Stopping of Heavy Ions in a Hydrogen Plasma

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Experiments are presented which demonstrate, for the first time, the extreme stopping power of fully ionized hydrogen plasma for low-energy (45 keV/u) heavy ions. The plasma was created by an electrical discharge in a 20 cm long quartz tube, producing electron densities up to 7×10^{16} cm^{-3} at plasma temperatures well above 1 eV. In the described experiment a stopping power of 1080 MeV/(mg/cm^2) was measured using krypton ions, which exceeds the corresponding value in cold neutral gas by a factor of 35. These measurements provide the first experimental confirmation of theoretical stopping power predictions close to the expected maximum in a fully ionized plasma.

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Heavy ion beams are potential candidates to serve as drivers for inertial confinement fusion [1–3]. The capability of heavy ion beams to generate dense plasmas and to heat matter to extreme conditions of temperature and pressure is expressed by the specific energy ε, the energy deposited per mass unit:

$$\varepsilon = \frac{dE}{dx}\frac{N}{\pi r^2}, \tag{1}$$

where dE/dx is the energy loss of a single heavy ion in matter in units of MeV/(mg/cm^2), N is the number of beam ions delivered to the target, and πr^2 is the focal spot area of the beam on target. At Gesellschaft für Schwerionenforschung (GSI) in Darmstadt, experimental investigations make use of these unique accelerator facilities to evaluate the key parameters of matter heated with heavy ion beams. Advanced focusing techniques for charged particle beams are under development using a plasma lens [4] to improve the focal spot area πr^2. The development of the high-current radio-frequency quadrupole accelerator MAXILAC (high number of ions, N) made it possible to generate the first heavy-ion-beam-heated plasmas and to study the hydrodynamic reaction [5] of those plasmas. The work described here is related to the experimental determination of the parameter dE/dx in a plasma.

The detailed modeling of ion-beam-heated matter at high energy density depends strongly on the precise knowledge of the energy deposition process of ions in a plasma. In a standard model approach [6–8] the energy loss of heavy ions in a fully ionized plasma is calculated in terms of a modified Bethe formula:

$$-\frac{dE}{dx} = \left(\frac{\omega_p Z_{\rm eff} e}{v_p}\right)^2 G\left(\frac{v_p}{v_{\rm th}}\right) \ln\left(\frac{0.764 m v_p^3}{Z_{\rm eff} e^2 \omega_p}\right), \tag{2}$$

where $\omega_p = \sqrt{4\pi n_e e^2/m}$ is the plasma frequency, $v_{\rm th} = \sqrt{kT/m}$ is the thermal velocity of the plasma electrons, v_p is the projectile velocity, and $Z_{\rm eff}$ is the effective charge of beam ions during passage through the target [9,10]; n_e, e, and m are electronic density, charge, and mass; $G(v_p/v_{\rm th})$, Chandrasekar's function, accounts for the reduction of the stopping power formula at low velocities. The major difference between a plasma and cold matter is expressed in the stopping power formula by a different effective ion charge $Z_{\rm eff}$, and by a modified Coulomb logarithm. In general, both modifications lead to an enhancement of energy loss in a plasma compared to neutral matter. In ionized matter, energy loss processes are dominated by collisions between heavy ion projectiles and free electrons, rather than by bound electrons of cold, neutral matter. For collisions with free electrons, the lower limit to the energy transfer is given by the plasmon energy $\hbar\omega_p$, which is a small quantity compared to the average ionization potential of neutral matter. The bulk of very small angle scattering processes increases the total energy loss of ions considerably compared to collisions with bound electrons. This effect enters the stopping power formula by a different Coulomb logarithm [8].

The dynamic equilibrium of ionization and recombination determines the ion charge state. Since the direct capture of a free electron into a moving projectile violates the simultaneous fulfillment of energy and momentum conservation, this process is greatly reduced compared to the capture of a bound electron [9–11]. Therefore the charge state of heavy ions crossing a fully ionized plasma is expected to be higher than for ions in cold, neutral matter. This effect is most important at low particle velocities, where the recombination rate in cold matter increases drastically. Already even minor changes in the effective

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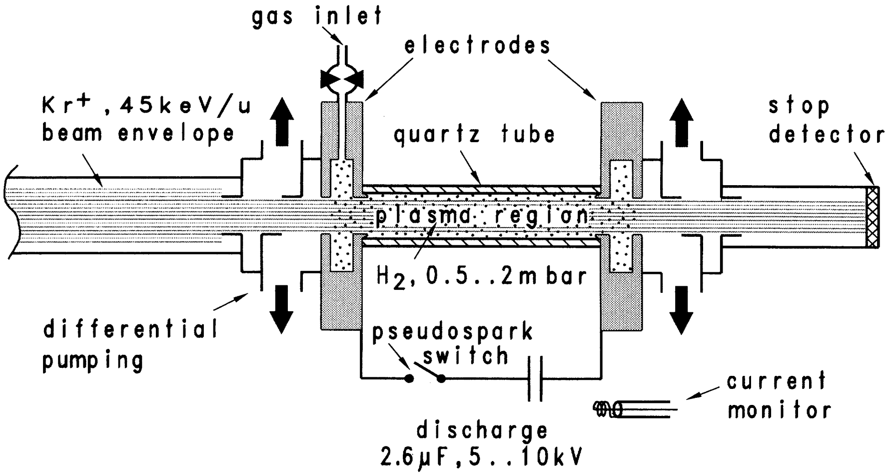

FIG. 1. Schematic setup of the stopping power experiment at MAXILAC.

ion charge do greatly affect the energy loss, since the stopping power depends on a quadratic term in this formula.

The first experimental evidence of plasma stopping power enhancement was observed for deuterons and protons [12,13], where no charge state effect is present. Later, systematic energy loss measurements in hydrogen plasma verified the difference in stopping power between a highly ionized plasma and cold matter also for heavy ions [14–16]. Experiments have been carried out at energies between 1 and 6 MeV/u for a large variety of ion species from carbon to uranium [17–20]. An enhancement factor of only up to 3 was demonstrated there. This enhancement was mainly attributed to the more effective energy transfer due to collisions with free electrons, which increases the Coulomb logarithm [Eq. (2)]. For lower kinetic energies, where the projectile velocity is comparable to the thermal velocity of the plasma electrons, the stopping power of a plasma is expected to be even higher than for the previous beam energies [7,8], whereas the stopping power of cold matter decreases by 1 order of magnitude. This qualitatively different behavior for the stopping power of hot and cold matter at low beam energies originates from the higher charge state of the beam ions [Z_{eff} in Eq. (2)] in a highly ionized plasma. The experiment reported here is the first measurement in this energy regime, where the enhanced charge state of ions in a plasma causes the main contribution to the increase in the stopping power.

Singly charged Kr^{+} ions at 45 keV/u (3.8 MeV) from a rf accelerator were used to investigate the stopping power at low beam energies. Figure 1 shows the principal setup of the experiment. A homogeneous plasma is produced in a 20 cm long cylindrical quartz tube. A capacitor bank (2.6 μF, 5–10 kV) supplies discharge currents of 10–20 kA to the plasma. This current is oscillating with a half period of about 4 μs. At initial hydrogen gas pressures of 0.5–2 mbar, electron densities of up to $10^{17}\ \mathrm{cm}^{-3}$ are produced in the discharge. The two-stage differential pumping system consists of a powerful root pump and two turbomolecular pumps at the second pumping stage, each reducing the pressure by about a factor of 100. Discharge tube, root pumping, and turbomolecular pumping are separated by small apertures (diameter of 3 mm, length of 30 mm), which allow a windowless penetration of the ion beam into the plasma. These small apertures define the beam path through the plasma close to the optical axis of the discharge tube.

The time-of-flight measurement to determine the energy loss is based on the 13.4 MHz radio frequency structure of the accelerator. The microstructure of the ion beam leads to an ion bunch every 74.8 ns registered by the final stop detector. The arrival time of these ion bunches is digitized at a sampling rate of 1 GHz and recorded during 20 μs. Figure 2 shows typical signals obtained from cold hydrogen gas and stop signals that arrive during the discharge of the pulsed power generator. The stop signals from ions passing cold hydrogen gas show a constant phase

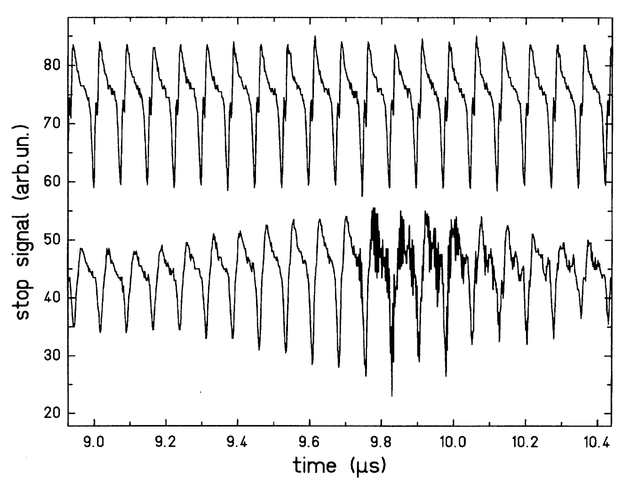

FIG. 2. Stop signals as obtained from the ion beam. The upper graph represents stop signals from cold hydrogen gas, whereas the lower graph shows detected signals during the plasma discharge. From the phase shift of these signals the energy loss is determined.

shift compared to the vacuum stop signals, whereas the arrival time of the plasma stop signals changes with the density variation of the plasma. The maximum phase shift registered during the discharge yields a 95 ns delay. Intensity variations of the stop signals are observed during the discharge, following the period of the oscillating current from the pulsed power generator. This intensity variation is caused by the time-varying azimuthal magnetic field associated with the strong discharge current, the so-called plasma lens effect [4,21]. According to the direction of the discharge current, the ion beam is focused or defocused, and the transmission of the ion beam through the apertures of the differential pumping system is changed. The active-ion optical behavior of the plasma target bends the ion beam trajectories as compared to a straight line, but the variation in path length of the detected ions is small, and thus the energy loss measurement is not affected.

Results of the energy loss measured by the time-of-flight system (crosses) and the corresponding electron density of plasma (solid line) are shown in Fig. 3. Data for the energy loss in cold hydrogen gas are obtained from the time-of-flight signal before the discharge. The start of the discharge has arbitrarily been chosen to be time zero. Because of the strong influence of the discharge on the ion transmission, no stop signals are observed at the beginning of the discharge. The first detected time-of-flight signals of the discharge about 5 μs after ignition correspond to an energy loss of 18 keV/u, or to a relative energy loss of 40%. The comparison of the energy loss during the plasma discharge with the values obtained for cold gas (1.2 keV/u), already shows a dramatic enhancement of energy loss in the plasma. For a calculation of the stopping power, the determination of the plasma density is a prerequisite. The plasma parameters were measured by side-on observation of the Balmer emission from the hydrogen plasma [22]. The system of a spectrometer, a streak camera, and a change-coupled device camera served as a tool for the time- and wavelength-resolved detection of the H_α and H_β lines of the plasma. The plasma electron density is derived from the Stark broadening of the H_β emission. The experimental error of the electron density is marked at two positions in Fig. 3. For the results shown above, the measured electron density reaches its maximum of $n_e = 7 \times 10^{16}$ cm^{-3} after about 3.5 μs heating time, decreasing during the subsequent 10 μs to $n_e = 1 \times 10^{16}$ cm^{-3}. During this period the energy loss in the plasma follows the decreasing electron density. Within the experimental accuracy obtained for the electron density, no further temporal dependence on plasma parameters for the energy loss except on plasma density can be deduced. The electron temperature of the plasma is determined from the ratio of H_β to continuum emission, or from the line ratio of H_α to H_β. The temperature maximum is observed about 4 μs after ignition of the discharge, reaching a value well above 3 eV. During the following 11 μs, the temperature decreases to about 1 eV, keeping the degree of ionization in the plasma for the first 14 μs to 99% and higher.

A comparison of the measured stopping power of a plasma and of cold hydrogen gas with theoretical calculations is shown in Fig. 4. The solid lines represent theoretical calculations of the hydrogen plasma stopping power performed with a Monte Carlo code [17]. This code is entirely based on the charge transfer cross sections of Ref. [8,10]. Theoretical values for the stopping power of cold hydrogen gas are represented by the dash-dotted line. The data shown here are in agreement with the values of Ref. [23] within 10%. For cold hydrogen gas the experimental result yields 33 ± 5 MeV/(mg/cm^2). The dashed area represents the region of stopping power achieved with the maximum charge state expected for a fully ionized plasma (upper curve) and the stopping in a plasma obtained with charge states of cold hydrogen gas (lower curve). The Monte Carlo simulations indicate that, for the energy

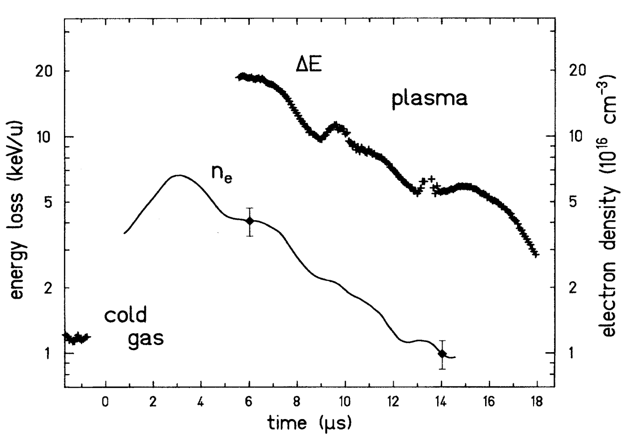

FIG. 3. Energy loss of krypton ions in a hydrogen plasma and corresponding electron density in the plasma.

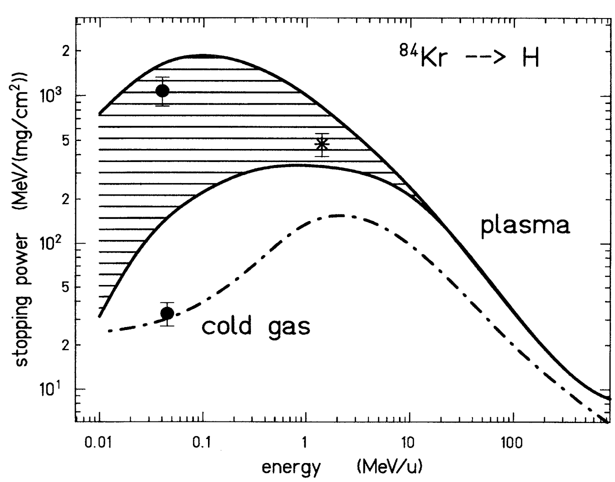

FIG. 4. Experimental results for the stopping power of a hydrogen plasma and cold hydrogen gas in comparison with theoretical calculations.

regime of this experiment, a fraction of a few percent of the used plasma length is sufficient to obtain the calculated charge states. For an average ion energy of about 40 keV/u, a hydrogen plasma stopping power of 1080 ± 210 MeV/(mg/cm^2) is measured. The experimental value at 1.4 MeV/u was obtained during an earlier plasma stopping experiment performed at the UNILAC accelerator [24].

A theoretical estimate of the charge states of krypton is available based on the cross sections of Ref. [10]. Given the energy of 45 keV/u, an effective charge state of about $Z_{\text{eff}} = 2$ is calculated for krypton in cold hydrogen gas. Comparing the rates for ionization and recombination in the plasma (taking into account dielectronic recombination and inverse photoeffect) effective charge states $Z_{\text{eff}} = 3.1$, 4.5, 6.4, and 7.8 [Eq. (2)] are expected for an ionization degree of 90%, 99%, 99.9%, and 100%, respectively. Because the recombination rate in cold gas is 2 orders of magnitude larger than the recombination rate in a fully ionized plasma, even small contributions of cold gas recombination will change the subsequent ion charge state substantially. The difference obtained for the measured stopping power of the hydrogen plasma to the maximum theoretical values (Fig. 4) can be understood as a reduced effective ion charge $Z_{\text{eff}} \approx 5.5$, due to the presence of a small fraction of neutral gas (about 1%) in the plasma. This explanation is supported by the ionization degree obtained from the plasma diagnostic. Thus, in the framework of an accepted theoretical model, the measurement of stopping power at low beam velocities provides a new tool to determine the ionization degree of a plasma.

In summary, the experimental results demonstrate, for the first time, the extreme enhancement of the stopping power of low-velocity heavy ions in a fully ionized plasma. In comparison to experimental and theoretical cold gas data, this is an enhancement factor of 35. The effect observed in this experiment is larger by 1 order of magnitude than any other result of plasma stopping power that has been reported previously. In the energy regime below 100 keV/u considered here, these results are close to the expected maximum energy loss in fully ionized hydrogen plasma, where these measurements provide a first experimental test of established stopping power models. In this energy regime an enhanced ion charge state compared to cold matter causes the main contribution to produce the large energy loss. A fully ionized plasma target may well be exploited as an effective plasma stripper for heavy ion accelerators [25], since the projectile ion charge states are far above the equilibrium charge states in cold, neutral gas.

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