Ultrahigh Brightness Laser Development at the Laboratory for Laser Energetics

E. M. Campbell
Deputy Director,
University of Rochester
Laboratory for Laser Energetics

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Collaborators

D. Haberberger, A. Davies, S.-W. Bahk, J. Bromage, J. D. Zuegel, and D. H. Froula

University of Rochester
Laboratory for Laser Energetics

J. Sadler and P. A. Norreys

University of Oxford

...and many others
LLE and collaborators are pursuing two paths for the development of multipetawatt, high-brightness lasers

- Raman plasma-wave amplifier
  - parametric amplification of a short seed pulse by stimulated Raman scattering in a matched plasma medium
- Optical parametric amplifier (OPA) pumped by multikilojoule Nd:glass laser
  - ~12-kJ (0.532-μm), 2.5-ns pulse pump (OMEGA EP) for OPA
  - large-aperture (80-cm), high-damage (300-mJ/cm²) grating for pulse compression [chirped-pulse amplification (CPA)]
Raman amplifiers: Exploit the nonlinear physics of laser–plasma interactions (LPI)’s

- Intense laser radiation can excite electrostatic waves in plasmas

**Step 1**
Laser light propagates through the plasma

**Step 2**
Oscillations in the plasma begin to radiate scattered light (linear Thomson scatter)

**Step 3**
The beating of the two light waves creates a ponderomotive force, pushing the particles into the troughs of the envelope

**Step 4**
If the bunching of the particles matches an electrostatic mode, the three waves become resonant and grow
If there is a resonance with electrostatic modes of the plasma, instabilities can result (example SRS, SBS)

- **Simulated Raman scattering (SRS)**
  - Laser light → Electron plasma wave (EPW) → Scattered-light wave
  - SRS occurs when:
    \[ \omega_0 = \omega_2 + \omega_{\text{EPW}} \]
    \[ \vec{k}_0 = \vec{k}_2 + \vec{k}_{\text{EPW}} \]

- **Simulated Brillouin scattering (SBS)**
  - Laser light → Ion sound wave (IAW) → Scattered-light wave
  - SBS occurs when:
    \[ \omega_0 = \omega_{\text{IAW}} + \omega_1 \]
    \[ \vec{k}_0 = \vec{k}_{\text{IAW}} + \vec{k}_1 \]

Raman amplifiers are “seeded” SRS.
National Plasma Science reports have identified plasma-wave (Raman) amplifiers as a potential for the next generation of pettawatt-class lasers

- Plasma [EPW ($\delta n_e/n_e \sim 1\%$)] is the medium that transfers energy from a long-pulse (ns) pump, high-energy laser to a short-pulse (~15 fs), low-energy seed laser

Manley–Rowe (energy and momentum conservation)

- $\omega_{\text{pump}} = \omega_{\text{seed}} + \omega_{\text{EPW}}$
- $\mathbf{k}_{\text{pump}} = \mathbf{k}_{\text{seed}} + \mathbf{k}_{\text{EPW}}$

High-energy compression gratings are NOT required.
Raman amplifiers require understanding and control of nonlinear plasma physics

- Goal: efficient energy transfer from long pulse pump to seed
  - pump depletion
- Challenges that limit efficiency and resonance condition and brightness (focusability)
  - filamentation
  - frequency detuning
  - amplitude of EPW
    - wave breaking
    - mode coupling
  - competition with plasma-wave interactions
    - Raman forward scattering of the seed pulse
    - Raman backscatter of the pump pulse

Pump intensity and plasma density are key controlling parameters.
Multidimensional particle-in-cell (PIC) codes have identified operating parameters for efficient pump-seed conversion

- **Strategy**
  - maximize Raman amplification of the pump
    - limit forward Raman scattering (gain < 10)
  - limit filamentation of the seed (gain < 10)

- **Strategy defines experimental parameters**
  - $I_{\text{pump}} < 5 \times 10^{14} \text{ W/cm}^2$
  - $2.5 \times 10^{18} < n_e < 5 \times 10^{18} \text{ cm}^{-3}$
  - $I_{\text{seed}} < 4 \times 10^{17} \text{ cm}^3$
A tunable seed laser is being built to access the optimal Raman amplification regime for a 1053-nm pump laser.

**Pump**

Multi-Terawatt (MTW) Laser System

- Nd:glass: **1053 nm**
- \(E_{\text{max}} = 75 \text{ J}\)
- \(\Delta t = 25 \text{ ps}\)

**Seed**

Optical parametric amplifier line (OPAL)

- \(E_{\text{max}} = 50 \text{ mJ (1100 nm to 1300 nm)}\)
- \(\Delta t \sim 0.1 \text{ ps}\)

The plasma density and seed wavelength will be varied to optimize amplification.
Research at LLE is exploring the laser–plasma physics with the goal of demonstrating an efficient petawatt plasma-wave amplifier

- Optical plasma densities
  - tunable pump and seed wavelengths
- Laser pump energy
  - ~75 J
- High-intensity seed pulse
  - \( E_{\text{seed}} \sim 75 \, \text{mJ} \)
  - \( I_{\text{seed}} \sim 2 \times 10^{14} \, \text{W/cm}^3 \)
- Homogeneous plasma
  - 4-cm-long gas cell
  - cold plasma (<70 eV)
    - limit EPW wave breaking
- Sophisticated diagnostics
  - optical Thomson scattering
  - EPW characterization
  - interferometry
    - plasma density
  - spectral phase interferometry (SPIDER)
    - phase and electric field of amplified laser pulse

\[ * \frac{E_{\text{pump}}}{E_{\text{seed}}} \sim 10^4 \text{ to } 10^6 \]  
(limits pump depletion and efficiency).
The goal of the present effort is to demonstrate the feasibility of a plasma-wave amplifier in the pump-depletion regime.

The next-generation ultrahigh-power, short-pulse system at LLE could use plasma-wave amplification as the final amplifier to achieve 100 PW.
LLE and collaborators are pursuing two paths for the development of multipetawatt, high-brightness lasers

- Raman plasma-wave amplifier
  - parametric amplification of a short seed pulse by stimulated Raman scattering in a matched plasma medium

- Optical parametric amplifier (OPA) pumped by multikilojoule Nd:glass laser
  - ~12-kJ (0.532-μm), 2.5-ns pulse pump (OMEGA EP) for OPA
  - large-aperture (80-cm), high-damage (300-mJ/cm²) grating for pulse compression [chirped-pulse amplification (CPA)]
LLE is developing a concept for a >50-PW single-aperture laser based on pumping an OPA with two OMEGA EP beamlines.

- The EP OPAL design at full scale would produce 75 PW (1.5 kJ at 20 fs) with high contrast.
Nd:glass lasers can pump large optical parametric amplifiers, producing bandwidth for sub-20-fs pulses

*Only KDP** and DKDP*** can be grown in boule sizes large enough for kilojoule amplifiers.

**KDP: potassium dihydrogen phosphate
***DKDP: deuterated potassium dihydrogen phosphate

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The multikilojoule Nd:glass OMEGA EP laser can serve as a pump for an OPA

- **OMEGA EP**
  - four beams
    - ~50 kJ at 1.05 \(\mu m\)
    - >25 kJ at 0.53 \(\mu m\)
    - >16 kJ at 0.35 \(\mu m\)
EP OPAL is an OPCPA* system, consisting of an ultra-broadband front end, large-aperture NOPA’s,** a compressor, and focuses on the OMEGA EP target chamber.

**OPCPA: optical parametric chirped-pulse amplifier**

**NOPA: noncollinear optical parametric amplifier**

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### Beamline 1
- Pumps to EPTC

### Beamline 2
- Pumps
  - ps (IR)
  - ns (UV)

### Beamline 3
- 6.3 kJ
  - 2.5 ns

### Beamline 4
- 6.3 kJ
  - 2.5 ns

### NOPA5 pump
- 100 J
  - 2.5 ns

### Compressor
- 1.6 kJ
  - 20 fs

### OMEGA EP target chamber (EPTC)
- ~75 PW
- ~$10^{24}$ W/cm²

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**Note:**
- 0.25 J, 2.5 ns, 160 nm
- 1053 nm
- 527 nm
- 810 to 1010 nm

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*OPCPA: optical parametric chirped-pulse identification*
Pump parameters for all noncollinear optical parametric amplifiers (NOPA’s): 527 nm, 2.5 ns, 2 GW/cm²

- Pump in: 4.5 cm (FWHM**)
  - 100 J
  - Signal out: 25 J

- Pump in: 35.5 cm (FWHM)
  - 6.3 kJ
  - Signal out: 1.5 kJ

- Pump in: 35.5 cm (FWHM)
  - ≤6.3 kJ
  - Signal out: ≤3 kJ

- Signal in: 73 cm (FWHM)
  - 2.3 kJ
  - Signal out: 20 fs
    - 1.6 kJ
    - 300 mJ/cm²

*VSF: vacuum spatial filter
**FWHM: full width at half maximum
A single-aperture >50-PW laser will require advances in several areas

- Advanced broadband, efficient, damage-resistant gratings
- Ultra-broadband wavefront control and focusing
- Large-aperture, high deuterated DKDP
- Damage-resistant short-pulse (broadband) coatings
- Diagnostics
- Ultra-broadband dispersion control
- NOPA gain control and adjustment
- Ultra-broadband front end

LLE is developing a scaled facility (MTW OPAL) to develop/demonstrate ultra-peak-power OPCPA lasers.
MTW OPAL has several technical and scientific goals

Goal 1: Develop and demonstrate laser technologies required for EP OPAL

Goal 2: Build operational experience with a mid-scale user facility

Goal 3: Grow a science program with ultrashort pulses
Although MTW OPAL is significantly smaller than EP OPAL, it uses the same technologies.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MTW OPAL</th>
<th>EP OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse width (FWHM)</td>
<td>15 fs</td>
<td>20 fs</td>
</tr>
<tr>
<td>Compressor beam size (FW 1%)</td>
<td>9 cm</td>
<td>60 to 80 cm</td>
</tr>
<tr>
<td>Compressor output energy</td>
<td>7.5 J</td>
<td>300 to 1600 J</td>
</tr>
<tr>
<td>Power</td>
<td>0.5 PW</td>
<td>14 to 75 PW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Technologies</th>
<th>MTW OPAL</th>
<th>EP OPAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced grating types</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Achromatic image relays</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>DKDP amplifiers</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Short-pulse coatings</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Short-pulse diagnostics</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
The MTW OPAL system uses the existing MTW laser at LLE to pump the final amplifier (NOPA5)

**Diagram Description:**

- **MTW front end**
  - 6 nm FWHM
- **OPCPA pump laser**
- **OPCPA**
- **SHG**: second-harmonic generation
- **MTW front end**
  - 6 nm FWHM
- **OPCPA laser**
- **UFE**
  - 200 nm FWHM
- **NOPA4**
- **Radial-group-delay compensator (RGDC)**
- **NOPA5**
- **Picosecond compressor**
- **MTW target chamber**
- **New target chamber**
- **Laser Development Laboratory (LDL)**
  - **LDL-Annex**
- **Operational**
  - UFE
- **Testing**
  - NOPA4
- **Under construction**
  - Radial-group-delay compensator (RGDC)
- **Ordered (except crystal)**
- **Optical design in progress**
- **527 nm**
- **830 to 1010 nm**
- **1053 nm**

*SHG: second-harmonic generation*
The UFE consists of a white-light–seeded chain of NOPA’s and a 1.5-ns stretcher.
The prototype UFE is operational and available to support MTW OPAL development

- UFE has been thoroughly characterized
- Additional measurements will be required after the full system is built (e.g., recompression)
Activation of the NOPA4 stages and transport to NOPA5 (DKDP final amplifier) will be completed this year.

NOPA4 stages are under construction

NOPA5 pump and signal transport have been designed and ordered

NOPA5

SHG table
A compressor chamber is being designed for multiple functions

- Demonstrate an achromatic relay (2× magnification)
- Recompress pulse from 1.5 ns to 15 fs
- Test gold (p-pol) and hybrid gratings (s-pol)
- Demonstrate femtosecond coatings (s- and p-pol)
- Develop a double-plasma mirror option for improved temporal contrast (~100×)
- Sample beams for short-pulse diagnostics

Optical design is underway and a full optomechanical design must be completed in 2016.
After MTW OPAL is completed, the technology readiness levels (TRL’s) for the main technical challenges will have improved to TRL 5–TRL 6

<table>
<thead>
<tr>
<th>Technical challenge</th>
<th>Current TRL</th>
<th>MTW OPAL</th>
<th>Progress</th>
</tr>
</thead>
<tbody>
<tr>
<td>Advanced gratings</td>
<td>2</td>
<td>5</td>
<td>Technology concept → Lab-scale prototype</td>
</tr>
<tr>
<td>Ultra-broadband wavefront control and focusing</td>
<td>2</td>
<td>5</td>
<td>Technology concept → Lab-scale prototype</td>
</tr>
<tr>
<td>Large-aperture, highly deuterated DKDP</td>
<td>2</td>
<td>5</td>
<td>Technology concept → Lab-scale prototype</td>
</tr>
<tr>
<td>Short-pulse coatings</td>
<td>3</td>
<td>5</td>
<td>Active R &amp; D → Lab-scale prototype</td>
</tr>
<tr>
<td>Short-pulse diagnostics</td>
<td>3</td>
<td>6</td>
<td>Active R &amp; D → Pilot-scale prototype</td>
</tr>
<tr>
<td>Ultra-broadband dispersion control</td>
<td>3</td>
<td>6</td>
<td>Active R &amp; D → Pilot-scale prototype</td>
</tr>
<tr>
<td>NOPA gain adjustment</td>
<td>2</td>
<td>6</td>
<td>Technology concept → Pilot-scale prototype</td>
</tr>
<tr>
<td>Ultra-broadband front end</td>
<td>5</td>
<td>6</td>
<td>Lab-scale prototype → Pilot-scale prototype</td>
</tr>
</tbody>
</table>
LLE vision: three world-class user laser facilities

- **OMEGA (60 beams)**
  - 30 kJ
  - 30 TW
  - 0.35 μm

- **OMEGA EP (four beams)**
  - Four beams (option 1)
    - ~16 kJ
    - ~8 TW
    - 0.35 μm
  - Two beams (option 2)
    - ~2 kJ
    - ~10 ps
    - 1.05 μm

- **EP OPAL (one beam)**
  - One beam
    - ~1.5 kJ
    - 20 fs
    - ~0.83 to 1 μm
Backup
A number of petawatt facilities are operational, but multipetawatt facilities are only in development.

<table>
<thead>
<tr>
<th>Name</th>
<th>Facility</th>
<th>Technology</th>
<th>Peak power</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apollon-10P</td>
<td>Laboratoire pour l’Utilisation des Lasers Intenses + Laboratoire d’Optique Appliquée + Institute Optique</td>
<td>OPCPA + Ti:sapphire</td>
<td>5 PW</td>
<td>Under construction</td>
</tr>
<tr>
<td>L4</td>
<td>Extreme Light Infrastructure-CZ + National Energetics</td>
<td>OPCPA + Nd:glass</td>
<td>10 PW</td>
<td>Under contract</td>
</tr>
<tr>
<td>–</td>
<td>Extreme Light Infrastructure-NP + Thales</td>
<td>OPCPA + Ti:sapphire</td>
<td>2 × 10 PW</td>
<td>Under contract</td>
</tr>
<tr>
<td>Vulcan 20 PW</td>
<td>Rutherford Appleton Laboratory (RAL)</td>
<td>OPCPA</td>
<td>20 PW</td>
<td>On hold</td>
</tr>
<tr>
<td>Exawatt Center for Extreme Light Studies</td>
<td>Institute of Applied Physics (IAP)</td>
<td>OPCPA</td>
<td>12 × 15 PW</td>
<td>Concept</td>
</tr>
</tbody>
</table>
The UFE consists of a white-light–seeded chain of NOPA’s and a 1.5-ns stretcher.
A UFE prototype has been built and testing is underway

- All parameters measured so far meet requirements
- Testing will be ongoing
  - operational maturity
  - spectral phase control for recompression
  - temporal contrast and prepulses
- A new stretcher is required for an EP OPAL-scale compressor
  - prototype: 1.5 ns/200 nm (7.5 ps/nm)
  - EP OPAL: 2.5 ns/150 nm (16.6 ps/nm)

Ultra-broadband front end for MTW OPAL
High power and intensity require large-aperture beams that are tightly focused

- Damage thresholds for femtosecond mirrors and gratings are in the 100’s of mJ/cm² range (cf., few J/cm² for ps)
- Tight focal spots place challenging requirements on the beam wavefront and the final-focusing optics

**Power versus compressor-beam size**

- Grating fluence = 300 mJ/cm²
- 200 mJ/cm²
- 100 mJ/cm²

**Intensity versus focal-spot width**

- $I = \frac{P}{\pi R^2}$
- $P = 75$ PW
- 50 PW
- 25 PW

**Intensity** ($\times 10^{23}$ W/cm²)

- 10
- 8
- 6
- 4
- 2

**Beam full width at 1% (cm)**

- 20
- 40
- 60
- 80

**Focal spot FWHM (μm)**

- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10
EP OPAL performance depends on the grating fluence and compressor beam size

Limited by size of current optics fabrication

<table>
<thead>
<tr>
<th></th>
<th>Grating fluence (20 fs)</th>
<th>Compressor beam size (FW 1%)</th>
<th>Diagonal for 45° angle of incidence</th>
<th>Compressor output energy</th>
<th>f-number and focal spot (μm)</th>
<th>Energy on target</th>
<th>Power</th>
<th>Intensity (W/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100 mJ/cm²</td>
<td>60 × 60 cm</td>
<td>110 cm</td>
<td>300 J</td>
<td>f/6</td>
<td>13</td>
<td>14 PW</td>
<td>1 × 10^{22}</td>
</tr>
<tr>
<td>Advanced gratings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>f/1.3</td>
<td>4.2</td>
<td></td>
<td>9 × 10^{22}</td>
</tr>
<tr>
<td>Increased beam size</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>f/1.3</td>
<td>4.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Full scale

|                         | 300 mJ/cm²              | 60 × 60 cm                   | 110 cm                              | 900 J                    | f/6                         | f/1.3          | f/1   | 3 × 10^{22}      |
| Advanced gratings       |                         |                              |                                     |                          | 13                          | 4.2             |       | 3 × 10^{23}      |
| Increased beam size     |                         |                              |                                     |                          | 10                          | 3.2             |       |                  |

- Energy on target: 290 J, 230 J
- Power: 14 PW, 12 PW
- Intensity (W/cm²): 1 × 10^{22}, 9 × 10^{22}
- Energy on target: 860 J, 700 J
- Power: 43 PW, 35 PW
- Intensity (W/cm²): 3 × 10^{22}, 3 × 10^{23}
- Energy on target: 860 J, 700 J
- Power: 43 PW, 35 PW
- Intensity (W/cm²): 3 × 10^{22}, 3 × 10^{23}

Advanced gratings

|                         | 300 mJ/cm²              | 80 × 80 cm                   | 149 cm                              | 1600 J                    | f/4.6                       | f/1            | f/1   | 1 × 10^{23}      |
| Advanced gratings       |                         |                              |                                     |                          | 10                          | 3.2             |       | 8 × 10^{23}      |
| Increased beam size     |                         |                              |                                     |                          | 1                           | 3              |       |                  |

- Energy on target: 1500 J, 1200 J
- Power: 75 PW, 62 PW
- Intensity (W/cm²): 1 × 10^{23}, 8 × 10^{23}
Challenges remain to scale femtosecond coating capability for meter-scale laser applications

- High film stresses for fully dense coatings
- $\lambda/4$ on a 1-m optic would require $\sim 16$-cm thickness (4-$\mu$m-thick coating)
- Current uniformity for 1 m masks with phase discontinuities
- Scaling femtosecond system geometry → 3.5-m chamber
- Match the dispersion over a curved optic aperture
- Enhanced/protected metals are preferred with sufficient laser-damage thresholds

Laser-damage thresholds at the correct pulse length, spectral bandwidth, and large aperture are critical to successful system scale-up.
Enhanced-metal coatings have been developed for the compressed-pulse section

- Several practical benefits for short-pulse transport
  - femtosecond damage thresholds comparable to dielectric mirrors
  - s- or p-polarized beam
  - low group-delay dispersion, stress-induced wavefront and sensitivity to coating thickness

<table>
<thead>
<tr>
<th></th>
<th>Al₂O₃: adhesion, environmental protection</th>
<th>Cu: environmental durability/adhesion</th>
<th>Ag: high %R</th>
<th>HfO₂/SiO₂: larger band gap versus Nb₂O₅ for improved LDT*</th>
<th>Nb₂O₅/SiO₂: maximum bandwidth and reflectivity</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>R (p-pol, 810 to 1010 nm)</th>
<th>&gt;97.4%</th>
<th>&gt;98.6%</th>
<th>&gt;99.3%</th>
</tr>
</thead>
<tbody>
<tr>
<td>GDD** (810 to 1010 nm)</td>
<td>2 fs²</td>
<td>13 fs²</td>
<td>35 fs²</td>
</tr>
<tr>
<td>LDT (N:1, 800 nm, 59 fs)</td>
<td>0.60 J/cm²</td>
<td>0.68 J/cm²</td>
<td>0.49 J/cm²</td>
</tr>
</tbody>
</table>

*LDT = laser-damage threshold  
**GDD = group-delay dispersion
Intermediate power levels are possible with smaller optics and two amplifiers

Pump parameters for all NOPA’s: 527 nm, 2.5 ns, 2 GW/cm²

- **Pump in:** 4.5 cm (FWHM) 100 J
  **Signal out:** 25 J
- **Pump in:** 26.6 cm (FWHM) ≤3.5 kJ
  **Signal out:** ≤0.88 kJ
- **Signal in:** 55 cm (FWHM) 0.43 kJ
  **Signal out:** 20 fs 0.30 kJ 100 mJ/cm²

- The full-scale infrastructure would be built for the NOPA crystals, compressor gratings, and mirrors
- Sub-aperture optics could be used for a >10-PW system during the early stages of operation
To support the science program, a concept for a joint target area is being developed

- A target area will be added west of LDL
- Both MTW and OPAL beams will be available for experiments
- The existing “Raman chamber” is shown
- Additional shielding, similar to what is used on MTW (5 cm of lead), would enable a large number of shots
A concept for the compressor chamber has been developed

- A detailed optomechanical design is required to advance this concept
- Requires novel beam-sampling schemes to effectively operate the system (no leaky mirror)
EP OPAL will use a two-element focusing system to provide experimental flexibility

- $f/4.6$ off-axis parabola (OAP) outside the target chamber
- Ellipsoidal plasma mirror* (EPM) inside the target chamber
  - part of the experimental design/target
  - disposable
  - could be concave or convex to tune the $f/#$

The scalability must be investigated to the kilojoule level.