Taming Plasmas and Controlling Laser Beams for Grand Challenge Applications

Laser-Plasma Amplifiers
- Raman Amplification

Laser Fusion
- 4th Generation ICF Lasers

Laser-Plasma Accelerators
- Dephasingless Laser Wakefield Acceleration

Advanced Light Sources for HED Facilities
- Nonlinear Thomson scattering with ponderomotive control

Can plasmas be used to achieve intensities above $10^{24}$ W/cm²?

Can laser-plasma instabilities be mitigated to enable high-yield inertial confinement fusion?

Can manipulating light in a plasma be used to achieve the dream of a TeV electron collider?

Can short-pulse lasers be used to meet the future High-Energy Density physics mission needs?

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Division Director, Plasma & Ultrafast Laser Science & Engineering Laboratory for Laser Energetics, University of Rochester

FESAC Meeting
Virtual
30 August 2021
Laser-plasma instabilities remains one of the greatest challenges to using high-power lasers for grand challenge applications

- Laser-plasma instability physics is inherently coupled to the plasma conditions and the plasma conditions are often dictated by the laser-plasma instabilities
- Thomson scattering provides a window into the electron motion within a plasma, which has allowed the laser-plasma instability physics to be decoupled from the uncertainties in plasma conditions
  - A better understanding of the plasma physics has led to an expanded design space for applications
- Manipulating laser-light provides opportunities to mitigate laser-plasma instabilities and overcome fundamental limitations of conventional systems
  - Broadband ultraviolet glass-lasers provide a path to LPI-free 4th generation ICF drivers
  - Spatiotemporal pulse shaping has opened avenues to in laser-plasma applications

Solutions to using high-power lasers in grand challenge applications exists through understanding plasma conditions and manipulating laser light
The University of Rochester’s Laboratory for Laser Energetics operates the world’s largest lasers in an academic setting.

**OMEGA EP**
- Operating since 2008
- 4 NIF beams
- 5 kJ/beam UV (10 ns)
- 2 CPA beams
- 0.5 kJ IR in 0.7 ps
- 1.5 kJ IR 10 ps

**OMEGA**
- Operating since 1995
- 60 beams
- 30 kJ UV on target

**EP OPAL**
- Proposed Facility
- 2 NIF beams
- 5 kJ/beam UV (10 ns)
- 2 beams
- 500 J/beam IR, 20 fs

**Fourth generation Laser for Ultrabroadband eXperiments (FLUX)**
- First light 2023
- $\Delta\omega/\omega > 1\%$ UV bandwidth
- 200 J UV, ns

**Multi-TeraWatt (MTW)**
- Operating since 2005
- 1 CPA beam
- 50 J IR, 1 ps

**Optical Parametric Amplifier Line (OPAL)**
- First light 2021
- 1 CPA beam
- 7.5 J IR, <20 fs
- Contrast $>10^{10}$

The University of Rochester lasers provide an outstanding environment of studying a wide range of plasma physics.
The community accesses the Omega Facilities through LaserNet, Laboratory Basic Sciences, National User Laser Facilities, and the NNSA laboratories.

The Omega Lasers support a national user program where more than 60 institutions participate in 60% of the experiments.
The PULSE Division is a center for innovative laser-plasma physics, impactful technology, world-class education, and engaged collaboration

PLASMA & ULTRAFAST LASER SCIENCE & ENGINEERING


Laboratory for Laser Energetics

Current Plasma Physics

Graduate Students

M. Ambat (ME, Shaw)
Z. Barfield (PAS, Froula)
P. Franke (PAS, Turnbull)
A. Hansen (PAS, Turnbull)
R. Henchen* (ME, Maximov)
L. Leal (ME, Maximov)
K. McMillen (PAS, Shaw)
A. Milder (PAS, Froula)
L. Nguyen (PAS, Palastro/Yin)
S. Nwabunwanne (ECE, Donaldson)
D. Ramsey (PAS, Palastro)
T. Simson (PAS, Palastro)
M. VanDusen-Gross (PAS, Rinderknecht)
Y. Zhao (ECE, Donaldson)

Current Undergraduate Students

K. Daub (Boni)
R. Ejaz (Boni)
T. Ha (Shaw)
J. Maltzahn (Boni)
H. Markland (Katz)

Community Collaborators

S. Jolly, F. Quéré
A. Colaitis
B. Malaca, A. Helm, J. Vieira
A. Arefiev
F. Tsung, W. Mori
S. Stoller, N. Vafaei-Najafabadi
C. Arrowsmith, G. Gregori
R. Bingham

University of Rochester, Laboratory for Laser Energetics

Driving innovation in science & technology through education & collaboration
Laser-plasma instabilities remain one of the greatest challenges to using high-power lasers in grand challenge applications.

Understanding the material properties (i.e., the plasma conditions) at the macro- and microscopic levels is critical to using high-power laser beams.
Thomson scattering has provided the window into the material properties of a plasma, which has enabled quantitative laser-plasma experiments.

Measurements of non-Maxwellian electron distribution functions

Milder et al. PRL127, 015001 (2021)

Measuring the plasma conditions is enabling the hydrodynamic uncertainties to be decoupled from the laser-plasma instability physics opening the design space for grand challenge applications.
Innovative technologies that manipulate light have historically advanced laser-plasma applications.

**Efficient Third-Harmonic Frequency Generation**

**Chirped-Pulse Amplification**
D. Strickland & G. Mourou

**Smoothing by Spectral Dispersion**

Controlling laser beams in a plasma through innovative technologies has been at the root of laser-plasma applications from the beginning of the field.
Laser-Plasma Amplifiers—a path to 100 PW lasers and $>10^{24}$ W/cm²

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Laser-plasma amplification has the promise to overcome current limitations in high-power amplification.

Laser-plasma amplifiers require:
1. understanding the plasma conditions to control laser beam propagation,
2. manipulating laser light to optimize the resonance—laser beams with the right wavelengths

A multi-disciplinary team has been assembled to address the plasma physics, laser science, and advanced diagnostics challenges.

**Raman Amplification Target Area**  
(completed January 2021)

**Novel Laser Technologies**  
(completed April 2021)  

Picosecond Thomson scattering measurements demonstrate the challenges in maintaining resonant plasma conditions*

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**Ultrafast Thomson scattering**

*Davies *et al.* PRL**122**, 155001 (2019)
To improve laser beam propagation, a high-temperature amplifier has been proposed*

Propagation of the pump laser is a challenge

Hot Raman Amplification

Vlasov Simulations

A proof-of-principle system scalable to high powers would demonstrate energy transfer efficiencies >30%, intensity gains >10, and output intensities >100× the pump intensity

Laser Fusion—a path to high yield and clean energy

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Laser-plasma instabilities set the maximum drive pressure for inertial confinement fusion and all pathways to high-yield and inertial fusion energy require LPI mitigation.

The history of ICF—a story of mitigation and control of laser-plasma instabilities through advancements in technology and improved physics understanding.
A series of experiments used Thomson scattering to isolate hydrodynamic uncertainties from laser-plasma instability physics to develop predictive models for ICF designs.

Higher temperature plasmas (>3 keV) are required for efficient laser beam propagation in hohlraums.

Non-Maxwellian distribution functions shift the CBET resonances used to tune symmetry in hohlraum experiments on the NIF.

Experiments demonstrate linear CBET energy transfer is robust.
To expand the ICF design space for high-yield implosions, LPI must be mitigated to enable higher intensities to be coupled to the capsules—high-bandwidth lasers provide the path.

Laser bandwidth $\Delta \omega / \omega > 1.5\%$ is predicted to mitigate hot electron generation, increase the laser absorption, and eliminate imprint, which will enable a robust ICF implosion.

**Cross-Beam Energy Transfer (Increased Drive Pressure)**

Follett et al., PRL 120, 135005 (2018)

**Hot-Electron Mitigation**

($n_{cr}/4$ ignition intensities)


**Imprint Mitigation**

(<1-ps asymptotic smoothing)

The Fourth generation Laser for Ultrabroadband eXperiments (FLUX) is under construction and will use the OMEGA LPI Platform to validate bandwidth modeling.

**Ultrabroad Band Laser** (concept demonstration)

A colinear OPA was used to amplify broad bandwidth long-pulse laser beam.

**Demonstrated Broadband UV Frequency Conversion**

Novel concept demonstrates efficient broad band ($\Delta\omega/\omega > 1.5\%$) UV frequency tripling.

**The FLUX laser will feed the OMEGA LPI Platform**

FLUX experiments will validate LPI modeling with bandwidth.

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*C. Dorrer et al., Opt. Express 28, 451 (2020)*

**C. Dorrer et al., Opt. Express 29, 16135 (2021)*
A successful technology demonstration (FLUX) will lead to a design for an upgraded OMEGA (i.e., using existing $1\omega$ laser driver) with ultra-wide bandwidth UV tripling.

A conceptual layout for a “OMEGA FLUX-60” leverages the existing infrared laser system, target area, and diagnostics.
Laser-Plasma Accelerators—a path to TeV electron accelerators

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Laser wakefield accelerators provide a promise to the next generation of High-Energy Physics electron drivers.

Spatiotemporal pulse shaping provides controllable velocity intensity peaks that can be sustained for long distances, which opens new ways to optimize laser wakefield accelerators.

Extending the pulse duration, produces a counter-propagating intensity pulse

The intensity peak is propagating faster than the group velocity of light

The intensity peak is counter propagating
Extending the pulse duration, produces a counter-propagating intensity pulse

The chromatic focusing creates an extended focal range, while the chirp sets the time at which each frequency comes to its focus providing control over the velocity of the intensity peak.
Flying focus opens a novel way to optimize laser wakefield accelerators by controlling the velocity of the intensity and extending the interaction length.

**Dephasingless Laser Wakefield Acceleration**

**Standard LWFA:** Acceleration length is limited by dephasing

$$a_0 \equiv 0.855 \frac{\sqrt{I}}{\lambda^2} \propto \sqrt{P / L}$$

**DLWFA:** Acceleration length is set by laser power

$$\tau_\Delta \propto \frac{1}{\sqrt{n_e}}$$

**Standard LWFA:** Density sets the laser’s pulse duration

$$c\tau \approx \frac{1}{\sqrt{n_e}}$$

**DLWFA:** Density is set by the laser’s pulse duration

**Standard LWFA:** Electron energy gain requires lower densities requiring longer laser pulses

$$\Delta E = qE_{LWFA} L \propto \sqrt{n_e} a_0^2 L \propto \sqrt{n_e} \frac{E_{laser}}{\tau}$$

**DLWFA:** Energy gain requires shorter laser pulses

$$\Delta E \propto \frac{E_{laser}}{\tau^2}$$

Spatiotemporal pulse shaping provides the opportunity to accelerate electrons to TeV energies in few-meter single-stage plasma without the need for a guiding structure.

**Figure:**
- **EP OPAL (500 J, 15 fs)**
- **Dephasingless LWFA**
- **MTW OPAL (7.5 J, 15 fs)**
- **Traditional LWFA**
- **OPAL (NOPA4) (200 mJ, 15 fs)**
- **BELLA (2019)**
- **Dream Beams (2004)**

Advanced Light Sources—a path to light sources with short-pulse lasers

**Outline**

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Short-pulse laser could drive future light sources that have the potential to be compact and provide unique capabilities for high-energy density facilities.
Nonlinear Thomson “Compton” scattering has the potential to produce high-energy photons beams from high-power lasers.
Spatiotemporal pulse shaping can control the ponderomotive force significantly improving the power scattered, the scattered photon energies, and the scattered emittance.

**Nonlinear Thomson scattering with ponderomotive control**

**Scattered power and frequency**

- Fundamental harmonic
  - $\gamma_0 = 5$
  - Matched
  - Traditional

- Scattered power
  - $a_0 = 3$, $\gamma_0 = 5$

**Scattered Emittance**

*D. Ramsey et al., In Review (2021)*
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