An Evaluation of Laser Fusion Energy Concepts

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1. Executive summary

The inertial fusion energy approach with the highest predicted target energy gain uses an ArF gas laser[2] with symmetric laser illumination of a spherical target, This approach also has the best economics, and the lowest risks of failure from either the physics or the engineering.

There is now a substantial (not yet complete) experimental and computational data base to support both the fusion target design and the laser system. The chamber concept and balance of plant systems also appear attractive. The high energy gain of the target combined with the high efficiency of the laser implies a low recirculating energy, and thus very favorable economics. In total, inertial fusion with symmetric ArF laser illumination appears to be ready for a major enhancement in funding. It is a potentially attractive way to solve the world's long-term needs for energy.

The research programs at the Naval Research Laboratory and the University of Rochester have demonstrated that there are many constraints on the laser: its wavelength, bandwidth, optical smoothing, zooming, temporal shaping, profile shaping, optical damage limits, wall plug efficiency, etc. Two competing lasers have been under consideration. The ArF gas laser appears able to meet all of the constraints. The diode-pumped-solid-state laser (DPSSL) probably can not. This White Paper includes the reasoning behind this assessment of the lasers.

The continued attempts by DOE's NNSA to cancel the NRL laser fusion program are inexplicable. Financial support by DOE's OFES for laser fusion energy has been tepid. The DOE should start a large dedicated program to evaluate laser fusion energy. This DOE program would have three near-term components.

First, a laser-target facility, using a low-pulse-rate ArF amplifier, with at least 10 kilojoules of energy, to verify the remaining laser-target interaction physics under conditions closer to a high-yield fusion target.

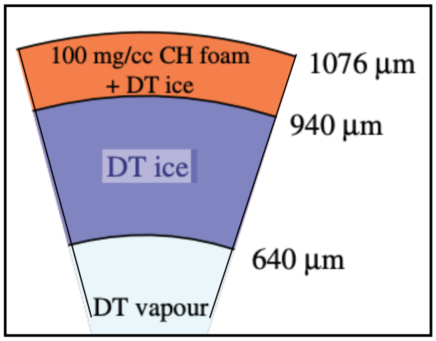
Second, development of a large ArF amplifier beam line that would meet <u>all</u> of the requirements for a fusion power plant. Funds should also be available to develop a DPSSL beam line as a backup laser system, if there is a qualified proposal.

Third, continued evaluation of chambers and the balance of plant.

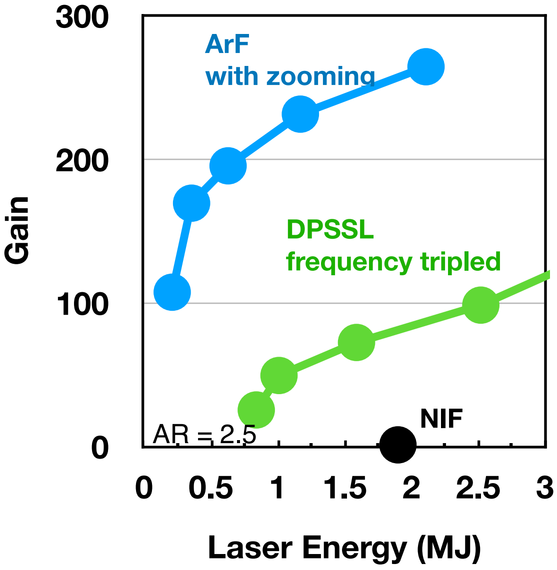
To maximize the chance of success, program management should be located within an organization that is primarily dedicated to developing a fusion power plant, not an organization whose primary mission is support for the military.

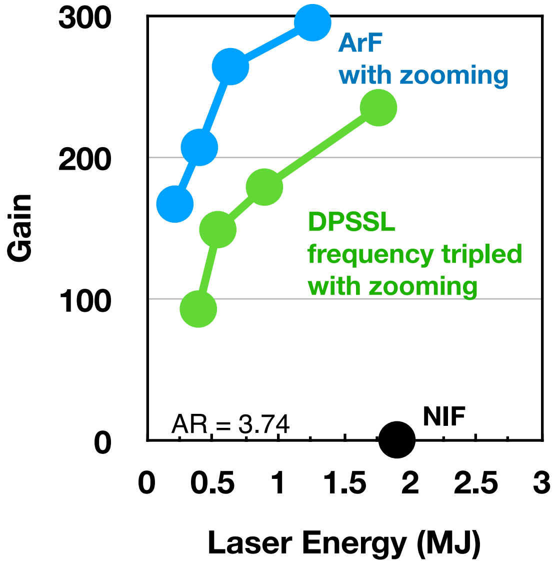
2. High gain target designs

The target design information in this Section 2 is taken from a 2021 APS presentation by Schmitt and Obenschain.[3] Here is their wedge drawing.



The spherical target is mostly DT ice with a low-density CH foam as part of the ablator, plus a very thin coating (not shown) of Au/Pd. There is no need for filling tubes, since the DT gas can diffuse through the thin coating of Au/Pd. Manufacturing cost for this simple target is estimated to be less than $0.25.





The figure on the left shows their computer-predicted spherical 1D energy gain calculations, with an initial target aspect ratio $R_0/\Delta R_0=2.5$. For comparison, the black dot is the NIF experimental result.

Schmitt has also performed extensive 2D implosion calculations.[3] Close to the threshold of ignition, the target performance could be poor. But well above ignition, at 0.5 MJ or higher, the gains can robustly reach 75% or more of the 1D spherical prediction.

At 1.9 MJ, the single best NIF shot had an energy gain of 0.7. With an ArF laser the 1D predicted gain is about 260. The ratio is 370. Correcting for 2D effects, the gain ratio would still be very high. There are four basic reasons for this huge disparity in energy gains: **(1)** The NIF target has poor energy coupling from the laser to their sphere. **(2)** The NIF target requires a high fuel adiabat to control various physics problems. **(3)** The NIF target is energy-poor and too close to its ignition threshold. If the indirect-drive NIF targets were driven with lasers far above 2 MJ, then perhaps the energy gains might reach 10. This gain is still far below a symmetric illumination target. **(4)** The ArF design uses two reductions in the focal beam size during the implosion (optical zooming) to better match the laser focal spot to the target size.

Since 1995 I had been predicting[4] that the NIF target would fail to achieve ignition due to low-mode time-dependent implosion asymmetries. After a decade of target experiments, the NIF scientists have found an operating window that avoids this asymmetry problem and produces significant energy yield. I was both surprised and pleased by their achievement. Their target demonstrates in the lab good spherical convergence, near-ignition, and a significant $\rho T\tau$ product, thereby further validating the basic inertial fusion implosion concept, and further justifying a vigorous laser fusion energy program.

Because the DPSSL has a longer laser wavelength, the light can not propagate to as high a plasma density. To produce the same plasma pressure as with ArF, Schmitt[2] has shown that the target design requires a higher laser intensity and thus more laser energy. Absorption is also lower, which implies still more laser energy. The higher laser intensity, higher plasma temperatures, and lower plasma densities imply a significantly higher risk of laser-plasma instabilities.

A thinner shell with a higher aspect ratio reduces the required laser intensity and the risk from laser-plasma instabilities, and increases the target energy gain. But the thinner shell also increases the risks from hydrodynamic instability and illumination asymmetry.

The plot above on the right shows target gains with $R_0/\Delta R_0$ increased from 2.5 to 3.74. The DPSSL laser profiles have been zoomed inward to provide a direct comparison of just the different laser wavelengths. Without zooming the DPSSL would produce lower target gains. Under this scenario DPSSL produces an acceptable 1D target energy gain above 2 MJ; still with a significant risk from laser-plasma instabilities.

3. Laser requirements

This Section compares ArF and DPSSL in more detail, using several of the known physics and engineering requirements developed over the years by NRL and U of R scientists. In summary, ArF meets all these requirements, but the DPSSL has several basic problems.

- **Laser bandwidth**

When NRL initiated the KrF gas laser program in 1987, we had hoped that its short 0.248 µm wavelength combined with its wide 3 THz bandwidth would suffice to control all of the various laser-plasma instabilities. We were a bit too optimistic. The newer shock-ignition target design requires a higher peak laser intensity. Also, experiments and theory at NRL and U of R have verified that there could be problems with the two-plasmon decay instability and with the cross-beam-energy-transfer instability. To solve all these problems, a shift to a shorter laser wavelength and/or larger bandwidth was advisable.

NRL shifted from KrF (*0.248 µm @ 3 THz*) to ArF (*0.198 µm @ 10 THz*). ArF became feasible after the integrated circuit industry developed optics for ArF with a sufficiently high damage threshold. Based upon a combination of theory and data base, NRL expects that the ArF laser light will now be below threshold for all of the laser-plasma instabilities during the main laser pulse. During the final shock heating the laser intensity will still be roughly a factor of four above instability threshold. They predict that using ArF will suffice to limit the suprathermal electron production to an acceptable value. This needs to be verified with a more than 10 kilojoule ArF flat-target experimental facility.

The DPSSL (*0.351 µm*) target has a narrow bandwidth, well below *1 THz*. To solve this problem, some DPSSL proponents[5] suggest using about 10,000 parallel laser beams, each with about 100 Joules, each with their own frequency-converting crystals and phase plates. The central frequency of the different laser beams would differ so that the parallel combination of beams would emulate a wide bandwidth; several times wider than ArF. A wider bandwidth than ArF is necessary to compensate for DPSSL's greater risks from laser-plasma instabilities. Alternatively, Rochester is now developing a high-bandwidth glass laser produced by optical parametric amplifiers, called FLUX. It is not clear to me if this very complex system could be utilized in a DPSSL system with acceptable cost, etc.

- **Laser Efficiency**

To produce practical amounts of net electricity the generally accepted requirement is that the laser efficiency times the target energy gain must exceed ten ($\eta_L G > 10$). Based upon testing of individual components, a fusion-energy-class KrF laser is predicted to have a wall plug to on-target efficiency in excess of 7%. Scaling from KrF component data to ArF with the known ratio of intrinsic efficiencies, it is predicted that the ArF wall plug efficiency will be at least 10%. Experiments are currently underway at NRL using the Electra laser to verify the > 10% efficiency of an ArF laser.

If the actual target gain is in the range of 160 to 200, then $\eta_L G$ equals 16 to 20, which leads to a recirculating power of less than 20%.

DPSSL proponents claim that their inferior target gain G can be balanced with a higher laser efficiency η_L. Detailed design studies have been developed[6] that predict wall-plug efficiencies of 18%. That would be impressive. However the only fully operational DPSSL that is relevant to laser fusion was the Mercury laser, developed at Livermore with funding from NRL's HAPL program. The Mercury laser[7] was an impressive advance in laser technology. But it failed by about a factor of four in efficiency. Mercury has been advertised as demonstrating 10% efficiency; but that was in the infrared. The laser light was never converted to the third harmonic. Frequency tripling with relevant pulse shaping would be at most about 60% efficient; thus reducing Mercury efficiency to at most 6%. It has been my observation that DPSSL efficiency is often quoted without the cooling requirement for the diodes. Correcting for diode cooling would reduce Mercury to about 4%. A 4% to 6% efficiency is much less than the advertised 18%, and well below the 10% ArF laser efficiency.

There is a basic design conflict in all solid-state laser designs. To efficiently extract the inverted stored energy, the laser fluence in J/cm^2 needs to be higher than the laser material's saturation fluence. But high fluence leads to optical damage. If one could somehow develop a laser glass with a lower saturation fluence then the optical damage could be avoided, but that would greatly increase the quantity of expensive laser glass and expensive diodes. There is a basic conflict between maximizing laser efficiency, avoiding optical damage, and controlling capital cost. (ArF has a low saturation fluence and a short inversion time. Energy is extracted cheaply and efficiently through a train of laser pulses, called multiplexing. This method is not applicable to solid state lasers.)

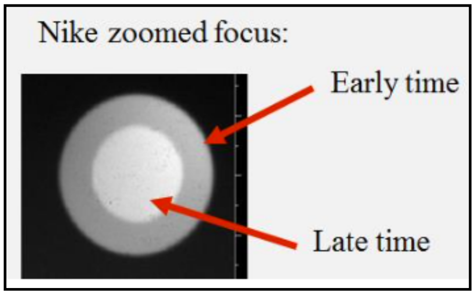
The DPSSL concept appears to me to be, in the phrase of Silicon Valley, vaporware. To prove it isn't vaporware, there has to be an actual experimental demonstration that a DPSSL 100 J beam line can simultaneously meet all of the target requirements..

- **Laser Profile Shaping and Zooming**

The low-mode pressure nonuniformity around the shell should be held to about 1%. This is calculated to be feasible[8] with laser beams coming from 32 to 80 portholes. However the target shell has to be accelerated inwards, at least until it reaches about half its initial radius. The laser profile I(r) has to change during the implosion, to maintain the uniform pressure. I estimate that five profile changes in the laser intensity profile will be needed. One should write $I_j(r)$ where j runs from 1 to perhaps 5.

Optical zooming[9] was originally proposed at NRL as a way to match the laser focal spot size to the target, thereby saving laser energy. Zooming will also help prevent the cross-beam-energy-transfer instability in the underdense plasma. A third reason for zooming is to maintain a sufficiently uniform pressure uniformity around the target shell as the implosion proceeds.

Zooming is simple with an excimer gas laser such as KrF or ArF. The ISI optical smoothing technique is just optical relaying from the oscillator area to the target. Multiple zooms can be accomplished using a set of small partially-reflecting mirrors and soft apertures just after the oscillator. Zooming has been experimentally demonstrated using the Nike KrF laser[10], as shown here.



The laser fusion program needs a more detailed specification of the required changes in the laser profile $I_j(r)$. This will best be accomplished with a 3D computer model. For a rapid survey one could first use the plasma profiles from a 1D target calculation. Later modeling should include the feedback to the plasma. (*Perturbation methods are not applicable because the large convergence ratio amplifies small perturbations into large perturbations.*)

Regardless of what this study concludes, it will be easy to adjust the ArF laser profiles as many times as needed, using multiple small mirrors and soft apertures in the laser's front end. It will however probably be impossible with a DPSSL that uses SSD optical smoothing. Image relaying is not possible with solid-state lasers because of nonlinear optical effects. The radial profile at the focus is instead determined by the "kinoform" phase plates at the end of the laser chain. If, for example, five profile modifications are needed then the DPSSL design would have to be changed from 10,000 beams to 50,000 beams; each with their own frequency converting crystals and kinoform phase plates, and each with a shorter pulse duration.

In addition to the difficulty adjusting the radial profile during the implosion, note that SSD optical smoothing is a periodic, not a random process. There is a residual low-mode nonuniformity that could prevent sufficiently uniform illumination. The ISI optical smoothing with ArF uses a true incoherence.

- **Laser repetition rate and reliability**

An advantage of laser fusion energy over magnetic fusion is that the high-tech components can be located outside of the radiation shielding for easier maintenance. However it is still highly desirable that the laser operate routinely and economically for as long as one year without maintenance.

When in 1987 NRL shifted its laser fusion program from a glass laser to the construction of the Nike KrF gas laser, no lab in the world had been able to operate an electron-beam-pumped KrF laser for more than a few shots without major repairs. The superb team of NRL scientists and engineers were able to exceed our internal goal of firing Nike at half-hour intervals for 100 shots without maintenance. Later, as part of the HAPL program, the Electra[11] KrF laser produced 90,000 shots, with more than 300 Joules each, continuously at 2.5 Hz (10 hours total). Improvements were underway to greatly enhance this lifetime when the HAPL program lost its funding.

The Mercury DPSSL had a series of runs, each 0.5-2 hours long at 10 Hz, 50 Joules each, for a total of 300,000 shots. However the laser light was in the infrared, with low efficiency.

4. Fusion Energy Technologies

In a light-water fission power plant the uranium pellets just stay in place for years. Heat is generated locally without any moving parts. In spite of this inherent simplicity, newer environmental safety rules have driven the capital cost of fission power plants to uneconomic levels. Generation IV nuclear reactors are now under development that will hopefully combine safety and proliferation-resistance with better economics.

With laser fusion, tritium is the only significant source of radioactivity. This could give laser fusion energy a major cost advantage over fission energy. However there is a concern that any laser fusion power plant will be too complex and too expensive; not cheaper than fission. There are several moving parts: target fabrication, target injection and tracking, operation and cooling of the ArF laser, and tritium recycling. To maintain the costing advantage over fission will require careful design, and a constant reminder of the KISS principle: Keep It Simple, Stupid.

The NRL-managed HAPL program was dedicated to develop all of the non-fusion technologies needed for a fusion power plant. The program included final optics, the chamber, mass target fabrication, target injection, target tracking, and the tritium-breeding blanket. Credible technologies were identified for all of these, and in most cases they were demonstrated in sub-scale and bench tests.[12]

5. New laser fusion energy program

The deep UV wavelength of an ArF laser, along with its wide spectral bandwidth, its ISI optical smoothing that produces near-ideal time-averaged spatially-smooth profiles, and the flexibility to adjust these spatial profiles during the implosion, is calculated to produce high target energy gains that substantially exceed the minimum requirements for economically attractive fusion energy. The U.S. laser fusion energy program should take advantage of the NIF success with ignition and concentrate on the major remaining scientific and engineering uncertainties. I believe that it is possible to complete the evaluation and development of an economically-attractive ArF laser fusion energy power plant in a very limited time period.

The program should start with three items:

- ✦ An ArF laser-target facility with a flat target is needed to verify the instability thresholds. To approximate the density and temperature profiles of a fusion target will require at least a 10 kJ laser.
- ✦ The program needs to develop one beam line of an ArF laser that simultaneously meets all of the requirements for a fusion power plant. The power plant would perhaps consist of about 20 parallel laser beam lines, each with about 25 kJ. The program needs to build one of these 25 kJ beam lines, and iterate until it meets all of the fusion requirements. The program would then know the capital and operating costs of the laser for a fusion power plant.

  A DPSSL is in my view not worth pursuing, because of the basic problems with efficiency, optical damage, time-dependent profile shaping, and laser-plasma instabilities. However if some qualified group wants to prove me wrong, they should be provided with sufficient funds to develop one or more of the 100 Joule DPSSL lasers. If the ArF program fails, it would be nice to have a backup.
- ✦ A national program should continue the HAPL evaluation of all of the needed non-fusion related science and technologies.

[1] Retired. Head of NRL laser fusion program from 1975 to 1999.

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[4] S E Bodner, "Time-dependent asymmetries in laser-fusion hohlraums", *Comments on Plasma Physics*, **16**, 35 (1995) https://www.academia.edu/6453024/Bodner_comments_on_NIF_1995

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[6] A Bayramian et al, *Fusion Science and Tech*, **60**, 28 (2011)

[7] A Bayramian et al, *Fusion Science and Tech*, **52**, 383 (2007)

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[9] R H Lehmberg and J Goldhar, *Fusion Technol.* **11**, 532 (1987)

[10] D M Kehne et al, *Rev. Sci. Instrum.* 84, 013509-1-013609-4 (2013)

[11] In Sophocles' Greek tragedy, Electra seeks revenge for the murder of her father. For Electra's modern accomplishments, see J D Sethian et al, *Proc. 15th IEEE Pulsed Power Conf*, Monterey CA, Jun 2005, pp 13-17

[12] J D Sethian plus 87 co-authors from 22 U.S. organizations, *IEEE Trans. on Plasma Science*, **38,** 690 (2010), plus the many references therein.