# EXPERIMENTS ON INTERACTION BETWEEN DENSE PLASMAS AND HEAVY IONS

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We report recent results on the interaction between dense plasmas and heavy ions.

Plasma targets for in-beam experiments are formed by irradiation of a polyethylene plate or a lithium metal layer with a $CO_2$ laser of 6 J energy/pulse. The laser is focused with a spot size of $0.5 \times 9\,\mathrm{mm}^2$ to obtain uniform areal density. Heavy-ion beams from the TIT 1.7 MV tandem bombard the target plasmas. A dipole magnet analyzes the momentum and the charge state of the outgoing ions, which are detected by fast plastic scintillators. The energy loss of a $900\,\mathrm{keV}$ $Li^+$ beam in the polyethylene plasma was measured to be $38\,\mathrm{keV}$.

Another laser plasma target is produced by irradiating LiH pellets with a Nd-glass laser. The plasma is diagnosed by means of Mach-Zehnder interferometry and measurement of the ion-velocity distribution.

We have also developed Z-pinch He plasma target for interaction experiments with high-energy ions, with a $165\,\mathrm{mm}$ long discharge column $27\,\mathrm{mm}$ in diameter. A capacitor bank of $4.4\,\mu\mathrm{F}$ drives the discharge current of $40\,\mathrm{kA}$ at $16\,\mathrm{kV}$ voltage. The Z-pinch is realized at $t = 1\,\mu\mathrm{s}$, while the rise time of discharge current is $2\,\mu\mathrm{s}$. The electron density of the plasma obtained from the Stark broadening ranges from 4 to $5 \times 10^{17}\,\mathrm{cm}^{-3}$. A beam of $6\,\mathrm{MeV/u}$ $Ar^{17+}$ is injected on the Z-pinch He plasma to measure the energy loss using a TOF method. The observed energy loss is compared with the energy loss value for cold matter.

## 1. Introduction

Energetic Beams of heavy ions (HIB) are known to be a promising energy driver for inertial confinement fusion (ICF). To initiate the ICF, a HIB pulse strikes a pellet or a Hohlraum target, and ignites a plasma around target material, whereas the late part of the beam pulse impinges on the plasma. To understand the interation between HIB and plasma is therefore essential for realizing ICF[1].

On the other hand, the interaction between HIB and cold matter is an old topic, and many data have been accumulated for cold matter interaction. In contrast, our knowledge of HIB interaction with hot matter is still limited. We will report results of recent irnteraction measurements of HIBs with plasma performed at Tokyo Institute of Technology (TIT).

## 2. Laser induced plasma experiments

The HIBs for the laser induced plasma experiments are generated by the 1.7 MV tandem accelerator at Research Laboratory for Nuclear Reactors of TIT.
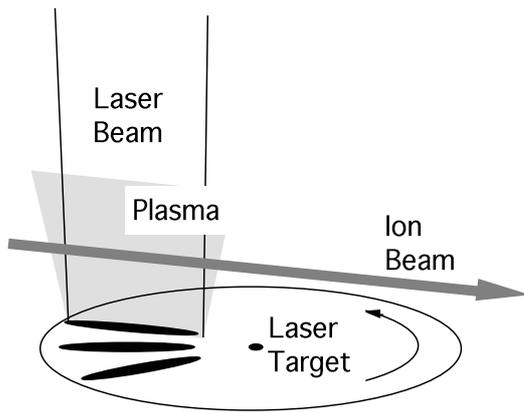
**Figure 1.** Schematic view of interaction
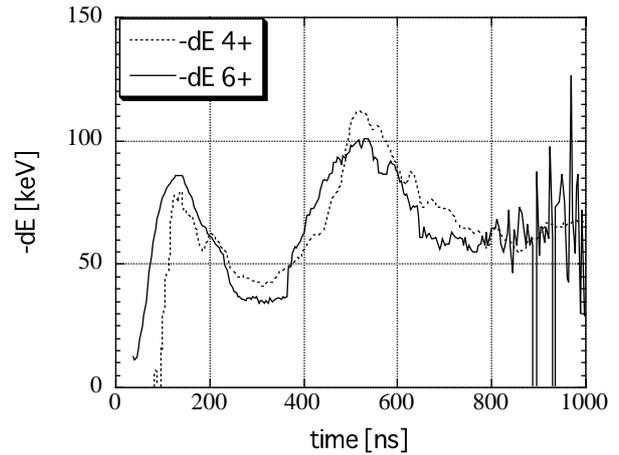


**Figure 2.** Energy loss of Oxygen beam in the polyethylene plasma

## 2.1. $CO_2$ Laser plasma experiments

These experiments were carried out with targets of polyethylene $((- CH_2-)_n$, 2 mm thick and of lithium ($12 \,\mu$m, evaporated on a 1 mm thick Cu backing). A 6 J/pulse TEA $CO_2$ laser beam ( $T_{FWHM} = 1.5 \,\mu$s) irradiates the target plate, which is oriented perpendicular to the laser beam. The spot size is $0.5 \times 9 \,\text{mm}^2$. This gives uniform electron density ( $n_e$) for the plasma volume near the target surface. The plasma is penetrated by the unpulsed HIB, oriented perpendicular to the laser beam, and parallel to the target plate (Figure 1). Already a single laser pulse essentially destroys a Li-target. We therefore evapolated lithium on a Cu-plate, which can be advanced stepwise after each laser pulse to provide a fresh Li-target. Since also the polyethylene target shows surface deterioration caused by the laser beam, it is handled in the same way.

The outgoing ions are momentum-analyzed by a dipole magnet and detected in three plastic schintillators with momentum defining slits. The momentum spectrum is recorded by increasing the dipole field stepwise after each shot. In addition we record for each event the time elapse from the leading edge of the laser pulse; these data give interesting information on the development of the plasma properties during the time of laser irradiation[1-3].

The Figure 2 shows a result of these measurements.

It gives the variation of the energy loss for $2.4 \,\text{MeV}$ $O^{2+}$ ions in a plasma formed through irradiation of polyethylene with a $CO_2$ laser pulses of $1.5 \,\mu$s duration. The two maxima in the early part of the pulse clearly reflect the two components of the $CO_2$ laser light. These maxima naturally should also appear in the electron density.

We determined it in a seperate experiment from the Stark broadening of the $H_\alpha$ line for the polyethylene plasma and the $610.3 \,\text{nm}$ line for the Li plasma in the plasma light. It is measured with an optical spectrometer placed in the HIB axis downstream from the plasma. The resulting electron densities are plotted in Figure 3.

Unfortunately, this measurement is limited to the time interval above $150$ ns, because in the early phase of the laser pulse the lines can not be observed due to the very intense light probably arising from recombination processes. The data however clearly show the second maximum, near 500 ns, also evident in the energy loss distribution. With our measured electron density of Figure 3, $n_e \sim 5 \times 10^{17}$ cm$^{-3}$, we can estimate the energy loss $-dE$ from the extended Bethe equation for hot matters[1,2,4,5]. In our first experiment we have measured the effective charge of the ion beam in the plasma to be very close to 5. With these values we obtain $-dE \sim 45$ keV energy loss for $2.4$ MeV $^{16}O^{2+}$ ions in polyethylene plasma, in accord with experiment.

## 2.2. Nd-glass Laser plasma experiment

In this experiment a Q-switched Nd-glass laser beam irradiates LiH pellets. The pellet diameter is sufficiently small to avoid a gradient of $n_e$ as well as to achieve high ionization rate. Each pellet is supported by a carbon fiber and placed precisely in the focal spot of the laser beam using a 3D manipulator. The laser beam diameter at the focal spot is $100$ $\mu$m, and the power density is $10^{12}$ Wcm$^{-2}$.

A pair of biased charge collectors is used to verify the homogeneity of the plasma expansion. Also the burn-up of the pellets is monitored by the BIC signal.

Typically, the plasma has a diameter of $10$ $\mu$m, and $n_e$ is $10^{17}$ cm$^{-3}$, measured by Mach-Zehnder interferometry. A polychrometer and a streak camera are used for spectroscopic plasma diagnosis. A wide range spectrum of moderate resolution can be obtained in a one-shot measurement. The spectroscopic measurements give the following results: (1)The plasma exists for the same duration for pellets with 60 to $300$ mm diameter. (2)The electron temperature Te is $1.9 \times 10^5$ K, and decreases to $2.2 \times 10^4$ K after 100 ns.

We are presently preparing stopping power measurements with a HIB penetrates the pellet plasma. It turned out that such measurements are only possible if the HIB start after ignition of the plasma. For this purpose a fast beam kicker was build. Moreover the beam is chopped with a high frequency, which will allow the time of flight (TOF) measurements to obtain the stopping power.

## 3. Z-pinch plasma experiment

For this experiment a Z-pinch target is connected to the HIB-line, and supplied with a suitable differential pumping system. The He discharge column of $27$ mm diameter is $165$ mm long. The discharge is operated at a gas pressure of $100$ pa with a $40$ kA, $10$ kV current driven from a $4.4$ $\mu$F capacitor bank. Plasma diagnosis is provided from streak pictures and by optical spectroscopy monitoring Stark broadening and characteristic line intensities. We find that the plasma is held for a duration of $1.0$ to $1.8$ $\mu$s from the beginning of the discharge. The pinch diameter is 6mm, the pinch speed $\sim 1.8 \times 10^4$ m/s, $n_e \sim 5 \times 10^{17}$ cm$^{-3}$, and Te $\sim 5$ eV. The HI energy loss is obtained from the TOF of the ejectile-ions. Since the TOF differences will be in few sub-ns range, we record the HIs in a multi-channel plate (MCP). The ejectiles are focused by a quadrupole magnet and are deflected in a dipole field to eliminate plasma light noise. The

MCP is placed 45 degree off beam axis and records secondary electrons from a $10\,\mu$m thick Au-foil released by the impinging ejectiles (Fig. 4). A negative bias is attached to the foil to increase detection efficiency.
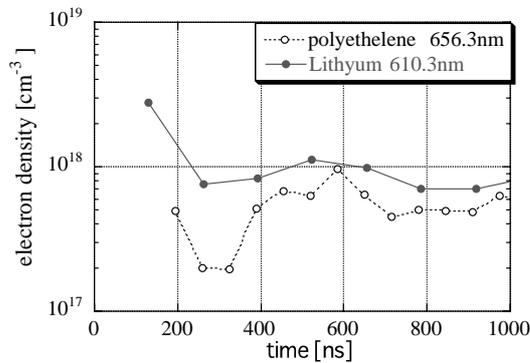


**Figure 3.** Electron density of plasma calculated
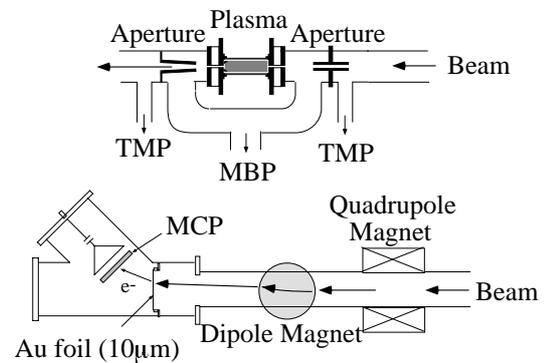


**Figure 4.** Experimental set up

The apparatus is installed at the HIMAC accelerator of the National Institute of Radiological Sciences (NIRS) in Chiba. The $6\,\mathrm{MeV/u}\,\mathrm{Ar}^{17+}$ beam used in the stopping power measurement has a $10\,\mathrm{ns}$ microstructure -which is exploited for the TOF measurement - during the macropulse. To get all the points through the pinch time as shown in the Figure 5 the discharge timing is shifted for each shot. The experimental result compared with calculation is shown in Figure 5. The charge state of the ions is assumed as 17+ and 18+ (fully stripped), and the stopping power is calculated using the extended Bethe equation. In the time interval from $1.0$ to $1.3\,\mu$s after beginning of the discharge, the data are $\sim 1.5$ times larger than calculated from theory, which might be caused by the observation direction of the optical spectrometer. At 90 degree to the discharge column, one expects less Stark broadening; but observation in the column direction is impracticable in the experiment. At $\sim 1.8\,\mu$s the data approach the cold matter prediction. This is supported by streak pictures which indicate plasma instability from $\sim 2.0\,\mu$s.

### Acknowledgments

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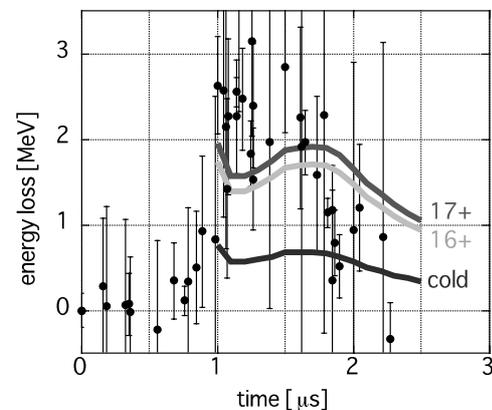
**Figure 5.** Energy loss at Z-pinch plasma