Acceleration of protons and electrons by ultraintense lasers, and its implications to laboratory astrophysics

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High-energy high-power lasers try to squeeze matter.

National Ignition Facility (USA)

\[ \frac{10^6 \text{ J}}{\text{a few } 10^{-9} \text{ s}} \approx 0.5 \times 10^{15} \text{ W (0.5 PW)} \]

for inertial confinement fusion

focusing on few mm size
\[ I \approx 5 \times 10^{16} \text{ W/cm}^2 \]

approx. 270 m x 120 m

https://lasers.llnl.gov
High-intensity high-power lasers try to tear matter.


\[
\frac{30 \text{ J}}{30 \times 10^{-15} \text{ s (30 fs)}} = 10^{15} \text{ W (1 PW)}
\]

for ultraintense laser-matter interactions

focusing on few μm size

\[ I \sim 10^{23} \text{ W/cm}^2 \]

World’s first and World’s strongest femtosecond petawatt lasers (being upgraded to 4 PW)

Types of high-power lasers
Material response depends on laser intensity: more rooms at higher intensity

Quantum vacuum
- pair creation, dielectric vacuum

R p, UltraR e, nucleons
- Direct p drive, radiation reactions, photonuclear processes

R e, NonR p
- HHG, self-focusing, transparency, self-steepening, laser wakefields, indirect p drive

NonR bound/free e
- non-perturbative nonlinear optics: HHG / ATI / …

Modified from Tajima et al., Optik & Photonik, 2010
Today’s strongest lasers can drive electrons relativistic: \( K \cdot E \geq m_e c^2 \).

Ponderomotive potential: average kinetic energy under EM field

\[
U_p = m_e c^2 \cdot \frac{a_0^2}{4}
\]

\[
a = \frac{eE}{m_e c \omega} \quad \text{dimensionless}
\]

\[
a_0 = 0.855 \cdot \sqrt{I_{18} \cdot \lambda_{\mu m}^2}
\]

\( I_{18} \): irradiance in \( 10^{18} \) W/cm\(^2\)

Ex.) \( a_0 = 1 \) \& \( \lambda = 0.8 \) \( \mu \)m
\( \rightarrow I = 2.14 \times 10^{18} \) W/cm\(^2\)

\( m_e c^2 \approx 0.5 \) MeV

\( \hbar \omega_{800 \text{ nm}} = 1.5 \) eV

\( I_p(H) = 13.6 \) eV

\( a_0 \geq 1 \Rightarrow U_p \geq m_e c^2 \gg I_p, \hbar \omega \)

Relativistic laser-plasma interactions
Radiation pressure pushes electrons, of which Coulomb force pulls protons.

The target should be so thin that the electron layer can be pushed as a whole and so thick that the laser pulse can be reflected well. Usually, $d \sim \delta = \frac{c}{\omega_p} \sim \text{nm} (\lambda = 800 \text{ nm})$. 

Radiation pressure acceleration of protons
In radiation pressure acceleration (RPA), $E_{\text{max}} \propto I^2$ or $I$, implying energy transfer into collective motion rather than into thermal motion.

\begin{align*}
E_{\text{max}} \propto I_L & \quad \text{Relativistic proton} \\
E_{\text{max}} \propto I_L^2 & \quad \text{Nonrelativistic proton}
\end{align*}

\begin{align*}
\mathbf{p}_{\text{photon}} & \propto I_L \\
\mathbf{p}_{\text{proton}} & \propto \mathbf{p}_{\text{photon}} \\
E_{\text{proton}} & \propto \begin{pmatrix} \mathbf{p}^2 & \text{nonrelativistic} \\ \mathbf{p} & \text{relativistic} \end{pmatrix} \\
E_{\text{proton,max}} & \propto \begin{pmatrix} I_L^2 & \text{nonrelativistic} \\ I_L & \text{relativistic} \end{pmatrix}
\end{align*}
RPA is efficient when radiation pressure balances Coulomb pressure.

\[
\frac{\text{Coulomb force}}{\text{Radiation pressure}} = \frac{\pi^2 \cdot \left( \frac{n_e}{n_c} \right)^2 \cdot \left( \frac{d}{\lambda} \right)^2 \cdot \frac{1}{a^2}}{a^2 \cdot \sigma^2}
\]

\[
\sigma = \frac{n_e}{n_c} \cdot \frac{d}{\lambda} \text{: normalized areal density}
\]

\[
\xi = 1 \text{: balance condition}
\]

\[
a = a_0 / \sqrt{2} \text{ (circ. pol.)}
\]

\[
\text{ex). } n_e = 200 \cdot n_c \rightarrow a_0 = 888 \cdot \frac{d}{\lambda}
\]

For a realizable magnitude of \(a\), the thickness should be a very small fraction of the wavelength.
Experimental setup

PW laser beam after plasma mirror
- Size of beam profile: 0.2 m
- Pulse duration: 30 fs
- Laser energy: 8.3 J
- Temporal contrast: < 10^{-11}

Thomson parabola
- E field
- B field
- Collimator (0.3mm)
- Magnet (0.4T)
- Electrode (20kV)
- Metal mirror
- Lens
- CCD

Target (10-100nm)+holder

F/4 OAP


Radiation pressure acceleration of protons
RPA was demonstrated clearly and 93-MeV protons were obtained.

\[ a_0 = 10^{-19} \]

[Graphs showing the relationship between laser intensity and maximum proton energy, and the effect of target thickness.]

3-dimensional relativistic particle-in-cell simulation (Vlasov+Maxwell) shows energetic proton bunches.

Phase space distribution of protons ($z$, $p_z$)

Radiation pressure acceleration of protons

arXiv:1411.5734 [physics.plasm-ph]
High-energy protons enable highly localized energy deposition in matter.

National Cancer Center (Korea)
Laser proton acceleration (LPA) may enable a more compact, economical beam source for cancer therapy.

- Applications of laser proton acceleration

- Research centers/projects dedicated to LPA-based cancer therapy
  - Germany: OncoRay Center (Dresden)
  - Japan: Photo Medical Research Center (Kansai)
  - France: European Proton Therapy Assisted by Ultra-Intense Laser (Paris)
  - ...

![Diagram of accelerator-based cancer therapy and laser-based cancer therapy](image)
LPA can provide a high-energy proton beam of ultrashort duration, low emittance, and synchronization with the driving laser pulse.

**Highly laminar, ultrafast source**
Emittance < 0.3 mm mrad, 0.004 mm mrad (100-fold better than accelerators)

**Probing dynamic electrostatic field**

**Proton-driven fast ignition**
Key, Phys. Plasmas (2007)

**Isochoric heating for warm dense matter generation**
The wakefield of an intense laser pulse can accelerate electrons up to GeV in cm.

$E_{\text{Coulomb}} > 1 \text{ GV/cm}$

$E_{\text{Coulomb}} < 1 \text{ MV/cm}$ for conventional accelerators
3-dim. relativistic particle-in-cell simulations depict the mechanism in detail.

Nature photonics 2, 571 (2008)

Laser wakefield acceleration of electrons
Experimental setup

Laser wakefield acceleration of electrons

Electron energy

Electron profile

Electron spectrometer 30 cm, 1.33 T

Dual-stage gas target

Holed mirror

Dual-stage gas Jet

PW laser pulse (E=25~30J, τ=30-100fs)

Focusing Mirror (f=4m)

10-mm He jet

Gas puff 1 (4mm)

Gas puff 2 (10mm)

4-mm He jet

Laser wakefield acceleration of electrons
Two-step acceleration scheme yielded 3-4 GeV electrons.


Laser wakefield acceleration of electrons
By controlling the spectral phase of the laser pulse, the profile of the ponderomotive force can be controlled to lead to better beams.
Laser-accelerated electrons can be used to generate $\gamma$-ray beams and study multiphoton QED.

Applications of laser wakefield acceleration of electrons

Corde et al., Rev. Mod. Phys. 85, 1 (2013)

\[ a_0 = 0.3, \gamma_e = 80 \ (1996) \]
\[ \rightarrow a_0 = 100, \gamma_e = 8 \ (2016) \]
High-power lasers provide extreme physical conditions unavailable with other terrestrial means.

<table>
<thead>
<tr>
<th>physical quantities</th>
<th>conventional means</th>
<th>high-power laser</th>
</tr>
</thead>
<tbody>
<tr>
<td>E (quasistatic)</td>
<td>$10^8$ V/m (accelerator)</td>
<td>$10^{12}$ V/m</td>
</tr>
<tr>
<td>E (electromagnetic)</td>
<td></td>
<td>$10^{14}$ V/m</td>
</tr>
<tr>
<td>B (quasistatic)</td>
<td>$10^6$ gauss (superconducting magnet)</td>
<td>$10^9$ gauss</td>
</tr>
<tr>
<td>B (electromagnetic)</td>
<td></td>
<td>$10^{13}$ gauss</td>
</tr>
<tr>
<td>Temperature</td>
<td>$10^9$ K (Tokamak)</td>
<td>$10^{12}$ K</td>
</tr>
<tr>
<td>Pressure</td>
<td>$10^5$ bar (diamond anvil)</td>
<td>$10^{10}$ bar</td>
</tr>
</tbody>
</table>

$E_{cr} \approx 10^{18}$ V/m
High-power lasers may reproduce or simulate astrophysical conditions (with some caveats).

**Configuration simulation**
simulate the actual, global plasma configuration of a system as well as some of the physical processes taking place within it ex). whole magnetosphere

**Process simulation**
simulate the local plasma processes ex). collisionless resistivity

Faelthammar, Space Science Reviews **15**, 803 (1974)
Different physical quantities scale differently, and only limited scaling is available.

<table>
<thead>
<tr>
<th>parameter</th>
<th>vary as</th>
</tr>
</thead>
<tbody>
<tr>
<td>length, time, resistivity</td>
<td>$L^1$</td>
</tr>
<tr>
<td>particle energy, velocity, temperature, potential, current, resistance</td>
<td>$L^0$</td>
</tr>
<tr>
<td>electric/magnetic fields, frequency</td>
<td>$L^{-1}$</td>
</tr>
<tr>
<td>space charge density, current density</td>
<td>$L^{-2}$</td>
</tr>
</tbody>
</table>

$L$: characteristic dimension

Alfven 1973

**Qualitative scaling**

- $\alpha$: a dimensionless parameter
- $\alpha_{\text{space}}$ need not be the same as $\alpha_{\text{lab}}$.
- $\alpha_{\text{space}} \ll 1 \iff \alpha_{\text{lab}} < 1$ vice versa
- $\alpha_{\text{space}} \gg 1 \iff \alpha_{\text{lab}} > 1$ vice versa

\[ a = \frac{eE}{m_e c \omega} \]
Laser fusion target and supernova may experience similar surface instabilities.

Remington, Science (1999)
We may design experiment qualitatively scaled to instabilities in supernova explosion.

### Table 10.1. Fundamental hydrodynamic parameters for a supernova experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Supernova 1987A</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length scale (cm)</td>
<td>$9 \times 10^{10}$</td>
<td>0.0180</td>
</tr>
<tr>
<td>Velocity (km/s)</td>
<td>2000</td>
<td>35</td>
</tr>
<tr>
<td>Density (g/cm$^3$)</td>
<td>0.0075</td>
<td>0.4</td>
</tr>
<tr>
<td>Pressure (dynes/cm$^2$)</td>
<td>$3.5 \times 10^{13}$</td>
<td>$5.2 \times 10^{11}$</td>
</tr>
<tr>
<td>Temperature (eV)</td>
<td>900</td>
<td>7.4</td>
</tr>
<tr>
<td>$Z_t$</td>
<td>2.0</td>
<td>0.6</td>
</tr>
<tr>
<td>$A$</td>
<td>4.0</td>
<td>11.4</td>
</tr>
<tr>
<td>Density of nuclei (cm$^{-3}$)</td>
<td>$1.1 \times 10^{21}$</td>
<td>$2.1 \times 10^{22}$</td>
</tr>
</tbody>
</table>

### Table 10.2. Derived scaling parameters for a supernova experiment

<table>
<thead>
<tr>
<th>Derived Parameter</th>
<th>Supernova 1987A</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u^* / \sqrt{\rho^* / \rho}$</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>Collisional mfp (cm)</td>
<td>$3.5 \times 10^{-3}$</td>
<td>$7.9 \times 10^{-8}$</td>
</tr>
<tr>
<td>Kinematic viscosity (cm$^2$/s)</td>
<td>$7.0 \times 10^7$</td>
<td>0.334</td>
</tr>
<tr>
<td>Reynolds number</td>
<td>$2.6 \times 10^{11}$</td>
<td>$1.9 \times 10^5$</td>
</tr>
<tr>
<td>Thermal diffusivity (cm$^2$/s)</td>
<td>$1.2 \times 10^6$</td>
<td>15</td>
</tr>
<tr>
<td>Peclet number</td>
<td>$1.5 \times 10^{13}$</td>
<td>$4.2 \times 10^3$</td>
</tr>
<tr>
<td>Radiation mfp (cm)</td>
<td>$6.8 \times 10^2$</td>
<td>$2.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Radiation Peclet number</td>
<td>$10^6$</td>
<td>$2.5 \times 10^9$</td>
</tr>
</tbody>
</table>
(a) Radiation pressure in space

RCW 120
Spitzer Space Telescope

(b) Laser radiation pressure

Foil (ions)
Accelerated plasma

Ion energy spectrum

(c) VULCAN Nd-glass laser (RAL)
60 J @ 1ps & 250 J @ 0.7 ps;
foils (3, 5 mum, Al & Cu)

experiment
simulation

Esirkepov and Bulanov, European Conference on Laboratory Astrophysics (2012)
(a) Wake waves in space

Wake behind a small moon in the Keeler gap in Saturn’s rings. Cassini spacecraft.

Tail behind the Mira star. GALEX satellite.

Tail behind the Mouse pulsar G359.23-0.82

Chandra X-ray

(b) Laser-driven wake waves

Experiment setup

Simulation

(c) Ship wake

Ti:Sa Salle Jaune laser (LOA)
2J @ 35fs

(proton imaging)

Simulation

Ion density
(a) Bow waves in space

(b) Laser-driven bow wave
PIC simulation

(c) Bow wave from a ship
(a) Magnetic line reconnection in space

Solar flare 2.09.2001 (12:18:51)

WIND spacecraft data

(b) Laser-driven magnetic line reconnection (experiment)

Laser

(c)
Material response depends on laser intensity: more rooms at higher intensity

Quantum vacuum
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R p, UltraR e, nucleons
- Direct p drive, radiation reactions, photonuclear processes

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