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Recent progress of experimental studies on fast-ignition inertial fusion energy

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The ignition of inertial confinement fusion was demonstrated at the National Ignition Facility in the United States in December 2022. This historical shot utilizes the indirect-drive method and the central-ignition scheme. The energy gain must exceed 100 to realize inertial fusion energy (IFE). The indirect-drive method has a low energy utilization efficiency because the laser is converted once into thermal X-rays. The fuel geometry is complex because a hohlraum is required in addition to a fusion fuel. The direct-drive method, which has a relatively simple fuel geometry and high energy utilization efficiency, is more suitable for IFE. In this study, we conducted the research aiming at the realization of IFE using the direct-drive method and fast-ignition scheme. The fast-ignition scheme can have a higher heating efficiency of fusion fuel than the central-ignition scheme , and the fast-ignition may be able to form a hot spark more efficiently than the central-ignition scheme.

One of the most serious obstacles of the central-ignition is hydrodynamic instability. The general fusion fuel is a spherical shell containing a thin deuterium-tritium ice layer on the inner surface of a thin hollow capsule called an ablator. The cavity of the spherical shell is filled with deuterium-tritium gas at saturated vapor pressure. The tiny holes and irregularities on the surface and inside of the spherical shell are instability seeds, and the spherical shell is greatly deformed as it is compressed. Since the hot spark, which is the starting point of fusion ignition, is formed by adiabatic compression of the deuterium-tritium gas, the deformation of the spherical shell makes the formation of the hot spark inefficient. In the fast-ignition, a portion of the high-density fusion fuel produced by implosion is heated by a short and intense laser pulse injected from outside the plasma to create the hot spark.

Interactions between the picosecond PW laser pulse and a plasma generate an electron beam with relativistic energy, called a relativistic electron beam (REB). This REB heats the high-density plasma in the REB-based fast ignition scheme. The advantage of the REB-based scheme is the high energy conversion efficiency from laser to REB (>30%). On the other hand, the average REB energy must be below 3 MeV to heat locally and efficiently a tiny volume of the high-density plasma, and REB has a large divergence angle (> 90 deg.) [1]. We are conducting the fast-ignition experiments using GEKKO-XII, a nanosecond TW laser system, to generate a high-density plasma by an implosion, and LFEX laser, a picosecond PW laser system, to heat the high-density plasma instantaneously. We have introduced plasma mirrors to the LFEX [2] to significantly improve the pulse contrast for heating the plasma by low-energy REB and shortening the distance between the high-density plasma and the interaction region so that the heat can diffusively propagate from the directly heated interaction region to the high-density region[3]. In addition, externally applying a laser-generated magnetic field improves the directionality of REBs, and the heating efficiency by collisions between REBs and ions (drag heating) is successfully enhanced [4]. The heating efficiency depends on the plasma density. We have proposed a solid ball fuel as a target for avoiding the breakup of the imploding plasma due to hydrodynamic instability [5]. We have also conducted experiments using a solid ball target to produce high-density plasma with a three-step pulse. We are also developing a liquid deuterium-containing solid ball for the world's first fast ignition experiment with deuterium plasma.

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