U.S. NAVAL RESEARCH LABORATORY

ArF Repetition-Rate Laser and Pulsed Power Technologies Enabling Smaller Lower Cost Fusion Power Plant Designs

ARPA-E FUSION WORKSHOP

Astor Crowne Plaza
New Orleans, LA
March 7-8, 2023

Work supported by:
ARPA-E, FES [BETHE]

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

Collaborators

Matthew Myers & Malcolm McGeoch[1] (Focused work in this presentation)

ArF Contributors → James Weaver, Jason Bates, Max Karasik, Jude Kessler, Steve Obenschain*, Andrew Schmitt#, Tzetelina Petrova^

Laser Plasma Branch, Plasma Physics Division (PPD), U.S. Naval Research Laboratory (NRL)

[1]PLEX LLC

*Retired

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

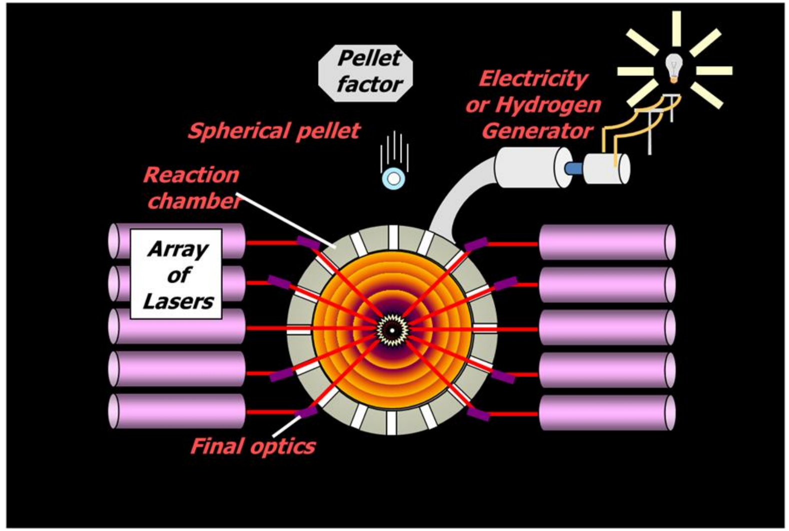
^ Radiation Hydrodynamics Branch, Plasma Physics Division, U.S. Naval Research Laboratory (NRL)

Argon fluoride lasers direct path to Inertial Fusion Energy (IFE)

NRL PPD

<u>Available ArF Laser Technologies ready now:</u>

- ❑ Modular, Scalable Driver Components
  - Solid State Switches
  - Inexpensive pulse power
  - Beam Smoothing for Target Illumination
  - Zooming for Laser to follow target
  - Short Wavelength 193 nm
  - Broad bandwidth, 11 THz at 193 nm

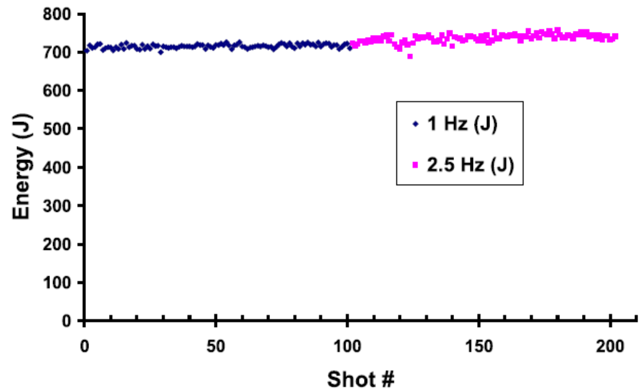


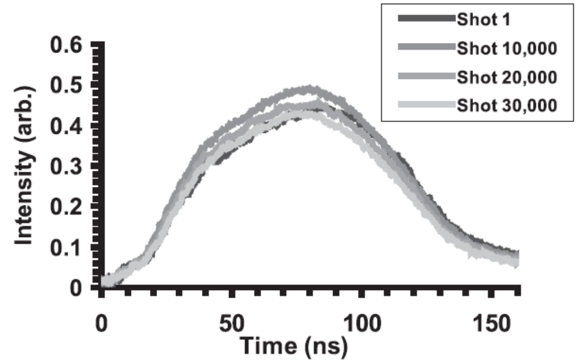
<u>What is needed still:</u>

- ❑ Scaling to fusion power plant size and lifetime ($1x10^9$ shots)
  - Many component lifetimes already evaluated
- ❑ ArF Direct Drive Target Physics
  - Implosion simulations and analysis very promising

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

NRL PPD





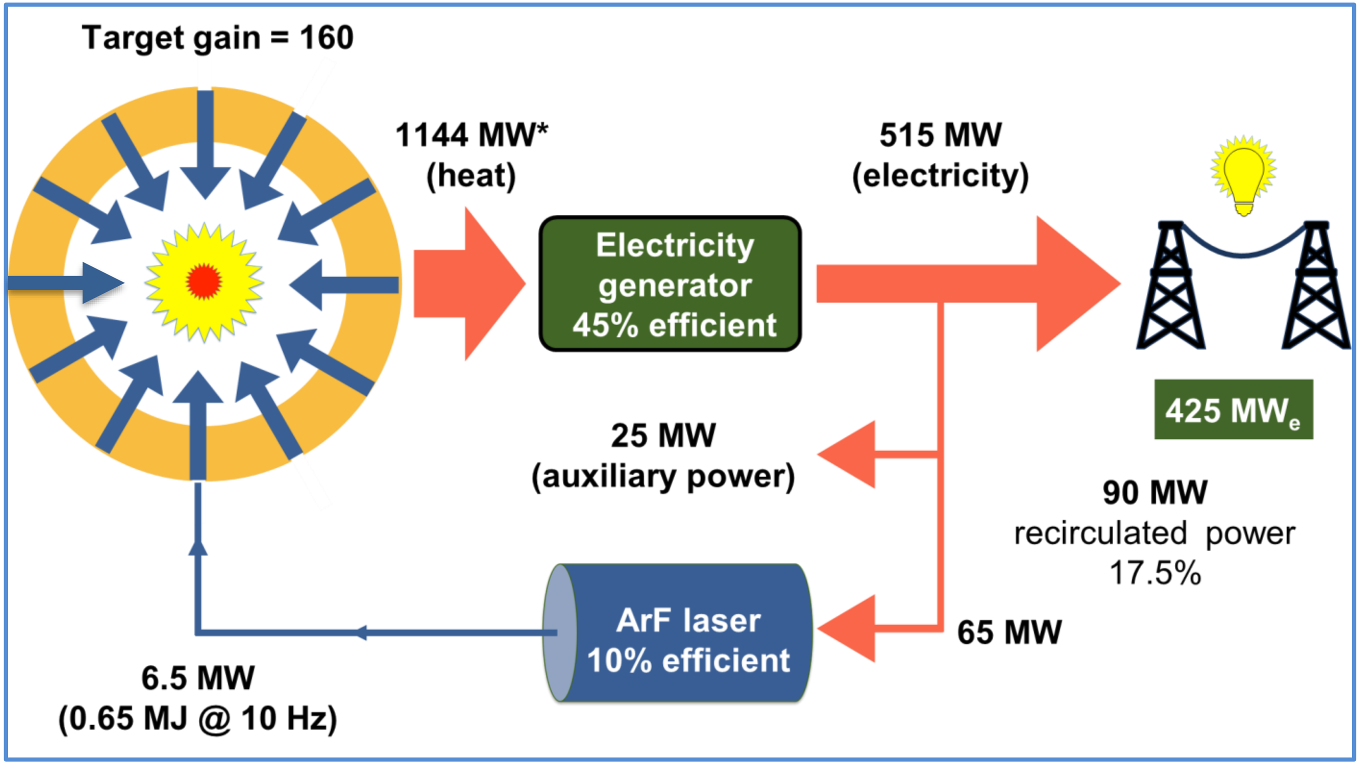
Continuous operation 90,000+ shots at 2.5 Hz for 10 hours

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

ArF Power Plant looks favorable due to reduced size and lower cost

NRL PPD

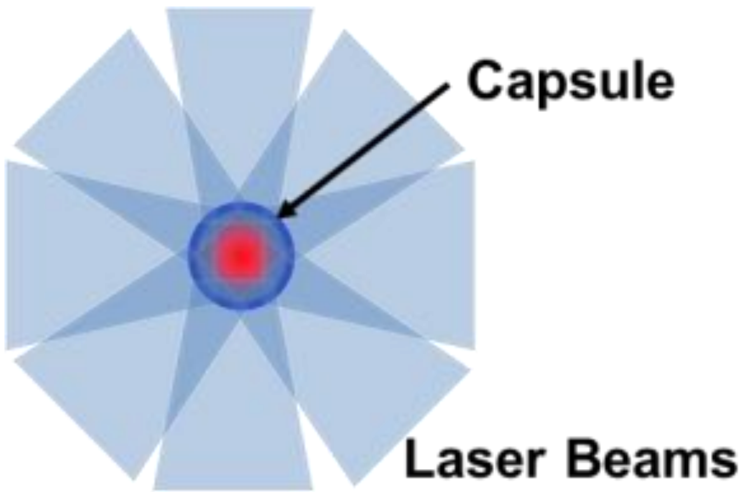
Power flow in 425 MWe ArF power plant
0.65 MJ ArF laser operating @ 10 pulses/sec.



Direct laser drive is a much more efficient approach

NRL PPD

Direct Laser Drive – laser light directly illuminates the capsule



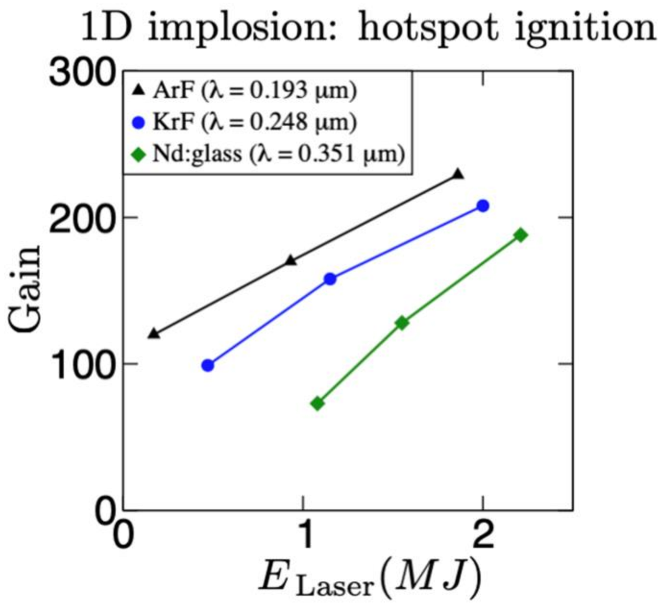
- Much more efficient than indirect drive (>6x)
- Potential to reach the high gains (100) required for the fusion energy application.

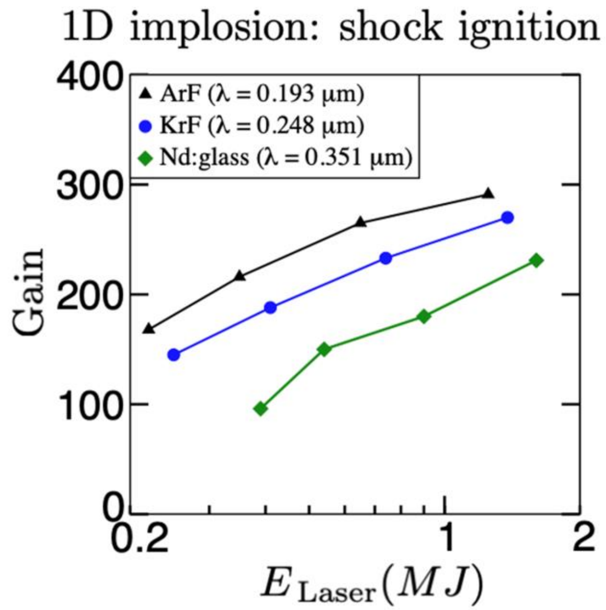
Best laser driver for high performance

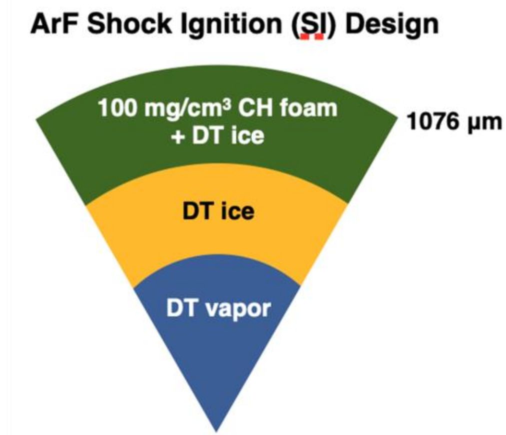
- Highly uniform target illumination
- Multi-THz bandwidth to suppress laser-plasma instabilities (LPI)
- Capable of zooming the focal diameter to follow imploding target
- Shorter laser wavelength to further suppress LPI and increase hydro-efficiency of implosion
- The 193 nm ArF laser best meets all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

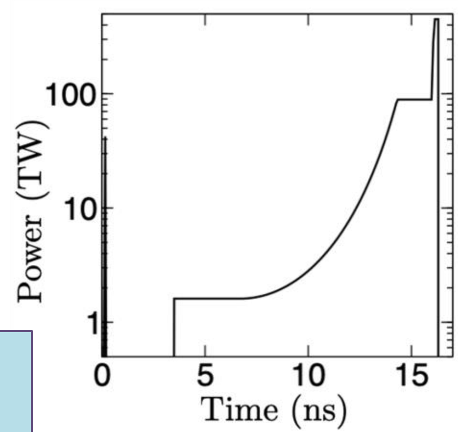
Simulations suggest high gains (> 100) are possible in conventional target designs using < 1 MJ of ArF laser light with zooming; even higher gains with shock ignition

NRL PPD









- LPI effects were not included in simulations

UPDATE:

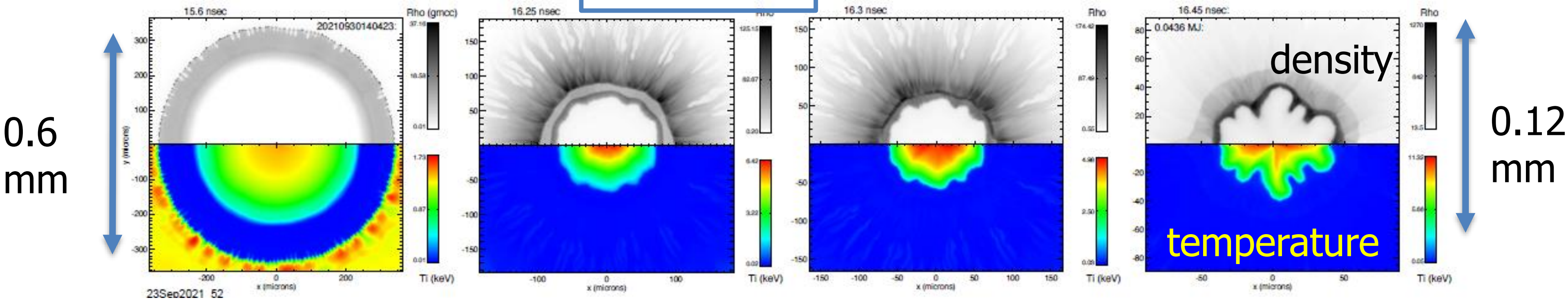
A.J. Schmitt and S.P. Obenschain, "The importance of laser wavelength for driving inertial confinement fusion targets. I. Basic Physics," Physics of Plasmas 30, 012701 **(2023)**

A.J. Schmitt and S.P. Obenschain, "The importance of laser wavelength for driving inertial confinement fusion targets. II. Target Design," Physics of Plasmas 30, 012702 **(2023)**

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

NRL PPD

Sample NRL 2D simulation of an 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
- An ArF laser with 10% electrical efficiency needs ~100x fusion gain for the power plant application.

UPDATE:

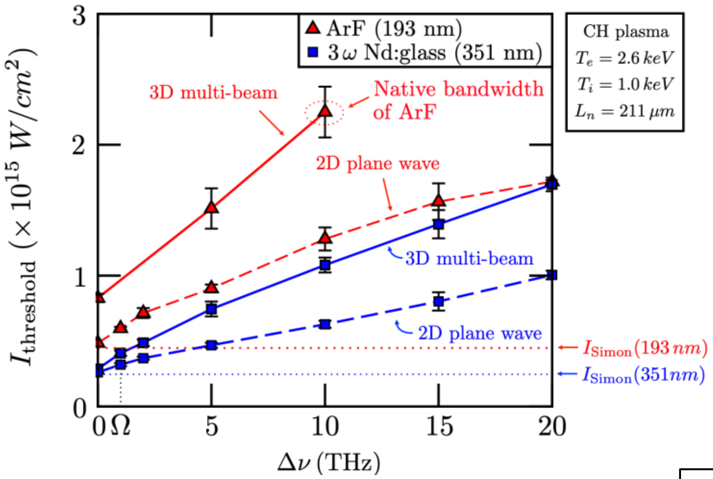
A.J. Schmitt and S.P. Obenschain, "The importance of laser wavelength for driving inertial confinement fusion targets. I. Basic Physics," Physics of Plasmas 30, 012701 **(2023)**
A.J. Schmitt and S.P. Obenschain, "The importance of laser wavelength for driving inertial confinement fusion targets. II. Target Design," Physics of Plasmas 30, 012702 **(2023)**

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

NRL PPD

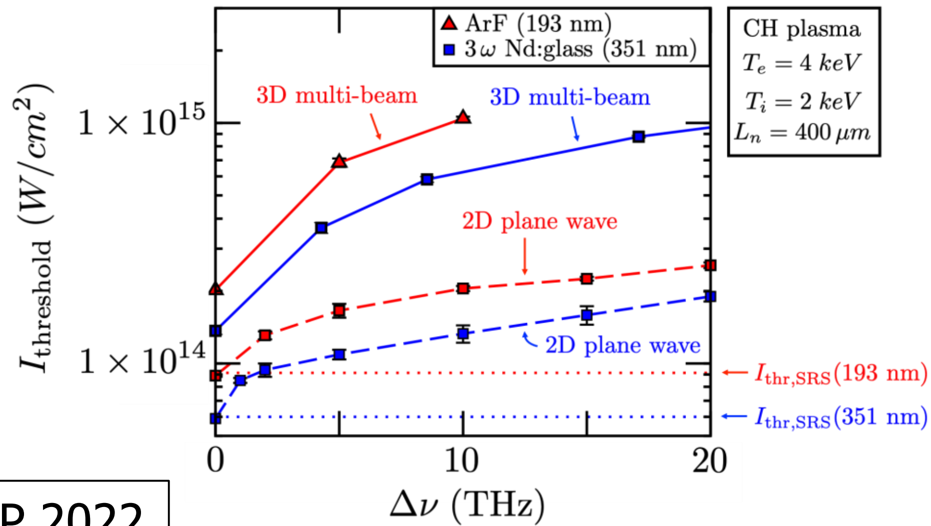
*Two Plasmon Decay

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



#Stimulated Raman Scattering Backscatter

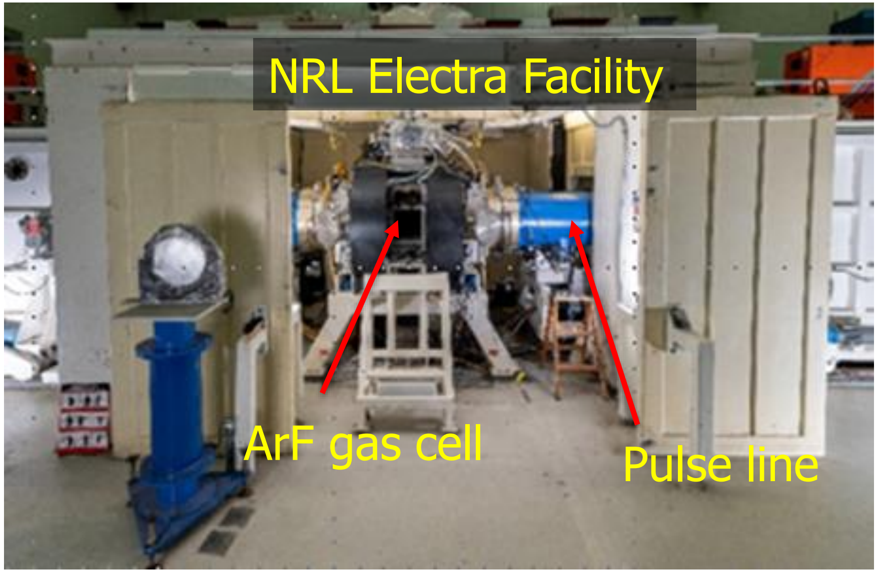
$$I_{thr,SRS} \sim 9 \times 10^{16}\, \lambda_{\mu m}^{-2/3}\, L_{\mu m}^{-4/3}\;\; W/cm^2$$

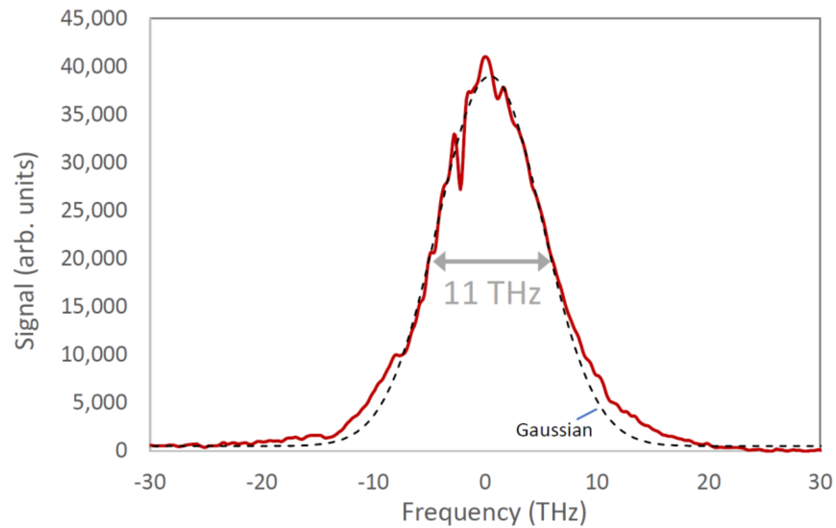


Bates APS DPP 2022

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

NRL PPD





- 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

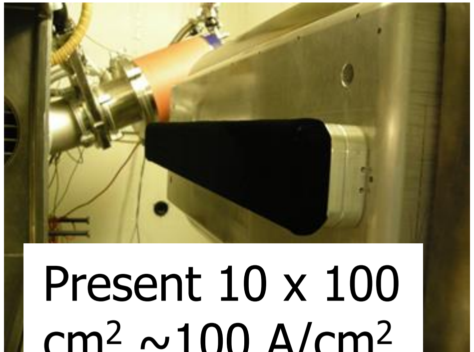
ArF World Record Laser Energy at NRL, 200 J occurred in step process

NRL PPD

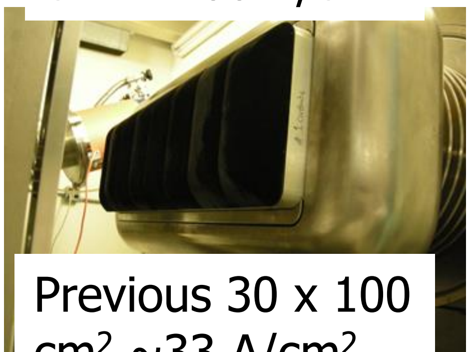
- Increased Electron Beam Power Deposition (MW/cm^3)
  Increases small signal gain (g_0) for ArF

Maximize optical extraction volume

Reduction in Cathode Area increases MW/cm^3



Present 10 x 100 cm^2 ~100 A/cm^2

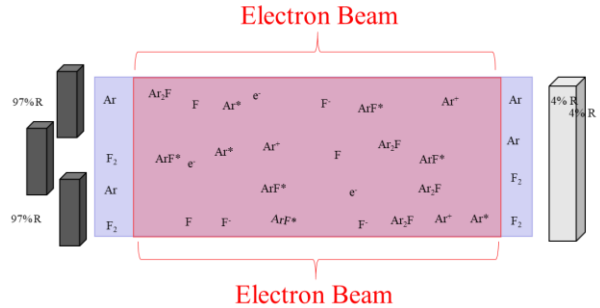


Previous 30 x 100 cm^2 ~33 A/cm^2

Lower operating pressure allows Removal of Support (Hibachi) Ribs increases MW/cm^3

Every other hibachi rib was removed

ArF Optical Design to utilize all of the 10 x 30 x 100 cm^3 gain medium volume



ArF Laser Energy Records over 100 J

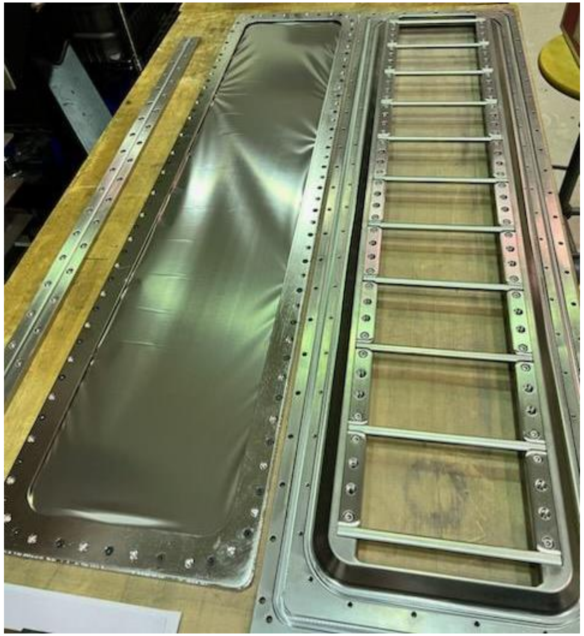
Date	Energy (J)	Location
9/17/2019	137 J	NRL
11/15/2019	172 J	NRL
11/19/2019	173 J	NRL
2/14/2020	186 J	NRL
3/5/2020	200 J	NRL

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

NRL PPD

foil hibachi

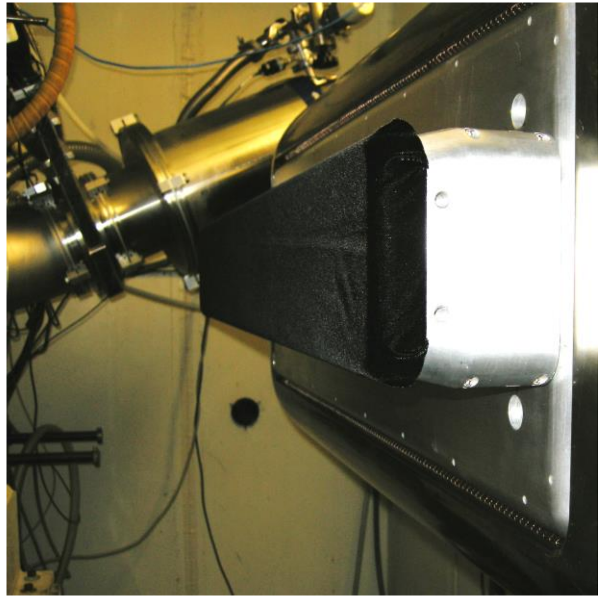
Reduced area allows advancement with 'better' foil materials



1meter

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

cathode



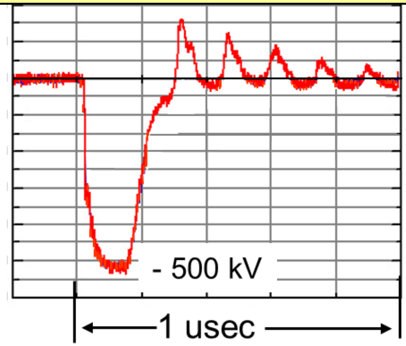
Reduced area for better coupling for ArF laser

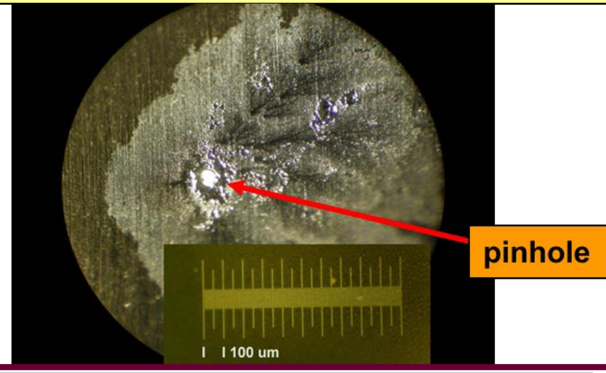
Key to long foil lifetime; minimize voltage reversals in the electron beam diode

NRL PPD

“100 ns timescale” > > > > > Emission from foil causes hole

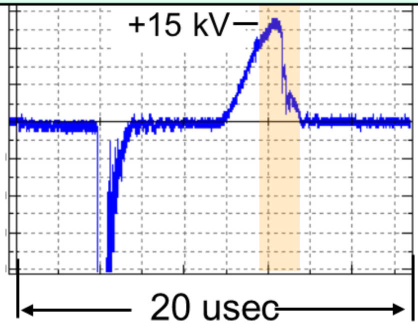
Diode Voltage

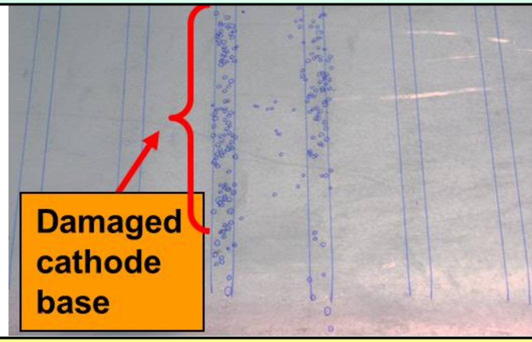


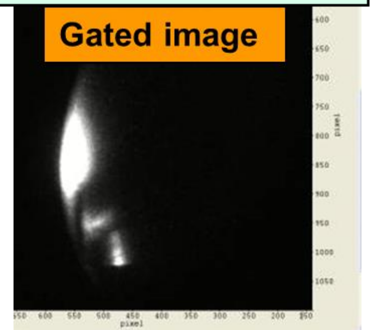


“10 μsec timescale” > > > > Arc from ribs damage cathode

Diode Voltage



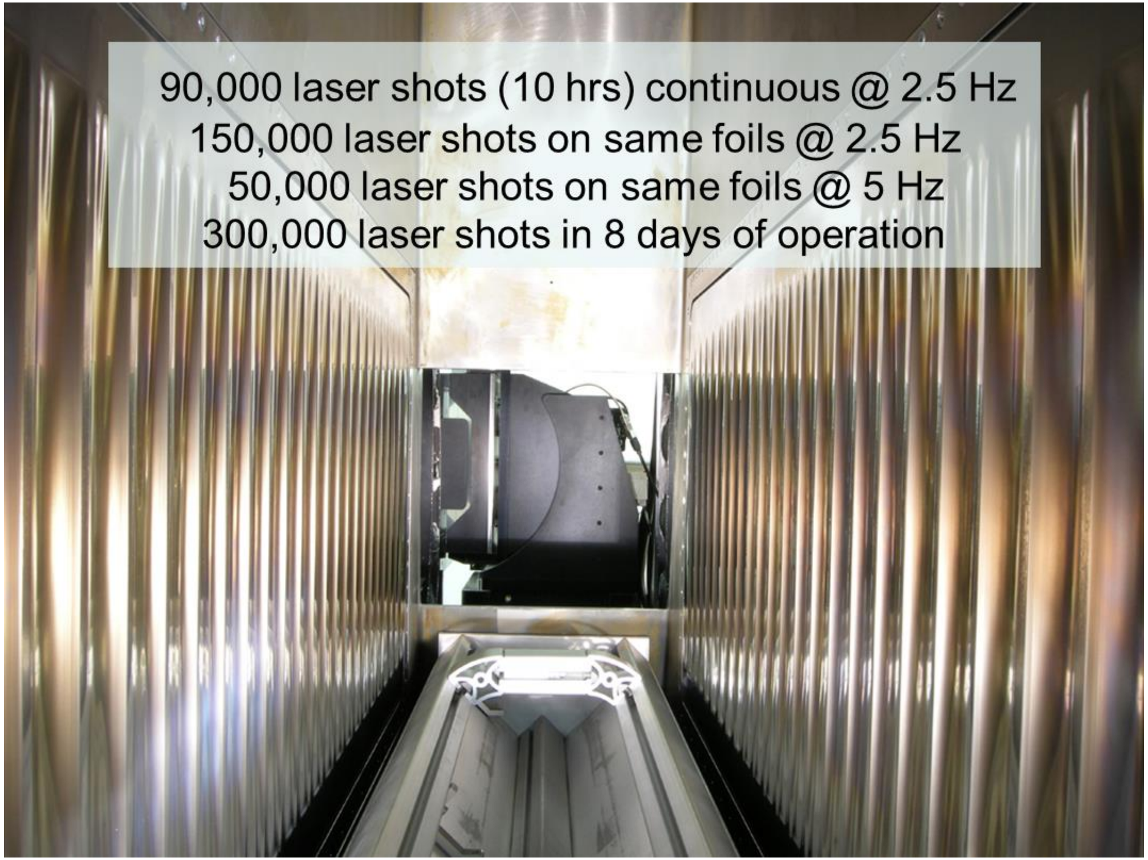




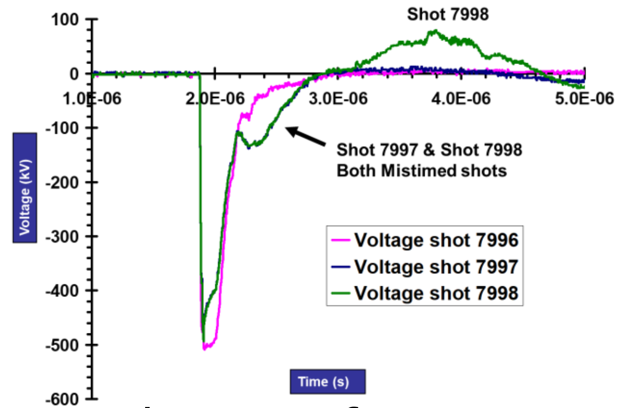
These correspond to < 1% of the energy in the system..but they cause damage

Suppressing these voltage reversals allowed on average longer duration runs
But, Voltage Reversal Due to Poor Performance of Laser Triggered Spark Gaps

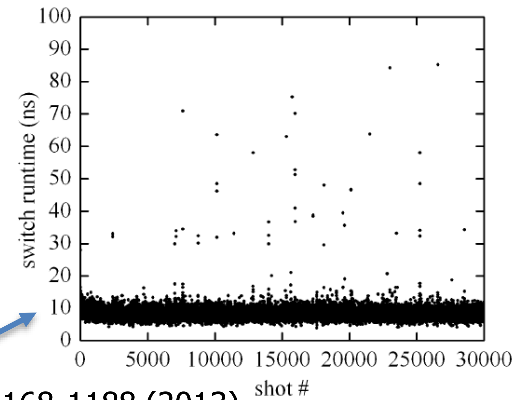
NRL PPD



Mistimed shots occasionally have reverse voltages (~60 kV)



Electra Performance



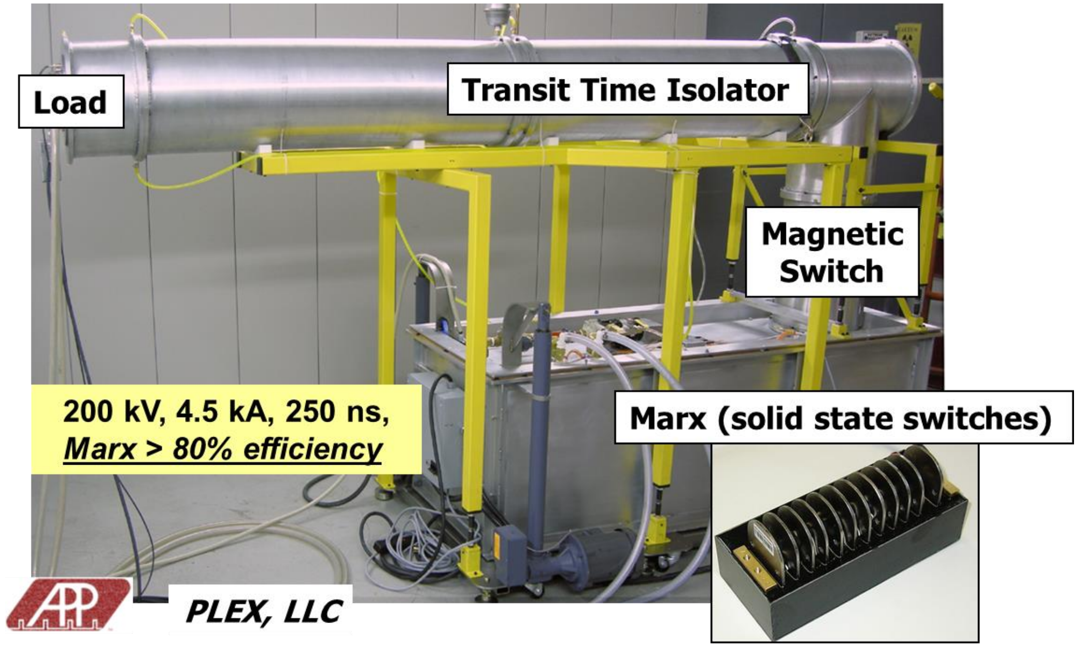
F. Hegeler et al. IEEE Trans. On Dielectrics and Insulation 20 (4) 1168-1188 (2013)

Solution Solid State Pulse Power, Electra is the Ideal Test Bed for continued ArF driver development

Tests of the electron gun have been limited by a 10^6 pulse spark gap switch life (Note: Spark Gap switch performance is also the cause of foil failure)

We have operated continuously to 10^7 pulses a 250kV, 10Hz thyristor-switched pulser

The test was stopped by capacitor failure, not a switch!



NRL has completed conceptual design for a $>10^8$ pulse, 15kJ, 140ns, all solid state driver for the existing Electra chamber, electron guns and flow loop. 83-90% efficient.

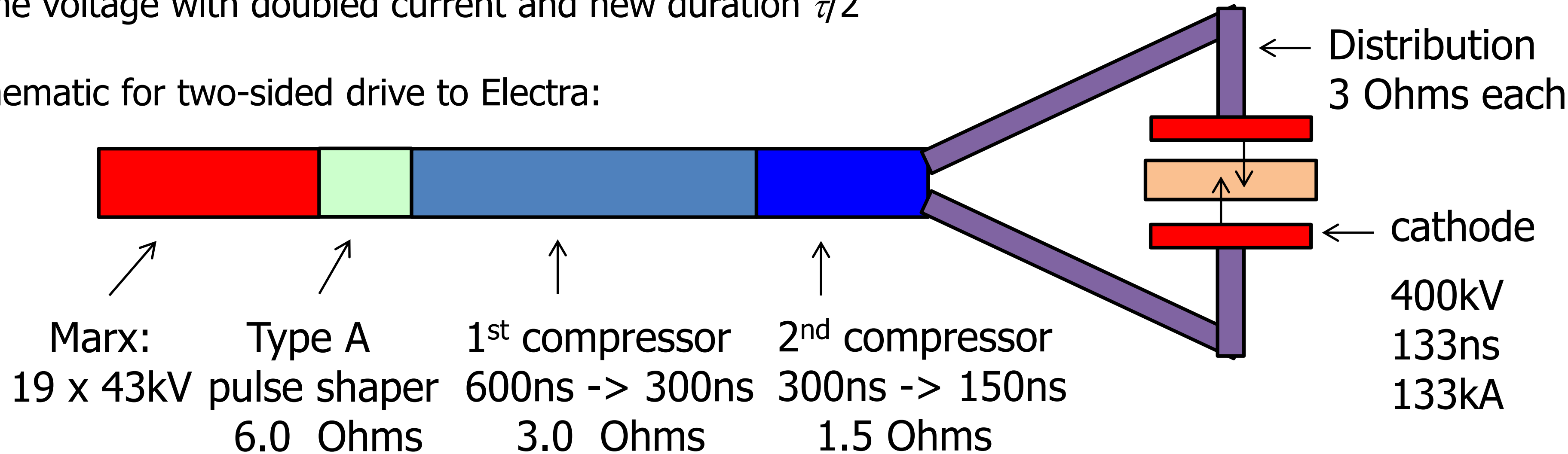
NRL-PLEX LLC Concept to Implement Solid State Pulse Power on Electra

The solid state driver depends on advanced "Pulse Compression"

A rectangular pulse of duration τ and voltage V enters a transmission line with impedance Z and an open circuit extension of round trip time $\tau/2$.

A saturable magnetic switch closes and incident and reflected pulses are then superimposed at the same voltage with doubled current and new duration $\tau/2$

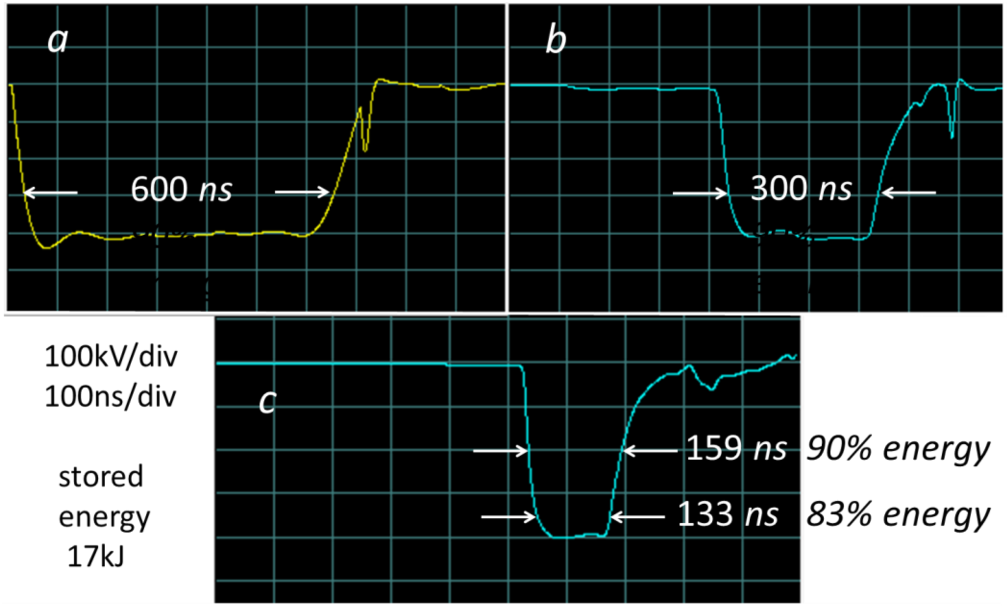
Schematic for two-sided drive to Electra:



Design details for solid state pulse power have already been performed on Electra size systems as well as larger systems with present technology

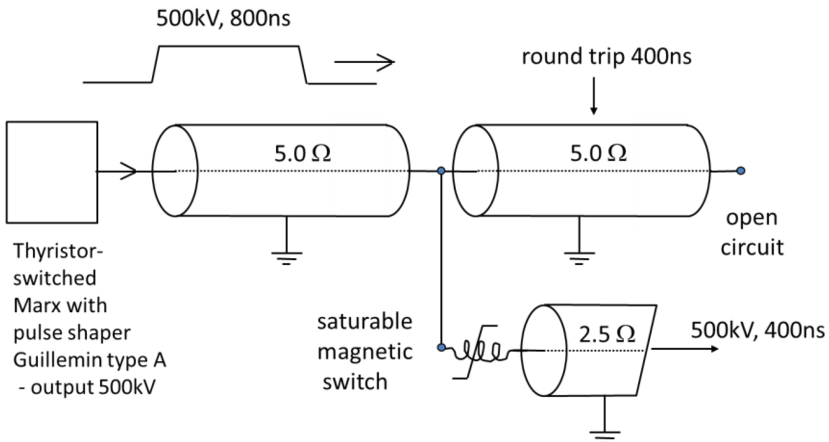
NRL PPD

Full "Spice" modeling of Electra $>10^8$ duration compressor circuit > 15kJ delivered



a) pulse shaper output *b*) waveform after 1st compressor *c*) output waveform.

We can make a 40kJ, 200ns driver module at 500kV, 400kA, 1.25 Ω with available technologies today

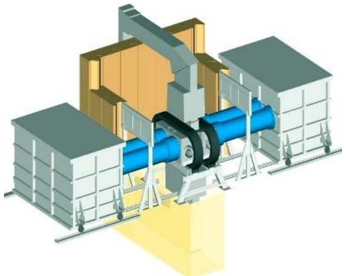


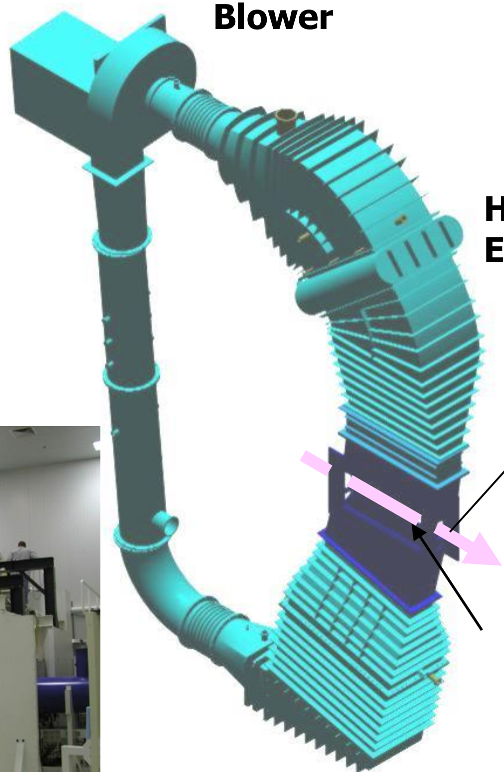
First compressor 500kV x 400ns = 0.2 V sec => core area 0.105 m^2 => L = 54nH, L/2.5 = 22ns

2nd compressor 500kV x 200ns = 0.1 V sec => core area 0.053 m^2 => L = 27nH, L/1.25 = 22ns

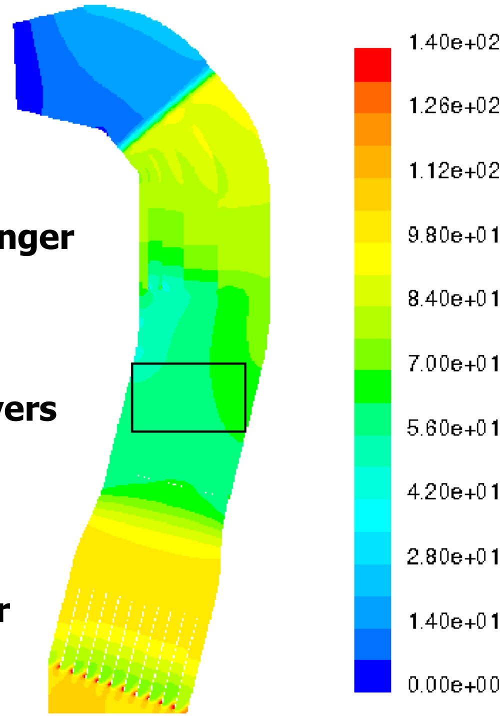
Development of recirculator to both cool and quiet laser gas *plus* provide hibachi cooling has been built

NRL PPD





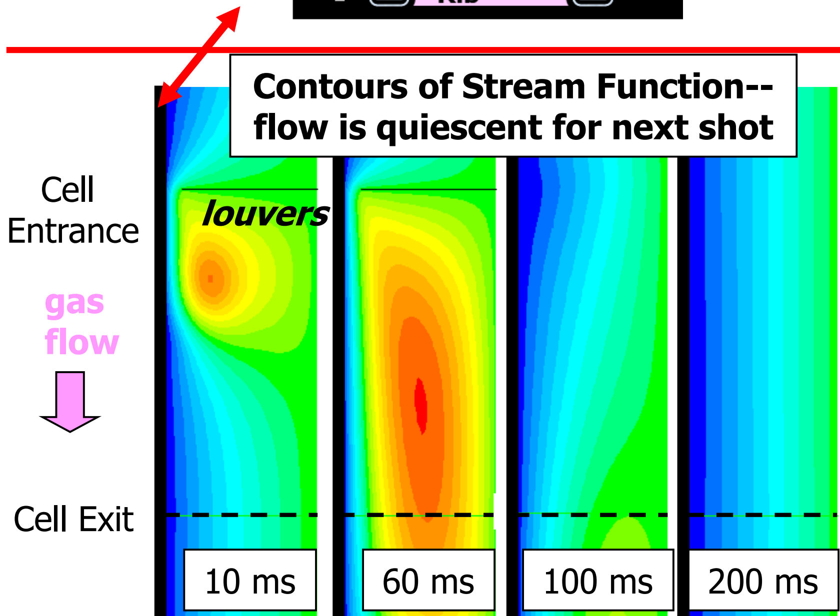
Homogenizers & Turning Vanes



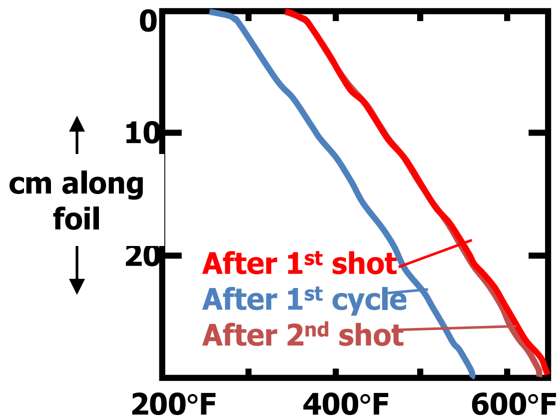
Static Pressure Contours varies by 14 Pa (10^{-4}) over laser cell

Technology for cooling hibachi foils for KrF can be directly applied to ArF and thermal conduction of the gas is improved for ArF

NRL PPD



Foil Temperature below required 650°F



Concept & Modeling:
A.Banka & J.Mansfield, Airflow Sciences, Inc

NRL is developing a high energy, single shot, ArF laser damage testing facility, experience with KrF Rep-Rate Amp Window Surface damage is 1st challenge

NRL PPD

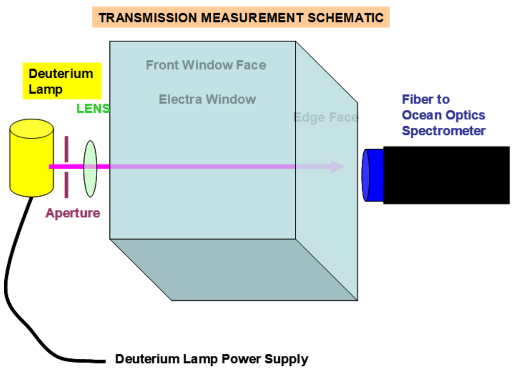
NRL ArF (193 nm) laser optical damage testing facility

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.)

Window materials such as uncoated CaF_2 exceed 6 J/cm^2 at 193 nm without AR coatings.
We are interested in finding high damage threshold AR coatings for 193 nm as well.

KrF Rep-Rate Experience
'Rear window no change in transmission even after long duration runs'
'front window transmission loss occur during long duration runs correlated to flow of recirculator'

Wolford et al. Fusion Science and Technology 64 (2) 179-186 (2013)



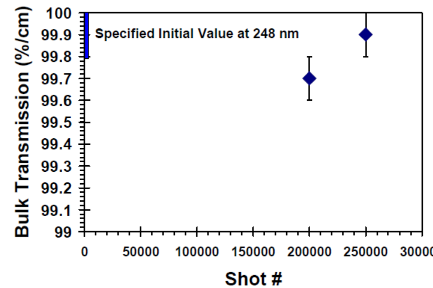


Fig. 9. Measurements of bulk transmission of fused silica in the Electra oscillator windows do not show a significant loss in transmission 250,000 shots.

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

NRL PPD

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 – 'short cut' to fusion energy

NRL PPD

- The physics underpinnings for laser fusion are well established
- The deep UV broad bandwidth 10 THz light with ≥ 10% wall plug efficiency from the ArF laser could be "game changing"
- All solid state ArF drivers < 200 ns are possible using Pulse Compression
- The Electra facility at NRL offers the fastest and least expensive route to ArF driver proof-of-concept at the 1 kJ level up to 10^8 pulses

Collaborations

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