Laser Direct Drive: Scientific Advances, Technical Achievements, and the Road To Fusion Energy

Presented by
John Sethian
Naval Research Laboratory
Fusion Energy with Lasers and Direct Drive

- Pellet factory
- Spherical pellet
- Reaction chamber
- Array of Lasers
- Final optics
- Electricity or Hydrogen Generator
Why we believe direct drive with lasers can lead to an attractive power plant

1. Simplest target physics:

2. Laser (most costly component) is modular

3. Separate components lower cost of development

4. Simple spherical targets:
   facilitates mass produced “fuel"

5. Power plant studies economically attractive

6. We have made a lot of progress!!
We are committed to Direct Drive for the Fusion Energy Mission

### Indirect Drive (Chosen path for NIF)
- Hohlraum
- Pellet
- Laser Beams
- x-rays

- Relaxed laser uniformity requirements
- Complex targets & physics
- Predict moderate energy gain ($\leq 40$) at 1 MJ laser energy

### Direct Drive (IFE)
- Laser Beams
- Pellet

- Advanced lasers/ target designs overcome uniformity requirements
- Simpler targets & physics
- Predict Fusion Class Gains (> 140) at lower laser energy (500 kJ - 1 MJ)
Two laser options for Direct Drive: KrF and DPPSL
Both have potential to meet the IFE requirements

Electra KrF Laser (NRL)
$\lambda = 248$ nm (fundamental)
Gas Laser

Mercury DPPSL Laser (LLNL)
$\lambda = 351$ nm (tripled)
Solid State Laser

See talk by Frank Hegeler
Thursday PM

See talk by Chris Ebbers
Thursday PM
We encourage competition.
It leads to innovation and a better product.
And leads to it faster

[Image of race cars with text overlay]
KrF lasers have advantages for fusion energy

PHYSICS

- Deeper UV (248 nm vs 351 for glass):
  - Greater mass ablation rate and pressure at given intensity
  - Higher threshold for deleterious laser plasma instability (LPI) ~1.8x
    (so maximum ablation pressure is further increased)

- Focus of KrF beams can be readily "zoomed" to follow imploding pellet
  - increases coupling by 30%

- KrF has most uniform pellet illumination ➤.
  - 0.2% non-uniformity overlapped beams

ENGINEERING

- Industrial robust technology (used in industry, medical applications)
- Gas laser medium is easy to cool (tough to break gas)
Advances and Achievements

- target design
- lasers
- final optics
- target fabrication and engagement
- chamber
New Direct Drive Designs: Power plant class gains, much smaller laser

- **Shock ignition, $\lambda=248$ nm**
  - Soft Conventional Compression (< 300 km/sec)
  - Then spike to shock heat to ignition

- **Conventional Direct Drive (KrF or DPPSL)**
  - ~300 km/sec implosion

- **FTF Designs, KrF $\lambda=248$ nm**
  - Higher ablation pressure
  - 350 to 450 km/sec

- **NIF Indirect Drive**

- **Gain for Fusion Energy**
  - Enough for energy
  - ...at < 500 kJ
Shock Ignition predicts comparable gains as Fast Ignition... *without the complexities*

![Graph showing comparison between Shock Ignition and Fast Ignition]
Shock Ignition:
Shell accelerated to sub-ignition velocity (<300 km/sec), Ignited by converging shock produced by high intensity spike

Low aspect ratio pellet helps mitigate hydro instability

Laser Intensities
Peak main drive $\sim 1.5 \times 10^{15}$ W/cm$^2$
Igniter pulse is $\sim 10^{16}$ W/cm$^2$
High resolution 2-D simulations show shock ignition designs are robust against hydro instabilities

2-D Gain: 60x

2-D Gain: 78x

2-D Gain: 69x

250 kJ shock ignited target – NRL FASTRAD3D simulations

Andy Schmitt NRL
Target physics codes have been benchmarked with experiments on Nike Laser.

![Graph showing mass variation (mg/cm³) over time (ns) for Cryogenic Liquid D₂ rippled targets and a computer model.](image)
Laser driven instabilities cause problems:
- Produces high energy electrons that preheat DT fuel
- Scatters laser beam, reducing drive efficiency

One challenge, in any laser target design --- Predicting Laser Plasma Instabilities (LPI)
Nike experiment to study Laser Plasma Instability at prototypical intensities (up to $10^{16}$ W/cm$^2$)

Targets can be cryogenic – e.g. liquid deuterium

Jim Weaver NRL
Nike Experiments are encouraging:
Higher threshold for KrF
Onset of LPI $\sim 3 \times 10^{15}$, above target design point

These experiments: 12 Nike backlighter beams will be repeated @ 1 kJ with 44 Nike main beams
LLNL (LASNEX) simulations suggest hot electrons induced by spike may be a **good thing**

Gain 60 target may be able to withstand hot electrons up to 100 keV
Advances and Achievements

• target design
  • KrF lasers
• final optics
• target fabrication and engagement
• chamber
Electra Krypton Fluoride (KrF) Laser
- electron beam pumped gas laser

Electra KrF Laser
300 - 700 Joules
1 Hz to 5 Hz
> 7% wall plug efficiency (based on component R&D)

see talk by Frank Hegeler (Thurs PM) for details
Advanced Solid State Pulsed Power Demo:
1 M shots at 5 Hz, 400,000 shots @ 10 Hz

- Based on Commercial switches (component life > 300 M shots)
- > 80% efficiency
- Attractive cost: < $ 2 M for Electra (15 kJ)

see talk by Frank Hegeler (Thurs PM) for details
Hibachi foil durability has been a challenge. This is a Hibachi Foil.

Typical Foil lifetime: 5,000 - 15,000 shots
Plasma Physics to the rescue

Penning Ionization Gauge

Spectrometer tuned to look at Ar emission (>700 nm: below Ar, above everything else)

before

after

J Giuliani & R Jaynes (NRL)
The Smoking Gun

Penning
Ionization
Gauge
Pinhole
Early
Notification
Increasing A-K gap 10%, lowering charge volts 15%: Eliminated voltage reversal, *and hence foil emission*

**Red**
- A-K gap 5.3 cm
- Charge 43 kV

**Blue**
- A-K gap 5.9 cm
- Charge 36 kV
Electra continuous durability has been extended to the 90,000 shot range.

Electra Cell after 30,000 shot continuous laser run

- 90,000 laser shots (10 hrs) continuous @ 2.5 Hz
- 150,000 laser shots on same foils @ 2.5 Hz
- 50,000 laser shots on same foils @ 5 Hz
- 300,000 laser shots in 8 days of operation
- 500,000 e-beam shots since 12/31/2008

Most runs NOW limited by pulsed power
A video starring Electra
Advances and Achievements

• target design
• lasers
• final optics
• target fabrication and engagement
• chamber
The final optics train

CAD Drawing of Final Optics, Coupled with MCNP simulation of Neutron flux

Mohamed Sawan (Wisconsin)
Malcolm McGeoch (PLEX)
GIMM laser damage threshold:
> 3.5 J/cm² @ 10 M shots

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

Mark Tillack (UCSD)
Dielectric mirror appears to resist predicted neutron fluence (0.02 dpa) on second mirror

The "key":
Match neutron-induced swelling in substrate and mirror layers

Experiment:
Expose in HIFR (ORNL Reactor)
Prototypical fluence, temperature

Measurements:
Reflectivity
Laser damage threshold

<table>
<thead>
<tr>
<th>Laser Damage Threshold (Al₂O₃/SiO₂)</th>
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<tbody>
<tr>
<td>No dpa</td>
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<tr>
<td>86-87%</td>
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Lance Snead (ORNL)
Tom Lehecka (Penn State)
Mohamed Sawan (Wisconsin)
Advances and Achievements

- target design
- lasers
- final optics
- target fabrication and engagement
- chamber
**Target fabrication:**

- Mass produce foam shells that meet specs
- Fluidized bed for mass cryo layering
- Estimate Cost < $0.16 each

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100 mg/cc foam shell

x-ray picture of 4mm foam

Mass Production: 22 shells/min

Cryogenic Fluidized bed to make smooth DT ice

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**Diagram:**

- Laser A
- Laser B
- Photodiode Sensors
- Variable Speed Pump
- Triple Orifice Generator
- DAQ
- Input/Output
- PC
- Data

GA, Schaffer, UCSD
Recent target fabrication advances:

♦ Higher yield in non-concentricity
♦ Apply thin solid coat on foam during gellation

Higher percentage of shells that meet non concentricity (NC) specs

Proof of concept: Thin solid coating on Divinyl Benzine foam

Additional coating advances made at GA
Target Engagement:
Concept based on detecting "Glint" off the target.

Target Glint source  
Target  
Target Injector  

Focusing mirrors  
Grazing incidence mirror  

Vacuum window  
Wedged dichroic mirror  

Coincidence sensors  

Amplifier / multiplexer/ fast steering mirrors  

Dichroic mirror  
Align Laser  
Drive Laser  

Cat’s eye retroreflector  

Glint off target

Lane Carlson (UCSD)
**Target Engagement:** Bench test: Mirror steers laser beam to target within 34 μm. Need ~20
Advances and Achievements

- target design
- lasers
- final optics
- target fabrication and engagement
- chamber
The "first wall" of the reaction chamber must withstand the steady pulses of x-rays, ions and neutrons from the target.
## Chamber options

<table>
<thead>
<tr>
<th>Chamber Type</th>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>Solid wall/vacuum</td>
<td>Simplest, Eases laser / target issues</td>
<td>Materials challenge</td>
</tr>
<tr>
<td>Magnetic Intervention/vacuum</td>
<td>Small chamber, Really eases laser / target issues, The ion dump</td>
<td></td>
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<tr>
<td>Replaceable solid wall/vacuum</td>
<td>Eases laser / target issues, Mechanical/operational complexity</td>
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<tr>
<td>Gas in chamber</td>
<td>Smaller chamber, Challenging laser / target issues, Clearing Chamber (plasma)</td>
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<tr>
<td>Thick liquid walls</td>
<td>No materials issues (inc neutronics), Challenging laser / target issues, Droplet formation/ complexity</td>
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**Sawan, Wed SP3B-16**

**Gentile, Wed SP3B-21**

*combo*
Solid Wall Chamber: Experiments/Modeling

Thermo-mechanical cyclic stress:  Mostly Solved

Surface & Interface

Ions: RHEPP (SNL)
Laser: Dragonfire (UCSD)
Plasma Arc Lamp (ORNL)

Helium Retention: Remaining Major Challenge

IEC (Wisconsin)
Van de Graff (UNC)

0.2 to 22.3 FPD

Modeling (Wisc/UCLA)

Modeling (UCLA/Wisc)
First "Nano-Engineered" Tungsten helium retention experiments are encouraging

Mass loss rate: high at first, slows afterwards

28 kg/FPY (< 1 um solid)

Actual exposure (He⁺/cm²)
(From 10 - 90 keV = approx 5% total spectrum)

Sam Zenobia (Wisconsin)
**Magnetic Intervention:**
Cusp magnetic field keeps ions off the wall
(in Plasma Physics terms: Conservation of $P_\theta = rA_\theta = 0$)

Plasma expansion initially spherical
Ion cloud deforms as it encounters cusp
Ions, *at reduced power*, leak into external dumps

1. Physics demonstrated in 1979 NRL experiment:
2. NRL experiment modeled by D. Rose at Voss Scientific (2006)
An example of a Magnetic Intervention Chamber

Ions deflected downward by magnetic fields
Ion energy absorbed in Gallium Rain Ion Dissipaters™

Chamber radius: 5 m
Point cusps: 16 T
Main coils: 0.75 T

Energy absorption in Ga:
85% in first 10 mg/cm²
15% in next 100 mg/cm²

Only first layer evaporates
Gallium inventory enough
so mean temp rise < 300°C

NB Vapor P of Ga = 10⁻⁶T at 720 C

A.E. Robson, NRL (ret)
Objectives for next two years

• Nike: Experiments/theory show physics advantages of KrF.
  -- Refine/validate high gain designs

• Electra: Demonstrate >1 M shots continuous laser operation.
  -- with technologies capable of 300 M shots (e.g. all solid state)

• Develop critical IFE technologies.
  -- Mirrors, chamber concept(s), target fabrication / tracking, materials

If these are successful, next is a three stage program to IFE
A three stage plan for Laser Fusion Energy

**Stage I**  Develop full size components
- Laser module (e.g. 18 kJ 5 Hz KrF beamline)
- Target fabrication/injection/tracking
- Chamber design
- Refine basic pellet physics

**Stage II** Fusion Test Facility (FTF)
- Demonstrate physics / technologies for a power plant
- Develop/ validate fusion materials and structures
- Operating: ~2022
- Significant participation by private industry

**Stage III** Prototype Power plant(s)
- Electricity to the grid
- Transitioned to private industry
What makes a credible fusion energy program?

The only function of economic forecasting is to make astrology look respectable.

*John Kenneth Galbraith*
What have we accomplished? or, the justification for pursuing an energy program

- KrF based target designs show energy class gains < 1 MJ.
  Designs backed with experimentally verified codes
  KrF advantages demonstrated (LPI, hydro, uniformity).
  - Need experiments at higher energies, more robust designs

- KrF lasers demonstrated, with scalable technologies:
  Rep rate (2.5 - 5 Hz)
  Efficiency (> 7%) (with individual components)
  High energy rep-rate operation (250-700 J).
  Continuous operation (10 hr)
  Credible path to durability
  - Need integrated 1 M shot continuous demonstration

Continued on next slide....
What have we accomplished?

• Optics components resistant to prototypical neutrons, laser damage
  – Need larger sizes, need extension to 300 M shots (from 10 M)

• Can mass produce high precision foam shells for targets
  – Need higher yield, Need gas tight coating

• Demonstrated smooth DT ice over foam layer
  – Need mass production layering demonstration (Fluidized bed)

• Demonstrated target engagement using glint technique
  – Need another 14 um pointing (now at 34, need 20)

• Several viable chamber concepts, backed with experiments/theory
  – Need refinement, integrated, economical design

• Have conceptual designs for ancillary components:
  – Blanket, tritium handling/processing, vacuum system, power conversion
The Vision...A plentiful, safe, clean energy source

A 100 ton (4200 Cu ft) **COAL** hopper runs a 1 GWe Power Plant for **10 min**

Same hopper filled with **IFE targets**: runs a 1 GWe Power Plant for **7 years**