IFE target physics with a KrF laser

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Work by the NRL laser fusion research team

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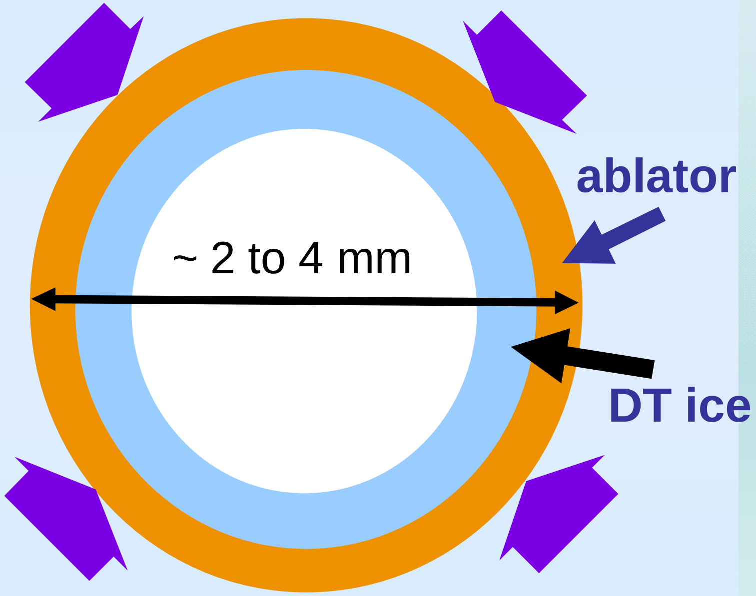
Opening remarks

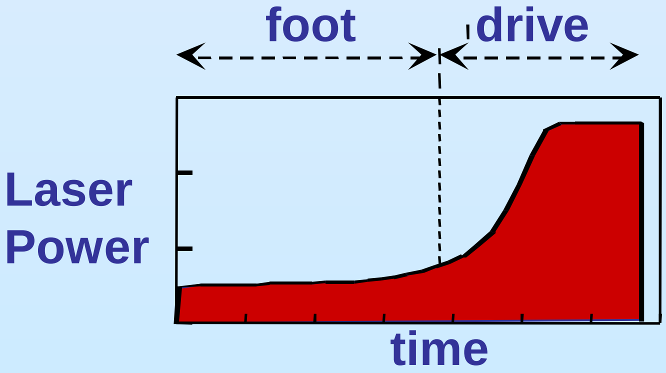
NRL program is developing an attractive path to inertial fusion energy (IFE) based on the krypton-fluoride laser and directly driven targets.

- Higher target performance (gain and resistance to instabilities) afforded by inherent physics advantages of KrF lasers due to its shorter wavelength, higher bandwidth, smoother beam on target and capability to zoom.
- Simulations, using codes checked against theory and experiments, predict high gains needed for fusion energy at relatively low laser energy (1MJ)

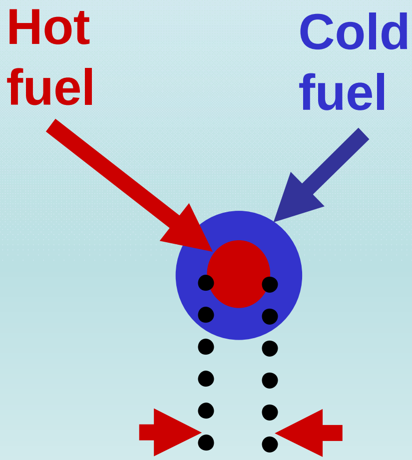
Inertial Fusion (via central ignition)

Lasers or x-rays heat outside of pellet, imploding fuel to velocities of ~300 km/sec



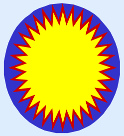


Central portion of DT (spark plug) heats to ignition.



~ 3% of original target diamter

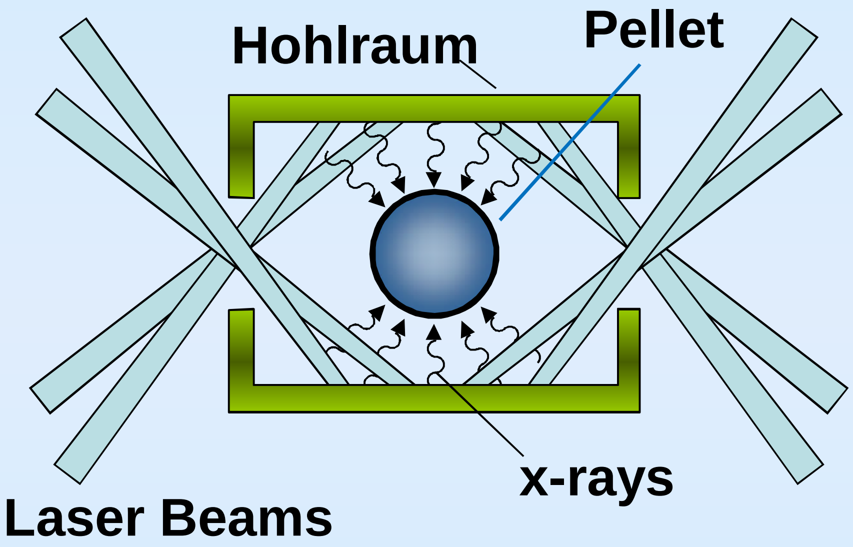
Thermonuclear burn then propagates outward to the compressed DT fuel.



- Simple concept
- Potential for very high energy gains
- Requires high precision in physics & systems
- Need to understand & mitigate instabilities

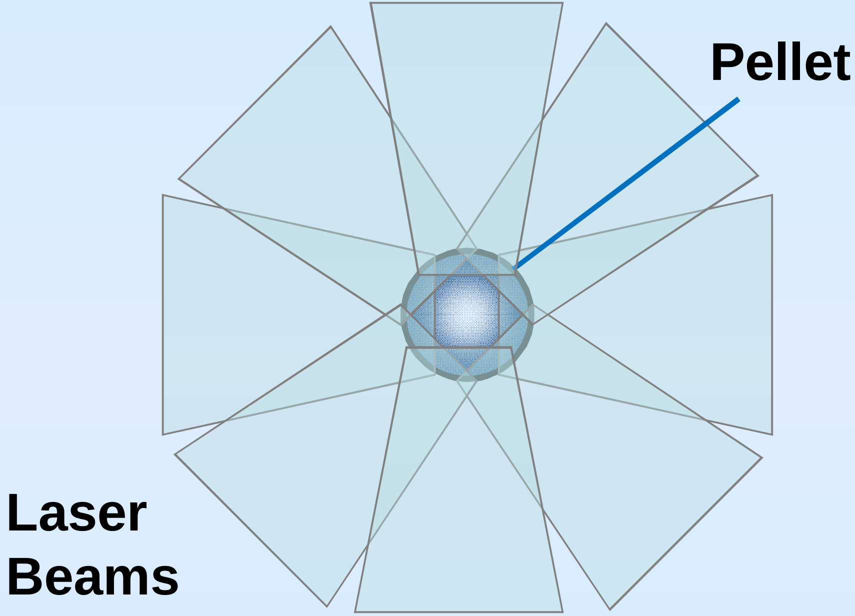
Higher potential gains with Direct Laser Drive makes it a better choice for Inertial Fusion Energy.

Indirect Drive (initial path for NIF)



- ID Ignition being explored on NIF
- Less stringent requirements on laser illumination uniformity.
- Conversion from laser light to x-ray drive on target is not efficient.(≤30%)

Direct Drive (IFE)



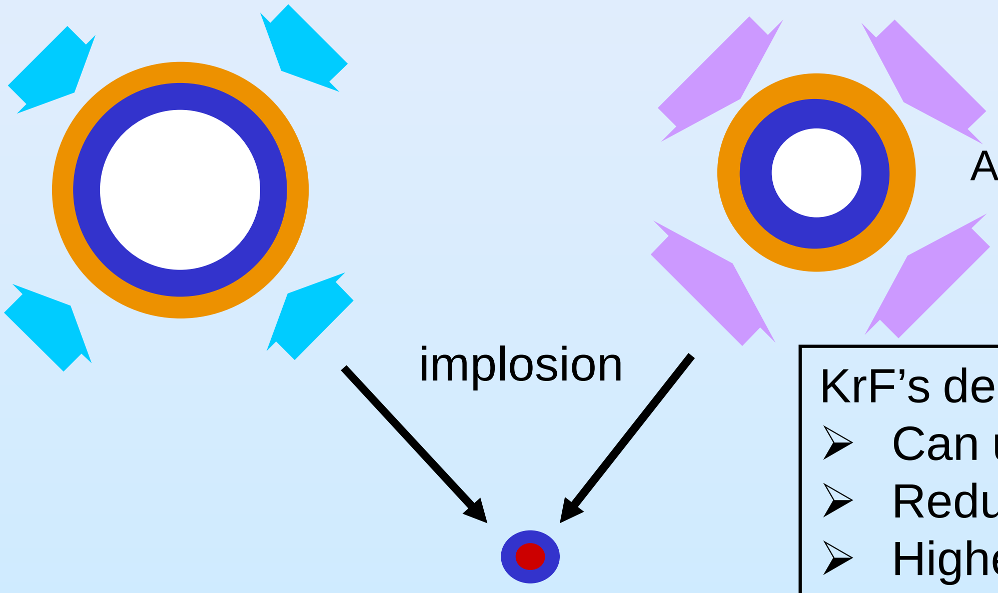
- Direct Drive Ignition physics can be explored on NIF.
- More efficient use of laser light
- Greater flexibility in pulse shaping

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

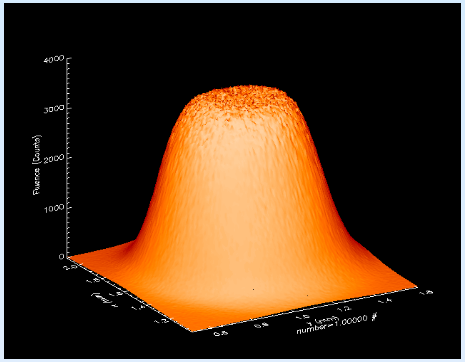


KrF's deep UV :

- ➢ Can use lower aspect ratio targets
- ➢ Reduced growth of hydro-instability
- ➢ Higher energy gain
- ➢ Less laser energy required

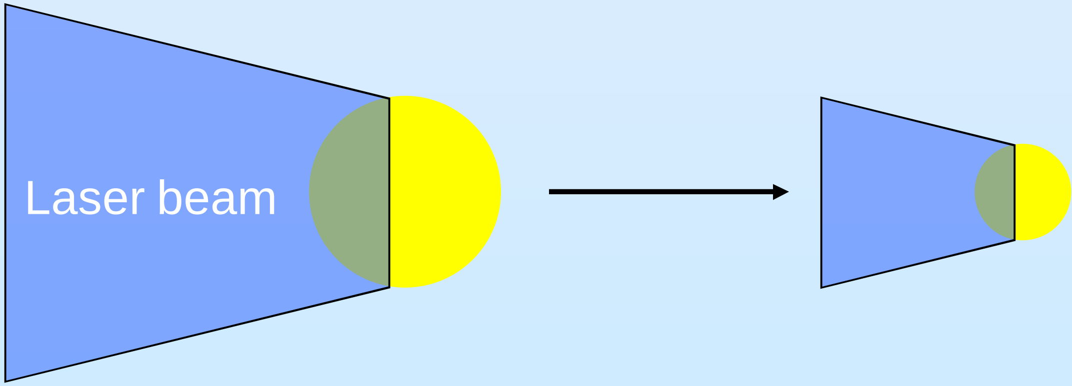
KrF Light helps the target physics (2)

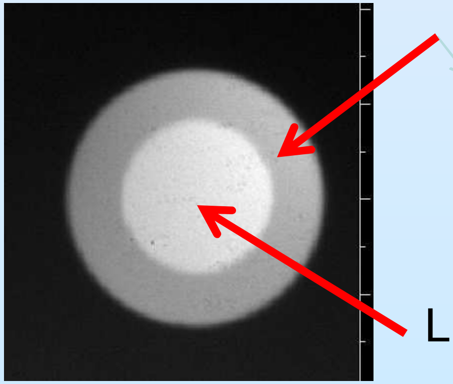
- KrF has most uniform target illumination of all ICF lasers.
  - **Reduces seed for hydrodynamic instability**



Actual Nike KrF focal profile

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





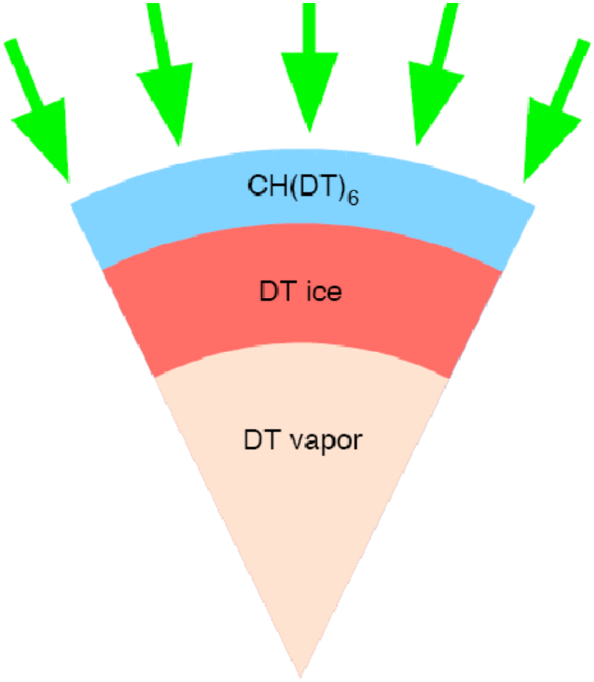
Early time

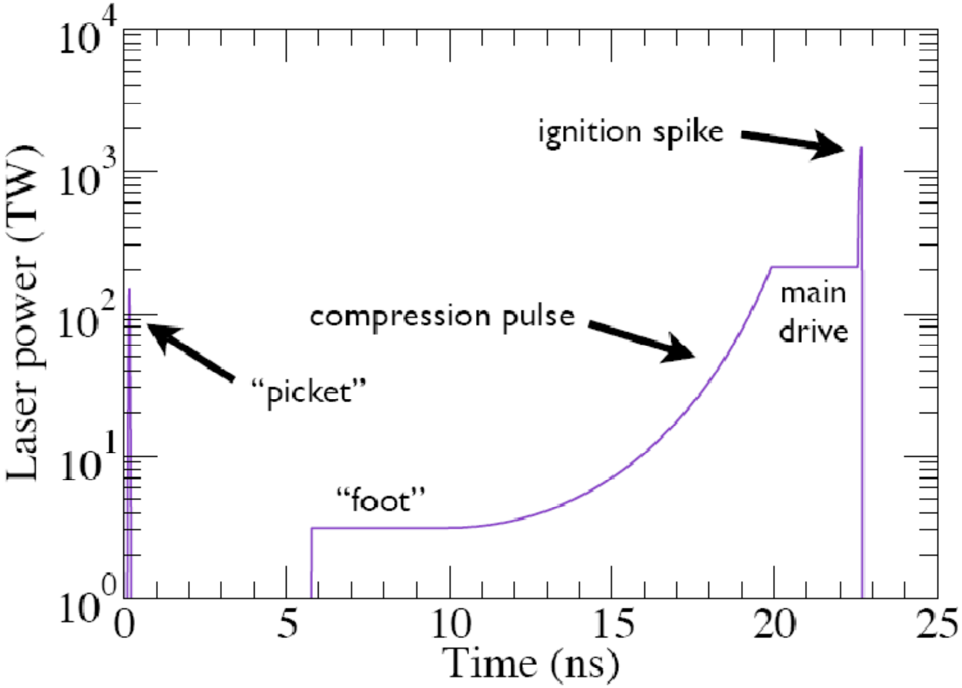
Nike zoomed focus

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

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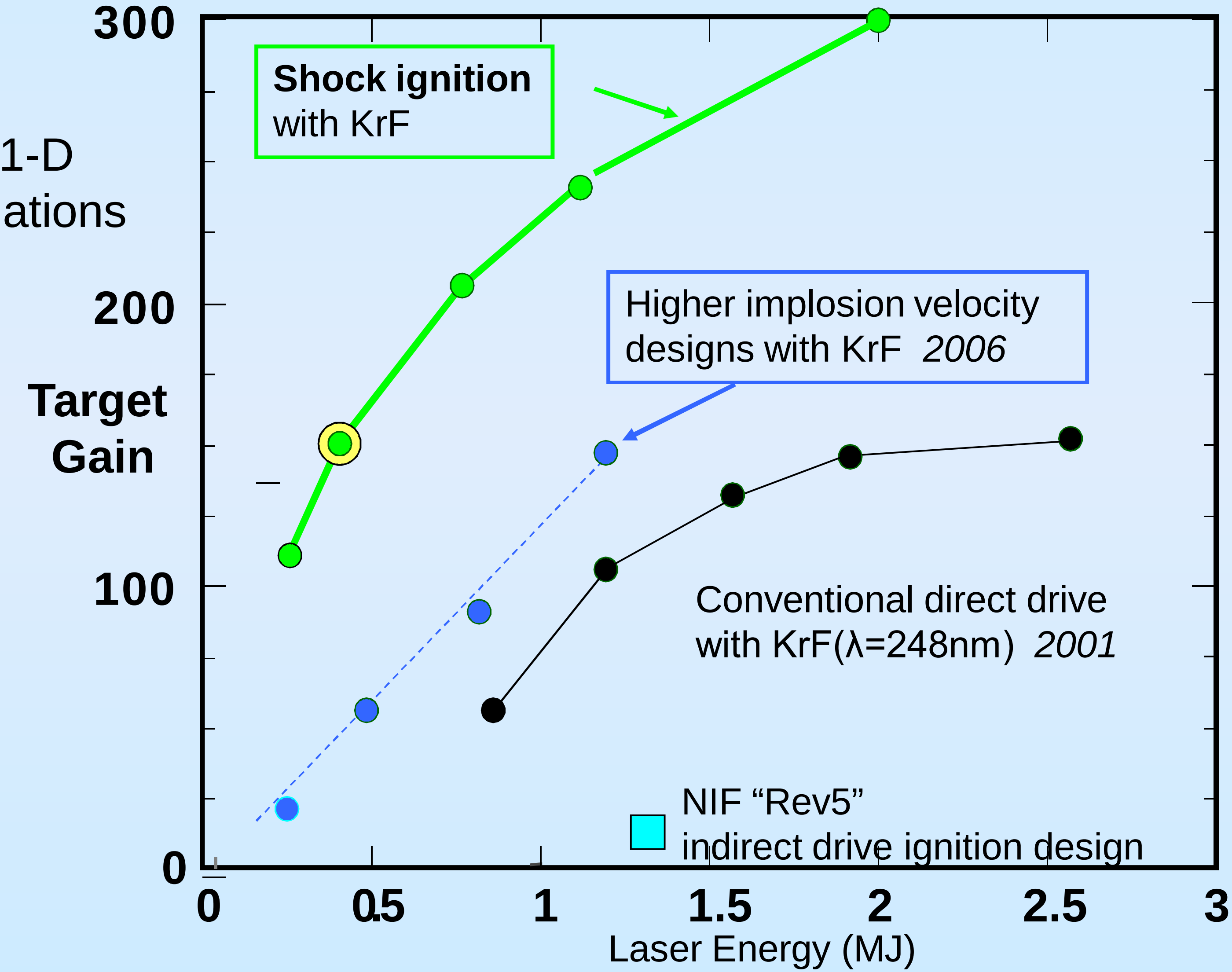
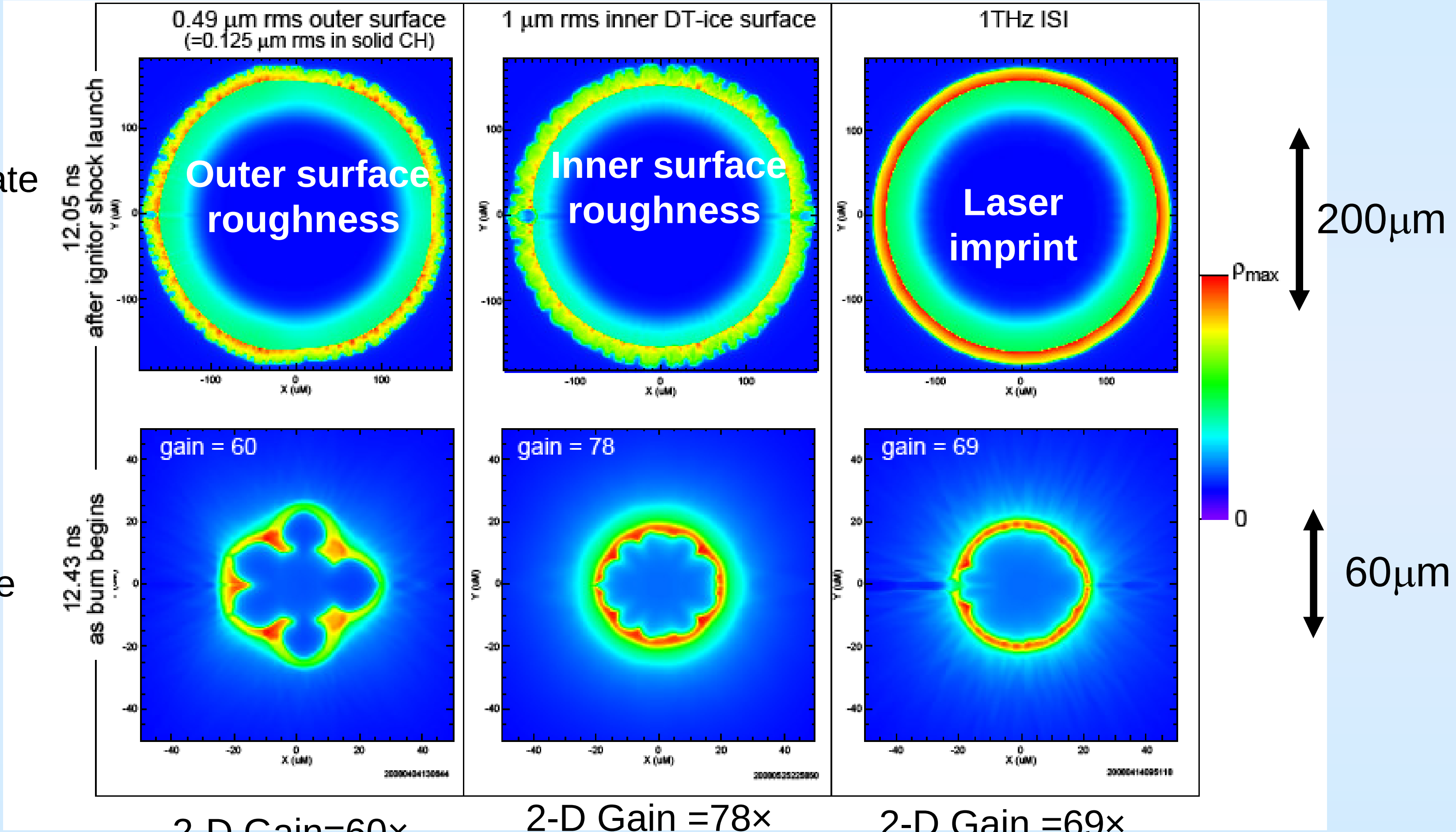
[*] *R. Betti et al., Phys.Rev.Lett.* ***98****, 155001 (2007)*

Gain curves show progress in direct-drive target designs

from 1-D
simulations



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



Intermediate time

Late time

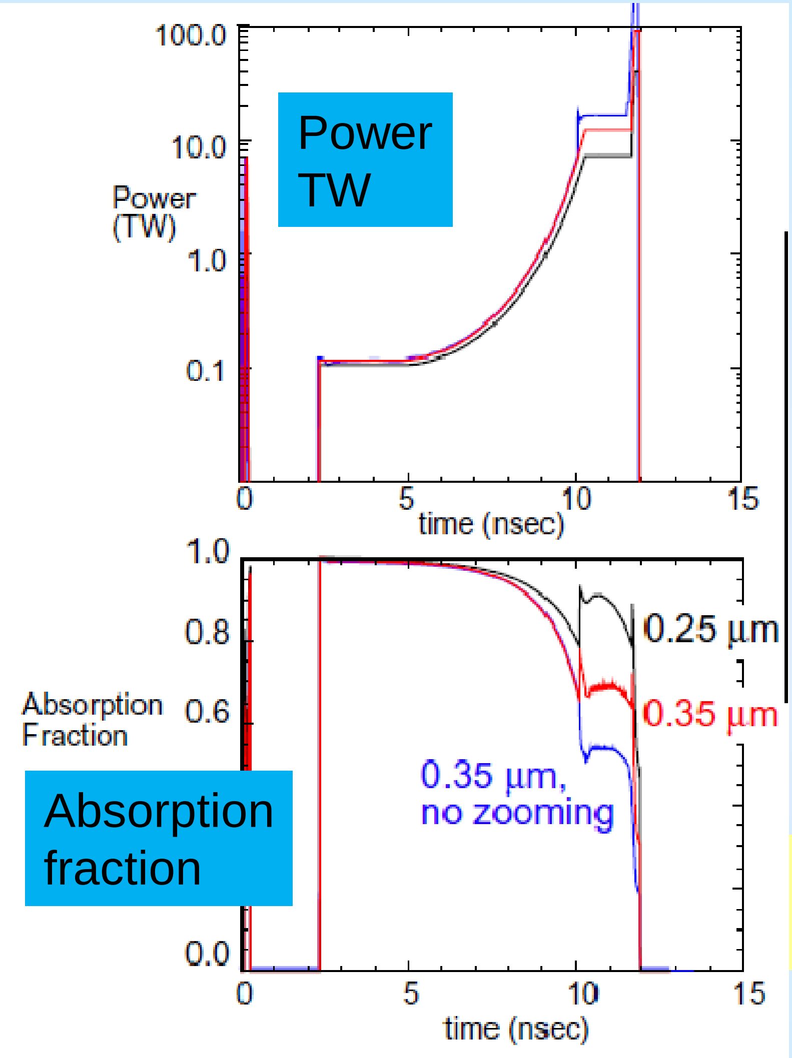
2-D Gain=60×

2-D Gain =78×

2-D Gain =69×

250 kJ shock ignited target – NRL FASTRAD3D simulations

Shock ignition benefits from shorter λ and zooming

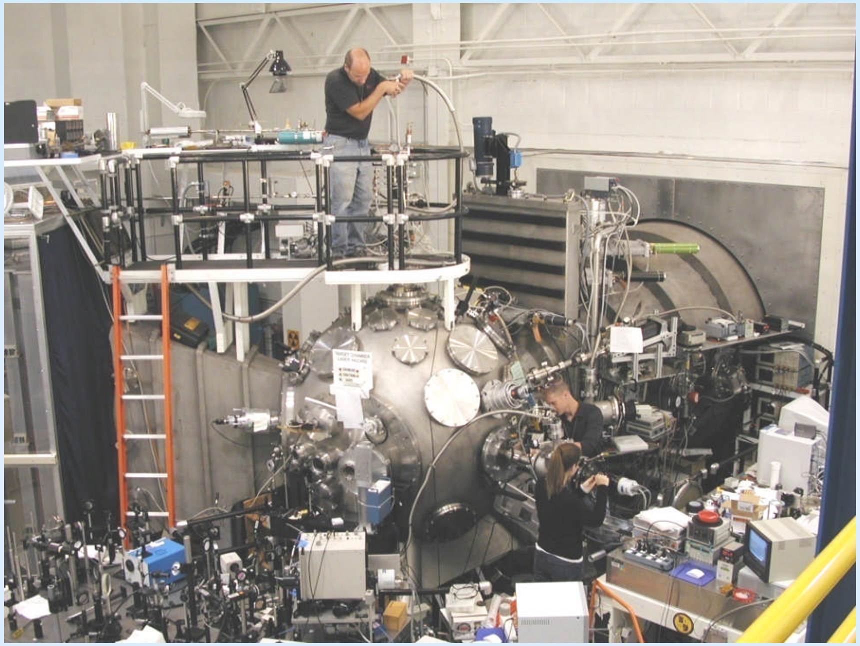


1-D Hydrocode simulations
Fixed low aspect ratio pellet

	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}	

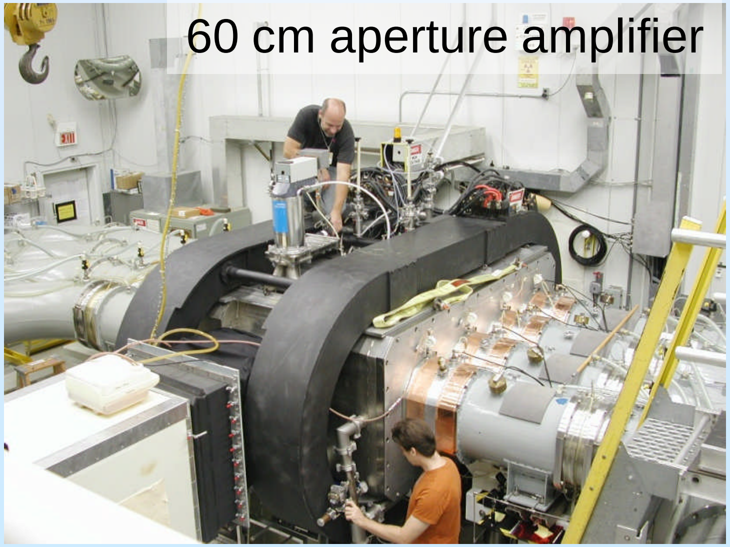
- ➢ Significantly higher gain with 248 nm & zoom
- ➢ Lower risk from laser plasma instability

Nike krypton-fluoride laser target facility



Nike Target chamber

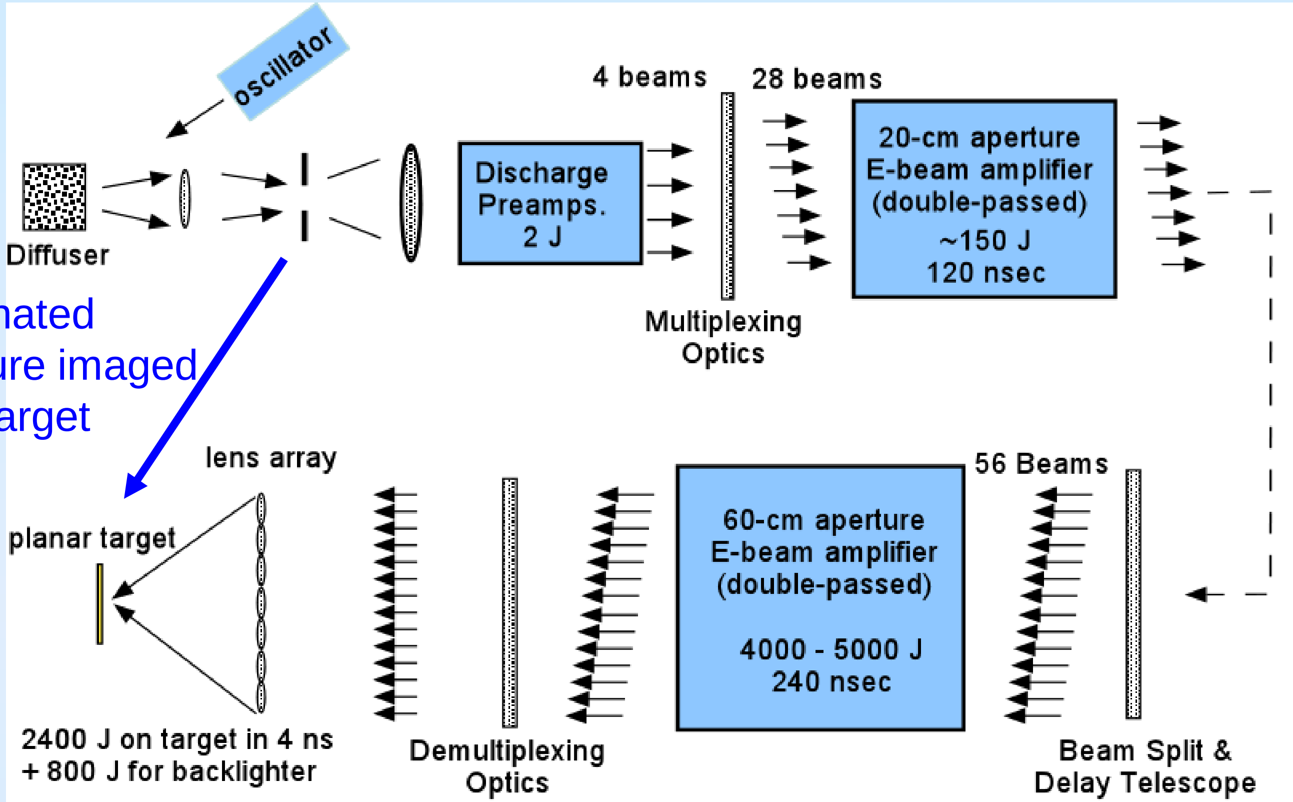
Target chamber optics



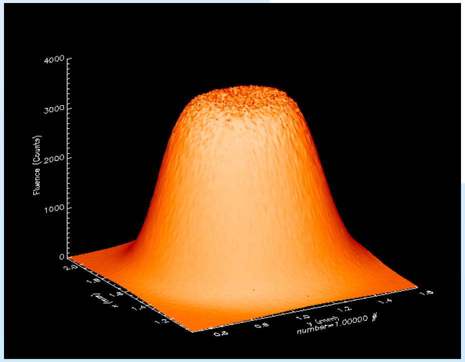
60 cm aperture amplifier

56-beam 3-kJ
KrF laser-target facility

Nike laser Chain



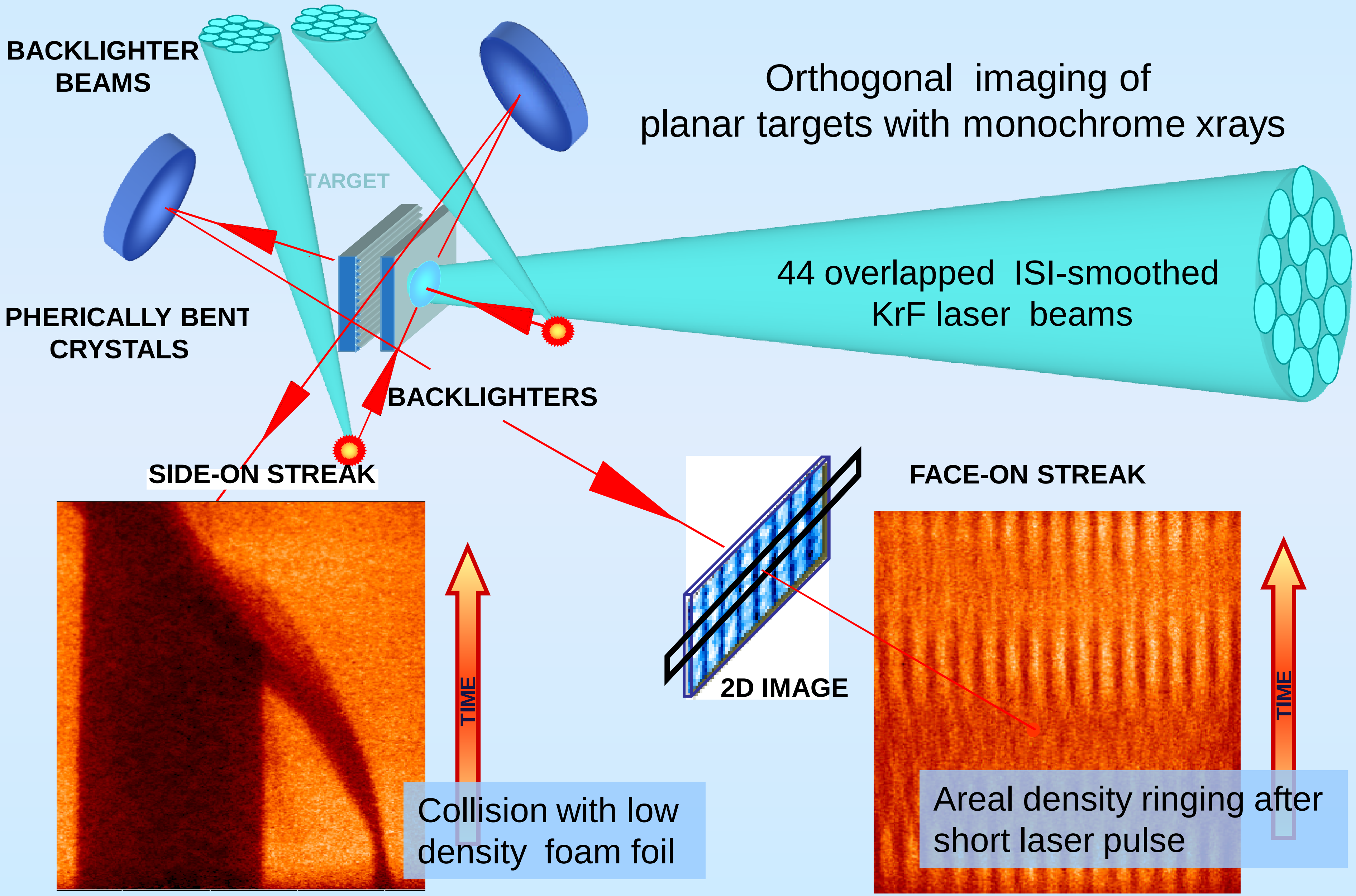
Illuminated aperture imaged onto target



Laser profile in target chamber

Overlap of 44 beams provides additional smoothing $\langle \Delta I/I \rangle \cong 0.2\%$

Nike is employed for studies of hydrodynamics and LPI



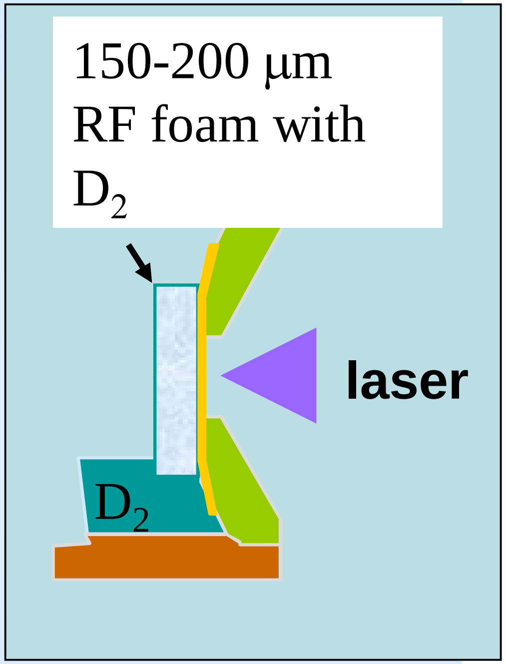
Orthogonal imaging of planar targets with monochrome xrays

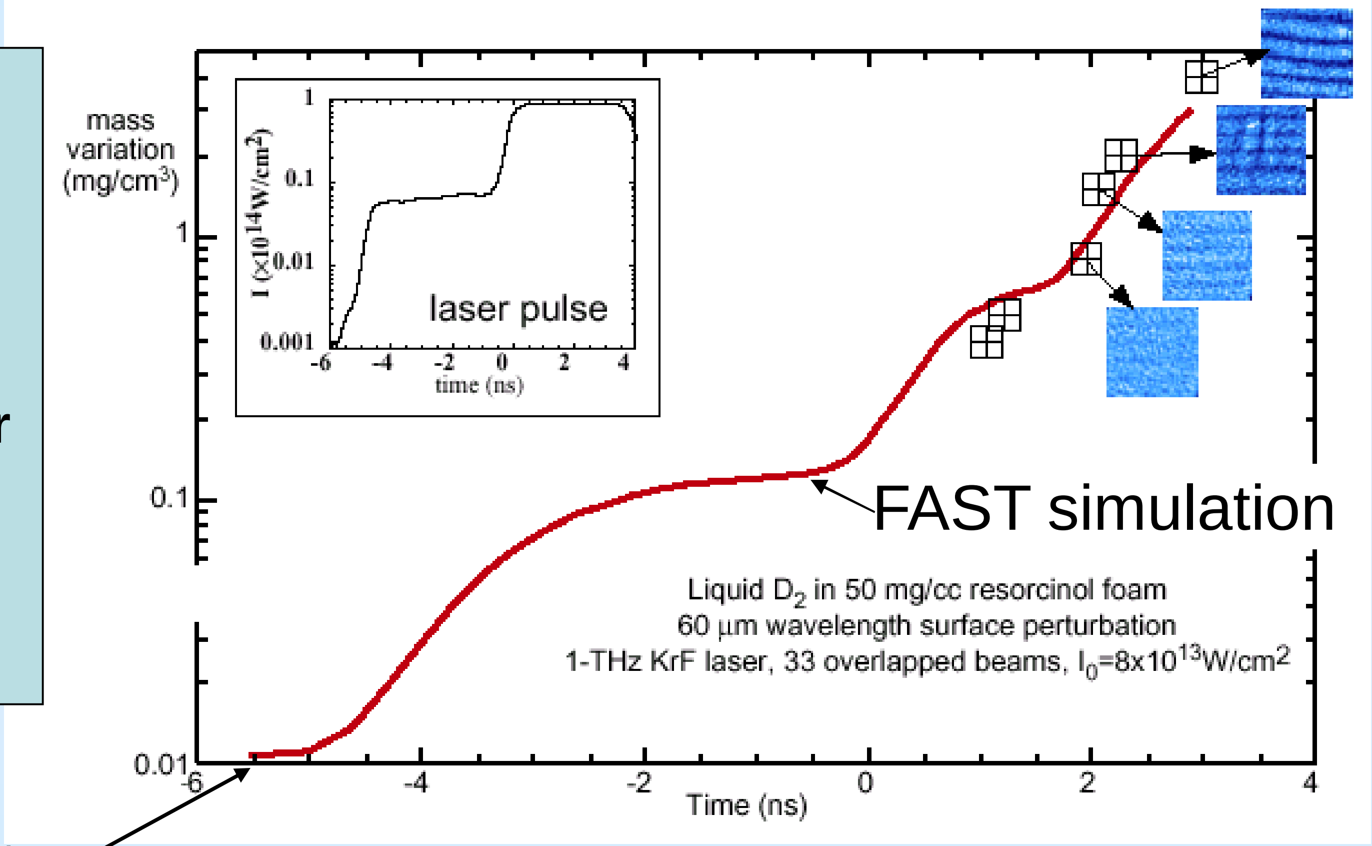
44 overlapped ISI-smoothed KrF laser beams

Collision with low density foam foil

Areal density ringing after short laser pulse

Planar cryo (deuterium wicked into foam) allow studies of Richtmyer-Meshkov & Rayleigh-Taylor instabilities with initial target thickness close to that of a high gain target.



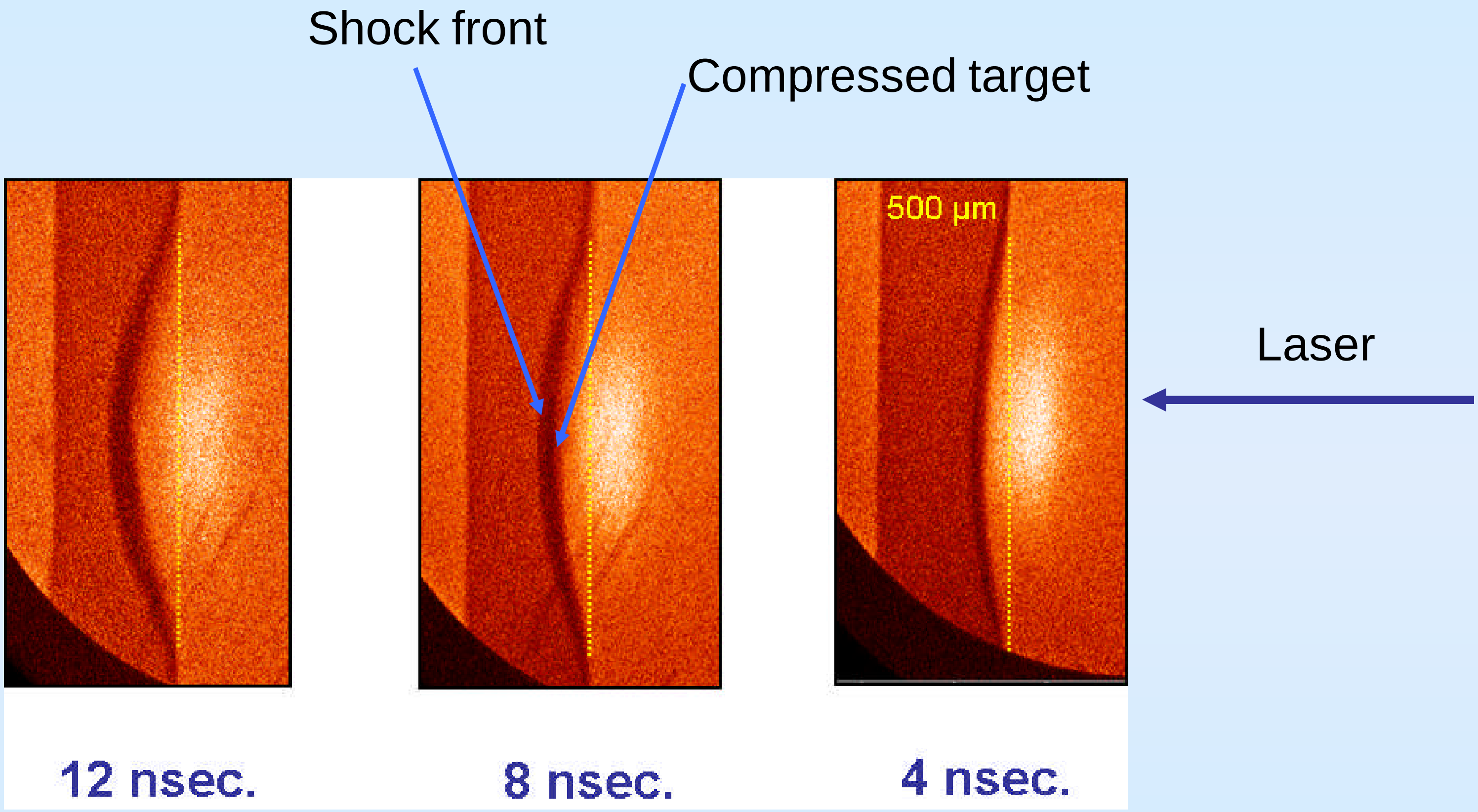


Initial imposed perturbation

RM

RT

5.2 keV x-ray images of shock propagation into plastic targets via 300 ps backlighter & spherical crystal optic.



Shock front

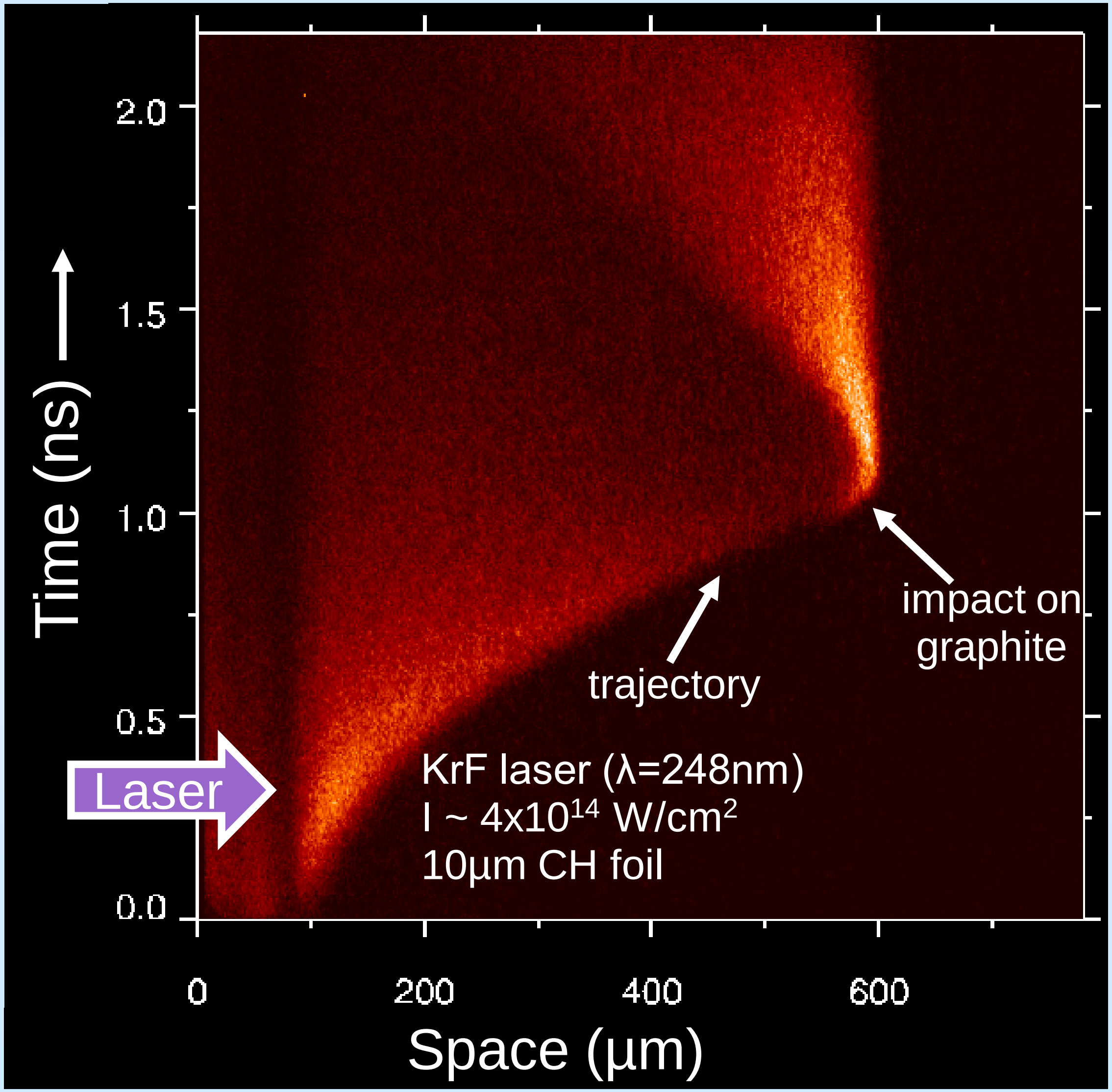
Compressed target

Laser

Nike target accelerated to greater than 1000 km/sec

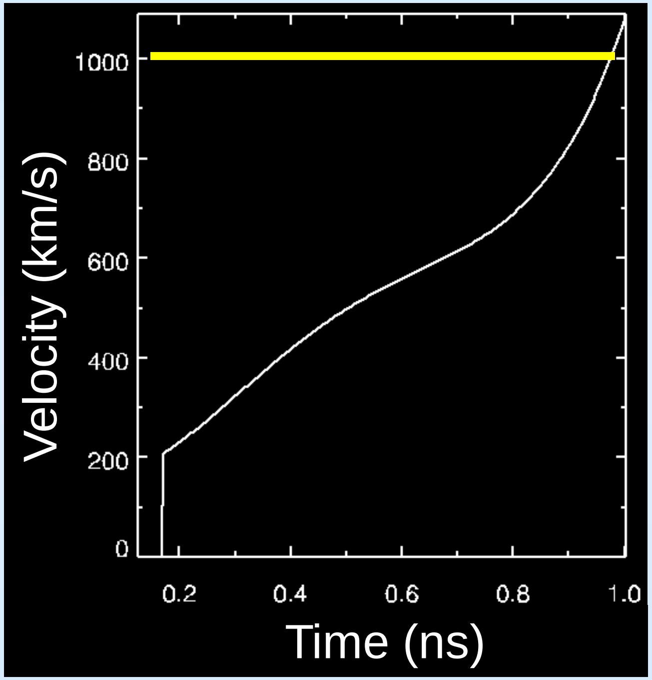
(0 to 2.2 million miles per hour in 1 billionth of a second)

Streak camera of emitted1.86 keV x-rays



KrF laser (λ=248nm)
I ~ 4×10^{14} W/cm^2
10µm CH foil

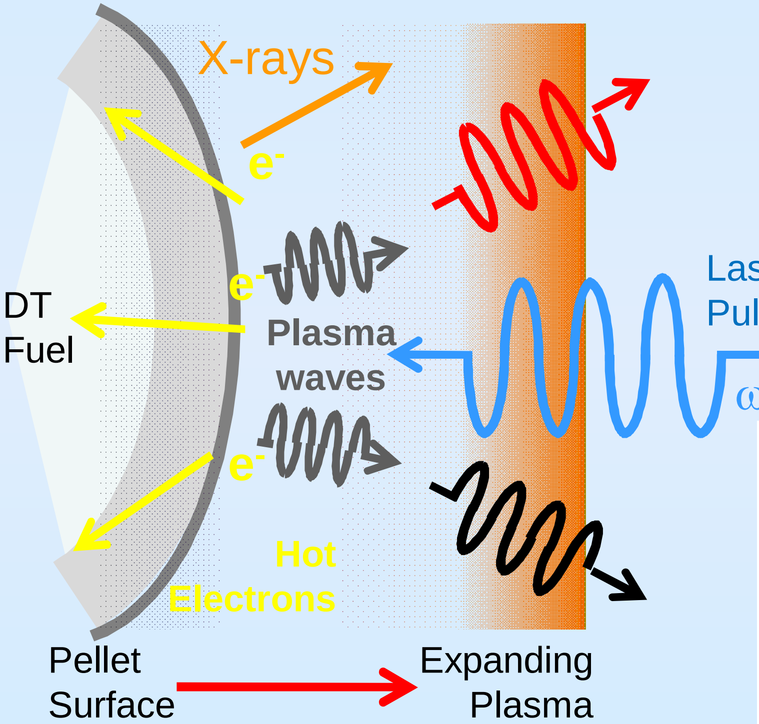
Target velocity verses time



Joint experiment with the
Institute for Laser Engineering,
Osaka University

Laser plasma Instability (LPI) limits the maximum intensity

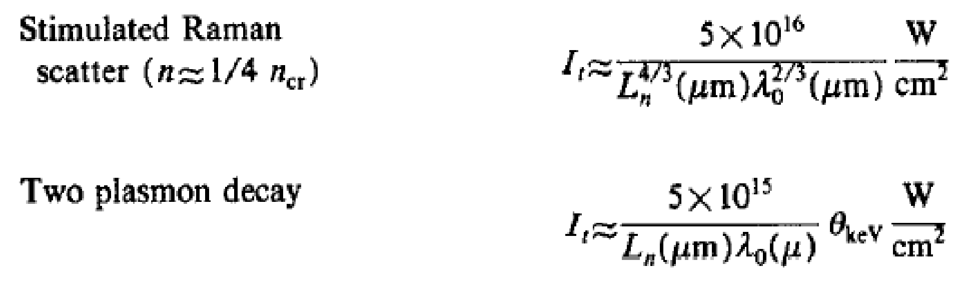
- Can produce high energy electrons that preheat DT fuel
- Can scatters laser beam, reducing drive efficiency



Shorter λ suppresses LPI

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

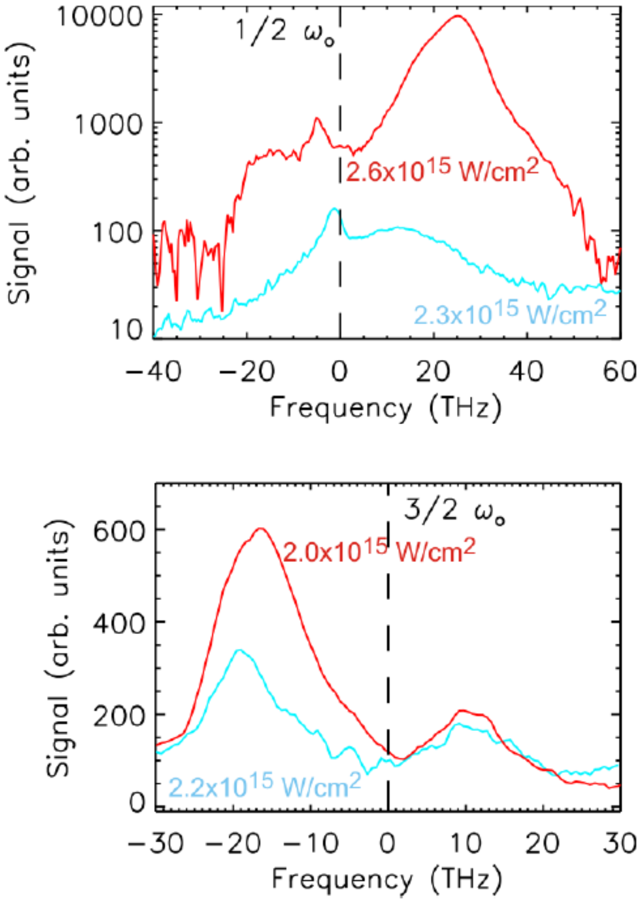
$N_c/4$ instability thresholds
(single planar beam)



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

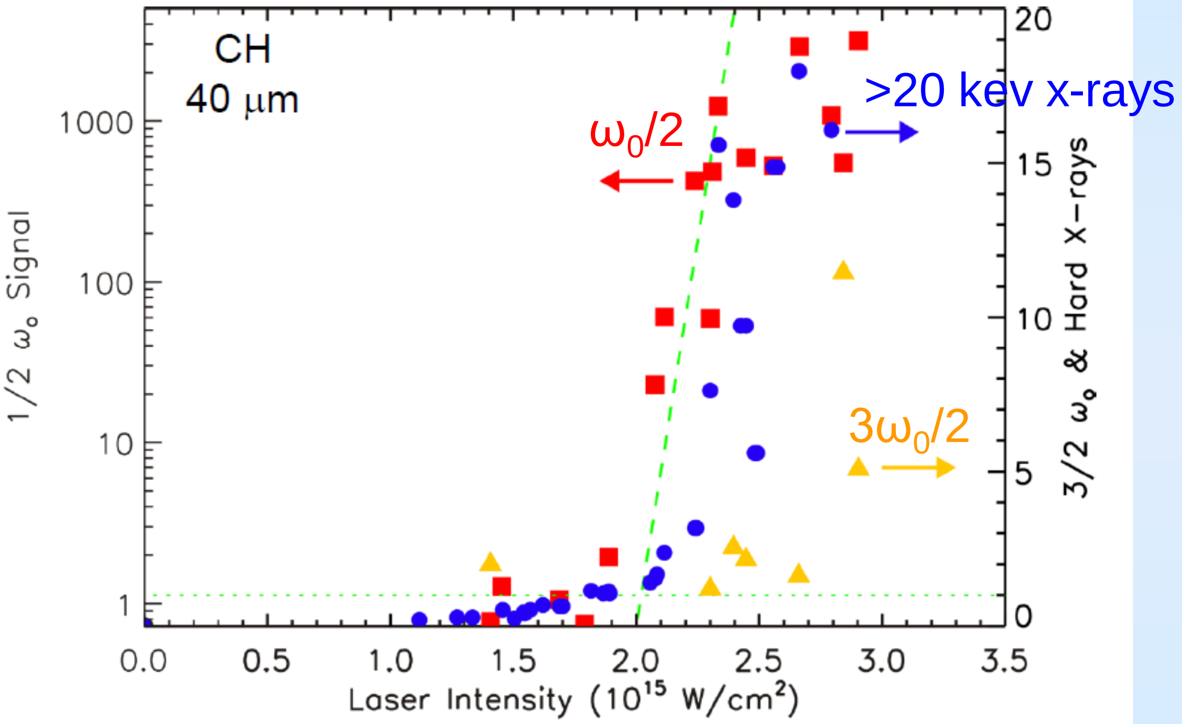
Idealized theory in a plasma density gradient
(no effects of crossed beams, bandwidth and beam smoothing)

Nike experiments are exploring physics of quarter-critical density laser plasma instability



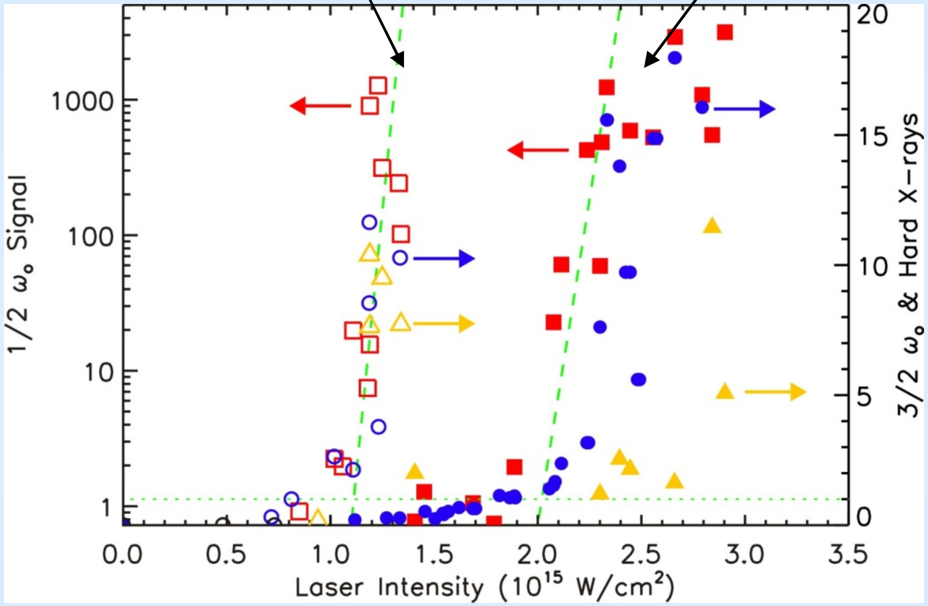
Spectra near $\omega_0/2$ and $3\omega_0/2$

325 ps, ≤1 kJ laser pulses in 40 overlapped beams



$\omega_0/2$ and x-ray signals give intensity thresholds ~2.0 10^{15} W/cm^2

Longer density scalelength plasma produced by ns laser pulses reduced thresholds



1 ns pulse

325 ps pulse

Computed density scale-lengths at quarter critical density

~60 μm with 325 ps pulse

~100 μm with 1 ns pulse

I_{th} = 2× 10^{15} W/cm^2 for 325 ps pulse

I_{th} = 1.2×10^{15} W/cm^2 for 1 ns pulse

Need to extend experiments to 2-3× longer plasma scale-lengths predicted for high gain targets

Similar physics to that observed with longer wavelength λ=351 nm lasers, but observed quarter-critical instability thresholds are higher with KrF.

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.

A path towards the energy application with KrF.

G ~100 with a 500kJ KrF laser

G ~170 with a 1MJ KrF laser

G ~250 with a 2 MJ KrF laser

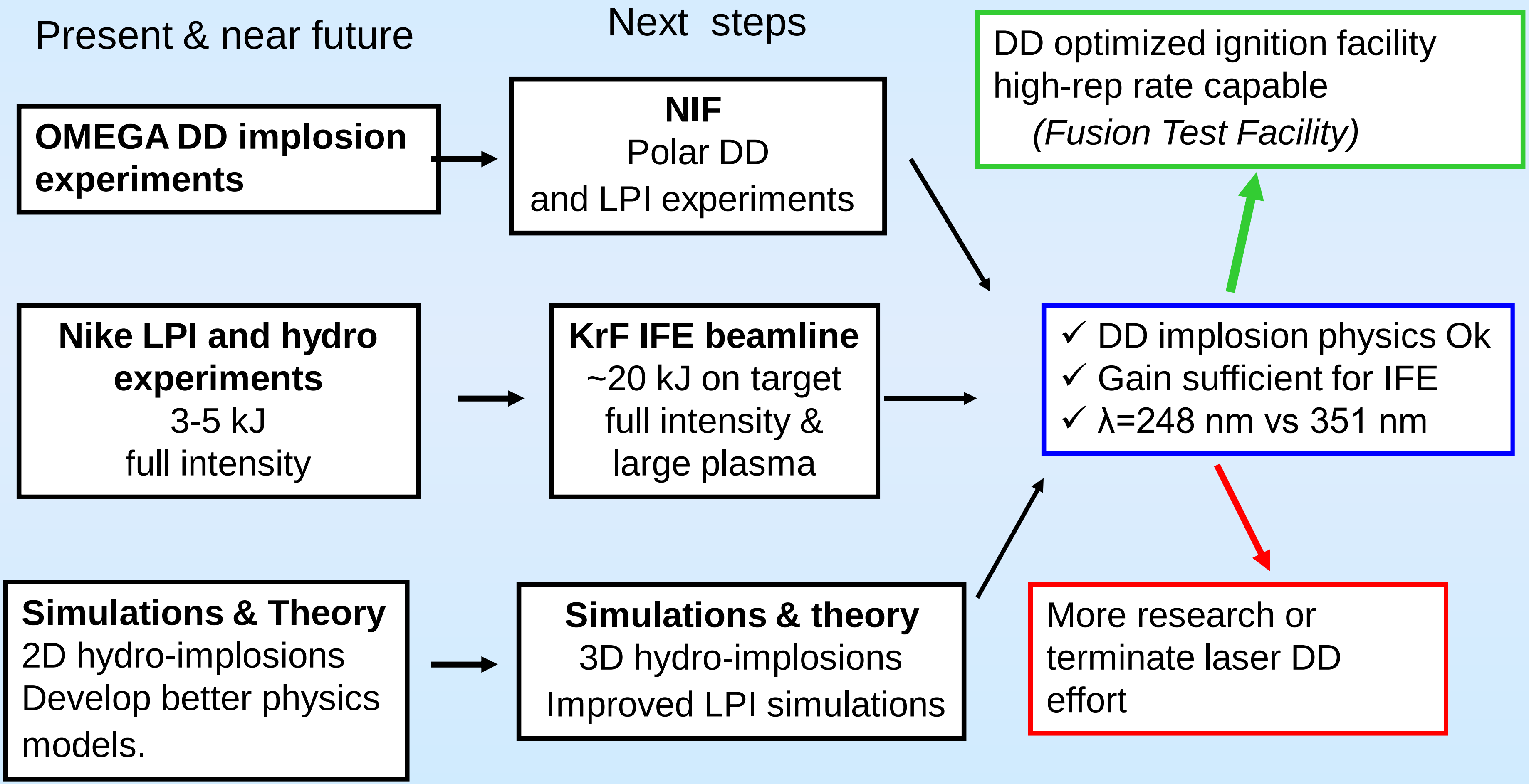
Fusion Power plants

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

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

need $G \geq 140$

Path Forward towards IFE
Direct Drive (DD) Target Physics



Present & near future

Next steps

OMEGA DD implosion experiments

NIF
Polar DD
and LPI experiments

DD optimized ignition facility
high-rep rate capable
(Fusion Test Facility)

Nike LPI and hydro experiments
3-5 kJ
full intensity

KrF IFE beamline
~20 kJ on target
full intensity &
large plasma

✓ DD implosion physics Ok
✓ Gain sufficient for IFE
✓ λ=248 nm vs 351 nm

Simulations & Theory
2D hydro-implosions
Develop better physics models.

Simulations & theory
3D hydro-implosions
Improved LPI simulations

More research or terminate laser DD effort

Summary

- Shock ignited direct drive looks very attractive for the energy application.
- Both simulations and experiments indicate KrF light significantly improves the laser-target interaction physics (improved coupling efficiency and suppression of deleterious LPI)
- High gain at relatively low drive energy (≤ 1MJ) could enable smaller lower cost IFE power plants.
- Good progress in the S&T of E-beam pumped KrF towards the goal of obtaining the efficiency and high system durability needed for IFE (next presentation).