KrF Lasers

Naval Research Laboratory
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Washington, DC 20375

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The goal for the Electra KrF Laser Program is to develop the technologies that can meet fusion energy requirements for durability, efficiency, and cost.

- Meet target physics and IFE requirements for laser beam uniformity and wavelength
- Wall plug efficiency > 6% (preferably > 7%)
- Operate at repetition rates up to 5 Hz
- Produce 400-700 J of laser light/shot per pulse
- Run continuously for tens of thousands of shots
- Technologies developed must scale to IFE size system
KrF lasers have short wavelength (248 nm), large bandwidth, and are based on pulsed power systems.

Short wavelength (248 nm) maximizes:
- **Target gain** (increases absorption and rocket efficiencies)
- **Target stability** (minimizes risk from laser plasma instabilities)
- **Laser-plasma interactions**

Demonstrated outstanding spatial uniformity and large bandwidth (>1 THz) on NIKE laser:
- **Decreases imprint** (hydrodynamic instabilities)

Straightforward zooming

**Pulsed power based** (low cost, industrial technology)

**High laser system efficiency** (predict 7% wall plug to laser light)
Electra’s main amplifier

Two-sided e-beam pumping: 500 kV, 100 kA, 140 ns FWHM
Operation of Electra’s main amplifier (oscillator)

Discharging through the 1:12 step-up transformer

Charging of the PFL to 1 MV (3-4 µs)

Matched diode provides 500 kV, 110 kA 140 ns pulse

Capacitor charging to +/- 43 kV (>160 ms)

Laser triggered switch
Operation of Electra’s main amplifier (oscillator)

Cathode generates electron beam

Electron beam ionizes laser gas

Diode

Magnet

Laser Gas

Kr + F₂ + Ar

1 mil SS pressure foil

cathode needs to be partitioned into strips

Ceramic cathode

Cathode generates electron beam

Electron beam ionizes laser gas
Operation of Electra’s main amplifier (oscillator)

Laser gas recirculates (provides cooling and quiescent flow)

e^- + Kr → Kr^* + e^-
Kr^* + F_2 → KrF^* + F
KrF^* + h\nu(248 nm) → Kr + F + 2 h\nu(248 nm)
Electra produced between 620 - 710 J of laser energy using high efficient velvet strip cathode.
Electra’s oscillator achieved an intrinsic efficiency of 9.7%...expect ~11% as an amplifier

As an IFE amplifier: KrF grade windows with AR coating
Amplification from input laser
Based on our research, an IFE-sized KrF system is projected to have a wall plug efficiency of ~7% (meets goal).

<table>
<thead>
<tr>
<th>Component</th>
<th>Description</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsed Power</td>
<td>Advanced Switch</td>
<td>87%</td>
</tr>
<tr>
<td>Hibachi Structure</td>
<td>No Anode, Pattern Beam</td>
<td>82%</td>
</tr>
<tr>
<td>KrF</td>
<td>Based on Electra expt’s</td>
<td>11%</td>
</tr>
<tr>
<td>Optical train to target</td>
<td>Estimate</td>
<td>95%</td>
</tr>
<tr>
<td>Ancillaries</td>
<td>Pumps, recirculator</td>
<td>95%</td>
</tr>
<tr>
<td><strong>Global efficiency</strong></td>
<td></td>
<td><strong>7.1%</strong></td>
</tr>
</tbody>
</table>

> 6% is adequate for fusion target gains > 100...
...and latest designs have 2D gains ~ 160
Durability tests – more than 16,000 shots in 24 hours

• 1\(^{\text{st}}\) day afternoon
  – 3740 shots @ 1 Hz (1 hour of continuous operation)
  – Laser output: 300 J per shot
  » Used “low quality” windows with 83% transmission
    (windows with 93% transmission yielded 400 J of laser output)

• 2\(^{\text{nd}}\) day morning
  – 1,352 shots @ 1 Hz
  – 10,015 shots @ 1 Hz (2.5 hours of continuous operation)
  – Laser output: 300 J per shot
  – 200 shots @ 2.5 Hz
  – 200 shots @ 5 Hz
  – 500 shots @ 5 Hz

Window transmission remained constant
Pressure foil: 1 mil stainless steel
Cathode: ceramic cathode (monolithic emission – not patterned)
Electra operated continuously for 10,000 shots (2.5 hours) laser output: 300 J / per shot @ 1 Hz
Last major challenge for the KrF laser system is durability. We are closing in on three technologies to address this:

1. Foil durability: Primarily an issue of thermal management

2. Cathodes: Demonstrate patterned emission from our durable ceramic cathode leading to high efficiency

3. Pulsed power: Achievable with new advanced solid state switch
We are developing three techniques to cool the foil

• Convection cooling by the laser gas
  Pro: Successful operation @ 1 Hz (foil temp < 200°C)
  Con: Foil temperature rises to 350-500°C @ 5 Hz operation

• Conduction cooling to hibachi ribs
  Pro: Simple cooling system
  Con: Requires close rib spacing, challenging e-beam transport through hibachi (may be reduced with advanced materials)

• Mist cooling of the foil (developed by Georgia Tech)
  Pro: Successful demonstration @ 5 Hz (foil temp < 140°C)
  Con: More complex system, lower e-beam transport efficiency
Convection cooling: Old louvers were replaced by “V” plate

First generation louvers

- Old louvers were bending
- Decreased gas flow velocity at foil
- Foil temp reached 500°C (too high for long life operation)
- Radiation cooling may play a role
- Stiffer louvers are under development

Currently in use

- “V” plate mimics “ideal” closed louvers
- Optimum gas flow velocity at foil
- Rep-rated oscillator laser output was not influenced by fixed “V” plate

Gas Velocity

Old louvers were bending

decreased gas flow velocity at foil

Foil temp reached 500°C (too high for long life operation)
Radiation cooling may play a role

Stiffer louvers are under development

“V” plate mimics “ideal” closed louvers
Optimum gas flow velocity at foil
Rep-rated oscillator laser output was not influenced by fixed “V” plate
Developed a durable cathode using ceramic honeycomb

Cathode has numerous examples for durability

<table>
<thead>
<tr>
<th>sides</th>
<th>Hz</th>
<th>shots</th>
<th>target</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>5x10,000</td>
<td>anode plate</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>10,000</td>
<td>laser gas</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>7,800</td>
<td>Ar gas</td>
</tr>
<tr>
<td>1</td>
<td>5</td>
<td>2x1,700</td>
<td>laser gas</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>500</td>
<td>laser gas</td>
</tr>
</tbody>
</table>
Ceramic cathode must be patterned into strips for high efficiency

Particle plot

B-field is altered locally at the cathode

Electron beam is compressed

→ Achieve higher current density without changing the A-K gap
Soft iron / velvet cathode yields 700 J of laser energy.

Ceramic cathode with soft iron will be tested on Front End.
 Newly demonstrated laser gated and pumped thyristor (LGPT) will be the basis for durable, efficient pulsed power

CONCEPT:
• All solid state
• Diode lasers flood entire thyristor with photons
• Ultra fast switching times (< 100 nsec)
• Continuous laser pumping reduces losses

PROGRESS:
• > 1,200,000 shots (multiple runs)
• Required specs (5 Hz, 16 kV, 1 kA/cm²)
• Has run @ 50 Hz
Advanced Pulsed Power System based on LGPT

This pulsed power architecture is being evaluated with the new Electra front end
The Electra Front End

a) Platform to develop advanced solid state pulsed power system
b) Provide 30-50 J of laser light input to the main amplifier

Has operated in e-beam mode @ 5 Hz, with very low jitter (<1000 ps)
Pulsed power runs > 100,000 shots without maintenance
The Electra Front End
Voltage and current diode waveforms

Time (ns):

Voltage (kV):

Current (kA):
Next generation KrF laser

Option 1

[Diagram showing laser cell, window, laser light, e-beam, mirror, and independent pulsed power systems.]

Distance from rear mirror (cm)

15 10 5 0

Time (ns)

200 400 500

I_OUT(MW/cm²)

10 x P_EB(MW/cm³)

10 x I_N(MW/cm²)

I(right)

I(left)

IASE

I_SAT

flat-top laser energy: 53.2 kJ

Intensity (MW/cm²)

Distance from rear mirror (cm)

3.4 meters

t1 = 50 t2 = 450

t = 200 ns
Higher e-beam pump power increases the intrinsic laser efficiency as well as the foil heat loading.

Diodes: 1 MV, 1.5 MA (total of both sides), 400 ns flat-top, 60 ns rise and fall
Pressure foil: 1 mil stainless steel

<table>
<thead>
<tr>
<th></th>
<th>Flat-top laser energy</th>
<th>Flat-top intrinsic efficiency</th>
<th>E-beam pump power</th>
<th>Diode current density</th>
<th>Foil loading factor</th>
<th>Compared to Electra</th>
</tr>
</thead>
<tbody>
<tr>
<td>Option 1</td>
<td>53.2 kJ</td>
<td>10.6%</td>
<td>627 kW/cc</td>
<td>37.6 A/cm²</td>
<td>9.2 W/cm²</td>
<td>2.2 times</td>
</tr>
<tr>
<td>Option 2</td>
<td>55.3 kJ</td>
<td>11%</td>
<td>836 kW/cc</td>
<td>50.2 A/cm²</td>
<td>12.3 W/cm²</td>
<td>3.0 times</td>
</tr>
<tr>
<td>Option 3</td>
<td>48.3 kJ</td>
<td>9.6%</td>
<td>314 kW/cc</td>
<td>18.8 A/cm²</td>
<td>4.6 W/cm²</td>
<td>1.1 times</td>
</tr>
</tbody>
</table>

All options have the same total e-beam energy deposition.
Next generation KrF laser

Option 1a

Shrinking the unpumped regions increases the laser output (and intrinsic efficiency)

laser light

2.2 meters

independent pulsed power systems

I_{OUT}(MW/cm^2)

10 \times P_{EB}(MW/cm^3)

10 \times I_{IN}(MW/cm^2)

t_1 = 50
t_2 = 450

I_{ASE}

I_{SAT}

I(right)

I(left)

flat-top laser energy: 60.3 kJ

intrinsic laser efficiency: 12%

t = 200 ns

Distance from rear mirror (cm)

Time (ns)
Main Amplifier for the next generation KrF laser: 50 kJ IFE beam line

Four electron beam generators per side each: 1 MV, 188 kA, 400 ns flat-top

Estimated cost of Pulsed power system:
- $30M (conventional)
- $50M (advanced switch)
Phase I goals are in sight with Electra

- Electra has produced 700 J/shot @ 1 Hz (700 W) and 400 J/pulse @ 5 Hz (2,000 W) in 100 second bursts

- Electra operated continuously and consistently for more than 2.5 hours: 10,000 shots @ 1 Hz (300 W)

- Oscillator results predict KrF intrinsic of efficiency ~11% for the Electra main amplifier

- Developed high transmission hibachi (>75% e-beam energy into gas)

- Demonstrated solid state switch, will be basis for durable, efficient (87%), cost effective pulsed power system

- Based on above, predict ~7% wall plug efficiency for IFE systems