Laser inertial fusion energy is highly separable

Driver
To heat and compress the target to fusion ignition

Fusion chamber
To recover the fusion energy from the targets

LIFE Chamber

Target factory
To produce low-cost targets rapidly

Balance of Plant
To convert heat into electricity
Next-generation laser technology could result in a very compact LIFE engine
Laser  
2.8 MJ (1ω),  
2.3 MJ (2ω) @ 15 Hz  
14% η

$G_{\text{fusion}} = 51$  
$G_{\text{blanket}} = 1.2$

42 MW laser  
1807 MW fusion  
2168 MW thermal

Power cycle  
η = 61%

303 MWe  
(27% recirc)

1329 MWe

839 MWth

Process heat

25 MWe  
1001 MWe

Pumps / aux. power

To grid

1001 MWe

To grid
LIFE is a credible extension of NIF, ignition on NIF and ongoing developments in the nuclear industry

- NIF-like fusion performance
- NIF-based lasers
- Mass produced NIF-like targets
- Target injection and engagement
- Fusion environment
  - Protecting first wall
  - Laser beam propagation
Diodes are significantly more energy efficient than flashlamps.

Flashlamps:
- 400 W average power electrical-optical efficiency

Diodes:
- 30 kW average power electrical-optical efficiency
Laser diodes and helium gas cooling enable NIF-like architecture to meet LIFE requirements.

These technologies have been developed as part of the Mercury Project.
Diodes are experiencing aggressive learning

Continuous wave diode bar performance has increased by 35× since 1988

Diode bar prices are dropping with growing market

1 cm bar CW power vs year

1 cm bar 60% learning curve
Advanced lasers and modular systems make the facility small and enable rapid construction and maintenance.

- Modular (advanced architecture) lasers that could be factory built
- Separate first wall & blanket modules for rapid & independent replacement
Targets can be produced very cost effectively

- Targets will be made with technologies from high-volume manufacturing industries
  - Low-cost materials: pennies per component
    - Silicon mandrel: Ball bearing technology
    - High-density carbon capsules: CH4 pyrolysis
    - High-Z: <$0.01 per target
    - Low-Z foam: SiO2, Carbon
  - Automated fabrication/assembly processes:
    - Laser drilling/machining of capsules
    - Stamped cones and hohlraums
    - Robotic assembly and packaging
Examples of mass produced components that are comparable to LIFE requirements in volume, precision, and cost

<table>
<thead>
<tr>
<th></th>
<th>LIFE</th>
<th>Lego ®</th>
<th>Mil Spec Bullet</th>
<th>Aluminum Cans</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number/year</td>
<td>$3 \times 10^8$</td>
<td>$1.8 \times 10^9$</td>
<td>$9 \times 10^9$</td>
<td>$1 \times 10^{11}$</td>
</tr>
<tr>
<td>Dimensional tolerance</td>
<td>± 50 (\mu\text{m})</td>
<td>± 10 (\mu\text{m})</td>
<td>± 40 (\mu\text{m})</td>
<td>± 100 (\mu\text{m})</td>
</tr>
<tr>
<td>Cost</td>
<td>$0.20–0.30$</td>
<td>$0.06$</td>
<td>$0.21$</td>
<td>$0.012$</td>
</tr>
</tbody>
</table>

Bullets are an interesting comparison; they are multi-component, multi-materials, that tolerate high acceleration and high velocity.
Injection demonstration at GA to simulate the full length of a LIFE fueling system have demonstrated many objectives:

- Injection at 6 Hz and 400 m/s to 5 mm accuracy demonstrated
- Additional R&D needed for cryogenic targets and higher accuracy
LIFE targeting requirement is similar to that of other demanding systems.

Airborne Laser:

- \( \sim 1 \mu \text{rad} \) angular precision
- \( \sim 10 \text{ cm}, 100 \text{ km} \)

LIFE:

- 2 \( \mu \text{rad} \) precision
- \( \text{HS, } 50 \mu \text{m}, f = 25 \text{ m} \)

Developing an integrated target injection, in-flight tracking and beam engagement system is a key technical challenge.
Target fratricide and heating during injection are manageable

- DT ice preheat of 100 mK is deemed acceptable (and conservative):
  - Target injector parameters satisfy fratricide constraints:
    - Injector nozzle ~15 m from chamber center
    - Two mean free paths of neutron shielding (~15 cm) on shutter
    - 250 m/s injection velocity

- Hohlraum acts as thermal insulator to protect capsule during injection:
  - Radiation heating to capsule:
    - Polyimide transmits in the IR
    - Radiation shield (Al/polyimide/Al) gives 99% reflectivity
  - Convective heating of polyimide window dominates:
    - Heat transfer coefficient ~8 W/m²-K at window edge
    - Window heats to ~80% of decomposition temperature

- Several options for reducing target injection risk:
  - Higher velocities / shorter distances $\rightarrow$ reduced heating time
  - Tailored target output $\rightarrow$ reduced chamber gas density
  - Injection with cool gas plume $\rightarrow$ reduced $\Delta T$ and $h$
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X-rays and ion fluxes are simply mitigated.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target yield</td>
<td>120 MJ</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>15 Hz</td>
</tr>
<tr>
<td>Fusion power</td>
<td>1800 MW</td>
</tr>
<tr>
<td>Chamber radius</td>
<td>4 m</td>
</tr>
<tr>
<td>X-rays</td>
<td>14 MJ (12%)</td>
</tr>
<tr>
<td>Ions</td>
<td>12 MJ (10%)</td>
</tr>
</tbody>
</table>

Chamber fill gas can attenuate x-rays and ions to protect the first wall.
Thermally robust targets allow for a protective chamber gas to absorb all ions and 90% of x-rays.

Protective background gas re-radiates ion and x-ray energy over a timescale thermal conduction can effectively remove it.
Chamber conditions must support laser beam propagation for the next shot

- Base case design is robust with respect to chamber design:
  - 120 MJ fusion yield @ 15 Hz
  - 4 m radius
  - 2.5 $\mu$g/cc xenon

- Chamber design trades-off:
  - First wall protection $\rightarrow$ stop ions & attenuate x-rays in Xe/Kr
  - Target heating during injection $\rightarrow$ dominated by IR from 1$^{\text{st}}$ wall
  - Laser beam propagation $\rightarrow$ ~1% inverse Bremsstrahlung loss

- System optimization is likely to result in smaller chambers:
  - Beam propagation with increased gas densities
  - Gas cocktails for better x-ray attenuation
  - Tailored target output for fewer x-rays
Chamber designed for rapid replacement

- Vacuum vessel
- Coolant extraction plenum
- Laser beam tubes
- Coolant injection plenum
- Blanket module
- First wall module
Modular chambers have independent first walls that can be replaced without moving the blanket.
LIFE final optic system

Aspherical (astigmatic) pair of lithographic Fresnel lenses (1mm SiO₂) at 3-6 J/cm² laser fluence

Potential gas injection for final optic protection

Neutron pinhole “baffle”

Vacuum window

Frequency conversion

Phase plate to broaden focal spot for pinhole

Dielectric turning mirror

Shield wall

Neutron “pinhole” (10 cm²)
A fused silica Fresnel is an attractive option for the final optic.

Neutron-irradiated SiO₂ can be annealed to remove color centers.

Molecular dynamics simulations confirm SiO₂ self-annealing.

Thin Fresnel technology has been demonstrated at large aperture.
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Different LIFE blankets provide unique energy systems

LIFE blankets options
- Li-based salt to make electricity and produce T for other LIFE-based missions (pure fusion-base case)
- Coolant with U, DU or TH pebbles for Once-Through Closed Energy Production (> 99% burn-up)
- Coolant with fertile or fissile pebbles for Once-Through Closed Waste Burning (> 99% burn-up)
  — SNF
  — WG – Pu, HEU

1.0–4.0 MJ laser @ 10-15 Hz

Hot Spot ICF Targets @ ~10-15 Hz

ICF Gain 15-70 provides 150-1750 MW fusion

2 – 8 x 10²⁰ 14 MeV n/sec
Summary

- LIFE systems will be highly modular and more compact than NIF
- The high degree of separability inherent to IFE translates into a significant development path advantage
- LIFE could be fielded as a pure fusion plant or as a hybrid to complete waste-related missions
- A pilot plant could be operational a decade after NIF ignition and that a commercial power plant could be running a decade after that
LIFE
Laser Inertial Fusion Energy