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LASERS FOR FUSION ENERGY

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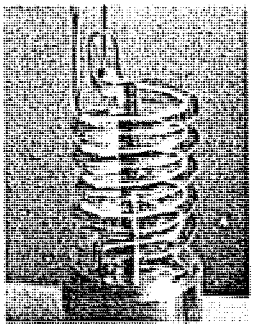
Solid state lasers have proven to be very versatile tools for the study and demonstration of inertial confinement fusion principles. When lasers were first contemplated to be used for the compression of fusion fuel in the late 1950s, the laser output energy levels were nominally one joule and the power levels were 10^3 watts (pulse duration's of 10^{-3} sec). During the last 25 years, lasers optimized for fusion research have been increased in power to typically 100,000 joules with power levels approaching 10^{14} watts. As a result of experiments with such lasers at many locations, DT target performance has been shown to be consistent with high gain target output. However, the demonstration of ignition and gain requires laser energies of several megajoules. Laser technology improvements demonstrated over the past decade appear to make possible the construction of such multimegajoule lasers at affordable costs.

Key words: Lasers, Fusion, Inertial Confinement

The evolution of high power solid state lasers designed for the inertial fusion application started shortly after the invention[1] and demonstration of the first laser by Maiman[2] in 1960. The invention of the Nd:glass laser by Snitzer[3] in 1961 made possible, in principle, the scaling of lasers to large sizes with concomitant high output energy and power. During the 1960s, the national laboratories of many nations—USA, France, Russia—experimented with laser irradiation of matter in various conditions. Later in the 1960s, researchers invented the needed laser technologies, which when optimized and assembled into systems consistent with propagation constraints, were able to heat matter to temperatures that began to interest fusion researchers. In the 1970s, our groups at Livermore, researchers at the University of Rochester and KMS Fusion, the Naval Research Laboratory, CILAS and the CEA Lemeil Laboratory in France, and the Lebedev in Moscow were able to obtain sufficiently accurate data on the generation of short pulses of 1.06 micron Nd laser light, on the amplification, the propagation, the isolation, the focusing, and the diagnostics that subsequent engineering of fusion lasers into large systems became possible. The development of accurate diagnostics with sufficient time resolution and dynamic range was critical to experimental progress and to subsequent theoretical interpretations during this decade.



First Ruby Laser 1961
1 J, 10^3 W.

1/4 scale prototype amplifier
for Nova upgrade > 10^6 J
and 10^{14} W.

Figure 1: On the left, the first laser demonstrated by Maiman generated about 1 joule in 1 msec. On the right is shown a 1/4 scale prototype amplifier for the Nova upgrade which will generate about 1.5 megajoules in 10 nsec. This is a one million fold increase in energy and eleven orders of magnitude increase in laser power over the 30 year period of high power laser design. [4]

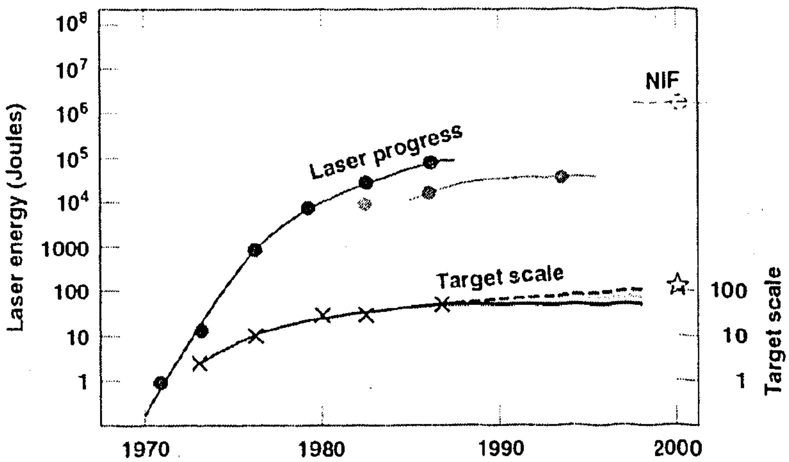


Figure 2: The laser energy (left vertical scale) used to irradiate increasingly large fusion targets is shown as a function of a 30 year development cycle. The associated increase in target scale is shown on the right vertical axis. The dotted line on the curve between now and the year 2000 shows that full scale experiments of target physics issues are being conducted using the Nova laser, but an integrated target demonstration will require a laser delivering energy exceeding 1 megajoule.

Early attempts to raise the energy of short pulse, high power laser systems were thwarted by the self-focusing instability. This propagation instability is associated with the modification of an optical material's index of refraction as an intense laser beam transverses it. Thus, a local increase in the beam intensity because of diffraction rings, dust specks, etc. caused a local increase in the index of refraction, which caused the beam to locally experience a lens-like focusing, leading to a higher intensity downstream, and eventually filamentation and optical material breakdown. The problem with this instability is that, like most instabilities, it grew exponentially and thus was a potential limiting condition on the continued development of high power lasers. The near field amplitude growth rates are given by the equation $I = I_0 \exp(B)$, where the "B" integral is equal to $\mathrm{const}/\lambda \int (n_2 I \, dl)$.[5]

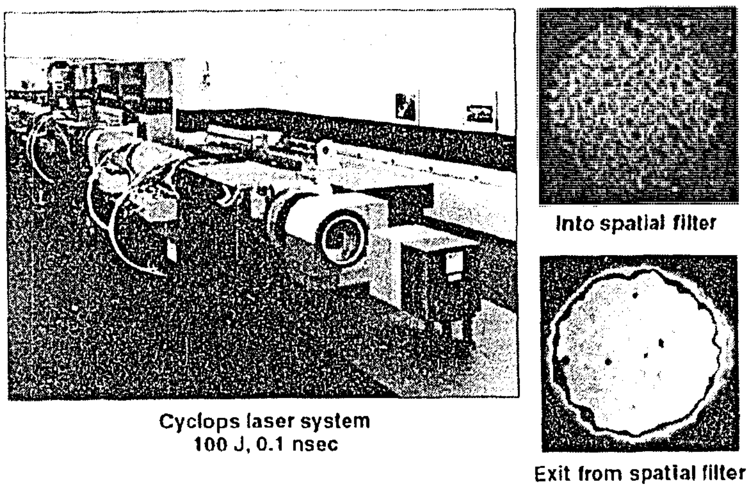


Fig 3: Early experiments showed the presence of beam break-up and loss of focusability. These experiments were conducted on the Cyclops laser facility at LLNL in the early 1970s by Simmons et al.[6]

Once the problem of self-focusing was understood (and controlled using high gain amplifiers and multiple spatial filters), as well as understanding the problems of controlling parasitic (longitudinal and transverse) and isolation, one was able to begin to conduct precise laser plasma experiments. These high gain, high power single beam-line laser target systems were stable against parasitic oscillations, against prepulse damage to the targets, and were focusable and diagnosable. Having understood single beam lines, the designers turned their attention to the problems of multiple beam lines.

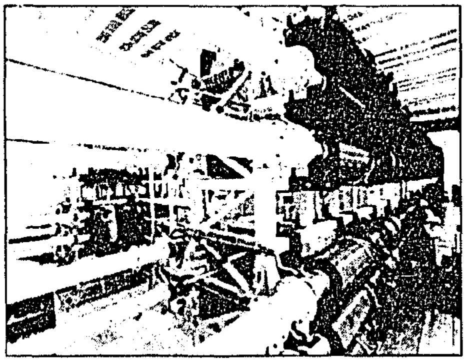
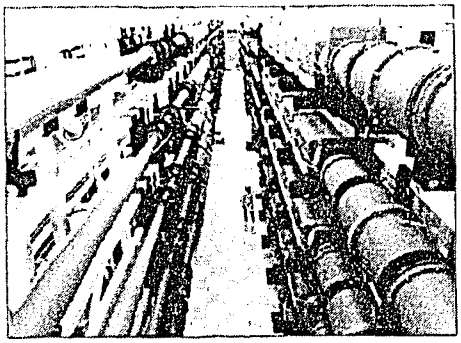


Fig. 4: The Shiva laser was a 20 beam, 10 kilojoule, 20 terawatt fusion laser system that was designed to irradiate a hohlraum fusion target with 1 nsec, 1.06 μm laser light, and to control implosion symmetry. Its construction was completed at the end of 1977.

The Shiva laser was a very successful system and demonstrated the use of large diameter (20 cm) laser apertures, multiple spatial filters, multiple beam control and aiming, and it was used to demonstrate the concept of ablative target implosions. (Through the middle 1970s almost all implosions were of the exploding capsule-wall type, which were not capable of producing high density implosions of the fusion fuel.) However, the most significant experimental result of this decade was the realization that wavelengths shorter than 1 μm, and probably shorter than 0.5 μm, were needed to control laser plasma coupling instabilities.

By the late 1970s, laser design and manufacturing had progressed to the point that new materials were available such as phosphate laser glasses and large KDP harmonic conversion crystals, as well as continued evolution in the mechanical, electrical, controls, and diagnostics of the unique electro-optic systems. A new 10-beam laser, Nova, was designed in 1978 and constructed in the early 1980s at the Lawrence Livermore Laboratory. A 2-beam prototype of Nova, called Novette, was used to validate design concepts and to validate the coupling of short wavelength radiation to the inertial fusion targets. This Nova laser is larger in diameter and is optimized for 3 nsec pulse duration and to produce an output of 100 kJ at 1.05 μm, 50 kJ at 0.53 μm, and 40 kJ at 0.35 μm At 1.05 μm each beam of Nova generated as much energy as the entire 20 beam Shiva system described above. Its cost on a per joule basis was 1/4 that of Shiva, and its controllability, maintainability, and diagnostics were far superior. A laser system, Gekko XII, based upon similar design principles was constructed in Osaka, Japan during this time period, and it too has been very successful in conducting inertial confinement fusion and laser plasma coupling experiments.

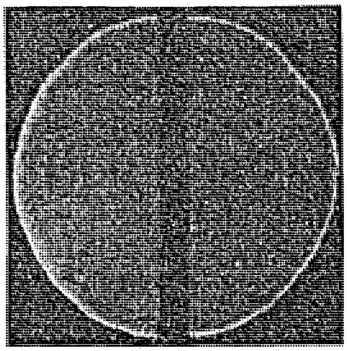
The most important physical constraints in the construction of these high performing systems were associated with the goal of high energy beam propagation as well as high power pulse propagation. This new operating condition is a consequence of extending the power levels of previous systems to longer time durations and, thus, the energy fluence through the optics could increase until breakdown. In addition, the long path lengths of these lasers, both longitudinally to the target, but also transversely (in up to 1 M diameter optics), allowed sufficient gain for new parasitic modes to develop that, if uncontrolled, would seriously limit the laser performance.



Issues were:

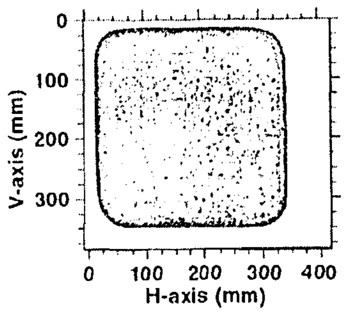
- Short wavelength (0.35 μm) coupling
- Both energy fluence and power limited
- Pulse shaped and bandwidth flexible
- Cost effective and maintainable
- Management of complexity

Fig 5: The Nova 10 beam laser system generates a 1.05 μm wavelength beam which is converted to 0.35 μm directly before the target focusing lens. The pulse duration is variable from 0.1 nsec to greater than 3 nsec.



74cm diameter full power "smooth" profile fill factor - 0.8

Extended to "upgrade" aperture



fill factor 0.85

Fig. 6: The beam quality of modern lasers is such that a 5% peak to average beam amplitude "ripple" is seen at the output of the system. The above left picture shows a 74 cm diameter full power Nova beam with aperture usage of 0.8. On the right one sees an experimental beam from "Beamlet" for the upgraded Nova laser (NIF) which is "square" in aperture and has a fill factor of 0.85.

The issues associated with designing and constructing the NIF (an extensive upgrade of the Nova laser) are strongly influenced by the wealth of new physics, engineering, and materials information obtained during the last 20 years of laser and target experimentation. The issues associated with the complexity of building the much larger system, which will have 192 laser apertures packaged 16 to 32 at a time, are those of cost and complexity. As a result, the accurate control and diagnostics of this system has deserved a great deal of attention. The dominant laser issues are associated with the efficient amplification and propagation of each laser beam at a higher fluence than has been used in the past. Operation at high fluence from a given aperture is desirable because the system costs are fixed for the mechanical hardware, controls, and diagnostics. More energy per unit fixed cost leads to an overall cost reduction when measured on a dollars/joule basis. Additional important laser design considerations are associated with controlling nonlinear parasitics covered by transverse Brilloin or Raman gain in the optical elements, with longitudinal parasitics associated with the very long propagation paths, with generating very accurately shaped temporal pulses, with efficient harmonic conversion, with purposefully generating and controlling the laser beam's spatial ($\Delta \underline{k}$) propagation vectors and temporal ($\Delta\omega$) bandwidth. These issues have been satisfactorily resolved, and the beam amplitude picture shown in the right hand images in Fig. 6, taken from the "Beamlet" prototype, shows successful realization of this design. In addition, continuing target experiments on Nova are validating many of the assertions that controlled spatial and temporal bandwidth, at the scale of NIF targets, will produce the desired implosion quality.

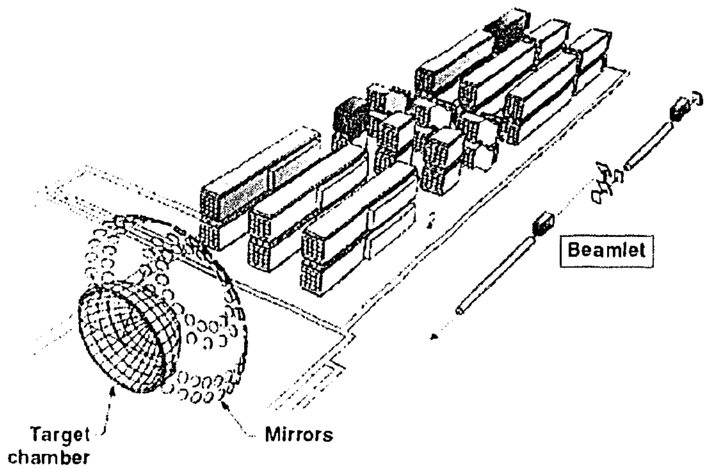


Fig. 7: The proposed National Ignition Facility is a 2 megajoule, 500 terawatt laser for research into fusion target ignition and gain. It is an extensive upgrade to the presently operating Nova laser. The Beamlet laser shown on the right side, has been recently completed. Laser propagation experiments have validated the operating conditions of the proposed NIF laser operating points.

Research on more effective ways to ignite laser fusion capsules continues because it is felt that the physics of capsule irradiation, capsule compression, ignition, and fuel burn will permit more efficient solutions than have been proposed so far. One of the most interesting is the "fast ignitor" concept of Tabak et al.[7] In this configuration, a target is compressed as efficiently as possible (isochorically, with no central ignition condition required that reduces present target compression efficiency). When the desired fuel density is achieved, a very short, few-picosecond duration, laser pulse is propagated as close to the compressed fuel as possible, where the pulse generates an intense beam of hot electrons that ignites the fuel from the edge. Realization of this concept (see Perry et al.[8]) could reduce the cost or increase the yield from a fusion laser facility by up to an order of magnitude.

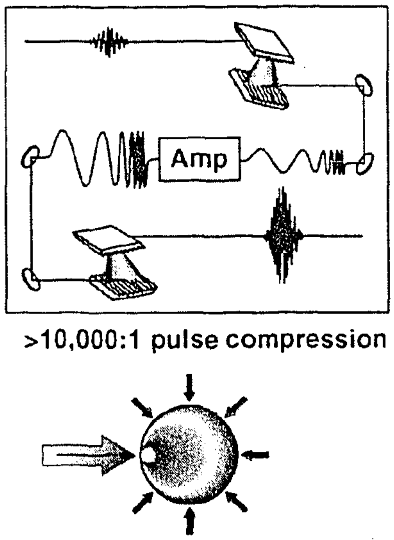


Fig. 8: Fast Ignitor: The lower image in this figure illustrates the concept of isochoric compression and edge ignition of a laser fusion target. The top image illustrates the large area pulse compression configuration being implemented on one beam of the Nova laser in order to test the physics of the "fast ignitor" concept.

Since its invention in 1959 by Nuckolls et al.,[9] the development of the inertial confinement fusion concept has been a remarkable achievement. The inventiveness of the target designers, the laser designers, the experimentalists, and the engineers have lead to a proposal for a system (NIF) that will demonstrate, without doubt, for the first time, high gain fusion in the laboratory.

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