Intense Laser Radiation Interacting with Nano-Structured Matter

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Motivation

Investigating the interaction of an ultra-intense, ultra-short laser pulse with nano-rods. This interaction leads to the ionisation of the nano-rods and their consecutive Coulomb explosion. . A number of simulations are performed to understand the nonlinear optical properties of the electronic subsystem interacting with the driver laser.

Scientific Goals

- Understanding the macroscopic ionization dynamics of the electrons in the nano-rods.
- Understanding the macroscopic recapturing dynamics of electrons of nano-rods.
- Understanding the Coulomb explosions of the nano-rods.

Aspects of the Theoretical Model

- Ultra-short, ultra-intense laser pulses with intensities in the range of 10^{18} W/cm^2 to 10^{21} W/cm^2 and wavelengths from 1000 nm to 100 nm interacting with composite nanorods made of protons and boron are considered.
- In the course of the interaction the nano-rods lose their electrons and the following radial electric field is created:

$$E_r(r) = \begin{cases} \frac{e\, n_i r}{2\,\epsilon_0}, & 0 \leq r < R \\ \frac{e\, n_i R^2}{2\,\epsilon_0\, r}, & r \geq R \end{cases},$$

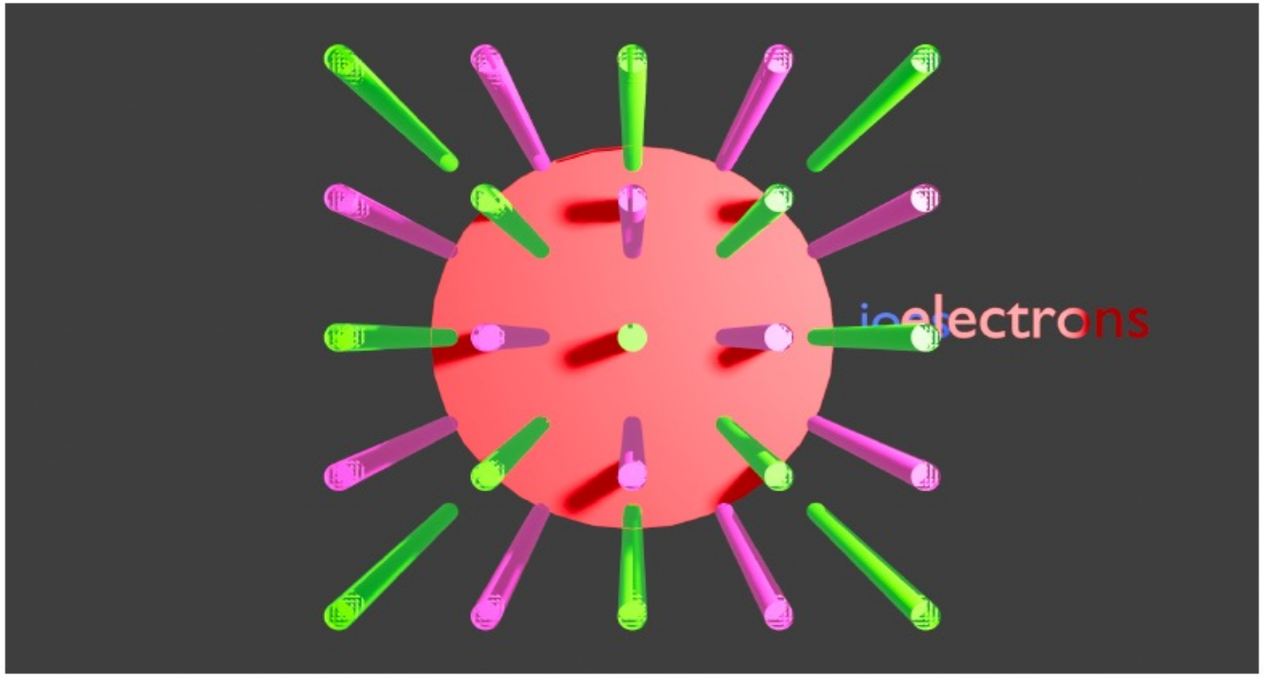
where n_i is the average positive charge density of a single nano-rod, $R > 0$ is the radius of the rod, and e the electron charge.

- The radial electric field drives the ions out of the cylinder in the radial direction.
- The interaction expells the protons from the nano-rods via nanoscopic Coulomb explosion.
- The electrons will try to return to the cylinder due to the charge separation potential.
- By changing the cylinder composition, the size of the cylinder, and the laser wavelength the average ionization can be controlled.
- The dynamics of e^-, ^{11}B, and p are governed by Vlasov-Maxwell equations for each specie.

- The laser pulses have to be adapted to the size, density, and composition of the nano-rods to make the Coulomb explosion as desired. The critical laser density n_c is given by

$$n_c = \frac{\epsilon_o m_e \omega^2}{e^2},$$

where ω is the laser frequency.



Nano-rods exposed to ultra-short ultra-intense laser radiation.

- In case of a multiple cylinder configuration the inter-rod gap has to exceed

$$D \geq \frac{\sqrt{\pi\, e^2\, n_i\, R^2}}{\sqrt{\epsilon_o\, m_e\, \omega^2}} ,$$

for stable driver laser propagation through the nano-structured material.

- The parameters that affect this simulation are: average ionization time, ionization degree, shape of the electron distribution function, the time scale of electron recapturing as a function of rod size, composition, laser energy, pulse length, and laser wavelength.

Plasma Simulation Code (PSC)

- The work is based on numerical modelling. Use is made of the PSC code. The PSC is an electromagnetic particle-in-cell code written in OOC [1].
- The PSC supports patch-based dynamic load balancing and supports GPUs.
- Its mean field part solves the following equations of motion for quasi-particles:

$$\frac{dx_i^s}{dt} = v_i^s , \frac{dp_i^s}{dt} = \mathrm{q_s}(E_i + v_i^s \times B_i).$$

- With the help of the equations of motion above the Vlasov-Maxwell system of equations is solved:

$$\frac{\partial f_s}{\partial t} + \mathrm{v} \cdot \frac{\partial f_s}{\partial x} + \mathrm{q_s} \, (\mathrm{E} + \mathrm{v} \times \mathrm{B}) \cdot \frac{\partial f_s}{\partial p} = 0,$$

$$\mathrm{v} = p/(\mathrm{m_s} \cdot \gamma),$$

where γ is the relativistic Lorentz factor

$$\gamma = \sqrt{1 + p^2/\,(\mathrm{m_s c})^2} \;.$$

The Vlasov equation describes the time evolution of the particle distribution functions $f_s(x, p, t)$, where s indicates the species.

- The electromagnetic fields E and B are evolved using Maxwell's equations:

$$\nabla . E = \frac{\rho}{\varepsilon_0},$$

$$\nabla . B = 0,$$

$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \partial_t E,$$

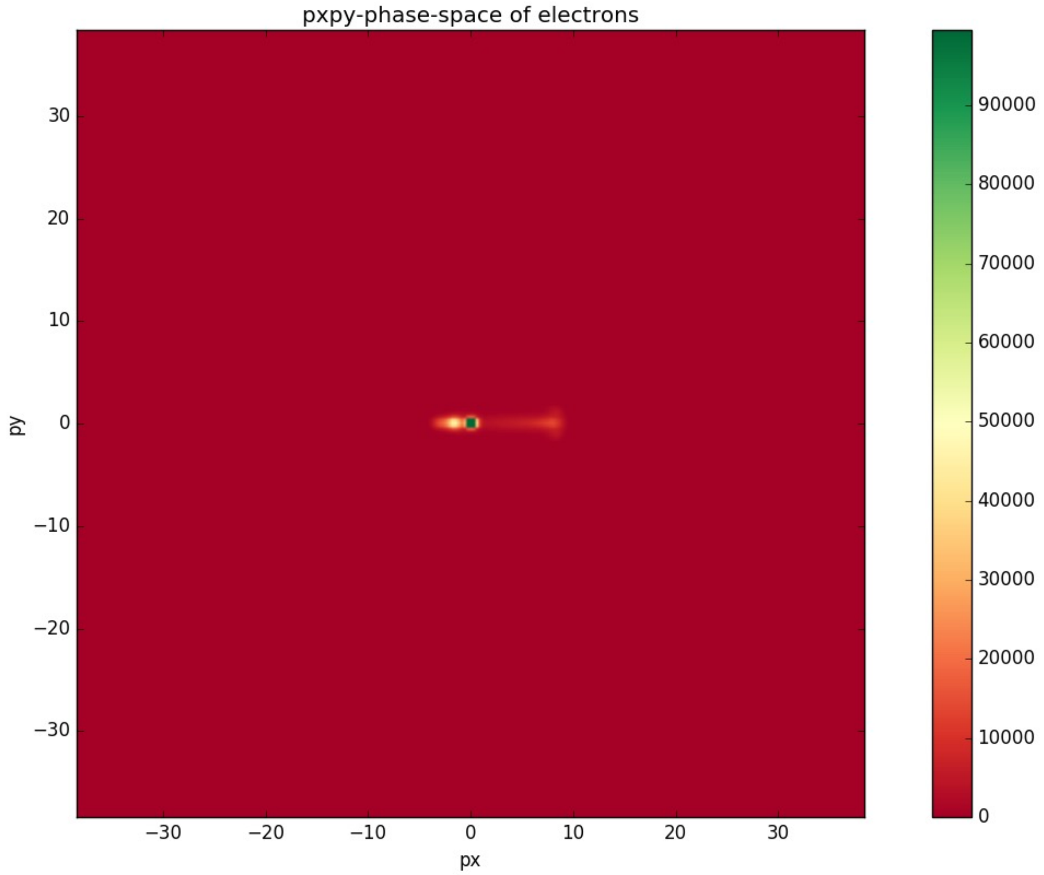
$$\nabla \times E = - \partial_t B.$$

- Maxwell's equations are solved here using the Finite Difference Time Domain (FDTD) method. It employs the staggered Yee grid.

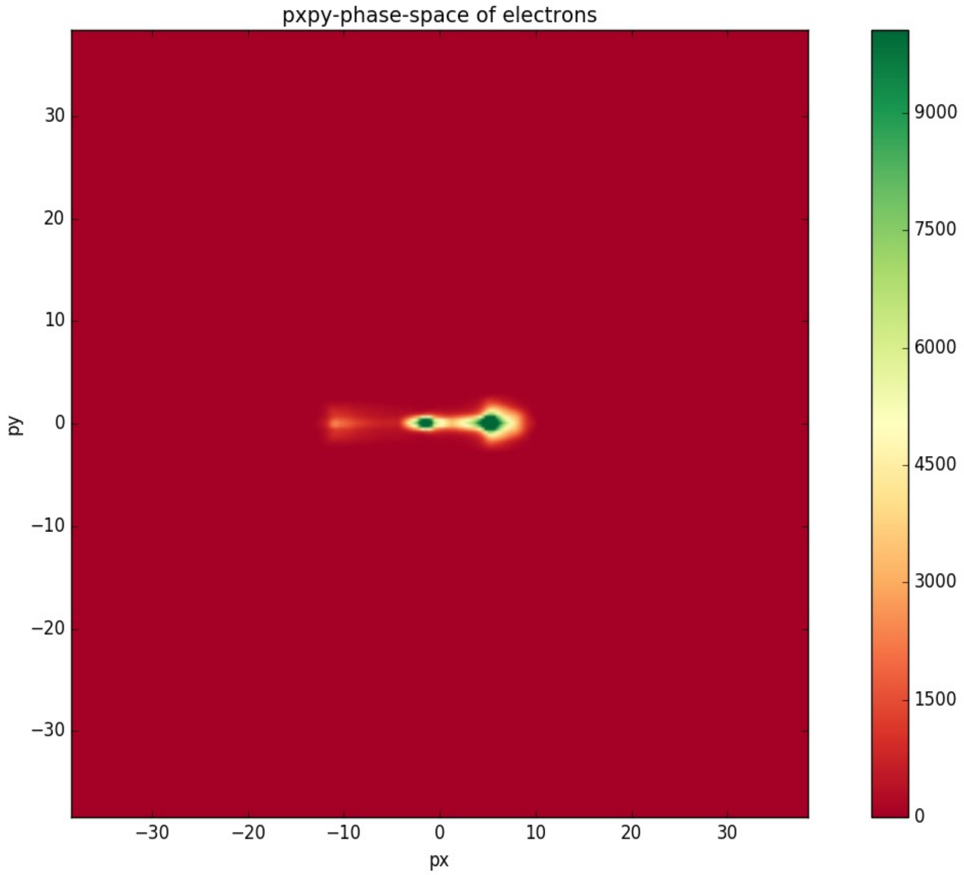
- Output is typically written as XDMF/HDF5 for visualizing the data with Paraview, though we typically use custom scripts in Python.
- Particle In Cell (PIC) does not solve the Vlasov equation correctly. Hence, PIC can not predict Coulomb explosions accurately.
- The PSC has been used to simulate a 30-m long 3D wake-field [2].

Preliminary Results

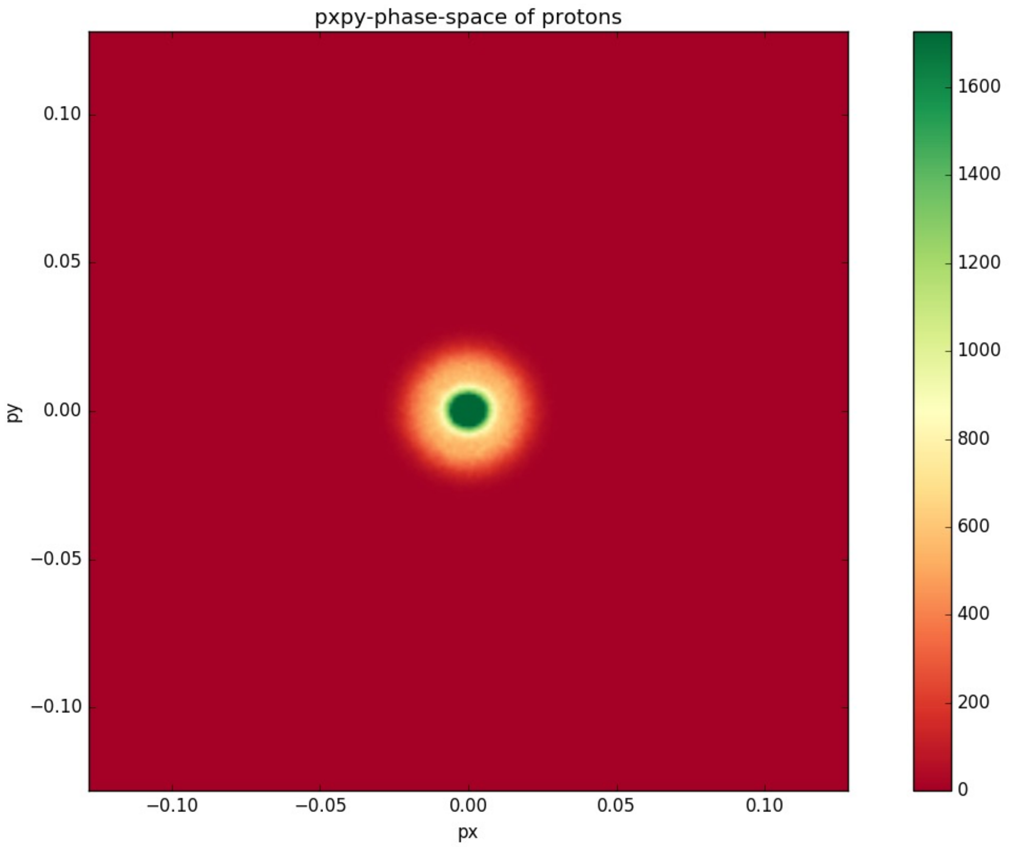
- Cylinder radius = 30 nm and length 70 um.
- Plasma frequency ω_p= 3.98912e^{+13} sec.
- Plasma skin depth c/ω_p = 7.520455e^{-05} m.
- Laser pulse length is 15 fs, laser wavelength is 1um, laser intensity is 10^{21} W/cm^2.



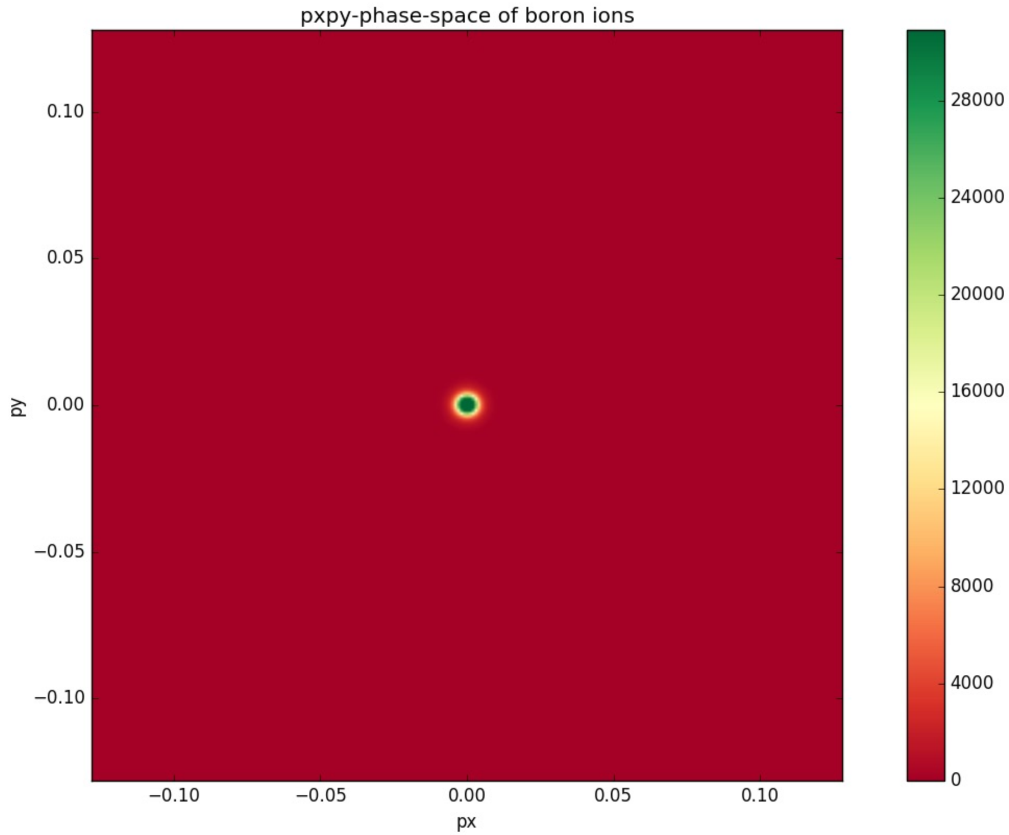
The plot shows the electron $p_x p_y$-distribution after 1400 time step.



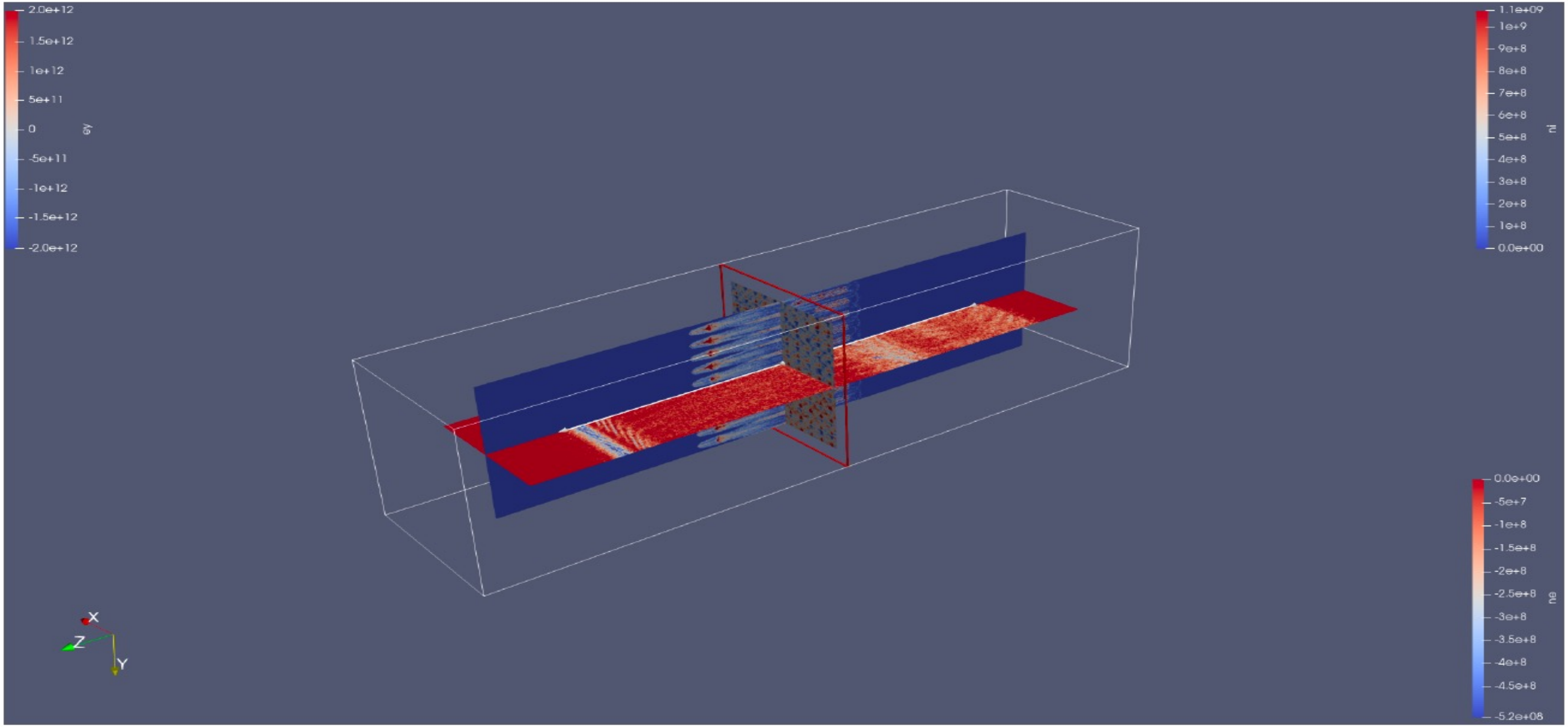
The plot shows the electron $p_x p_y$-distribution after 1800 time step.



The plot shows the protons $p_x p_y$-distribution after 1400 time step.



The plot shows the boron $p_x p_y$-distribution after 1400 time step.



A ultra-short, ultra-intense optical laser pulse has propagated through a configuration of multiple nanoscopic rods. The plot shows n_i, n_e, and E_y after 1200 steps. Hot electrons and nanoscopic Coulomb explosions are observed.

References

[1] Germaschewski, Kai, et al. "The Plasma Simulation Code: A modern particle-in-cell code with load-balancing and GPU support." *arXiv preprint arXiv:1310.7866* (2013).

[2] Moschuering, N., et al. "First fully kinetic three-dimensional simulation of the AWAKE baseline scenario." *Plasma Physics and Controlled Fusion* 61.10 (2019): 104004.

Thank you for your attention.

Questions?