Mono-charge super-heavy ion beams accelerated by a multi-PW laser

J. Domański, J. Badziak

Institute of Plasma Physics and Laser Microfusion, Warsaw, Poland

Modern laser technology makes it possible to generate femtosecond laser pulses with the power of 10 PW [1] and intensity reaching 10^{23} W/cm^2 [2]. Such laser pulses have the potential to accelerate heavy and super-heavy (mass number A > 200) ions to the multi-GeV energies required in nuclear physics, high energy density physics (HEDP) and inertial fusion. The advantage of laser-produced heavy ion beams is their short (fs, ps) duration and high beam intensities and fluences [3,4], which are difficult to achieve in conventional RF-driven accelerators. However, as demonstrated in both numerical [4-6] and experimental [7,8] studies, laser-produced ion beams are usually multi-charge beams. This hinders their possible application in nuclear physics, HEDP or accelerator technology. In this paper we show that it is possible to obtain practically mono-charge beams of super-heavy ions accelerated by laser.

In order to check this possibility, the acceleration of super-heavy ions from a 100-nm lead (Pb) target irradiated by a femtosecond laser pulse with an intensity of 10^{23} W/cm^2 was investigated using an advanced 2D3V particle-in-cell code[9]. The thickness of the target was chosen to be thick enough to avoid occurring relativistic transparency during the process of acceleration and thin enough to ensure reaching the rear side of the target by the laser pulse and effective ionisation of the target by the pulse. The intensity of the laser beam has been chosen in relation to the ionisation energy gap situated near the Pb^{+72} ions and is high enough to perform massive ionisation of the target's atom to the ionisation level of Z=72 and low enough to significantly reduce the ionisation to the levels higher than Z = 72. The target was irradiated by 30 fs, circularly polarised near-infrared (λ = 0.8 μm) laser pulses. The laser energy was equal to 270J while the focal spot diameter was set to 3 μm. The Pb atoms' density in the target corresponds to the density of a solid state and was equal to 3.3 x 10^{22} 1/cm^3. Additionally, a 20 nm thick pre-plasma layer of density profile described by an exponential function was placed at the front of the target. The space step of the simulation was equal to 13.3 nm while the time step was equal to 2.22 as. The number of ion macro-particles was assumed to be 1082700 (100 particles/cell).

Figure 1 presents a 1D spatial profile of the ion and electron charge density as well as the accelerated electric field component along the laser propagation direction E_x for three stage of ion acceleration. In the initial stage of acceleration (Fig.1a) when the laser pulse interacts with the target, both Target Normal Sheath Acceleration (TNSA)[10] and Radiation Pressure Acceleration (RPA)[10] mechanisms contribute to the process of acceleration, while the RPA mechanism dominates. During this stage, a compact ion bunch is formed with a density which

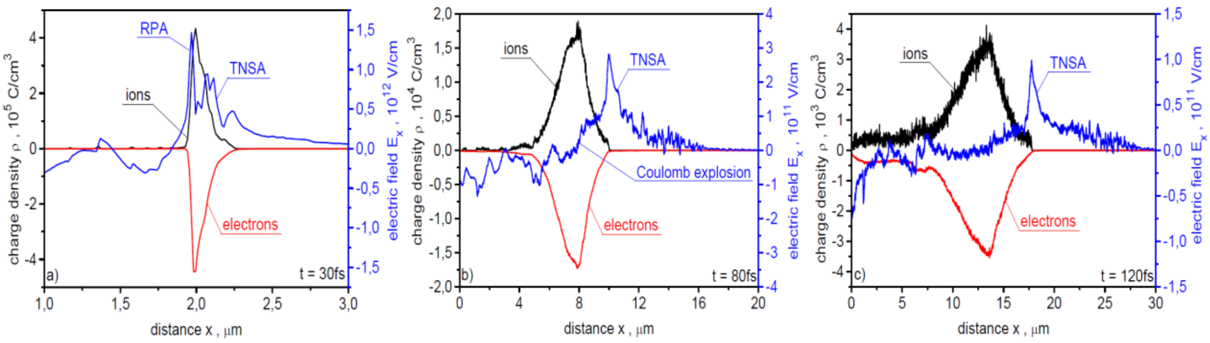

Fig.1. The 1D spatial profiles of the ion charge density, the electron charge density and the accelerating electric field Ex along laser beam axis at the early (t = 30 fs), middle (t = 80 fs) and late (t = 120 fs) stage of ion acceleration process.

correspond to the solid state density. When the laser-target interaction terminates (around 50fs) RPA mechanism stops being active, while due to the existence of hot electrons generated during previous stage the TNSA mechanism still contributes to the process of acceleration (Fig.1b). Additionally, due to not fully neutralisation of ions charges in the beam by the electrons, Coulomb explosion starts to be active.(Fig1b). These processes cause a decline of ion density in a bunch and effect in an increase of ion beam angular divergence. During the final stage of acceleration only TNSA mechanism still contributes to the process of ion acceleration(Fig.1c).

The ionisation process highly influences the ion acceleration. The ionisation level of ion strictly define its Z/A ratio and in effect its strength of interaction with the electro-magnetic field. For the laser-target parameters investigated in this article the field ionisation mechanism is a dominant mechanism of ionisation and the target atoms are ionised by both the laser field and the field generated in a plasma by hot electrons. As it could be seen in figure 2, the central part of the beam is dominated by the Pb^{+72} ions with small contributions of higher ionized atoms. This part of the beam is ionised mainly by the laser field during the initial stage of acceleration. The rest of the beam contains many types of ions with a dominant role of Pb^{+54}. This part of the beam is ionised mainly by the TNSA field.

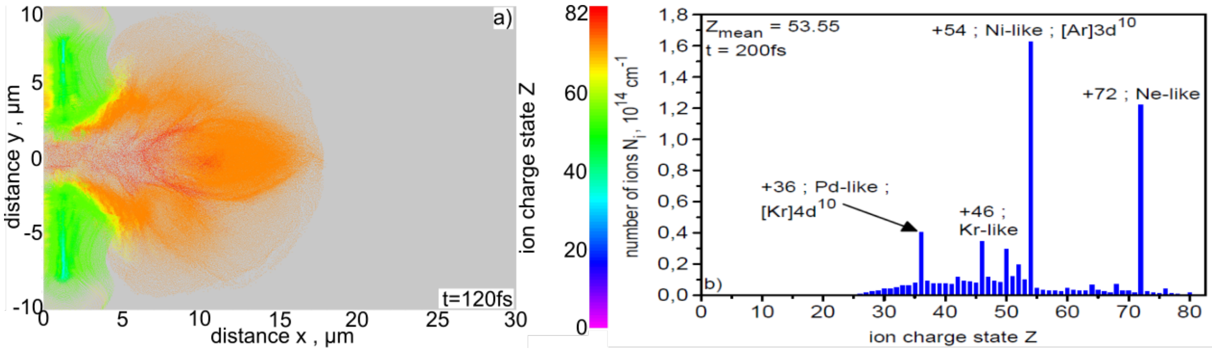

Fig.2. The 2D spatial profile of the ion charge state at the final stages of ion acceleration (a) and the ionisation spectra of ions at the end of acceleration (b).

The mean and maximum ions energies (a) as well as the energy of the beam with charge state Z (b) as a function of the ion's ionisation level for the end of ion acceleration (t=200fs) are shown in figure 3. It is visible that both mean and maximum ion energy increases proportionally to the ion charge state up to the Pb^{+72} ions. This dependence is understandable because the ions of the higher Z have a higher Z/A ratio. Additionally, such ions are situated closer to the centre of the beam where the accelerating fields are stronger. The energy of the beam of a charge state higher than 72 starts to decline. Consequently, the Pb^{+72} ions are characterized by the highest energies. The decline of ions energy for the Z>72 could be explained by the fact that the ions of the highest Z are situated at the back of the ion beam in the region of direct laser plasma interaction (see Fig. 2a). These ions originate from the Z=72 ions of the lower energy/velocity(position at the back of the beam) which are ionised to a higher level at the end of direct laser-beam interaction. Additionally, as an effect of their position these ions are not accelerated by the TNSA mechanism and could even be de-accelerated by the Coulomb explosion. All these effects results in a lower energy of the beam. As can be seen Pb^{+72} ions are the second most populated type of ions (Fig.2b) and have the highest energies (Fig.3a). As a results they carry around 92% of total beam energy (more than an order of magnitude higher than any other type of ions – see Fig.3b). Thus, the produced ion beam is, in practice, a mono-charge beam.

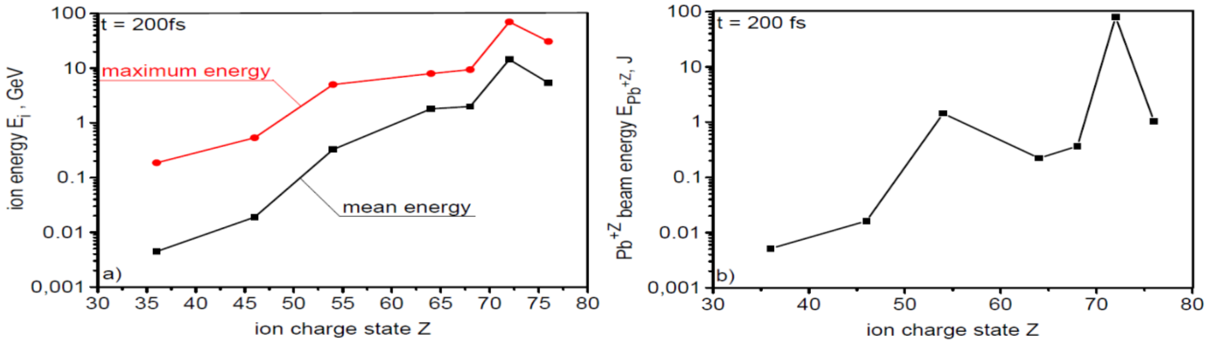

Fig.3. The dependences of mean and maximum energy of ions with the charge state Z (a), as well as the energy of the beam of ions with the charge state Z (b) on the ionisation level.

Figure 4 shows the spatial distribution of the ion beam fluence (a) and the temporal distributions of the ion beam's intensity (b) for three types of ions: Pb^{+72}, Pb^{+76} ,and Pb^{+68} . It is visible that both the fluence and intensity of the Pb^{+72} ion beam are much higher than those for other ions. The beam of this ions has a quasi-Gaussian shape of the fluence in space with the peak value of 13.5 MJ/cm^2 and have a quite compact structure in the time domain with the peak intensity equal to 6.5*10^{19} W/cm^2. The structure of the rest of the beams are much more complex and the values of fluences and intensities are significantly lower than for the Pb^{+72} beam.

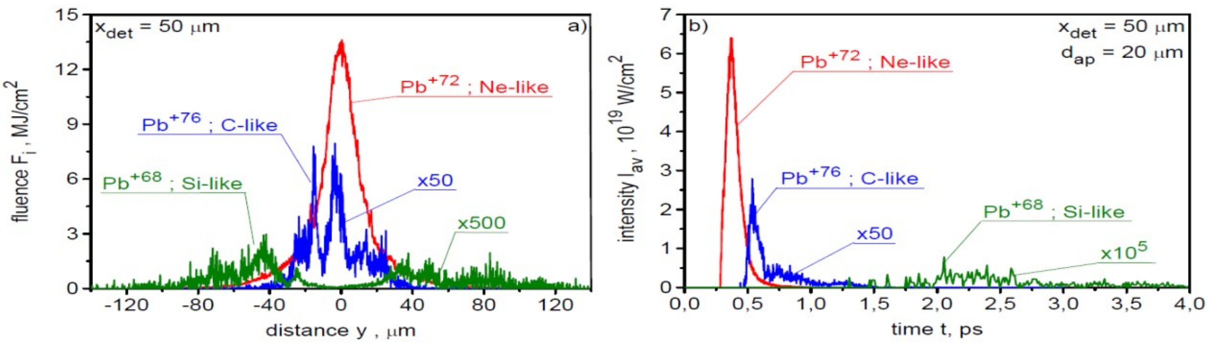

Fig.4. The spatial distribution of the ion beam fluence recorded at a distance of 50 μm (a) and the temporal distributions of the ion beam's intensity recorded at 50 μm behind the initial position of the target and averaged over the y range equal to 20 μm (b) for three types of ions: Pb^{+72}, Pb^{+76} ,and Pb^{+68} .

In summary, the acceleration of super-heavy ions from a 100-nm lead target irradiated by a femtosecond laser pulse with an intensity of 10^{23} W/cm^2 was investigated using an advanced 2D3V particle-in-cell code. It was found that by properly selecting the laser pulse parameters, it is possible to produce a practically mono-charge Pb ion beam with multi-GeV ion energies and the laser-to-ions energy conversion efficiency approaching 30%. At the assumed laser, Pb ions with the charge state Z = 72 carry over 90% of the total energy of all ions, while the peak intensity and peak fluence of the Pb^{+72} ion beam are at least two orders of magnitude higher than for other types of ions. Moreover, the Pb^{+72} ion beam is more compact and has a smaller angular divergence than those for other types of ions.

The unique properties of mono-charge super-heavy ion beams demonstrated in our work, create a prospect for the application of these beams in high energy-density physics and in new areas of nuclear physics as well as in accelerator technology as an intense ion source for large RF-driven heavy ion accelerators.

Acknowledgments

The simulations presented in this paper were carried out with the support of the Interdisciplinary Centre for Mathematical and Computational Modelling (ICM), University of

Warsaw under grant no. G83-16 and the Poznan Supercomputing and Networking Centre under grant no. 417.

References

[1] Lureau F et al. 2020 High-energy hybrid femtosecond laser system demonstrating 2 × 10 PW capability *High Power Laser Science and Engineering* **8** e43.

[2] Yoon J W, Kim Y G, Choi I W, Sung J H, Lee H W, Lee S K and Nam C H 2021 Realization of laser intensity over 10^{23} W/cm^2 *Optica* **8**, 630

[3] Domanski J and Badziak J 2018 Ultra-intense femtosecond super-heavy ion beams driven by a multi-PW laser *Phys. Lett. A* **382** 3412

[4] Badziak J and Domanski J 2019 Towards ultra-intense ultra-short ion beams driven by a multi-PW laser *Laser and Particle Beams* **37** 288

[7] Braenzel J, Andreev A A, Platonov K, Klingsporn M, Ehrentraut L, Sandner W and Schnurer M 2015 Coulomb-Driven Energy Boost of Heavy Ions for Laser-Plasma Acceleration *Phys. Rev. Lett.* **114** 124801

[8] Wang P et al. 2021 Super-Heavy Ions Acceleration Driven by Ultrashort Laser Pulses at Ultrahigh Intensity *Phys. Rev. X* **11** 021049

[5] Petrov G M, McGuffey C, Thomas A G R, Krushelnick K and Beg F N 2016 Generation of heavy ion beams using femtosecond laser pulses in the target normal sheath acceleration and radiation pressure acceleration regimes *Phys. Plasmas* **23** 063108

[6] Li J, Arefiev A V, Bulanov S S, Kawahito D, Bailly-Grandvaux M, Petrov G M, McGuffey C and Beg F N 2019 Ionization injection of highly-charged copper ions for laser driven acceleration from ultra-thin foils *Sci. Rep.* **9** 666

[9] Domanski J and Badziak J 2020 Generation of ion beams from a high-Z target irradiated by a laser pulse of ultra-relativistic intensity *Acta Phys. Polon. A* **138** 586

[10] Macchi A, Borghesi M and Passoni M 2013 Ion acceleration by superintense laser-plasma interaction *Rev. Mod. Phys.* **85** 751 and references therein.