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Monte Carlo particle collision model for spectral analysis of neutrons from laser-driven neutron sources

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Neutron energy spectrum from laser-driven inertial confinement fusion (ICF) can be used to determine several fundamental parameters of extremely hot and dense fusion plasma [1-3]. The spectral broadening of neutrons emitted from deuterium-deuterium ($D(d,n)^3He$) reactions is a parameter of particular interest as it scales with the fuel ion temperature in excess of 10 million Kelvin, which is one of the most essential information to approach the fuel ignition condition. Spherically convergent plasma fusions in typical ICF schemes are known to produce a Gaussian-shaped neutron spectrum, and now it is possible to analyze fuel ion temperature, as well as ion density and implosion asymmetry from a slight modulation of the neutron spectrum.

These diagnostic techniques are also expected to be used to ensure the fuel temperature improvements by a new fuel ignition technique, called "fast ignition (FI)" [4]. There is an issue that the energy spectrum of product neutrons is not easily calculated analytically in many cases of FI. Fast ignition relies on the localized energy deposition of energetic particles (electrons, protons, deuterons *etc.*) into a pre-compressed fuel through the interaction between an ultra-intense laser pulse with matter. Neutron production in this case can be dominated by the fusion reactions associated with the laser-accelerated ions with multi-MeV energies because such energetic ions have much higher cross sections for $D(d,n)^3He$ reaction than the thermal ions in a compressed fuel, whose typical ion temperature is only a few keV.

In addition, the energetic ions may also trigger some other nuclear reactions such as D(*p,n*), C(*p,n*) and C(*d,n*) and produce neutrons. These effect results in a significant broadening and/or a peak energy shift of the neutron spectrum, which is strongly correlated with the spectrum and directionality of the ions. The significant modulation of the neutron spectrum due to anisotropic non-thermal ions is also observed in other types of ICF experiments [5]. These modulated spectra are also worth analyzing because they contain information about the properties of the laser-accelerated ions and their contribution to fusion reactions. However, the analysis requires a massive, large-scale, multi-dimensional hydrodynamic and Particle-in-Cell (PIC) simulations for modeling the complex laser-plasma interactions, and therefore takes time and relies on large computational resources.

We have developed a three-dimensional (3D) Monte Carlo particle collision model for the qualitative analysis of the neutron spectrum produced by unknown plasma dynamics [6]. The code simulates the kinetics of two-particle collisions for a huge number of fusion events assuming arbitrary configuration of ion velocity and geometric collision. Instead of omitting the calculation for complex particle transport in plasmas, the simulation runs even on laptops and displays the results within a few minutes. The ability to quickly explore the effects of various ion dynamics on neutron spectrum encourages discussions on possible mechanisms of neutron production and provides a feedback to ongoing experiments. This quickness can also contribute for optimization of future high-repetitive laser fusion experiments, as well as laser particle accelerator and high energy density physics.

In the presentation, we present the calculation process of the 3D Monte Carlo code and discusses its usability by showing an example of the numerical analysis for a neutron spectrum obtained in the ``cone-free-shell" fast ignition experiment conducted at the GEKKO-XII and LFEX laser facility of Osaka University.

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