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Experimental apparatus for the measurement of non-linear stopping of low-energy heavy ions

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Abstract

We developed an experimental apparatus for the study of non-linear stopping of low-energy heavy ions in non-ideal plasmas. The target plasma was produced by an electromagnetically driven shock tube. A pair of 50-μm-diameter beam apertures was attached to the shock tube wall. These apertures confined hydrogen gas of ≈ 5 Torr in the tube and sustained the pressure difference ($\sim 10^5$–10^6) between the tube and the beam line. In order to measure the energy loss in the plasma in the tube, we used a semiconductor charged-particle detector, which could directly measure the kinetic energy of single particles, since the beam transmission through these apertures was very small. To synchronize the plasma production in the shock tube and the injection of projectiles, a fast beam kicker was installed in front of the plasma target. Results of preliminary experiments using thin carbon foil targets showed that the measured energy loss of single projectiles after passing through the target was in agreement with other data. The time resolution of the energy-loss measurement system was ≈ 150 ns, which is enough to measure the projectile energy loss during the life time of the target plasma.

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1. Introduction

For the design of heavy-ion inertial fusion (HIF) schemes, data on the energy loss of heavy ions in plasmas are important to analyze the energy deposition profile in the fuel pellet. Although the data for low projectile energies ($\lesssim 1\,\mathrm{MeV}/u$) may not be important for this purpose, this energy region is very rich in interesting physics issues, because the projectile velocity is comparable to that of electrons in the targets. Nevertheless, the experimental data especially for projectile energies below $500\,\mathrm{keV}/u$ are scarce [1–4]. Against this background, we have investigated the stopping power of low-energy ions (100–$300\,\mathrm{keV}/u$) in laser-produced plasmas [3–5]. So far enhancement of the stopping power and projectile charge in non-hydrogenic plasmas with electron densities of $\sim 10^{18}\,\mathrm{cm}^{-3}$ and temperatures of ≈ 10–20 eV has been successfully observed [3–5].

If the target plasma is not so dense and the coupling between the projectile and the plasma is weak, like in the above case, the stopping power of swift ions, for example, is proportional to the square of the projectile charge. On the other hand, if the plasma is very dense and cold, this relationship can deviate from the proportionality. This is so-called "non-linear stopping" of projectiles in non-ideal plasmas.

To measure the strength of the non-linear effect, a projectile-plasma coupling constant defined by

$$\gamma \equiv \frac{\sqrt{3} z_{\mathrm{eff}} \Gamma^{3/2}}{\{1 + (v_{\mathrm{proj}}/v_{\mathrm{th}})^2\}^{3/2}} \tag{1}$$

can be used [6–9]. In the above equation, z_{eff} is the projectile effective charge, Γ is the plasma coupling

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constant, v_{proj} is the projectile velocity, and v_{th} is the thermal velocity of the electrons in the plasma. From Eq. (1), one sees that low projectile velocities are preferable to obtain high γ for given conditions. According to MD calculations, non-linear effects are observable for experimental conditions with $\gamma \sim 0.1$ [9]. We use $\sim$10-keV/u projectiles with $z_{\mathrm{eff}} \approx 2$, which is the equilibrium charge in the target plasma. In this case, $\gamma = 0.05$ is achieved for a fully ionized hydrogen plasma target with a temperature of ≈ 1.5 eV and an electron density of $\approx 3 \times 10^{18}\,\mathrm{cm}^{-3}$ [10].

To fulfill these conditions, we adopted a target plasma produced by an electromagnetically driven shock wave. According to preliminary experiments, the initial hydrogen gas pressure in the tube before discharge must be ≈ 5 Torr [10], whereas the beam-line pressure must be lower than 10^{-6}–10^{-5} Torr. That is, we have to confine the hydrogen gas in the tube and sustain a pressure difference of $\sim 10^5$–10^6 between the tube and the beam line. Thin film windows cannot be used for the gas confinement because the projectile energy loss in such films is too large for $\sim$10-keV/u projectiles. Therefore, we must adopt a differential pumping method using two small thin apertures to sustain the pressure difference.

In previous experiments using laser-plasma targets [3–5], we have used a Time-Of-Flight (TOF) method based on pulsed beams and MCP detectors to measure the projectile energy loss. In order to carry out this method, peak beam currents higher than $\sim$100 nA were needed to obtain clear time signals. However, in the present experiment, the beam transmission through the target apertures is expected to be very small ($\sim$10 pA). So we have stopped using the TOF method and employed a semiconductor charged-particle detector, which can directly measure the kinetic energy of single particles. The life of the target plasma is ≈ 200 ns, whereas the time resolution of the detector is $\sim 1\,\mu$s. In order to realize a time-resolved measurement, we need to synchronize the plasma production in the shock tube and the injection of projectiles by using a beam kicker.

In this paper, we present performances of an experimental setup for the measurement of non-linear stopping of low-energy heavy ions in non-ideal plasmas based on above ideas. Results of preliminary test experiments using thin foil targets are reported. The time resolution of the whole measurement system including the fast beam kicker is discussed.

2. Experimental setup

2.1. Differential pumping system

Fig. 1 illustrates the experimental setup that will be installed at the 1.6 MV electrostatic tandem accelerator facility at RLNR, Tokyo-Tech. Beams of 10–30-keV/u heavy ions with a charge of $q \approx 2$ will be used as the projectile.

To confine hydrogen gas in the shock tube, we used a two-stage differential pumping system. A pair of 50-μm-diameter apertures sustains a pressure difference of 10^5–10^6 between the tube (1–10 Torr) and the medium-pressure room ($\sim 10^{-5}$ Torr). A pair of tubular orifices with a

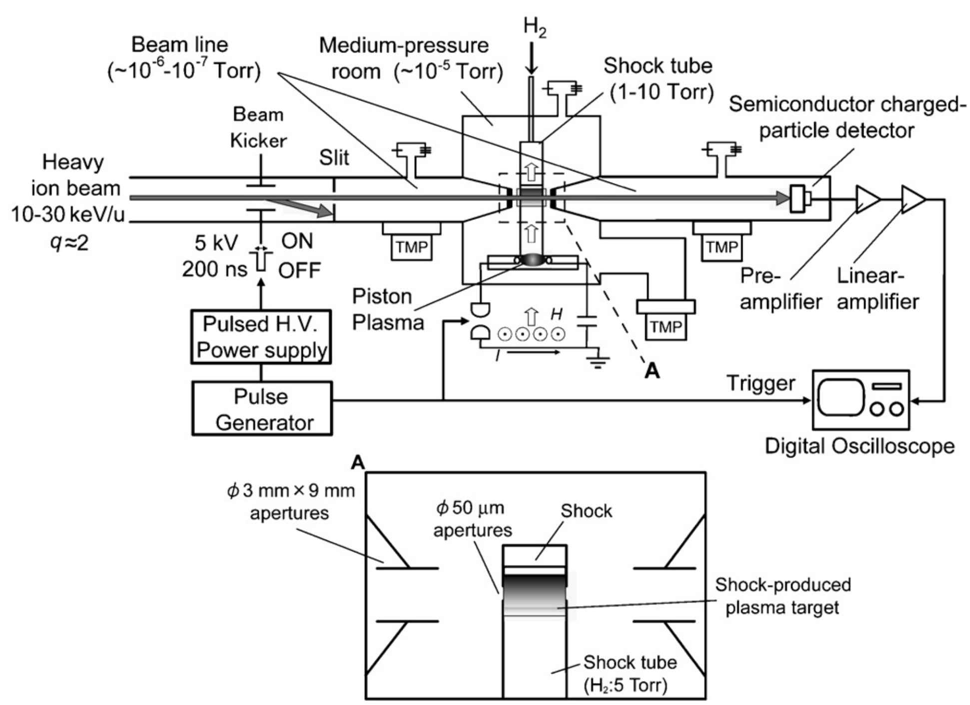

Fig. 1. Experimental setup for the non-linear stopping experiment.