Goals

1. Identify methods for next generation light intensities
2. Identify new effects in highly compressed plasma
3. Formulate general description of fundamental wave effects

Supported in 2019: Y. Shi, E. Kolmes and V. Munirov (graduate students);
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M. Edwards *19 (LLNL)

This talk will cover:
1. Underlying motivation
2. Some recent work
3. Mainly present directions
K. Qu and N. J. Fisch,
*Creating localized plasma wave by ionization of doped semiconductors*,

M. R. Edwards, Y. Shi, J. M. Mikhailova, and N. J. Fisch,
*Laser Amplification in Strongly-Magnetized Plasma*,

R. Gueroult, Y. Shi, J. M. Rax, and N. J. Fisch,
*Determining the rotation direction in pulsars*,
Nature Communications 10, 3232 (July, 2019).

K. Qu and N. J. Fisch.
*Laser frequency upconversion in plasmas with finite ionization rates*,
Physics of Plasmas 26, 083105 (August, 2019).

V. M. Munirov and N. J. Fisch,
*Radiation in equilibrium with plasma and plasma effects on cosmic microwave background*,
Physical Review E 100, 023202 (August, 2019).
Recent Ph.D. Dissertations acknowledging support from NNSA

V. Geyko *17 (LLNL)
D. Ruiz *17 (SNL)
S. Davidovits *17 (LLNL)
Y. Shi *18 (LLNL), Plasma Physics in Strong Field Regimes (co-advisor H. Qin)
M. R. Edwards *19 (LLNL) Ultrafast Sources of Intense Radiation (advisor J. Mikhailova)

Patents acknowledging support from NNSA

V. I Geyko and N. J. Fisch, Otto and Diesel Cycles Employing Spinning Gas,
US patent Application 14/669,936, Filed March 26, 2015
Major Goals in Next Generation Light Sources

1. Highest intensity light beyond chirped pulse amplification
   a. at optical wavelengths
   b. at shorter wavelengths (no CPA competition)

2. Highest power light at ever shorter wavelengths
   a. Megajoules available at optical wavelengths
   b. Efficient upconversion to shorter wavelengths

Solutions lie through mediation of light in plasma
CPA - chirped pulse amplification

1. Short light pulse from a laser.
2. The pulse is stretched, which reduces its peak power.
3. The stretched pulse is amplified.
4. The pulse is compressed and its intensity increases dramatically.

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How can light be compressed in time in plasma?

Goal: Reach laser intensities higher than possible using material optical elements

CPA techniques are limited by material properties

Limitation in intensity at grating ~ TW/cm² at 1μ
Limitation in fluence ~ J/cm² at 1μ and 1-10 ps

But plasma is not so limited (nonrelativistic at TW/cm² at 1μ)
Resonant Raman Amplification and Compression

- pump beam
- seed pulse
- resonance condition
- amplified pulse
- depleted pump
- Self-similar “π-pulse” regime
  Malkin, Shvets, and Fisch (PRL, 1999)

\[ \omega_a - \omega_b = \omega_p \]
\[ \vec{k}_a - \vec{k}_b = \vec{k}_p \]

Goal:
- focused intensity at 1 micron
- \( \sim 10^{25} \text{ Wcm}^{-2} \)
Creating plasma waves by ionizing doped semiconductors

- Ionize periodically aligned p-n junction semiconductors.
- Differential doping creates electrostatic fields $E \sim 100$ kV/cm.
- Upon ionization, the E-fields initiate plasma waves.
- Get quasi-homogeneous ion density. Issues in collisional damping and dissipation in ionization.

Flash ionization upshifts frequencies
In gradient, produce chirped pulse, allowing recompression.

High-efficiency, resonant frequency-doubling in very under-critical plasma


Towards Megajoule X-ray Lasers via Relativistic 4-Photon Cascade in Plasma

\[ k_1 + k_2 = k_3 + k_4 \]
\[ \omega_1 + \omega_2 = \omega_3 + \omega_4 \]

\[ \omega_i^2 = c^2 k_i^2 + \omega_p^2 \]

MJ in optical \( \rightarrow \) MJ in x-ray in 10 frequency doublings

MJ in optical \( \rightarrow \) kJ in x-ray at 50% efficiency in each stage
Frequency Doubling via 4-wave interaction in very under-critical plasma

Pump pulses (1) and (2) → amplified pulse (3) and a disposable laser pulse (4).

Decouples plasma amplification from plasma resonance
1. Insensitive to plasma inhomogeneities
2. Low plasma density delays filamentation instability of output pulse
3. Automatic resonance — since (4) is generated and lost, carrying entropy
4. Near doubling of frequency
5. Many possible resonances
In principle, high efficiency, reasonable growth distance

For \( k_1 \approx k_2 \) and \( k_4 \ll k_3 \), nearly all energy flows to pulse 4

Linear growth rate

\[
\gamma \approx 3 \omega_p^2 k_{1\perp} a_1^2 \frac{1}{2k_1^2 \sqrt{\omega_3 \omega_4}}
\]

For \( a_1=0.1 \), \( k_{1\perp}=k_1/7 \), \( \omega_4=\omega_1/5 \), \( \omega_p=\omega_1/50 \), \( \lambda_1=350 \text{ nm} \)

\[
c / \gamma \approx 30 \text{ cm}
\]
Waveguide implementation (reflection at grazing angles)

60 cm amplification enables 2 exponentiations in amplitude, or 4 exponentiations in intensity

\[ a_1 = 0.1, \, k_{1\perp} = k_1/7, \, \omega_4 = \omega_1/5, \, \omega_p = \omega_1/50, \, \lambda_1 = 350 \text{ nm} \]

\[ P_{cr} = 4.25 \text{ TW} \]
\[ R = \sqrt{2} \omega_1 \lambda_1 / \pi a_1 \omega_e \approx 0.08 \text{ mm} \]

2 pump implementation: \( P = 2P_{cr} = 8.5 \text{ TW} \)
in over-moded cylindrical channel
azimuthal wavenumbers perpendicular
ground state radial mode

8 pump beams
Avoiding Transverse Filamentation Instability at Overcritical Powers

Solution: Use multiple weakly-coupled pumps with each below the critical power

Coupling is weak enough if all sub-pumps are separated by \( \delta \omega \) and \( \delta k_\perp \) satisfying

\[
(\delta \omega / \omega_p - 1) \frac{\delta k_\perp^2 c^2}{\omega_p^2} \gg a_1^2
\]

which is a mild condition accommodating many pump pulses
Opportunities in higher order nonlinear laser interactions

• Mildly relativistic intense laser pulses, with quiver electron velocity $v$ small, can be expanded in powers of $a = v/c \ll 1$.

• For large laser power below the critical power of relativistic self-focusing, $P_{cr} = m^2 c^5 \omega^2 / e^2 \omega_e^2 \approx 17 \omega^2 / \omega_e^2$ GW, require $\omega/\omega_e \gg 1$.

• Regimes with $\omega_e/\omega \ll a \ll 1$ are of interest, with rates of nonlinear $N$-wave interactions $\sim a^{N-2}$.

• Finding the dominant interaction at mildly small $a$ is complicated by presence of other small parameters.

• 6-photon interactions hold particular promise for frequency tripling.
Preliminary Studies: Optimizing Focal Spot for 4-wave Seed Amplification

A. Griffith et al (2020)

Over-focusing:
Large dump beam dispersion
Short pump-seed overlap
⇒ Wide and low energy amplified seed

Moderate-focusing: $w_0 = 12$
Less dump beam dispersion
Depleted pumps
⇒ Higher intensity amplified seed
⇒ 20% of total pump energy captured

Under-focusing:
Lower intensity pumps
weaker nonlinear interaction
⇒ Energy left on the table for seed

Solve coupled-mode equations
View in seed frame
Preliminary PIC Simulations: Filamentation seeds Forward Raman Scattering

K. Lezhnin et al.

transverse filamentation & FRS pulses

uniform underdense plasma $n_e/n_c=0.2$

laser pulse $I=3 \times 10^8$ W/cm$^2$, 100 fs micron wavelength

Kinetic simulations show simultaneous appearance of FRS, BRS & filamentation

QED laser intensity with Colliding e-Beams

Schwinger limit \(E_{cr} \sim 1.3 \times 10^{18} \text{ V/m}\) for \(e^- - e^+\) creation in vacuum.

Reach \(E_{cr}\) with state-of-the-art lasers in rest frame, with \(E^* \rightarrow \gamma E > E_{cr}\), when colliding with an energetic \(e^-\) beam.

When \(\chi = E^*/E_{cr} \gg 1\), the QED cascade can create a pair plasma

Each \(e^-\) can create \(\sim \chi = 25\) pairs.
Pair energy decreases to \(\gamma \sim 100\) via synchrotron radiation.

Difficulties in observing collective effects of pair plasmas

• High pair energy \((\gamma > 100)\) → increased particle mass → low plasma frequency

• High velocity \((\sim c)\) → difficult to detect plasma evolution while tracking

• Small dimension \((L \sim \mu m)\)
  • The pair size \(L < \lambda_D\) (Debye length) → not quasi-neutral
  • The pair size \(L < l_s\) (skin depth) for typical lasers/RF waves → no reflection
  • The cut-off wavelength \(\lambda_{CO} > a few hundred \mu m\)
Signature of collective plasma effects: laser frequency upshift

Pair plasmas generated inside laser field.

$$\omega_0 = ck \rightarrow \omega = \sqrt{\omega_p^2/\gamma + c^2k^2}$$

Laser frequency increases with pair increase
or with pair energy decrease

3 Signatures in laser spectrum

1. Blue shift

2. Diffraction

3. Frequency Chirp
Frequency upshift --- QED-PIC simulations

Frequency upshift linearly increases with $e^-$ beam density and $e^-$ beam energy:

\[ n_p \sim \tilde{X}_e n_e, \quad \gamma f \sim a_0. \]

\[ \Delta \tilde{\omega}^2 \sim \frac{2\tilde{X}_e n_e}{n_c a_0} \sim 4\gamma_0 \frac{\hbar \omega_0}{m_e c^2} \frac{n_e}{n_c} \]

Frequency upshift is, however, not sensitive to laser intensity:
PIC simulation

- Gaussian Laser: 0.8\(\mu m\), 50fs \(\times\) (5\(\mu m\))^2, 6 \(\times\) 10^{22} W/cm^2, \(\alpha \approx 160\)
- \(e^-\) beam: 300GeV, 1nC (Gaussian distribution 1\(\mu m^3\), 4 \(\times\) 10^{20} cm^{-3})
- Created pair plasma: \(~3.2 \times 10^{22} \text{ cm}^{-3}\), \(\gamma \approx 100\)
- Laser spectrum: \(\Delta \omega_{center}/\omega_0 \approx 0.2\%\), \(\Delta \omega_{chirped,max}/\omega_0 \approx 3\%\).
Summary

1. **Goal:** Highest intensity light beyond chirped pulse amplification
   a. Could initiate Raman compression with plasma wave
   b. Suggestion: ionize p-n junction to produce plasma wave (dissipative)

2. **Goal:** Upshift optical light at high power
   a. Ionization upshift and stretching cascade – (dissipative)
   b. Resonant 4-wave: in principle highly efficient

3. **Goal:** 4-photon plasma-mediated upconversion – optical to x-ray
   a. Use density just for coupling → insensitive to inhomogeneity
   b. Solve critical power by multiple resonances
   c. Carry off entropy in disposable pulse 4
   d. Get MJ optical to MJ x-ray in 10 stages (or kJ at 50% efficiency)!

4. **Goal:** Identify signatures of pair plasma
   a. Upshift optical light, identify features in frequency chirp and radiation pattern
   b. Suggests opportunity in co-locating laser and beam sources!