View into the cauldron

Seeing what intense lasers do to solid targets

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Targets heated by fs pulses are inertially confined...

Picosecond Pulse

Femtosecond Pulse

Interplay among collisional, resonance & vacuum heating absorption governed by relative values of $L$, $\lambda$, and $z_{osc}$

Recent experiments use ultrafast x-ray$^1$ & proton$^2$ irradiation to achieve more uniform isochoric heating than fs optical pulses

... and isochorically* heated...


* constant density

brown dwarfs

“astrophysical” states of matter

Jupiter interior

Warm Dense Matter: at the crossroads of condensed matter & plasma physics

Strongly coupled plasma:

\[ \Gamma = \frac{Z^2 e^2}{r_0 k T_e} < 1 \]

where \( r_0 \) ≡ average interatomic spacing

... providing access to exotic states of matter of astrophysical interest
Pump-and-probe experiments measure time evolution of the hot target surface.

**Diagram Description:**
- **Pump** and **probe** beams are directed towards the target.
- An **off-axis parabola** focuses the beams.
- A **frequency filter** and an **optional nonlinear optical frequency shifter** are used.
- A **variable time delay** is adjusted for the experiment.
- **REPEAT PROCEDURE** is indicated.
- **CCD** captures images of the target.
- Sample rastering is shown.

**Text:**
Pump-and-probe experiments measure the time evolution of the hot target surface.
Femtosecond Movie of Silicon Melting & Evaporation

Red numbers denote pump-probe time delay $\Delta t$ in ps

### Pump Parameters:

- $\lambda = 620$ nm
- $w_0 = 75 \mu$m on target
- $\tau = 80$ fs
- Energy = 0.1 mJ
- $E_{\text{max}} = 0.5$ J/cm$^2$ on target
- $I_{\text{max}} = 10^{13}$ W/cm$^2$ on target

### Silicon Melting Threshold:

$E_{\text{THRESHOLD}} = 0.1$ J/cm$^2$

### Major Events:

- $\Delta t < 0$: semiconducting Si surface ($R = 0.3$)
- $-0.04 < \Delta t < 0.04$ ps: pump absorbed
- $\Delta t \approx 1$ ps: liquid metal Si surface ($R = 0.6$)
- $\Delta t \geq 10$ ps: absorption from ejecta ($R \to 0$)

Laboratory observations of solid targets irradiated by intense ultrashort laser pulses

I. Absorption
   - resonance
   - vacuum heating
   - j X B

II. “Hot” electrons

III. X-rays

IV. Magnetostatic Fields

V. Ions
Measurements of fs Resonance Absorption

**Single pulse reflectivity**

\[ \tau_p = 250 \text{ fs}, \lambda = 248 \text{ nm} \]

Integrating sphere measured non-specular scatter

Brewster angle shift

**Fs time-resolved reflectivity**

\[ \tau_p = 90 \text{ fs}, \lambda = 620 \text{ nm}, I_{\text{pump}} = 10^{13} \text{ W/cm}^2 \]

\[ kT_e^{\text{max}} \approx 15 \text{ eV} \]

Combined model

\[ \int \text{step } n_e(z) \] (Fresnel reflectivity)

\[ \varepsilon(t) = 1 - \frac{\omega_p^2}{\omega [\omega + i\nu(t)]} \] (Drude dielectric function for free-electron metals)

\[ \nu(t) = C_n Z^2 T_e(t)/\omega_p^2 \] (electron-ion collision frequency for kT_e < 20 eV)

\[ C_e(T_e) \frac{\partial T_e}{\partial t} = K V^2 T_e - g(T_e - T_p) + A(r,t) \]

Collisonal electron heating & cooling model

\[ C_i \frac{\partial T_i}{\partial t} = g(T_e - T_i) \]

Heat capacities electron-phonon coupling coefficient
Surface expansion also shifts phase $\Delta \phi_{s,p}$ of probe pulse; frequency-domain-interferometry (FDI) measures this shift


$\tau_p = 100$ fs, $\lambda = 620$ nm, $I_{\text{pump}} \approx 10^{15}$ W/cm$^2$, $\theta_{\text{probe}} = 60^\circ$

Fe target

probe phase shift

probe reflectivity

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$\tau_p = 100 \text{ fs}, \lambda = 620 \text{ nm}, I_{\text{pump}} \approx 10^{15} \text{ W/cm}^2, \theta_{\text{probe}} = 60^\circ$

peak-to-pedestal contrast: $>10^5 @ 1 \text{ ps}; >10^3 @ 0.2 \text{ ps}$

Vacuum Heating (VH) appears as extra absorption of obliquely incident pulse when $z_{\text{osc}} > L$

corona of scale length $L$

Fe target
$L < 0.003\lambda$ during high-contrast pump

“Extra” absorption of intense, high-contrast, obliquely-incident, p-pol pulse when $z_{osc} \geq L$ reveals Vacuum Heating

Chen, Phys. Plasmas 8, 2925 (2001)

Magnitude of VH absorption agrees with first principles models

Extra VH absorption is ...
... strongest for large $\theta_{inc}$ (as expected)
... independent of target material (as expected)

2 Gibbon & Bell, Phys. Rev. Lett. 68, 1535 (1992)
II. “Hot” electrons

Simulation of hot electrons produced by RA
Kruer, The Physics of Laser Plasma Interactions (Addison-Wesley 1988), c. 10

Measured hot electron energy distribution from 50 µm Al foil irradiated at ~$10^{18}$ W/cm² by 0.6 ps laser pulse

A universally observed and calculated feature of intense laser-solid target interactions is production of two electron temperatures
An electron crossing a dielectric interface emits Optical Transition Radiation (OTR)

A single electron emits a broad OTR spectrum

Transition Radiation
(where fields from moving $e^-$ and induced polarization $\mathbf{P}(x',t)$ interfere constructively)

$\gamma \equiv [1 - v^2/c^2]^{-1/2}$

OTR has become a powerful tool for characterizing hot electrons generated by intense laser-plasma interactions
RA, VH & jxB absorption create micro-bunched hot electrons, which emit Coherent Transition Radiation (CTR).

\[ \nu = \frac{o}{\gamma \omega_p} \]

\[ I_{TR}(\nu) = N \eta(\nu) \]

TR from individual electrons adds incoherently:

\[ I_{TR}(\nu) = \frac{N \eta(\nu)}{2\pi/\omega} \]

ICTR decreases & harmonic peaks broaden as electrons propagate.

Assumptions:
- Electrons mono-energetic
- Angular variations neglected
- Electron spatial profile neglected
- Electron energy loss in material neglected

\[ \omega, 2\omega, 3\omega, 4\omega, 5\omega, 6\omega, 7\omega, 8\omega, 9\omega, 10\omega, \text{ etc.} \]

\[ j \times B \text{ harmonic series} \]

\[ VH/RA \text{ harmonic series} \]

Observations of CTR at $2\omega_{\text{laser}}$ demonstrate microbunching of hot electrons


Blackbody radiation at $kT_e \sim 0.5 \text{ MeV}$ observed on ns time scale, due to resistive target heating by return current neutralizing forward fast e- flux. **These electrons contain \(~35\%\)** of the incident laser energy.

Decay of CTR signal with increasing target thickness enables an estimate of hot electron temperature

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Decay of CTR signal with increasing target thickness enables an estimate of hot electron temperature

The micro-bunched electrons responsible for CTR contain \(<1\%\) of the incident laser energy.

... sharply peaked around $2\omega_{\text{laser}}$

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CTR observations at $2\omega_{\text{laser}}$ with obliquely-incident laser reveal TWO hot electron streams

Laser: $I = 2 \times 10^{19} \text{ W/cm}^2$, $\theta = 45^\circ$, $\lambda = 800 \text{ nm}$

Area of spot A is 3.5x larger than B

This observation clearly distinguishes $j \times B$ heating from VH & RA

CTR images reveal self-organized filaments in fast electron beam


SIMULATION attributes behavior to Weibel instability

e- density magnetic field

propagation distance

10 µm

20 µm

100 µm
Grazing-incidence laser pulses produce hot $e^-$ that skate along the target surface.

**Lasers**
- LASER: 0.6 J, 30 fs, 800 nm, ~$10^{18}$ W/cm$^2$
  - $\theta = 22^\circ$
  - $\theta = 45^\circ$
  - $\theta = 70^\circ$

**Targets**
- TARGET: 30 µm Al foil
  - $\theta = 45^\circ$

Simulations show large quasistatic self-generated B & E fields confine SFEs to oscillating trajectories along target surface.

PROPERTIES OF SURFACE FAST ELECTRONS (SFEs):
- $kT_{SFE} \approx 0.3$ MeV
- $\sim 10^{10}$ SFEs for $\theta = 70^\circ$
- Detected by Image Plate (IP) stacks surrounding laser focus
- $B_z$ and $E_z$ are normalized to incident laser field $m\omega/c/e$
Laser-generated hot electrons ...

- transport 30-40% of intense laser pulse energy into target
- propagate mainly along target normal (VH, RA), incident laser direction (\(j \times B\)), and target surface
- produce currents of \(\sim 10^7\) A, current densities > \(10^{12}\) A/cm\(^2\)

... and are important for:

- fast ignition of laser fusion
- producing ultrafast x-ray pulses for flash radiography
- compact acceleration of ions
Fast ignition of inertial confinement fusion


ADVANTAGES OVER CONVENTIONAL ICF:

- separate fuel compression from fuel heating
- reduce fuel density $\sim 5\times$
- produce fusion energy $\sim 20\times$ more efficiently
- relax stringent requirements on smoothness & sphericity of fuel capsule & uniformity of drive pressure

INITIAL DEMONSTRATIONS EXPLOIT LASER-DRIVEN SFEs TO ENHANCE NEUTRON YIELD

III. X-rays

Laser-generated hot electrons produce x-rays by two dominant mechanisms:

- **Line emission**: Fast electrons knock free core electrons from the inner shell (typical recombination lifetimes: several fs)
- **Bremsstrahlung**: Electrons deflected by nucleus

X-ray line spectroscopy is a standard method to infer electron temperature & density in laser-produced plasmas


**Applications to suprathermal electrons:**

**Typical experimental setup**

- **K-shell spectrum of Cu target irradiated by 0.7 ps, 447 J laser pulses @ 3x10^20 Wcm^2**

**Relative line strengths change with laser intensity and kT_e**

- **Bremsstahlung continuum subtracted**

Such data contributes to developing scaling laws for e.g. 

$$kT_e \text{ vs. } I_{\text{Laser}}$$

Measurements are time-integrated

- When an x-ray photon is absorbed in a pixel, a number of charged carriers proportional to the x-ray photon energy is created (typically one carrier for each 5 eV of photon energy).

- Data from all pixels are collected to compile a single-shot x-ray spectrum.

- Exposure must be limited to << 1 x-ray photon per pixel per shot.

Bremsstrahlung continuum x-rays also measure $kT_e$  

\[
T_e = 16.4 \text{ keV}
\]

Nees, JSTQE 12, 223 (2006)

Al target irradiated @
\[0.5 \times 10^{18} \text{ W/cm}^2\]
by 25 fs $\lambda^3$ laser

CdZnTe detector
(insensitive below 5 keV)

\[
\text{kT}_e^{(1)} 
\approx 390 \text{ keV}
\]


\text{CD target irradiated @}
\[5 \times 10^{18} \text{ W/cm}^2\]
by $\sim 1$ ps Vulcan laser

\[
\text{kT}_e^{(2)}
\]

\[
\sim 2 \text{ keV}
\]

Some studies have correlated X-ray spectroscopy with independent measurements of $kT_e$ based on e.g.

  and ions (Tan, Phys. Fluids 27, 296 (1984); Beg, Phys. Plasmas 4, 447 (1997))

- CTR vs. target thickness (Cho, JOSA B 25, B50 (2008); Baton, Phys. Rev. Lett. 91, 105001 (2003))

\[
kT_e = 100 (I_{17} \lambda_{\mu m}^2)^{1/3} \text{ keV}
\]

e.g. Beg, Phys. Plasmas 4, 447 (1997)

for experiments in which RA is the dominant source of hot electrons
Tightly focused fs lasers create the world’s smallest hard x-ray source (~4 µm) for precision imaging


x-ray picture of rat tail: Cu target

x-ray picture of rat tail: Mo target

x-ray source size is ~ 4× larger than laser focus because of lateral heat transport*

Fs X-ray pulses shorter than a molecular vibrational period probe ultrafast structural dynamics of materials


Most fs x-ray experiments to date have used an x-ray probe produced by laser-solid interaction

Response times $\tau < 200$ fs are observed, placing an upper limit on the x-ray pulse duration

$\sim 10^{11}$ K, photons/s

x-ray diffraction from melting InSb
Lindenberg, Science 308, 392 (2005)

x-ray diffraction showing lattice vibrations in bismuth
IV. Magnetic Fields

Magnetic Field Strength [Tesla]

Ways to measure them:

Magnetic fields predicted in dense plasmas during relativistic laser-plasma interactions
The strongest B fields produced in relativistic laser-plasma interactions are near the critical surface, where optical harmonics are also generated.
The magnetized plasma is birefringent

Equation of motion of plasma electron:

\[\vec{r}_x(t) = -e \left[ \vec{E}_{\text{harm}}(t) + \vec{r}(t) \times \vec{B}_0 \right] \]

Obtain dielectric function \(\varepsilon\) from:

\[P = -n_e e \vec{x} = \varepsilon_0 \left( \frac{\varepsilon}{\varepsilon_0} - 1 \right) \vec{E}_{\text{harm}}\]

Cutoffs at \(\omega = \omega_p\) (depend on \(\omega\) and \(n_e\) only)

Cutoffs at \(\omega_p^2(\omega^2 - \omega_n^2) = \omega^2(\omega^2 - \omega_h^2)\) (depend on \(\omega, n_e\) and \(B_0\))
Observed harmonic X-wave cutoffs reveal $B > 340$ T, the strongest $B$ field ever produced in a laboratory

Cutoffs for harmonics:
- 3rd: 220 T
- 4th: 340 T
- 5th: 460 T

at $n_e = 2.4 \times 10^{21}$ cm$^{-3}$ (relativistically corrected critical density)

Vulcan laser parameters:
- $\lambda = 1.054$ µm
- $\tau_p \sim 1$ ps
- Energy $\sim 90$ J

Plot of X-wave cut-offs for various harmonics

X-wave harmonic emission vs laser intensity

no cutoff observed for 5th harmonic
V. MeV Protons & Ion Beams

Target Normal Sheath Acceleration: hot electrons traversing target electrostatically accelerate impurity hydrogen ions on the rear surface
Proton Therapy enables precise exposure of small tumors with minimal damage to surrounding healthy tissue ...
... but requires large, expensive facilities

“There are too few physicists in the world, and they are an incredibly important part of doing this... We have one of the largest physics departments in the world, with more than 50 medical physicists.”

--- Dr. James D. Cox, head of Radiation Oncology at MD Anderson Cancer Center, Houston, Texas

Laser proton therapy could be much smaller & cheaper:

MeV proton beams create uniform Warm Dense Matter (WDM) for precise Equation-of-State Measurements


Ultrashort pulses of laser-generated MeV protons provide:

• more uniform volumetric heating over µm scale lengths than fs laser pulses
• isochoric heating to kT ~ 20 eV with higher efficiency than laser-generated hot electrons or x-rays


Results show SESAME Livermore equation-of-state tables to be accurate in a dense plasma regime where few previous experiments were available.
SUMMARY

Intense ultrashort laser pulses heat solid targets isochorically to exotic states

Laser absorption mechanisms ...

- collisional (inverse Bremsstrahlung)
- collisionless (RA, VH, j x B)

... are distinguished by careful pump-probe measurements

Relativistic interactions yield ultrafast secondary radiation...

- MeV hot electrons $\rightarrow$ fast ignition of laser fusion, fs x-rays, proton acceleration
- keV x-rays $\rightarrow$ fs structural dynamics of condensed matter
- MeV protons $\rightarrow$ cancer therapy, rare isotope production, flash radiography,

... and the strongest B fields every measured in a laboratory

- Mgauss magnetic fields $\rightarrow$ physics of white dwarfs & neutron stars