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

International Workshop on ICF Shock Ignition
Laboratory for Laser Energetics
Rochester, NY
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Presented by:
Steve Obenschain
Plasma Physics Division
Naval Research Laboratory

Work by the NRL laser fusion research team

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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 wavelength (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 ($\lambda=248$ 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

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

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

- 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 $1 \times 10^{15}$ W/cm²
Igniter pulse is $\sim 10^{16}$ W/cm²

Gain curves show progress in direct-drive target designs from 1-D simulations.

- **Shock ignition with KrF**
- **Higher implosion velocity designs with KrF 2006**
- **Conventional direct drive with KrF(λ=248nm) 2001**
- **NIF “Rev5”**
- **Indirect drive ignition design**
Shock Ignition connects continuously to conventional direct drive implosions.

- 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.

250 kJ shock ignited target – NRL FASTRAD3D simulations
Simulations predict sufficient energy gains ($G$) for development of energy application.

- $G \sim 100$ with a 500kJ KrF laser
- $G \sim 170$ with a 1MJ KrF laser
- $G \sim 250$ with a 2 MJ KrF laser

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

$\eta$ = laser wall plug efficiency $\approx 7\%$ for KrF

$\rightarrow$ need $G \geq 140$
Shock ignition benefits from shorter $\lambda$ and zooming

1-D Hydrocode simulations
Fixed low aspect ratio pellet

<table>
<thead>
<tr>
<th></th>
<th>KrF $\lambda=248$ nm with Zoom</th>
<th>Nd:glass $\lambda=351$ nm with Zoom</th>
<th>Nd:glass $\lambda=351$ nm no Zoom</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Energy</td>
<td>230 kJ</td>
<td>430 kJ</td>
<td>645 kJ</td>
</tr>
<tr>
<td>Yield</td>
<td>22 MJ</td>
<td>24 MJ</td>
<td>23 MJ</td>
</tr>
<tr>
<td>Gain</td>
<td>97</td>
<td>56</td>
<td>35</td>
</tr>
<tr>
<td>Peak compression intensity (W/cm²)</td>
<td>$1.55 \times 10^{15}$</td>
<td>$2.2 \times 10^{15}$</td>
<td></td>
</tr>
<tr>
<td>Peak igniter intensity (W/cm²)</td>
<td>$1.6 \times 10^{16}$</td>
<td>$3.1 \times 10^{16}$</td>
<td></td>
</tr>
</tbody>
</table>

- 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
Orthogonal imaging of planar targets with monochrome x-rays

44 overlapped ISI-smoothed KrF laser beams

Nike is employed for studies of hydrodynamics and LPI

Collision with low density foam foil

Areal density ringing after short laser pulse
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

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

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

- Shorter \(\lambda\) suppresses LPI

Stimulated Raman scatter (\(n \approx 1/4 \, n_{cr}\))

\[
I_i \approx \frac{5 \times 10^{16}}{L_n^{-4/3}(\mu m) \lambda_0^{2/3}(\mu m)} \frac{W}{cm^2}
\]

Two plasmon decay

\[
I_i \approx \frac{5 \times 10^{15}}{L_n(\mu m) \lambda_0(\mu)} \frac{W}{cm^2}
\]
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.

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

Above threshold (10^{15} \text{ W/cm}^2) \quad T_{\text{hot}} \approx 30 \text{ KeV}

Below threshold

Nike planar LPI experiments with 1 ns pulse

X-ray signal

$T_{\text{hot}}$ 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

- 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.
- If 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.

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

- Electron beam
- Laser cell (Kr+F₂+Ar)
- E-beam window (hibachi)
- Pulsed power
- Laser Gas Recirculator
- KrF laser Physics
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 >10⁷ shots continuous

Components show > 300 M shots, no failures

High efficiency E-beam transport to gas

electron beam guided by tailored magnetic field

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

Ceramic Cathode

Patterned cathode

No physics limit on diode size

>7% wall-plug efficiency looks feasible.

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
</tr>
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<tbody>
<tr>
<td>Intrinsic (experiment)</td>
<td>12%</td>
</tr>
<tr>
<td>Pulsed power (experiment)</td>
<td>82%</td>
</tr>
<tr>
<td>Hibachi @ 800 kV (experiment)</td>
<td>80%</td>
</tr>
<tr>
<td>Optical train to target (est)</td>
<td>95%</td>
</tr>
<tr>
<td>Ancillaries (est)</td>
<td>95%</td>
</tr>
<tr>
<td>Global Efficiency</td>
<td>7.1%</td>
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</table>
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
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

Lower estimated cost

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

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.

Calculations indicate pellet should survive injection with background pressures up to 50 mTorr.
Target injection: LANL experiment indicates beneficial 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

Pure DT @ 19 k (NIF)
DT over foam @ 16 k
DT over foam @ 19 k

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

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

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

A Raffray, UCSD

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

First Wall: 
Tungsten armor on 
Low Activation Ferritic steel

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**

- Axis
- Polar cusp (2)
- Equatorial cusp
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

Present & near future

- OMEGA DD implosion experiments
- Nike LPI and hydro experiments
  - 3-5 kJ full intensity
- Simulations & Theory
  - 2D hydro-implosions
  - Develop better physics models.

Next steps

- NIF
  - Polar DD and LPI experiments
- KrF IFE beamline
  - ~20 kJ on target full intensity & large plasma
- Simulations & theory
  - 3D hydro-implosions
  - Improved LPI simulations

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

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

More research or terminate laser DD effort
A three stage plan for Inertial Fusion Energy (IFE) technologies developed in parallel with the science.

**Stage I**: 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

**Stage II**: Fusion Test Facility (FTF) ~250 MW Fusion power
- Demonstrate integrated physics / technologies for a power plant
  \[ \eta G > 6, \quad G \sim 100 \]
- Tritium breeding, power handling
- Develop/validate fusion materials and structures

**Stage III**: 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)

<table>
<thead>
<tr>
<th>Target Engagement:</th>
<th>First wall experiments &amp; modeling</th>
</tr>
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<tbody>
<tr>
<td>Glint system: accuracy 35 microns</td>
<td>Study threats on Chamber Wall</td>
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Developing two chamber concepts

<table>
<thead>
<tr>
<th>Engineered Wall</th>
<th>Magnetic Intervention</th>
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</table>

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

![Image of a mirror](image1)

10 M shots at 3.5 J/cm² (not a limit!)

**Penultimate Optics:**
Neutron Resistant Dielectric Mirror

**Laser Damage Threshold**
(Al₂O₃/SiO₂)

<table>
<thead>
<tr>
<th>No dpa</th>
<th>0.001 dpa</th>
<th>0.01 dpa</th>
<th>0.1 dpa</th>
</tr>
</thead>
<tbody>
<tr>
<td>86-87%</td>
<td>84-86%</td>
<td>78-83%</td>
<td>83-84%</td>
</tr>
</tbody>
</table>

**Target Fabrication:**
Mass Produced Foam Shells

![Image of foam](image2)

Estimate Target Cost 16 ¢ each

**Target Fabrication:**
Smooth DT ice layers over foam

![Graph showing RMS (μm) vs. L-mode number](image3)
References

Laser Inertial fusion energy technology


High Average Power :Laser Program  [http://aries.ucsd.edu/HAPL](http://aries.ucsd.edu/HAPL)

Shock Ignited direct drive designs


Fusion Test Facility (FTF) utilizing a KrF laser
