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# Enticing Approach to Direct Drive Laser Fusion Performance -Deep UV ArF Laser Enabling Smaller Lower Cost Facilities

**Fusion Power Associates**
**43rd Annual Meeting and Symposium: The Road Ahead**
December 7-8, 2022

Work supported by:
ARPA-E, FES for fusion power plant design
NNSA for high-gain laser-target physics

**Presented by Dr. Matthew Wolford**
**Head Electron Beam Science & Applications Section**
**Laser Plasma Branch**
**Plasma Physics Division**

PLASMA PHYSICS DIVISION NAVAL RESEARCH LABORATORY

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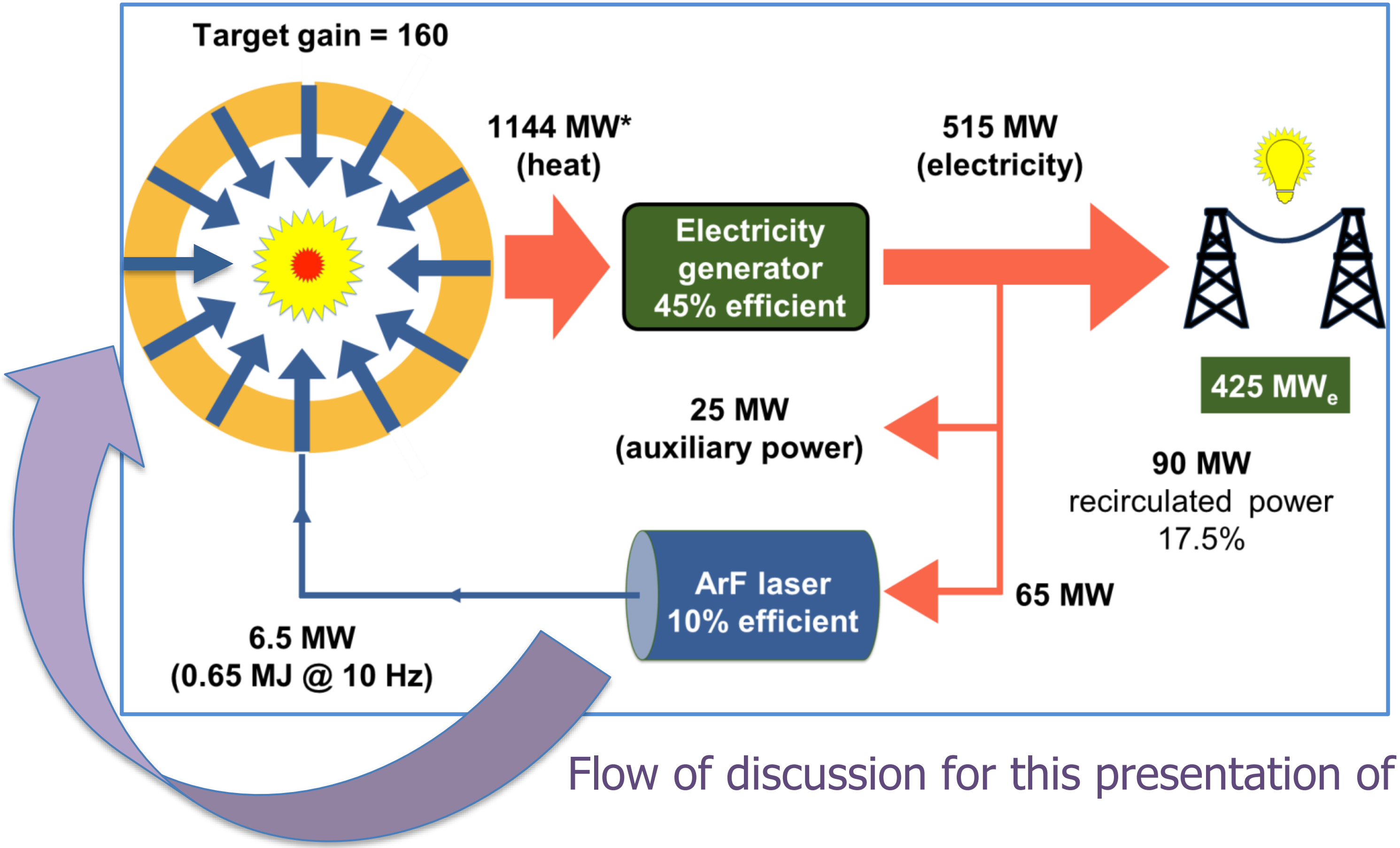
# Power flow in 425 MWe ArF power plant

0.65 MJ ArF laser operating @ 10 pulses/sec.

NRL PPD




Flow of discussion for this presentation of NRL technologies

# Collaborators

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#Commonwealth Technology Innovation LLC (CTI) A Huntington Ingalls Industries Company

# More than a decade ago NRL already had these excimer technologies in hand in terms of reproducibility, reliability, rep-rate, cost and moderate durability

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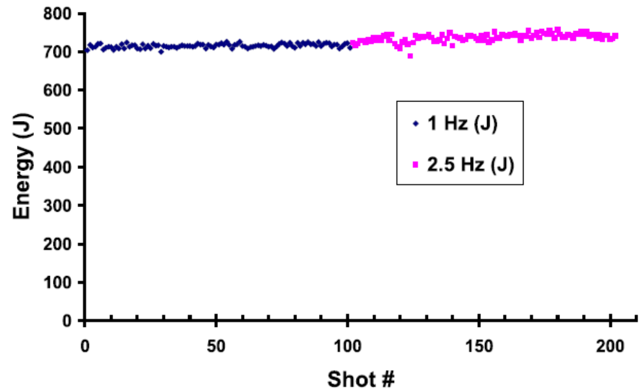


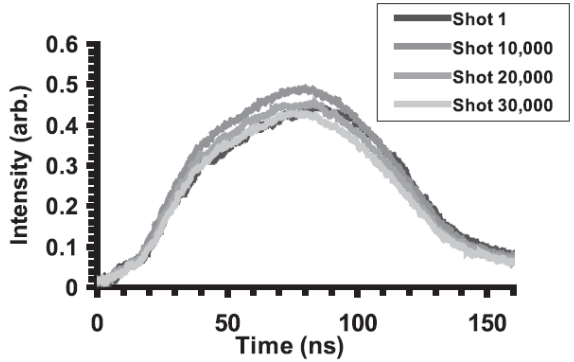


KrF Laser Development for Fusion Energy, M.F. Wolford, J.D. Sethian, M.C. Myers, F. Hegeler, J.L. Giuliani, S.P. Obenschain, Plasma And Fusion Research Vol. 8, Issue SPL.ISS.2, 3404044 (2013). https://www.jstage.jst.go.jp/article/pfr/8/0/8_3404044/_pdf/-char/en

# Now: The NRL Electra electron-beam-pumped system is advancing the S&T of the high-energy ArF laser

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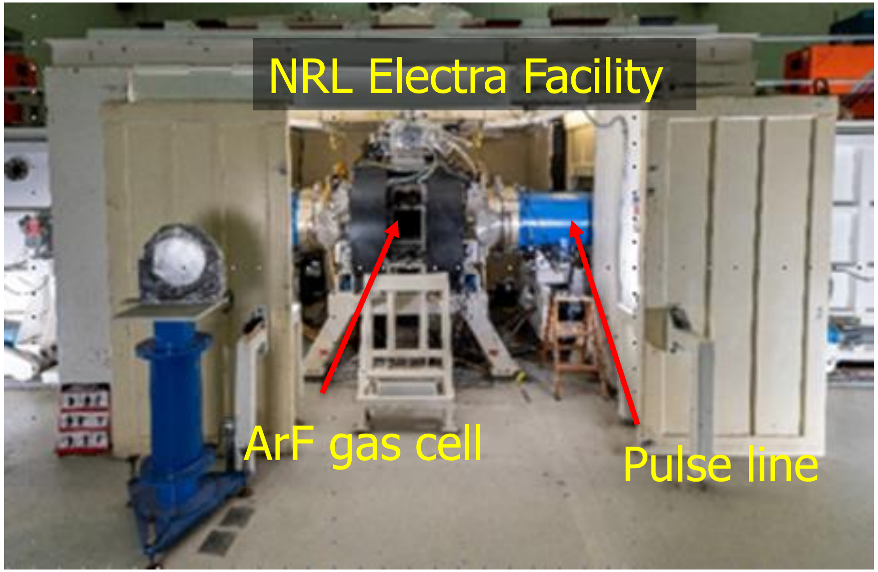
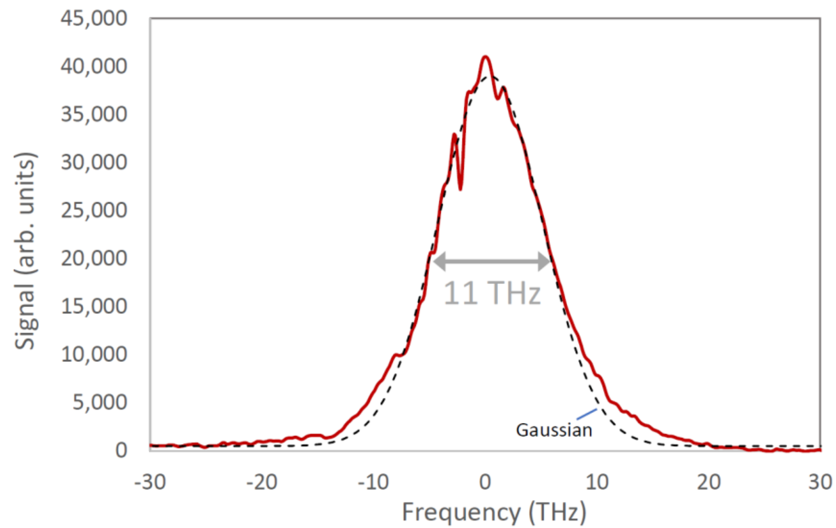



- Converted to ArF to advance basic electron-beam pumped ArF S&T
- World record ArF energy (200J)

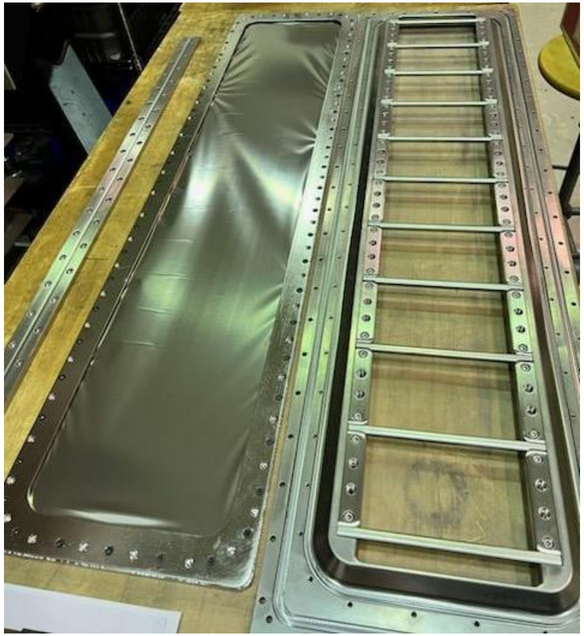
- 11 THz FWHM bandwidth observed from Electra (single pass ASE output)
- ArF's short wavelength and broad bandwidth mitigate laser plasma instability.
- 10% "wallplug" efficiency expected

# We are building robust, efficient electron beam diodes to pump the ArF laser to enhance capability for excimer laser inertial fusion energy



Reduced area allows advancement with ‘better’ foil materials

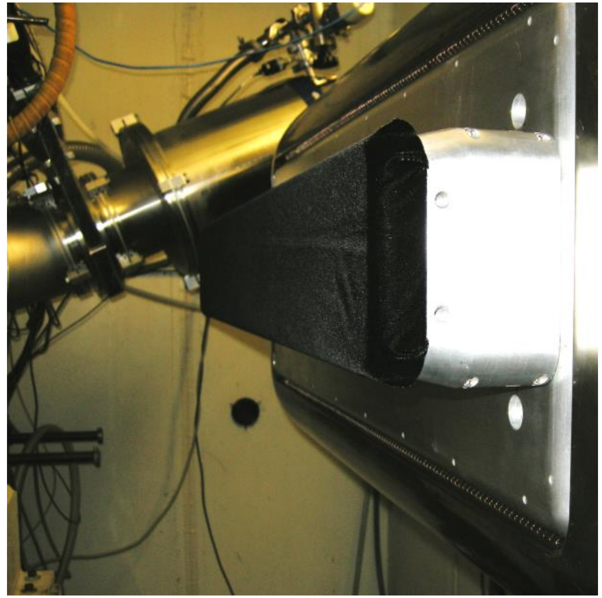
foil hibachi



1meter

Hibachi Rib spacing flexibility to balance highest efficiency with greatest robustness trade-off

cathode



Reduced area for better coupling for ArF laser

# Direct laser drive is a much more efficient approach

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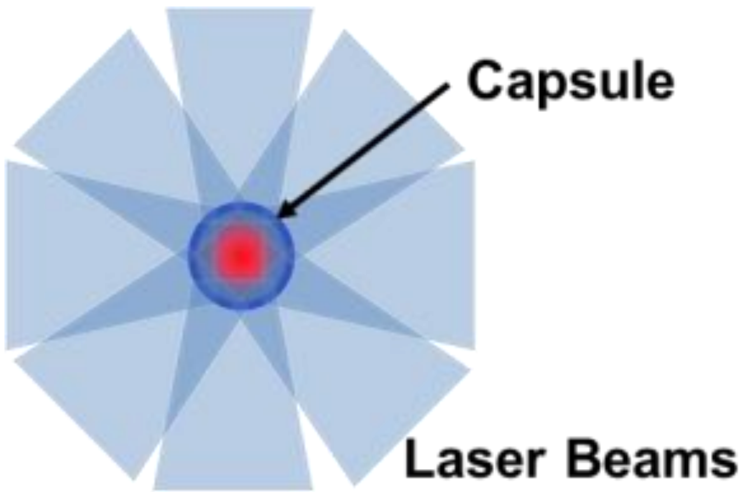
**Direct Laser Drive** – laser light directly illuminates the capsule




- 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

# Shorter Wavelength has increased ablation pressure as well as increased laser absorption and reduces CBET*

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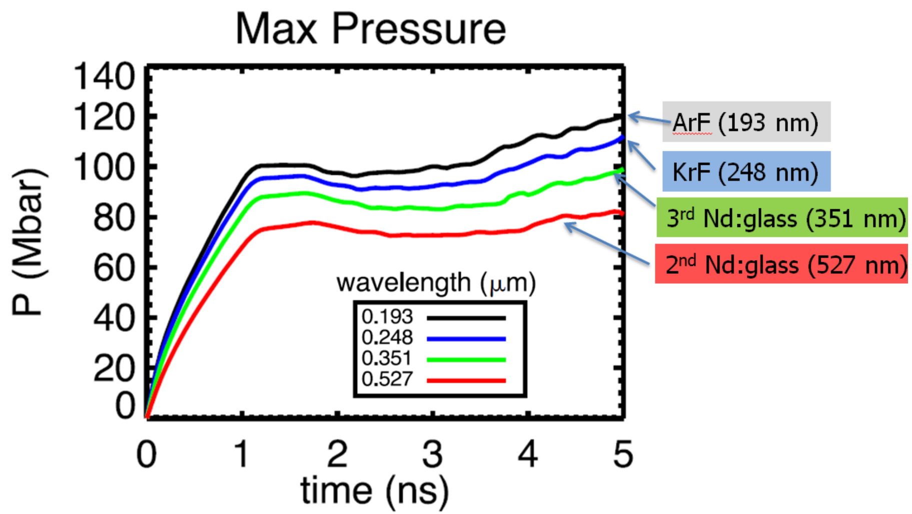
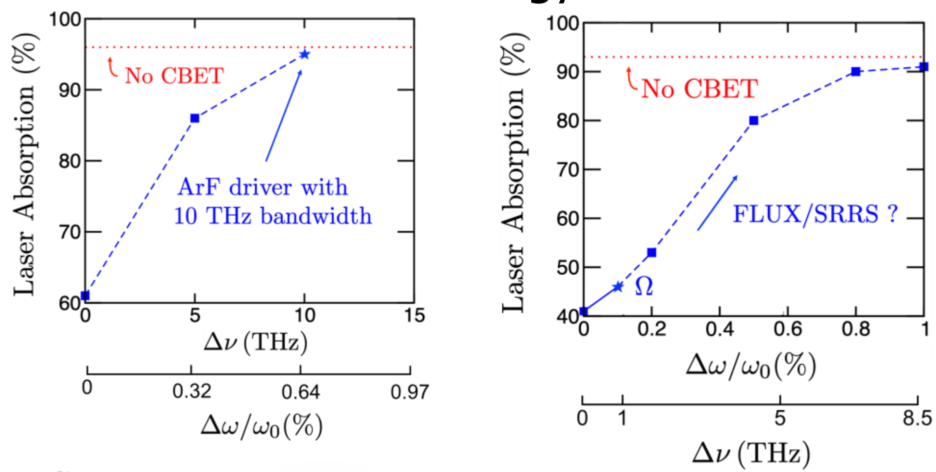
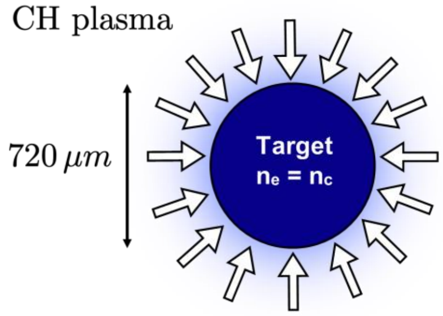
**Ablation pressure vs laser λ from hydrocode**
$10^{15}$ W/cm$^2$ 2.6 mm solid CH sphere




Direct drive ablation pressure increase's with shorter laser wavelength

*Cross beam energy transfer




(NB: Polarization smoothing can also help to mitigate CBET, but s-polarized light was modeled here to maximize CBET gain); also, increasing the laser intensity at nc/4 by mitigating CBET could result in increased hot-electron production from TPD and SRS

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# Simulations using the LPSE code show the benefits of bandwidth and shorter wavelength for mitigating the absolute TPD* and SRS backscatter# instability

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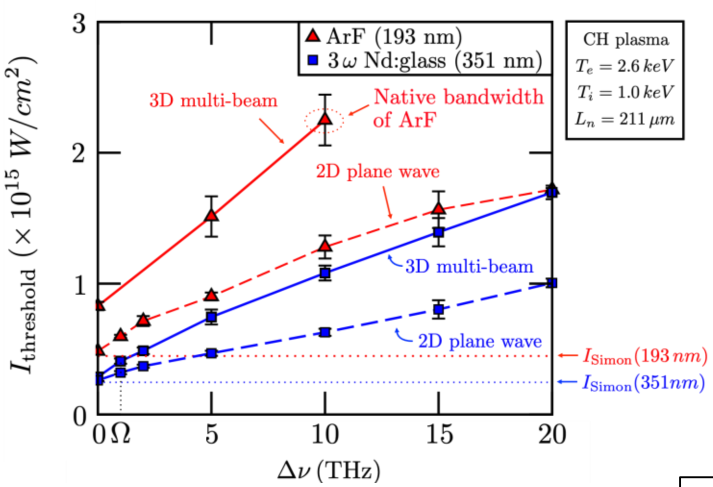
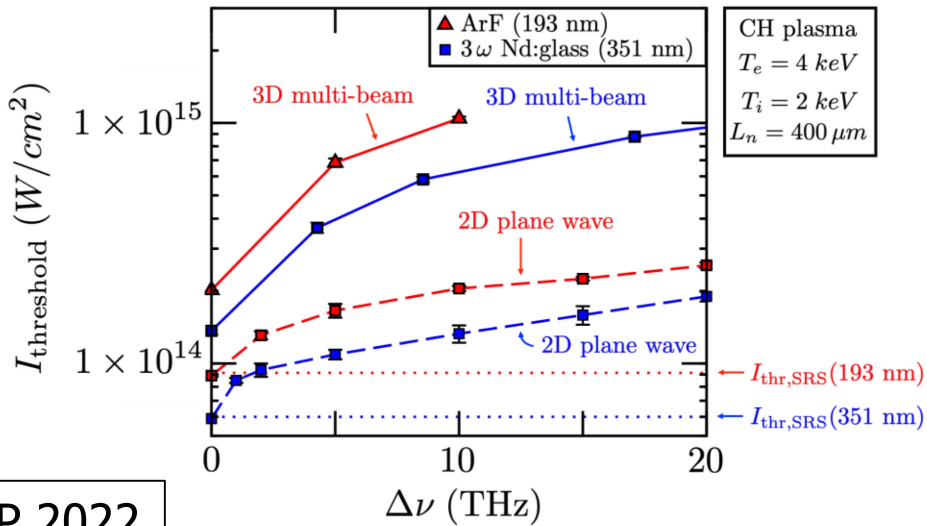
## *Two Plasmon Decay

$$I_{\text{Simon}} \sim 7 \times 10^{15} \frac{T_{keV}}{L_{\mu m}\, \lambda_{\mu m}} \; W/cm^2$$




## #Stimulated Raman Scattering Backscatter

$$I_{thr,SRS} \sim 9 \times 10^{16}\, \lambda_{\mu m}^{-2/3}\, L_{\mu m}^{-4/3} \;\; W/cm^2$$

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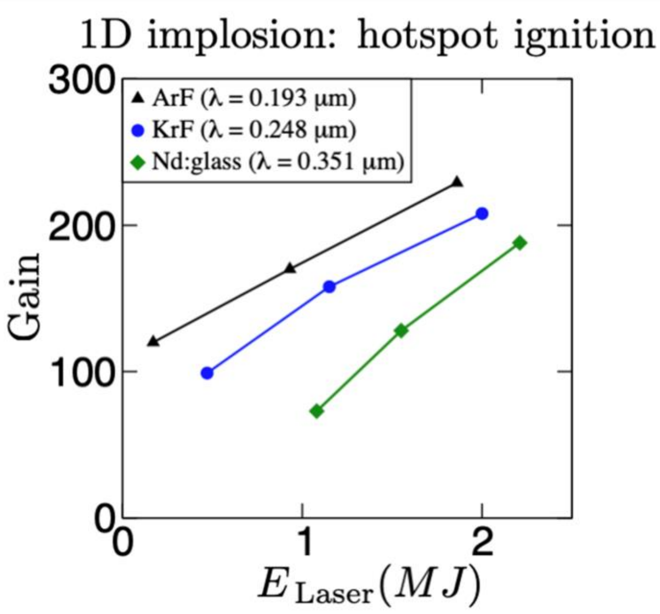
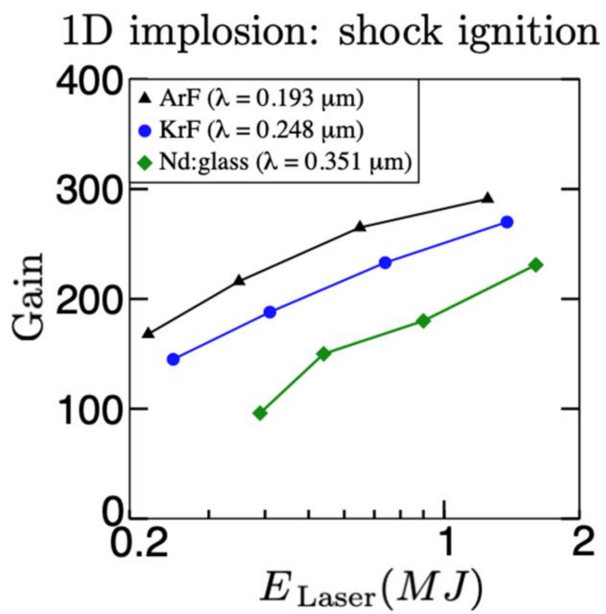
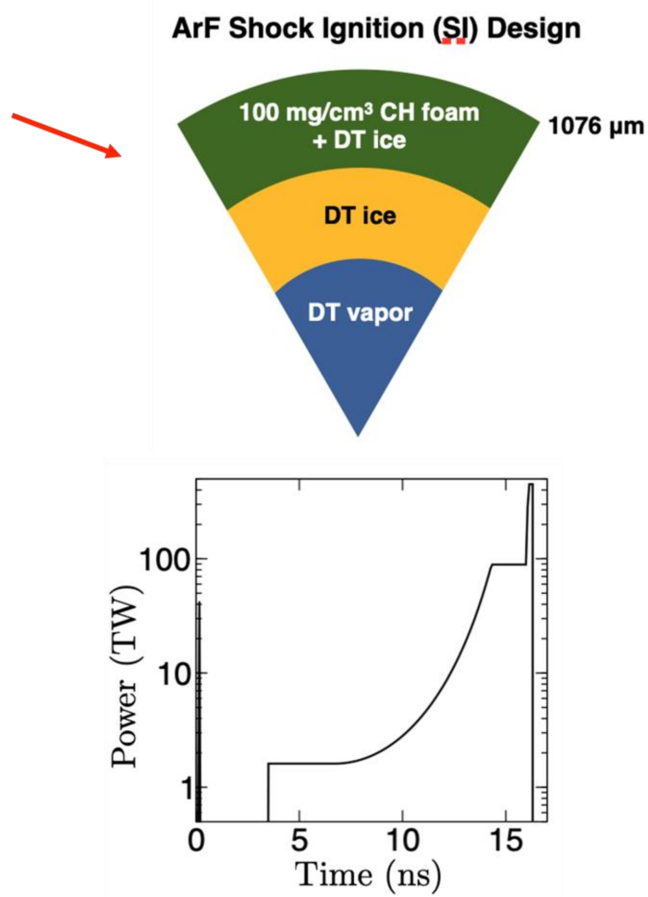
# Simulations suggest high gains ( > 100) are possible in conventional target designs using < 1 MJ of ArF laser light with zooming; even higher gains with shock ignition

NRL PPD




- **LPI effects were not included in simulations**

# 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

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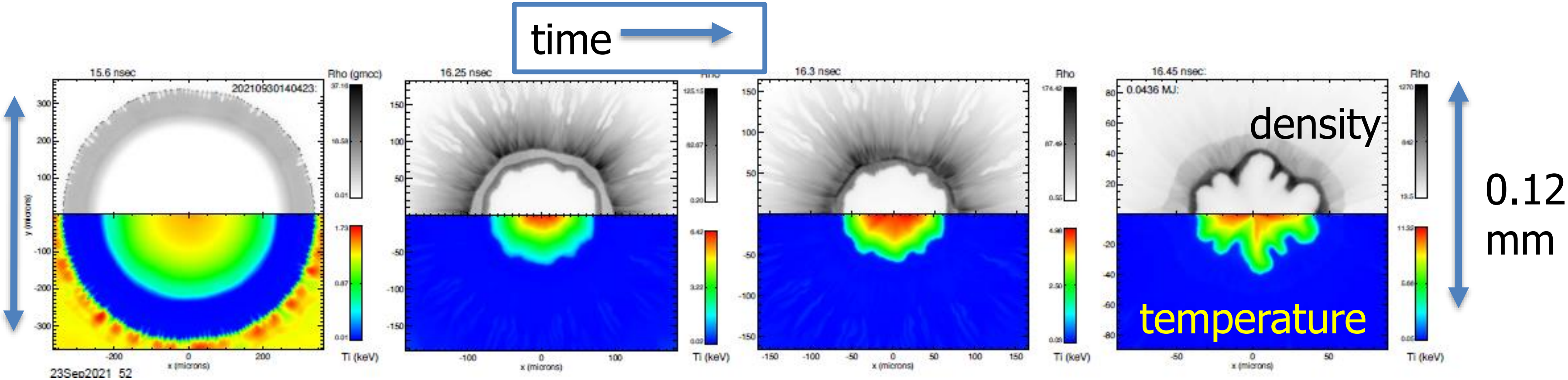
Sample NRL 2D simulation of a ArF driven implosion that includes effects of an imperfect target




- 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.

# Phased plan progress from present to a pilot ArF laser fusion power plant

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Physics channel – primarily public support

**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 $MW_e$)

IFE technology channel – attractive for private investment

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

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- 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.

Collaborations

- Open to discussions in advancing inertial fusion energy as well as inertial confinement fusion

# Dr. Steve Obenschain recently retired NRL, December 2$^{nd}$, 2022

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Steve has made and looks forward to continuing to make significant contributions to many areas of relevance to inertial confinement fusion and inertial fusion energy. His achievements include:

- Co-inventor of Induced Spatial Incoherence - the first (and still best!) temporal beam smoothing technique
- The Pharos **glass laser** upgrade as well as development and construction of the two most energetic **excimer lasers** – the Nike KrF laser and the Electra ArF laser
- Vision toward high gain for ICF and IFE
- Any many, many more…

We would like to thank him for all his contributions!

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# Back-Up Slides

# ArF optics continue to progress toward higher damage thresholds and improved durability

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ArF use by lithographic industry has advanced durable 193 nm optics

ArF grade calcium fluoride windows survive up to 20 $J/cm^2$ in 20 ns without bulk damage in advancements of microlithography
(Azumi M., Nakahata E., 2015 "Laser damage of Calcium Fluoride by ArF excimer laser irradiation," Proc. Of SPIE 9632, 932131-7.)

Commercial vendors advertise High Reflectors as high as 2 $J/cm^2$. $AlF_3/LaF_3$ high reflector coatings have been reported to have damage thresholds at 193 nm up to 4.5 $J/cm^2$.
(H. Blaschke, R. Thielsch, J. Heber, N. Kaiser, S. Martin, E. Welsch, "Laser resistivity and damage causes in coating materials for 193 nm by photothermal methods" SPIE Vol. 3578 (1998) 74-82.)

High Damage threshold (29.8 $J/cm^2$) fluorine resistant coatings have been developed for KrF amplifiers that may be adaptable to ArF
(Zvorykin V, Gaynutdinov R, Isaev M, Stravroshii D, Ustinovskii 2020 "Towards high-optical-strength, fluorine-resistant coatings for intracavity KrF laser optics," Appl. Opt. 59, A198-A205)