*Laser and Particle Beams* (2005), *23*, 521–526. Printed in the USA.

DOI: 10.1017/S0263034605050706

# Investigation of PbMg target characteristics by a laser mass-spectrometer

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(RECEIVED 5 January 2005; ACCEPTED 12 February 2005)

**Abstract**

Characteristics of two-element (PbMg) laser generated plasma ions were studied using a mass-spectrometer. It was found that increasing the fraction of Mg leads to widening of the energy spectra of Pb ions by more than a factor of two, while the intensity of Pb ions of all charge states does not depend on the Mg fraction. This effect is explained by the friction existing between light and heavy ions during their expansion away from the target.

**Keywords:** Interaction of ions of different masses; Mass-spectrometer; Two-element plasma

## 1. INTRODUCTION

Inertial confinement fusion (ICF) is one of the promising approaches toward the realization of controlled thermonuclear fusion reactors (Hora, 2004). To achieve ignition of an ICF pellet, it needs to be compressed by more than a thousand times and at peak compression, heat at least a critical portion of it to a temperature exceeding 6 keV (Mulser & Bauer, 2004). A heavy ion fusion (HIF) scenario employs very intense heavy ion beams, which can deliver energy of several megajoules to a fusion target during a time of about 10 ns (Tahir *et al.*, 2004). One of the main problems facing HIF is to find a source of ions with characteristics suitable for ICF (Ogawa *et al.*, 2003; Hasegawa *et al.*, 2000; Sharkov *et al.*, 1998; Gushenets *et al.*, 2003). It is well known that a laser source of ions can provide the highest intensity of multiply charged ions for injection into practically any accelerator (Dubenkov *et al.*, 1996; Breschi *et al.*, 2004). For practical use of these sources it is desirable to have high momentum without reduction in intensity and charge of ions. One of the ways to increase the momentum of ions is to use multi-element targets. It was demonstrated that the energy spectra of ions obtained by laser irradiation of multi-element targets appreciably differ from the spectra of ions obtained from single element targets (Doria *et al.*, 2004; Ying *et al.*, 2003; Rosmej *et al.*, 2002; Rafique *et al.*, 2005; Semerok *et al.*, 2002; Osman *et al.*, 2004; Rai *et al.*, 2003; Bedilov *et al.*, 1987, 1995; Bikovskie *et al.*, 1977; Magunov *et al.*, 2003). In the former case, the exchange of energy between ions of different mass is observed (the so called "ion friction effect"), which leads to the widening of energy spectra of both light and heavy ions.

In most of the experiments carried out so far, either targets consisting of only one element or targets consisting of fixed fraction of composing elements, that is, chemical compounds such as NaF, NaCl, NaBr, $CuCl_2$, Cu $Br_2$, $PbCl_2$, and $PbI_2$ were used (Sharkov *et al.*, 1998). In this paper, properties of multiply charged ions formed under irradiation of PbMg targets with 15%, 25%, and 35% mass fraction $n$ of Mg, respectively, are investigated. Since we use an amalgam of Pb and Mg, their relative fractions can be varied at will.

## 2. EXPERIMENTS AND RESULTS

Experiments were carried out using a laser mass-spectrometer (see Fig. 1) with mass resolution of $dm/m \sim 0.01$ and time-of-flight distance $L = 100$ cm. Detail description of the spectrometer can be found in Bedilov *et al.* (1987).

A Neodymium glass laser, in pulse mode, delivered pulses of 15 ns duration with peak power intensity around $I = 5 \times 10^{10}$ W/cm$^2$ at the target at normal incidence. The peak power of the pulses varied within 5% and the data are

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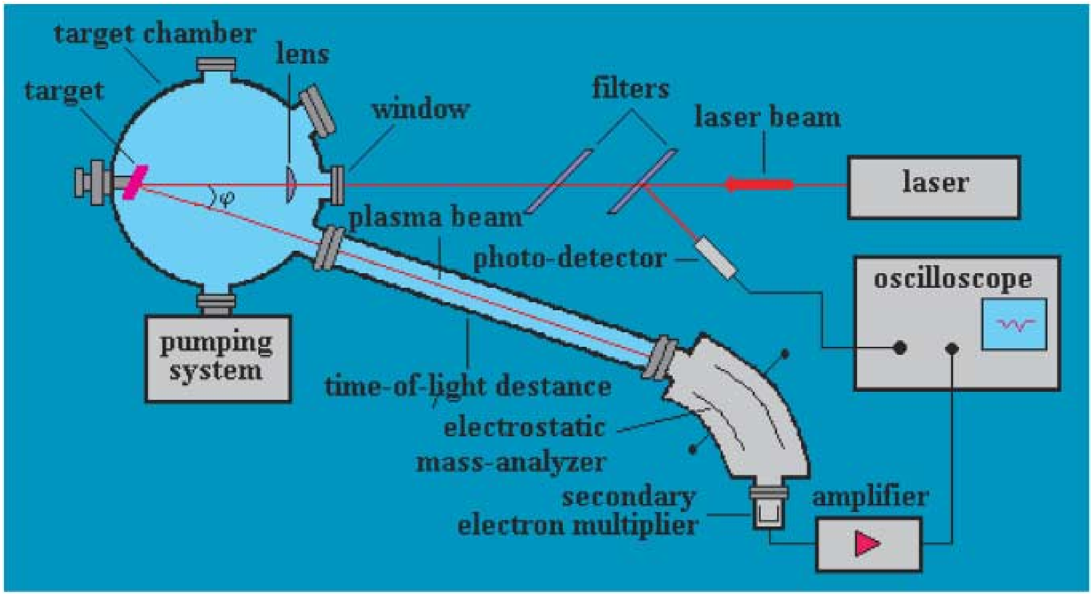


**Fig. 1.** Experimental setup.

averaged over five pulses. All experiments were carried out under the same conditions (vacuum $10^{-6}$ Tor). The construction of the target chamber allowed one to mount 10 targets with 10 mm diameter and change the location of laser incidence.

Experimentally observed mass-charge spectra of PbMg plasma ions for the different concentration of Mg shows that the plasma consists of Pb and Mg ions, and variation of $n$ leads to variation of the composition of plasma and intensity of both kinds of ions emerging from the plasma. These variations are clearly seen for relatively low energy ions ($E/Z \leq 80$ eV), as shown in Figures 2a and 2b for mono-(Pb) and two-component (PbMg) plasma ($n = 35\%$).

It is seen from this figure that the inclusion of light element in the target leads to reduction of the charge of Pb ions and to the increase of the velocity of these ions. Experimental results also show that the maximum charge of ions of mono-element Pb plasma $Z_{max} = 5$, while the maximum charge of Pb (Mg) ions from two-element PbMg plasma is $Z_{max} = 4$. It is possible to detect Mg ions with maximum charge $Z_{max} = 3$ together with Pb ions with charge $Z_{max} = 4$ at the energy intervals 800–2500 eV for Pb ions and 250–800 eV for Mg ions. For relatively higher energies of ions ($E \leq 1000$ eV) peaks of Mg ions disappears, and peaks of Pb ions are clearly seen.

Figure 3 shows the energy spectra obtained from mono-element targets consisting of Mg (a), Pb (b), and two component PbMg targets with $n = 15\%$ (c), 25% (d), and 35% (e), respectively. Ions from mono-element Pb and Mg targets have energies in the range of 150–1200 eV and 250–2000 eV with maximum charge $Z_{max} = 4$ and 5, respectively. In the case of the two-element targets $Z_{max}$ with both kinds

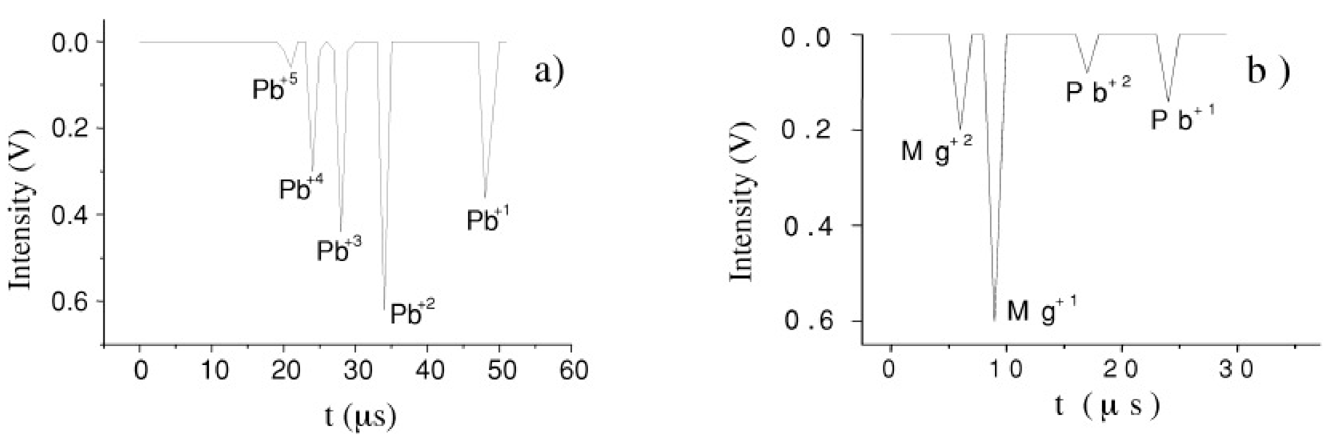


**Fig. 2.** Mass-charge spectra of plasma ions obtained from (**a**) Pb and (**b**) PbMg ($n = 35\%$) targets at $I = 5 \times 10^{10}$ W/cm$^2$.

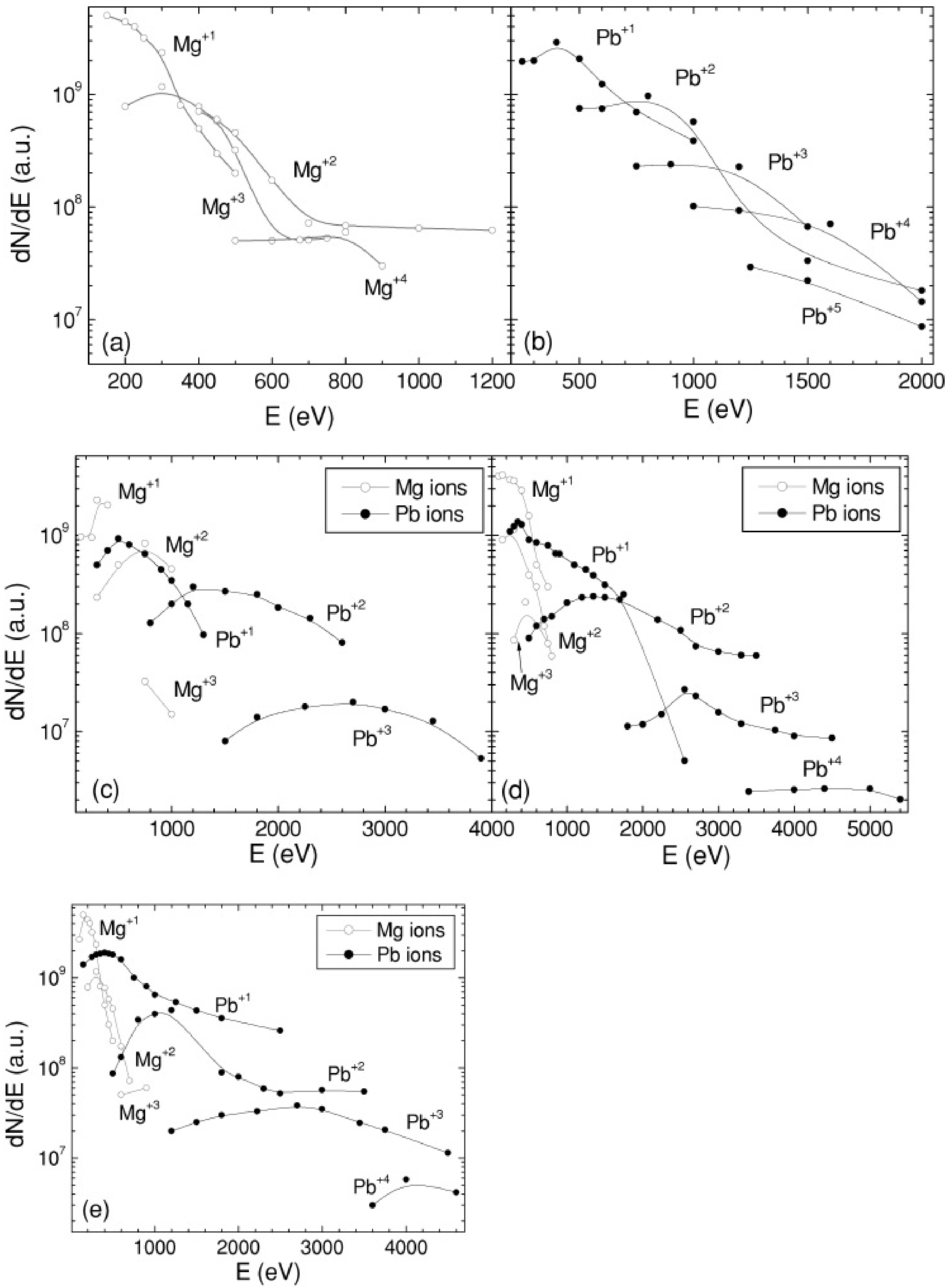


**Fig. 3.** The energy spectra of ions from mono Mg (**a**) and Pb (**b**), and two-element PbMg plasma for the concentration of Mg $n = 15\%$ (**c**), 25% (**d**), 35% (**e**).

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**Table 1.** *The maximum and minimum energies of Pb ions with Z = 1–5 for different concentration of Mg*

| Z | N | 100% Pb | 15% Mg | 25% Mg | 35% Mg | E (eV) |
|---|---|---|---|---|---|---|
| 1 | $N_{max} = 8{,}5 \times 10^8$ | 950 | 950 | 1350 | 1600 | $E_{max}$ |
| | $N_{min} = 4 \times 10^8$ | 675 | 500 | 600 | 800 | $E_{min}$ |
| 2 | $N_{max} = 2{,}8 \times 10^8$ | 1275 | 2600 | 2700 | 1950 | $E_{max}$ |
| | $N_{min} = 8 \times 10^7$ | 1075 | 1200 | 1200 | 750 | $E_{min}$ |
| 3 | $N_{max} = 2 \times 10^7$ | 1880 | 3500 | 3500 | 4500 | $E_{max}$ |
| | $N_{min} = 1{,}2 \times 10^7$ | 1750 | 1680 | 1800 | 1200 | $E_{min}$ |
| 4 | $N_{max} = 2 \times 10^7$ | 4000 | — | 5380 | 3520 | $E_{max}$ |
| | $N_{min} = 1{,}2 \times 10^7$ | 3750 | — | 4380 | 3370 | $E_{min}$ |
| 5 | $N_{max} = 3 \times 10^7$ | 2000 | — | — | — | $E_{max}$ |
| | $N_{min} = 10^7$ | 1250 | — | — | — | $E_{min}$ |

**Table 3.** *Pulse length of Pb ions for different concentration of Mg*

| | $\Delta t$, $\mu$s | | | |
|---|---|---|---|---|
| Z | 100% Pb | 15% Mg | 25% Mg | 35% Mg |
| 1 | 4.9 | 8.7 | 9.7 | 7.4 |
| 2 | 1.8 | 6.6 | 6.9 | 9.8 |
| 3 | 0.6 | 5.3 | 4.7 | 9.8 |
| 4 | 0.4 | — | 1.1 | 0.26 |
| 5 | 4.2 | — | — | — |

of ions is at least one unit lower. The energy spectra of Pb ions extend to ≥ 4000 eV, whereas the spectra of Mg ions shrink to ≤ 1000 eV. For any concentration of Mg, two groups of ions of different spectral range are clearly seen and with increasing $n$ the energy spectra of Mg ions remains virtually unaltered while the spectra of Pb ions extends to higher energies. To our knowledge, the extension of energy spectra of two-element plasma ions in comparison with mono-element plasma is due to the change of recombination processes and this effect can be used to control the charge and intensity of the ions with a given charge.

The maximum $E_{max}$ and minimum $E_{min}$ energies and total number $N$ ($N_{max}$ and $N_{min}$ is the maximal and minimal number of ions in the region which was taken to be constant for ions with given charge) of Pb ions with $Z = 1$–5 are given in Table 1 for different concentration of Mg. These results show that for Pb ions with $Z = 1{,}3$ $E_{max}$ increases with increasing $n$, while ions with $Z = 2{,}4$ $E_{min}$ increases up to $n = 25\%$ and thereafter decreases. For the $E_{min}$, we see a nonlinear dependency on $n$. Such a tendency was found for Mg ions as well (see Table 2).

The pulse duration of Pb and Mg ions is shown in Tables 3 and 4 for different concentrations of Mg. It is seen that with increasing fractional concentration of Mg the pulse length increases.

Figure 4 shows the total number of Pb ions as a function Mg fraction $n$. It is seen that the intensity of Pb ions with charge $Z \leq 3$ increases with increasing $n$, while the intensity of Pb ions with charge $Z = 4$ is independent of $n$.

The extension of energy spectra to higher energies and the presence of a maximum in the spectra (see Fig. 3) show that, processes in two-component targets subjected to laser irradiation occur in two stages. In the first stage (up to the maximum of the pulse) intense ionization takes place entailing the increase of multiply charged Mg and Pb ions. The second phase (after the maximum) is characterized with the increase of recombination processes, that is, with energy exchange between light (Mg) and heavy (Pb) ions of plasma.

## 3. DISCUSSION

Results presented in this paper permit us to conclude that the formation of charge and energy spectra of multiply charged ions in two-element PbMg plasma is defined not only by the ionization and recombination processes, but also by the mutual interaction of ions of different species in the plasma. Furthermore, the results can be explained by assuming the flow velocity of the plasma away from the target is determined by the average ion mass defined as

$$m_{av} = \frac{m_{Pb} n_{Pb} + m_{Pb} n_{Mg}}{n_{Pb} + n_{Mg}}$$

where, $m_{Pb}$ and $m_{Mg}$ are masses of Pb and Mg ions and $n_{Pb}$ and $n_{Mg}$ are their number densities, respectively. The observed energy and charge spectra are a consequence of the interplay

**Table 2.** *The maximum and minimum energies of Mg ions for different concentration of Pb*

| Z | N | 100% Mg | 65% Pb | 75% Pb | 85% Pb | E (eV) |
|---|---|---|---|---|---|---|
| 1 | $N_{max} = 2 \cdot 10^9$ | 337 | 337 | 537 | 400 | $E_{max}$ |
| | $N_{min} = 9{,}5 \cdot 10^8$ | 300 | 300 | 450 | 150 | $E_{min}$ |
| 2 | $N_{max} = 8{,}5 \cdot 10^8$ | 575 | 575 | 620 | 750 | $E_{max}$ |
| | $N_{min} = 2{,}3 \cdot 10^8$ | 225 | 225 | 150 | 300 | $E_{min}$ |
| 3 | $N_{max} = 6 \cdot 10^7$ | 700 | 850 | 830 | 630 | $E_{max}$ |
| | $N_{min} = 5 \cdot 10^7$ | 600 | 600 | 800 | 580 | $E_{min}$ |

**Table 4.** *Pulse length of Mg ions for different concentration of Pb*

| | $\Delta t$, $\mu$s | | | |
|---|---|---|---|---|
| Z | 100% Mg | 65% Pb | 75% Pb | 85% Pb |
| 1 | 2.3 | 2.3 | 2.8 | 2.2 |
| 2 | 1.8 | 1.8 | 2.9 | 1.5 |
| 3 | 2.2 | 4.6 | 1.5 | 1.2 |

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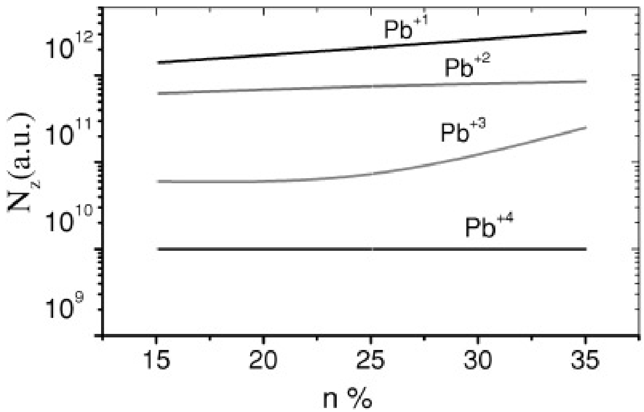


**Fig. 4.** Total number of Pb ions N as a function of Mg fraction *n*.

between plasma life time and the ionization/recombination time scales of various ion species (Bikovskie *et al*., 1977). For example, in order to obtain ions of charge state *Z*, it is necessary that the condition $T_i(Z) < T_0 < T_r(Z)$ is fulfilled, where $T_i(Z)$ is the time scale for the production of charge state *Z*, $T_0$ is the plasma life time, and $T_r(Z)$ is the time scale for the destruction of charge state *Z*. Note that these time scales can be controlled by varying the composition of the target.

## 4. CONCLUSIONS

We have investigated the interaction of laser radiation with two-element PbMg targets and the formation of charge and energy spectra of multiply charged ions for different relative fractions of the target components. The experiments show that, due to exchange of energy between light and heavy ions, with increasing fraction of Mg, the maximum energy of the Pb ions spectrum extends to twice that of the one obtained with pure Pb targets alone. The intensity of Pb ions increases with increasing concentration of Mg, due to the reduction of the effective ion mass.


## ACKNOWLEDGMENTS

This work has been supported by DAAD and by IAEA. Khaydarov likes to acknowledge fruitful discussions and the kind hospitality of D.H.H Hoffmann and his Plasma Physics research group at GSI during two research stays, during which this work was prepared.


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