Electron radiation damping effects in laser-plasma interactions

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1. Introduction

The high power laser has experienced rapid development in the past decades and 10 PW class laser facilities have already been under operating [1]. The state-of-the-art lasers are able to deliver the short pulse with the peak intensity up to 10^{22} W/cm^2 [2, 3]. The next generation 100 PW laser facilities are expecting to further enhance the intensity to $10^{23\text{-}24}$ W/cm^2 [4, 5].

Under such the high intensity, the electron radiation effect becomes important since the momentum of the emitted photons becomes comparable to the electrons [6]. The dynamics and the trajectories of the electrons will be significantly changed by the damping force provided by the photon emission processes as shown in Figure 1. In laser-plasma interactions, the electrons absorb energy from the EM (electromagnetic) field of the laser pulse and the electrostatic field such as the laser wakefield [7]. The radiation friction effect is dominant when the rate of radiation emission overcomes the rate of absorption. In the extreme conditions, the energy gain is balanced by the radiation loss, then the electron acceleration is fully damped. In the condition of high energy electron and strong EM field case, the photon radiation transits from the classical regime to QED (quantum electrodynamics) regime. Novel physical processes such as electron–positron pair creation, gamma-photon emission and QED-cascade come into play under these extreme intensity conditions. The abundant new phenomena provide possibilities of studying high-energy density physics, laboratory astrophysics, and to address the fundamental physics in QED [8-11].

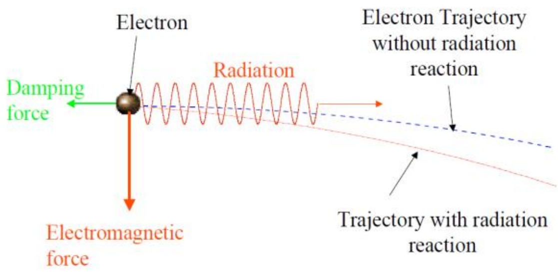

Fig. 1：The schematic of the electron radiation and radiation damping effect.

2. Computational Model of Radiation Reaction in Laser-plasma interactions

In laser-plasma interactions, one of the widely used numerical tool is the kinetic code PIC (particle-in-cell) simulation. In general PIC simulations, physical particles (electrons and ions) are represented by a number of pseudoparticles (super-particles). The fields generated by the laser pulse and the motion of particles are calculated by a Finite Difference Time Domain (FDTD) method. All the electromagnetic field components are calculated within a grid with fixed spatial resolution. The forces generated by these fields are applied on the pseudoparticles and used to update their velocities and positions according to Lorentz equation. At the end of the loop, the new calculated pseudoparticles' positions and velocities are used to update the fields again via Maxwell equations according to the currents and charge distributions. The typical algorithm and calculation loop of PIC code is shown in Figure 2.

Therefore, it is also clear that the electron radiation effect is not included in the general PIC calculations. It is understandable that in the low intensity laser case, the radiated photons have relatively low energy. Their contributions to the total energy balance and the change of the electron trajectories are not so significant. It is still a reasonable approximation to neglect the radiation effects.

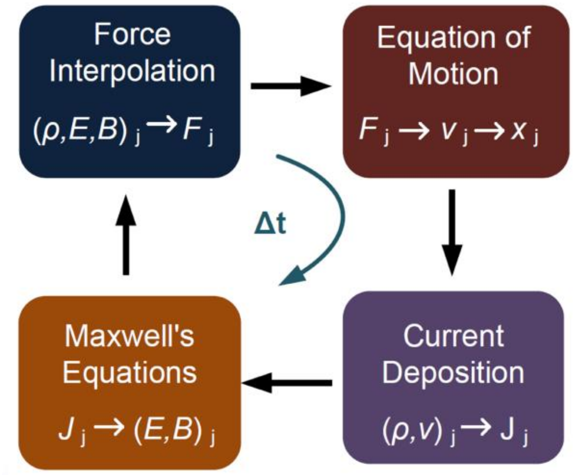

Fig. 2：The typical loop of PIC code.

However, as mentioned in the introduction part, such approximation will be invalid under the high intensity laser and strong field case. Therefore, it is necessary to modify the code by adding the radiation effect to satisfying the laws of energy conservation and momentum conservation.

The first and straightforward way is to model the classical radiation according to the Landau-Lifshitz radiation damping force [6], $F_{rr} = -(\frac{2e^4}{3m_e^2c^5})\gamma^2\boldsymbol{v}[\left(\boldsymbol{E}+\boldsymbol{v}\times\frac{\boldsymbol{B}}{c}\right)^2-(\boldsymbol{E}\cdot\boldsymbol{v})^2/c^2]$. Then update the damping force in Lorentz equation, as $F = q\left(\boldsymbol{E}+\boldsymbol{v}\times\frac{\boldsymbol{B}}{c}\right)+\boldsymbol{F}_{rr}$. In this case, the emitted photons are treated as the EM field with relatively long wavelength. The corresponding algorithm is shown in Figure 3.

```
! Compute Lorentz force
F_L = charge * (E + v × B)

! Compute radiation reaction force
F_RR = (2.0 * charge**3 / (3.0 * mass * c**3)) *
        (gamma * (E + v × B) × B +
        (charge / mass) * (E . v) * E -
        (charge**2 / mass**2 * c**2) * (E**2 - c**2 * B**2) * v)

! Update momentum
p = p + dt * (F_L + F_RR)
```

Fig. 3 Algorithm for classical radiation correction.

However, in the high energy photon emission case, the QED effects such as nonlinear Thomson scattering and Compton scattering become dominant. The radiation process becomes stochastic, and the wavelength of the emitted high energy photons is extremely short. Such the photons should be treated as particles. Therefore, the Monte Carlo approach is applied in modeling the radiation. The quantum efficiency parameter as $\chi_e = \frac{e\hbar}{m^3c^4}\sqrt{(F^{\mu\nu}p_\nu)^2}$ is calculated to sample the photon emission probability. The Monte Carlo process is shown in Figure 4.

```
! Look up the photon emission probability from a table
prob_emit = lookup_emission_probability(chi, dt)

! Generate a random number
rand_number = random()

! If random number < prob_emit, photon is emitted
if (rand_number < prob_emit) then
    photon_emitted = .true.
else
    photon_emitted = .false.
end if
```

Fig. 4 Monte Carlo Algorithm

Once the photon emission is confirmed, the corresponding photon energy and momentum should be calculated in order to update the electron motion by the conservation law of energy and momentum. The calculation is shown in Figure 5.

```
if (photon_emitted) then
    eta = sample_spectrum(chi)   ! Sample photon energy fraction
    photon_energy = eta * gamma * me * c^2
end if
if (photon_emitted) then
    electron_energy = electron_energy - photon_energy
    p_new = update_momentum(p_old, photon_energy)
end if
```

Fig. 5 Calculation of energy and momentum for photons and electrons.

By adding the Monte Carlo method in the standard PIC loop, it is possible to model the high energy photons emission process in a self-consistent way.

3. Simulation Results

Here the typical simulation results are presented to show the radiation damping effect on the electron dynamics. The simulation is limited in the 2D x-y plane with a size of $0.25mm \times 0.1mm$. The resolutions on each direction are both $0.01\mu m$, i.e. the cells number is 25000×10000. The total number of pseudoparticles is 1.5×10^{10}. The total time is 780 fs which corresponds 2.7×10^4 timesteps. The simulation was running on SQUID-CPU nodes with 20 nodes and accomplished in 1D22H22M.

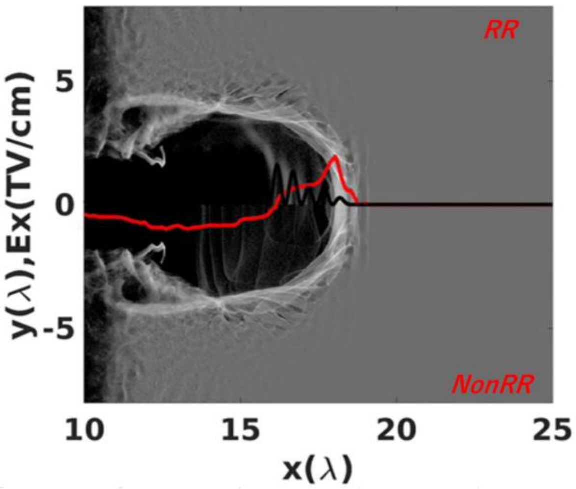

Fig. 6 The electron density comparison in the condition with and without the consideration of radiation effect.

The radiation and non-radiation simulation results are compared in Figure 6. The upper half is the electron density distribution in the case with radiation consideration. The lower half is the corresponding one without radiation effect. The red line and black line are the longitudinal and transverse electric field on the laser axis. It is clear that the electron density distributions are quite similar in the region where the laser field is weak. It is consistent with the theory that the low field region indicates a minor quantum efficiency parameter. Therefore, the probability for high energy photon radiation and strong damping force generation is almost negligible. However, in the region where the laser field is intensive (on laser axis and within the pulse duration), the electron distributions become completely different. In the case of non-radiation, the electrons are drifting into the upstream of the laser pulse with the modulated structure. The electrons in the case of radiation show relatively slow back drifting. The confinement effect is actually due to the damping effect originating from the photon radiation. The momentum of the photons is in the direction of the electron drifting resulting a delay to the electron motion. The red spots shown in Figure 7 demonstrate the sampling of the emitted photons when the electrons are penetrating the laser field. Most of the photons move in the direction opposite to the laser field.

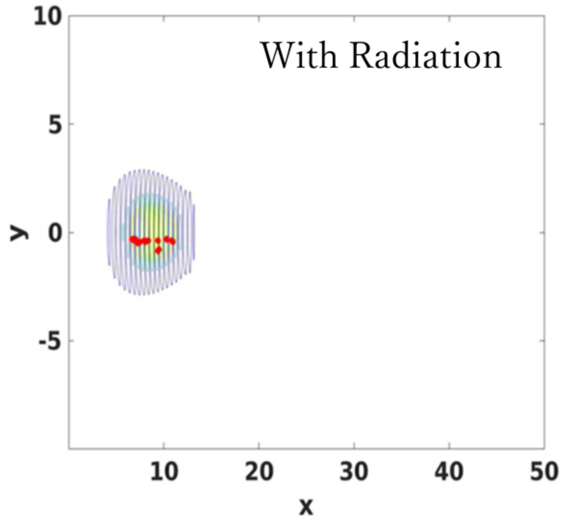

Fig. 7 Photon emission inside the laser field

4. Discussions

Although the high energy photon radiation and the corresponding damping effects have been modeled and realized in the simulations, there are still some necessary improvements and optimizing of the code.

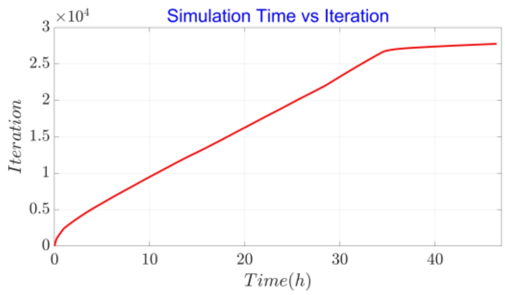

Fig. 8 The iteration evolution of the simulation

As presented in the time evolution of the iterations in Figure 8, the simulation becomes much slower after 35 hours, i.e. 2.6×10^4 steps. By checking the data, it shows that a large number of photons are produced and accumulated in the simulation box at that time. Also, the electron distribution becomes strongly nonuniform due to the pushing of the laser field. A large number of electrons are concentrated resulting a high density region. In the standard MPI process, the simulation region is uniformly separated according to the spatial region. The non-uniform distribution resulting a high particle loading on one calculating domain. The other domains with less particle calculation have to wait until all the domains enter the next timestep. It significantly reduces the efficiency of the simulation. Therefore, a dynamic balancing or adaptive loading method is necessary to add in the future.

5. Conclusion

High power laser facility provides the ultra-intense laser pulse which induces the strong radiation reaction and QED effects in laser-plasma interactions. To model the electron radiation process and the damping effects of the electron dynamics, the classical radiation and Monte Carlo QED algorithms are plugged in the standard PIC code. The simulation results show a large number of photons emitting in the central region of the pulse center and a strong damping effect on the electron motion. The current 2D simulations are not sufficient since the z-direction oscillation contribution is not well resolved. Another issue in the simulation is the electron concentration and the unbalanced particle loading effects. To simulate the interactions efficiently, it is necessary to solve the problem by dynamic balancing or adaptive loading method.

References

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