“Development of a shock-produced plasma target for nonlinear beam-plasma interaction experiments”

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Beam-plasma interaction experiments with non-ideal plasma targets are being planned at RLNR/Tokyo-Tech.

- Experiments performed so far using Tokyo-Tech 1.7 MV tandem accelerator:
Nonlinear effects are expected for projectile stopping in dense \( n_e \approx 10^{22} \text{ cm}^{-3} \) plasmas in fusion targets.

- **Ideal (dilute hot) plasmas** → “Linear stopping”:
  - Induced decelerating field \( E_{\text{ind}} \propto q \)
  - \(-dE/dx = q \times E_{\text{ind}}\) \(-q \times q = q^2\) (\(q\): projectile charge)

- **Non-ideal (dense cold) plasmas** → “Nonlinear stopping”:
  - Induced decelerating field \( E_{\text{ind}} \propto q^m \) (\(m < 1\))
  - \(-dE/dx = q \times E_{\text{ind}}\) \(-q \times q^m = q^{1+m} = q^n\) \((1 < n < 2)\)
Projectile-plasma coupling constant $\gamma$ is defined for projectiles moving in the plasma.

- Perturbations to the plasma electrons are possible only for the collision parameters $b$ smaller than screening length $\lambda$:

  $$b < \lambda = \frac{\langle v_r \rangle}{\omega_p}, \quad \langle v_r \rangle = v_{\text{th}} \sqrt{1 + \left( \frac{v_{\text{proj}}}{v_{\text{th}}} \right)^2}$$

  $\langle v_r \rangle$: averaged relative velocity

- If $b$ is smaller than the classical collision diameter $b_0$, the perturbation is strong enough to induce nonlinear effects:

  $$\frac{q e^2}{4 \pi \varepsilon_0 b_0} = m \langle v_r \rangle^2, \quad \text{or} \quad b_0 = \frac{q e^2}{4 \pi \varepsilon_0 m \langle v_r \rangle^2}. $$

- The projectile-plasma coupling strength is estimated by the critical ratio $\gamma \equiv \frac{b_0}{\lambda}$:

  $$\gamma \equiv \frac{b_0}{\lambda} = \frac{q e^2 \omega_p}{4 \pi \varepsilon_0 m \langle v_r \rangle^3} = \frac{\sqrt{3} q I^{3/2}}{1 + \left( \frac{v_{\text{proj}}}{v_{\text{th}}} \right)^2}^{3/2}$$

  Numerical calculation by a particle code

  $\rightarrow$ Nonlinear effects are clearly observable for $\gamma > \approx 0.1$
An electromagnetically-driven shock tube is being developed to produce weakly-non-ideal plasma targets.

- Discharge energy $\approx 0.1 \text{ kJ}$ during $\approx 1 \mu \text{s}$:
Conditions to realize $\gamma > 0.1$ have been searched by adjusting different projectile-target parameters.

- **Projectile:**
  - Projectile (tentative): 12.5 keV/u $^{91}$Nb
  - Effective charge $q \approx 4$
    cf. averaged charge in cold H$_2$ gas $\approx 3$

- **Plasma target:**
  - Beam-plasma coupling constant $\gamma > 0.1$
    to observe nonlinear effects
  - High ionization degree $\alpha >> 0.5$
    to clearly observe plasma effects
  - Target thickness $> 5$ mm
    to eliminate tube wall effects
  - Energy loss $\Delta E/E < \approx 0.2$
    to define interaction energy
  - Compact size and low discharge energy
    for installation in the beam line

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Rankine-Hugoniot relations (+ SESAME-EOS)

Initial condition: $p_1 = 5$ Torr, $T = 300$ K

Goal of the R&D:
Shock speed $u_s = 48$ km/s
(Mach number $M \equiv u_s/c = 36$)
The shock velocity was measured by a fast photography with a streak camera.

- **Streak imaging of the shock front propagating in the tube:**

  - The shock front was clearly observed on the streak images:

  - The shock front was fired at $t = 0$.
  - Discharge voltage $V_d = 20$ kV.
  - Propagation time: $3 \mu s$ for $p_1 = 1$ Torr, $0.9 \mu s$ for $p_1 = 5$ Torr.
  - Observed areas: $x = 5$ cm, $4$ cm, $3$ cm.
  - Shock speed $M = 31$, $M = 23$, $M = 15$.
  - Slope $= \text{shock speed}$.

The discharge voltage $V_d = 20$ kV.
So far $M = 24$ ($u_s = 32$ km/s) has been obtained for $p_1 = 5$ Torr at the interaction point.

- Measured shock speed at the interaction point ($x = 4$ cm):
  - Low initial pressure is favorable to reach higher shock speed
  - $u_s = 48$ km/s (goal) is expected for discharge voltages of $V_d \approx 40$-50 kV.
Electron density of the plasma was determined by laser interferometry with two different wavelengths.

- A Mach-Zehnder interferometer was integrated on the shock-tube base:
  - Laser streak camera
  - Observed region
  - Contribution of neutral species was canceled!
  - Free electron density $n_e$
  - Distorted shock front near wall (?)

$\lambda_1 = 488$ nm (Ar laser)
$\lambda_2 = 633$ nm (He-Ne laser)
Spatial and temporal homogeneity was enough to perform the planned beam experiments.

- $n_e$ behind $0.2 \mu s$ the shock front (lateral spatial distribution):
  - So far $\approx 10^{17}$ cm$^{-3}$ ($\alpha \approx 0.2$)
  - Much better homogeneity than laser plasmas
  - $\phi 1$ mm-beam can be used.

- $n_e$ at the interaction point (temporal evolution at $y = 0$):
  - Decreases due to recombination after passage of the shock.
  - $\approx$ constant (?) for $\approx 100$ ns
  - Pulsed beams with duration $\approx 100$ ns can be used.

**Graph:**
- Electron density $n_e$ vs. Lateral position $y$ (cm)
- Electron density $n_e$ vs. Time $t$ (µs)
- Parameters: $V_d = 20$ kV, $P_1 = 5$ Torr
- R&D goal
To establish a well-defined target thickness, very small beam apertures are needed.

- **Pressure requirements:**
  - Initial pressure $p_1 = 5$ Torr
  - Beam line pressure $p_0 < 10^{-5}$ Torr

- **Low energy (keV/u) heavy projectiles:**
  - Can stop even by 1 µm plastic film
  - Windowless target

- **Fast valve does not work!**

- **Differential pumping system with very small apertures:**
  - Target thickness ($\approx 1$ cm) must be $>>$ relaxation length $\delta w$.
  - $\delta w \approx$ aperture diameter $D$ (?)
  - $D$ must be $< \approx \phi 100$ µm!
A differentially-pumped gas cell with \( \phi 100 \, \mu m \)-apertures was employed for the test experiment with He.

- Relationship between the tube pressure \( p_1 \) and the chamber pressure \( p_0 \) was investigated for different gas-flow rates.
Measured results were fairly-well reproduced by a simple calculation assuming molecular flow.

- **Experimental result using He gas:**
  - $\phi 100 \, \mu m \text{ aperture} < \approx \text{mean free path of He gas molecules} \ (\approx 150 \, \mu m)$
  - Solid line: calculation using molecular-flow conductance of a “thin” small aperture

\[ F = C(p_1 - p_0) \]
\[ C = \frac{62.5}{\sqrt{M}} A \]
\[ p_0 = \frac{F}{S} \]

- $F$: flow rate
- $C$: conductance (l/s)
- $A$: aperture area (cm$^2$)
- $M$: gas molecular weight
- $S$: pumping speed of TMP
If the orifice diameter is further reduced, the beam line pressure can be as low as $\approx 10^{-5}$ Torr.

- Beam line pressure $p_0$ expected for operations with $\text{H}_2$ gas:

![Graph showing the relationship between pressure in the shock tube $p_1$ (Torr) and beam line pressure $p_0$ (Torr) for $\text{H}_2$ gas. The graph includes two lines: one for an orifice diameter of $\phi 100 \ \mu\text{m}$ with a pressure of $2 \times 10^{-5}$ Torr, and another for $\phi 50 \ \mu\text{m}$ with a pressure of 5 Torr.]
Si surface-barrier detector (SSD) was used to measure very low intensity beams through very small apertures.

- MCPs for TOF measurements:
  - High time resolution (< ns)
  - Sensitive to “beam current”，not to particle energy
  - Single-particle detection efficiency < 100%
  - Very sensitive to surface conditions
  - Expensive

- Direct energy measurement by SSDs:
  - Energy-sensitive, single-particle detection
  - 100% detection efficiency
  - Much more robust than MCPs
  - Low time resolution (≈ μs)
  - Unable to use for high intensity beam

![Typical time signal of a bunched beam measured by an MCP](attachment:time_signal.png)
For time-resolved measurements, the SSD has to be used in combination with a fast beam deflector.

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

![Diagram of ion beam system with shock tube, beam deflector, and detection components.](attachment:image)

- Beam intensity must be very low: $\ll \tau^{-1}$ (ions/s)
Energy loss of each single projectile can be evaluated by measuring the height of each pulse from the detector.

- SSD output waveforms for measurements with Mylar™ foil targets:
  - Projectile: 800 keV-protons through two apertures
  - Very low intensity (≈ $10^3$ ions/s) beam through the apertures
  - Fast beam deflector not yet in operation
The statistical energy resolution is enough to evaluate the projectile energy loss.

- Pulse height distribution for many shots (= energy spectrum):
  - Beam current was kept as low as possible to prevent “pile up” of pulses.
The measured energy loss was in a good agreement with calculations using a Monte-Carlo code.

- Comparison between the experimental and calculated results:
  - Circles : measurement with SSD
  - Solid line : Monte-Carlo calculation using “SRIM2003”

![Graph](http://www.srim.org/index.htm)

Target: 4 μm Mylar™

“Stopping and Range of Ions in Matter 2003”

http://www.srim.org/index.htm
Shock speed must be increased further by +50% ($M = 24 \rightarrow 36$):
- Higher discharge energy
- High-voltage switch with lower impedance
- Square tube $\rightarrow$ cylindrical tube to reduce friction losses (?)

Differentially-pumped gas cell works well:
- Aperture should be further reduced from $\phi 100 \, \mu m$ to $\phi 50 \, \mu m$.
- Alignment of two apertures will be tough!

Projectile energy loss was successfully measured by an SSD:
- Low-intensity beams through small apertures can be measured.
- Fast deflector is necessary for time resolved measurement. (R&D under way.)
- Noise due to plasma emission (?)

Atomic physics issues:
- Projectile charge $q$ (effective charge) $\approx$ averaged charge?
- Charge-changing reactions of slow ions in partially-ionized plasmas