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2006 J. Phys. A: Math. Gen. 39 4749

(http://iopscience.iop.org/0305-4470/39/17/S69)

INSTITUTE OF PHYSICS PUBLISHING JOURNAL OF PHYSICS A: MATHEMATICAL AND GENERAL

J. Phys. A: Math. Gen. **39** (2006) 4749–4754 doi:10.1088/0305-4470/39/17/S69

Shockwave-driven, non-ideal plasmas for interaction experiments with heavy-ion beams

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Received 20 September 2005, in final form 6 December 2005
Published 7 April 2006

Abstract
Plasma targets for measuring energy loss and charge-state distribution of heavy ions in non-ideal plasmas have been developed. Ar plasmas with Γ-parameters 0.55–1.5 could be realized and the interaction with several ion species studied. Here, the results for 5.9 MeV/u C ions are presented. The energy loss in plasma was reproduced in different experiments.

PACS numbers: 52.27.Gr, 52.40.−w, 52.40.Mj, 52.50.Lp

1. Introduction and motivation

For ideal plasmas the energy loss of interacting charged particles exhibits a Z_{eff}^2-proportionality. Recently, non-ideal plasmas in the 'warm dense matter' regime have found closer scientific interest, since they are important for laboratory astrophysics [1], inertial confinement fusion [2, 3] and the design of fusion targets [4]. Non-ideal plasmas are also called strongly coupled and are characterized by a Γ-parameter with $\Gamma = e^2/k\,\mathrm{T}r_D \geqslant 1$. A difference compared to ideal plasmas is a predicted proportionality of the stopping power or energy loss of charged particles in the plasma of Z_{eff}^b with $b < 2$ [5–8].

An accurate knowledge of the physics of the energy deposition of a heavy-ion beam in dense matter is a very essential problem for the fields mentioned above. While a variety of experimental data have been accumulated concerning the stopping of ions in cold matter or in ideal plasmas [9–14] no experimental database exists yet for the interaction of heavy ions with non-ideal plasmas.

To understand the behaviour of the stopping power of dense non-ideal plasmas, correlation effects have to be considered due to strong coupling: multiple scattering, dynamic screening, bound states and lowering of the ionization energy. These non-ideality effects can lead to

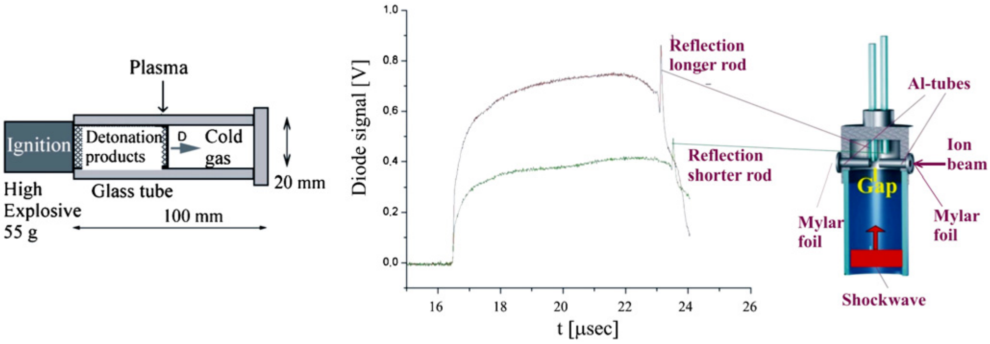

Figure 1. Scheme of the explosive target and plasma creation (left-hand side), the explosive gap target developed for experiments with heavy ions and the principle of shockwave velocity measurement (right-hand side).

strong deviations from the Z_{eff}^2-dependence of the stopping power, especially for ion energies with $v \leqslant v_{\mathrm{th}}$ of the plasma electrons [6, 7].

2. The targets and plasma parameter

A possibility of creating non-ideal, strongly coupled plasmas which are very homogeneous, are shockwave-driven plasmas, where gas is compressed and becomes ionized in front of a shock front and a plasma sheath of a thickness of several millimetres is created [15, 16]. The shockwave is initiated by a small amount of a high explosive material (55 g of RDX) and reaches velocities of several km s^{-1}. Flyer plates between high explosive and gas volume improve the planeness of the shockwave.

Figure 1 shows the scheme of such a target (left-hand side) and the later realization of a target for creating non-ideal plasmas developed for the experiments at GSI (right-hand side). The interaction experiments at GSI extended for the first time experiments with non-ideal plasmas and protons in the MeV/u energy region to heavy ions. The first stage of the experiments at GSI involved this target development. The targets originally developed at ITEP, Moscow, for the proton experiments [15, 16] were not compatible with heavy-ion beams. The finally successful design was the ‘gap target’. While the lower part with the explosive, flyer plate and gas inlets stayed unchanged, the target head was redesigned.

In the head section of this target, two small metal tubes with 1.5 μm mylar foil windows face each other 180° opposite (diameter of target head = 28 mm). Between them is a gap of several millimetres. This is the interaction zone with the plasma. Like in the earlier targets, the shockwave travels through the target, but the outer areas with possible inhomogenities due to plasma–wall interaction are shaded by the tubes. The short-interaction distance in the gap with the compressed gas in the plasma phase minimizes straggling losses. Two glass rods protrude with different lengths into the target head. A peak in the light emission of the plasma observed with photo diodes originates from the reflection on the surface of the rods. The timely difference between the peaks recorded with an oscilloscope gives the shockwave velocity. The plasma parameters are determined by the SAHA-4 code [17], which needs initial gas pressure and shockwave velocity as input parameters to calculate the plasma properties. The code is based on the chemical model of the plasma and extensive data from spectroscopic measurements (IPCP). The plasma parameters for Ar plasmas with initial Ar-gas pressures between 0.2 and 3 bar, which were obtained with the gap targets, are listed in table 1.

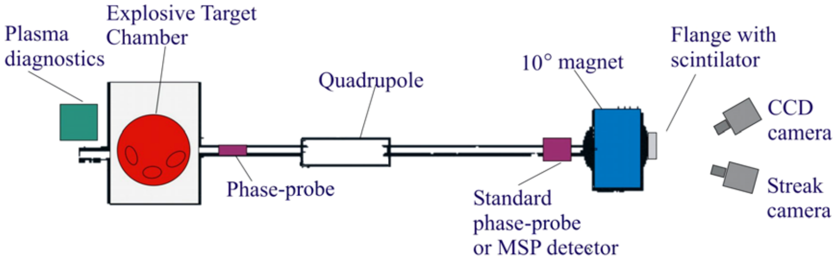

Figure 2. Scheme of the experimental set-up for measuring the interaction of heavy ions with explosively driven non-ideal plasmas at the experimental area Z6 at GSI.

Table 1. The plasma parameters obtained with gap targets for Ar plasma.

N_e (cm^{-3})	T_e (eV)	Compression factor	Γ-Parameter	Ionization degree (%)
3×10^{19}–1.5×10^{20}	1.8–2.0	10–8	0.55–1.5	30–50

3. Experimental set-up

At the UNILAC accelerator at GSI an experimental set-up was used measuring the energy loss of heavy ions in these plasma targets. A compact vacuum-pumped steel chamber, designed for explosions up to 200 g RDX, which was originally used for the proton experiments at ITEP, was aligned to the beam line. Fast valves [18] connected to the chamber protect the high vacuum beam line from the pressure increase and detonation products. A schematic set-up of the experimental area can be seen in figure 2. The energy loss measurements are performed by time-of-flight (TOF) methods with a microspherical plate (MSP) or phase probes at sufficient beam intensity as stop detectors. The charge-state distribution of the ions after passing the plasma can be analysed by a 10° magnetic spectrometer and a scintilator. With either a CCD camera a static charge state distribution or a streak camera a dynamic charge state distribution can be recorded. A phase probe as stop detector in front of the magnet provides a non-beam-destructive TOF measurement and therefore simultaneous analysis of the charge-state distribution after the magnet.

4. Results for the energy loss for 5.9 MeV/*u* C ions in the plasma

Between December 2002 and January 2005 interaction experiments with C, Ar and Xe ions [19] at energies 5.9 MeV/u and 11.4 MeV/u were carried out. In this paper, we concentrate on the results for 5.9 MeV/u C ions. For them the plasma data were reproduced in two different beam times and led to the realization of some principal problems with the cold gas data. Also after the first 1.5 μm thick mylar foil and 180 mbar Ar gas in the target the C ions are fully ionized. So any observed difference in energy loss compared to cold gas is not due to changes in the charge state of the ions in the plasma. This cannot be excluded for Ar and Xe ions. A different charge-state distribution in the gas at pressures as in the compressed plasma phase for 11.4 MeV/u Ar ions was calculated with the ETACHA-Code [20].

Figure 3 shows the energy loss of 5.9 MeV/u C ions in Ar plasma at initial gas pressures of 200–800 mbar (measured with a precision pressure gauge, Pfeiffer TPG 261) before ignition. In December 2002 measurements were carried out with a MSP detector and a 500 μs beam

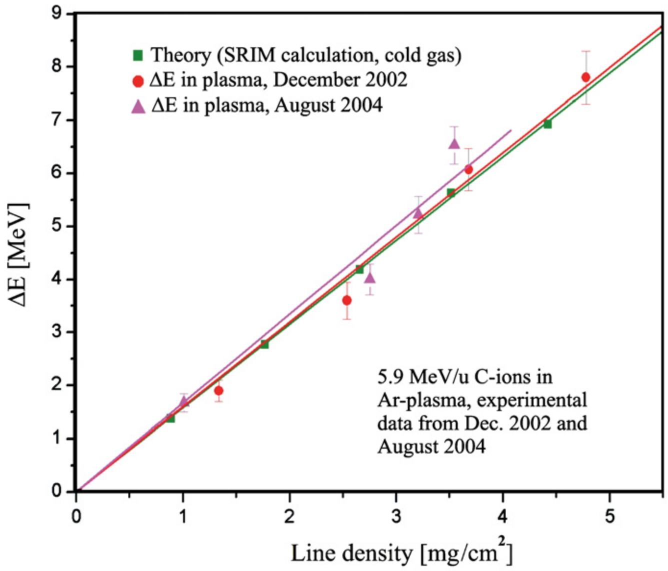

Figure 3. Energy loss of 5.9 MeV/u C ions in an Ar plasma and the calculated energy loss of 5.9 MeV/u C ions in Ar gas of the same line density.

pulse and in August 2004 with phase probes and a 100 μs beam pulse. Phase probes and MSP detector give exactly the same results for the energy loss in cold gas measured at the same time in the macro pulse. This was verified in a beam time in January 2005. The energy loss in the plasma is compared to the energy loss in cold gas at the same line density calculated with SRIM2003 [21]. The linear fit curve through the data points indicates a slight enhancement of the energy loss in the plasma. The data are reproducible within the error bars for both experiments. But the error bars at ~10% of the measured values and the known precision of SRIM for C ions of this energy (~5%) are in the same order of magnitude. Also some density effect is indicated for the data points at higher pressures, which are located above the fit curve.

5. Special features from the target geometry for measuring energy loss in cold gas

We do not present our measured energy loss data in cold gas here to compare with the plasma results. For this the knowledge of the correct line density is necessary. But the energy deposition of the ion beam in the target is sufficient to heat up the Ar gas and initiate a gas flow through the gap, which reduces the line density in the interaction zone. Only recently this effect has been realized and simulated by a code by Varentsov [22]. A previously measured enhancement of the energy loss in the plasma which was presented at the 24th International Workshop on Physics of High Energy Density in Matter in Hirschegg, Austria, in 2004 can now be attributed to a lower line density in the cold gas than assumed during the measurement of the energy loss.

Figure 4 shows the measured energy loss for 5.9 MeV/u C ions in Ar gas in the first half of a 100 μs beam pulse, which is very close to SRIM calculations for cold gas. The single data points below, line densities corresponding to initially 300 mbar and 600 mbar, were measured in a 500 μs beam pulse at four different time windows inside the pulse. The later in the pulse the measuring time window is set the lower is the measured energy loss, due to longer heating times of the gas and a stronger thinning out in the interaction zone. This behaviour

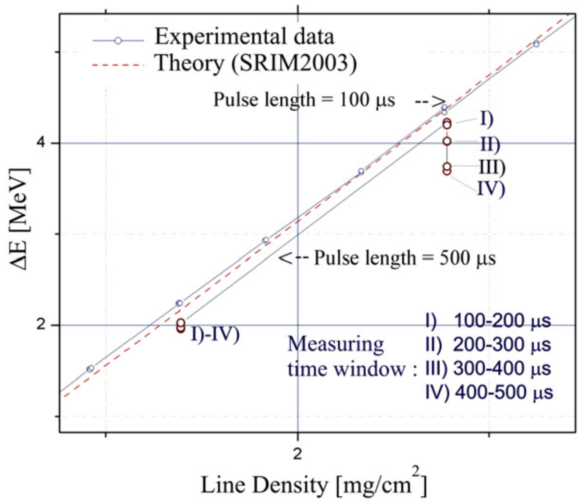

Figure 4. Comparison of the energy loss of 5.9 MeV$/u$ C ions in Ar gas measured at the beginning of a 100 μs pulse and in a 500 μs pulse at later times.

was investigated in a very recent beam time in November 2005 by systematically scanning the energy loss development from beginning to end of the beam pulse in time windows of 20 μs. Time windows of 20 μs are a compromise between sufficient micro pulses for good statistics and avoiding considerable changes in line density during the measurement. This will possibly allow us to define the right line density of the cold gas at the time of measurement in comparison to our plasma shots and compare the energy loss directly. The plasma sheath passes the interaction zone within a few microseconds, and so the beam causes no significant heating and expansion of the compressed gas. Here, with the initial gas pressure and the compression factor the line density can be determined directly.

The experiments have demonstrated that shockwave-driven plasmas, which are produced by low amounts of high explosives (55 g RDX), are really non-ideal plasmas with Γ-parameters up to 1.5. Nevertheless, a direct comparison of the measured energy loss in cold gas and plasma will become possible only after the calibration of the line density belonging to the measured cold gas energy loss can be carried out. The very recent experimental results for the development of the energy loss of 5.9 MeV$/u$ C ions measured as a function of time during the whole macro pulse will be used as base. Nevertheless, the non-ideality effects in the energy regime of several MeV$/u$, where $v/c \sim Z\alpha$, will be very small. The deviation from the Z_{eff}^2-dependence is much less prominent than in the region of low-ion velocities [6] and is even counteracted by a $1/Z$-dependency in the Coulomb logarithm present in our energy region.

References

[1] Philippe F, Canaud B, Fortin X, Garaude F and Jourdren H 2004 *Laser Part. Beams* **22** 171–4
[2] Leon P T, Elizier S, Piera M and Martinez-Val M J 2005 *Laser Part. Beams* **23** 193–8
[3] Hora H 2004 *Laser Part. Beams* **22** 439–49
[4] Koresheva E R, Osipov I E and Aleksandrova I V 2005 *Laser Part. Beams* **23** 563–71
[5] Zwicknagel G, Toepffer C and Reinhardt P G 1995 *Laser Part. Beams* **13** 311
[6] Zwicknagel G 1999 *Phys. Rep.* **309** 117
[7] Gericke D O and Schlanges M 2000 *J. Phys. Fr.* **10** Pr5–481

[8] Gericke D O, Schlanges M and Bornath Th 2002 *Phys. Rev.* E **65** 65
[9] Hoffmann D H H *et al* 1990 *Phys. Rev.* A **42** 2313
[10] Hoffmann D H H *et al* 1990 *Z. Phys.* D **16** 229
[11] Dietrich K-D *et al* 1992 *Phys. Rev. Lett.* **69** 3623
[12] Stöckl C *et al* 1997 *Fusion Technol.* **31** 169
[13] Roth M *et al* 2000 *Eur. Phys. Lett.* **50** 28
[14] Turtikov V *et al* 2001 *Nucl. Instrum. Methods* A **464** 247–52
[15] Mintsev V *et al* 1998 *Nucl. Instrum. Methods* A **415** 715
[16] Mintsev V, Gryaznov V, Kulish M and Fortov E V 2001 *Contrib. Plasma Phys.* **41** 119
[17] Ebeling W *et al* 1991 *Thermophyscal Properties of Hot Dense Plasmas* (Leipzig: Teubner)
[18] Gardes D *et al* 1990 *Laser Part. Beams* **8** 575
[19] Hoffmann D H H *et al* 2005 *Laser Part. Beams* **23** 47
[20] Rozet J P, Stephan C and Vernhet D 1996 *Nucl. Instrum. Methods* B **107** 67
[21] http://www.SRIM.org
[22] Varentsov D 2005 Technical University Darmstadt private communication