Abstract

Using particle-in-cell (PIC) simulations, we numerically investigate the processes of bulk electron heating and the impact it has on the ion dynamics in high-Z* solid density targets irradiated by high-intensity (I ≈ 5 × 10^{20} \text{Wcm}^{-2}) circularly polarized (CP) femtosecond laser pulses. The enhanced collisionality caused by the high-Z* ion species and high plasma density results in increased laser energy absorption due to an inverse Bremsstrahlung type mechanism. The higher electron temperatures facilitate the formation of an electrostatic shock. However, in a case where the size of the plasma has been increased and a change of materials has lead to an even higher plasma density, the generated shock wave is not sufficient to reflect ions. Instead a slower, hydrodynamic-like shock is sustained.

1 Electron heating

The electrons are energized in the transverse plane by the laser. Then, collisions scatter them into the longitudinal direction (p_z).

During the laser pulse, the electrons in the shock vicinity reach T_e ≈ 100 \text{keV} temperatures - sound speed c_s ≈ (Z/Z_{Cu})c_{Cu}/\sqrt{\mu_0} ≈ 5 × 10^{7}\text{cm/s}.

Proton longitudinal momentum distributions from collisional (black) and collisionless (gray) simulations at different spatial locations and times - Gray: Fitted Maxweillians (red dashed and dash-dotted) indicate the proton temperatures of the upstream populations

2 Electrostatic shock

Initially, radiation pressure accelerates Cs-ions and protons at twice the hole-boring velocity 2v_{tb} ≈ 2v_{tb}[Z/Z_{Cu}]c_{Cu}/(\sqrt{\mu_0}) ≈ 0.02c – the charge separation field clearly is visible.

The initial local Mach number, \mathcal{M}_0 = v_{tb}/c ≈ 2.5, is withint he electrostatic shock stability condition 1.6 \leq \mathcal{M} \leq 3.5 [3].

Then, the high electron temperature in the collisional case facilitates the formation of an electrostatic shock [4] – as seen by the downstream modulations of the electric field and the ion distributions. In the collisionless case, the field quickly decays after the laser extinction, and no shock is formed.

However, after the laser pulse is over, the electron temperature homogenizes throughout the plasma, leading to a decrease in the local sound speed near the shock. The Mach number thus exceeds the upper limit and the shock energy is quickly dissipated.

The collision-enhanced heating also promotes target normal shock acceleration (TNSA) at the backside, which is, however, suppressed by the front-side shock-induced acceleration.

Collisions also generate heating of the reflected ions to temperatures of T_{he} ≈ 710\text{eV}.

- This set-up is almost identical to the one used by Turrell et al. [5]. However, they instead observe the “ultrafast ion heating” in the downstream passing population, and to a higher temperature by a factor of ~ 4.

- Here, the heating occurs mainly in the reflected population from proton-Cs collisions. Also to some degree in the upstream population from electron-ion thermalization.

3 Copper simulation, case B

A second simulation was performed with a target consisting of a single-species Cu^{2+} plasma of 2.5 \mu m thickness. The laser parameters are changed to n_0 = 18 and 40fs FWHM duration; 200 particles per cell and species are used. The plasma is at solid density which corresponds to n_{fit} = 2.5 × 10^{22}\text{cm}^{-3}.

- The lower intensity and higher electron density compared to case A decreases the hole-boring velocity to v_{tb} ≈ 4 × 10^{-9}\text{cm/s}.

- The collisional electrons reach a local T_e ≈ 20 \text{keV} at the shock front, which corresponds to \mu_e ≈ 3 × 10^{-6}\text{cm}^2/\text{eV}.

- Mach number \mathcal{M} ≈ 1.4 is below the lower limit for a steady state electrostatic shock \mathcal{M}_{\text{min}} ≈ 1.6.

4 Conclusions

- At high Z*, the enhanced electron heating, due to electron-ion collisions, facilitates the formation of an electrostatic shock.

- Proton-Cs collisions heat up the reflected ion fractions to ~keV temperatures on a ~10 fs time scale. However, no downstream “ultrafast collisional ion heating” [5] of the protons is observed.

- The solid density copper plasma and lower laser intensity, does not produce a reflective electrostatic shock wave. However, a hydrodynamic-like shock is launched.

The downstream ions reach T_i ≈ 10\text{keV}.

References


Simulation parameters, case A

- We used the Stmilie PIC code [1, 2].
- Laser: n_0 = 15, \lambda = 800\text{nm}, Gaussian profile with 10fs FWHM duration, circularly polarized (CP).
- 1D box: length 20\mu m, \Delta x = 0.39\text{nm} (51200 cells).
- Plasma: 300 nm thick, starting at x = 1.0\text{pm}; equal mixture of protons and Cu^{2+} ions such that n_{fit} = 250n_i (skin depth L_i = 8.0\text{nm}); initial temperatures T_{ei} = 1\text{eV} and T_{ei} = 0.1\text{eV}; 500 macro particles per species per cell.

Electron distributions at (left) and after the laser peak intensity (right), with (top) and without (bottom) collisions using CP. "Gaussian" longitudinal electric field \mathcal{E}_x.

Distribution of copper ions in a collisional (top row) and collisionless (bottom row) simulations of a solid density target, at three different times: Collisionless temperature (solid) and density (dashed) profiles at different times. The collisionless temperature profile (bottom row) has been calculated with the strongly non-thermal accelerated ions excluded.