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Progress in the ICF Program at the Lawrence Livermore National Laboratory

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13-TC-392.3, 1986-04-15, PROGRESS IN THE ICF PROGRAM AT THE LAWRENCE LIVERMORE NATIONAL LABORATORY*, HOGAN, W.J., Lawrence Livermore National Laboratory, P. O. Box 5508, L-480, Livermore, CA 94550

ABSTRACT

Experiments using the harmonically converted Nd:glass lasers at the Lawrence Livermore National Laboratory (Novette with 2-10 kJ at 0.26 and 0.53 micron and Nova with 30-80 kJ at 0.35 and 0.53 micron) have demonstrated favorable coupling of laser light to fusion targets. The coupling of short-wavelength laser light to these plasmas is now well understood and is primarily collisional in nature, in contrast to previous experiments at 1.06 microns and 10 microns, where the coupling was collective. Increased absorption and conversion to x-rays and decreased production of suprathermal electrons was measured with decreasing wavelength. Stimulated Raman scattering was identified as the primary source of the suprathermal electrons. The collisionality of the laser target coupling can be controlled by the proper selection of laser wavelength and target material.

The coupling improvements led directly to the demonstration of higher-density ablative implosions of DT fusion fuel. Experiments on Novette demonstrated a better than 100-fold compression of the DT fuel with two-sided illumination. The Nova laser is extending laser-plasma studies to plasmas several times larger than those used on Novette. Recent experiments have produced a yield of over 10^{13} neutrons. Temporally shaped pulses on Nova will be used to compress DT fuel close to the 200 g/cm^3 densities ultimately required for high-gain target performance.

1. PROGRAM GOALS

The objectives of the Inertial Confinement Fusion (ICF) Program at LLNL are to understand, develop, and show how to utilize ICF technology. The current emphasis and the largest fraction of our effort is on understanding fundamental target physics and driver/target interactions, learning how to fabricate targets of various design, and developing a driver capable of igniting a high-gain target. However, the ultimate attainment of well-diagnosed, high-gain, thermonuclear explosions in the laboratory is necessary for the full realization of all potential ICF applications. In this discussion I distinguish between achieving "ignition" or "breakeven" and achieving high gain. Achieving "breakeven" or gain one would be a spectacular technical achievement and could provide an important impetus for the program. However,

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only high gain will allow ICF to realize its full potential. Not only would high gain experimentally establish the scientific feasibility of economic ICF power production, but the large fluxes of X rays and neutrons available from such a target would satisfy the requirements for a broad range of other applications.

Studies of the economics of ICF power production show that the relative cost of electricity is a strong function of the cost of the driver and the fusion cycle gain (the inverse of the recirculating power fraction)[1]. Figure 1 shows this relationship for a 1000 MW_e power plant. The fusion cycle gain is the product of the driver efficiency η, the target gain G, the blanket multiplication factor M, and the thermal to electric conversion efficiency ε. To be competitive with future coal and fission plants[2], the driver must cost less than a few hundred million dollars and the fusion cycle gain must be greater than 4. For usual values of the electric conversion efficiency and blanket multiplier, this implies an ηG of more than 8 and for driver efficiencies between 10 and 20%, gains must, therefore, be greater than 40 to 80. Note that once this value of ηG is obtained, it is driver cost, more than any further improvements in gain or efficiency, that will make ICF economically competitive.

To achieve high gain in the laboratory, LLNL is carrying out a program that focusses on two complementary thrusts: target physics and advanced laser development. The goal of the target physics element of the program is to understand driver/target coupling and target implosion dynamics required for high gain well enough that we can confidentially predict the necessary driver characteristics. The goal of the advanced laser development element is to provide the fundamental information necessary to determine if a laser can be built with high confidence and at reasonable cost that will fulfill those characteristics.

2. REQUIREMENTS FOR HIGH GAIN

To achieve high gain, the requirements on the target implosion are stringent. The DT fuel must be compressed to a density of about 200 g/cm^3. The density-radius product (ρr) of the fuel must be greater than about 3 g/cm^2 for efficient burn. The central few percent of the fuel must be heated by the implosion shock to a few keV and the ρr of this region must be above 0.3 g/cm^2 so that the alpha particles will deposit their energy locally and initiate burn in the cold part of the fuel. Figure 2 shows the ion temperature and fuel density profiles that are most desirable at the end of the implosion. The fuel to ablator mass ratio must be as large as we can get it, implying that cryogenic fuel must be used. The implosion velocity must be uniform over the spherical surface of the capsule to within about 1% so that instabilities don't spoil the compression. To allow the lowest driver energy, the driver/target coupling should be very efficient and the fuel preheat low. Preheat from early shocks and X rays should be avoided as well as that from hot electrons. To limit the impact of instability growth, it is advisable to have a low capsule aspect ratio (ratio of the shell radius to its thickness) and to gradually accelerate the pusher during the whole implosion. In order to accomplish this it is desirable to temporally shape the driver pulse. Figure 3 shows three equivalent pulse shapes that keep the fuel on a nearly Fermi-degenerate compression path. Our strategy for accomplishing these requirements is to emphasize hohlraum targets, study laser/target coupling at wavelengths less than 1 µm, and seek methods of using liquid DT fuel in thick spherical shells for direct drive targets.

While we continue to pursue basic laser/matter interaction and fluid instability physics that are of fundamental importance to any approach to ICF, our primary focus is on the radiation-driven or indirectly-driven target concepts in which the laser light is converted to soft X-rays that, in turn cause the target compression. Relative to directly-driven targets, radiation-driven ones represent a more assured technical path to high gain in the laboratory. Some of the advantages of radiation-driven capsules in this context are:

- Very good capsule drive symmetry with a few beams.
- Less sensitivity to implosion instabilities.
- Less sensitivity to hot electron preheat.
- Lower required beam balance and quality on target.

On the other hand, using the indirect-drive approach requires that a high laser-to-x-ray conversion efficiency be obtained. Recent experimental results indicate that this may be much easier to accomplish than the difficult requirements for direct drive.

3. RECENT TARGET PHYSICS EXPERIMENTAL RESULTS

The primary objective of the laser/plasma interaction experiments was to study wavelength scaling in plasmas with dimensions on the order of 1000 λ. Such large plasmas more closely resemble those expected with future high-gain targets than do the plasmas generated with lower power lasers. Experiments were done on Novette in 1983 and 1984 and are now being done on Nova. They include measurements of target absorption of laser light, x-ray conversion efficiency, suprathermal electron production, and parametric instabilities.

These experiments confirmed that the interaction physics observed with submicron light follows a more classical behavior. In addition, we have also seen the equally important role that the plasma scalelength plays in determining the mix of coupling processes. Absorption experiments conducted with 0.53 μm light agree well with previous results obtained with the smaller Argus facility (< 0.1 TW) for intensities < 10^{15} W/cm^2. At higher intensities, the Novette absorption values are higher than those observed on Argus (70% as compared to 40 to 50% for $I \sim 3 \times 10^{15}$ W/cm^2). The lower absorption values at Argus are most likely due to the very small focal spots (d < 40 μm) that were required on Argus to achieve these intensities.

Suprathermal electron production for these disk targets at 0.53 μm and 0.26 μm show the now-familiar result of decreasing production efficiency with decreasing wavelength. For nearly identical conditions, the suprathermal electron level inferred at 0.26 μm is approximately 10 to 20% of that obtained at 0.53 μm.

We have spent considerable effort to understand the principal generation mechanism for the suprathermal electrons seen in these experiments. The Novette experiments have demonstrated that stimulated Raman scattering (SRS), occurring at $n_e < n_{crit}/4$, is the dominant source of hot electrons in the 0.53 μm experiments. A more limited data set at 0.26 μm is also consistent with this observation. This conclusion is based on the excellent quantitative correlation between the optical emission from SRS (yield and timing) and the suprathermal x-ray emissions (yield and temperature), as seen in FIG. 4.

Although SRS can be large in long-scalelength plasmas, it is possible to suppress the instability in highly collisional plasmas. We have observed a drastic reduction in SRS efficiency when gold exploding foils are irradiated with 0.26 μm light. Figure 5 shows that measured SRS efficiencies are less than 10^{-5} for gold foils, in contrast to levels greater than 10^{-2} for CH foils. We ascribe this reduction to collisional damping of SRS in the gold plasma in which the electron-ion collision frequency is comparable to the SRS growth rate.

In addition to studying the underdense corona, we have spent some effort in observing wavelength effects in the overdense plasma. In particular, we have performed a limited number of experiments to measure the X-ray conversion efficiency as a function of intensity and wavelength. Highlights of these experiments include X-ray conversion efficiencies as great as 85% obtained with 0.26 μm light at an intensity of 1 to 3 times 10^{14} W/cm^2. Figure 6 summarizes the very favorable scaling of laser/plasma coupling with shorter wavelength for high-Z disk targets.

A limited number of X-ray driven implosion experiments were also conducted on Novette with 0.53 μm light. The collisionally dominated interaction physics resulted in ablative implosions in which suprathermal electrons did not influence the target performance or interpretation of the diagnostic results. Substantial pusher compressions were measured by neutron activation. Increases in the pusher areal density, $\rho\Delta R$, as great as 80 times the initial value were obtained. This represents on the average a factor of 2 to 3 improvement over similar targets irradiated with the same laser energy on Shiva with 1.06 μm light. The inferred fuel density from the Novette experiments is $> 20\ g/cm^3$.

The hardware construction and activation phases of the Nova laser project were completed on schedule and on budget. Nova is a three-wavelength laser system, capable of irradiating targets with 100 to 120 kJ at 1.06 μm, or 40 to 80 kJ at 0.53 μm or 0.35 μm in 1 to 5 ns Gaussian or highly shaped pulses. Over the next several years, Nova will be used to demonstrate that the conditions required to drive a high-gain capsule can be generated with a properly scaled, laser-driven hohlraum target. Although Nova does not have sufficient energy to achieve the ρr necessary for high gain, it is possible to demonstrate individual physics performance criteria separately. That is, in individual experiments we will show that we can obtain the required X-ray temporal pulse shapes and drive uniformity, the scaling of transport and plasma instabilities at high gain target scalelengths, the required stability of the imploding shell, the implosion velocities necessary for ignition, and large compressed DT densities.

Recently we have obtained our first target implosion results using the Nova laser. Several direct-drive, glass-shell targets were imploded. The shells were about 1 mm in diameter and about 2 μm thick, filled with about 14 atmospheres of DT gas. The ten Nova beams contained about 20 kJ of 0.35 μm light. Neutron yields of 0.5 to 1.1×10^{13} were measured --- the largest ever. Ion temperatures of 8-11 keV with fuel ρRs of 0.4-0.6 mg/cm^2 were achieved. These yields give gains of 0.15%.

The above targets will play an important role in the development of advanced neutron diagnostics but it should be recognized that they are not likely to achieve high gain in spite of their near term successes. To achieve high gain we will need high-compression, indirect-drive targets. In our first tests of these target types on Nova we have achieved a neutron yield of 4.5×10^{10} --- a factor of 5000 improvement over previous results. The neutron yield was 40% of the pre-shot calculated value, the closest ever. Ion temperatures measured were 1.7 keV. The measurements allow us to infer a fuel density of 10-12 g/cm^3 leading to a Lawson criterion value of over $10^{14} cm^{-3} s^{-1}$. The target radius converged sufficiently that 10 Gbar pressures were achieved in the fuel.

Progress has also been made in our ability to create thick cryogenic fuel direct drive targets. We have been investigating a new target fabrication concept (see FIG.7) in which the liquid DT spherical shell is held in place with a matrix of low density open cell foam (i.e., a sponge). In this design the DT wetted foam serves as ablator, tamper, and fuel layer. Capillary forces generate by the DT wetting the foam matrix stabilize the liquid against flow caused by any accelerations, including that of gravity. A pore size of 1 μm is sufficient to provide stability when subjected to accelerations up to 1000 g. Glass foam with the desired characteristics (e.g., density between 70 and 150 mg/cm^3) is commercially available and we have demonstrated the ability to fabricate targets and soak up liquid DT to the proper shape with this material. To minimize energy loss due to Bremsstrahlung, however, we must have low atomic number foam. A development program is underway to provide us with this material.

4. PROGRESS IN ADVANCED LASER DEVELOPMENT

Our past work in laser research and development has been crucial in supporting the design and construction of large, sophisticated systems like Nova. To meet our performance goals for Nova we had to develop greatly improved laser glasses, high-damage-threshold optical components, techniques for propagating intense optical beams (> 10^9 W/cm^2) while maintaining high beam quality, and techniques for extending nonlinear frequency conversion technology to beam diameters of 74 cm. In FIG. 8 is shown the progress in the development of high-energy and -power, solid-state lasers.

Beyond support of the existing Nova system, our laser development work is oriented toward two goals:

- o To develop the technology, design and cost basis for an affordable 5 to 10 MJ driver for an ICF research facility that would demonstrate, optimize, and use high-gain targets that do not require high pulse rate.
- o To invent an efficient, low-cost driver capable of high pulse rate applications.

To reach these goals we have examined many laser and ion beam driver concepts. While the greatest amount of effort has been on solid state lasers because of their obvious advantages as a research tool, we will continue to consider other candidates, as we have in the past. For example, up to 1982 we had a large effort devoted to the study of KrF and other gas lasers. In this program we built a 850 J/150 ns module with which we demonstrated 20-fold pulse compression and validated KrF systems models. Our kinetics experiments showed that improved efficiency could be obtained with Kr-rich gas mixtures. We sponsored a design/cost study with Bechtel for a 1.5 MJ, 2 Hz KrF driver. This study concluded that 5% might be the upper limit to the overall system efficiency and that costs would be about \$300/J for a 10^7 shot lifetime. Our active development work on KrF ended in 1982 when the results of our work indicated that the KrF laser was not likely to fulfill the requirements of a reactor driver. At the present time we are actively studying advanced solid state lasers and free electron lasers. Small efforts are devoted to the compact torus, heavy ions, light ions, and to following current developments in gas lasers.

The requirements for a research driver are different from those for a reactor driver. The next research driver built should be capable of assuredly producing high gain. In addition, it should be flexible enough to drive a number of different target designs so that the target gain curves can be fully explored and that the maximum gain at each driver energy can be obtained. This will require an excess of pulse energy and peak power as well as having flexibility in wavelength, pulse shape, and pulse duration. On the other hand, driver efficiency will matter only insofar as it affects facility cost in relation to the benefits gained. Only a few pulses per day would be needed on this facility.

In contrast, the reactor driver requirements are more difficult in some respects and more relaxed in others. For this paper a reactor is defined as a facility in which fusion pulses must occur at 1 Hz or more. Applications that require a reactor driver include nuclear materials production, fusion power, and space propulsion. For these the requirement for high pulse rate (and consequently high average power), durability, reliability, maintainability, efficiency, low cost, and in one case, low mass become dominant. Requirements for flexibility in pulse shape and wavelength, as well as peak energy and power, are more relaxed than for a research driver. It would be nice, but not necessary, if the same driver technology could serve both research and reactor needs.

The success that has been achieved in building the Nova system convinces us that a 5-10 MJ Nd:glass laser of the same basic design could be built today. The technology is scalable to that energy. The only difficulty would be the cost. To bring the costs down we are examining new multipass laser architectures, ways to increase amplifier efficiency, new pulsed power systems, new glass and crystal manufacturing methods, and higher-damage-threshold materials and coatings. Significant progress has been made in these areas. An amplifier has been tested with an efficiency of over 5% (compared to the Nova amplifier's 1.5% at the same stored energy). A factor of ten increase in crystal growth rate has been achieved. Sol-gel coatings with a damage threshold of 40 J/cm^2 have been demonstrated. A lower cost (\$0.10/J) pulsed power system has been designed. A new, continuous-pour, glass-manufacturing technique has been identified.

There is still more work to be done. However, the progress to date is encouraging and the track record for lowering system costs in past facilities shown in FIG. 9 indicates we are likely to achieve our goal of a 5-10 MJ facility for about $500 M.

Opinion has changed recently regarding the long-range prospects of solid state lasers as drivers for ICF reactors. Nd:glass lasers have made excellent research tools because of their high beam quality, flexible pulse shaping, and ease of achieving high power, power density and pulse energy. However, they have traditionally had low efficiency and it was generally assumed that the high average power necessary for high pulse rate was not achievable because of the difficulty of removing the heat from the solid medium without destroying beam quality. Recent studies[3] and preliminary experiments are altering that view. A thin plate gain geometry is the key to high average power solid state systems. In this geometry the beam propagation, optical pumping and heat removable are all done through the large surfaces of a thin plate. The beam propagation is in the same direction as the gradients in the gain plate and therefore gradient induced distortions are suppressed. Using selected crystals as the host medium will maximize the thermal power that can be safely handled in a plate because of their high thermal conductivity and low thermal expansion coefficient. In fact, with such materials stress birefringence probably replaces stress failure as the limiting process. Experiments with few-kilowatt, flow-cooled, zig-zag and disc lasers are now underway to determine if beam quality can be maintained. Calculations indicate that the few megawatt average power systems needed for ICF reactors may be possible in solid state lasers. A storage efficiency of over 6% was achieved in an experimental large disc amplifier. We have identified techniques for increasing the efficiency even further (e.g., through Chromium sensitization). Calculations indicate (see TABLE I) that bottom line system efficiencies of more than 10% may be achievable. For these reasons we have put advanced solid state lasers back on the list of viable candidates for a reactor driver and are pursuing an active analytical and experimental program to see if a solid state system can achieve all the requirements simultaneously.

5. CONCLUSIONS

The major goal for the ICF program is obtaining high gain. LLNL has undertaken a multithrust attack on understanding the science and technology necessary to attain this goal. Progress has been made in defining the target implosion requirements and in laying out a strategy for success. Laser/plasma interaction experiments and analyses have shown that using wavelengths of 0.25 to 0.53 µm will solve the coupling problems that plagued the program at longer wavelengths. Much progress has also been made that give us increasing confidence in our understanding of implosion dynamics and in our ability to build cryogenic targets. We now believe we can obtain high gain with driver energies of 5 to 10 MJ. Our advanced laser development effort has also made progress in reducing the costs associated with high energy Nd:glass lasers to the point that a research facility may be able to be constructed at that energy for an affordable price (a few hundred million dollars). Furthermore, due to new work on high average power solid state lasers we believe they should now be viewed as a viable candidate for future reactors. Finally, we have found a reactor concept (to be discussed in another paper) that appears to put ICF power in an advantageous position economically. These developments make it a very exciting time to be working in inertial fusion.

REFERENCES

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[2] DELENE, J.G., et al., "Nuclear Energy Cost Data Base - A Reference Data Base for Nuclear and Coal-fired Powerplant Power Generation Cost Analysis," U. S. Department of Energy Report, DOE/NE-0044/3 (1985).

[3] EMMETT, J.L., et al., "The Future Development of High-Power Solid State Laser Systems," Lawrence Livermore National Laboratory UCRL-53344 (1982).

TABLE I. Advanced solid state laser efficiencies > 10% appear to be possible. Data from the 31 cm diameter Nova amplifier and an experimental single segment amplifier (SSA) are shown along with estimated projections based upon identified improvements.

	Efficiency factor	Flashlamp pumped: 31 - amp. Nova	Flashlamp pumped: SSA (data)	Flashlamp pumped: Optimized (projected)	Semicond. array: Optimized (projected)
System / Power amplifier	Lamp plasma radiation	0.80	0.80	0.80	0.40
	Cavity transfer	0.27	0.60	0.85	0.95
	Glass abs. fraction	0.3_0	0.37	0.65	0.95
	Quantum defect	0.63	0.63	0.63	0.90
	Fluorescence decay	0.37	0.6_0	0.80	0.85
	Energy storage eff. η	0.015	0.065	0.22	0.27
System	Extraction/fill factor			0.75	0.75
	3ω conversion (350 nm)			0.85	0.85
	Staging/flow-cooling			0.85	0.90
	Total system η			0.12	0.16

FIG. 1. Relative cost of electricity for a 1 GW_e power plant assuming a conventional steam cycle balance of plant. Future fission and future coal costs are taken from Ref. [1].

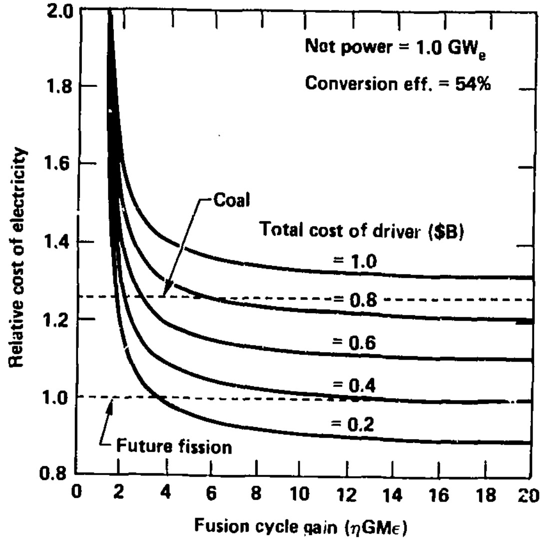


FIG. 2. ICF capsules utilize central ignition and prcpagation into compressed DT to achieve high gain.

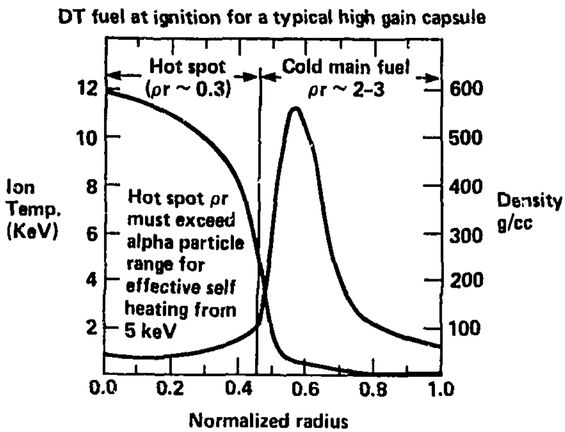


FIG. 3. For high-gain ICF capsules, most of the fuel must remain nearly Fermi-degenerate. For typical capsules, the entropy of the fuel must not exceed the entropy generated by about a 1 Mb shock. Since capsules are imploded with peak pressures of 80 to 100 Mb, the pressure must be increased in such a way that strong shocks are not generated after an initial shock of about 1 Mb. This can be accomplished if successive shocks differ in pressure by less than a factor of 4. To achieve this throughout the fuel, the power at each point in the pulse must be controlled with an accuracy of 5 to 10% and the timing must be accurate to less than 1 ns for megajoule-scale capsules.

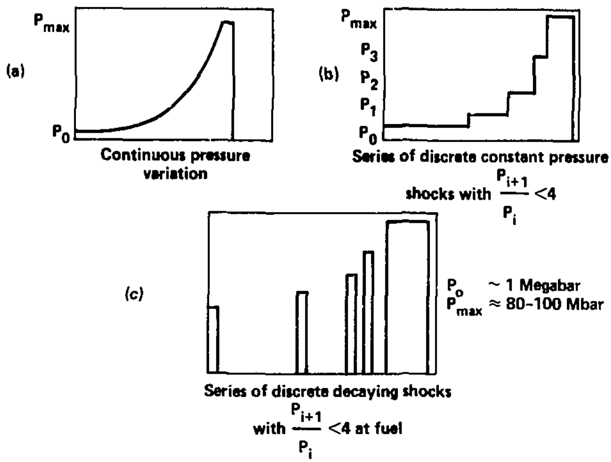


FIG. 4. The strong correlation between the Raman-scattered light and hot electron fraction is strong evidence that Raman scattering is the probable source of hot electrons in the Novette experiments.

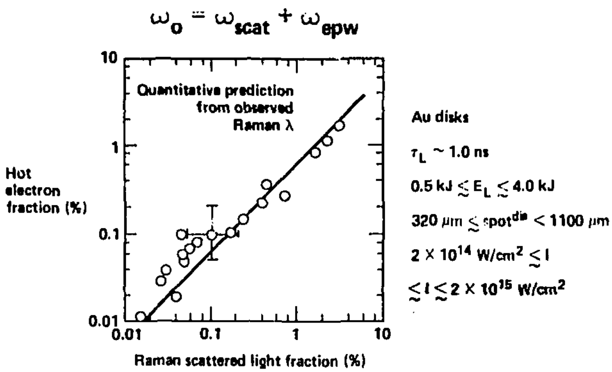


FIG. 5. For gold foils, the electron/ion collision frequence is comparable to the SRS growth rate and allows collisional damping to greatly reduce the stimulated Raman scattering.

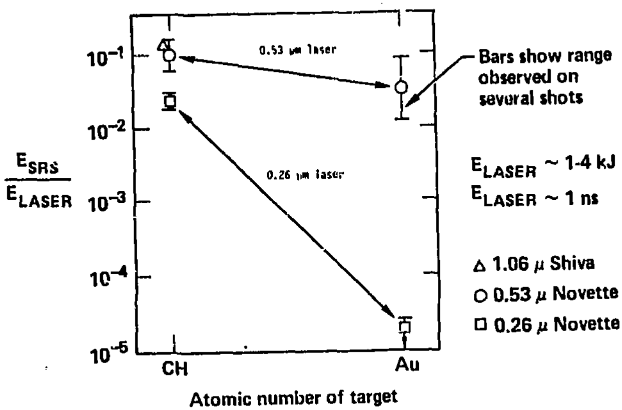


FIG. 6. Summary of laser plasma experiments with gold disks. Target coupling is very favorable at short wavelengths.

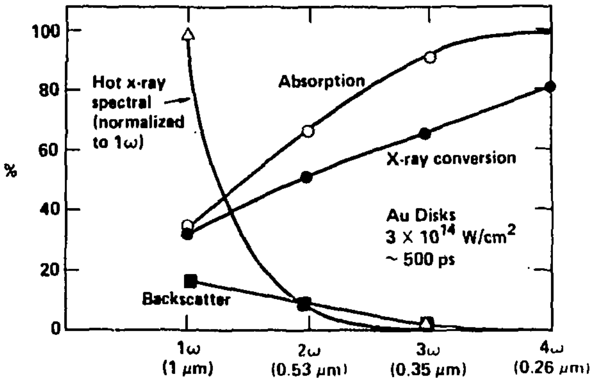


FIG. 7. Use of low density, low Z foam to define and stabilize the DT shell allows an attractive single shell, direct drive target design.

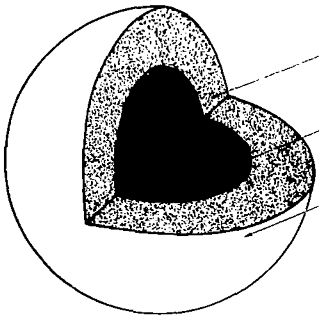


FIG. 8. The peak power and energy capability of the Nd:glass solid state laser systems built at LLNL has progressed rapidly. It is now technically assured that solid state laser systems in the multi-megajoule and 500 TW range can be built. Ongoing research and technology development suggest that high repetition rate (~10 Hz), high efficiency (>10%), affordable (~$50/J) costs may also be attained for advanced solid state systems.

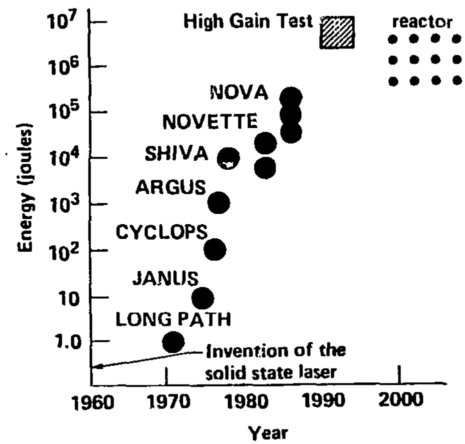
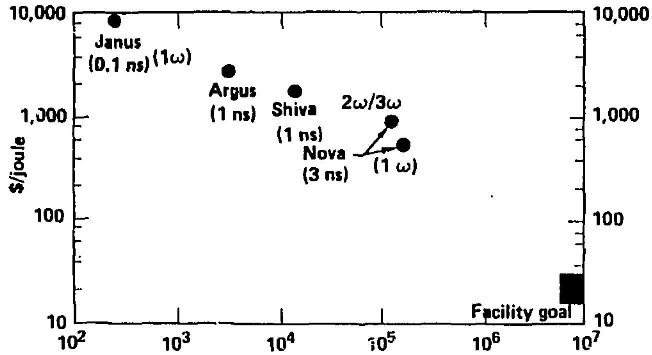


FIG. 9. Historical cost performance of Nd:glass lasers.



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