The Argon Fluoride laser as an enabler for low cost inertial fusion energy

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Why an ArF laser driver could enable lower cost modest size laser IFE power plants

The superior laser target coupling with ArF’s deep UV light (193 nm) could enable the high target gains needed for the energy application at much lower laser energies than previously thought feasible. The combination of deep UV light and broad native bandwidth (>5 THz) suppresses laser-plasma instabilities that limit the laser intensity and ablation pressures of current 351 nm frequency-tripled glass lasers which are the traditional laser drivers for fusion. ArF is a potentially disruptive technology for laser fusion that shares several advantageous technologies with the krypton fluoride (KrF) laser technology (λ=248 nm) used on the Nike laser system located at the Naval Research Laboratory (NRL). The ArF laser would utilize similar electron-beam pumping to that used for large KrF amplifiers. It would also be able to use the beam smoothing technology demonstrated on Nike that enables very uniform illumination of directly driven targets and provides the capability to “zoom” the focal profile to follow an imploding target. The KrF technology was chosen for the Nike facility because of numerous advantages for achieving laser fusion. ArF laser light in turn would be superior to KrF. For the IFE application, kinetics simulations indicate that ArF would have as much as 1.6x higher intrinsic efficiency than KrF. The advantages would enable the development of modest size and low cost power plant modules utilizing laser energies well below 1 MJ. This would drastically change the present view on inertial fusion energy (IFE) as being too expensive and the power plant size too large.
Inertial Fusion (via central ignition)

Lasers or x-rays heat outside of pellet, imploding fuel to velocities of \( \sim 300 \text{ km/sec} \)

Central portion of DT (spark plug) heats to ignition.

~ 3% of original target diameter

Laser power

Simple concept
• Potential for very high energy gains
• Requires high precision in physics & systems
• Need to understand & mitigate instabilities
Laser plasma instabilities (LPI) cause problems for ICF/IFE

- LPI produced high energy electrons can preheat target impeding its compression.
- LPI induced scattering reduces laser drive and can spoil symmetry.
- LPI limits the maximum usable laser intensity and ablation pressure

- Short laser wavelength increases the instability intensity thresholds
- Broad laser bandwidth can disrupt the coherent wave-wave interactions that produce LPI
Simulations utilizing LLE’s LPSE code indicate cross beam energy transport (CBET) can be suppressed with broad laser bandwidth.

Simulations show that 2 THz bandwidth produced by discrete randomly phased lines begins to mitigate CBET, while 5 THz has a large effect. The ArF laser should easily provide > 5 THz bandwidths on target.

Deeper UV light improves hydro efficiency and increases LPI thresholds

**Ablation pressure vs laser \( \lambda \) from hydrocode**  
\( 10^{15} \text{ W/cm}^2 \) 2.6 mm solid CH sphere

**TPD thresholds vs laser \( \lambda \) from hydrocode**  
\( 10^{15} \text{ W/cm}^2 \) 2.6 mm solid CH sphere

Direct drive ablation pressure increases with shorter laser wavelength.

In this simulation one remains below the TBD threshold with 193 nm light.
NRL FAST radiation hydrocode 1-dimensional simulations of the gain of conventional and shock ignition\textsuperscript{1,2} direct-drive implosions for ArF, KrF and a frequency tripled glass laser.


Key Parts of a Laser Inertial Fusion Energy Power Plant

Operation at 5 to 10 pulses per second.

Pellets containing frozen or liquid DT fuel are injected and engaged by multiple laser beams.

Reaction chamber ID is ~10 meters.

Lithium containing “blanket” in the walls breed tritium.

Major components are modular and separable.
Diagram of the energy flow of a laser fusion power plant using a 10% efficient 0.5 MJ ArF laser system operating at 10 Hz. and a 190x gain shock ignited target. The large product of laser efficiency times energy gain allows most of the produced electricity to be distributed to the grid.

Target "Gain" = Fusion power OUT / laser power IN
(Nuclear reactions in chamber “blanket” add 1.1x to target gain)

- Target Gain = 190x
- 1045 Megawatts (heat)
- 418 Megawatts (electricity)
- 368 Megawatts
- 50 Megawatts
- 50/418 = 12%

Recirculating power

start here

ArF Laser 10% efficient

Electricity Generator (40%)

Power Lines
KrF and ArF excimer laser drivers are attractive driver candidates for ICF – deep UV and broad native bandwidth

- Gas laser (easier to cool enabling faster shot rate)
- Electron beam pumping for large amplifiers
- The NRL Nike 3-kJ KrF system (248 nm with up to 3 THz bandwidth) has operated for 24 years
- Electra KrF system demonstrated 5 pulses per second operation for hours
- The deeper UV (193 nm) and broader native bandwidth ArF laser would provide still better light for ICF

Nike 60-cm aperture KrF amplifier
Excimer angularly multiplexed laser optical systems provide high target illumination uniformity and easy implementation of focal zooming.

Nike KrF optical system with ISI smoothing
An ArF system would be similar

Time averaged laser spatial profile in target chamber

Nike zoomed focus:
- Early time
- Late time
NRL 6.1 funded effort is advancing the basic physics of E-beam pumped ArF laser using the Electra facility.

Parametric experimental studies on Electra

Modify & validate NRL Orestes laser kinetics model for ArF

Notes
- ArF can utilize electron-beam pumping developed for KrF
- But details are different – lower gain and higher saturation flux
- ArF lithographic industry has developed durable 193 nm optics – need to be scaled up in size for ICF
Path forward for developing S&T for IFE using an ArF laser driver.

Tasks consistent with APRPA-E mandates

- Modify the Electra amplifier to be optimized for ArF operation (higher current, lower voltage), to verify NRL codes for ArF laser performance.

- Develop and test lower cost more compact high-repetition rate pulse power – applicable to both ArF and other fusion concepts. A conceptual design has been done by NRL for a 700kV, 100ns, 1 Ohm module with >108 pulse life at 10Hz. It has less than half the number of silicon thyristor stacks and capacitors required in alternate approaches such as a hypothetical solid state Linear Transformer Driver (LTD).

- Develop ArF optimized amplifier and system designs using simulations, test where feasible.

- Work with vendors to advance high-power long-lived ArF optics

- Conduct 2-D and 3-D simulations of ArF target designs to determine minimum laser energy needed for robust performance.

- Develop target designs optimized for tritium recovery and recycling
Phased development path to IFE power plants using an ArF driver – parallel target physics and IFE technology efforts

**Phase I**
- Advance basic E-beam pumped ArF laser S&T
- Develop/evaluate high energy ArF architecture designs
- Evaluate potential for robust high fusion yield/high-gain ArF direct drive implosions via simulations

**Phase II**
- Design and build high energy (~20 kJ) ArF beamline(s)
- LPI/hydro experiments with above to check ArF laser-matter interactions
- Develop design for a 0.5 to 1 MJ class implosion facility

**Phase III**
- Design and build ~0.5 to 1 MJ implosion facility
- High scientific rep rate (many shots per day) for experiments
- **Demonstrate the robust high-energy gain implosions needed for IFE**

**Develop and test S&T for IFE application**
- Efficient high rep-rate (~ 10 Hz) driver operation
- Low cost targets, target injection & engagement
- Long lived chambers and optics
- Economical system designs

**Inertial Fusion Test Facility**
- Power plant prototype to test materials and components

**Build Fusion Power plants**


