Modeling mesoscopic light-matter interaction using MicPIC method

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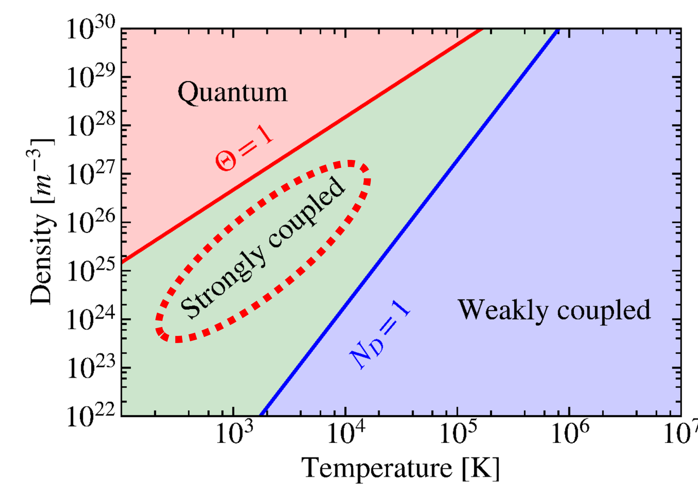
Abstract

An accurate description of light-matter interaction in strongly coupled region is indispensable for bridging up microscopic and macroscopic physics that concerning many predominant topics such as HHG, nuclear processes and near-field microscopy. Microscopic Particle-in-Cells methods, a hybrid method of Molecular Dynamics and Particle-in-Cells, open a brand new avenue that can model above mentioned topics with minimum assumption required. We study the plasma formation process in laser-droplet interaction using PIC simulation by considering field ionization process. In the future, the main goal is to incorporate Molecular Dynamics into our PIC simulation to study light-matter interaction in strongly coupled region.

Introduction

There are three main regions in laser-matter interaction depending on the temperature and density of the target. In particular, the interaction between **low intensity laser ($< 10^{10}\ W/cm^2$)** and matter belongs to **strongly coupled** region of which **short-range** interactions dominate **long-range** interactions. **Particle-in-Cells** method has been widely used for modeling weakly coupled systems, but the lack of short-range force prohibit its application for strongly coupled systems. Therefore, a hybrid method, which combine **Molecular Dynamics** simulation and **Particle-in-Cells simulation** is implemented for modeling the strongly coupled systems, it's called **Microscopic Particle-in-Cells method (MicPIC).** In this poster we study the process of plasma formation in droplet using PIC simulation with field ionization. The prospect is to incorporate Molecular Dynamics into our simulation to study light-matter interaction in strongly coupled region



Debye Number

$$N_D = \frac{4\pi}{3} n\lambda_D^3 = \frac{4\pi}{3}\frac{(\varepsilon_0 k_B T)^{3/2}}{\sqrt{n}e^3} \quad (1)$$

Degeneracy Parameter

$$\Theta = {k_B T}/{E_F} = \frac{2m_e k_B T}{\hbar^2 (3\pi^2 n)^{2/3}} \quad (2)$$

Figure 1. Three regions of Laser-Plasma interaction which is characterized by Debye number(N_D) and degeneracy(Θ). Strongly coupled region lies between $N_D \lesssim 1$ and $\Theta > 1$.

E_F: Fermi energy
λ_D: Debye length
n: Density

	MD	PIC
Pros	• nanometer target • Collision • plasma micro-field	• $O(N_p) = \alpha N_p + \beta(N)$ • Wave propagation • $N_p \sim 10^{11}$
Cons	• $O(N_p) = 10N_p^2 - N_p$ • EM wave propagation • $N_p \sim 10^6$	• Short-range interaction • Many body collision • Plasma micro-field

Table 1. MicPIC inherit the advantages of MD and PIC simulations for simulating light-matter interactions with $\sim 10^{11}$ particles. The simulation time is **linearly scaled** with $O(N_p, N_n) = \alpha N_p + \beta(N) + \gamma N_p N_n$.

N_p: Number of particles
N_n: Number of neighbors
α, γ: constants
β: A function of N (*e.g.* $5N^3\ log_2\ N^3$)
N: # of gird (*e.g.* $N \times N \times N$)

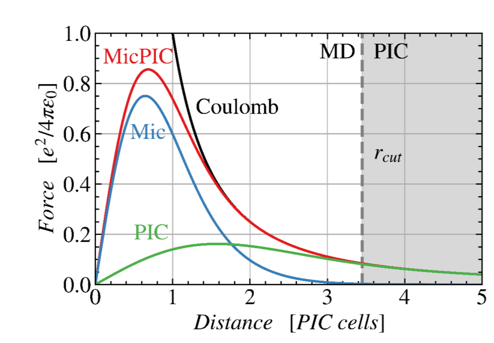
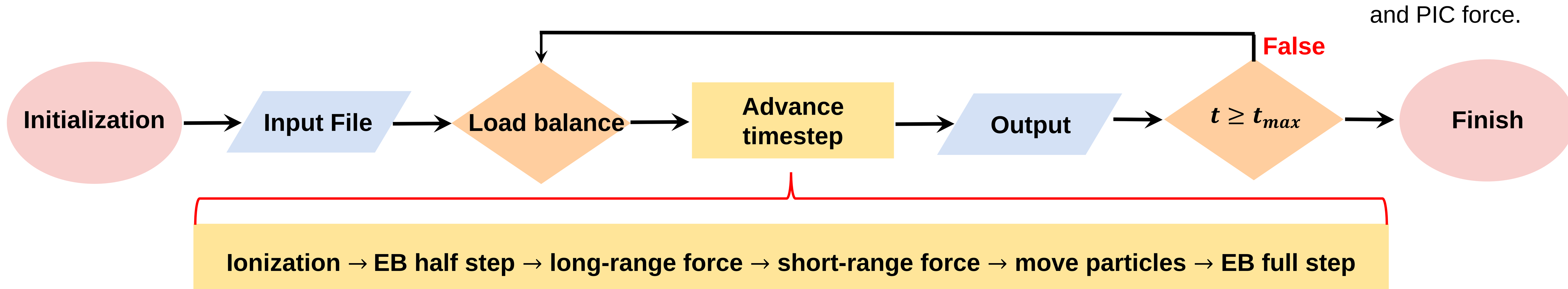


Figure 2. Coulomb force decompose into Mic force and PIC force.

MicPIC Simulation



Laser-Droplet interaction

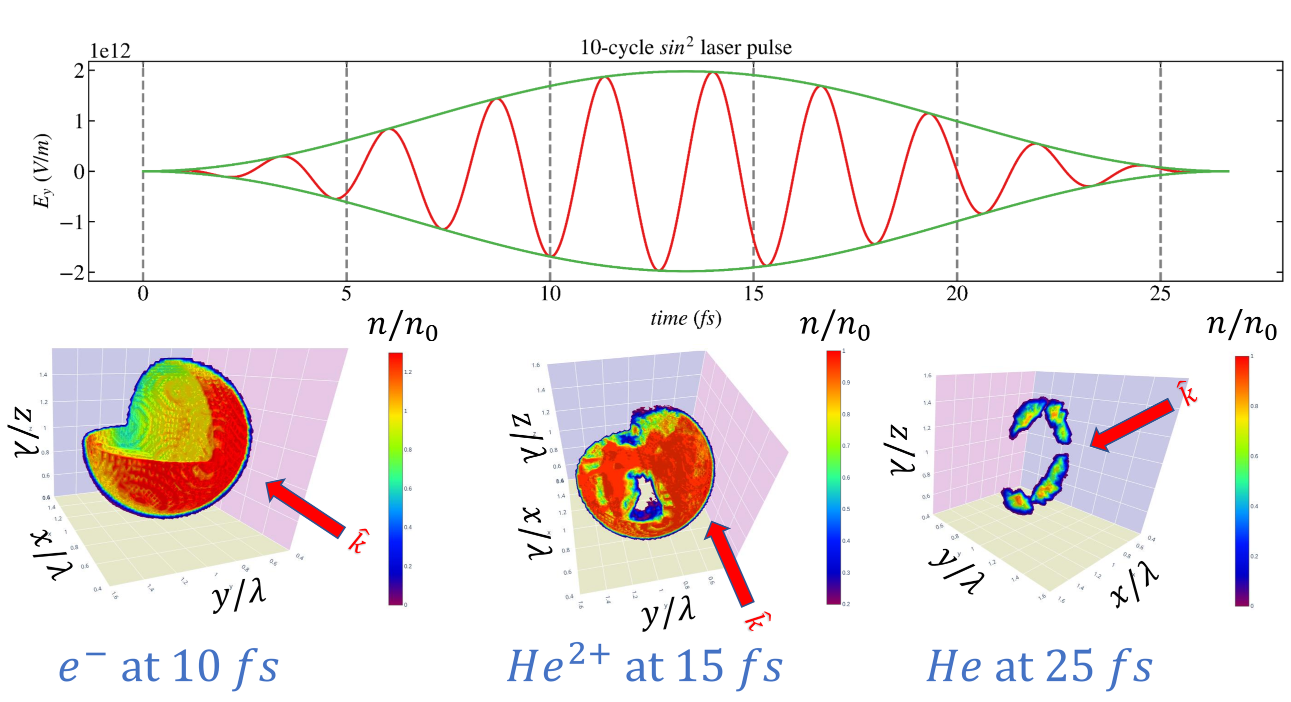


Figure 3. Above is the 10-cycle sin^2 laser profile. Below are different species density at different time with the red arrow indicate the direction of laser propagation.

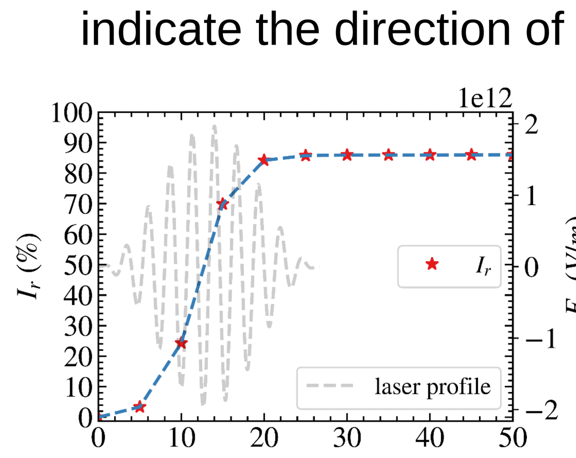


Figure 4. Ionization fraction $I_r = \frac{3}{4\pi R^3 n_{e0}} \int n_e(r) d^3r$ reach roughly 85% after laser interaction.

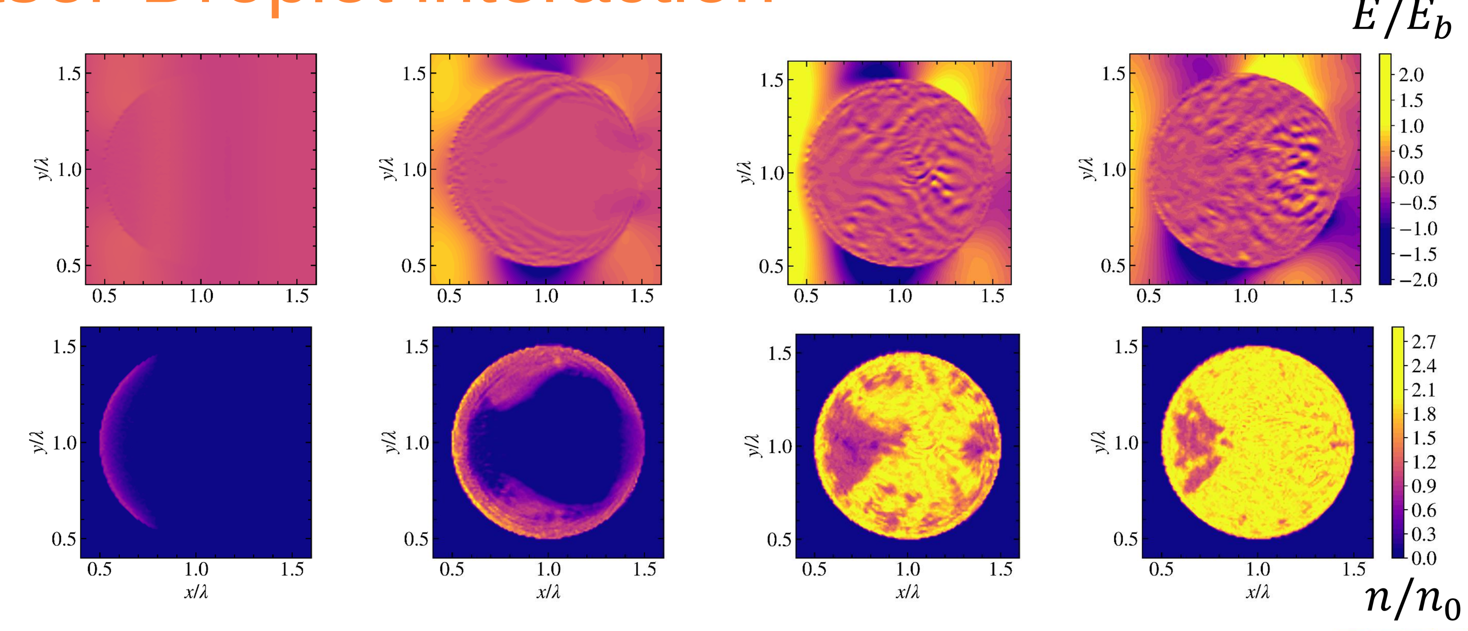
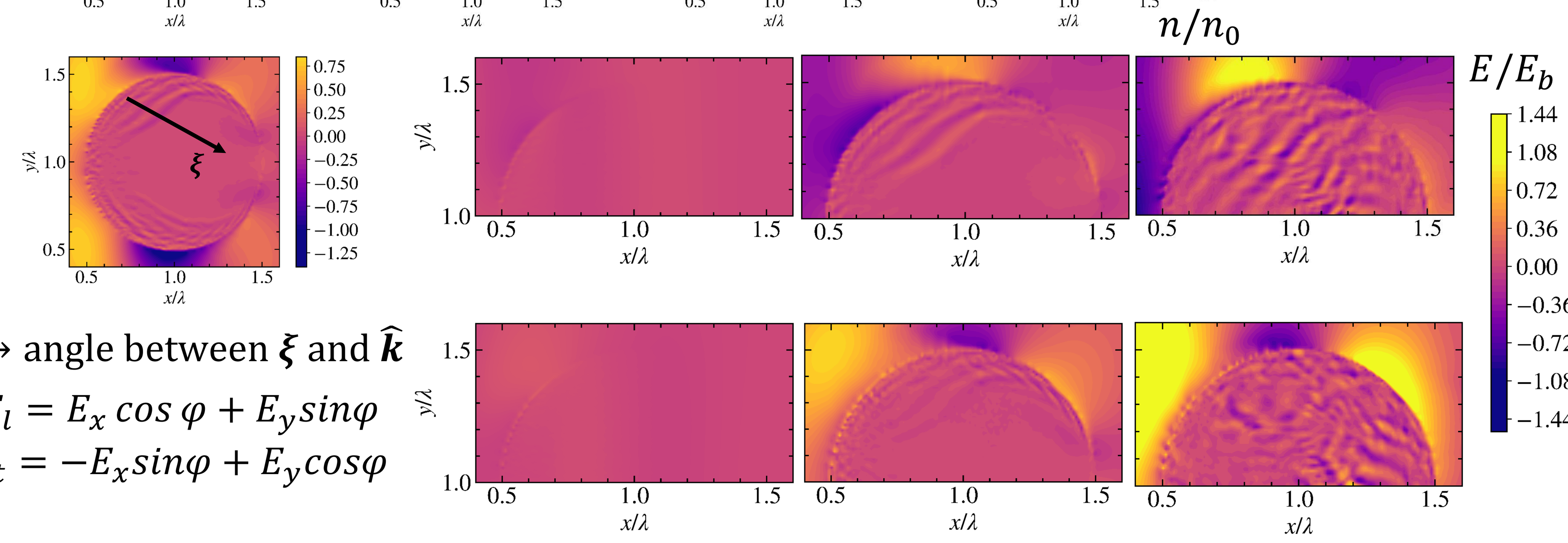


Figure 5. e^- density(up) and E_y component(down).
First, oscillating electric field penetrate into droplet → plasma wave → deeper ionization.
Second, Mie-enhanced field at the surface → ionization ↑.
Lastly, above certain angle respect to $\hat{k}$ have stronger ionization ($\theta \geq \pi/2$).



φ → angle between $\boldsymbol{\xi}$ and $\hat{\boldsymbol{k}}$

$$\begin{cases} E_l = E_x \cos\varphi + E_y \sin\varphi \\ E_t = -E_x \sin\varphi + E_y \cos\varphi \end{cases}$$

Figure 6. First, $E_l \gg E_t$ → Longitudinal plasma wave. Second, phase velocity of plasma wave $< c_0$ → angle between $\boldsymbol{\xi}$ and $\hat{\boldsymbol{k}}$. Lastly, field enhanced at the focal spot of plasma wave → ionization fraction ↑.

Conclusion

1. Laser field interact with wavelength-sized neutral droplet can create **inhomogeneous** density distribution.
2. The laser pulse with certain incident angles can **penetrate into droplet** and create enhanced fields that cause highly ionization inside droplet.
3. Tin ion of high charge states inside the droplet can emanate **EUV light**.
4. Further incorporation of Molecular Dynamics into our PIC simulation is an imminent task to study light-matter interaction in strongly coupled region.

Reference

[1] T. V. Liseykina and D. Bauer, Phys. Rev. Lett. 110, 145003 – Published 2 April 2013
[2] Fennel T, Ramunno L, Brabec T. Highly charged ions from laser-cluster interactions: local-field-enhanced impact ionization and frustrated electron-ion recombination. Phys Rev Lett. 2007 Dec 7;99(23):233401. doi: 10.1103/PhysRevLett.99.233401
[3] Ann. Phys. (Berlin) 526, No. 3–4, 135–156 (2014) / DOI 10.1002/andp.201490001
[4] Barnes, J., Hut, P. A hierarchical O(N log N) force-calculation algorithm. Nature 324, 446–449 (1986).
[5] C.K. Birdsall, A.B Langdon, Plasma Physics via Computer Simulation, CRC Press, 1991