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Progress in the S&T to enable high-gain laser inertial fusion @ NRL

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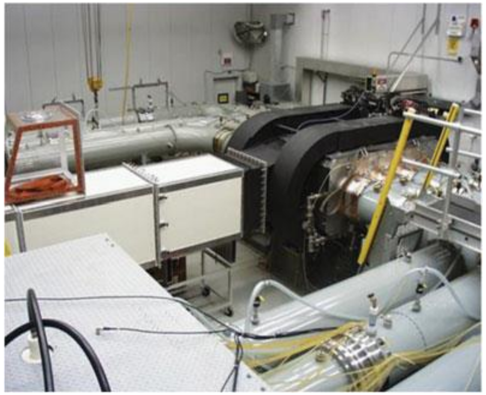
For over 30 years NRL has been developing & utilizing excimer lasers for ICF

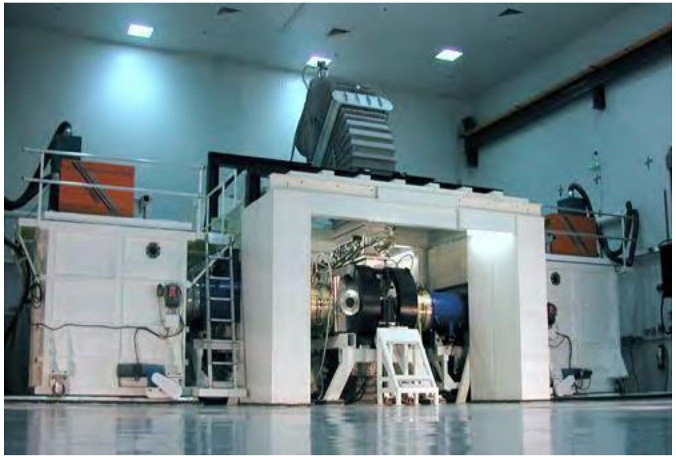
The 2-3 kJ Nike krypton-fluoride (KrF) laser facility has been performing planar target experiments for 25 years. Most of the optics are original. Small operating crew (2).



60-cm E–beam pumped amp.

Nike planar target in chamber

The 750 J KrF Electra facility demonstrated efficient E-beam coupling to the laser gas (75%) and 5 Hz operation. *Now converted to Argon Fluoride (ArF) operation.*



We need next generation drivers to continue progress in laser ICF

The Challenge

- Laser plasma instabilities (LPI) limit the intensity that can be employed with both direct drive and indirect drive.
- The limited drive pressure increases the risk from hydrodynamic instabilities.
- Cross beam energy transport (CBET) reduces the coupling efficiency for direct drive and complicates indirect drive.
- Progress has slowed in both direct and indirect drive with current frequency multiplied Nd:glass lasers, ignition is so far elusive and high gain likely not achievable.

Potential Solutions

Develop broad bandwidth (>>1 THZ) laser drivers that suppress LPI

Stimulated Rotational Raman Scattering (NRL) and FLUX technology (LLE) are being explored to impose multi-THZ bandwidth on existing ICF lasers

Develop much shorter wavelength laser drivers (than 351 nm) to suppress LPI and improved coupling efficiency

It's best of course to utilize both shorter wavelength **and** broad bandwidth e.g. ArF laser

The ArF laser could be the ultimate laser driver for <u>both direct and indirect</u> laser drive

NRL PPD

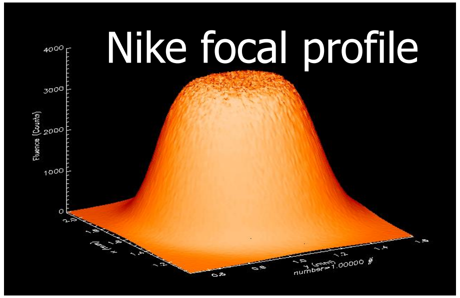
- Deeper UV light (193 nm) than KrF (248 nm) and frequency tripled glass (351 nm).
- Broader native bandwidth (5-10THz) than NIKE KrF (3 THz), OMEGA (1 THz) and NIF (0.3 THz).
- Compatible with **ISI beam smoothing** which allows flexible routine changes to the focal distribution including **zooming**.
- Gas media is easier to cool which would enable many shots per day on large systems.

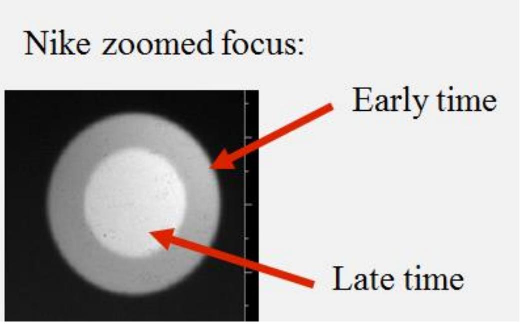
Advantages for direct drive

- Less LPI - enables higher irradiance and ablation pressure.
- Higher hydro-efficiency.
- Excellent target illumination by numerous ISI smoothed laser beams.

Advantages for x-ray drive

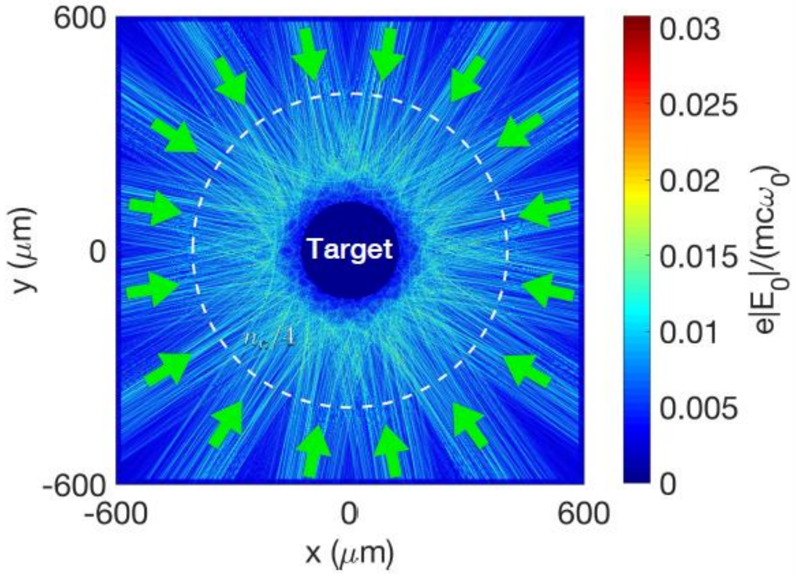
- Higher LPI thresholds and critical density will enable higher gas fill density and/or higher peak irradiance.
- More flexible hohlraum illumination (e.g. shaped focal profiles and 1000's of beamlets) would enable nearly contiguous rings and thereby less shadowing by fill tubes.


Nike focal profile


Nike zoomed focus:

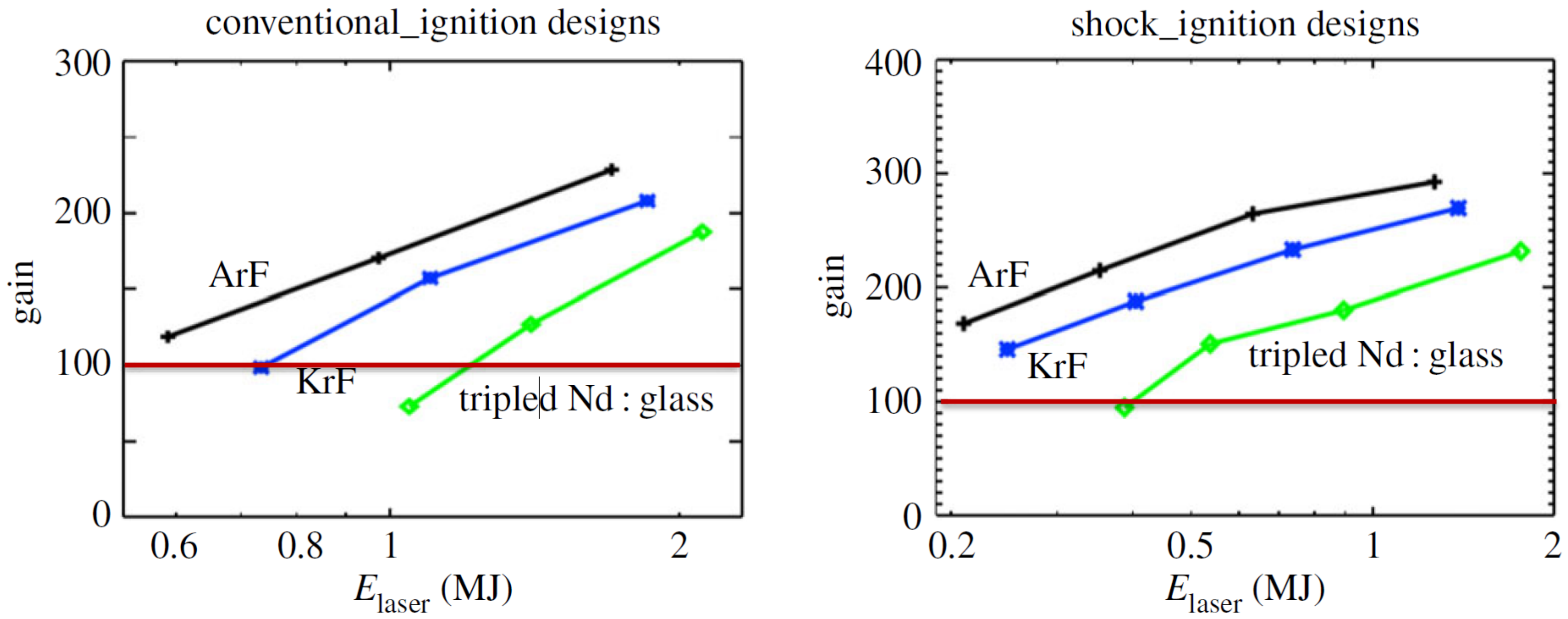
2D LPSE simulations for Omega-size target show large increase in absorption with a broad bandwidth ArF driver

Laser Driver	Wavelength λ_0 (μm)	Approximate bandwidth $\Delta\nu$ (THz)	Time-averaged absorption (%)
Nd:glass	0.351	1	65
KrF	0.248	3	86
ArF	0.193	5	91



For the CH plasma corona in this example, Te = 3 keV, Ti = 1 keV and Ln = 200 μm
Increased absorption with ArF in this example is primarily due to suppression of CBET

NRL FAST radiation hydrocode 1-dimensional simulations of the gain of conventional and shock ignition[1,2] direct-drive implosions for ArF, KrF and a frequency tripled glass laser.

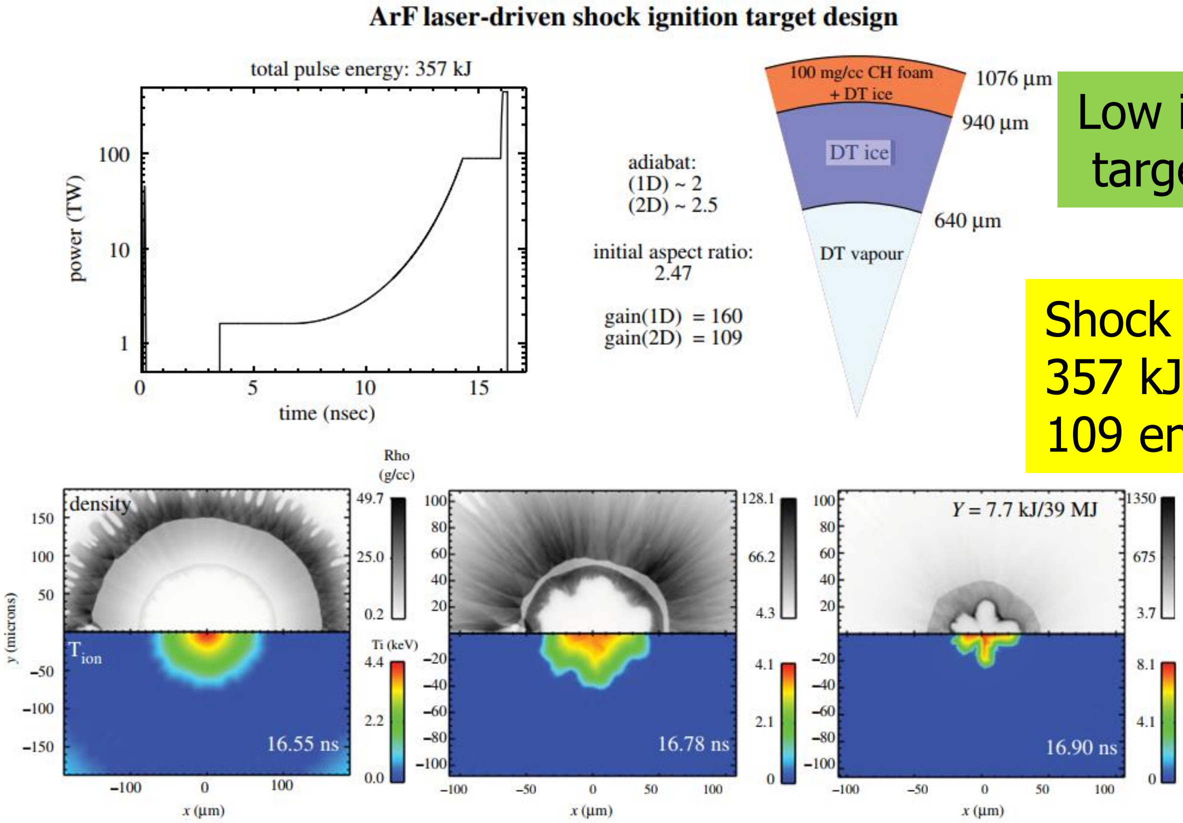


3.74 initial aspect ratio foam-DT ablator targets -- LPI/CBET not included

1.R. Betti, C.D. Zhou, K.S. Anderson, L.J. Perkins, W. Theobold, A.A. Solodov, Phys. Rev. Lett. 98 (2007) 155001.

4 *Simulations of high-gain shock-ignited inertial-confinement-fusion implosions using less than 1 MJ of direct KrF-laser energy*, Jason W. Bates, Andrew J. Schmitt , David E. Fyfe , Steve P. Obenschain , Steve T. Zalesak, High Energy Density Physics 6 (2010) 128–134

2D hydro simulations indicate ArF light could enable gains>100 @ well below 1 MJ laser energy



ArF laser-driven shock ignition target design

Low initial aspect ratio (R/ΔR) target (2.5)

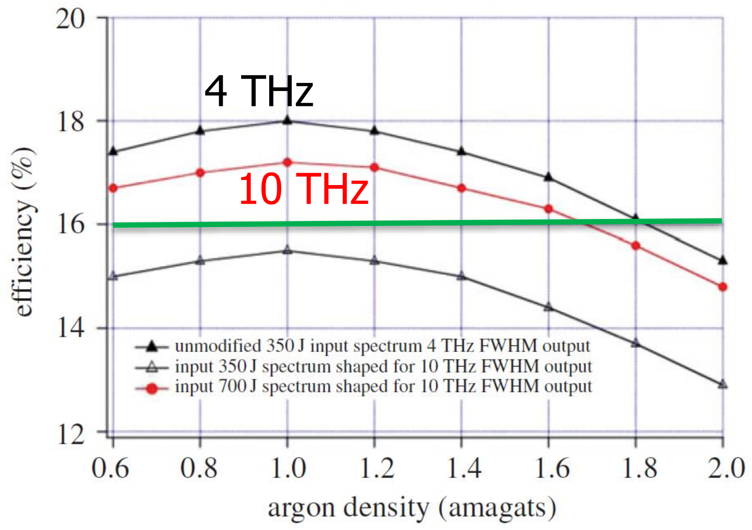
Shock ignited direct drive
357 kJ ArF laser energy
109 energy gain

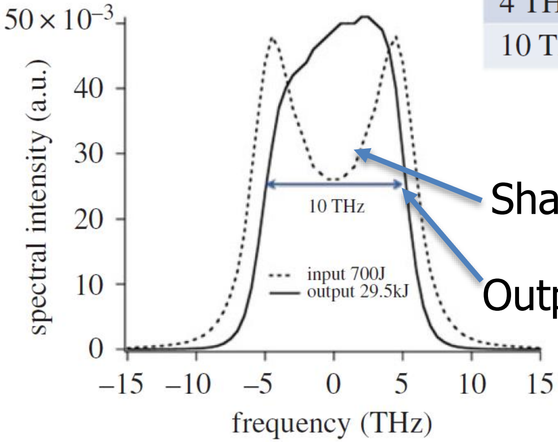
ArF Kinetic simulations show potentially high intrinsic efficiency (>16%) over a broad operating regime.

- Intrinsic efficiency = (laser power out)/(E-beam pump power in)
- With 16% intrinsic efficiency we project 10% wallplug efficiency

ArF laser kinetic simulations
- 60 cm × 60 cm aperture
- 200 cm gain length
- e-beam pumped at 1 MW cm^{-3}

bandwidth	input	output
4 THz	350-J	31-kJ
10 THz	700-J	29.5-kJ



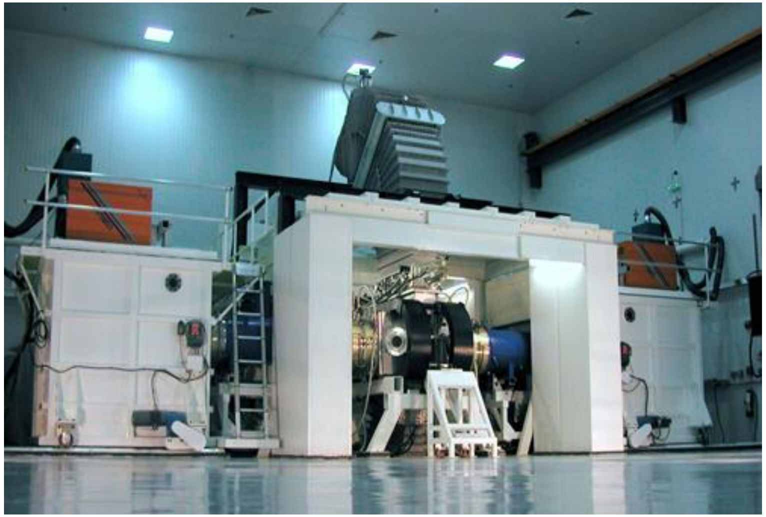


Shaped input spectra

Output spectra 10 THz bandwidth

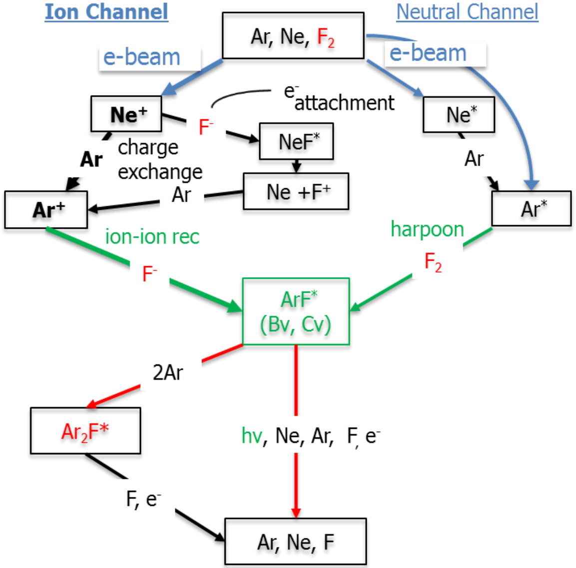
NRL 6.1, DoE ARPA-E and FES support advancing high-energy ARF S&T

Parametric experimental studies on Electra facility



Modify & validate NRL Orestes laser kinetics model for ArF

ArF theory and simulations

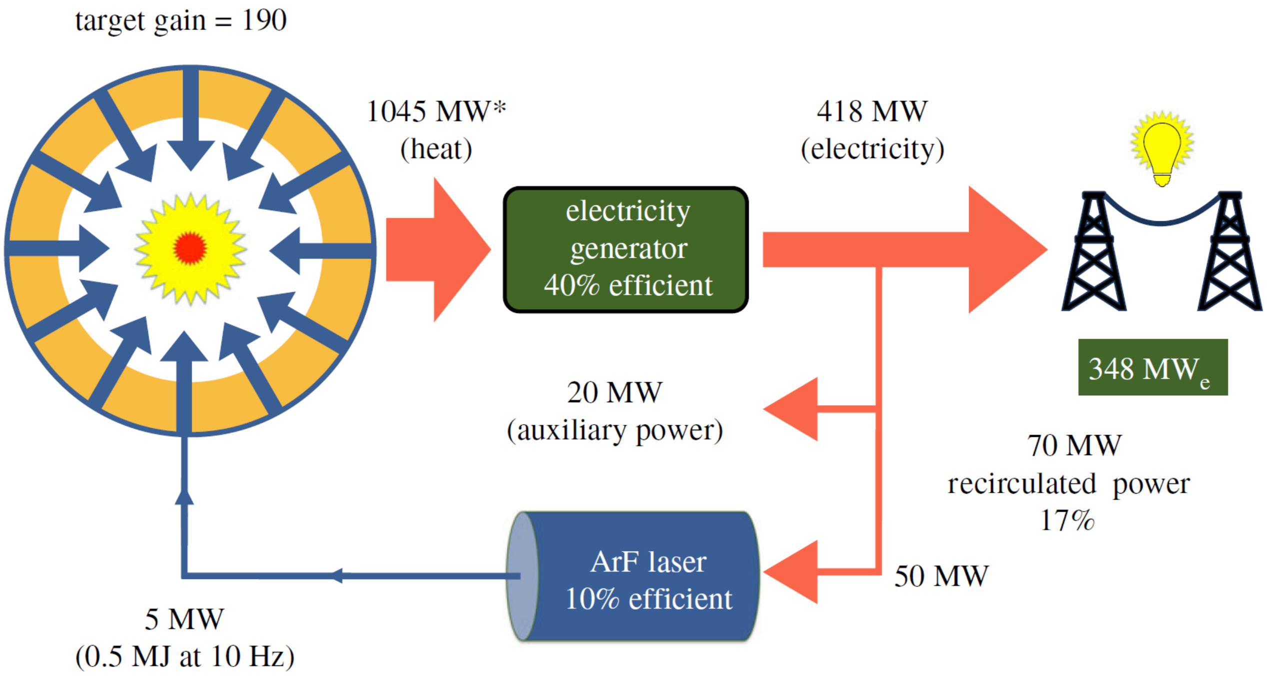


Notes

- 200 J obtained in oscillator mode (vs 96 J previous ArF record)
- Measuring gain, saturation flux, intrinsic efficiency, bandwidth & compare with simulations
- ArF lithographic industry has developed durable 193 nm optics – need to be scaled up in size for ICF

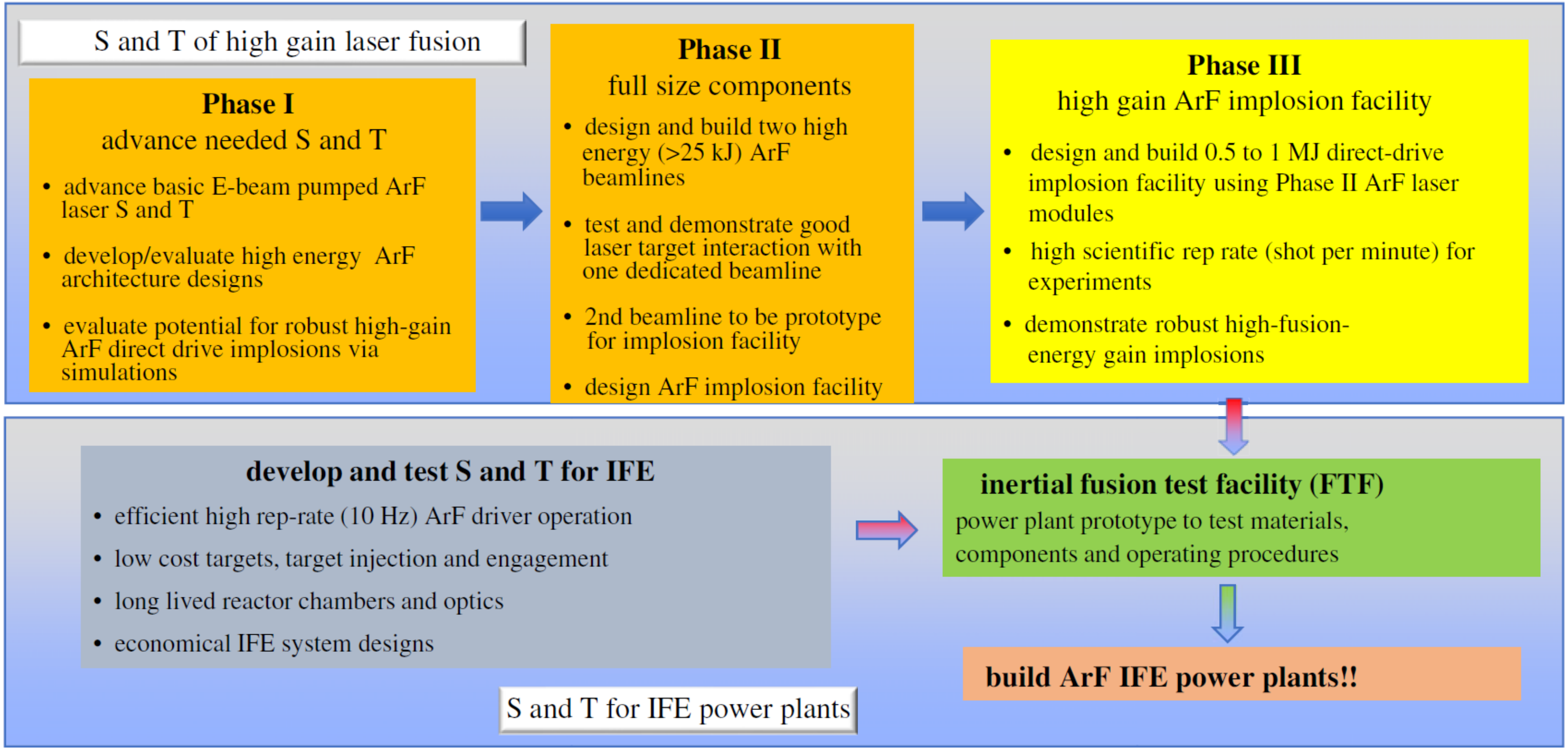
Use of ArF's broad bandwidth 193 nm light may enable construction of smaller lower cost IFE power plants with laser energy well below 1 MJ

Power flow with 500 kJ 10% efficient ArF driver and 190 gain shock ignited target



Phased development path to IFE power plants using an ArF driver – parallel target physics and IFE technology efforts

NRL PPD



S and T of high gain laser fusion

Phase I

advance needed S and T

- advance basic E-beam pumped ArF laser S and T
- develop/evaluate high energy ArF architecture designs
- evaluate potential for robust high-gain ArF direct drive implosions via simulations

Phase II

full size components

- design and build two high energy (>25 kJ) ArF beamlines
- test and demonstrate good laser target interaction with one dedicated beamline
- 2nd beamline to be prototype for implosion facility
- design ArF implosion facility

Phase III

high gain ArF implosion facility

- design and build 0.5 to 1 MJ direct-drive implosion facility using Phase II ArF laser modules
- high scientific rep rate (shot per minute) for experiments
- demonstrate robust high-fusion-energy gain implosions

develop and test S and T for IFE

- efficient high rep-rate (10 Hz) ArF driver operation
- low cost targets, target injection and engagement
- long lived reactor chambers and optics
- economical IFE system designs

S and T for IFE power plants

inertial fusion test facility (FTF)

power plant prototype to test materials, components and operating procedures

build ArF IFE power plants!!

Summary

- We need to develop new drivers for inertial fusion to advance both the defense (stockpile stewardship) and energy applications
- The argon fluoride laser's deep UV light and broad bandwidth capability could provide a revolutionary increase in target performance – high gain at substantially reduced laser energy for direct drive implosions.
- The projected 10% wallplug efficiency and high gain targets maek it very promising for the energy application.
- Both the laser and target ArF S&T are relatively undeveloped – there is lots to do – **collaboration is welcome in this endeavor.**

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