Direct Drive Utilizing Shock Ignition: physics and its potential IFE application

International Workshop on ICF Shock Ignition
Laboratory for Laser Energetics
Rochester, NY
8 March 2011

Presented by:
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Naval Research Laboratory

Work by the NRL laser fusion research team

Work supported by: the Office of Naval Research and the U.S. Department of Energy, NNSA.

Opening remarks shock ignition and its application to IFE

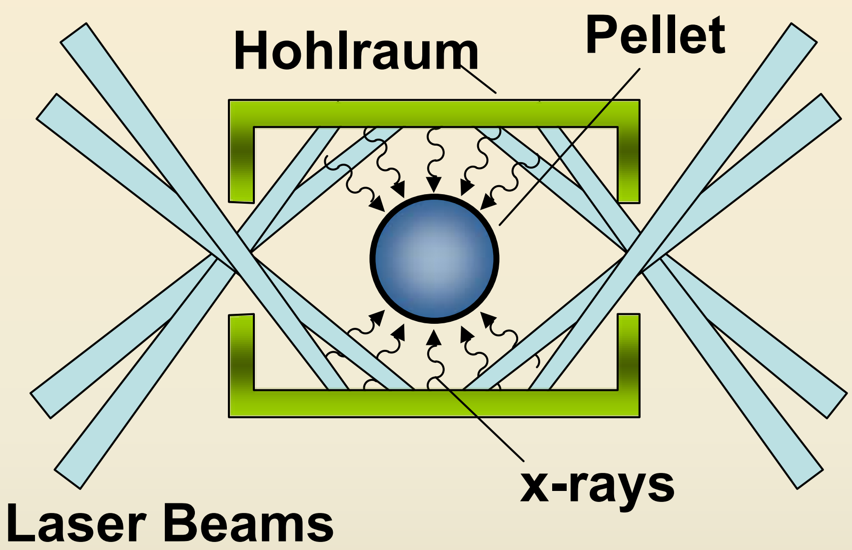
- Shock ignition provides potential much higher gain and reduced susceptibility to hydrodynamic instability than conventional central ignition implosions.
- NRL laser fusion program has adopted SI as its primary approach towards obtaining target performance needed for Inertial Fusion Energy (IFE).
- Nevertheless there are challenges to be resolved – particularly effects of laser plasma instability (LPI).
- Use of a KrF laser provides physics advantages for reducing the risks and increasing the target performance with SI.
- KrF's demonstrated performance is competitive with solid state lasers as a high-rep-rate durable, efficient IFE driver. (on several important parameters KrF technology leads).
- Credible solutions for the other critical direct-laser-drive IFE science and technologies such as target fabrication, target injection, final optics and reaction chambers have been identified, and in many cases demonstrated on laboratory scale tests. (via HAPL program.

Outline

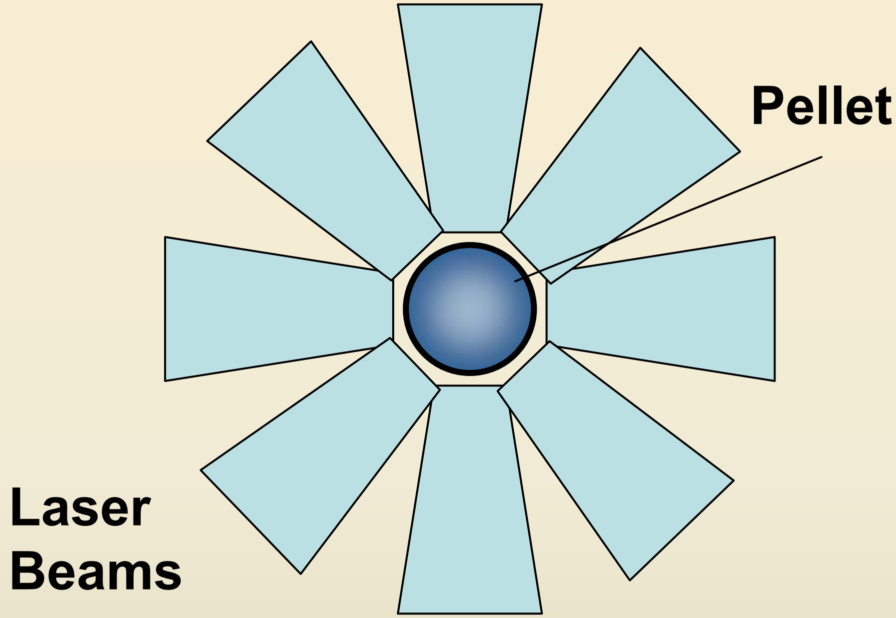
- High gain direct-drive target designs utilizing shock ignition and advantages to using short laser wavelengh (e.g. KrF).
- Supporting experiments
- Status of KrF technology
- Status of Direct Drive technologies (promising avenues have been indentified for target fabrication, injection, reaction chambers)

Direct Laser Drive is a better choice for Energy

Indirect Drive (initial path for NIF)



Direct Drive (IFE)



- ID Ignition being explored on NIF
- Providing high enough gain for pure fusion energy is challenging.

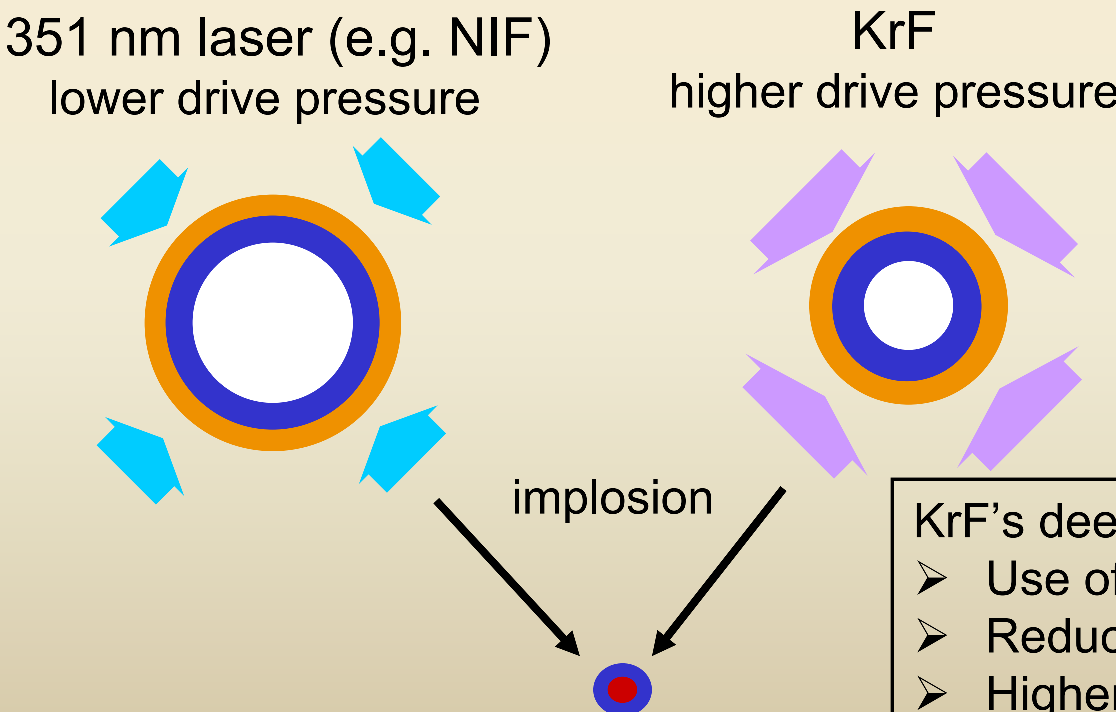
..

- DD Ignition physics can be explored on NIF.
- More efficient use of laser light, and greater flexibility in applying drive provides potential for much higher gains.

KrF light helps Direct Drive target physics (1)

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

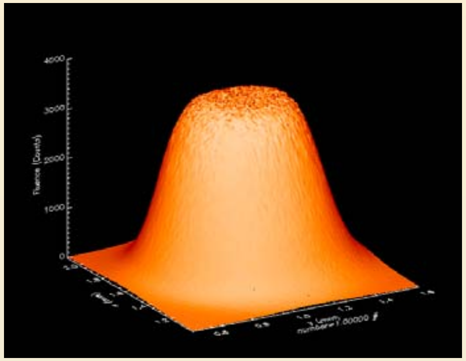
Deeper UV →
- Higher thresholds for laser-plasma instability
- Higher mass ablation rates and pressure
- Higher hydrodynamic efficiency
- Higher absorption fraction



KrF's deep UV allows:
- ➢ Use of lower aspect ratio targets
- ➢ Reduced growth of hydro-instability
- ➢ Higher energy gain
- ➢ Use of less laser energy

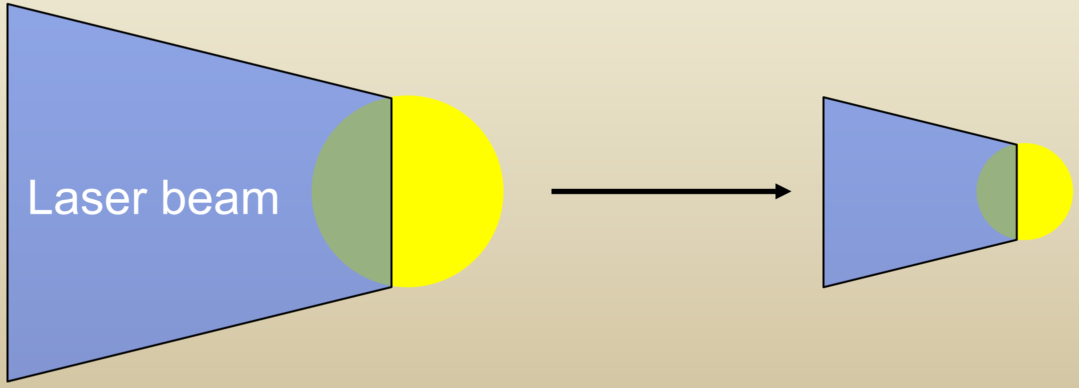
KrF Light helps the target physics (2)

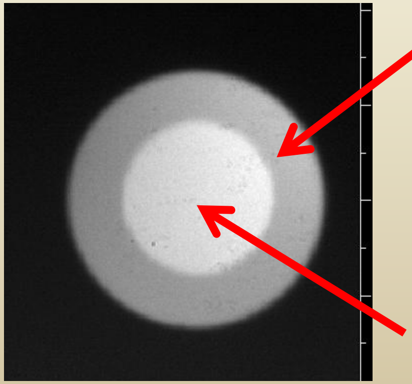
- KrF has most uniform target illumination of all ICF lasers.
  - **Reduces seed for hydrodynamic instability**



Nike KrF focal profile
Bandwidth up to 3 THz

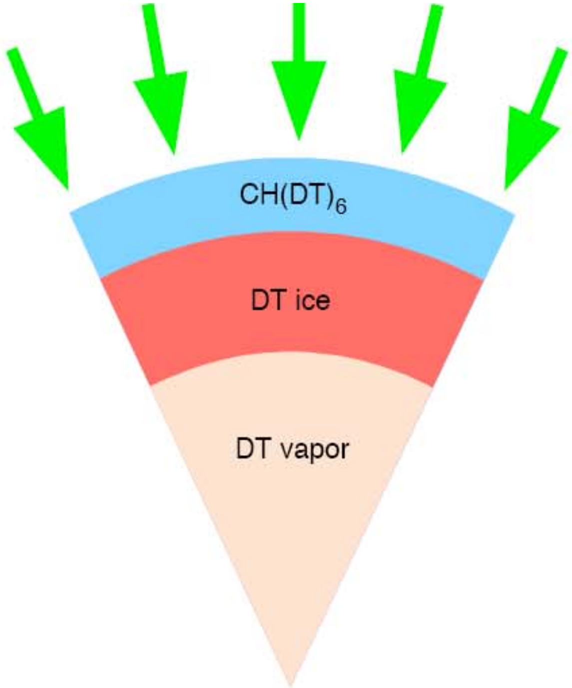
- KrF focal profile can zoom to "follow" an imploding pellet.
  - **More laser absorbed, reduces required energy by 30%**

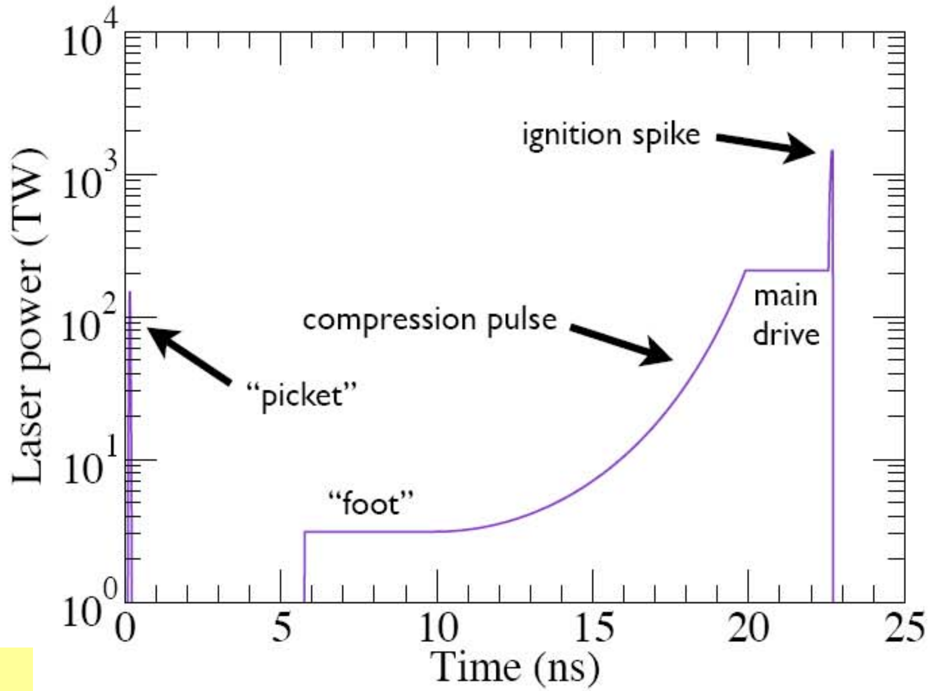




Shock Ignited (SI) direct drive targets*

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.





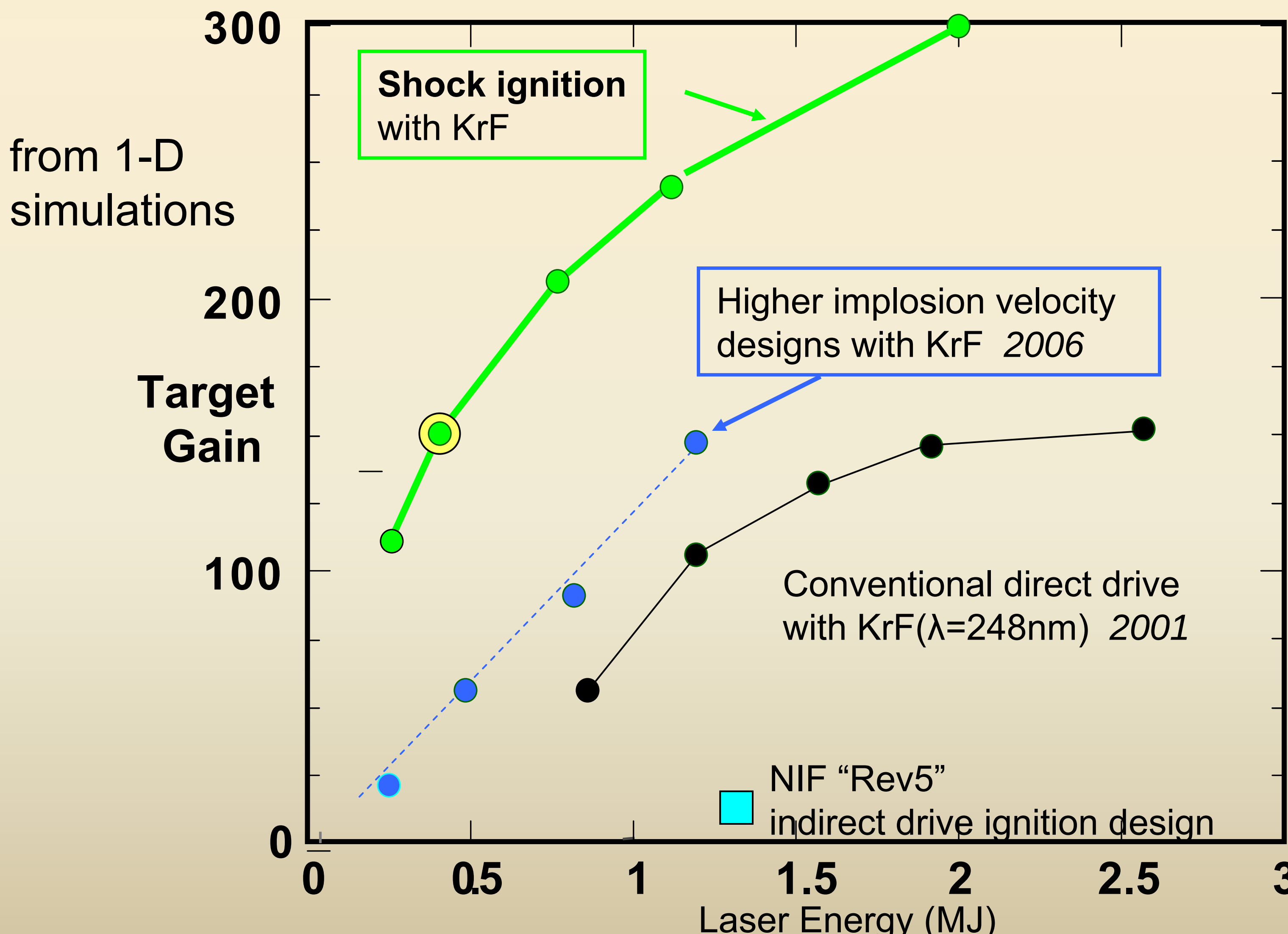
Low aspect ratio pellet helps mitigate hydro instability

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

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

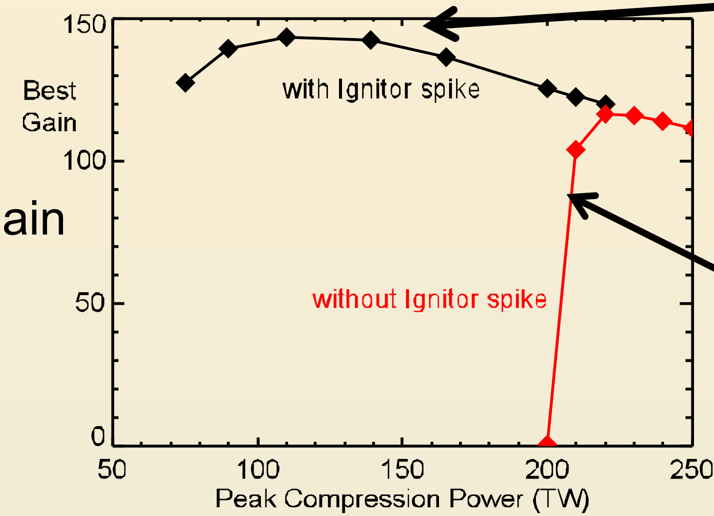
* *R. Betti et al., Phys.Rev.Lett.* ***98****, 155001 (2007)*

Gain curves show progress in direct-drive target designs



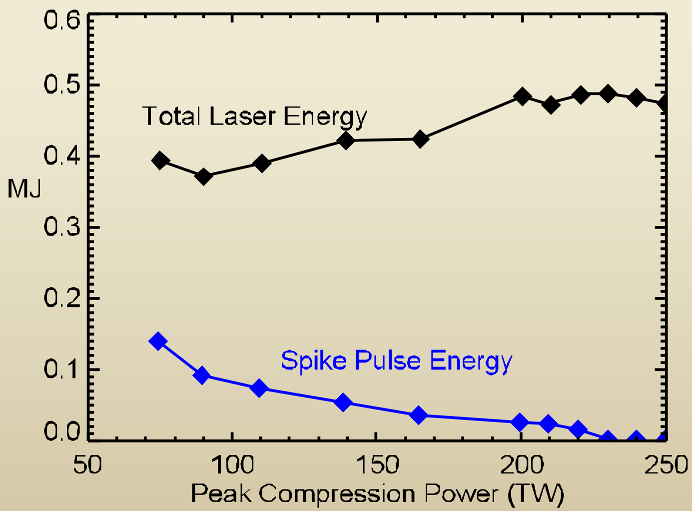
Shock Ignition connects continuously to conventional direct drive implosions.

Gain



Shock Ignition (SI)
(NRL "Scale 2" target)

"Conventional" direct drive
(with similar adiabat to SI)

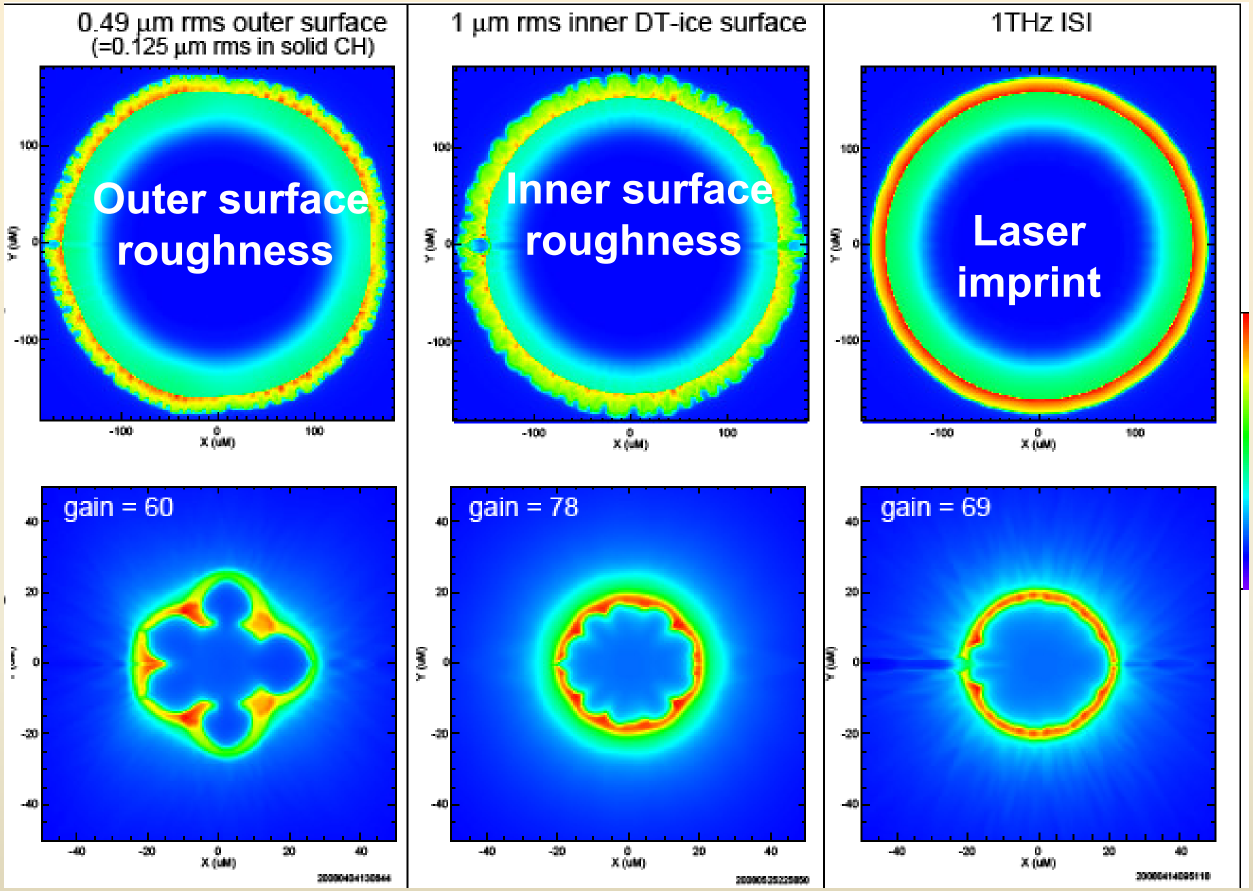


- Shock ignition provides more gain than a similar adiabat conventional implosion..
- One can trade off intensity of the igniter spike against main drive intensity (implosion velocity)

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

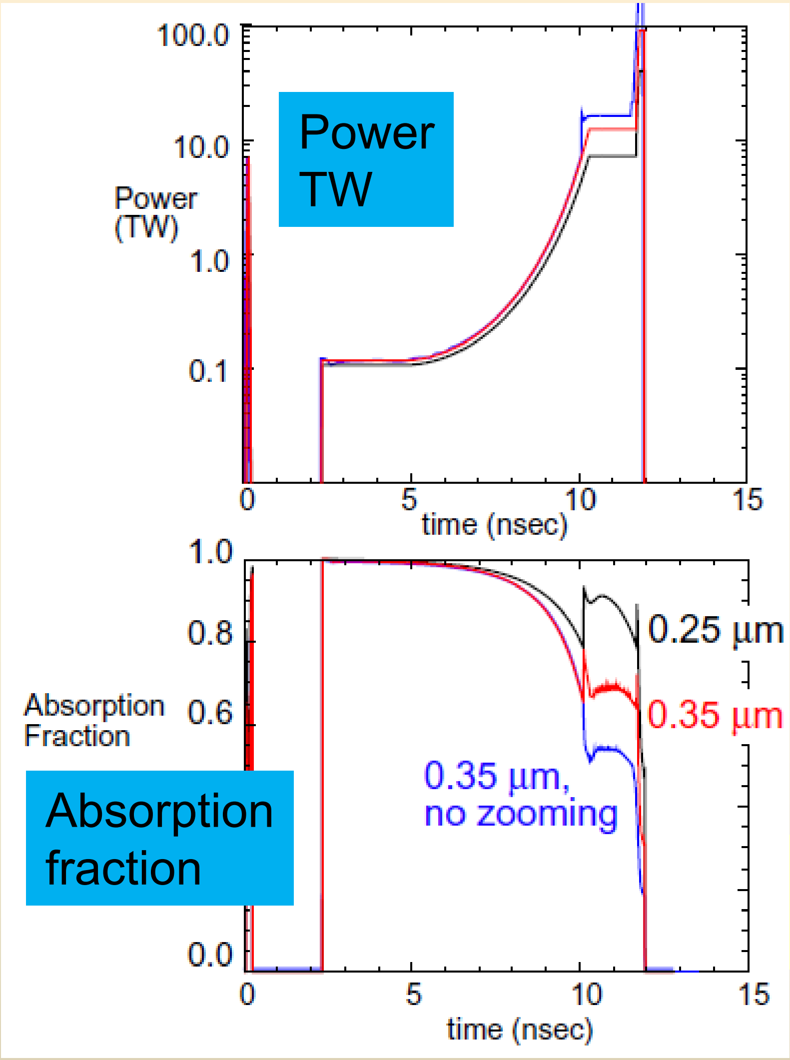
G ~250 with a 2 MJ KrF laser

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

η = laser wall plug efficiency $\cong$ 7% for KrF

→ need $G \geq 140$

Shock ignition benefits from shorter λ and zooming

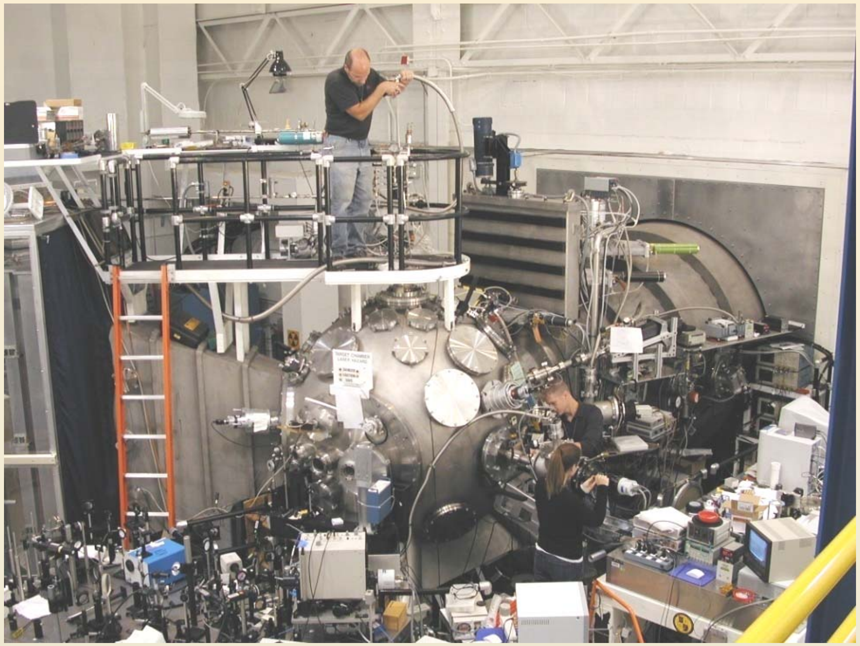


1-D Hydrocode simulations
Fixed low aspect ratio pellet

	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
- Lower risk from laser plasma instability

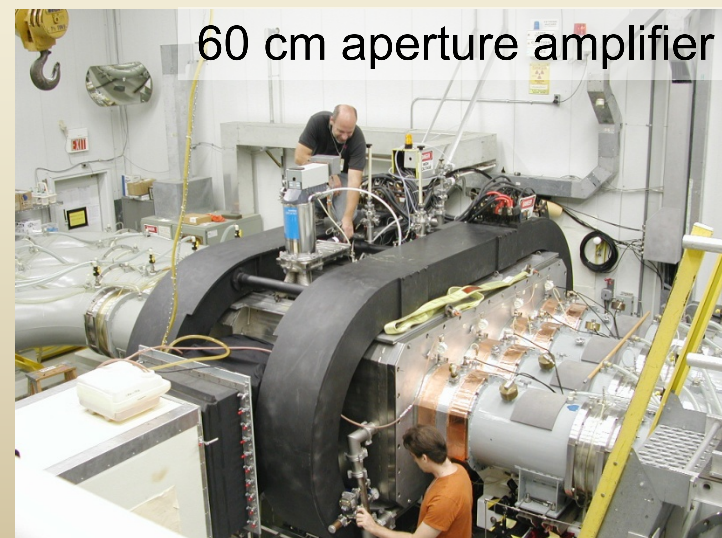
Nike krypton-fluoride laser target facility



Nike Target chamber

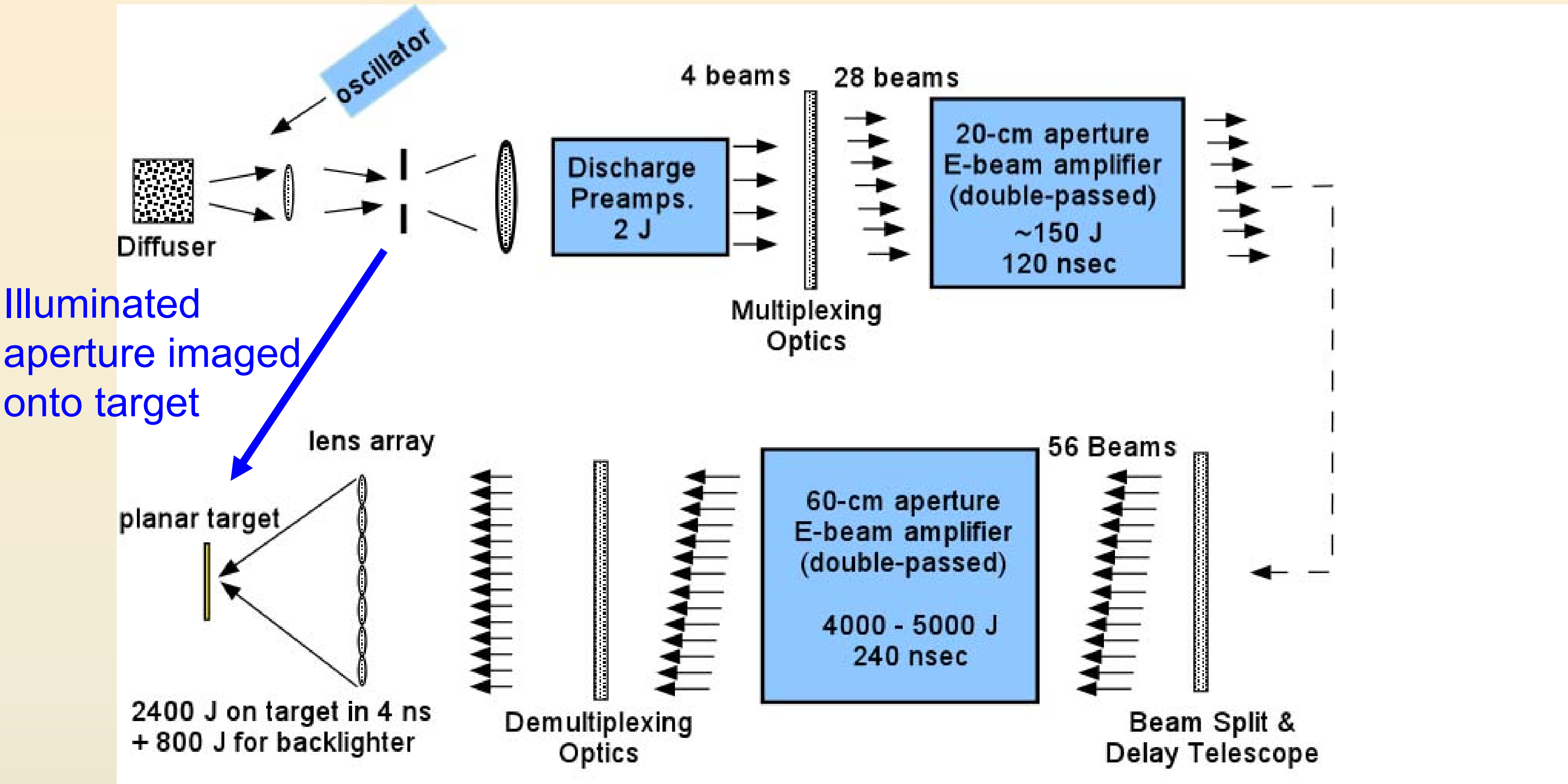
56-beam 3-kJ
KrF laser-target facility

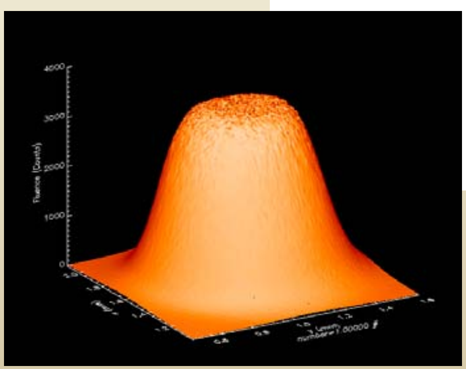
Target chamber optics



60 cm aperture amplifier

Nike laser Chain



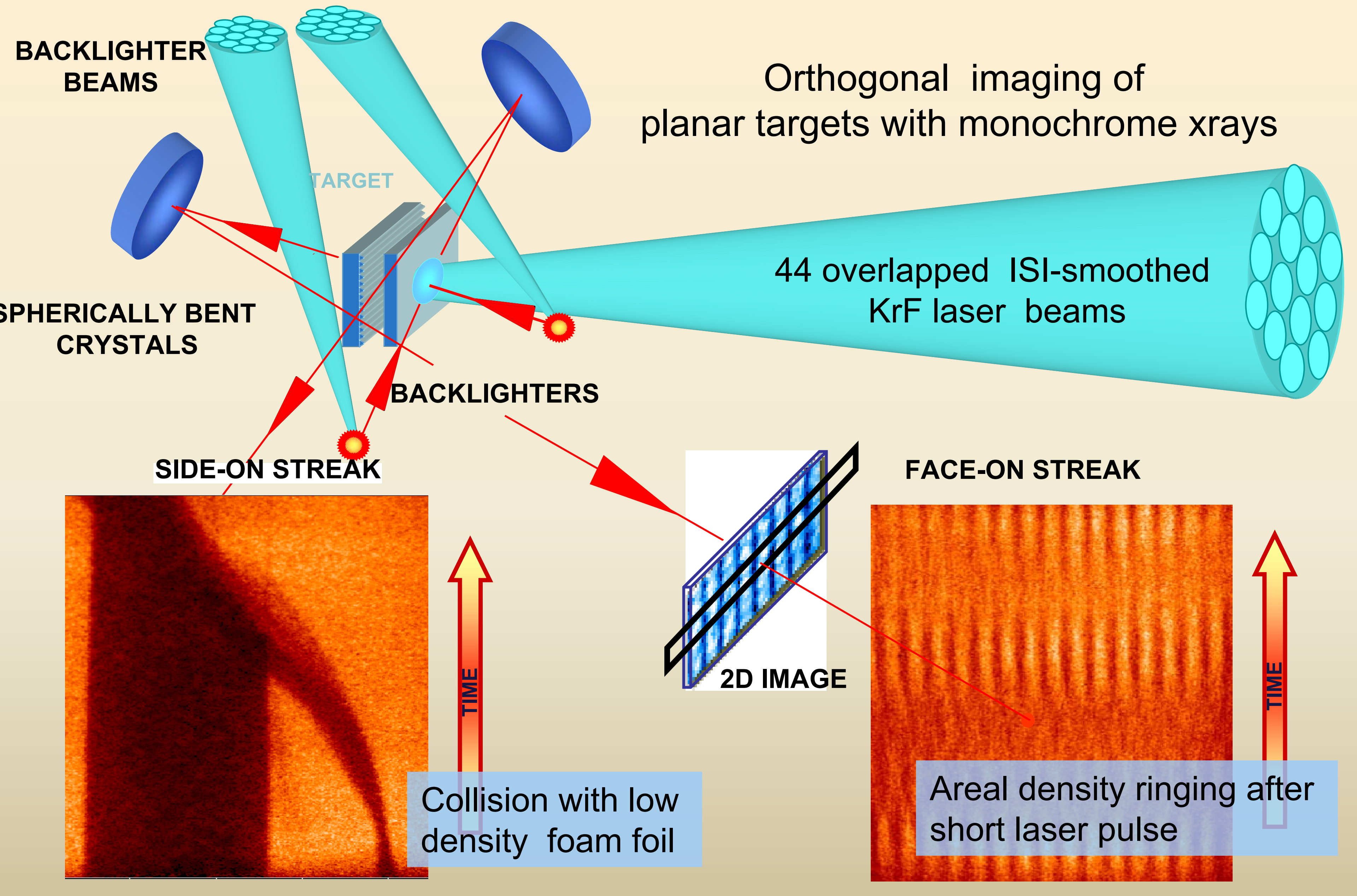


Overlap of 44 beams provides additional smoothing

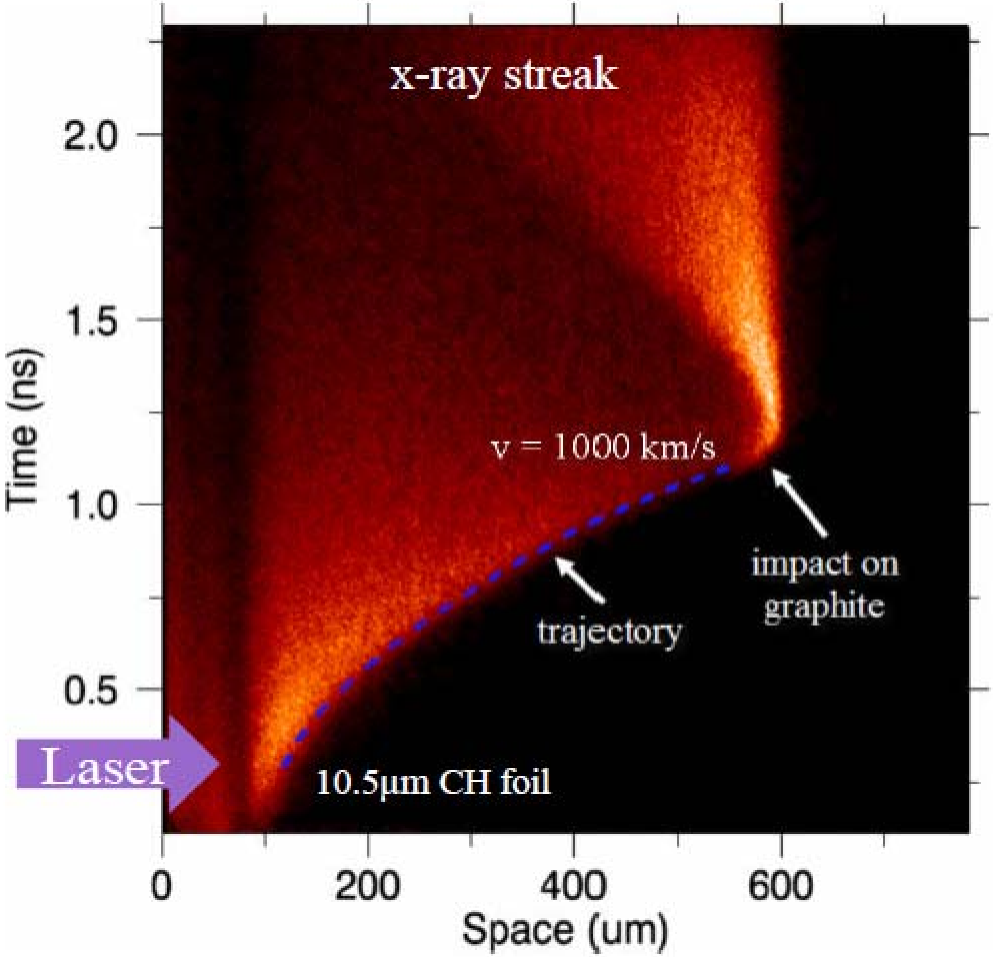
$\langle \Delta I/I \rangle \cong 0.2\%$

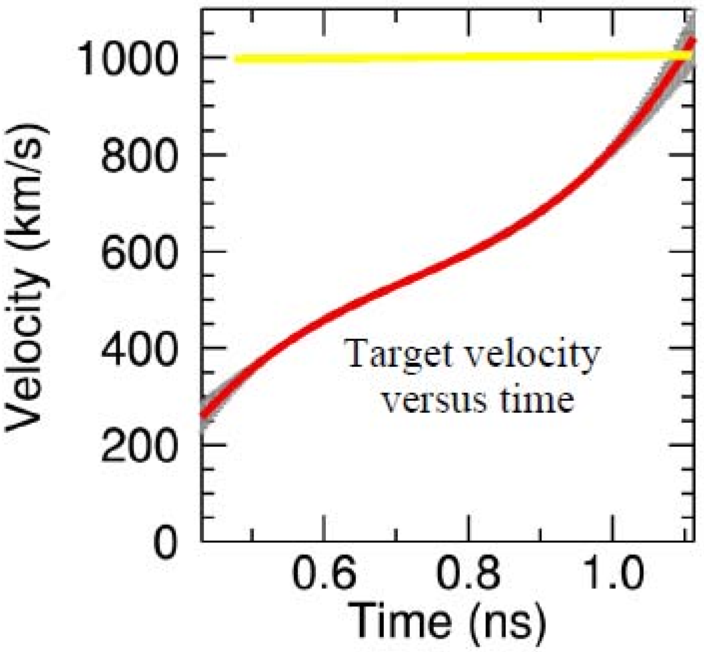
Laser profile in target chamber

Nike is employed for studies of hydrodynamics and LPI



Target accelerated to 1000 km/sec using Nike

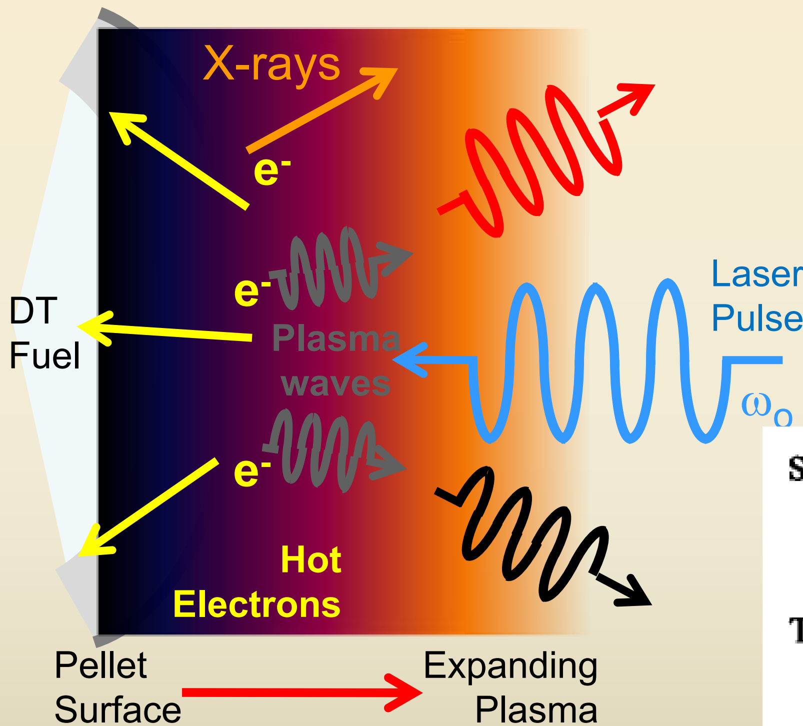




Joint experiment in support of impact ignition with the Institute for Laser Engineering, Osaka University

Laser Plasma Instability limits the maximum intensity

- ➢Can produce high energy electrons that preheat DT fuel
- ➢Can scatters laser beam, reducing drive efficiency



Shorter λ suppresses LPI

$$(V_{osc}/v_{the})^2 \sim I\lambda^2$$

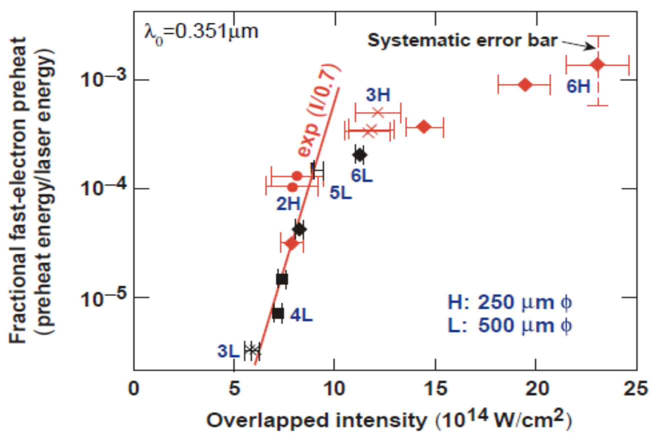
$N_c/4$ instability thresholds (single planar beam)

Stimulated Raman scatter ($n \approx 1/4\ n_{cr}$)	$I_t \approx \frac{5\times 10^{16}}{L_n^{4/3}(\mu m)\lambda_0^{2/3}(\mu m)} \frac{W}{cm^2}$
Two plasmon decay	$I_t \approx \frac{5\times 10^{15}}{L_n(\mu m)\lambda_0(\mu)} \theta_{keV} \frac{W}{cm^2}$

Both Nike and OMEGA experiments' quarter critical instability thresholds are approximate agreement with planar beam $2\omega_p$ theory

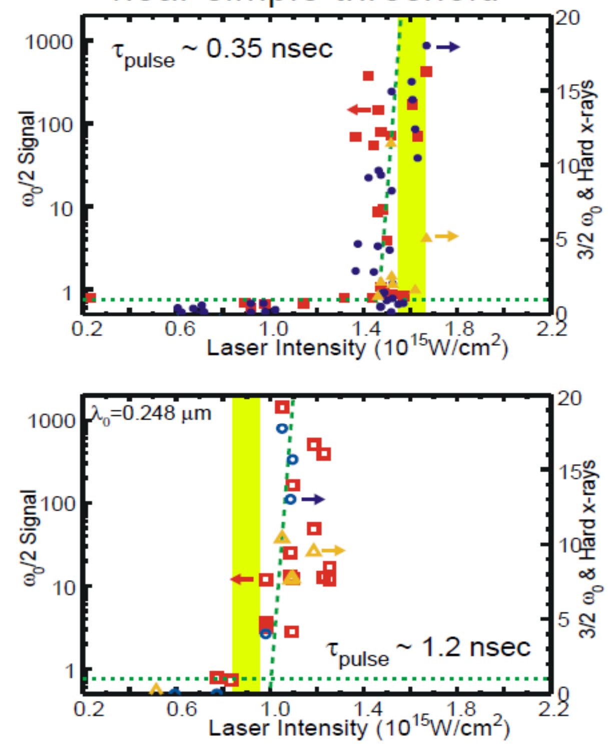
- Theory does not account for ISI/SSD & beam overlap nor saturated levels.
- Direct-drive ignition targets will likely operate above this theoretical threshold.

Omega experiments show $2\omega_{pe}$ near simple threshold



Stoeckl, et al., Phys. Rev. Lett. **90** *235002 (2003), and Anomalous Absorption Conf. 2003*

Nike experiments also show $2\omega_{pe}$ near simple threshold



predicted $I/I_{2\omega pe\text{-}threshold}$

$$I_{15} \sim 80 \frac{T_{kev}}{\lambda_{\mu m} L_{d,\mu m}}$$

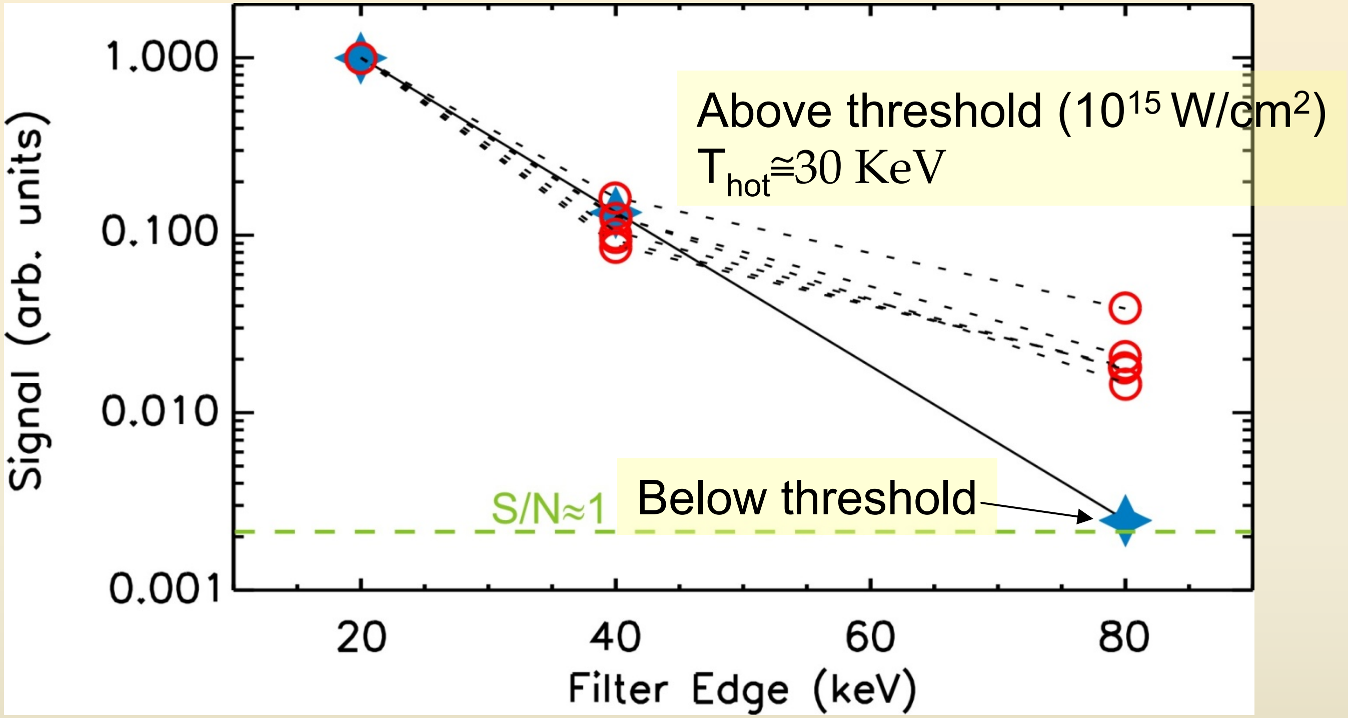
based on plane EM wave linear plasma ramp analysis

Unresolved:
Will simple formula continue to hold?
If over threshold, will LPI harm gain?

A critical issue is the number and temperature of hot electrons

Nike planar LPI experiments with 1 ns pulse

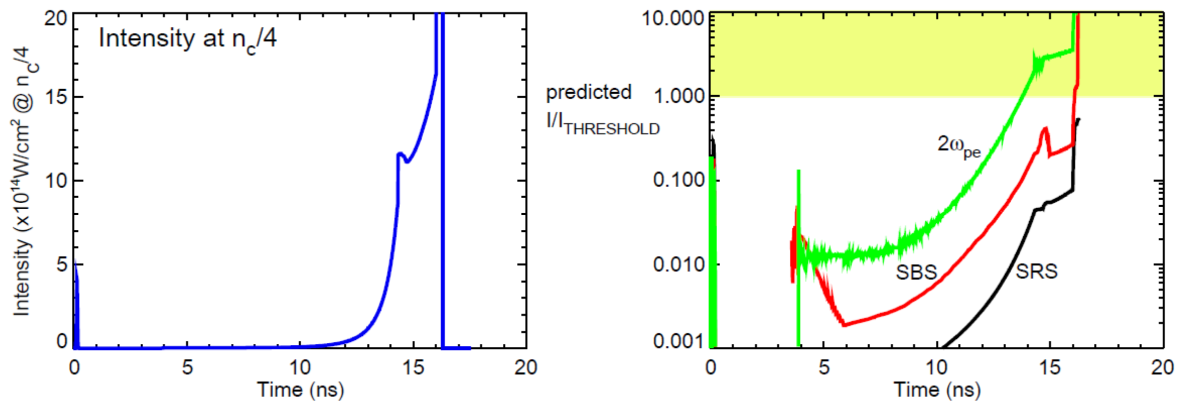
X-ray signal



T_{hot} with 248 nm and ISI beam smoothing **may** be lower than that typically observed with 351nm and SSD beam smoothing.

Shock ignition targets can be above quarter critical instability threshold during compression.

Example with 500 kJ KrF driver



predicted $I/I_{2\omega pe\text{-}threshold}$

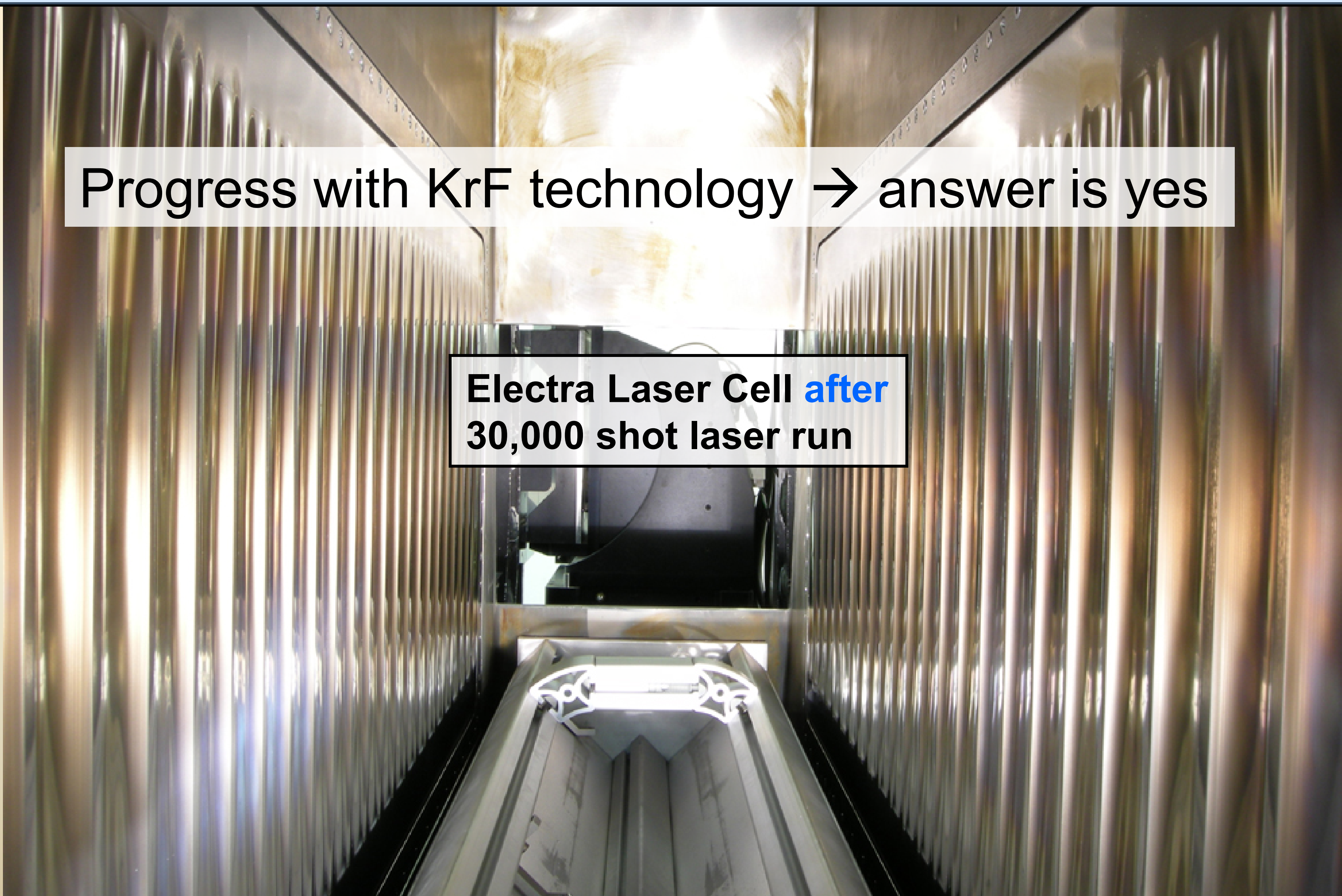
$$I_{15} \sim 80\,\frac{T_{kev}}{\lambda_{\mu m}\,L_{d,\mu m}}$$

based on plane EM wave linear
plasma ramp analysis

- Can be operate above this theoretical LPI threshold ?
- Will thresholds follow theory with SI plasma ?
- Above threshold could be acceptable if hot electron preheat of fuel is low enough.
- I f not: reduce intensity during compression and use larger aspect ratio targets.

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

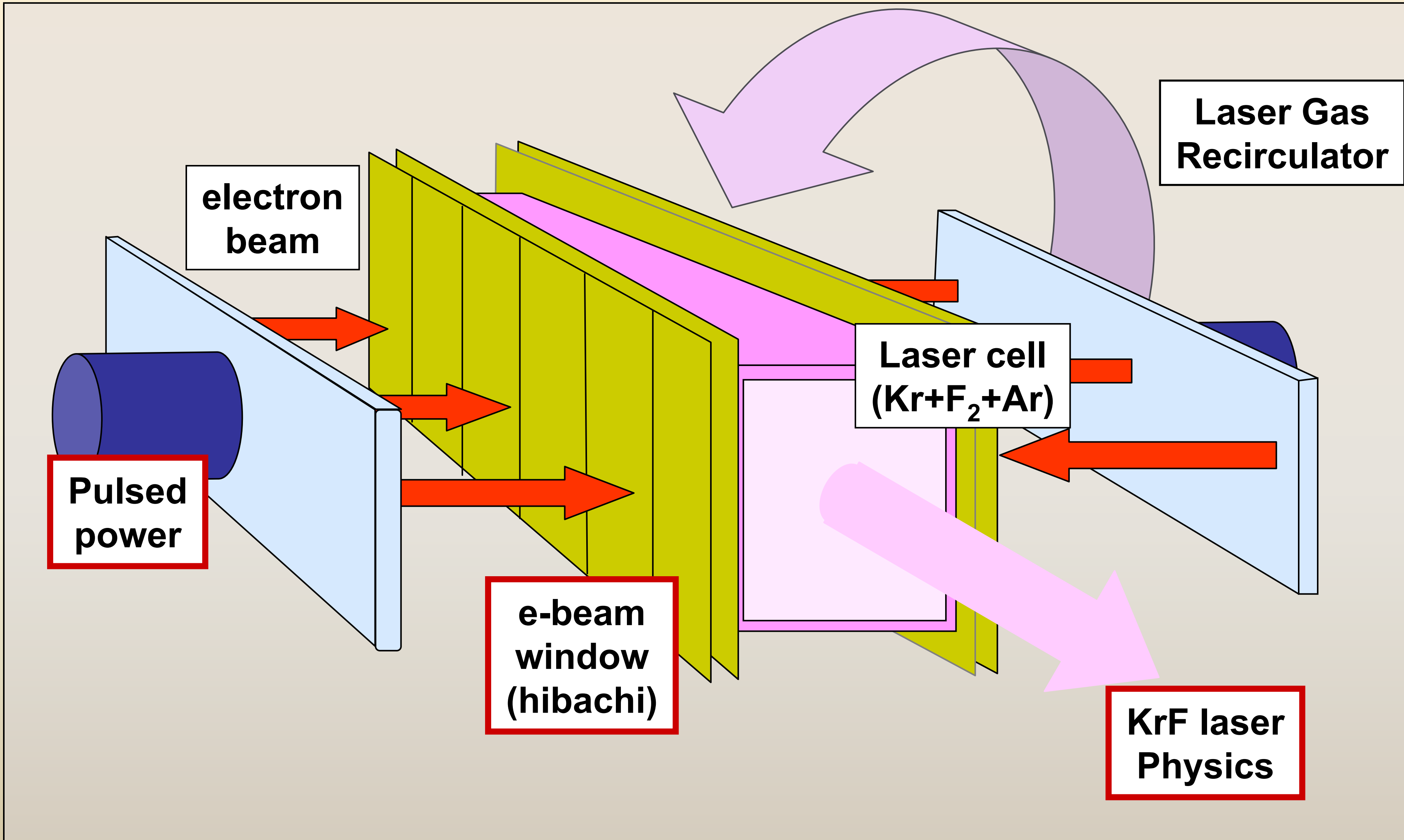
Laser Fusion



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

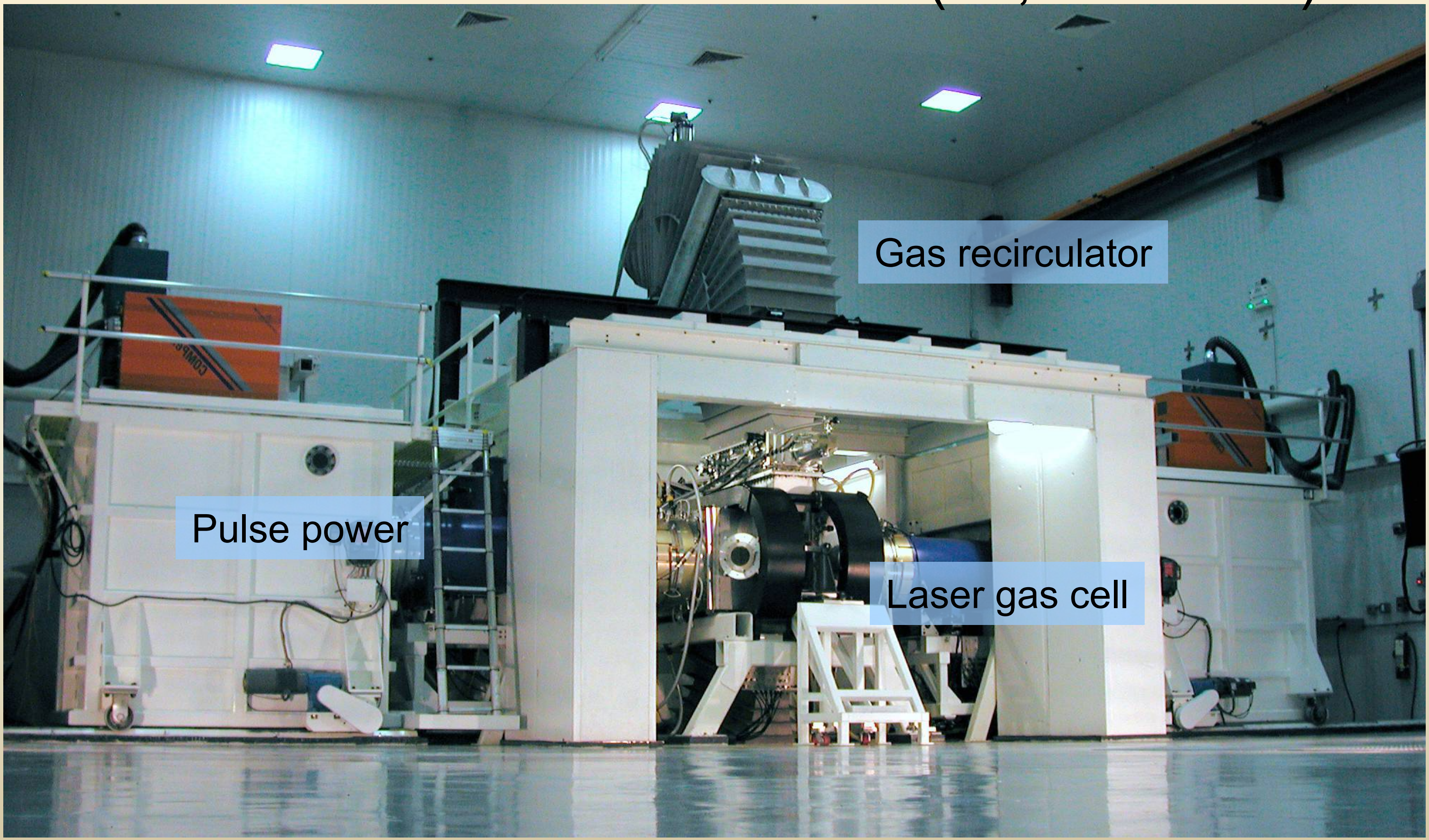


Electra Krypton Fluoride (KrF) Laser

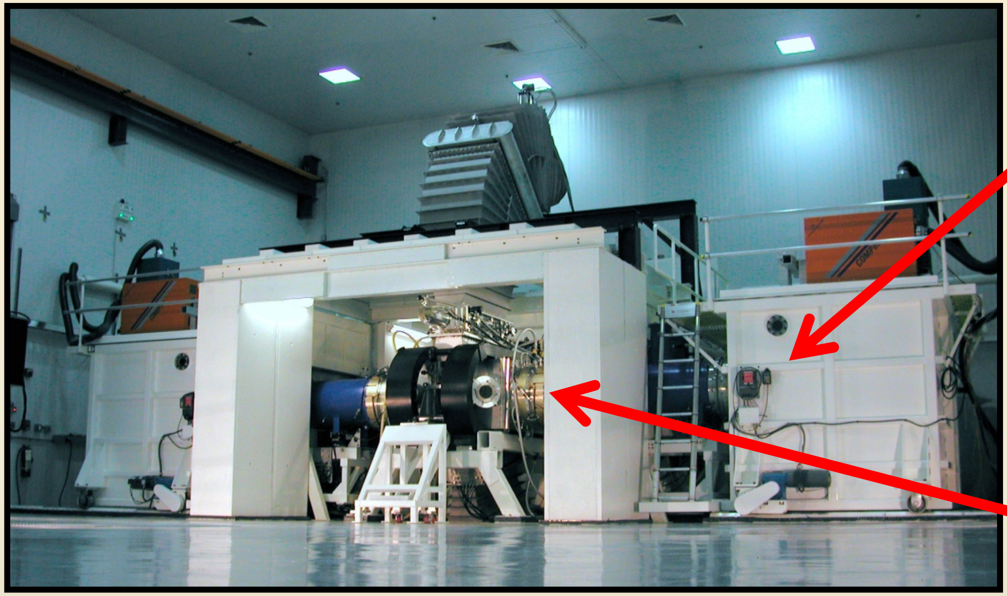
Laser Energy: 300 to 700 Joules

Repetition rate: up to 5 pulses per second

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



Path to much higher durability for Electra identified and developed.



Replace spark-gap switched pulse power with all solid state system.

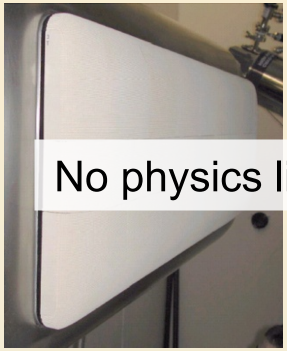
Understand and control late time plasma closure between anode and cathode which causes erosion.

Progress in KrF science and technology

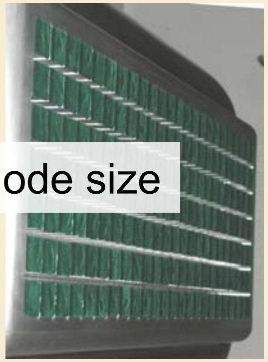
All solid state 10 Hz 180 kV 5KA pulse power system >10^7 shots continuous

Components show > 300 M shots, no failures

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



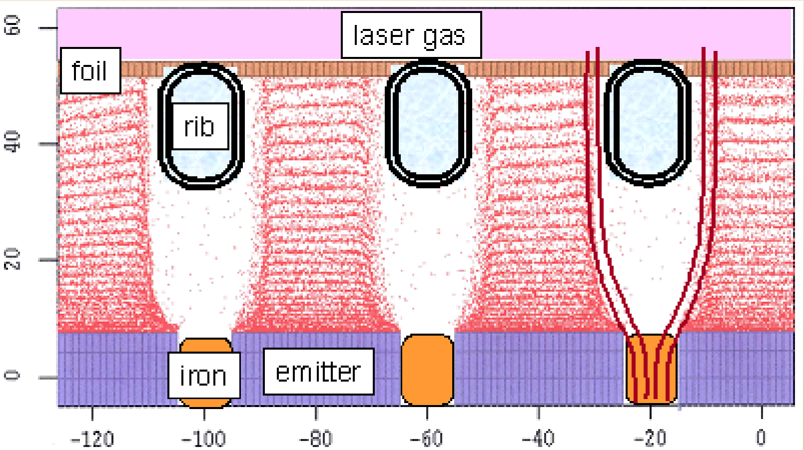
No physics limit on diode size



Ceramic Cathode

Patterned cathode

High efficiency E-beam transport to gas

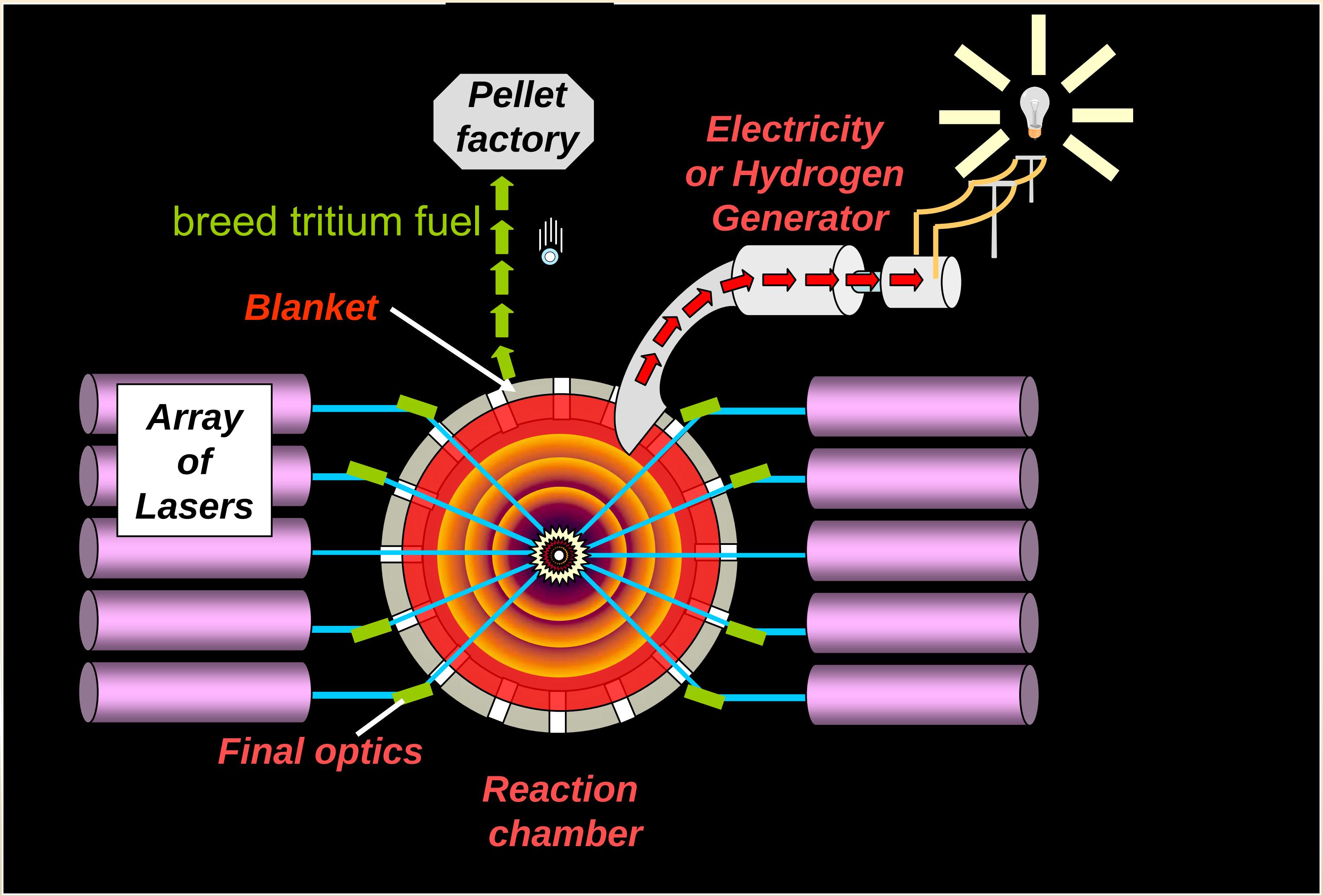


electron beam guided by tailored magnetic field

>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

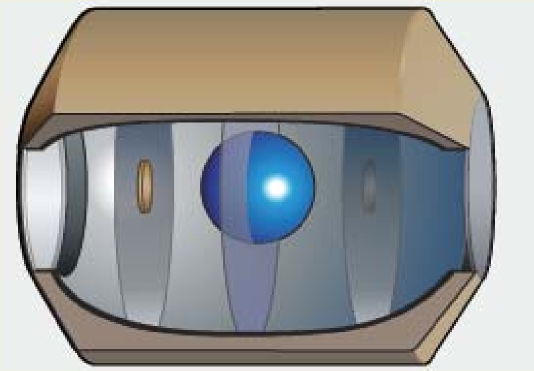
Industry
1. General Atomics
2. L3/PSD
3. Schafer Corp
4. SAIC
5. Commonwealth Tech
6. Coherent
7. Onyx
8. DEI
9. Voss Scientific
10. Northrup
11. Ultramet, Inc
12. Plasma Processes, Inc
13. PLEX Corporation
14. APP
15. Research Scientific Inst
16. Optiswitch Technology
17. ESLI

Cost study of high-volume fabrication by GA is favorable for Direct Drive IFE Targets

Simpler Target Fabrication

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

Concept for Indirect Drive IFE Target



Foam shells, mass produced for Direct Drive IFE target

Schafer Corp/GA

Lower estimated cost

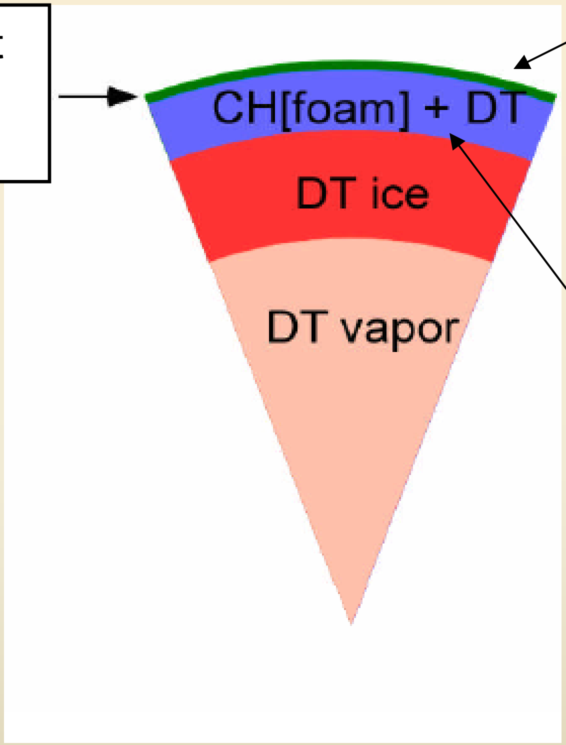
IFE Concept	Target Design	Target Yield (MJ)	Est'd Cost/target for 1000 MW(e)	% of E-value
Laser Fusion	Direct drive foam capsule	~400	$0.17	~6
HIF	Indirect drive distributed radiator	~400	$0.41	~14
ZFE	Dynamic hohlraum	~3000	$2.90	~13
LIFE	Indirect drive Pb rugby hohlraum	~132	~$0.30	~30

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

Studies indicate that with a minor modification (high reflectivity outer layer) direct drive targets can survive injection into a hot IFE reaction chamber

Plastic overcoat with thin outer Pd-Au layer

~50 nm metallic overcoat reflects IR



CH foam produces smoother inner ice layer and allows cooling to lower temperate without initiating surface roughness.

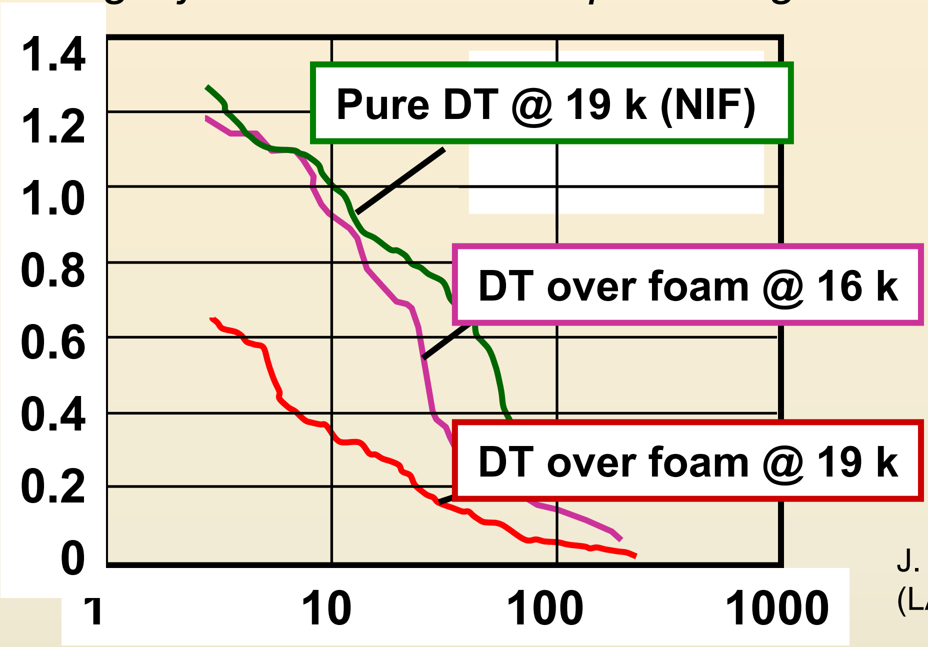
Calculations indicate pellet should survive injection with background pressures up to 50 mTorr.

Target injection: LANL experiment indicates benifical effects of utilizing foam on inner DT surface.

DT ice layer over foam demonstrated to be smoothest, thermally robust

Allows warm up of ~ 3° during injection without compromising DT ice layer

Cumulative Reverse Spectra RMS (μm)
vs
L Mode number

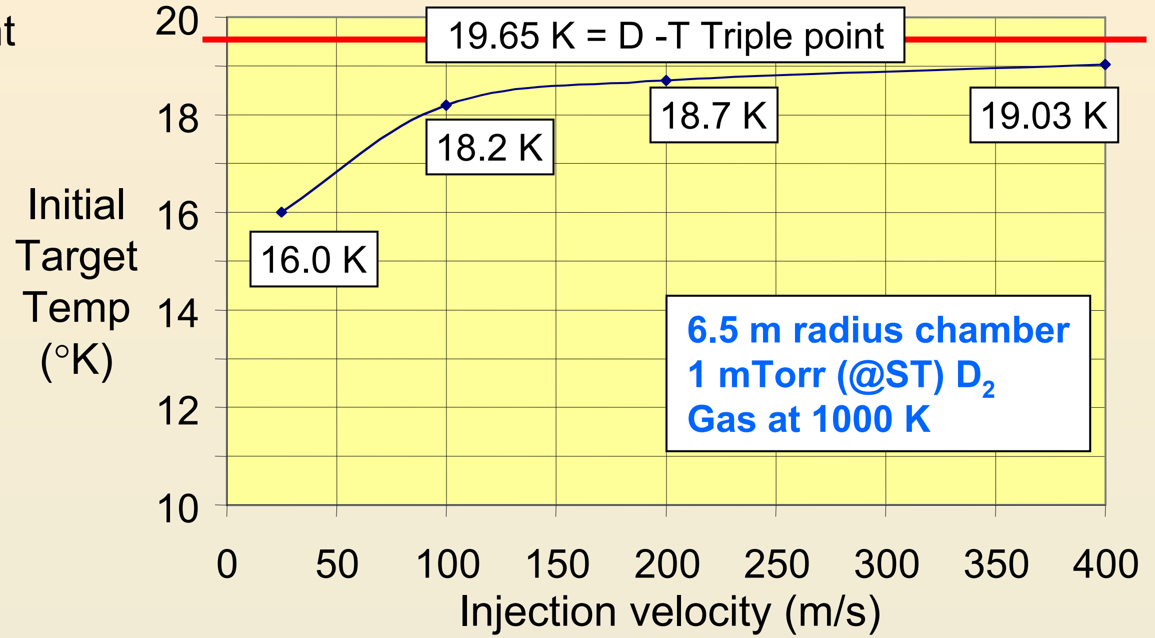


J. Hoffer & Drew Geller (LANL)

Encouraging target injection results for direct drive:

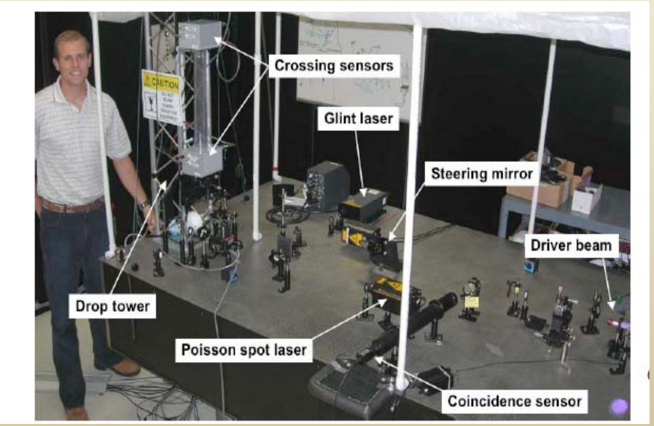
Modeling shows direct drive target can survive injection into solid wall chamber

Target stays below D-T Triple Point
Can have buffer gas < 50 mTorr
Scales with preliminary LANL exp't



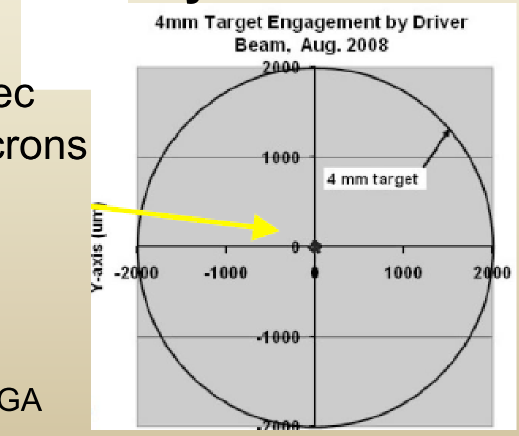
A Raffray, UCSD

Demonstrated on bench, a way to engage injected targets, accuracy 28 microns

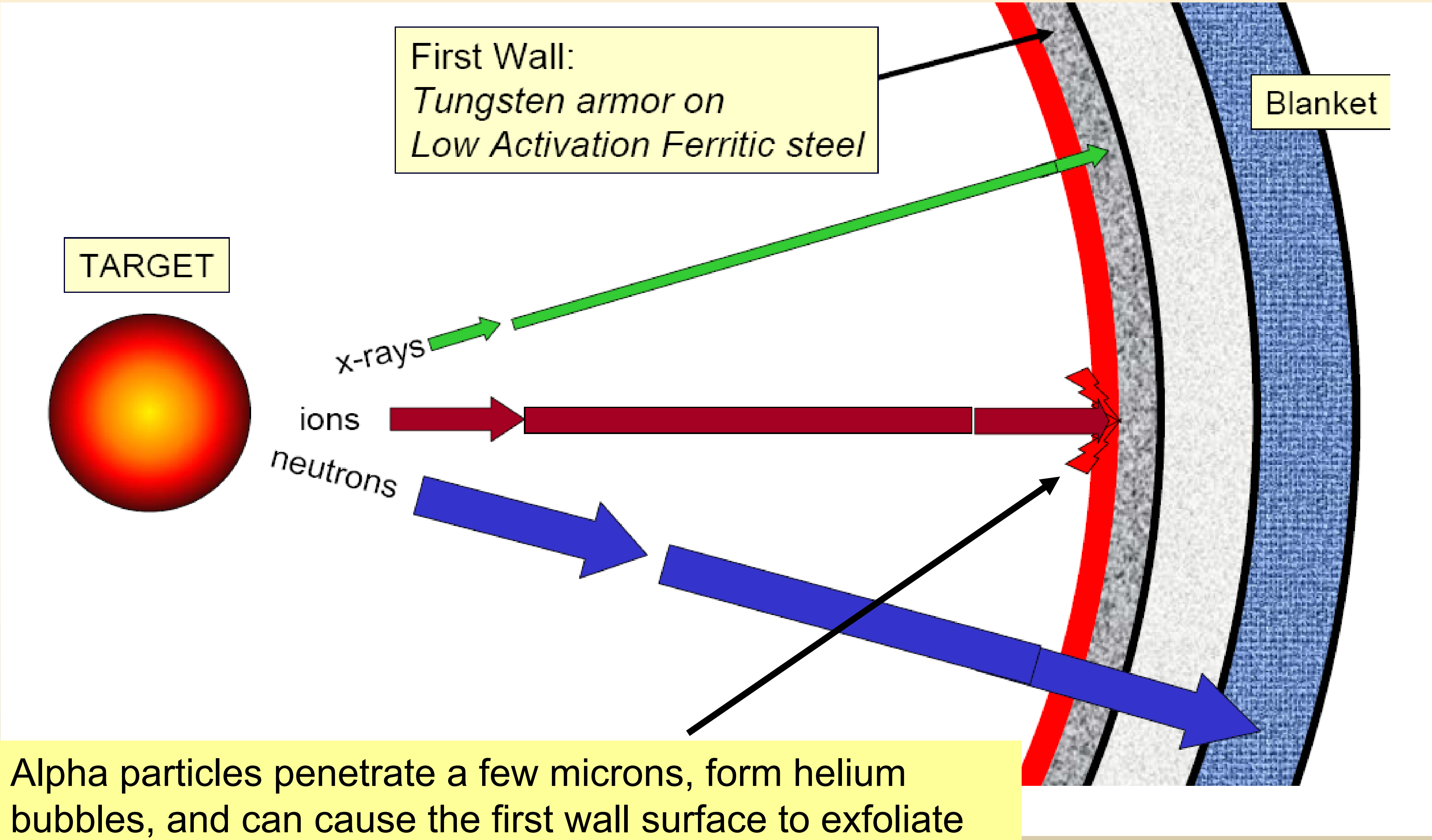


Scaled experiment @ 5 m/sec
Standard deviation: ~ 28 microns

UCSD/GA



The first wall of an IFE reactor must survive the “threat” spectrum from a the target – which is sensitive details of the target design.

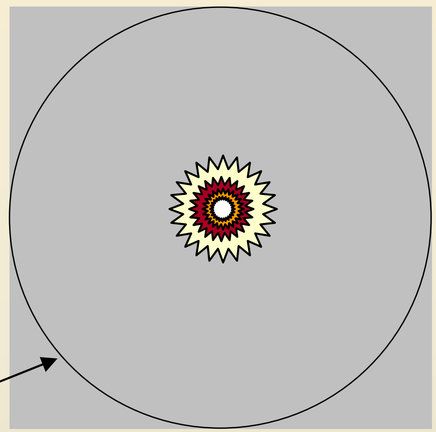


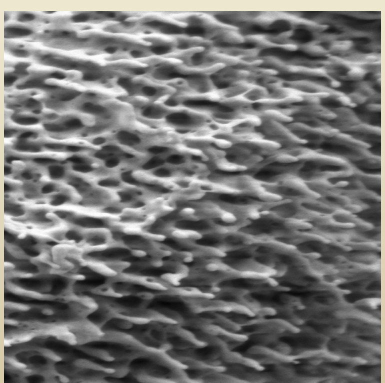
Alpha particles penetrate a few microns, form helium bubbles, and can cause the first wall surface to exfoliate

Chamber concepts to prevent damage from alphas

(pressure from helium bubbles exfoliates surface)

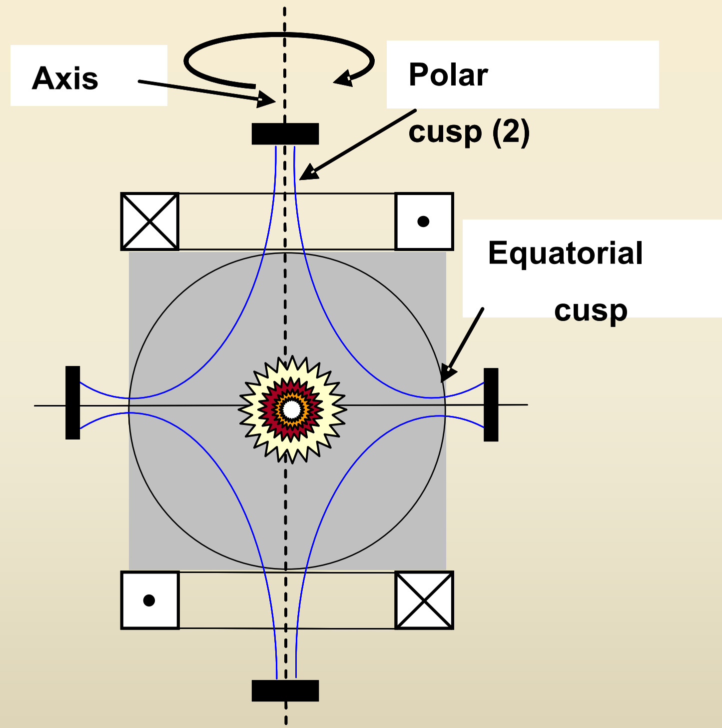
Engineered first Wall





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

Magnetic Intervention



Summary

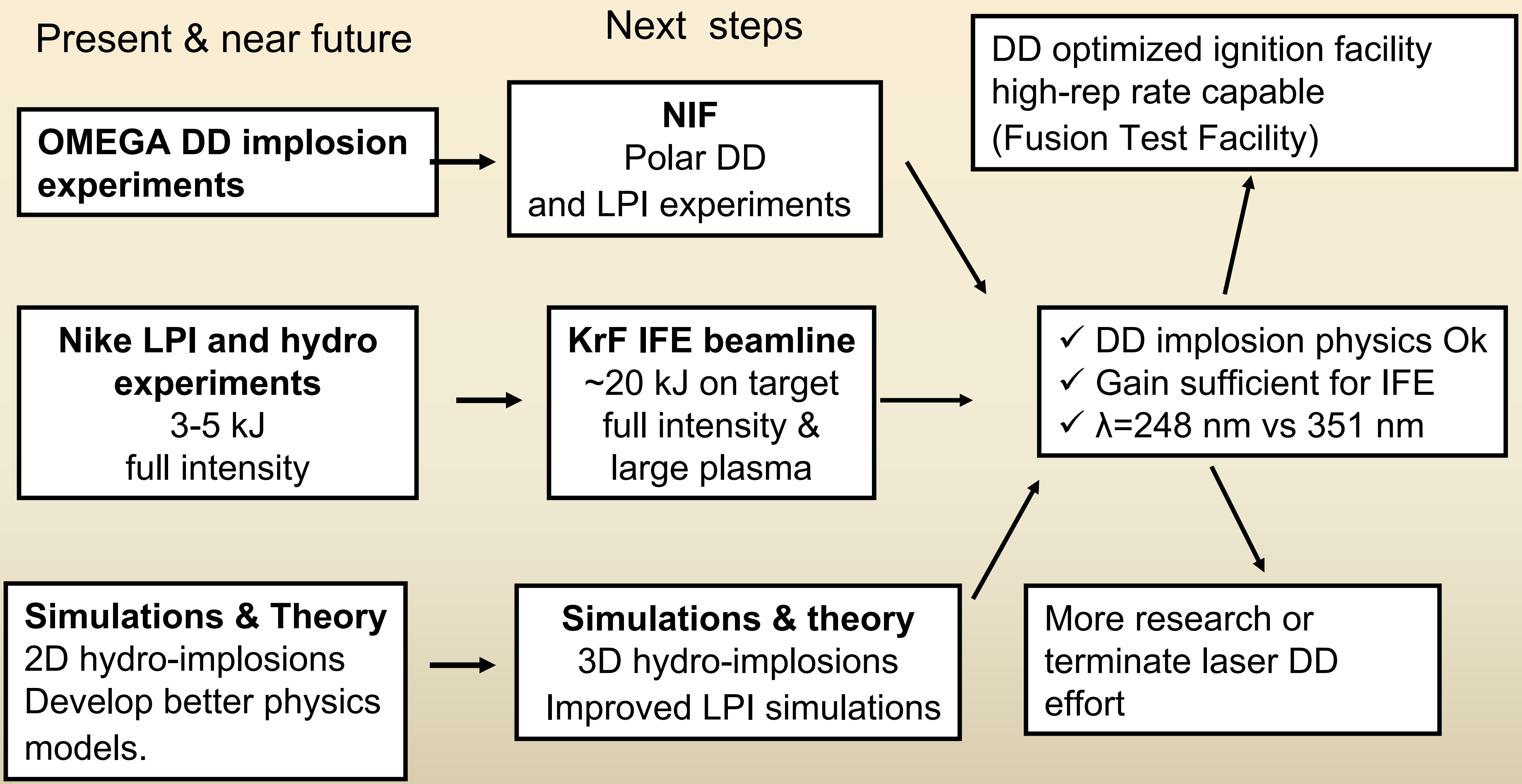
- Thanks to LLE staff for organizing this workshop.
- Shock ignited direct drive if promising towards achieving high gain with reduced laser energy, but we need to understand better and deal with limits set by LPI.
- We see challenges, but no fundamental technical obstacles to the IFE application. There are inherent technical advantages to utilizing high performance laser direct drive for IFE.

Extra slides

Status of the laser direct-drive target physics

- Hydrocodes and understanding of hydro-instabilities are well advanced and in agreement with experiments.
- Need to extend routine hydro-simulations from 2-D to 3-D. (petaflops required)
- Need more advanced non-local models in heat transport applicable to hydrocodes. (NRL is a leader developing these)
- Need better theory, simulation capability and experiments in laser plasma instabilities.

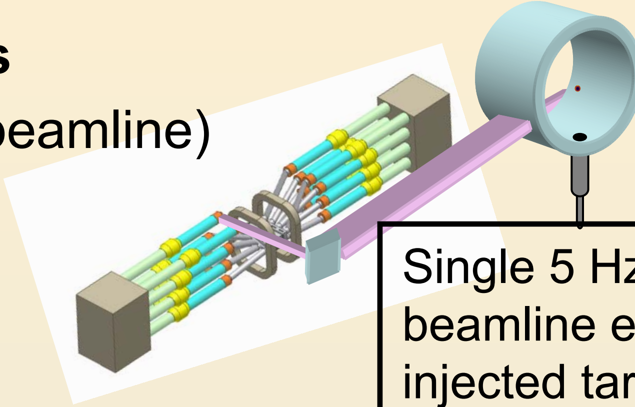
Path Forward towards IFE
Direct Drive (DD) Target Physics



A three stage plan for Inertial Fusion Energy
IFE technologies developed in parallel with the science

<u>Stage I</u> : Develop full size components

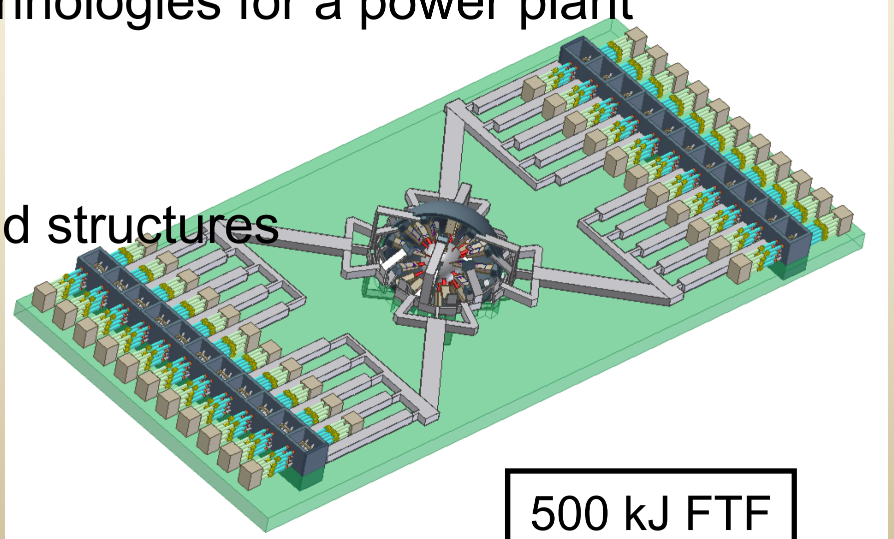
- Laser module (e.g. 17 kJ, 5 Hz KrF beamline)
- Target fabrication/injection/tracking
- Chamber, optics technologies
- Refine target physics
- Power plant/FTF design



Single 5 Hz FTF beamline engages injected targets

<u>Stage II</u> Fusion Test Facility (FTF) ~250 MW Fusion power

- Demonstrate integrated physics / technologies for a power plant
  $\eta G > 6$, $G \sim 100$
- Tritium breeding, power handling
- Develop/ validate fusion materials and structures



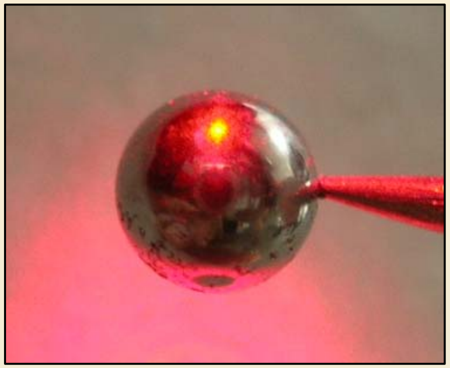
500 kJ FTF

<u>Stage III</u> Prototype Power plant(s)

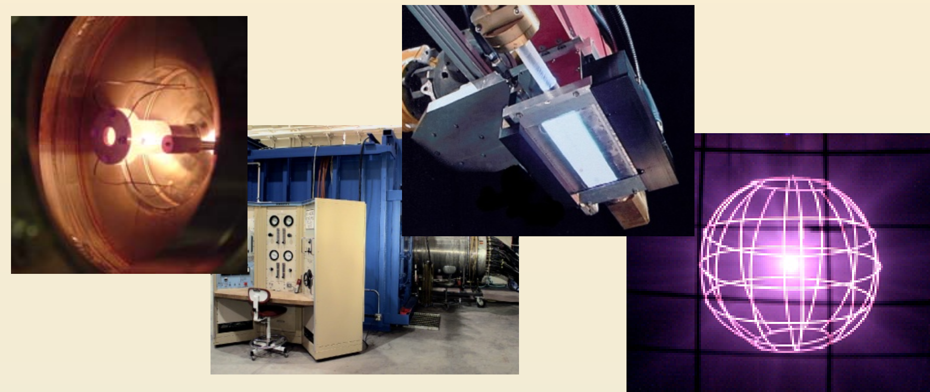
- Electricity to the grid
- Transitioned to private industry

HAPL generated credible solutions for most key components needed for IFE (2 of 2)

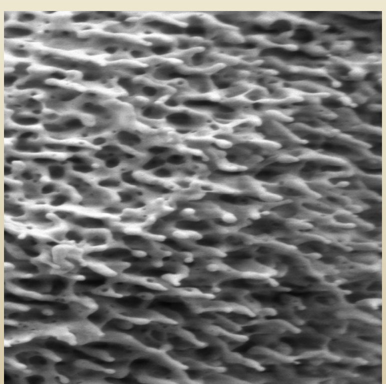
Target Engagement:
Glint system: accuracy 35 microns

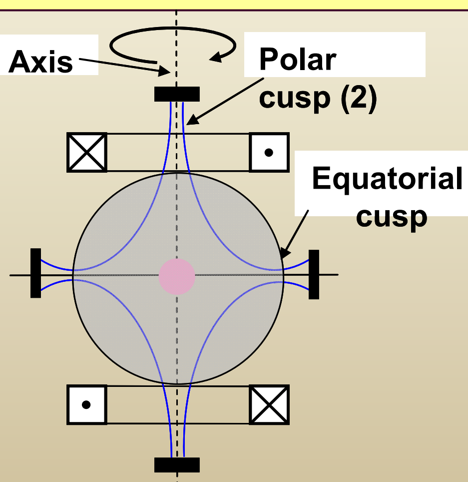


First wall experiments & modeling
Study threats on Chamber Wall



Developing two chamber concepts
Engineered Wall *Magnetic Intervention*





Conceptual designs for ancillary components:

- Chamber/structure
- Blanket
- Tritium Breeding/processing
- Vacuum system
- Power conversion

HAPL generated credible solutions for most key components needed for IFE (1 of 2)

Final Optics:
High Laser Damage Threshold Grazing Incidence Metal Mirror

10 M shots at 3.5 J/cm^2
(not a limit!)

Penultimate Optics:
Neutron Resistant Dielectric Mirror

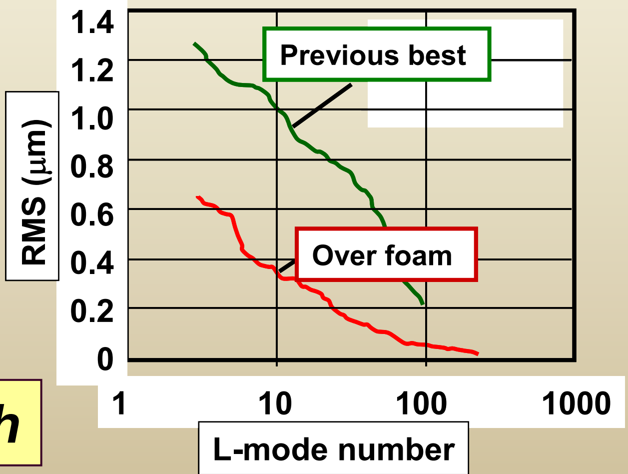
Laser Damage Threshold (Al_2O_3/SiO_2)

No dpa	0.001 dpa	0.01dpa	0.1 dpa
86-87%	84-86%	78-83%	83-84%

Target Fabrication:
Mass Produced Foam Shells

Estimate Target Cost 16 ¢ each

Target Fabrication:
Smooth DT ice layers over foam



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