Japan Geoscience Union Meeting 2010
(May 23-28 2010 at Makuhari, Chiba, Japan)

PEM031-P02 Room: Convention Hall Time: May 23 17:15-18:45

Relativistic particle orbit analysis in high intensity short pulse laser fields using non-canonical perturbation method

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The development of ultra-high intensity short pulse lasers has opened up various applications in the field of science and technology, such as compact particle accelerators, fast ignition-based laser fusion, high intensity X-ray and neutron sources etc. In studying these applications, it is necessary to know individual and/or collective particle motions irradiated by such lasers. However, they are extremely complicated since the processes are highly nonlinear and non-stationary especially in the relativistic regime.

Among them, the ponderomotive force (light pressure), which inevitably exists in spatially localized short pulse laser in both longitudinal and transverse direction to the laser propagation, plays an essential role. The ponderomotive force can be derived by applying the averaging method directly to the equation of motion assuming scale splitting between laser wavelength and pulse length. On the other hand, when we approach to more complex problems such as the particle dynamics in multiple short pulse laser fields [1] and/or those in complicated perturbed electromagnetic fields, the canonical Hamiltonian perturbation method, which performs perturbation expansion directly to the Hamiltonian, has been traditionally employed. However, the procedure is generally complicated due to the complexity of the perturbation expansion especially in relativistic Hamiltonian. To analyze such complex particle motions in electromagnetic fields, a methodology based on the Hamiltonian perturbation theory which employs non-canonical variables and Lie transformation has been explored [2]. This method has been successfully introduced in gyro-kinetic formalism in magnetically confined fusion plasmas [3, 4] and also in the beam orbit analysis in focusing fields in a free-electron laser [5].

Here, we extend the method to the problem in analyzing the particle motion in high intensity short pulse lasers. We at first apply the method to derive the ponderomotive force in tightly-focused short pulse laser. We introduce non-canonical variables which make the ordering of perturbation expansion clearer and more prospective especially in the relativistic regime. As is well known, in a uniform monochromatic electromagnetic field, a charged particle exhibits a figure-eight motion drifting slowly to the direction of laser propagation [6]. In order to capture the secular motion properly, we transform the coordinates to the lowest order oscillation-center system. Then, we apply the Lie perturbation analysis to the particle motion under a non-uniform laser field originating from the finite transverse and longitudinal size. Here, we choose the ratio between laser wavelength and scale length of the laser pulse as a smallness parameter. A remarkable feature of the Lie perturbation analysis is that the influence of higher order rapid oscillations can be included into the next higher order trajectories by repeating the coordinate transformations, so that we can obtain additional higher order secular terms. Through these procedures, a long time scale behavior of the particle will be clarified.

We will extend this method to higher order terms such as the curvature of the laser pulse shape and also more complicated situations in the presence of the secondary laser field. We will also try to extend the method to the case including dissipation terms such as radiation damping.

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Keywords: non-canonical perturbation method, Lie transformation, high intensity laser field, short pulse laser, ponderomotive force