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Development path to smaller lower-cost inertial fusion power plants using direct drive with the argon fluoride (ArF) laser

Fusion Power Associates
Pathways to Fusion Power
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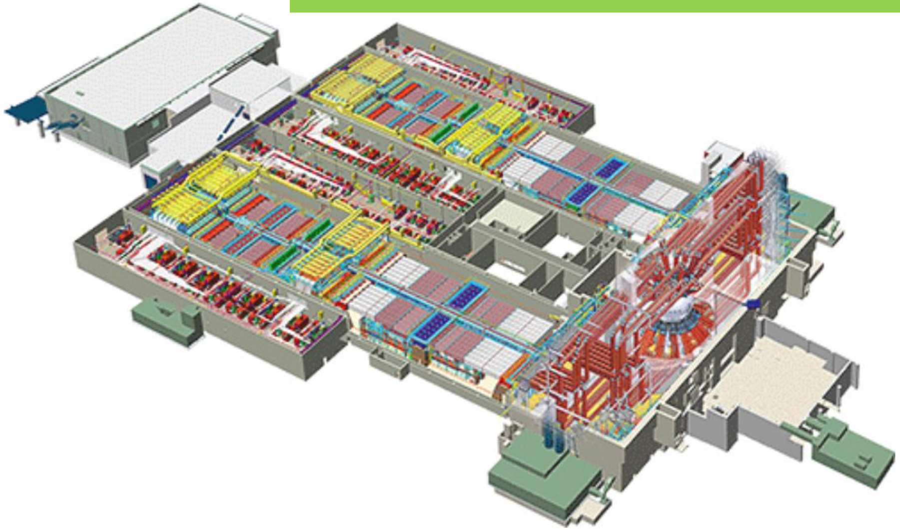
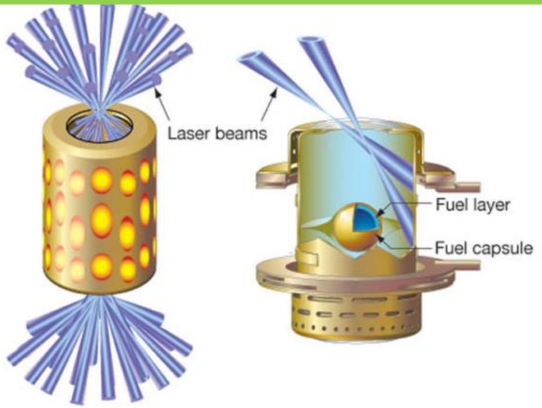
National Ignition Facility (NIF) recently achieved a record inertial fusion yield 1.3 MJ with 1.9 MJ of laser energy (gain =0.7)

The NIF result demonstrated basic feasibility of inertial confinement fusion



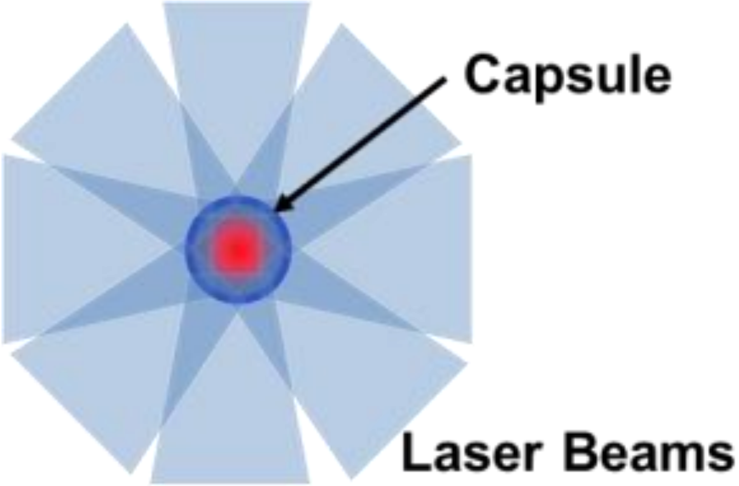


Indirect Drive – laser light converted to x-rays that drive the implosion – approach chosen for NIF.

- The result is particularly impressive as the 1.3 MJ yield was achieved with only 230 kJ of x-rays absorbed by the capsule.

Direct laser drive is a much more efficient approach

Direct Laser Drive – laser light directly illuminates the capsule

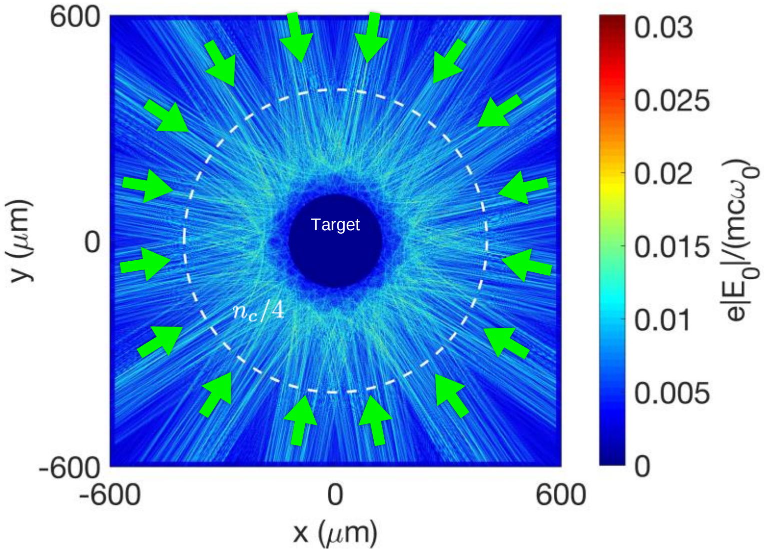


- Much more efficient than indirect drive (>6x)
- Potential to reach the high gains (100) required for the fusion energy application.

Best laser driver for high performance

- Highly uniform target illumination
- Multi-THz bandwidth to suppress laser-plasma instabilities (LPI)
- Capable of zooming the focal diameter to follow imploding target
- Shorter laser wavelength to further suppress LPI and increase hydro-efficiency of implosion
- The 193 nm ArF laser best meets all of the above criteria

The effects of broad laser bandwidth with short laser wavelength on cross beam energy transfer (CBET) scattering in a full-scale, spherical ICF plasma



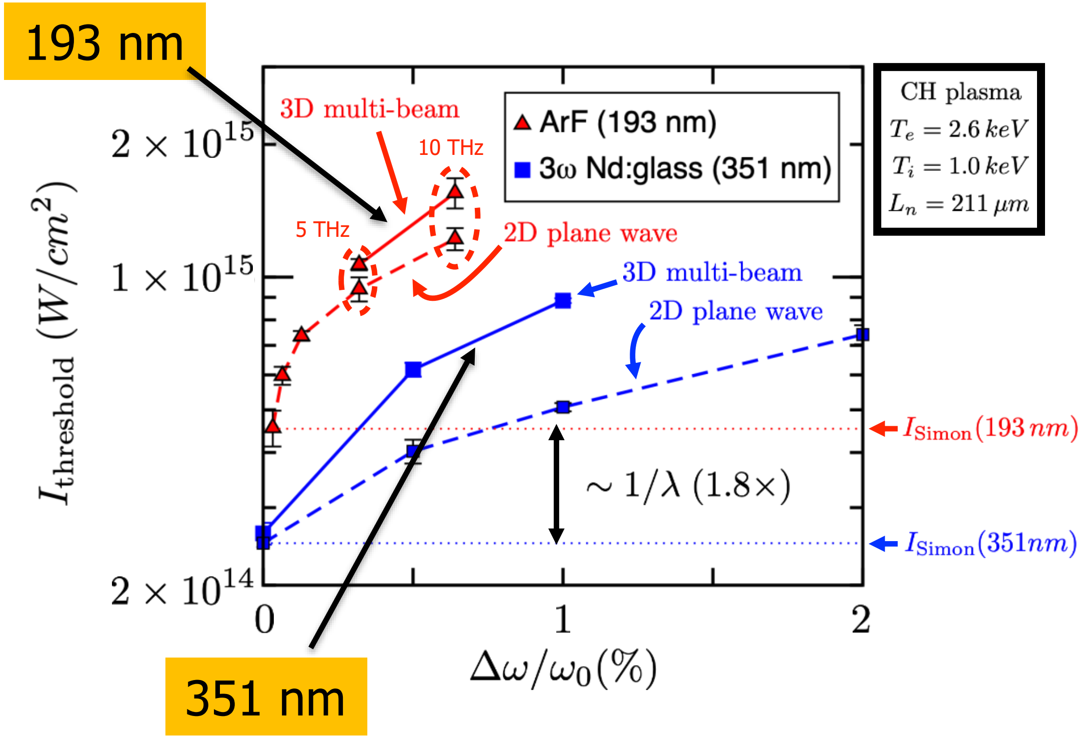
Laser Driver	wavelength	bandwidth	absorption
3rd-harmonic Nd:glass	351 nm	1 THZ	65%
KrF	248 nm	3 THz	86%
ArF	193 nm	5 THz	91%

LPSE* simulations used 16 beams, each with intensity 5 x 10^{14} W/cm^2

*** code was developed at LLE**

Increased absorption ArF & KrF excimer lasers is due to both shorter wavelengths & larger bandwidths which reduce CBET scattering.

Simulations using the LPSE code show the benefits of bandwidth and shorter wavelength for mitigating the two plasmon decay (TPD) instability



- Analytic TPD threshold for a single monochromatic plane wave beam given by*

$$\boxed{I_{\rm Simon} \sim 7\times10^{15}\,\frac{T_{keV}}{L_{\mu m}\,\lambda_{\mu m}}\;W/cm^2}$$

- 2D, plane-wave, LPSE simulation results agree with theoretical predictions in limit of zero bandwidth, and have the ratio

$$\frac{I_{\rm Simon}(193\ \rm nm)}{I_{\rm Simon}(351\ \rm nm)} = \frac{351\ \rm nm}{193\ \rm nm} \simeq 1.8$$

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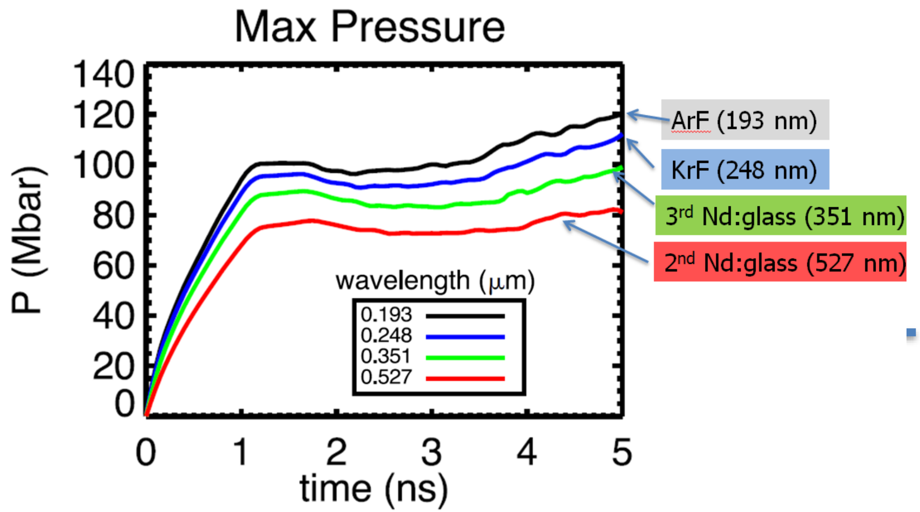
*A. Simon, R. W. Short, E. A. Williams and T. Dewandre, Phys. Fluids 26, 3107 (1983).

Hydrocode simulations show increased drive pressure and reduced risk from the two-plasmon decay instability with shorter laser wavelength

Ablation pressure vs laser λ from hydrocode
10^{15} W/cm^2 2.6 mm solid CH sphere



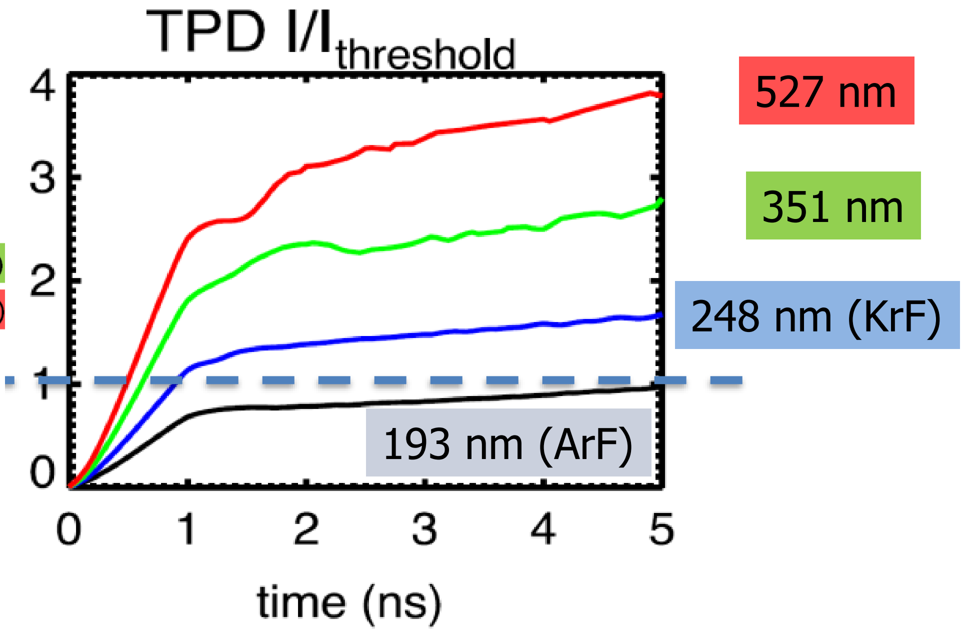
ArF (193 nm)

KrF (248 nm)

3rd Nd:glass (351 nm)

2nd Nd:glass (527 nm)

TPD thresholds vs laser λ from hydrocode
10^{15} W/cm^2 2.6 mm solid CH sphere



527 nm

351 nm

248 nm (KrF)

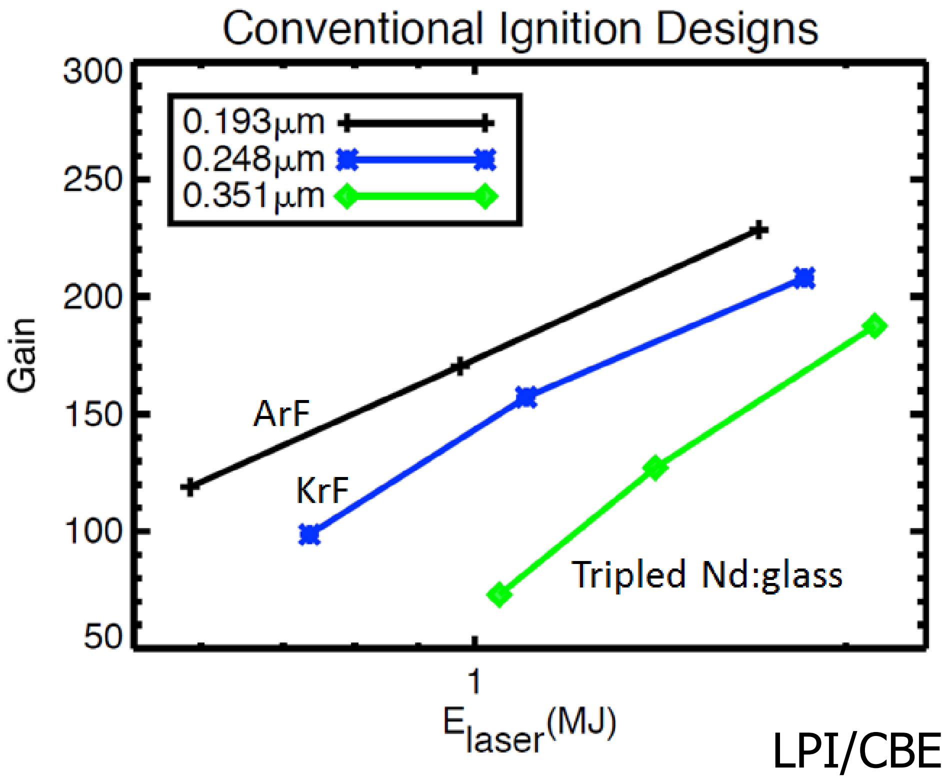
193 nm (ArF)

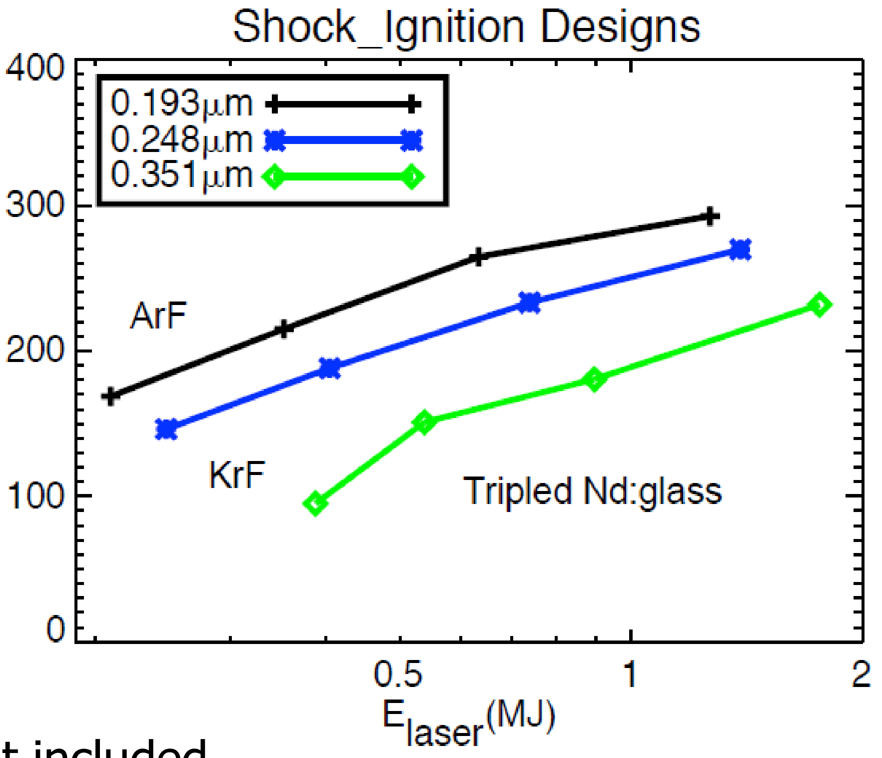
Direct drive ablation pressure increase's with shorter laser wavelength

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[1,2] direct-drive implosions for ArF, KrF and a frequency tripled glass laser.

NRL PPD


Conventional Ignition Designs


Shock_Ignition Designs

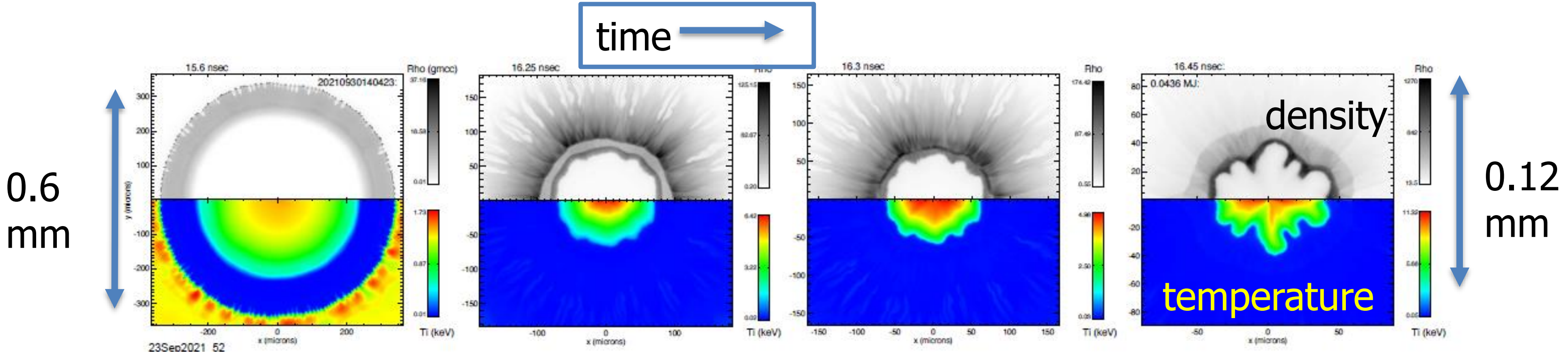
LPI/CBET not included

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

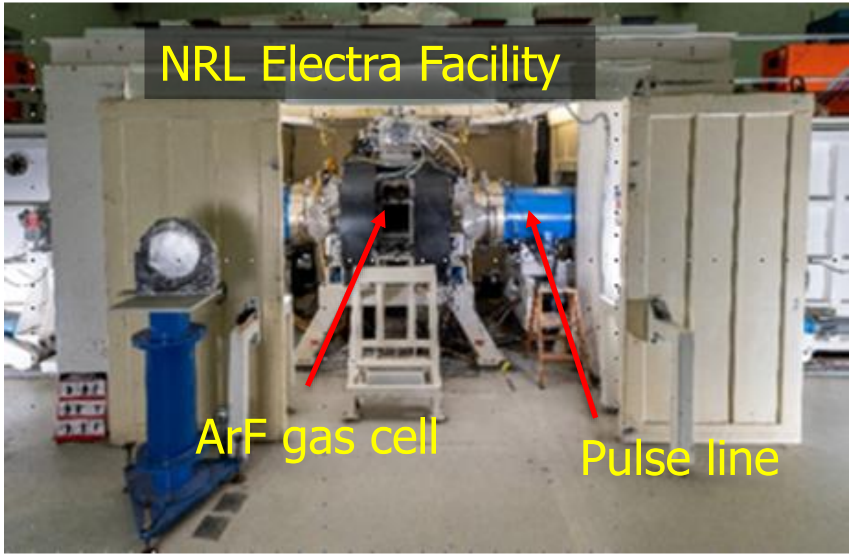
NRL simulations indicate an ArF laser can achieve target gains (>100) needed for laser fusion power plant with much less laser energy than achieved by NIF

Sample NRL 2D simulation of a ArF driven implosion that includes effects of an imperfect target

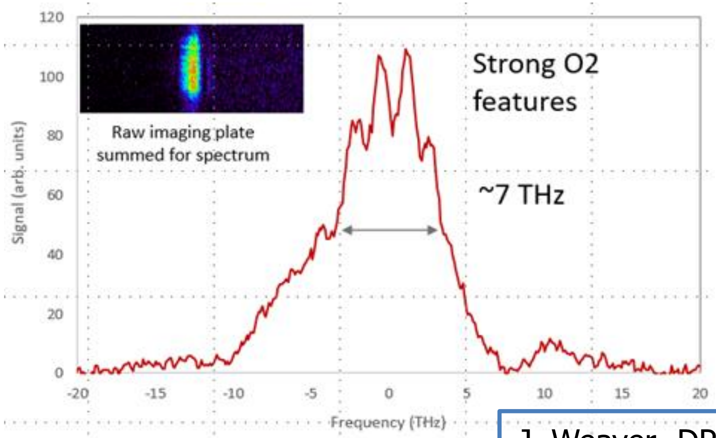


- This ArF driven shock-ignited target implosion achieved 160x fusion gain (ratio of fusion energy out to laser energy in) with 411 kJ of laser energy, less than ¼ of NIF's energy (1,900 kJ)
- An ArF laser with 10% electrical efficiency needs ~100x fusion gain for the power plant application.

The NRL Electra electron-beam-pumped system is advancing the S&T of the ArF laser



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



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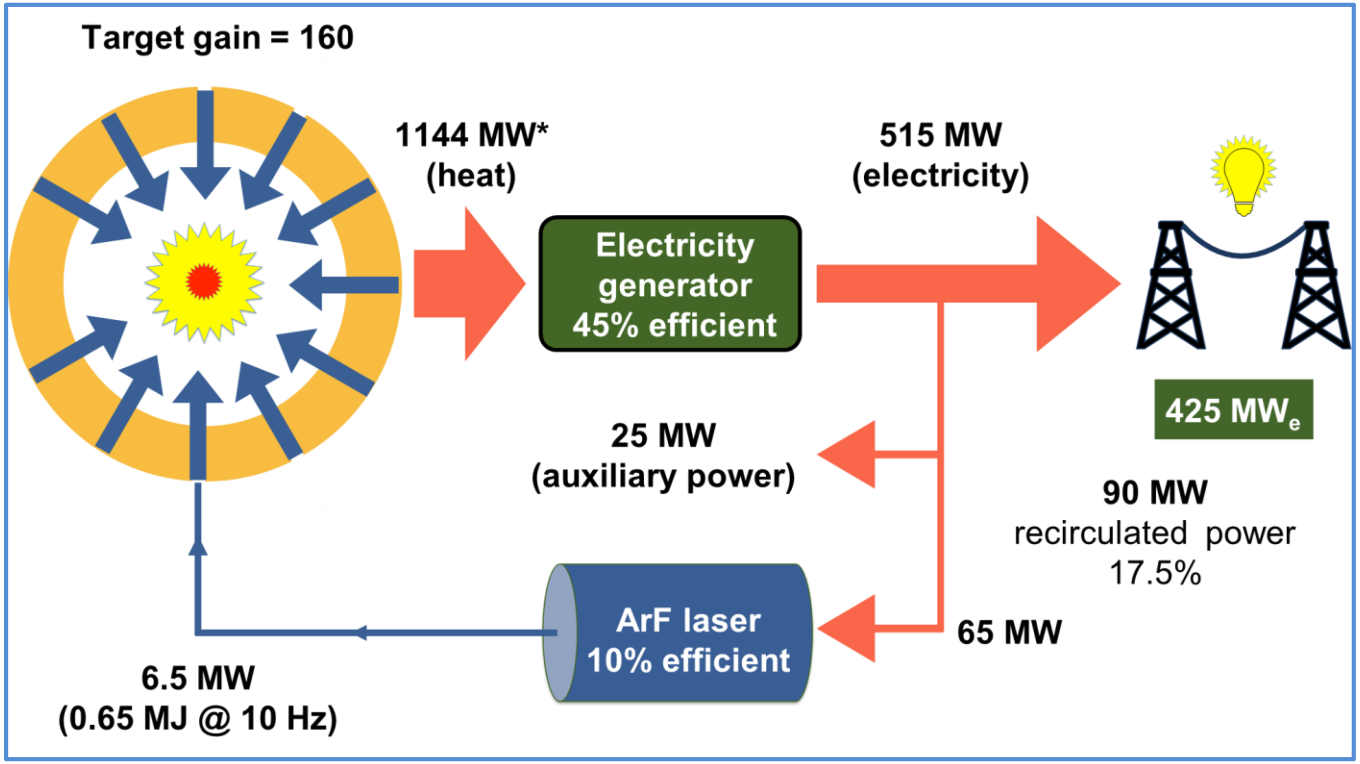
- 7 THz FWHM bandwidth 193 nm light observed with Electra
- Kinetic simulations predict 10 THz feasible on large ArF systems with >16% intrinsic efficiency
- Expect 10% net electrical efficiency

Power flow in 425 MWe ArF power plant

0.65 MJ ArF laser operating @ 10 pulses/sec.



3-phase plan to develop a 400 MW_e ArF laser fusion power plant

NRL PPD

Phase I

DEMO high fusion gain

- Advance ArF S&T
- Build full scale 30 kJ ArF beamline (10 shots/hour)

Power plant tech

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

Phase II

DEMO high fusion gain

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

Power plant tech

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

Phase III

Pilot 400 MW_e ArF laser fusion power plant

- Complete design & build
- Test components & procedures.
- Generate power

The ArF laser could enable power plants with laser energy below 1 MJ, which would speed development time and reduce cost.

ArF laser direct drive inertial fusion – path to fusion energy

- The physics underpinnings for laser fusion are well established.
- The deep UV broad bandwidth light from the ArF laser could be "game changing" towards reduced cost and development time for inertial fusion power plants.

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