

## **Noncanonical Lie perturbation analysis for the relativistic ponderomotive force**

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In strongly focused high-intensity laser fields, the ponderomotive force exists inevitably and plays an important role in the particle dynamics. Here, an analysis of a relativistic particle motion in a non-uniform high-intensity laser field is presented by using the noncanonical Lie perturbation method, which is based on the perturbation theory of phase space Lagrangian [1]. Assuming that the ratio between the excursion length of the oscillatory particle motion and the scale length of the transverse laser amplitude variation is small, the relativistic ponderomotive force and the corresponding particle motion including higher harmonic oscillations are derived [2]. The result is consistent with that obtained by applying the perturbation analysis directly to the equation of motion. However, the present analysis rigorously keeps the Hamiltonian structure.

[1] J.R. Cary and R.G. Littlejohn, *Ann. Phys.* **151** (1983) 1.

[2] N. Iwata, K. Imadera and Y. Kishimoto, *Plasma Fusion Res.* **5** (2010) 028.

## **Particle based integrated code EPIC3D for laser-matter interaction including atomic process**

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In order to investigate high power laser-matter interaction, we have developed a particle based integrated code, EPIC3D, which includes various atomic and collisional relaxation process for all species. Using the EPIC3D, we performed successfully large simulation of laser-solid film and also laser-cluster interaction [1]. We found a new ionization dynamics in solid carbon film which is sustained by the field ionization due to the ionization driven wake field. We also applied the EPIC3D to investigate the discharge and lightning process of compressed neon gas. We have reproduced a complicated branching structure and its explosive development for the first time [2]. Non-local ionization dynamics by energetic electrons plays an important role for the sudden appearance of lightning [3]. The branching structure shows a power law wave number spectrum, suggesting that the lightning exhibits a fractal nature.

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[2] Y. Kishimoto and T. Masaki, *J. Plasma Physics* 72, part 6 (971)

[3] A. Sasaki, Y. Kishimoto et al., *Phys. Rev. Lett.* 105, 075004 (2010)