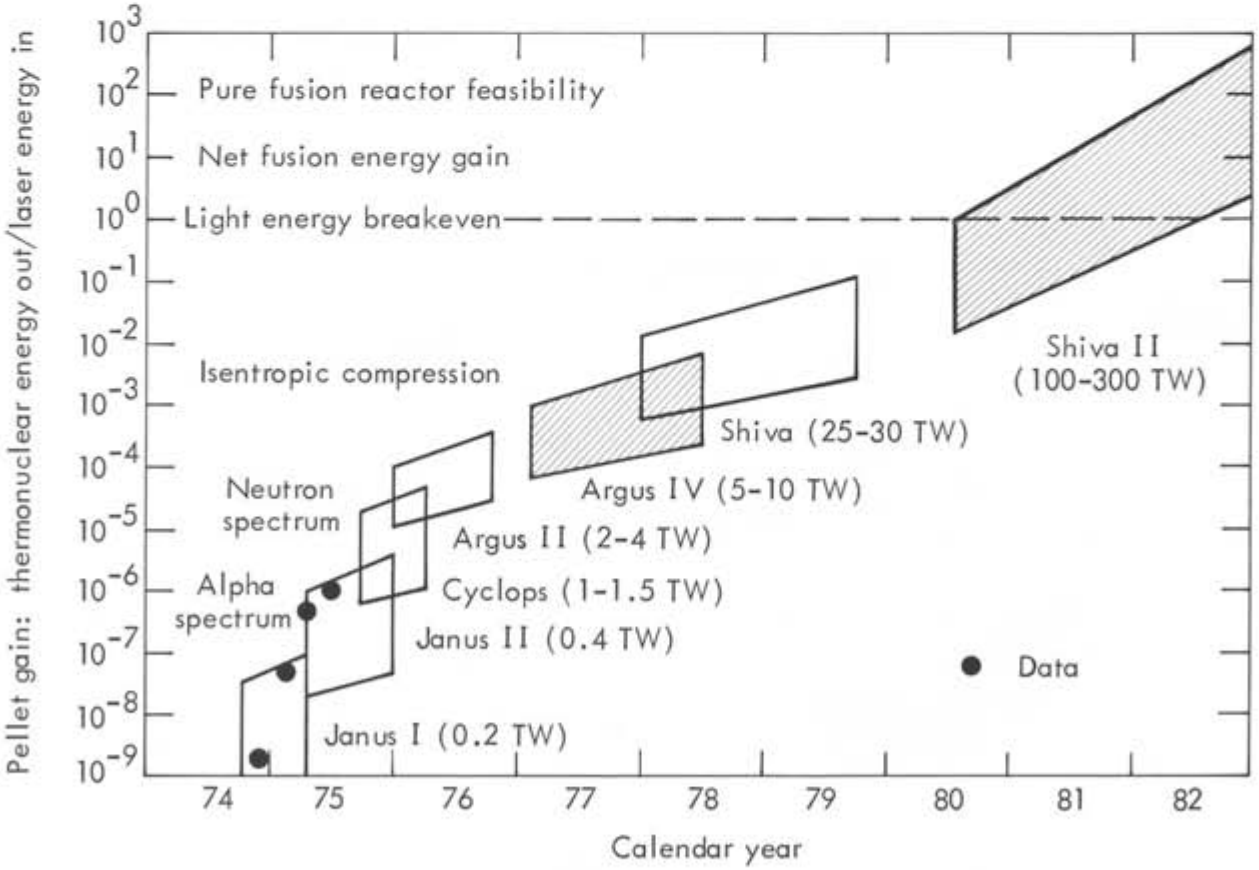


Fig. 1. Laser fusion energy yield projections. With this series of scaled-up Nd:glass laser systems, we expect to demonstrate significant thermonuclear burn, light energy breakeven, and probably net energy gain, all on a single-pulse basis.

Our target date for the third milestone – significant thermonuclear burn – is FY 1978-79 and depends on success with the Nd:glass Shiva laser system scheduled for operation in late FY 1977. We believe that Nd:glass lasers offer the most reliable means for reaching the first four milestones and probably even the fifth on a single-pulse basis. However, the high energy and high average power eventually required for controlled thermonuclear power generation will preclude solid-state lasers as now conceived. We are investigating several alternatives, including gas lasers.

Glass Laser System Development. Nd:glass lasers are presently the best understood high-energy, short-pulse lasers and, thus, are well suited to laser-fusion development. They are capable of delivering tremendous amounts of energy in short bursts to tiny targets. As shown in Fig. 1, our solid-state development program calls for a series of scaled-up Nd:glass laser systems as driving sources for target experiments. Also shown is the anticipated relationship of these systems to target performance, including light energy breakeven and the demonstration of scientific feasibility.

Two of the systems are now operational: Janus (0.4-TW) and Cyclops (1-TW). Argus, at 2 TW, and Shiva, at 25 TW, are scheduled for April 1976 and July 1977, respectively. Breakthroughs with solid-state materials and laser components now permit the construction of laser systems operating at unprecedented, higher power levels. Based on these technological advances, we envision the possibility of an upgraded Shiva system with target irradiations up to 300 TW.

Laser fusion target irradiation puts unusual requirements on the laser system. For this application, peak power performance is more important than total energy extraction. This emphasis leads to severe nonlinear optical constraints on beam propagation and laser design. Considerable effort has gone into understanding these problems*; the payoff has been a sixfold increase in the maximum power capability of a single laser chain. Detailed optimization studies have indicated the best approaches to laser system staging, and engineering studies have resulted in reliable, cost-effective components.

Near-Term Systems. It was with the Janus system (Fig. 2) that we first attained 10^7-neutron fusion yield and verified the thermonuclear nature of the neutrons. Cyclops, presently the world's most powerful single-beam laser, is now being applied to fusion targets. With the Argus system (Fig. 3), which is

*For example, in this issue is an article (p. 18) discussing two difficult beam-propagation problems: small-scale self-focusing, which limits the spectral brightness of the beam, and whole-beam distortion, which degrades our ability to focus the beam.

Fig. 2. Janus, our first two-arm laser system, consists of a dye-mode-locked oscillator, pre-amplifiers, beam-shaping optics, and a series of Nd:glass disk amplifiers with optical isolators. Most components are the same as in our single-arm Cyclops system.

Fig. 3. Argus laser system features a "driver-booster" design in which the final stage (the booster) is a constant-aperture, filtered amplifier that produces the chain's maximum beam intensity. The driver, which operates conservatively, has enough gain reserve to allow flexibility in choosing the input flux to the booster.

nearing completion, the fusion-energy yield from the targets will be adequate to measure the neutron spectrum and conclusively prove the thermonuclear origin of the neutrons from these fusion reactions. Argus will remain operational to supplement Shiva, so as to ensure efficient use of this costlier and more complex system. An upgraded version of Argus is being considered but is not yet funded.

Shiva System. This system will produce more than 20 TW from 20 simultaneously fired laser chains. The number of chains and their convergence geometry have been chosen to enhance the uniformity of spherical target illumination. With this combination of very high power and uniform illumination, isentropic spherical compression of D-T targets to many thousand times the liquid density of D-T should be possible. Significant thermonuclear burn yielding a few percent of light energy breakeven can begin to be demonstrated at this level.

Figure 4 shows the Shiva system and the building in which it will be housed. The building is nearly completed. Shiva is of such magnitude and complexity that one begins to comprehend the scale of the systems that may eventually be required for power generation. The technological developments for Shiva in high-laser-power optics and propagation, system control, laser diagnostics, optical stabilization and alignment, large-system maintenance, reliability engineering, and target-chamber design will be directly applicable to future laser fusion systems using advanced laser media.

Options for the upgraded Shiva are given in Table 1. The alternative configurations and choices represent many advances in materials, propagation physics, and construction techniques. If funds become available, this system – delivering 100 to 300 TW of on-target power – could be operational early in the next decade.

Fusion Targets. The thermonuclear energy generated by a laser-driven implosion can be significantly affected by the laser energy, peak power, temporal pulse shape, low-level prepulse energy, wavelength, angle of light incidence on the target surface, and the temporal and spatial symmetry of target irradiation. The various target designs have somewhat different sensitivities to these laser parameters, the sensitivity decreasing as laser energy increases. We are continuing to explore this extremely complex multidimensional parameter space with a sophisticated computer program, LASNEX, that simulates laser-driven implosions.

Thermonuclear-energy generation can also be significantly affected by the tolerances to which the target is fabricated. Important parameters include the

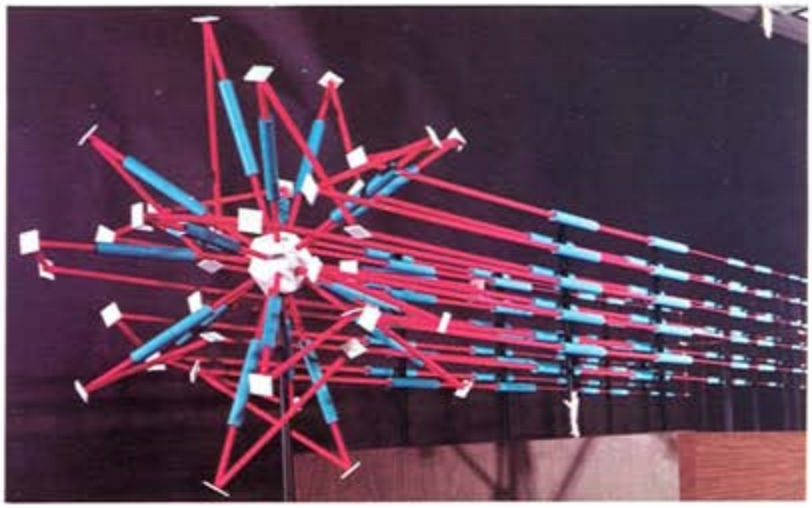


Fig. 4. Shiva laser system (left), to be housed in the building shown beneath, will deliver 25 TW of spherically symmetrical irradiance to fusion targets. Each amplifier chain in Shiva is made up of amplifier modules of increasing aperture size. Finally, at full power the beams converge on the target chamber, shown as an icosahedron at the left. To upgrade Shiva, more chains can be added to the existing space frame.

surface finish, uniformity of shell thicknesses and densities, concentricity and sphericity, and the presence of impurities. LASNEX once again is the workhorse code. Because of fluid instabilities, surface finish is the most severe constraint. For targets capable of reaching light energy breakeven when imploded by a 10-kJ laser pulse, the surface finish of the ablator and pusher shells must be accurate to ±10 nm for spatial wavelengths varying from one-tenth the shell thickness up to the shell thickness. For 1% breakeven pellets, the surface finish need be accurate only to about ±1000 nm.

Within these confines, the task of our fusion targets program is to design and fabricate the tiny microtargets for our fusion experiments. Target-design calculations conceptually model fundamental laser fusion processes and, as such, are the driving function for the rest of the program. Designs have progressed from simple glass spheres filled with D-T gas (see Fig. 5) to complex, multilayered assemblies using cryogenic fuel. The largest of our targets thus far has an outer diameter of about 200 μm – a little more than one-tenth the size of the head of a common pin. A small shotglass can hold about 10 million of these glass spheres.

During the past year, we have made more than 900 targets for experiments on Janus and Cyclops. A sequence of exploding-pusher targets has demonstrated thermonuclear conditions. As shown in Fig. 6, our predictions for these experiments agree well with experimental results on target designs spanning more than five orders of magnitude of neutron output. We have also fielded many "physics" targets – those not containing fusion fuel – to help unravel the scientific aspects of laser-target interactions.

During the year, we have developed techniques for building, measuring, and characterizing many different targets. The critical areas associated with their physical realization include materials science, micromanipulation (assembly, handling, and storage), and parts production. Because of the requisite accuracies and the program's experimental nature, target production is now very expensive: 30 manhours per target (direct labor) during 1975. Future targets for power applications must, of course, cost only a tiny fraction of this amount.

The problems of target production in the foreseeable future are crucially dependent on the surface smoothness needed to produce symmetrical

Table 1. Typical Shiva upgrade performance options[a] and estimated focusable power in terawatts

Configuration	Option	Characteristic laser material		
		Silicate	Fluorophosphate	Fluoroberyllate
20 chains	Shiva	27	54	80
	Shiva + ϵ	44	88	132
	Shiva + δ + ϵ	60	120	180[c]
32 chains	Shiva	43	86	130
	Shiva + ϵ	70	140	210[c]
	Shiva + δ + ϵ	96	192[b]	288[c]
42 chains	Shiva	57	113	170[c]
	Shiva + ϵ	93	186[b]	279[c]
	Shiva + δ + ϵ	126	252[b]	378[c]

[a]Shiva performance can be improved by using lower n_2 optical materials such as fluorophosphate and fluoroberyllate glasses, by adding 20-cm-diam-aperture δ and 30-cm-diam-aperture ϵ amplifiers, and by increasing the number of laser chains.

[b]Proposed Shiva upgrade performance.

[c]Advanced Shiva upgrade performance.

implosions. The maximum allowable root-mean-square roughness is predicted to be in the range 10 to 1000 nm. To get such smoothness we will use, whenever possible, liquid materials influenced by surface tension, damped by viscous forces, and rapidly cooled to avoid crystal growth. Evaporative deposition, sputtering, and ion-beam milling and deposition techniques also hold promise for nanometre-range control of surface configurations. The measurement and characterization of surface quality to 1 nm (for targets as small as 20 or 30 μm) are in themselves very difficult problems.

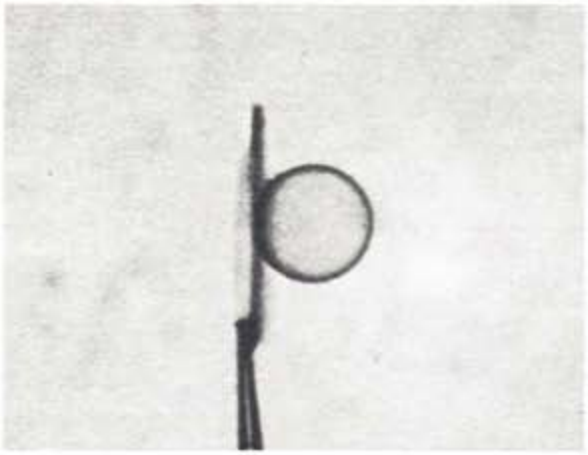
We anticipate that the D-T fuel in the targets will have to be frozen as a hollow, spherical layer on the target's innermost surface. However, we are now in early testing of some candidate cryogenic systems; results should be available by mid-1976.

Because laser targets during the next few years will most certainly consist of layered, spherical shells, we are working on the problems of depositing layers of substances such as plastics, glass, metals, and cryogenic materials. The integrated-circuit industry has made great strides in surface-layer deposition and control; we are drawing as much insight and technology as possible from their processes and applying them to these problems.

Fusion Experiments. The primary goal of this program is to reduce to practice the concept of fusion produced by laser irradiation of inertially confined targets. The study of laser target implosions involves time resolution on the order of picoseconds and spatial resolution of less than 1 μm. The physics of the interaction of high-intensity coherent radiation with plasmas is a relatively new field.[3]

Generally speaking, the objectives of this program can be divided into the following elements:

- Implosion of spherical shells filled with D-T gas. The requisite densities are 1 to 10 times liquid density. These experiments do not demand a high degree of irradiation symmetry and can be accomplished with as little as 10 J in 100 ps from a Nd:glass laser.
- Large-aspect-ratio spherical shell (LASS) implosions (i.e., $R/\Delta R >> 1$). These experiments emphasize the implosion of LASS targets to produce significant thermonuclear burn.
- LASS modeling experiments, both plane and cylindrical. The main purpose of using these targets is to allow diagnostic study of the shell-acceleration process and the implosion symmetry.
- Optical interaction experiments. The objective here is to determine the laser-energy distribution in the target plasma.
- Plasma-physics experiments. The purpose is to characterize the adsorption process for laser radiation, transport properties in the plasma, and the induced electric and magnetic fields.
- X-ray conversion experiments. These are designed to diagnose the conversion of laser energy to x rays.



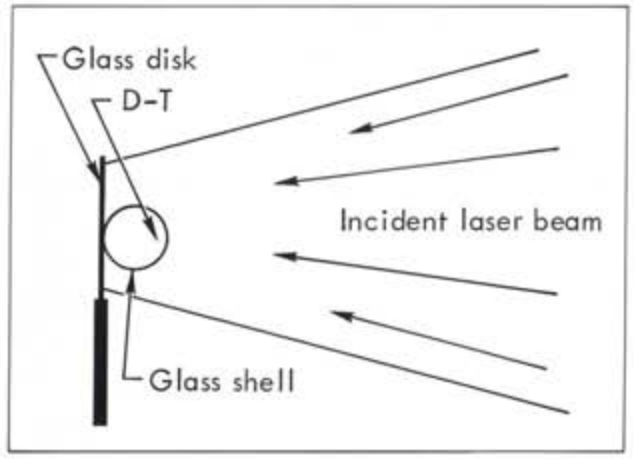


Fig. 5. Ball-and-disk single-beam target, in which the fuel ball is attached to or mounted near a flat glass disk on a standard stalk.

• Diagnostic devices and techniques. This is an important aspect of our work. A large number of diagnostic techniques are being developed to achieve the desired spatial and temporal resolution over the densities (10^{16} to 10^{26} cm^{-3}) and temperatures (1 eV to 50 keV) of interest.

During the past year, we performed many hundreds of target experiments with Janus, Cyclops, and Valkyrie, a 50-GW CO_2 laser that is no longer operational. Approximately 200 single-beam complex targets were irradiated on Janus and Cyclops at peak power levels of 0.2 and 1 TW, respectively. Some 100 two-beam complex targets and 200 simple glass microspheres were irradiated on Janus and Cyclops at peak power levels of 0.5 and 0.7 TW, respectively. Time-of-flight measurements of the 3.5-MeV alpha particles produced in the D-T reaction were used to prove that the May 1975 neutrons were thermonuclear and that we had achieved ion temperatures of 2 keV.

The extent of diagnostics instrumentation for target experiments is roughly comparable to that for an underground nuclear test at the Nevada Test Site or for hydrodynamics experiments at this Laboratory. A single experiment may involve as many as 89 oscilloscope traces, 7 computer printouts, 112 photographic images, and 19 chart records.

In addition to our extensive plasma diagnostics, we have carefully diagnosed laser output and laser intensity at the target plane. The laser output diagnostics have been crucial in defining power limits; the target-plane information has been essential for analyzing the experiments.

This year, we will use 4π illumination systems on Janus and Argus for both low- and high-density implosions. Argus will be used also with $f/1$ and $f/2.5$ lens focusing.

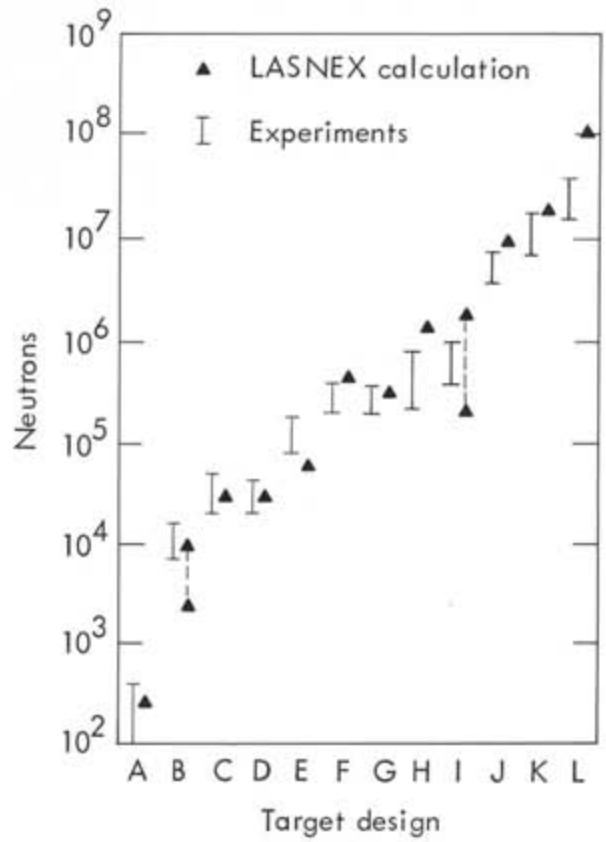


Fig. 6. We view the predictability of experimental results (illustrated here) as crucial to future computer simulations and the upward scaling of experiments, which could substantially reduce future research and development costs.

As regards diagnostics development, we are continuing to adapt and improve our streak cameras,

particle and x-ray diagnostics, and microscope imaging systems. We have started developing ultrafast framing cameras and a computer program for data acquisition and analysis.

Our x-ray streak camera has been used for experiments on Janus with six K-edge channels of data. The data show a temporal peak emission at the time of implosion, which agrees with LASNEX calculations. This camera has also been coupled to a pinhole camera to make the first time-resolved x-ray pictures of imploding laser targets. New high-resolution x-ray microscopes have been designed and built by means of single-point diamond machining. We have also developed a capability for optical probing with the fourth harmonic of the Nd:glass laser frequency. Thus, in 1976, we will be able to make measurements in the plasma corona up to densities of 10^{21} cm^{-3}.

Our expectation is to use minicomputers for data acquisition and analysis. On Janus and Cyclops, one-dimensional data are gathered and scaled by PDP-11/10 computers. The system for Argus will use a PDP-11/40 and will gather and reduce both one- and two-dimensional data.

Laser Isotope Separation Program

The conceptual basis of our laser isotope separation process is the ability of a laser to excite the atoms of one isotope selectively without affecting the atoms of other isotopes that are present. This is possible because the various isotopes respond to different frequencies (wavelengths) of light. The difference – the so-called isotopic shift – is slight, barely a thousandth of a percent, but lasers can be fine-tuned within this range. Once the atoms have been excited, they can be separated by various techniques.

The driving incentive behind laser isotope separation is largely economic. The demand for separated uranium isotopes will soon outstrip U.S. production capacity by the gaseous diffusion process (the present method), forcing the construction of new plants totaling some $40 billion by the year 2000. Laser isotope separation plants show promise of being less expensive to build and operate. The potential savings could run from $2 to 5 billion per year between 1980 and 2000.

The advantages of laser isotope separation over gaseous diffusion are many. Even allowing for laser inefficiencies, laser isotope separation may require up

URANIUM ISOTOPE SEPARATION

Ever since 1945, the practical separation of uranium isotopes has remained a recurring challenge. The wartime effort that temporarily solved the problem was the cornerstone of this nation's headstart in nuclear technology. Except for the competing electromagnetic separation process that produced uranium for the first nuclear detonation, gaseous diffusion has been the source process for both the nuclear weapons program and the nuclear power industry. The cost is 3 MeV per atom as compared with the 200 MeV per atom released by fission.

Now, however, the demand for enriched uranium is rising sharply. Various studies put the annual growth rate of nuclear-electrical generating capacity in this nation at 15 to 26%. Even at the lower figure, demand soon outstrips our present production capability. By the year 2000, we will evidently need eight times as much capability; ten $4-billion gaseous diffusion plants are proposed to fill the gap. The costs for enriched uranium alone will run, by then, to about $10 million daily. These economic realities have prompted many different isotope-separation schemes including laser isotope separation.

This process, now under intensive development elsewhere as well as at Livermore, has many attractive features. Theoretically, it can operate at an energy cost as small as 30 eV – about 1/300 000 of that for gaseous diffusion. Various inefficiencies could reduce the margin by as much as 10 000, but this would still leave a thirtyfold advantage in favor of laser isotope separation. Another advantage of the laser process is its ability to concentrate the percentage of uranium-235 in natural uranium – in one stage – from 0.7% (natural occurrence) to about 3% (reactor grade). Gaseous diffusion requires thousands of stages to accomplish this enrichment. Moreover, the gaseous-diffusion plant is a vast network of pipes, pumps, and valves all filled with a corrosive, highly reactive gas, UF_6. The laser isotope separation system is much simpler and probably can use a uranium alloy instead of the volatile compound.

Laser isotope separation also shows promise for reducing the proportion of uranium-235 discarded in depleted tailings (the gaseous diffusion process discards more than 40%). Salvaging this waste could reduce the expansion of uranium mining and refining otherwise required to meet the demand. It might even be worthwhile to rework our 30-yr accumulation of tailings. The same considerations apply to recovering unused uranium-235 from spent reactor fuel.

Fig. 7. Recent experiments in the selective photoionization of atomic uranium vapor have produced significant single-stage enrichment. Our studies are continuing in the laser isotope separation laboratory shown here.

to 97% less energy. It will also be simpler, performing in one stage the equivalent of thousands of stages of gaseous diffusion separation. Experience indicates that laser separation is capable of extracting a much higher percentage of uranium-235 from a mixture with uranium-238 than gaseous diffusion. Each of these advantages translates into lower costs.

is this really right?

In our work to date, we have demonstrated a single-stage multiphoton process for separating uranium isotopes that produced 3 mg of reactor-grade enriched material from natural uranium in a 2-h run.[4] Since then, using the facilities shown in Fig. 7, we have completed a series of experiments that open up exciting possibilities for three- or four-photon processes. We have identified a series of long-lifetime energy levels in atomic uranium,* allowing efficient laser isotope separation with available laser technology. Using the energy levels thus obtained, we have operated a process (Fig. 8) on the actual wavelengths that would be used for a full-scale process, producing significantly greater single-stage enrichment than ever before. These and companion studies – considered a major breakthrough – were reported in last month's *Energy and Technology Review.*[5]

The separation of 3 mg of reactor-grade uranium from natural uranium in a single stage constitutes a demonstration of process feasibility. Accomplishing this milestone makes it possible for us to project additional milestones leading to a full-scale operating facility: a technology demonstration by the end of 1979, an engineering demonstration by the end of 1981, a prototype facility (an economic demonstration) before 1984, and full-scale plant operation by the end of 1986.

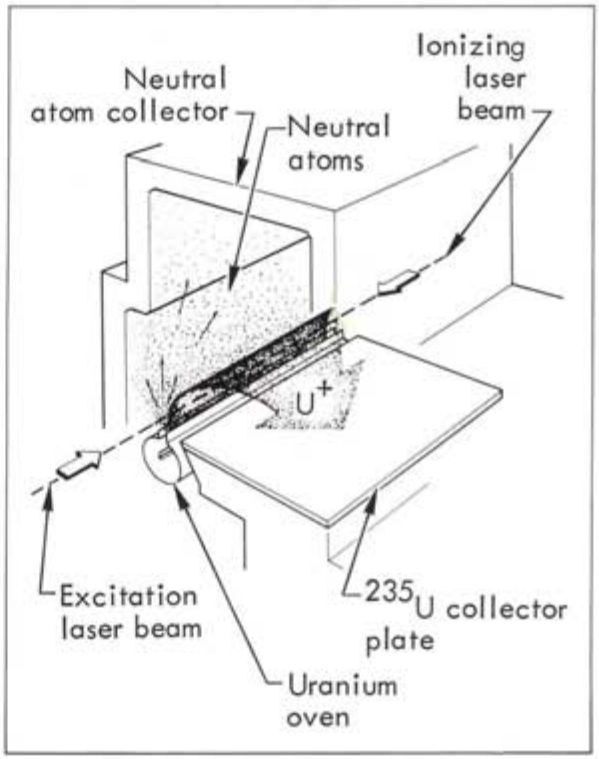


Fig. 8. In this photoionization process, the uranium vapor stream produced by an oven source is electronically excited by the beam from a xenon-ion laser passing very close to the vapor slit of the oven. The laser is tuned to excite only the uranium-235 while leaving the uranium-238 unexcited. The uranium-235 is then ionized by light absorption from a krypton laser. The positive ions are collected on a plate that is negatively charged with respect to the oven.

*For a description of this work in laser isotope spectroscopy, see the article beginning on p. 23.

To accomplish these and other program objectives, we have divided our laser isotope separation effort into four principal activities:

- Atomic uranium vapor processes.
- Advanced uranium separation processes.
- Plutonium separation processes.
- Other isotopes and laser chemistry.

Supporting these is a major program of laser research and development (discussed later) whose functions include developing the reliable, efficient, low-cost lasers that are crucial to economically practical laser isotope separation. The goal is a laser with 100-W average power and a pulse repetition frequency up to 20 Hz that is efficient to the 1% level and has an operating life of thousands of hours. The

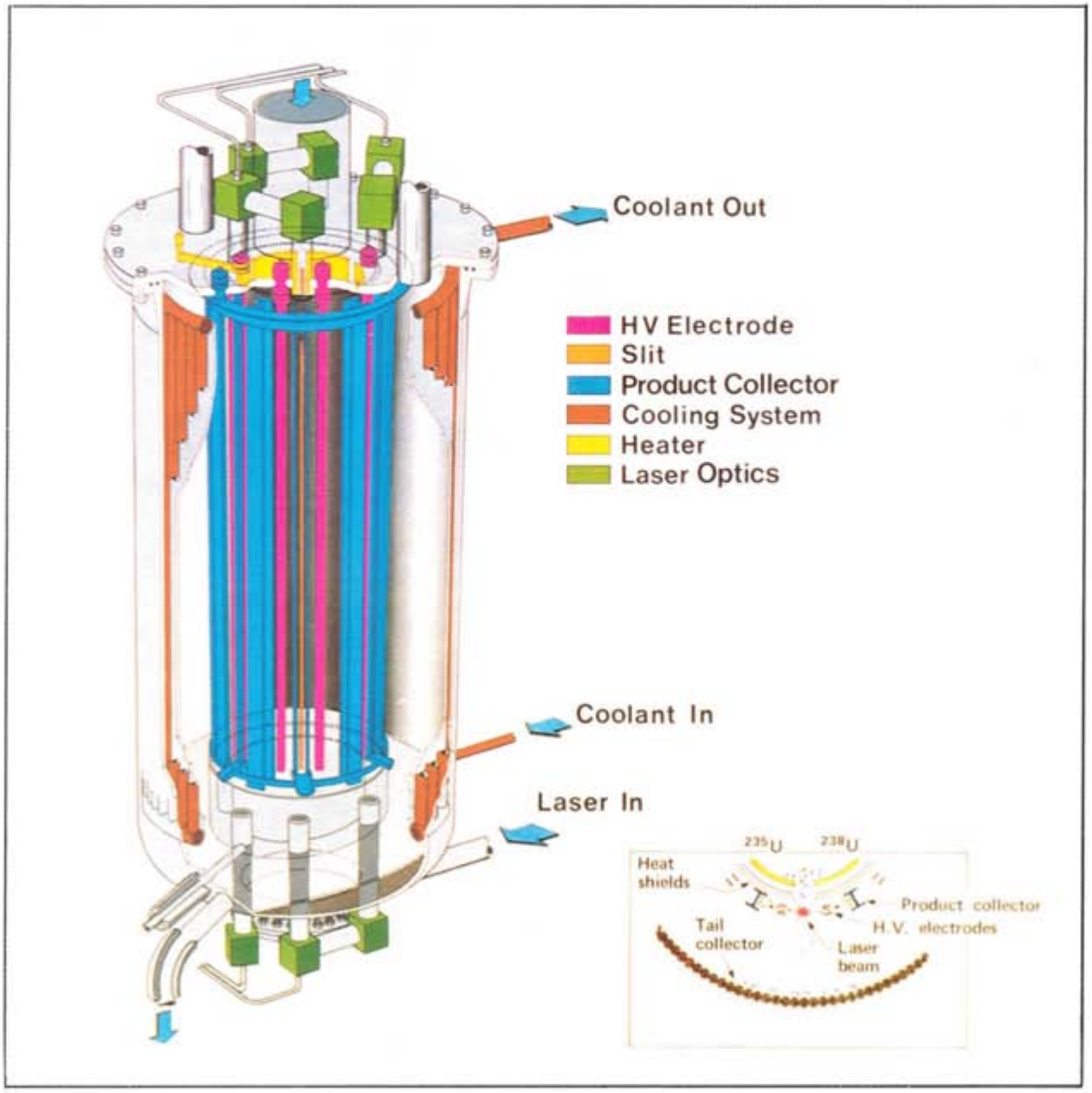


Fig. 9. Vacuum-tight reaction chamber and six-slit oven for processing atomic uranium vapor. The estimated capacity is 5 kg of uranium feed per hour. The reaction-zone detail (lower right) shows the interaction of the uranium vapor, laser beams, and ion collector.

copper-vapor-pumped dye laser is presently a strong candidate.

Atomic Uranium Vapor Processes. Efforts during the past year have centered on developing copper-vapor lasers and methods for creating atomic uranium vapor from both equilibrium and nonequilibrium sources. Various spectroscopy options for selective photoionization have been experimentally demonstrated, and various techniques for removing laser-induced ions have been evaluated. We have developed modeling programs that allow us to evaluate process performance and establish guidelines for future component development.

We have begun construction of a test-bed facility to evaluate atomic vapor process options at densities appropriate to future cost-effective systems. The target enrichment is 3.2% uranium-235. The goal is to demonstrate process feasibility with scalable components rather than a large product output (the anticipated production rate is about 10 mg/h). Aside from that, all the operating parameters will be characteristic of a production module.

Simultaneously, we are proceeding with detailed design studies for a substage capable of producing about 400 SWU (separative work units) of enrichment capacity per year. Figure 9 is a concept drawing of a reaction chamber and oven for processing atomic uranium vapor. Figure 10 shows an enrichment stage

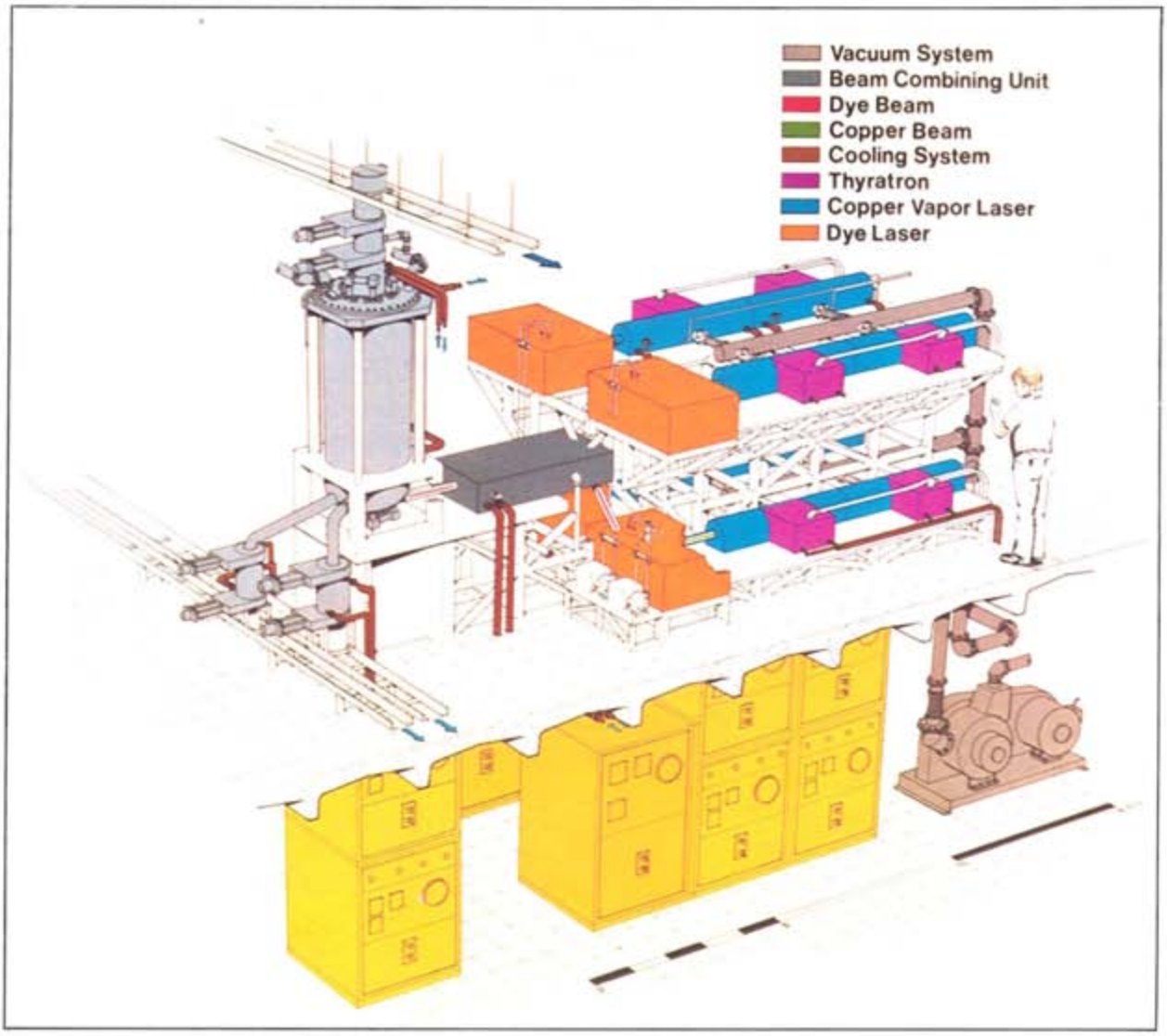


Fig. 10. Conceptual design of a 10 000-SWU/yr uranium enrichment stage for the atomic vapor photoionization process being developed by LLL.

capable of producing 10 000 SWU per year. Modeling and evaluation of these systems and components are continuing; however, a specific design was needed to estimate the plant costs and technical requirements for large-scale laser isotope separation.

Advanced Uranium Separation Processes. Because the cost savings to be achieved by laser isotope separation will ultimately be dictated by the overall component economics and the process technology, we are also addressing alternative processes for uranium enrichment.

Techniques involving photochemical reaction of both atomic uranium and molecular uranium compounds are being actively investigated. If successful, these could provide significant payoffs in process efficiency and simplicity and, hence, dramatically reduce long-term system costs.

Nearing completion is a new, versatile experimental facility to provide molecular beams for evaluating molecular processes and photochemical techniques. We have also completed an apparatus for experimental study of dissociative electron-attachment techniques on UF_6. Experiments on this latter process will begin shortly.

Plutonium Separation Processes. Laser isotope separation technology is generally applicable to any element. We are applying our experience with uranium to the study of plutonium. A spectroscopy laboratory has been set up at the LLL plutonium facility to investigate atomic plutonium and PuF_6. Experimental studies will be carried out this year to determine the scientific feasibility of various process options. Within present funding constraints, we do not anticipate a test-bed system or major expansion of this work during 1976.

Other Isotopes and Laser Chemistry. Uranium studies have dominated this effort to date, but preliminary work on titanium and boron separation for reactors has indicated a market if low-cost laser isotope separation processes can be developed. During 1976, we intend to expand our studies of potential markets for low-cost isotope enrichment.

One aspect of our work with other isotopes has been a demonstration of highly selective isotope separation of deuterium in laser-irradiated mixtures of H_2CO and HDCO. Using an HDCO absorption line coincident with a helium-cadmium laser at 325.03 nm, we have achieved single-step, fifteenfold enrichment in the deuterium content of hydrogen gas.[6] This accomplishment has important bearing on our studies on improved techniques for producing heavy water.[7]

The technology being developed for laser isotope separation has many applications in the chemical industry. We are now beginning studies to evaluate these applications. Though uranium enrichment and plutonium enrichment (cleanup) are now at the forefront of public attention, they represent only a subset of the potential for this technology.

Laser Research and Development

In support of the laser fusion program, our advanced quantum electronics program is already looking past the scientific milestones to the applications milestones – hybrid and pure-fusion prototype reactors and eventually a pilot reactor – whose time schedules stretch into the 1990's. Although the scientific milestones may be achieved on a single-pulse basis using facilities under construction (Shiva) or planned (Shiva upgrade), laser fusion reactors will require new, more efficient lasers capable of delivering high average power in the form of a continuous series of short pulses ($\geqslant$100 kJ; $\geqslant$1 ns). During the past year, we have theoretically predicted and experimentally demonstrated several promising new laser media and measured their characteristics. The development of such media on a time scale that will maintain laser fusion as a viable option in the national laser program is a priority matter.

The need in laser isotope separation is for reliable, high-repetition-rate, high-peak-power laser systems that function at the proper wavelengths for economical operation of enrichment plants. For both programs, our research in advanced quantum electronics seeks not only to develop advanced lasers but also to establish sound theoretical bases for understanding atomic and molecular reactions for future applications.

Performance requirements for advanced lasers for fusion applications vary radically with respect to various target designs. During the past two years, the emphasis has centered on targets that demand rigorous performance of laser sources (10% efficiency and short wavelengths). In response, the advanced quantum electronics program has been directed toward identifying laser media and pump technologies to satisfy these requirements. Several interesting candidate media have been identified: photolytically pumped atomic iodine, oxygen, and sulfur, and *in situ* electron-beam-pumped, rare-gas group-VI excimers such as KrO, XeO, and

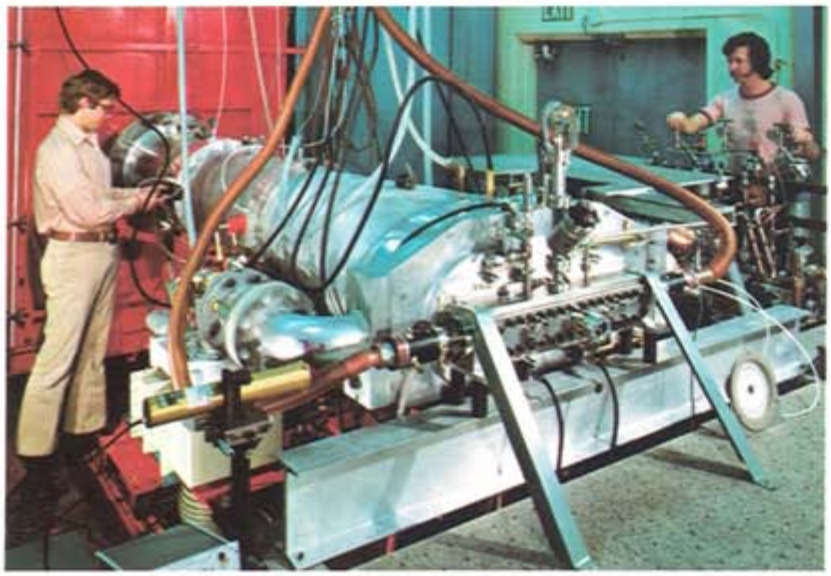


Fig. 11. Electron-beam-pumped, krypton oxide, visible laser using the MEG II facility at LLL. The multipass, 50-cm-long cell provides optical gain at 557.7 nm for a saturating pulse from a pulsed dye laser.

ArO.* Experiments have been performed to establish the operating-parameter regimes (mixtures, pressure, voltage, current density, geometry, etc.) of these media. Progress in these experimental and theoretical studies has led to a gain-saturated krypton oxide laser (Fig. 11) and an atomic iodine laser photolytically pumped by an electron-beam-driven ultraviolet fluorescer, the XeBr excimer. (The latter was reported in the November issue of *Energy and Technology Review*.[8]) A new generic class of fusion lasers based on trivalent rare-earth molecular vapors has been identified on theoretical, analytical, and limited experimental grounds. This class is currently being assessed at a low level of effort.

It may be possible to develop high-performance targets that can be used with other lasers. A relaxation of efficiency and wavelength requirements would open new vistas for both laser media and pumping techniques. For this work, we have developed a critical capability in the discipline of electrical-discharge physics, and we have designed and built an experimental facility for rapid assessment of spectroscopic and kinetic parameters of many new potential laser media.

*Our criteria for candidate media appear to be well satisfied by the group VI elements – oxygen, sulfur, selenium, and tellurium – and by the electronic analogs – carbon, silicon, germanium, and tin.

In support of the multistep photoionization laser isotope separation of atomic uranium vapor, we have executed a quantitative assessment of the current copper-vapor laser technology. Performance data for both metallic copper and copper-halide laser devices have been assembled. Basic kinetic and laser-staging models have been defined, inadequacies and scaling laws isolated, and limiting device technologies determined. Several dye oscillator designs consistent with transient pumping by copper laser pulses have been identified.

To optimize the use of the experimental facilities completed in FY 1976, we have created a small theoretical atomic and molecular physics effort to help in interpreting experimental spectroscopic and kinetic data and in directing the experimental effort in the most productive directions.

During FY 1977, we expect to identify and evaluate several new laser media and pumping techniques and also to consolidate our knowledge about laser media already identified: rare-gas excimers, rare-gas-group VI excimers, rare-gas halogen photolytic sources, and rare-earth molecular vapors. Based on this information, we will be making recommendations about future experiments and device development.

Key Words: lasers; laser beams; lasers – excitation; laser induced fusion; laser isotope separation; lasers – Lawrence Livermore Laboratory; laser materials; isotope separation; uranium isotope separation; Janus; Cyclops; Argus; Shiva.