Overview of High Energy Density Physics Research in Japan

Kazuhiko Horioka, Tohru Kawamura, Mitsuo Nakajima,
Toru Sasaki, Kotaro Kondo, Yuuri Yano

Department of Energy Sciences, Tokyo Institute of Technology

Masao Ogawa, Yoshiyuki Oguri, Jun Hasegawa

Research Laboratory for Nuclear Reactors, Tokyo Institute of Technology

Ken Takayama

High Energy Accelerator Research Organization

Shigeo Kawata, Takashi Kikuchi

Utsunomiya University
Laser related topics will be given in this meeting by

- Implosion and Ignition Physics
  H.Azechi, M.Murakami, K.A.Tanaka (ILE)
- WDM Physics with Ultra-short pulse Laser
  H.Yoneda (UEC)
- Laser-Plasma Acceleration toward High Energy Physics
  K.Nakajima (KEK)
- Monoenergetic Acceleration of Electrons by Laser Driven Plasma
  K.Koyama (AIST)

ILE   : Institute of Laser Engineering
UEC   : The University of Electro-Communications
KEK   : High Energy Accelerator Research Organization
AIST  : National Institute of Advanced Industrial Science and Technology
Activities on Accelerator and/or Pulse-power based High-Energy-Density Physics Researches in Japan

- Pulse Power driven WDM and Strong Shock Studies (TIT)
- Ion Source Development (TIT, RIKEN)
- Repetitive induction Modulator (TIT, KEK, JAERI)
- kHz Induction Voltage Modulator (TIT, KEK)
- Beam Physics in Final Transport (TIT, RIKEN, UU)
- Beam Plasma Interaction Experiments (TIT, RIKEN)
- Target Physics (ILE, UU)
- New Concept (ILE, UU, TIT,..)

- **TIT:** Tokyo Institute of Technology
- **RIKEN:** The Institute of Physical and Chemical Research
- **KEK:** High Energy Accelerator Organization
- **JAERI:** Japan Atomic Energy Research Institute
- **UU:** Utsunomiya University
- **ILE:** Institute of Laser Engineering, Osaka University
Outline of Presentation

• Pulse-power-driven HED Physics
  – EOS and transport coefficient
  – Electromagnetically driven strong shock waves

• Accelerator based HED Physics
  – Beam dynamics
  – Ion beam interaction with HED plasma
Warm-dense matter studies using pulse-powered wire plasma in water

**Experimental Setup**

![Experimental Diagram]

- **Load Section Filled with Water**
  - Tamper Effect
  - Transparent
- Fast Framing Camera
- Plasma Boundary Shock Wave Behavior
- Low Inductance by Coaxial Circuit
- Charge Voltage: 10kV
  - C: 3.2μF
  - Circuit Inductance: 112nH
- Load: Al, Cu and W Wire

**Experimental Arrangement**

**Advantages of This Scheme**

1. Electrical conductivity is directly measured by wire voltage and current.
2. Density is measured by evolution of wire radius.
3. Pressure history can be measured by shock wave trajectories in water.
Typical waveforms (voltage and current) of wire explosion in water

- Voltage
- Discharge current

- The voltage waveform depends on the wire materials.
- Waveforms are reproducible.
Evolutions of wire/plasma conductivity

- Conductivity curve has a bottom at \(\sim 500\text{ns}\) for Al and Cu-Wire, at \(\sim 1.2\text{us}\) for W-Wire.
- About 10 times compared with Spitzer’s conductivity.
Numerical Hydrodynamic Behaviors depend strongly on EOS Model

A Streak-shadow image of wire explosion in water

SW: Shock Wave
PB: Plasma Boundary

Comparison with numerical simulation
Semi-empirical fitting of hydrodynamic behavior brings us EOS modeling.
Formation of 1-D strong shock wave

- 1-D assumption enables us to use simplified analytical estimation
Criterion for radiative shock wave

• 1-D simplified analytical estimation yields a criterion* of shock speed for radiative regime,

From the requirement of $Prad/Pthe > 1$

$$D \geq D_{rad} = \left(\frac{7^7 k^4 n_1}{72 a \mu_1^3}\right)^{\frac{1}{6}} [\text{m/s}]$$

$K$: Boltzmann’s Constant, $a$: Radiative constant
$n_1$: Particle Density, $\mu_1$: Particle mass

Experimental arrangement for E-M driven 1-D strong shock wave formation

Gases: Xe, Ar
Initial pressure: 50 ~ 8000 mtorr
Quasi-one dimensional shock wave was formed by tapered electrodes and a guiding tube.

Initial condition 300mTorr (Xe)

- **Without guiding tube**
  - $D=17\text{km/s}$

- **Guiding tube**
  - Observing region
  - $D=23\text{km/s}$

- **With guiding tube**
  - Tapered electrodes

### Table

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>
Shock Mach Number exceeds 200 at low filling pressure
Typical Images of fast framing/streak camera

Initial pressure 4500 mtorr (Xe)

15 μs

16 μs

17 μs

18 μs

Front speed ~ 3.40 km/s

Luminosity at just behind the front is strong

M ~ 20

Initial pressure 150 mtorr (Xe)

2.0 μs

2.2 μs

2.4 μs

2.6 μs

Front speed ~ 25 km/s

Luminosity at far behind the front is strong

M ~ 200

Visible image changed with shock strength
At low filling pressure shock speed exceeds $D_{rad}$.

Indicating the existence of radiative front in strong shock waves ($M > 100$).
Summary of pulse-power-driven shock experiments

- Quasi-1D strong shock waves can be formed
- Shock Mach number exceeded 200 under low pressure condition of Xe
- When the front speed exceeded a critical value $D_{rad}$, the image structure changed
- Results indicates formation of a radiative shock wave
Accelerator based HED Physics

Possible Research Topics

- High Power Beam Dynamics
  - Induction synchrotron, Beam Compression,
  - Plasma Lens, Integrated simulation code

- Beam-(HED) Plasma Interaction
  - Energy deposition profile

- HED Physics using Ion Beam Produced Plasma
  - With well-defined and large scale-length plasma
Concept for Waveform Control

Parallel Stacking
(4kV-500nsec)

Module Structure
FET-Driver

Series Stacking
(20kV-100nsec)

Typical Waveform of Module
(4kV-100nsec-kHz)

Waveform Stacking
Robust against Load Condition

Voltage Driver
Arrangement of Devices/Cables

12GeV Main Ring
DC Power Supply
Booster
Induction Accelerating Cavity

1st Step for 10 KV Acceleration in FY2003

CW 1MHz
2kV/unit, 250nsec FT operation
All Ion Accelerator (more by K.Takayama)

- Driven by controllable induction modulator
- Induction modulator works both for acceleration and confinement
- Can accelerate ions with arbitrary masses and charges
- Modification of KEK500MeV Booster is planning

Balance Eq.

\[ M \gamma \frac{(c\beta)^2}{\rho} = Q \cdot (c\beta) \cdot B \quad \Rightarrow \quad A \cdot m \cdot \gamma \frac{c\beta}{\rho} = Z \cdot e \cdot B \]

Acceleration

\[ A \cdot m c^2 \cdot \gamma \dot{X} = \frac{Z \cdot e c \beta}{C_0} \cdot V_{acc}(t) \]

Acceleration Voltage

\[ V_{acc}(t) = \rho \cdot C_0 \cdot \frac{dB}{dt} \]
Induction buncher consists of periodic lattice, acceleration gaps & FODO quadrupole.

Beam head is decelerated by
Beam tail is accelerated

Head & tail velocities are modulated.
\[ \Delta \beta / \beta \] indicates Velocity Tilt.
Final Beam Bunching

Research of Beam Dynamics during Final Beam Bunching

Pb\(^{1+}\) 10GeV, Beam Current 400A⇒10kA

Transverse PIC Simulation with Initial KV Beam

For chlorine plasmas, ion energy of more than few tens MeV is necessary to occur the K-shell ionization.

T.Kawamura, Numerical Study on K-alpha Radiation from High Density Plasma by Energetic Particles, (This meeting)
Consideration of $K_\alpha$-radiation by ion beams for plasma diagnosis. With spatial resolved observation of $K_\alpha$-radiation, plasma heating process can be understood clearer than the traditional way of "TOF".

$Tokyo\ Institute\ of\ Technology$

Spatial resolved diagnosis of heating process is possible.
Beam-plasma interaction experiments using a dense z-pinch plasma at Tokyo Tech.

Large enhancement of energy losses of xenon ions was observed under target plasma densities above $10^{19}$ cm$^{-3}$, which was caused by an increase in projectile effective charge due to some density effects.

Energy loss of fully-stripped oxygen ions showed good agreement with theoretical predictions.
An electromagnetically-driven shock tube is being developed to produce weakly-non-ideal plasma targets.

- Discharge energy $\approx 0.1$ kJ during $\approx 1$ $\mu$s:

- Capacitor bank
- Magnetic field $i$
- Fast switch
- Electromagnetically driven piston plasma
- H$_2$ gas
- Initial pressure $= p_1$
- Accelerator
- Plasma diagnostics
- Shock wave
- Lorenz force
- Energy $E$
- Shock-produced plasma
- $1$ cm $\times$ $1$ cm (Square)

[more detail; Y. Oguri]
For time-resolved measurement, the SSD has to be used in combination with a fast beam deflector.

- The fast beam deflector has to be synchronized to the shock wave:

![Diagram showing the setup of the experiment]

- Beam intensity must be very low: \( \ll \tau^{-1} \) ions/s

- Pulse height \( \propto \) Energy = \( E - \Delta E \)

- Time scale \( \tau \approx \mu s \)

RLNR/Tokyo-Tech Heavy-Ion ICF Research Group
Driver beams interact with converter plasmas having $\Gamma$ values of 0.1~1.

Target Heating in HIF

X-ray converter (T~300 eV) is highly ionized $\Rightarrow$ stopping power enhancement, range shortening

Plasma parameter $\Gamma_{ee} = \frac{e^2}{4\pi\varepsilon_0 a kT}$

X-ray converter (T~300 eV) is highly ionized $\Rightarrow$ stopping power enhancement, range shortening

Plasma targets for interaction exp. $\Rightarrow$ Z-pinch plasma, Laser-produced plasma

↓ (higher density and $\Gamma$ value)

Thin-foil-discharge (TFD) plasma
The Principle of Thin-Foil-Discharge (TFD) plasma generation

- Areal density keeps constant in the early stage of discharge.
- Dense plasma is easily available. (~0.01 n_{solid})
- Plasma effects on stopping power can be easily extracted.

[J.Hasegawa; this meeting]
Time evolution of TFD plasma (Aluminum, 12 μm)

- TFD plasma expands freely into vacuum with time.
- Until 750 ns, the plasma boundary looks stable.
- At 820 ns or later, the surface became jaggy.
Ion-Bunch Compression and Beam-Target Interaction Experiments

In collaboration with TIT, KEK, Utsunomiya-U and LBL, LLNL, Princeton-U
Expected experimental range of pulse power and accelerator driven HED physics research in Japan

Wire Discharged Plasma in Water

Plasma Target

Strong E-M Shock Waves
Concluding remarks

• Compared with laser driven HED researches, we have just begun to study pulse-power and/or accelerator based HED physics

• There have been some advances in WDM physics, strong shock wave researches and beam-plasma interaction experiments

• Design works for a modification of the KEK facility are in the making stage and a 5-years US-J collaboration project in the HED (fast ignition) physics has been proposed