5. Simulation of Intense Short-Pulse Laser-Plasma Interaction

Mitsuru YAMAGIWA and Simulation Group for Advanced Photon Science
Advanced Photon Research Center, Kansai Research Establishment,
Japan Atomic Energy Research Institute
1, Umemidai 8-chome, Kizu, Kyoto 619-0215, Japan

We have completed the massive parallelization of a 2-dimensional giga-particle code and have achieved a 530-fold acceleration rate with 512 processing elements (PE's). Using this we have implemented a simulation of the interaction of a solid thin film and a high intensity laser and have discovered a phenomenon in which high quality short pulses from the far ultraviolet to soft X-rays are generated at the back surface of the thin layer. We have also introduced the atomic process database code (Hullac) and have the possibility for high precision simulations of X-ray laser radiation. With respect to laser acceleration we have the possibility to quantitatively evaluate relativistic self-focusing assumed to occur in higher intensity fields. Ion acceleration from a solid target and an underdense plasma irradiated by an intense and an ultra intense laser, respectively, has also been studied by particle-in-cell (PIC) simulations.

Keywords: Giga-Particle Simulation, PIC, Solid Thin Film, Short-Pulse Laser, X-ray Laser, Atomic Kinetics, Multiple Charged Ion, Laser Acceleration, Relativistic Self-Focusing, Ion Acceleration, Underdense Plasma, Positron Emitting Radionuclide

1. Introduction

Computational science is a science that involves analysis, construction of new theories, or the discovery or clarification of phenomena. Typically this type of analysis is carried out on research objects which are difficult to do experimentally and/or observe, and problems which are theoretically difficult to analyze, by combining and building up many known principles. In recent years, due to the rapid development of super computers more complex close to realistic models have become treatable.

One of the main subjects of the Advanced Photon Research Center is the 100 trillionth of a second duration ultrahigh peak power laser (T3 laser). When such a laser is focused to its limits and is irradiated onto a solid or something else, in an instant, an ultrahigh energy high density plasma is generated, and in an extremely short time it is said that various phenomena occur which up till now were not expected. To make progress in the analysis of these phenomena, large scale plasma particle simulations are important. Now, by optimized calculations with massively parallel computers, we have clarified in the manner below results of great interest. In this
calculation we used the Kansai Research Establishment massively parallel Paragon XP/S 75MP834 computer which is provided with 2502 CPU'S, has the ability of 125 GFLOPS and 106 GBytes, and has the possible demonstrated ability of above 100 times that of a regular super computer.

We are doing simulation research using massively parallel computers for the prediction of new phenomena induced by high peak power lasers for which doing experiments is presently difficult, along with supporting experiments of X-ray lasers and laser acceleration.

In this paper, we report some recent research activities of the simulation group for advanced photon science of the Advanced Photon Research Center, JAERI Kansai Research Establishment

2. Higher harmonics generation from a solid thin film irradiated by an intense laser

When a laser is irradiated onto a solid thin film, the laser is reflected from the surface. However, in the case of an ultrahigh peak power laser, a part is transmitted through the thin film. Furthermore, in a subject of great interest, we have found that this transmitted light is composed of more fine intervals, and powerful short wavelength coherent light below 1/10 of the laser wavelength (far ultraviolet or soft X-rays) is emitted as shown in Fig. 1 [1].

3. X-ray laser radiation

We have developed a collisional radiative model of electron collisional excited X-ray lasers. We have calculated the ion abundance and soft x-ray gain for the 4d-4p transition of Ni-like multiply charged ions, in short pulse laser irradiated plasmas. We have combined a detailed model using the atomic data calculated by the HULLAC code and an averaged model based on the screened hydrogenic approximation. Calculations of the soft X-ray gain have been carried out both for stationary plasmas and plasmas subject to the irradiation of double two short laser pulses to show the advantage of the transient pumping scheme. Figure 2 shows a large transient gain for a thin Ag foil irradiated by a double short pulse laser. The transient gain is more than 40 times greater than the steady state gain. It has also been found that the gain occurs immediately after heating by the second laser pulse and that a larger gain is obtained at the center of the target where the plasma density is higher. At the surface of the plasma, the density might be too low and the temperature is too high to produce large gain [2].

4. Laser acceleration

One of the key issues in attaining high energy electrons from acceleration by a laser generated wake field is the maintenance of the wake field over long distances. To attain this the laser pulse needs to remain focused in the plasma over distances much longer than the Rayleigh length of the laser pulse in vacuum. One mechanism to achieve this is the relativistic self-focusing of the laser pulse which occurs at high laser powers. To quantitatively determine the
effects of this self-focusing for the 100 TW laser system of the Kansai Research Establishment on the laser pulse we have performed 2-dimensional PIC simulations of a high intensity short pulse laser propagating in a homogeneous plasma. Figures 3 (a) and (b) show the results of the simulation for the laser beam and the electron density, respectively. It can be seen in Figure 3 (a) that the laser pulse is self-focusing. The intensity of the laser pulse has increased by a factor of 1.5 and there is filamenting of the laser pulse in the direction transverse to the laser propagation direction. In Figure 3 (b) it can be seen that electron cavities have formed where the electrons have been completely expelled due to the pondermotive force of the self-focusing laser pulse. We are now investigating whether these cavities can also be used for proton acceleration.

5. Ion acceleration

Ion acceleration and expansion in the interaction of a relativistically intense short-pulse laser with an underdense plasma layer has been investigated. Ion and electron dynamics have been studied by using a two-dimensional PIC simulation code with a real mass ratio. It has been shown that the longitudinal electric field induced by electron evacuation due to the large ponderomotive force or light pressure can accelerate ions to several MeV in the direction of the laser propagation. It is after the laser completely passes through the plasma layer that the ion explosion starts to be significant. Figure 4 (a) shows the electron density contour indicating that some of the electrons have moved forward. Electron acceleration continues until when the electrons are overtaken by the peak point of the laser intensity. Ion acceleration and expansion near the original plasma boundary are also clearly seen, as shown in (b) the ion energy spectrum ($E_{\text{max}} < \sim 5$ MeV) and (c) the ion density contour, respectively. Figure 4 (d) shows a contour of the ion distribution in the x-$P_x$ plane, where $P_x$ is the ion momentum in the x-direction, indicating that ions are accelerated in the x direction near the original plasma boundary [3].

A new method has also been proposed for producing $^{18}\text{F}$, a positron emitter, via $^{18}\text{O}(p,n)^{18}\text{F}$ reactions with fast protons from the interaction of a relativistically-intense short-pulse laser with an underdense plasma layer. The instantaneous production rate of $^{18}\text{F}$ has been found to be two orders of magnitude larger than by the standard method using a cyclotron [4].

Using a collisional PIC simulation, which incorporates nonlocal-thermodynamics-equilibrium ionization including optical field induced ionization, we have obtained the plasma temperature, line shape, and maximal energy of accelerated ions, which agree well with those determined from experimental spectra for the irradiation of a solid target by an intense laser [5].


Fig. 1
Injected, reflected, and transmitted laser light in an ultrahigh peak power laser-solid thin film (hatched) interaction.

Fig. 2
Temporal evolution of the soft x-ray gain of the plasma produced from a thin Ag foil target irradiated by two short laser pulses. The smaller the index number, the closer to the center of the target the position is.

Fig. 3
(a) Time sequence of a 100 TW 19fs laser pulse propagating in a uniform ionizing plasma at a density of $5 \times 10^{19}$ cm$^{-3}$ and (b) the corresponding electron density at the last time frame of the laser.

Fig. 4
(a) The electron density contour, (b) ion energy spectrum, (c) ion density contour, and (d) contour of the ion distribution in the $x$-$P_x$ plane after the laser completely passes through the plasma layer ($\Lambda$ is the grid size).