Development Path for Inertial Fusion Energy

Advantages of Utilizing Direct Drive with the Krypton Fluoride Laser

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Work by the NRL laser fusion research team

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and the Office of Naval Research

Opening remarks

NRL program is developing an attractive path to inertial fusion energy (IFE) based on the krypton-fluoride (KrF) laser and directly driven targets

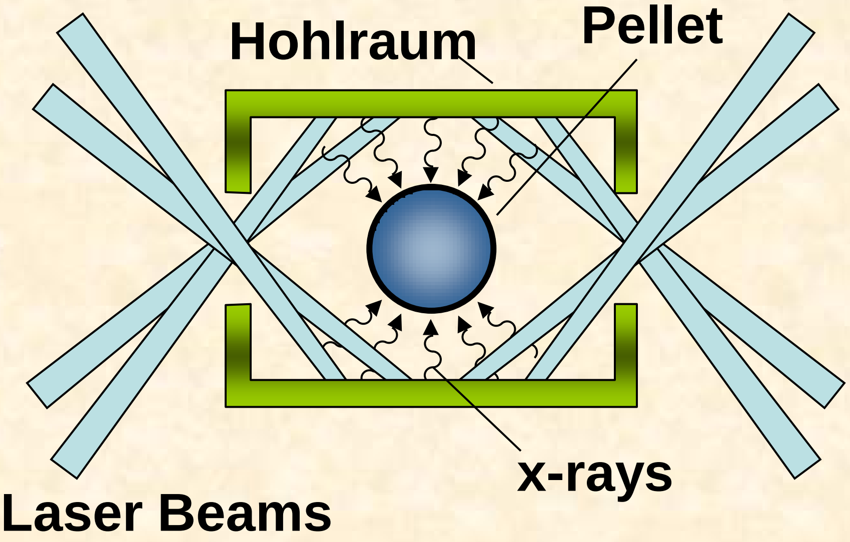
KrF
+
advanced direct drive

- High gain at reduced laser energy
- More robust against hydro and laser plasma instabilities
- May enable power plants with sub-megajoule laser energy

- Progress in KrF technology is promising towards obtaining the energy, durability and efficiency needed for IFE.
- Paths identified to obtain needed performance in other critical IFE technologies (e.g. reaction chamber, low cost target fabrication)

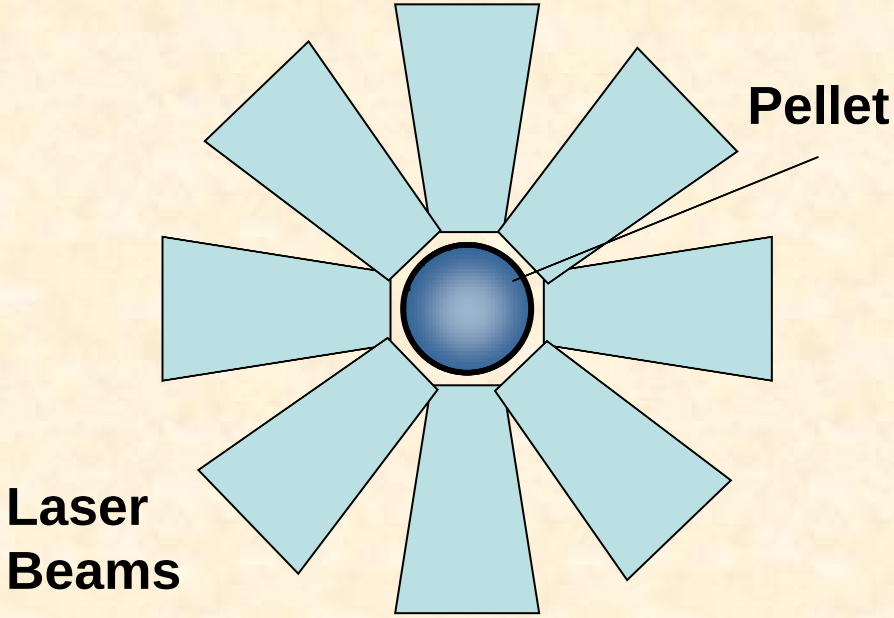
Direct Drive has substantial advantages for Energy

Indirect Drive chosen for NIF



- Complex physics
- Inefficient illumination
- Relaxed laser uniformity requirements

Direct Drive IFE

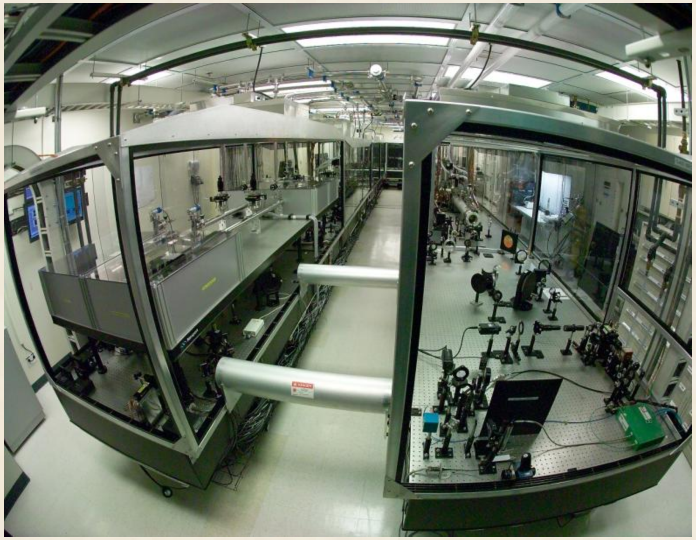


- Simpler physics and targets
- More efficient use of laser light, and greater flexibility in applying drive provides potential for much higher gains.

Two laser options for Direct Drive.
Both have potential to meet the IFE requirements

Electra KrF Laser (NRL)
λ = 248 nm (fundamental)
Gas Laser

Mercury DPSSL Laser (LLNL)
λ = 351 nm (tripled)
Solid State Laser

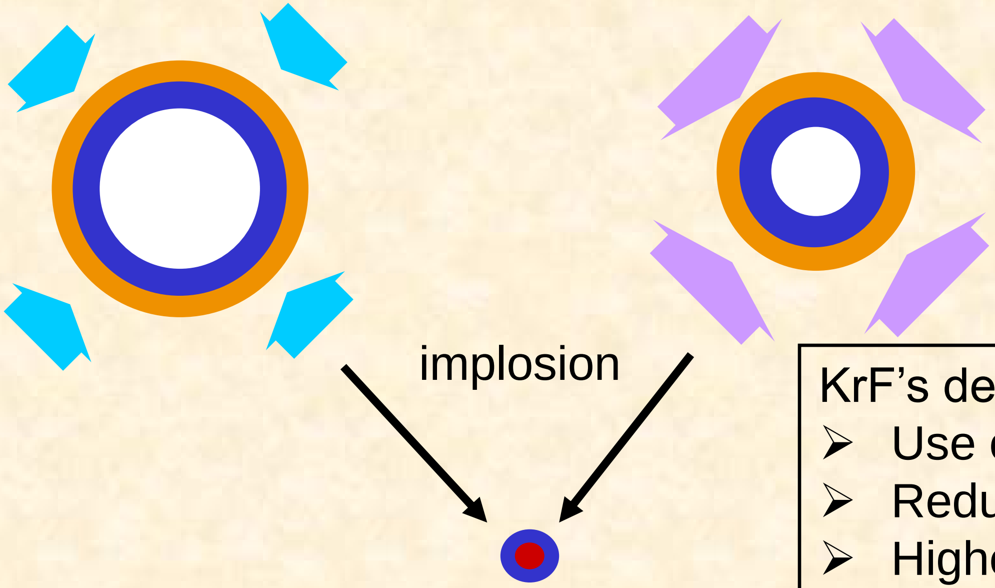


KrF light helps Direct Drive target physics (1)

Provides the deepest UV light of all ICF lasers (λ=248 nm)

Deeper UV →

- Higher thresholds for laser-plasma instability
- Higher mass ablation rates and pressure
- Higher hydrodynamic efficiency
- Higher absorption fraction



351 nm laser (e.g. NIF)
lower drive pressure

KrF
higher drive pressure

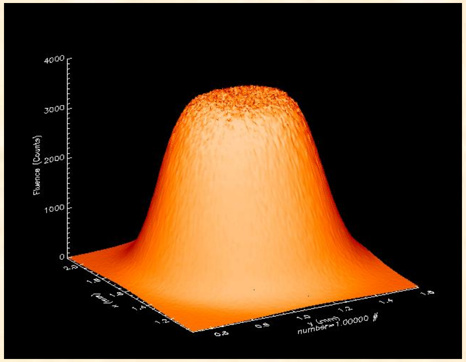
implosion

KrF's deep UV allows:

- Use of lower aspect ratio targets
- Reduced growth of hydro-instability
- Higher energy gain
- Use of less laser energy

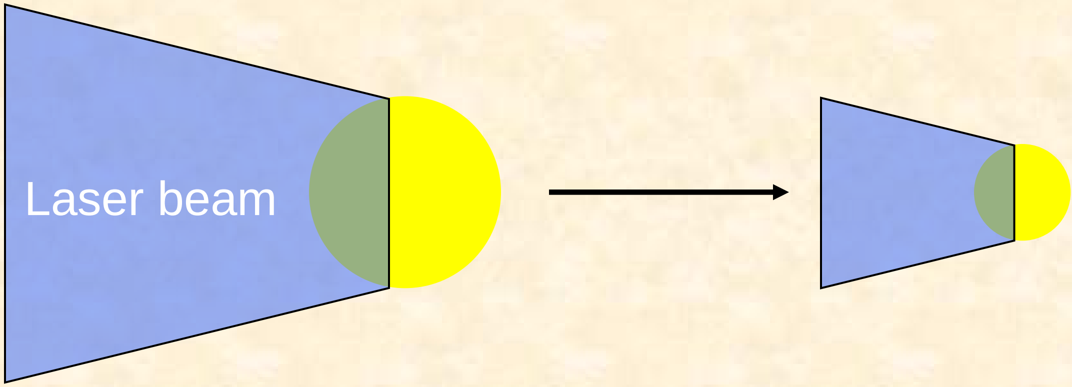
KrF Light helps the target physics (2)

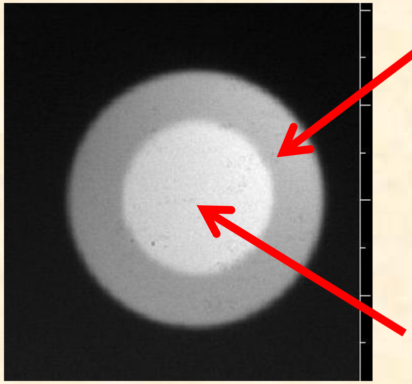
- KrF has most uniform target illumination of all ICF lasers.
  - **Reduces seed for hydrodynamic instability**



Nike KrF focal profile
Bandwidth up to 3 THz

- KrF focal profile can zoom to "follow" an imploding pellet.
  - **More laser absorbed, reduces required energy by 30%**





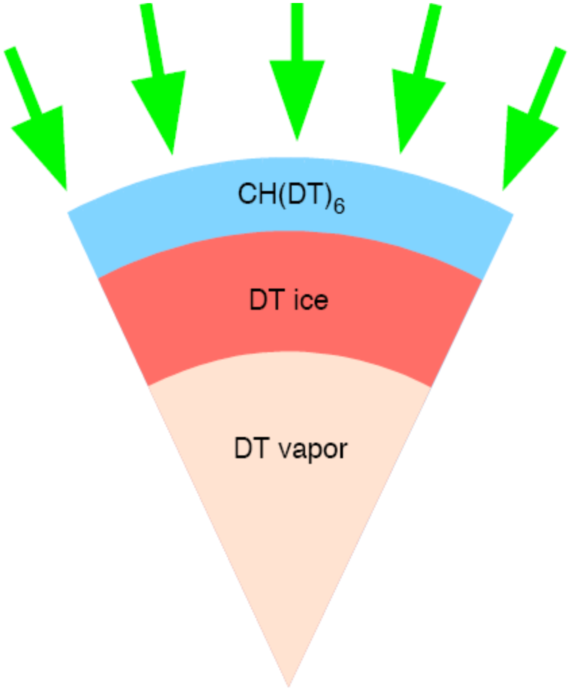
Early time

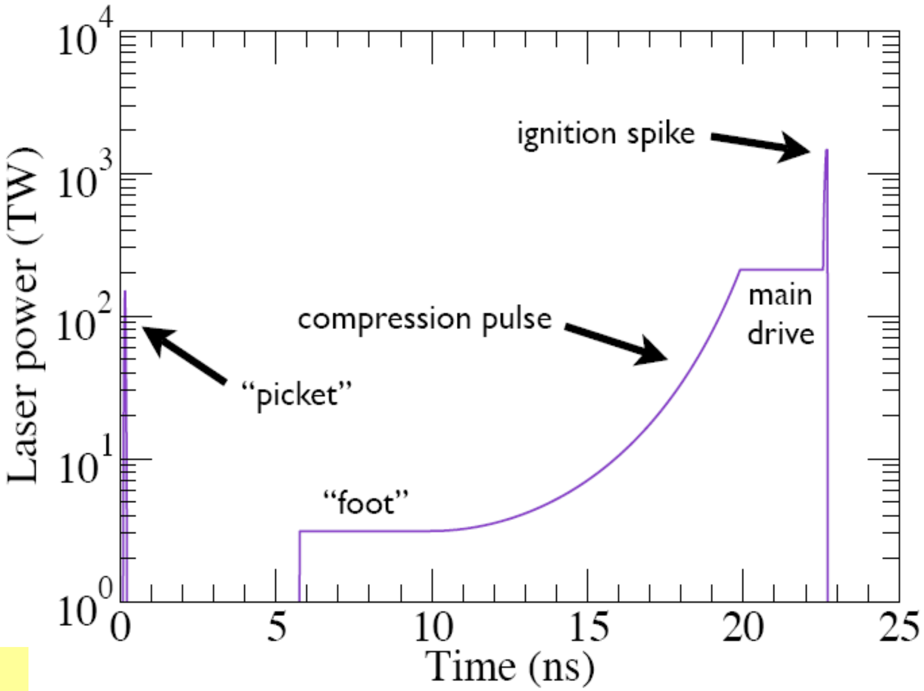
Nike zoomed focus

Late time

Shock Ignited (SI) direct drive targets[*]

Pellet shell is accelerated to sub-ignition velocity (<300 km/sec), and ignited by a converging shock produced by high intensity spike in the laser pulse.





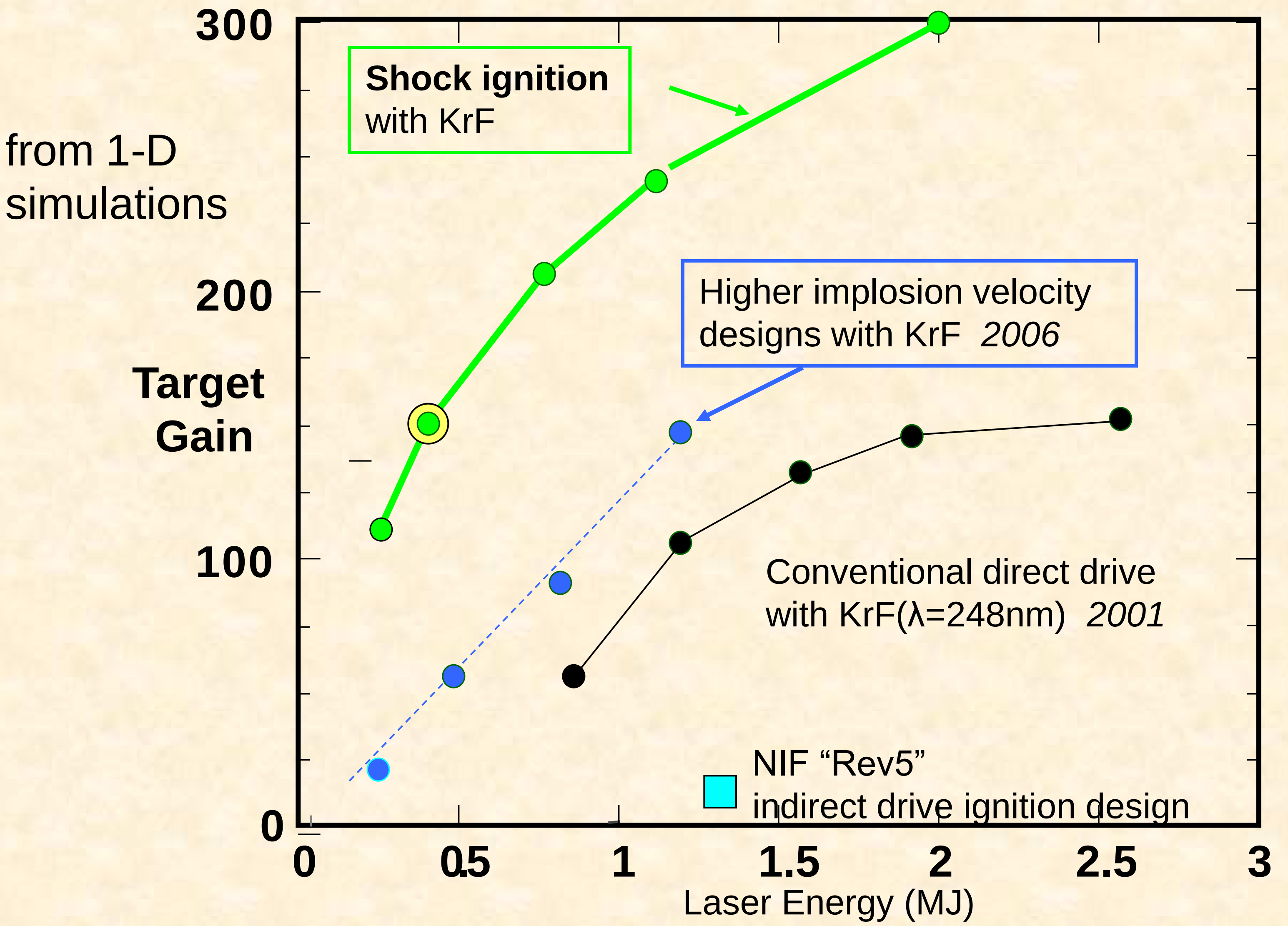
Low aspect ratio pellet helps mitigate hydro instability

Peak main drive is 1 to 2 × 10^{15} W/cm^2

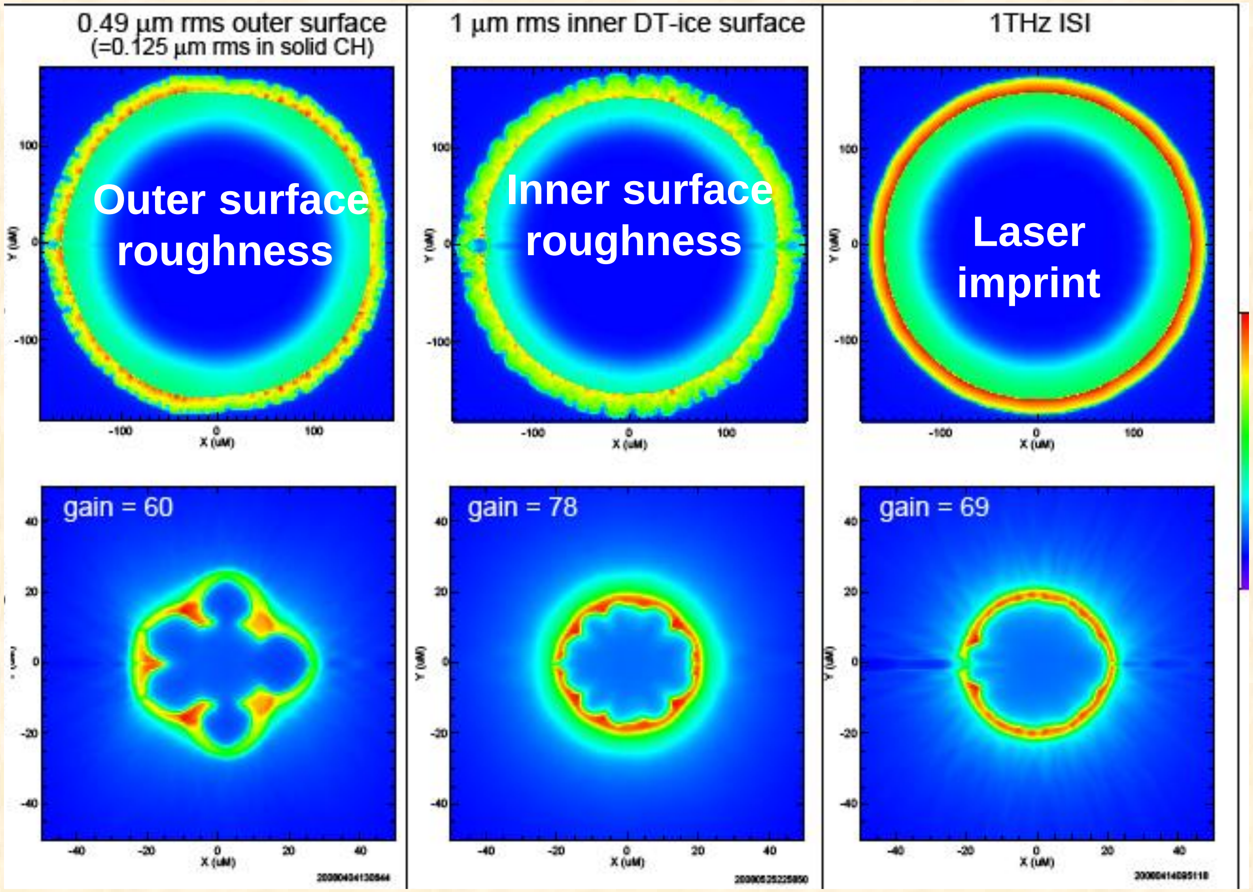
Igniter pulse is ~10^{16} W/cm^2

[*] *R. Betti et al., Phys.Rev.Lett.* ***98****, 155001 (2007)*

Gain curves show progress in direct-drive target designs



High resolution 2-D simulations show that the SI energy gains should be robust against hydro-instability growth.



Intermediate time

Late times burn begins

200µm

60µm

2-D Gain=60×

2-D Gain =78×

2-D Gain =69×

250 kJ shock ignited target – NRL FASTRAD3D simulations

Simulations predict sufficient energy gains (G) for development of energy application.

G ~100 with a 500kJ KrF laser

→ Fusion Test Facility (FTF)

G ~170 with a 1MJ KrF laser

→ Fusion Power plants

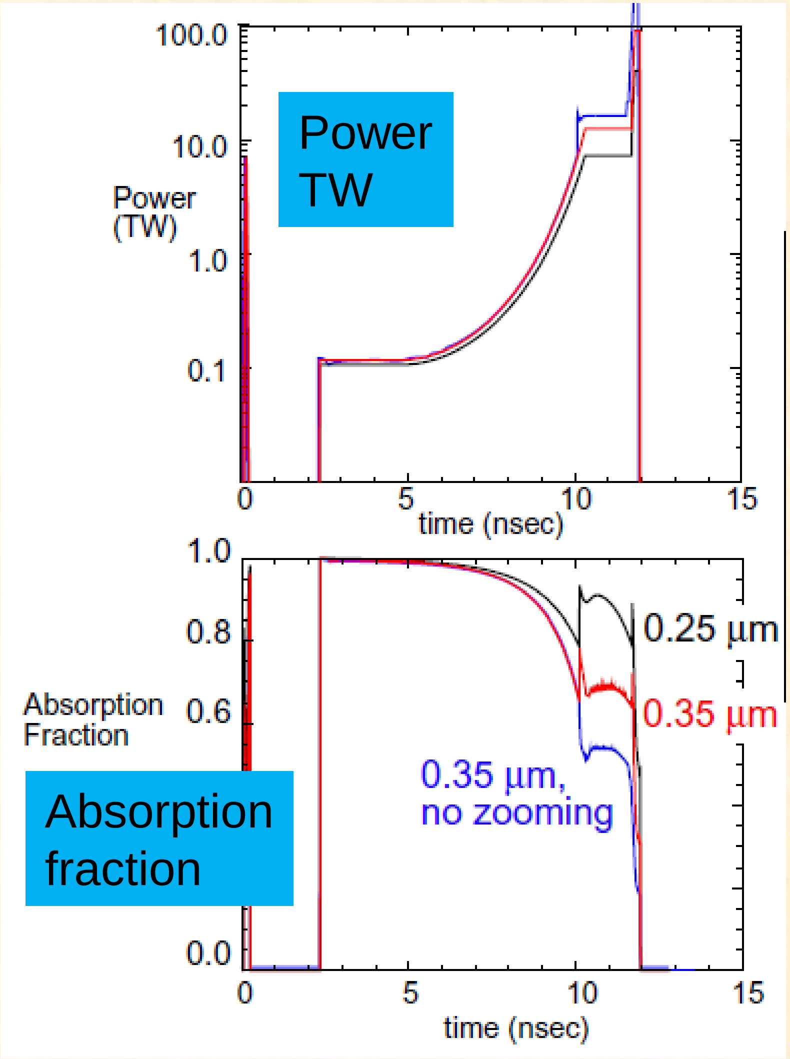
G ~250 with a 2 MJ KrF laser

Desire $G \times \eta \geq 10$ for energy application

η = laser wall plug efficiency ≅ 7% for KrF

→ need $G \geq 140$

Shock ignition benefits from shorter λ and zooming

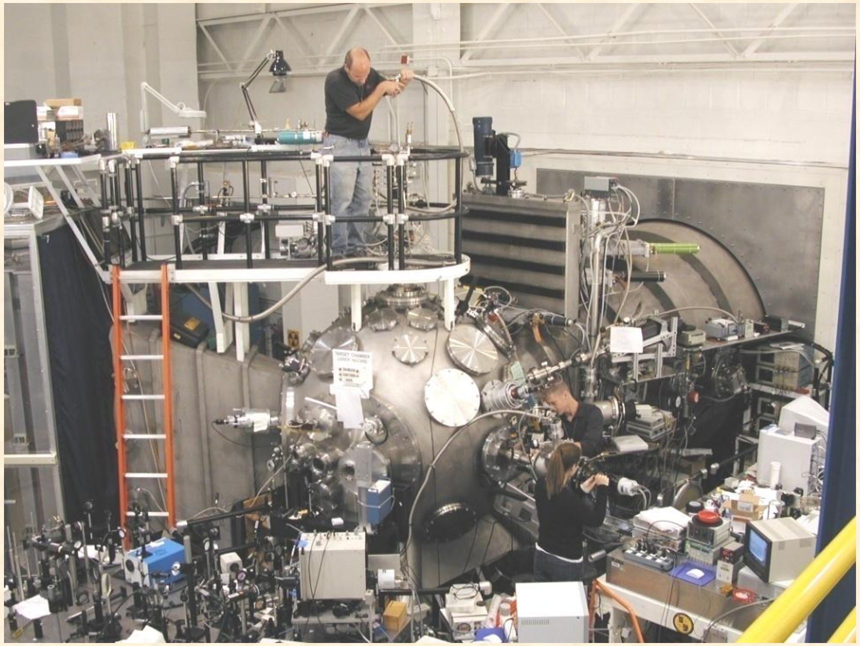


1-D Hydrocode simulations
Fixed low aspect ratio pellet

	KrF λ=248 nm with Zoom	**Nd:glass** λ=351 nm with Zoom	**Nd:glass** λ=351 nm no Zoom
Laser Energy	**230 kJ**	**430 kJ**	**645 kJ**
Yield	22 MJ	24 MJ	23 MJ
Gain	**97**	**56**	**35**
Peak compression intensity (W/cm^2)	1.55×10^{15}	2.2×10^{15}	
Peak igniter intensity (W/cm^2)	1.6×10^{16}	3.1×10^{16}	

- ➢ Significantly higher gain with 248 nm & zoom
- ➢ NIF has more than sufficient energy to test the physics

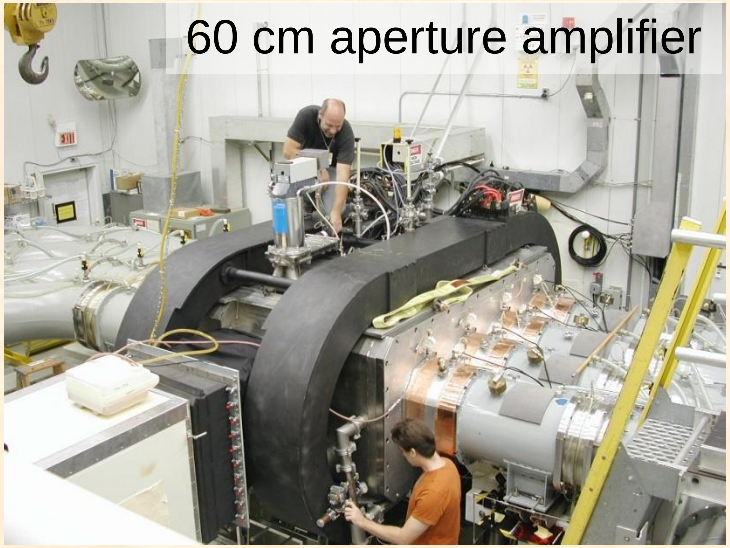
Nike krypton-fluoride laser target facility



Nike Target chamber

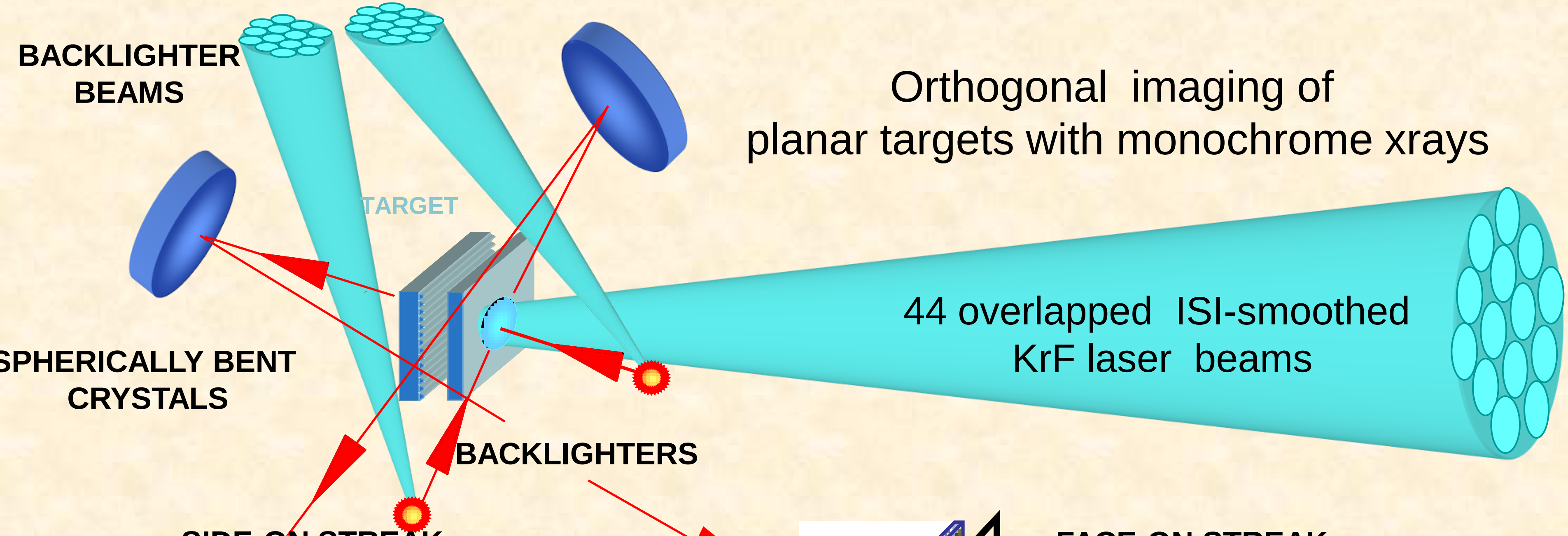
56-beam 4-kJ
KrF laser-target facility

Target chamber optics



60 cm aperture amplifier

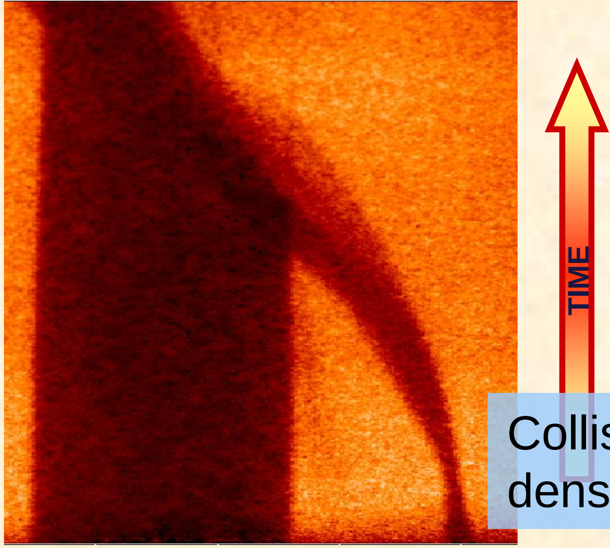
Nike is employed for studies of hydrodynamics and LPI



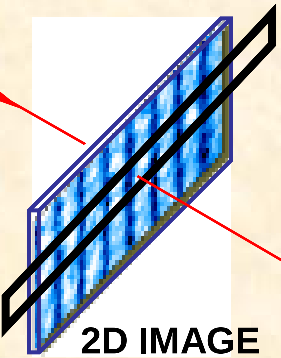
Orthogonal imaging of planar targets with monochrome xrays

44 overlapped ISI-smoothed KrF laser beams

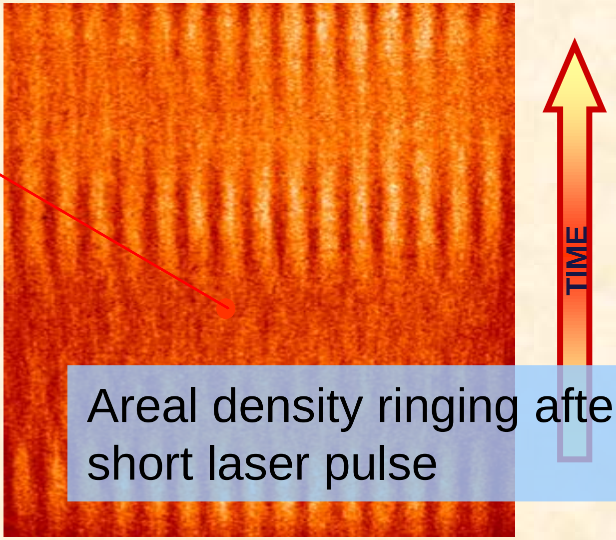
SIDE-ON STREAK



Collision with low density foam foil

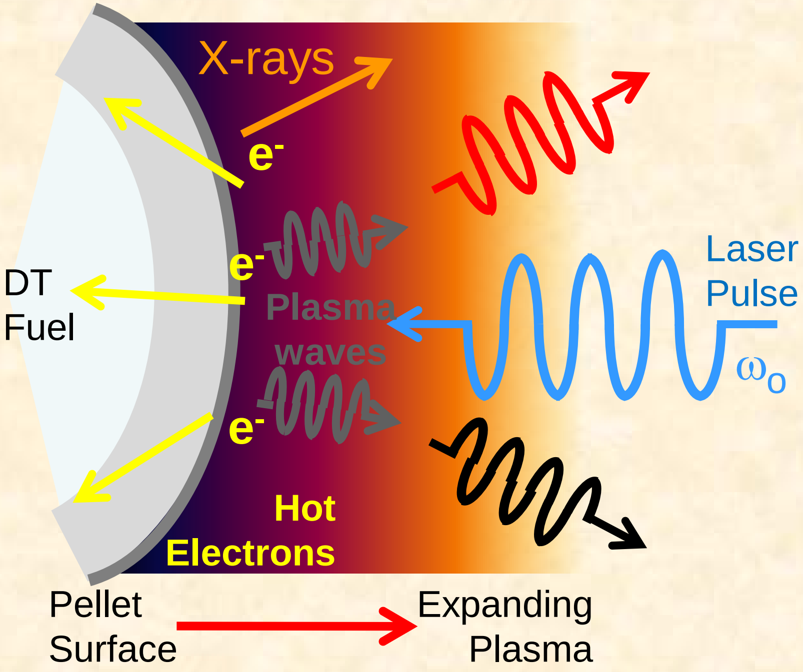


FACE-ON STREAK

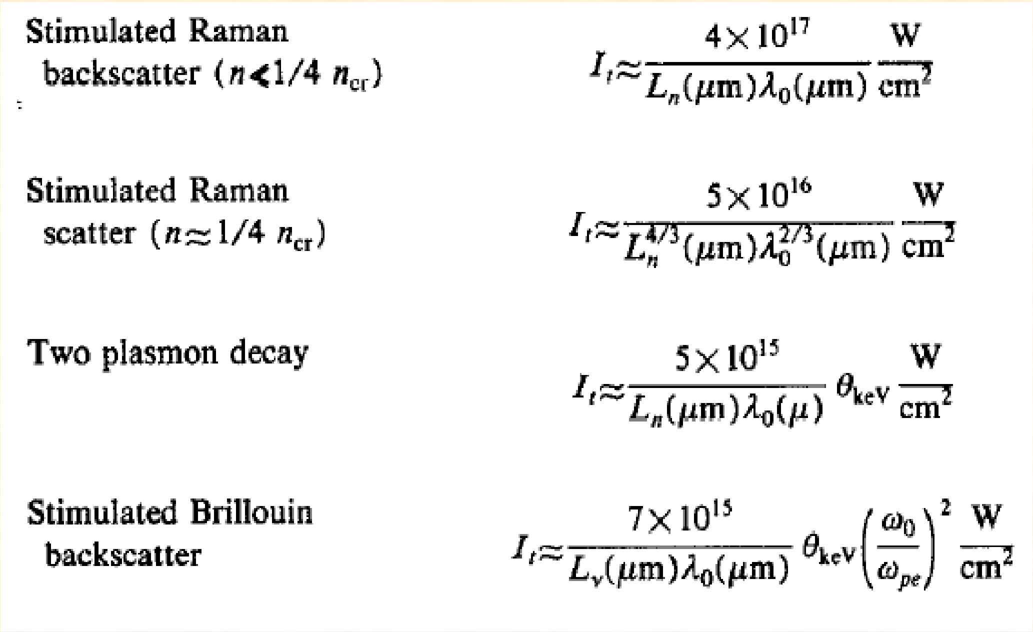


Areal density ringing after short laser pulse

Risk from Laser Plasma Instability (LPI) is predicted to decrease at shorter laser wavelengths



Intensity threshold formulas predict increase of ~40% for 248 nm versus 351 nm laser light



Stimulated Raman backscatter ($n < 1/4\ n_{cr}$)	$I_t \approx \frac{4\times10^{17}}{L_n(\mu m)\lambda_0(\mu m)} \frac{W}{cm^2}$
Stimulated Raman scatter ($n \approx 1/4\ n_{cr}$)	$I_t \approx \frac{5\times10^{16}}{L_n^{4/3}(\mu m)\lambda_0^{2/3}(\mu m)} \frac{W}{cm^2}$
Two plasmon decay	$I_t \approx \frac{5\times10^{15}}{L_n(\mu m)\lambda_0(\mu)} \theta_{keV} \frac{W}{cm^2}$
Stimulated Brillouin backscatter	$I_t \approx \frac{7\times10^{15}}{L_v(\mu m)\lambda_0(\mu m)} \theta_{keV} \left(\frac{\omega_0}{\omega_{pe}}\right)^2 \frac{W}{cm^2}$

Laser driven instabilities cause problems

- High energy electrons preheat DT fuel
- Increased scattering reduces laser drive

Quarter critical region has lowest thresholds

- scattering can generate hot electrons

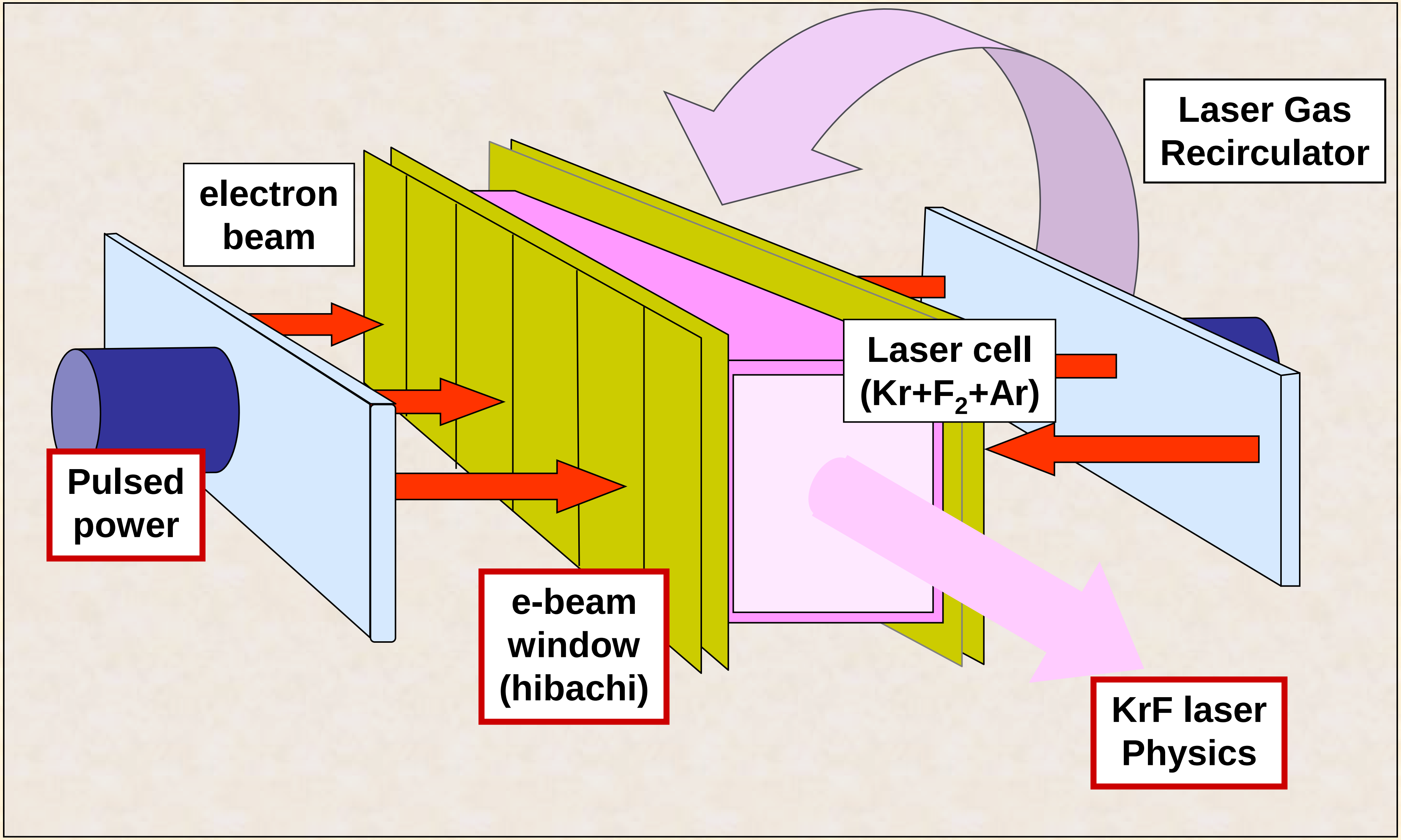
Results from high intensity (>10^{15} w/cm^2) Nike experiments are consistent with theoretical predictions of increase increased thresholds with shorter wavelength

Ok, so the physics is great with KrF.. But can you make it large, efficient, reliable etc.

Progress with KrF technology → answer is yes

Electra Laser Cell after 30,000 shot laser run

Elements of a Krypton Fluoride (KrF) electron beam pumped gas laser

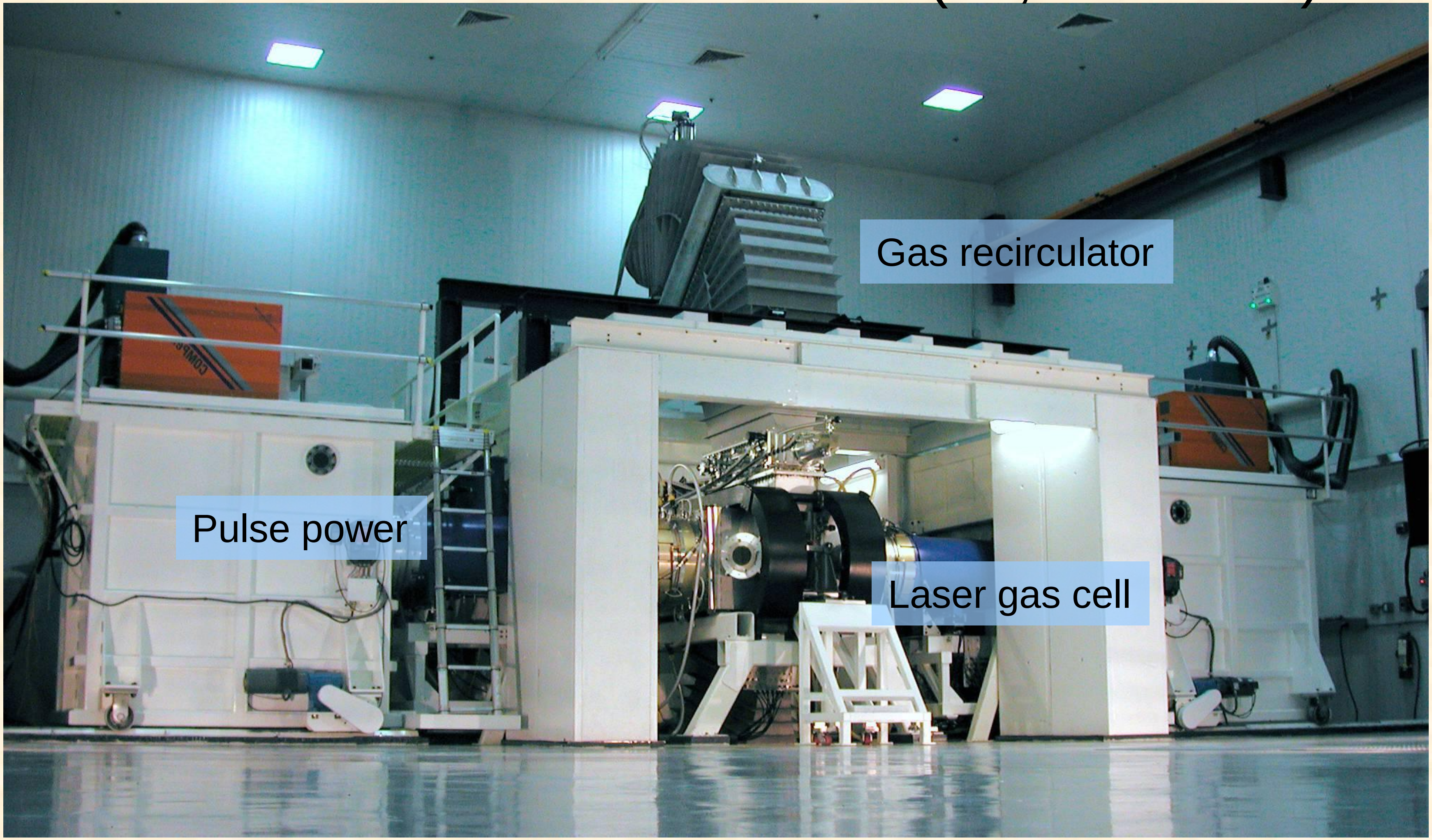


Electra Krypton Fluoride (KrF) Laser

Laser Energy: 300 to 700 Joules

Repetition rate: up to 5 pulses per second

Continuous Runs: 10 hrs at 2.5 Hz (90,000 shots)



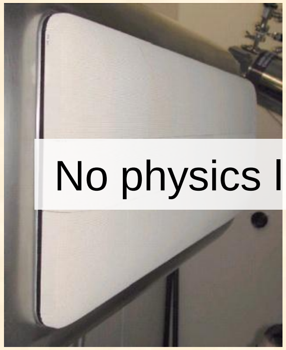
Progress in KrF science and technology
See Frank Hegeler’s presentation SO4B-1

All solid state 10 Hz 180 kV 5KA pulse power system >10^7 shots continuous

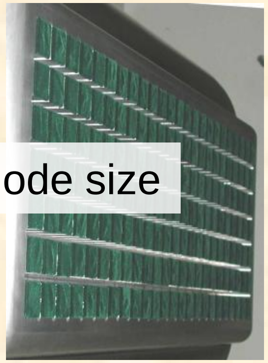
Components show > 300 M shots, no failures

Demonstrated two methods to suppress E-beam instability on Nike Main amplifier

No physics limit on diode size

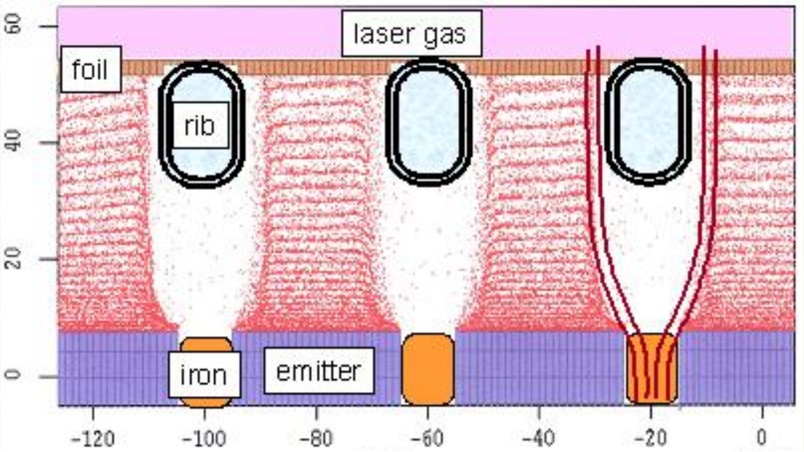


Ceramic Cathode



Patterned cathode

High efficiency E-beam transport to gas

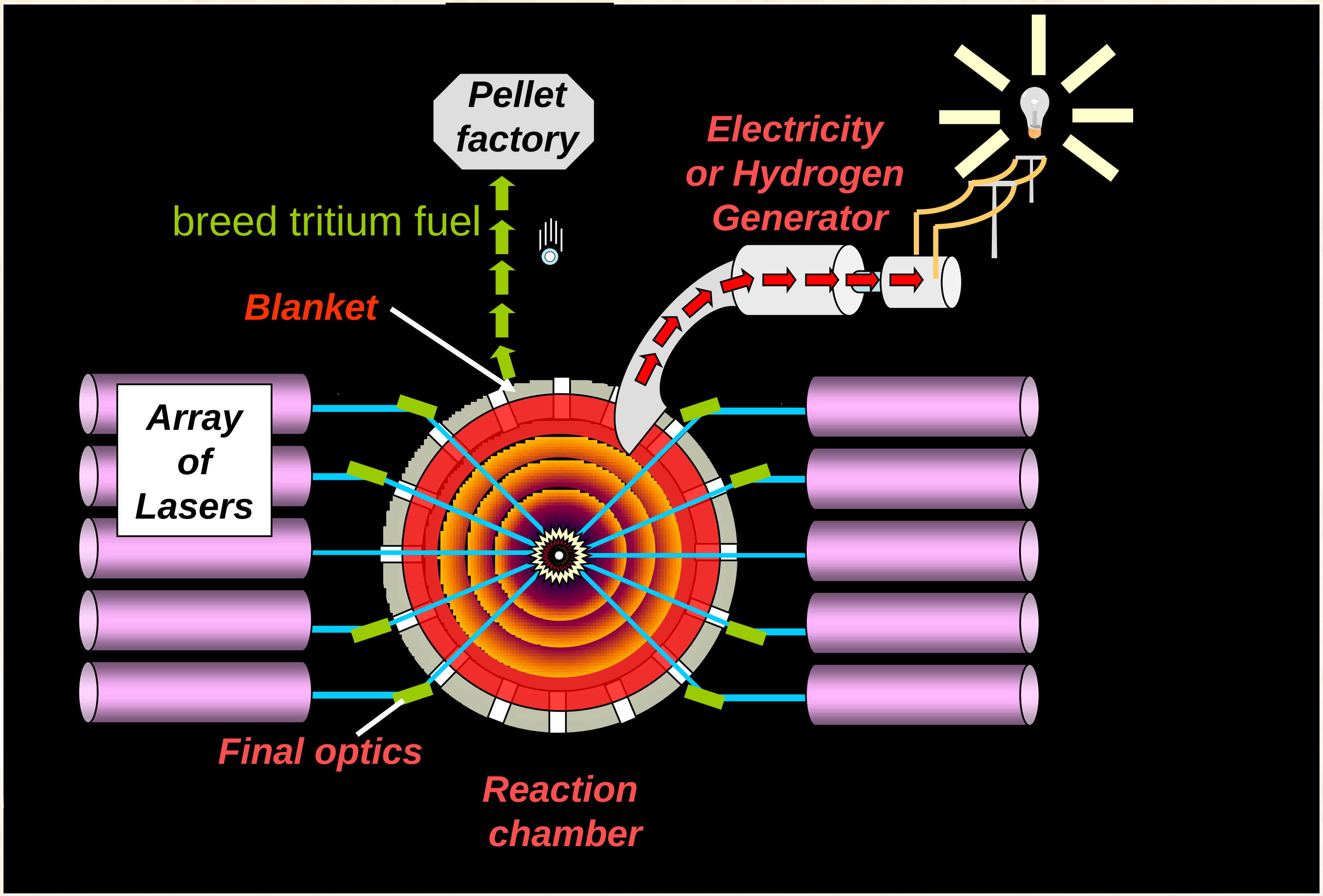


electron beam guided by tailored magnetic field

>7% wall-plug efficiency looks feasible.

Intrinsic (experiment)	12%
Pulsed power (experiment)	82%
Hibachi @ 800 kV (experiment)	80%
Optical train to target (est)	95%
Ancillaries (est)	95%
Global Efficiency	7.1%

A laser fusion energy power plant



Many components are modular and separable →
helps speed development and lower risk

The HAPL Program:
Integrated program to develop the science and technologies for Fusion Energy with Laser Direct Drive

19th HAPL meeting
Oct 22-23, 2008
Madison, WI
54 participants, 10 students

Government Labs
1. NRL
2. LLNL
3. SNL
4. LANL
5. ORNL
6. PPPL
7. SRNL

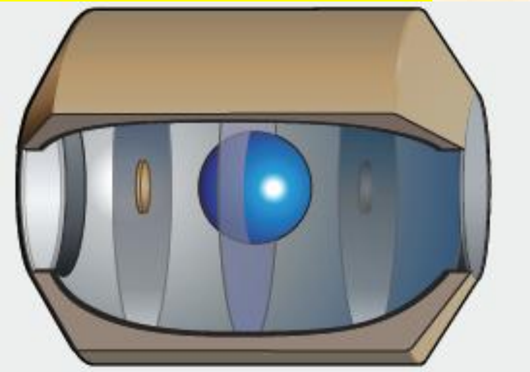
Universities
1. UCSD
2. Wisconsin
3. Georgia Tech
4. UCLA
5. U Rochester, LLE
6. UC Berkeley
7. UNC
8. Penn State Electro-optics

Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. APP
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

Direct Drive targets should be easier to make at low cost in volume prodtion needed for energy

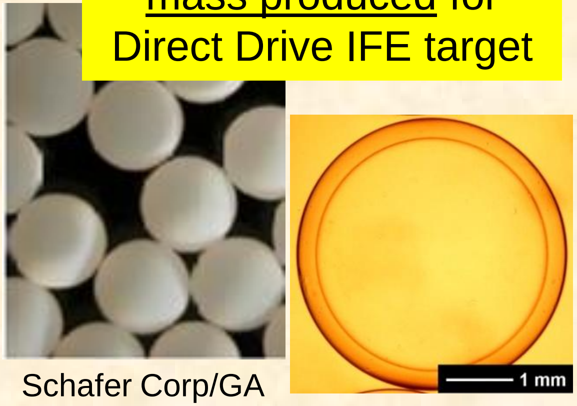
1. Simpler Target Fabrication

Concept for
Indirect Drive IFE



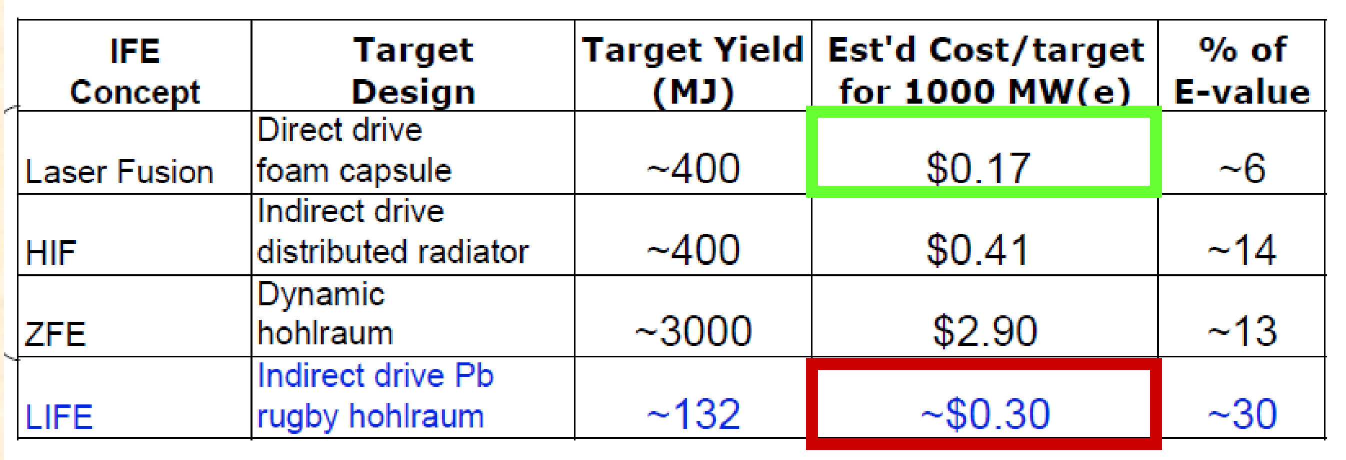
L. Latkowski, NAS Panel Presentation,
29 Jan, 2011

Foam shells,
mass produced for
Direct Drive IFE target



Schafer Corp/GA

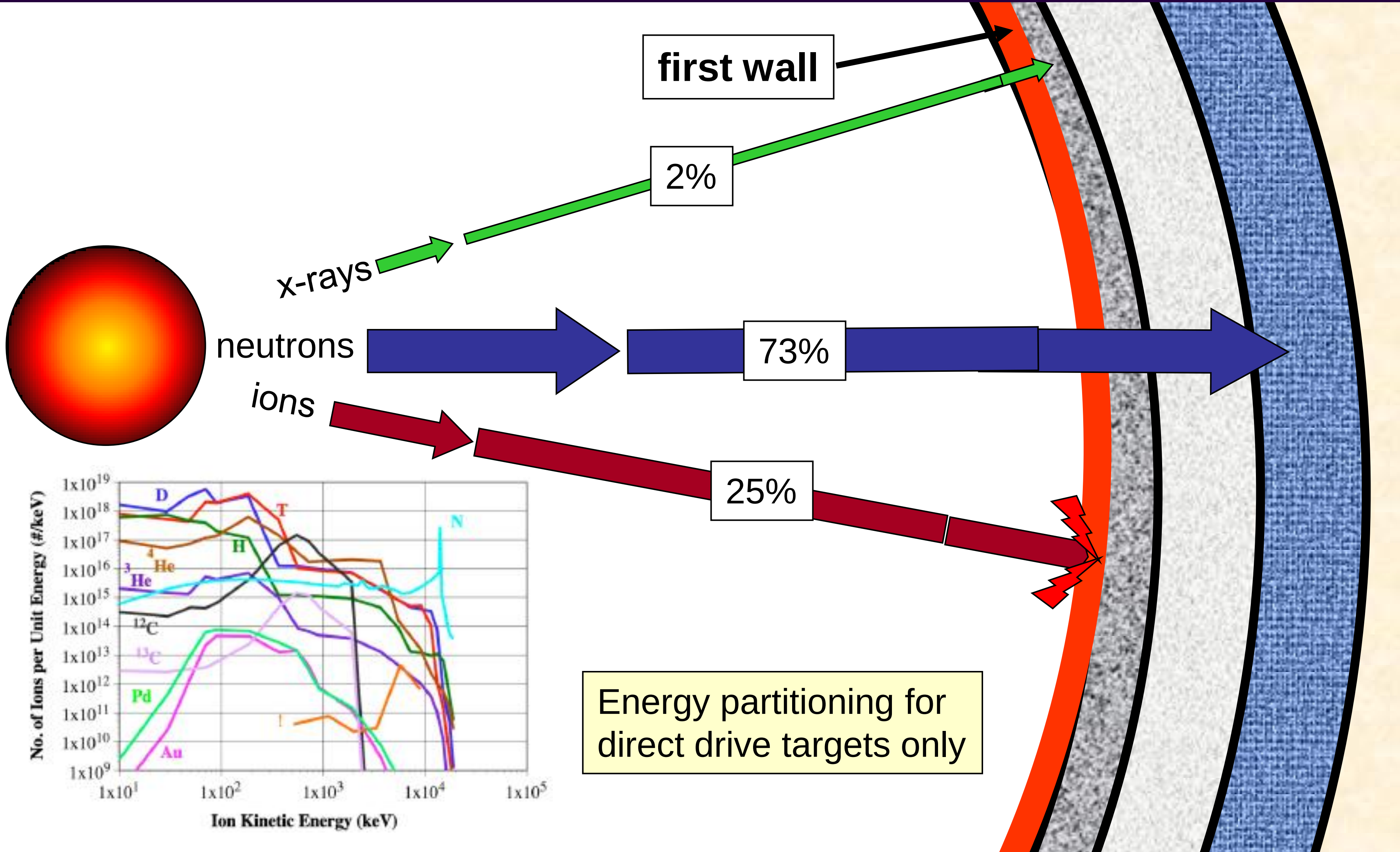
2. Lowest estimated cost



IFE Concept	Target Design	Target Yield (MJ)	Est'd Cost/target for 1000 MW(e)	% of E-value
Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
HIF	Indirect drive distributed radiator	~400	$0.41	~14
ZFE	Dynamic hohlraum	~3000	$2.90	~13
LIFE	Indirect drive Pb rugby hohlraum	~132	~$0.30	~30

Chart from D.T. Goodin, NAS Panel Presentation, 30 Jan, 2011

The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.

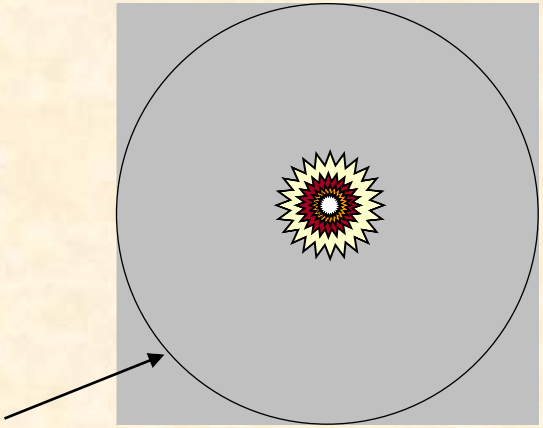


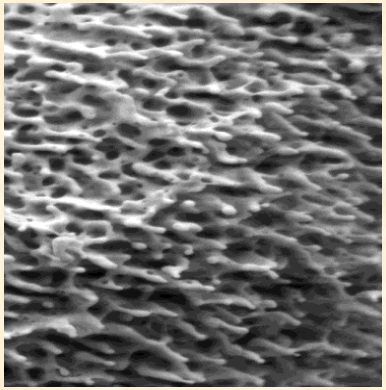
Energy partitioning for direct drive targets only

Chamber concepts to prevent damage from alphas

(pressure from helium bubbles exfoliates surface)

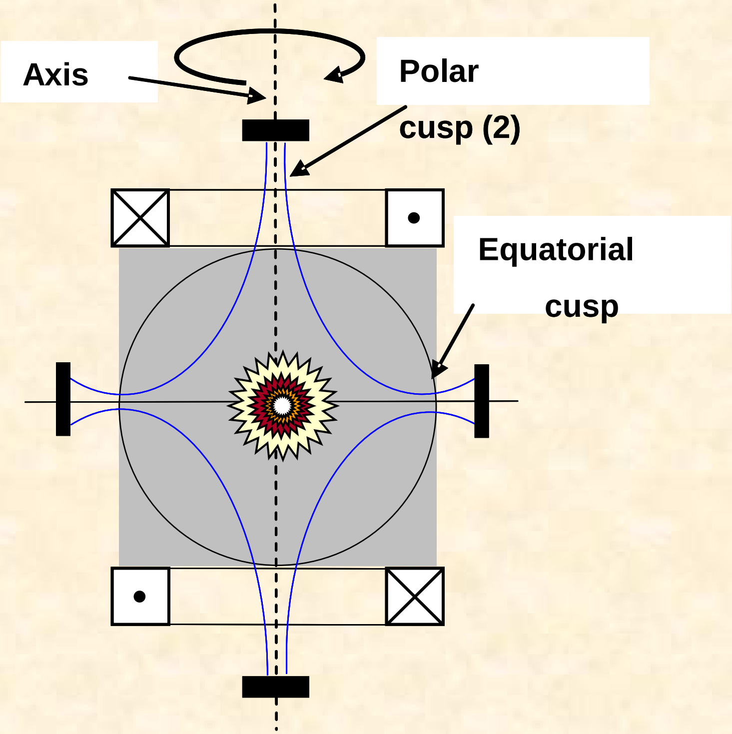
Engineered first Wall





Tungsten “foam” with cell size small enough for helium to escape

Magnetic Intervention



There are multiple approaches to IFE. (drivers, target configurations, reaction chambers designs).

“A phased (IFE) program with competition and unambiguous selection criteria is needed.”

Was one of nine consensus points agreed to by representatives from GA, LANL, LBNL, LLE, LLNL, NRL, and SNL in a discussion hosted by Mary Hockaday and presented to the NAS IFE review committee,

Fusion should be developed as a phased program, with well defined gates to advance to the next phase

Phase I:

Basic IFE Science and Technology

- High rep rate driver
- IFE target design
- IFE target physics
- Target fabrication
- Reaction Chamber
- Fusion materials

Phase II

Develop full size components

- Full scale driver module
- DEMO low cost mass target fabrication
- DEMO target engagement
- IFE ignition experiments
- Design Fusion Test Facility

Phase III

Fusion Test Facility

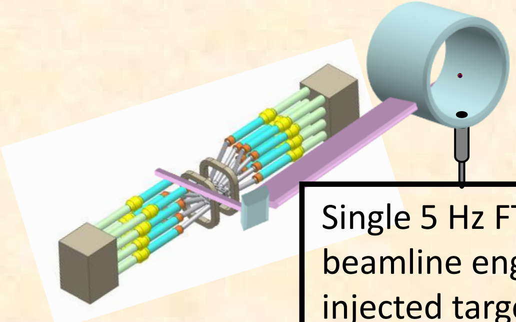
- Demonstrate integrated physics / technologies for a power plant.
- Tritium breeding, fusion power handling.
- Develop/ validate fusion materials and structures.
- **READY FOR PILOT POWER PLANT**

Increasing size
Increasing performance
Decreasing scientific risk
Increasing Industry Partnership

Some particulars of a Phased program with KrF

Complete Phase I:

- Install solid-state pulse power on Electra system
- Demonstrate long continuous runs (e..g >500J, >100 hours
- Complete auxiliary IFE S&T efforts begun by HAPL
- Design full scale beamline.
- Refine target design and physics



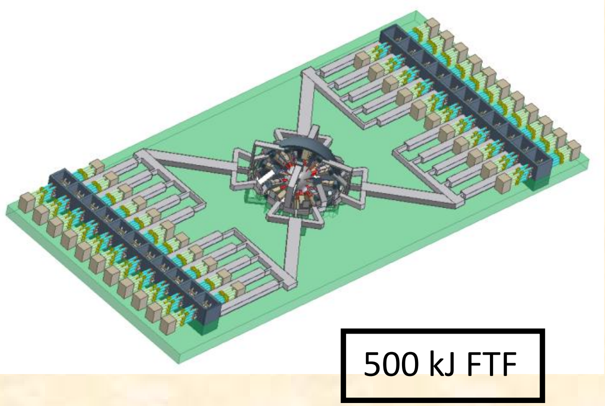
Single 5 Hz FTF beamline engages injected targets

Phase II : Develop full size components (~5 years)

- Develop full scale KrF laser beamline (e.g. 18 kJ, 5 Hz KrF beamline)
- Engage injected targets with beamline.
- Increased efforts in all critical IFE technologies
- Develop high confidence in pellet designs & physics

Phase III Fusion Test Facility (FTF)

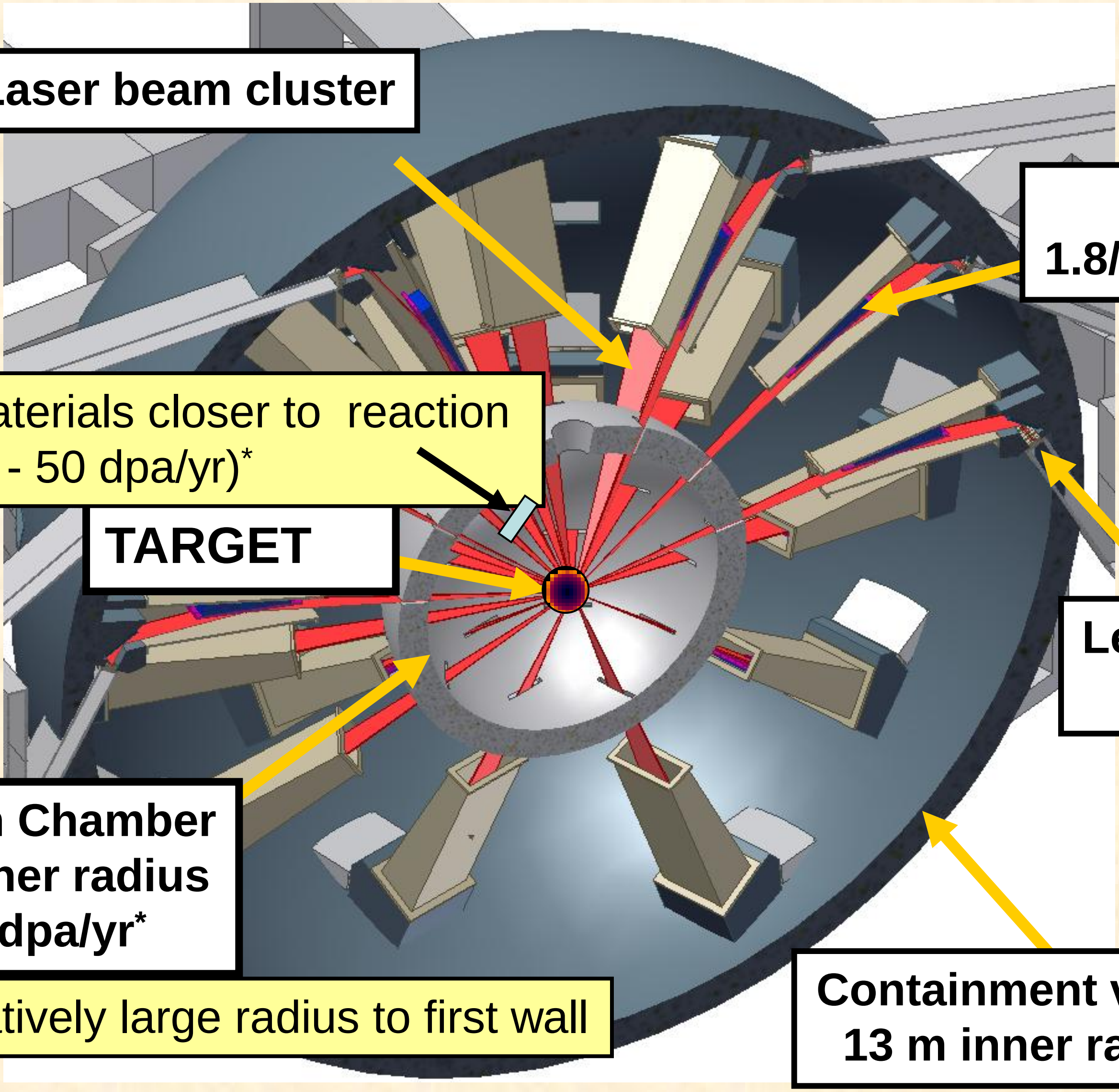
- 500 kJ 5 Hz KrF system utilizing shock ignition.
- 250 MW fusion power
- Develop/ validate fusion materials and structures
- Significant participation by private industry



500 kJ FTF

The FTF Chamber (conceptual)

*dpa assumes 70% availability, 250 MW Fusion Power, 70% in neutrons



Laser beam cluster

GIMM
1.8/3.4 J/cm^2

Introduce test materials closer to reaction
(10 - 50 dpa/yr)*

TARGET

Lens/window
1.0 J/cm^2

Reaction Chamber
5.5 m inner radius
= 3.2 dpa/yr*

Conservatively large radius to first wall

Containment vessel
13 m inner radius

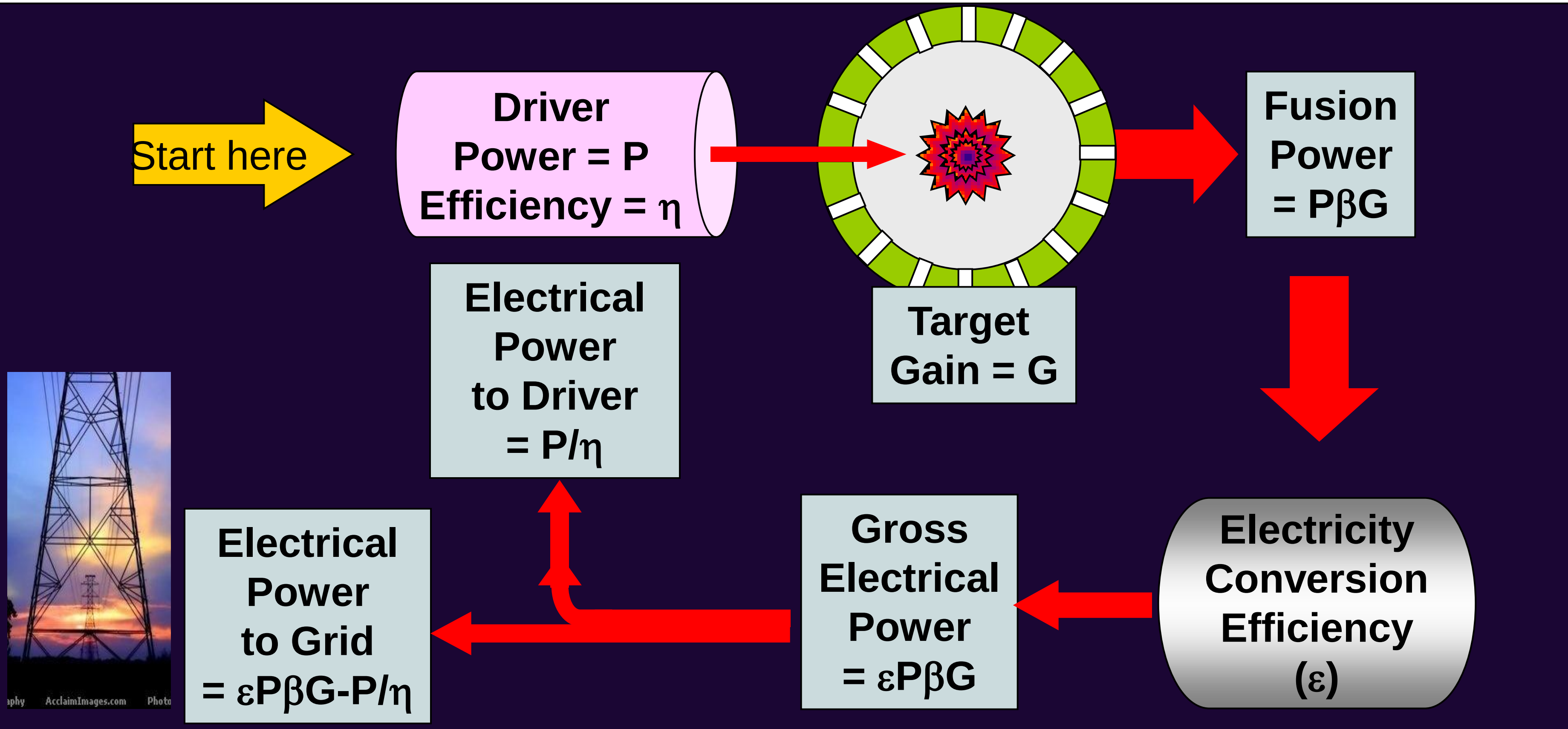
Summary

- Combination of the KrF lasers with shock ignition looks particularly attractive for achieving the target performance required for IFE
- Advances in the KrF technology have defined a development path where it should meet the demanding requirements for an IFE driver.
- A phased program aimed a developing a Fusion Test Facility could resolve the remaining technical issues.

BACKUPS

The target has to have enough gain to power the reactor…AND produce electricity for the grid

ε = conversion efficiency, η = driver efficiency, G = gain, β = Burnup in blanket



Electrical Power to Grid = P/η ((1/f) -1))

f = 1/εηβG ≡ Recirculating Power Fraction

References

Laser Inertial fusion energy technology

J.D. Sethian et al, “The science and technologies for fusion energy with lasers and direct drive targets,” Proceedings, 23rd Symposium on Fusion Engineering. *IEEE Transactions on Plasma Science*. Vol. 38, NO. 4, 690 (2010).

High Average Power :Laser Program http://aries.ucsd.edu/HAPL

Shock Ignited direct drive designs

A. J. Schmitt, J.W. Bates, S. P. Obenschain, S T. Zalesak and D. E. Fyfe, " Shock Ignition target design for inertial fusion energy, *Physics of Plasmas* 17,042701 (2010).

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Fusion Test Facility (FTF) utilizing a KrF laser

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R. H. Lehmberg, J. L. Guiliani, and A.J. Schmitt, “Pulse shaping and energy storage capabilities of angularly multiplexed KrF laser fusion drivers,” *Journal of Applied Physics* **106**, 023103 (2009).