Dynamics in a non-equilibrium state revealed with ultrashort light pulses

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Japan Intense Light Field Science Society (JILS) was established in 2003.

We promote the new science with intense light filed and operate international collaboration.

We handle the International Symposium of Ultra Intense Light Field Science (ISUILS).
Outline

- Introduction: multi-time-scale dynamics
  - Hyper velocity impact
  - Dynamics in non-equilibrium condition
- Laser ablation & laser shock
  - Laser ablation
  - Laser shock compression
  - Flyer acceleration
- Dynamics under shock compression
  - Phase transition of bismuth in nanoseconds
  - Higher pressure / much faster dynamics
- Summary
Hyper-velocity impact, such as collision of space debris or planet, causes extremely high pressures and high strain rate, which is far from an equilibrium state.

Lab-size experiment

Gun experiment

Laser experiment

From ASME homepage
Dynamics in non-equilibrium states

Grand Challenge: How Do we characterize and control matter away - especially very far away – from equilibrium?

A system is in equilibrium when it does not change with time. All natural and most human-caused phenomena occur away from equilibrium.

Understanding non-equilibrium behavior of physical, chemical, and even astronomical phenomena promises huge advances in our ability to manufacture super-hard, super-strong, and self-repairing materials, and in a great many other areas.

DOE reports (2008)
Multi-time-scale dynamics

Time (s)

$10^{-44}$

Plank time

$5.39 \times 10^{-44}$ (s)

$10^{-9}$

Clock-PC (GHz)

$10^8$

1 year

Age of Universe (138E8 year)

$10^{17}$

$10^1$

$10^{-9}$

$10^{-12}$

$10^{-15}$

$10^{-18}$

atto

femto

pico

nano

micro

Electronic transition

phonons

Structure change

fracture

Spin relaxation

63 as: Shortest pulse

2.7 fs: 800 nm Optical cycle

113 fs: GaAs phonons

100 ps: Cs-atom clock

30 μs: Quartz vibration
Pulsed laser

Laser generates coherent and intense light.

Ultrashort pulses can be generated by pulse operation and causes non-linear phenomena and monitor ultrafast phenomena.

Peak intensity = energy / pulse width

![Graph showing relationships between laser intensity and ponderomotive potential](image)

- Nuclear fusion
- Fast electron & ion
- X-ray generation
- Ultrafast X-ray spectroscopy diffraction
- Tunneling ionization
- Avalanche ionization
- Multiphoton absorption
- Laser processing
Laser ablation: plasma formation

High-power laser irradiation causes laser ablation, which generates plasma emission.

Plasma is the fourth phase of matter and consists of ions and electrons.

Plasma in nature (Example)

- **Lightning**
  - [Link](http://thecoderedeempire.weebly.com/lightning-strikes)

- **Sun’s Corona**
  - [Link](http://www.nasa.gov/mission_pages/sunearth/news/coronal-cavities.html#.VOu_L2DQHx4)
Laser Induced Breakdown Spectroscopy


Example of a Spectrum from Curiosity’s ChemCam Instrument

This image provides an example of the type of data collected by the Chemistry and Camera (ChemCam) instrument on the Mars Science Laboratory mission’s Curiosity rover. Image credit: NASA/JPL-Caltech/LANL

NASA Mars Land rover
Laser ablation and shock

Shock wave is generated by reaction of laser ablation.

P = 8.6(I / 10^{14})^{2/3} \lambda^{-2/3}

P: Pressure (Mbar)
I: Laser power density (W/cm^2)
\lambda: wavelength (micron)

Benuzzi et al., PRE 54 (1996) 2162.

Y. Okano, K.G. Nakamura+ APL 83 (2003) 1536
Laser power density & shock pressure

- **Direct irradiation:** Benuzzi (1996)
- **Plasma confinement:** Devaux (1993)

- **Upper mantle:**
  - Benzene solid (Raman)
  - Bi phase transition (XRD)
  - Over compressed state (XRD)

- **Lower mantle:**
  - Polymer structure change (Raman)

- **Core:**
  - TPa state; Ta, C
  - GEKKO/HIPER

- **Jupiter:**

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**Laser power density (W/cm^2)**

**Pressure (Pa)**

- $10^8$ to $10^{13}$

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**Graphical Elements**

- Diagram illustrating the relationship between laser power density and shock pressure in the context of astrophysical conditions in Jupiter's interior.
A flyer can be accelerated by laser ablation up to 10 km/s, which can simulate debris impact.
Flyer impact to Zirconia ceramics

Hyper velocity impact causes phase transition of zirconia ceramics (11 GPa).

FIG. 2. Optical micrograph of the recovered sample.

How can we see dynamics?

Molecular movie:
We use a pump and probe technique.

A pump pulse excites the matter. After delay, the probe pulse shows a snapshot of the phenomena. By changing the delay, we can get a movie in atomic levels.

Pump: laser
Probe: laser, x rays, electron

http://blogperso.univ-rennes1.fr/eric.collet/index.php/homebis
Laser pump & X-ray probe technique

Laser-shock compression

X-ray pulses from SR/FEL/

Direct observation of atomic motion under shock compression
Target

Target: before shock

Target: after shock
Structural dynamics under shock compression

Much higher pressures

Metallic carbon at 2 TPa: New materials

Much faster dynamics

We can get real atomic motions with femtosecond probe pulses.

X-ray Free Electron Laser
Big size and fs regime

XFEL is operating in Japan, US, EU

Ultrashort electron pulses
Laboratory size and sub-ps regime

atom motion in diamond
Summary

- The laser pulse can accelerate a flyer more than 10 km/s and simulate debris collision.

- Dynamics of structural change under shock compression and further fracture can be directly studied.

- Newly developing facility with ultrashort pulses (X-rays, electrons, photons) can directly monitor atomic motion and reveal the dynamics in non-equilibrium states.
Collaborators

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