High energy density science (HEDS) experiments with table top terawatt lasers: the why and how

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1. Intense Laser-Matter Interaction: Some Basics
[mainly for ultrashort (femtosecond) pulses]

2. High energy density science (HEDS)
experiments with table top terawatt lasers: the why
and how – TODAY!

3. Physics issues and challenges in HEDS with
table top lasers: some examples
High energy density science (HEDS) experiments with table top terawatt lasers: the why and how

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Ultrashort Pulse High Intensity Laser Laboratory (UPHILL)
Tata Institute of Fundamental Research, Mumbai, India
www.tifr.res.in/~uphill
Collaborators

P. Ayyub and students (DCMP & MS, TIFR)


P. P. Rajeev, A. P. L. Robinson, J. Pasley (Simulation) (RAL and York, U.K)

K. A. Tanaka, H. Habara, R. Kodama, K. Mima and others (ILE, Osaka)

W. M. Wang, Z. M. Sheng (Shanghai)
Ultra short Pulse High Intensity Laser Laboratory, TIFR

20 TW, 30 fs, 10 Hz

www.tifr.res.in/~uphill
$I_{\text{peak}} = 10^{18-19} \text{ W cm}^{-2}$

$E = 10^{10-11} \text{ V cm}^{-1}$

$\tau = 30 \text{ fs}$

$E = 0.60 \text{ J}$

$I_{\text{peak}} = 20 \times 10^{12} \text{ W}$

A bird’s eye view
Plan of the Talk

- Introduction and motivation
  * high energy density science
- High energy density science with ultrashort lasers - how and why?
- Illustrative examples
- Conclusions
High Energy Density

External energy density applied to a material ~ comparable to the material’s room temperature energy density.

~

bulk moduli of solid-state materials

$10^{11} \text{ J/m}^3$

At this energy density, the pressure is 1 Mbar.
What is ‘High Energy Density’?
Shaded - HED region possible to explore
HIGH ENERGY DENSITY SYSTEMS

Physical properties

- **Nonlinear and collective responses**
- **Full or partial degeneracy**
  pressure determined by the Pauli exclusion principle rather than by temperature.
- **Dynamic systems**
  High Reynolds number-turbulence, ultimate nonlinear response
  
  *High Mach no* (= kinetic energy / thermal energy)-form and sustain shocks.

\[ Re > 10^4 \text{ and } Ma > 0.5 \] relevant to large scale astrophysical phenomena.
High Energy Density Physics

seeks to answer some of the most basic questions in science............
How does matter behave under conditions of extreme temperature, pressure, density, and EM fields?

What are the opacities of the stellar matter?

What is the nature of the matter at the beginning of the universe?

How does matter interact with photons and neutrinos under extreme conditions?

What is the origin of intermediate-mass and high-mass nuclei in the universe?
- Achieve high-yield fusion ignition in the lab?
- Simulate mechanisms for formation of astrophysical jets in laboratory?
- Equation of State for stellar and planetary structures?
- Can electron-positron plasmas relevant to gamma-ray bursts be created in the laboratory?
High Energy Density Science with Small (Tabletop) lasers

= ‘High Intensity Physics’

A study of Extremely excited states of matter produced by Extremely short, energetic pulses of light.

Impulsively kicked physical systems
Energy Scales involved

Photon energy - 1.5 ev (~ $10^0$ eV)

Ionization energy of atom (typ.) – $10^1$ - $10^2$ eV $\gg$ Photon energy

Energy given to the electron $\gg\gg\gg\gg\gg\gg\gg$ both the above!
Plasma formation in a DENSE medium

Initial ionization of valence electrons by light field

Acceleration of ionized electrons by light
(Oscillation)

Collisional absorption
Collisions of these individual electrons with other particles `Inverse bremsstrahlung`

Resonance Absorption
Excitation of a plasma wave (Collective effect)

Damping of wave

Repetitive processes

Hot, dense plasma

Hot electrons and finally Hot ions
Physics In ULTRA-INTENSE Light Fields

Matter totally ionized

Large charge densities ($>10^{24}$ cm$^{-3}$)

Energetic electrons ($10^3 - 10^6$ eV)

Nonequilibrium dynamics - violently driven systems

Gigantic magnitudes
- Magnetic fields $10^9$ G
- Electric field $10^{10}$ V cm$^{-1}$
- Pressure $10^9$ bars
- Temperature $10^8$ K (for e$^-$)

Relativistic and QED effects
- Multiphoton Compton scattering, pair production

Nuclear excitation and fusion

Laboratory Astrophysics

Sun

neutron star
HED with a Table Top TW Laser (HEDS-T\(^3\))

Why???

Experimental:
- Simplicity
- Repetition Rates
- Easier verifiability/reproducibility
- All the above lead to ‘robustness’ of the experiment (averaging, systematics ...)
- Larger participation (multiple groups, cross referencing)
Ultrafast CPA Characteristics

• Compactness and high repetition rate

Nova
Pulse duration 1 ns
10 kJ/beam
10 beams @ 10 TW/beam = 100 TW
1 shot/hour

Ultrafast Ti:S Amplifier
Pulse duration 15 fs
1.5 J/beam
100 TW/pulse
36,000 shots/hour
HEDS – $T^3$

Why ????

**Physics**
- Ultrafast excitations ($<<100$fs)
- Easier temporal and Spatial Manipulation of Laser beam
  - Steep gradient plasma [Ultrahigh contrast pulses ($10^{-10}$)]
  - High repetition rates (0.1-10 shots/sec as opposed to 1 shot/hour!)

Testing/matching/pushing PIC Simulations.
Femtosecond pulses excite matter before ions can move.

Time scale for motion of ions:

- Femtosecond: $10^{-15}$ s
- Picosecond: $10^{-12}$ s
- Nanosecond: $10^{-9}$ s
Liquid carbon sighted!

First evidence - by fs, INTENSE light

RESEARCHERS at the University of Texas, Austin, may have caught the first, fleeting glimpse of fluid carbon. D. H. Reitze, H. Ahn and M. C. Downer describe in Physical Review (B45, 2677–2693; 1992) how both graphite and diamond can be melted momentarily by intense laser irradiation before expanding as a hot plasma.

The liquid phase of the element carbon is elusive, as it appears to exist in equilibrium only at temperatures of about 5,000 K and at pressures above several hundred atmospheres. The phase cannot be contained in any vessel, because all other materials melt or chemically react before the temperature required for the liquid state of carbon is reached. Clearly the structure of this state is of interest to those studying condensed matter physics, but because these conditions can be found in planetary interiors, it is also important for geophysics and astrophysics.

The first evidence for this phase came from experiments using pulsed ohmic heating of graphite electrodes. Shock-wave studies and pulsed-laser heating of graphite and diamond have also been tried (see F. B. Bundy's review in Physica 156 A, 169–178; 1989). Downer and colleagues used laser pulses lasting less than a picosecond (10^{-12} s) in their new experiments, both to create and to probe their fluid carbon.

It is well known that short, intense laser pulses are capable of turning any substance into a high-temperature, high-density plasma. By careful control of the energy fluence in the pump pulse it is possible to determine a threshold for melting as the first stage in the process of plasma formation. A second, probe pulse will be reflected or will generate second-harmonic (or frequency-doubled) light, and the change in either of these can be followed as a function of the pump fluence, the time elapsed, and the wavelength, polarization and angle of incidence of the probe. This parameterization gives detailed information on the changes in electronic structure of the
HEDS – $T^3$

HOW ???

*Here is one example*
Real Time Ultrafast Dynamics of Dense, Hot Matter Measured by Pump-Probe Doppler Spectrometry
Laser Plasma Interaction

Intensity: $10^{18}$ W/cm$^2$

Laser $\tau$ : $30 \times 10^{-15}$ s

Plasma $T$ : $10^2 / 10^5$ eV

Plasma Velocity: $10^7 - 10^8$ cm/s
Plasma Dynamics – Extremely Important Need to See Plasma Dynamics “as it happens”

Pump-Probe Experiment

Pump

800 nm, fs

To Polarimeter/
Spectrometer/
Interferometer/…

Probe (Time Delayed w. r. t. Pump)

400 nm, fs

Target

Our earlier work:
Plasma motion occurs at very high velocity

($> 10^7$ cm/sec)

So plasma profile changes rapidly

This implies, plasma conditions change significantly during laser interaction
Motivation

To Estimate
the Plasma Expansion Velocity and
thereby
the Instantaneous Plasma Profile
Spatial Matching of Two Beams

Probe Spot size ~60 μm

Pump Spot size ~17 μm
Idea of pump-probe geometry

Probe ahead of pump
Reflects from Metal

No plasma contribution as yet

Pump Probe Overlapped
Time = 0
Partly reflected from plasma

Now probe reflected from plasma
formed by the pump
Studying evolution of plasma
Temporal Matching of Two Beams

Many Interesting results on time resolved reflectivity in the Posters of Prashant K. Singh and Gourab Chatterjee on Thursday
Temporal Matching of Two Beams

Beams are hitting a new target spot every time

Pump and Probe arrive at the same time

Many Interesting results on time resolved reflectivity in the Posters of Prashant K. Singh and Gourab Chatterjee on Thursday
Time Delayed Spectra

Target: Aluminium

Wavelength (nm)

Norm. Intensity (a. u.)
Target: Aluminium

Time Delayed Spectra

- Norm. Intensity (a. u.)
- Wavelength (nm)

Time Delayed Spectra for Aluminium
Dynamics Over 30 ps

**Pump:**
- 800 nm,
- $3 \times 10^{18}$ W/cm$^2$

**Target:** Aluminium

**Probe:**
- $\lambda = 400$ nm

**Visual Guide**
- 30 ps
- 26 ps
- 22 ps
- 19 ps
- 16 ps
- 8 ps
- 4 ps
- 2 ps
- 0 ps
To Observe Small Shifts it is Better to Observe Differences

i.e.

Time Delayed Probe Spectrum – Reference Probe Spectrum
If the time delayed spectrum is red-shifted with respect to zero time delayed spectrum:
subtracted spectrum (later spectrum - zero time delay spectrum) will show minima followed by maxima.
If the time delayed spectrum is blue-shifted with respect to zero time delayed spectrum:
subtracted spectrum (later spectrum-zero time delay spectrum) will show maxima followed by minima.
Dynamics Over Time Scale of 30 ps

Wavelength (nm)

Difference (a. u.)

30-0
26-0
22-0
19-0
16-0
8-0
4-0
2-0

396 398 400 402 404

Wavelength (nm)
Doppler Shift

Why Red Shift ???

The pump laser launches a compression wave into front surface plasma

At early times compression wave forces the critical surface into the target
Why Blue Shift ???

At later times a compression wave has propagated into a region of overdense plasma.

Critical surface of the probe sits in the region that is undergoing rarefaction, thus critical surface is moving into the vacuum and towards the laser.
Pump: 800 nm, $3 \times 10^{18}$ W/cm$^2$

Probe: 400 nm

Target: Aluminium

Doppler Shift in Reflected Probe Spectra

A polynomial fit

Blue-shift

Red-shift

Delay Time (ps)

$\Delta \lambda$ (nm)
\[ V_{\text{expansion}} = 0.5c \left( \frac{\Delta \lambda}{\lambda} \right) \left( \frac{1}{\cos \theta} \right) \]

**Velocity and Acceleration from Doppler Shift**

Instantaneous

**Velocity**

**Acceleration**
Doppler Shift : Simulations

1D PIC+1D Hydrodynamic Simulations : HYADES
Results of PIC simulation as input of HYADES
500 µm Al target : 100 Lagrangian cells
Two different Laser Sources : 800 nm and 400 nm

Red line is 800 nm pump profile
Blue line is 400 nm probe profile
Pump main pulse is 30 fs flat top
Probe is 80 fs flat top

Simulations by : John Pasley
Doppler Shift in Reflected Probe Spectra

Pump:
\(\lambda = 800\ \text{nm}\)

Probe:
\(\lambda = 400\ \text{nm}\)

Target: Aluminium

\[\Delta \lambda = \frac{2 \dot{x}_{\text{crit}} \lambda_{\text{probe}}}{c}\]
Doppler Spectrometry for Ultrafast Temporal Mapping of Density Dynamics in Laser-Induced Plasmas

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(Received 19 October 2009; revised manuscript received 25 May 2010; published 30 August 2010)

We present high resolution measurements of the ultrafast temporal dynamics of the critical surface in moderately overdense, hot plasma by using two-color, pump-probe Doppler spectrometry. Our measurements clearly capture the initial inward motion of the plasma inside the critical surface of the pump laser which is followed by outward expansion. The measured instantaneous velocity and acceleration profiles are very well reproduced by a hybrid simulation that uses a 1D electromagnetic particle-in-cell simulation for the initial evolution and a hydrodynamics simulation for the later times. The combination of high temporal resolution and dynamic range in our measurements clearly provides quantitative unraveling of the dynamics in this important region, enabling this as a powerful technique to obtain ultrafast snapshots of plasma density and temperature profiles for providing benchmarks for simulations.

DOI: 10.1103/PhysRevLett.105.105002

PACS numbers: 52.38.-r, 52.50.Jm, 52.65.-y
How short is a femtosecond pulse?

**Uncompressed parts – pedestal**

- **Picosecond pedestal**: $10^{-5}$ times weaker

**Can they form plasma before the main pulse arrives?**
100TW, 25 fs, high contrast laser at TIFR (2011)
Establishing basic physics with ultrasteep pulses with solids, clusters and mesoscopic matter

New experiments planned

$10^{20}$ W cm$^{-2}$

$10^{10}$ W cm$^{-2}$ @ -20 ps

$10^{-11}$

> 10 orders of temporal contrast
Invitation!

• Please ask more questions about the experimental techniques in the Discussion Session in the afternoon today
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