Path to reduced-size laser fusion power plants with direct drive using the argon fluoride laser

White paper on research opportunities in Inertial Fusion Energy

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Executive Summary

We describe an attractive approach to laser inertial fusion energy (IFE) employing direct drive[1] with the argon fluoride (ArF) laser. ArF is the shortest wavelength laser (193 nm vs 351nm on the NIF) that can reach the energy and power required for high-gain laser fusion. The short wavelength improves the laser-target coupling efficiency thereby reducing the laser energy required to obtain conditions for a high gain implosion. The combination of short wavelength and multi-THz bandwidth can suppress undesired laser plasma instabilities (LPI). ArF shares desired capabilities with the krypton fluoride (KrF) laser demonstrated on the NRL Nike facility.[2] This includes the flexible induced spatial incoherence (ISI) beam smoothing where the desired focal distribution is imaged from an aperture in the laser front end to the target.[3] This beam smoothing approach enables straightforward implementation of zooming down the focal diameter to follow an imploding pellet.[4] For laser direct drive, zooming substantially increases the coupling efficiency to an imploding target.

Hydrocode simulations indicate that the combination of the ArF driver with shock ignition[5,6] pellet designs could enable implosions achieving gains needed for power plants with laser energies below 1 MJ.[7] The projected electrical efficiency of an optimized ArF IFE laser system is about 10%. We provide as an example a 425 MWe power plant utilizing a 650 kJ ArF laser driver operating at 10 pulses per second. The modest size should reduce the unit cost and speed development time for laser fusion power plants. A phased development program is described that first develops a high repetition-rate implosion facility for scientific studies (10 shots/hour) to advance the ArF laser target interaction physics and demonstrate high gain implosions (100x). In parallel the higher repetition-rate laser hardware and other technologies required for a power plant would be developed. With success in the target physics and supporting laser IFE technologies, one would then be prepared to build a pilot power plant.

The ArF laser was recognized as having attractive properties as a driver for inertial fusion more than 40 years ago. Researchers in the United States and Japan constructed two 100 J class systems in the late 1970's and mid 1980's.[8,9] Work on ArF was abandoned for many years in belief that frequency multiplied glass laser drivers would suffice. Modest size efforts continued with the 248 nm KrF laser (similar to ArF in architecture).[10,11,12] The NRL program has advanced the KrF driver for ICF/IFE culminating in the 4-kJ Nike facility used for planar target experiments[13] and the 750-J Electra facility that demonstrated 5 pulse-per-second operation.[14] Recently, NRL researchers decided to explore the feasibility of using the deeper UV ArF option for ICF/IFE because in addition to the shorter wavelength advantage it a) can provide substantially wider bandwidth light to target and b) the projected electrical efficiency is higher than for KrF. The high-energy ArF amplifiers employ electron-beam pumping similar to that developed for KrF. The Electra facility has been modified for ArF operation[15] and has demonstrated a world record ArF energy (200 J). It is being utilized to advance the basic science and technologies of electron-beam-pumped ArF operation. Migration to ArF is aided by advances in and widespread use of ArF technologies for lithography over the past two decades by the semiconductor industry.

The ArF laser has the potential to substantially improve the laser target coupling physics and may thereby allow construction of power plants with much lower energy laser drivers than previously thought possible.

The current effort at NRL would benefit from additional investments in the ArF technologies, e.g. high-repetition-rate pulsed power for the electron beam diodes, an amplifier test bed optimized for ArF operation (Electra was optimized for KrF) and advancing 193 nm optics for the conditions required for IFE.

Success with laser IFE requires advancing a broad range of technologies common to all drivers. These include: low-cost target fabrication, target injection and precision engagement by the driver beams, durable neutron resistant final optics, and long-lived first wall for the target chamber. The 1998-2008 HAPL program advanced all these technologies.[16] We would recommend that a new DOE-supported IFE program build on this earlier effort.

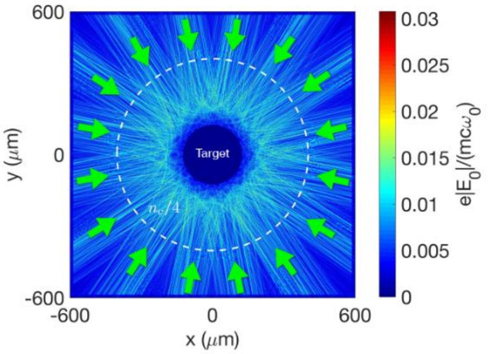
Direct Drive Target Physics

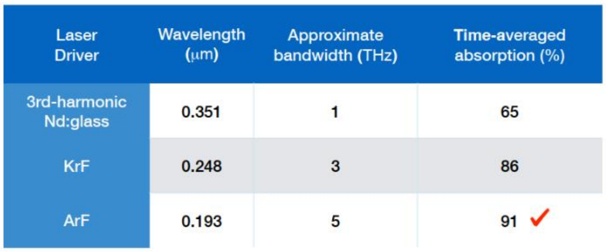
The recent 1.3 MJ yield indirect drive implosion on the NIF using 1.9 MJ of 351 nm light showed the basic viability of inertial fusion.[17] The result was particularly impressive given that only 230 kJ of x-rays were absorbed by the imploding capsule. Direct laser drive provides the opportunity for more than 6 times more efficient use of the laser light but requires that the laser beams more uniformly and symmetrically illuminate the target. The required and desired characteristics of the laser to achieve high performance direct drive implosions include:

- Uniform target illumination with precise pulse shaping
- Multi-THz bandwidth (> 6 THz) to suppress laser-plasma instabilities
- Shortest feasible laser wavelength to further suppress LPI and increase hydro-efficiency of implosion
- Capability to zoom the focal diameter to follow an imploding target

The first requirement is primarily a facility engineering challenge that all direct drive approaches will need to face. Broad laser bandwidth reduces early-time laser imprint from beam smoothing techniques, and can also help suppress LPI. Current frequency multiplied glass lasers are limited to 0.5 THz bandwidth on the OMEGA system and 135 GHz on NIF before the tripling conversion efficiency begins to suffer. These systems do not have capability to zoom the focal diameter of individual beams to follow an imploding capsule. However, a means has been identified and tested that might enable future solid-state laser drivers to provide broad bandwidth laser light to target, but not with wavelengths shorter than about 351 nm.[18] In contrast, the ArF driver offers multi-THz bandwidth (~10 THz), multi-stage focal zooming and by far the shortest wavelength among ICF drivers. These will improve the target performance and offer the option of utilizing higher pressure to drive the implosion. Higher pressure would allow use of lower aspect ratio targets (radius to shell thickness) that reduce the growth of hydrodynamic instability and lowers the overall precision required in the laser illumination and target fabrication.

Below we provide simulations and a discussion of the advantages of using ArF light for high performance direct drive implosion. Figure 1 shows LPSE[19] simulations of the absorption fraction for various bandwidth 351 nm, 248 nm, and 193 nm light onto a spherical target at intensity of 5 x 10^{14} W/cm^2.[20] The simulation captures the effects of inverse bremsstrahlung absorption and losses from cross beam energy transfer (CBET). The superior absorption fraction with ArF light is primarily due to the 5 THz bandwidth suppressing CBET. Similar suppression is predicted for broad bandwidth 351 nm light, although inverse bremsstrahlung absorption would be lower. Two LPIs that can produce hot electron preheat, two plasmon decay (TPD) and stimulated Raman scattering (SRS), have thresholds that vary inversely with laser wavelength.[21] This increase in threshold with 193 nm light adds to the suppression by broad bandwidth.





Laser Driver	Wavelength (μm)	Approximate bandwidth (THz)	Time-averaged absorption (%)
3rd-harmonic Nd:glass	0.351	1	65
KrF	0.248	3	86
ArF	0.193	5	91 ✓

Fig.1. LPSE simulations of absorption fraction for a OMEGA size target using 1 THz 351 nm, 3 THz 248 nm (KrF) and 5 THz 193 nm light. The ArF light is 91% absorbed versus 65% for the 351 nm light.

Shorter wavelength light penetrates to a higher plasma density, causing the blow-off plasma from a laser-illuminated target to have lower temperature and lower expansion velocity. This results in higher rocket efficiency for driving an implosion to the speeds needed for DT fusion and higher overall coupling efficiency. Figure 2 (right) shows the net effects of wavelength on the 1-D gain of conventional and shock-ignited targets as a function of laser energy. These particular simulations employ targets with DT loaded foam ablators with initial aspect ratio of 3.75. For both conventional and shock ignited designs the ArF light allows high gains at lower energy than 351 nm. This effect becomes larger for lower aspect ratio targets that require higher drive pressure. The 1-D gains can be reduced by imperfections in the target and laser illumination leading to growth of hydrodynamic instability. A 2-D simulation (Fig. 2 right) for an ArF shock ignited target that includes the effects of target non-uniformity provides a still impressive gain of 160 with 410 kJ laser energy.[22] Addition of laser imprint effects with ISI beam smoothing and 5 THz bandwidth only reduced the gain to 148. Imprint could be further reduced by higher bandwidth and use of a thin high-Z layer overcoat to produce an early time x-ray drive.[23]

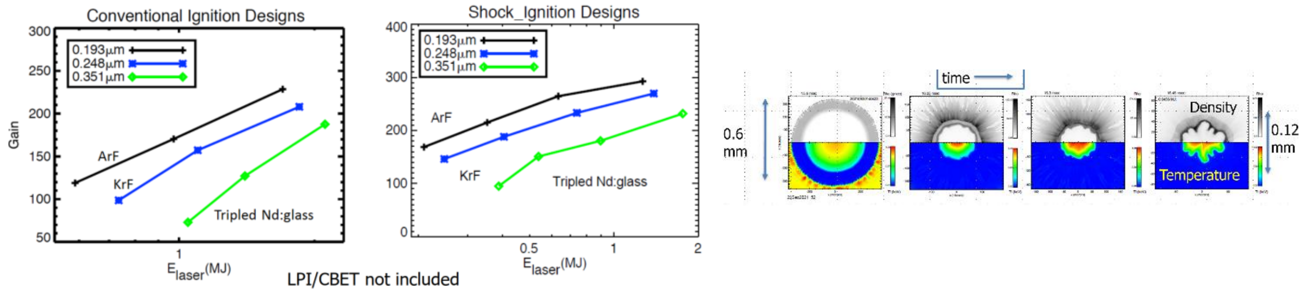
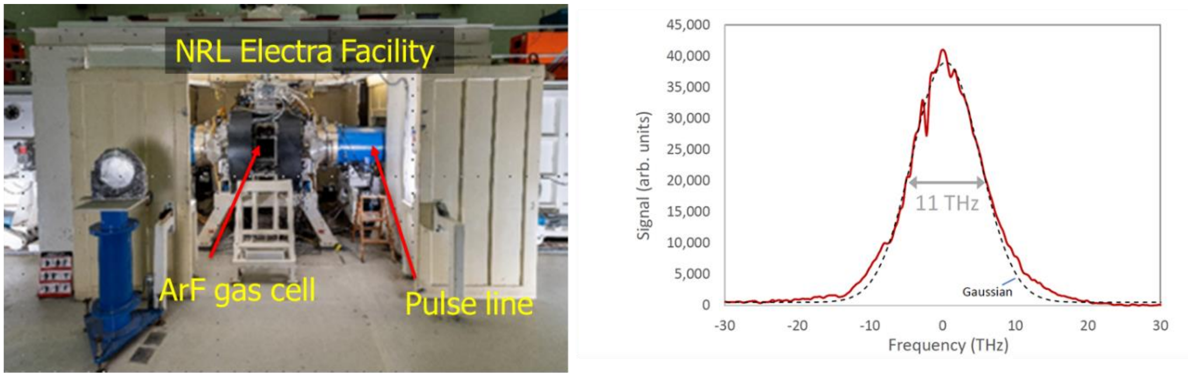


Fig 2. (left) 1D NRL hydrocode simulations of energy gain as a function of laser energy for 351 nm, 248 nm, and 193 nm laser drivers from reference 7. (right) 2-D simulation of ArF shock ignited implosion with effects of target imperfections. (410 kJ ArF laser energy, fusion energy gain 160x)

We expect ArF to provide sufficient bandwidth to suppress SBS and CBET losses for the conditions of the above implosions. The effects on other LPI that involve electron plasma daughter waves are under study to determine the maximum ArF laser intensities that can be employed. Kinetics simulations indicate that 10 THz bandwidths should be achievable with large ArF systems, (see ref. 7) which combined with ArF's short wavelength would allow much higher drive intensities than current modest bandwidth 351 nm systems allow.

Advancing ArF Science and Technology

Figure 3 shows the Electra electron-beam pumped amplifier, which has been converted from KrF to ArF operation. It demonstrated a world record 200 J ArF output in oscillator mode. We use Electra to advance the basic S&T of high-energy ArF lasers and to test the laser kinetics code predictions. Bandwidth of 11 THz FFWHM was observed from the single pass amplified spontaneous emission (ASE) output. This bandwidth is in agreement with our kinetics code simulation of the experimental conditions.



- Demonstrated 5 pulse per second operation with similar KrF operation
- Converted to ArF to advance basic electron-beam pumped ArF S&T
- World record ArF energy (200J)

- 11 THz FWHM bandwidth observed from Electra (single pass ASE output)
- Kinetic simulations predict indicate large ArF systems built for ICF/IFE can provide 10 THZ bandwidth light on target. See ref. 7

Fig. 3. Photo of the Electra amplifier and ArF bandwidth measurement of 11 THz FWHM ASE

The Electra system demonstrated 5 pulse-per-second operation with the similar KrF mode. Electra demonstrated 100,000-shot continuous runs limited by the use of the spark gap switches. Next generation ArF systems for IFE would employ solid-state pulsed power switching. A separate all solid-state-switched pulsed power system (4.5 kA, 200 kV) demonstrated over 10 million shot continuous operation at 10 Hz.[24]

Support needed to advance the ArF direct drive option

The current NRL ArF program utilizes codes developed for NNSA's ICF program to determine the potential benefits of ArF light towards achieving the high fusion yield desired by NNSA and the high energy gain required for IFE. ARPA-E and the Office of Science are supporting the S&T of the ArF high-energy driver at a modest level. The present program has as primary goals testing the ArF codes against Electra results and identifying paths for efficient ArF operation. The rate of progress would be greatly enhanced by support from a future IFE program that would enable advancing the basic ArF technologies and the target physics. The topics for development would include the following:

- Design and development of all solid-state-switch pulsed power modules[25]
- Implementation of an electron beam pumped preamplifier for Electra to enable saturated gain measurements
- More comprehensive target simulation effort including 3D hydrocode simulations
- Advancing and testing durable ArF optics for IFE
- Conceptual design of a high energy ArF beamline

Collaboration with others would be welcome.

Path to a fusion power plant

Figure 4 below shows the power flow in a 425 MWe ArF laser fusion power plant that utilizes a 160 gain shock-ignited target and 650 kJ ArF laser energy operating at 10 pulses per second. The gain is that seen in a high-resolution 2D simulation shown in Fig. 2 with 410 kJ ArF laser energy. A 50% increase in laser energy was added as a contingency to obtain that gain.

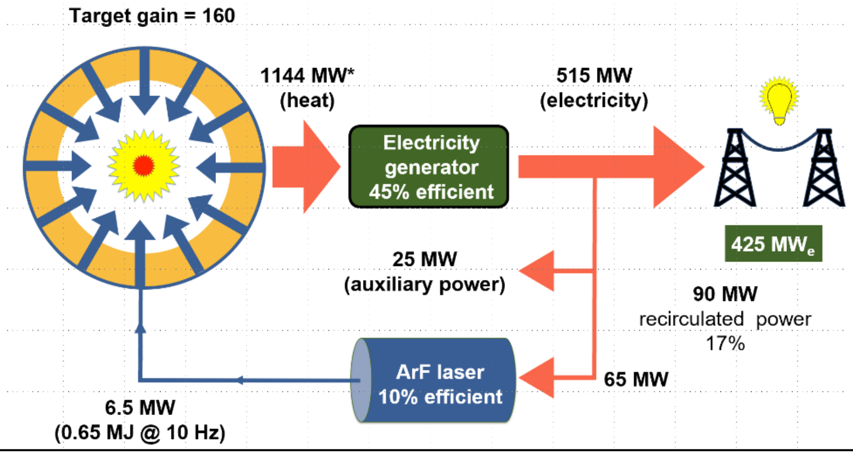
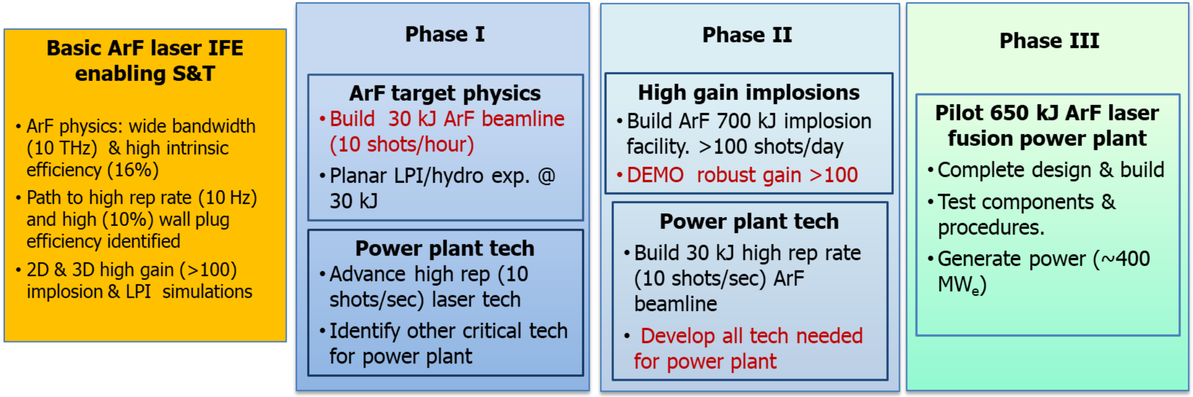


Fig. 4. Power flow in an ArF laser fusion power plant. Most of the generated power goes to the grid. *Nuclear reactions in the lithium blanket increase the power by 10%.

Figure 5 shows a phased path to a pilot power plant that begins after the basic science and technologies of the ArF laser approach are well established. The plan advances in parallel the capabilities needed to demonstrate high gain ArF driven implosions and the technologies needed to build a power plant. Phase I includes construction of a 30-kJ 10-pulse-per-hour ArF beamline prototype for the target physics implosion facility. The beamline would be available for planar ArF target experiments. In Phase II a high gain implosion facility is built and employed to advance the target physics and demonstrate high gain. A high repetition rate (10 pulses per second) 30-kJ beamline and other needed IFE technologies are also advanced and tested in Phase II. Phase III progresses to building a pilot power plant similar to that illustrated in Fig. 4. The pilot plant would have the task of testing materials, optical components, tritium breeding and procedures in addition to demonstrating power production. It would perform a similar function to the fusion test facility (FTF) described elsewhere.[26]



Basic ArF laser IFE enabling S&T

- ArF physics: wide bandwidth (10 THz) & high intrinsic efficiency (16%)
- Path to high rep rate (10 Hz) and high (10%) wall plug efficiency identified
- 2D & 3D high gain (>100) implosion & LPI simulations

Phase I

ArF target physics

- Build 30 kJ ArF beamline (10 shots/hour)
- Planar LPI/hydro exp. @ 30 kJ

Power plant tech

- Advance high rep (10 shots/sec) laser tech
- Identify other critical tech for power plant

Phase II

High gain implosions

- Build ArF 700 kJ implosion facility. >100 shots/day
- DEMO robust gain >100

Power plant tech

- Build 30 kJ high rep rate (10 shots/sec) ArF beamline
- Develop all tech needed for power plant

Phase III

Pilot 650 kJ ArF laser fusion power plant

- Complete design & build
- Test components & procedures.
- Generate power (~400 MW_e)

Fig 5. Phased plan to advance both the target physics and technologies to build a pilot ArF laser-fusion power plant.

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