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Status and Prospects of Laser Fusion and High Energy-Density Science by Giant Lasers

大型レーザーを用いたレーザー核融合研究と高エネルギー密度科学の現状と展望

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1. Introduction

Fast ignition has high potential to ignite a fusion fuel with only about one tenth of laser energy necessary for the central ignition. One of the most advanced fast ignition programs is the Fast Ignition Realization Experiment (FIREX) [1]. The goal of its first phase is to demonstrate ignition temperature of 5 keV, followed by the second phase to demonstrate ignition-and-burn. Relativistic fast electrons as the energy carrier, however, unfavorably diverge at high laser intensities necessary for significant heating [2]. This difficulty is overcome by kilo-Tesla magnetic field collimating fast electrons towards a compressed fuel. Such super-strong field has been created with a capacitor-coil target driven by a high power laser [3], and subsequent collimation has also been demonstrated, suggesting that one can achieve ignition temperature at the laser energy available in FIREX. Repetitive creation of fast ignition plasmas has been demonstrated [4] together with the technology development of high-efficient rep lasers [5] and pellet injection, tracking, and beam steering.

2. Heating Laser

As for the heating laser, a high-energy peta-Watt laser called LFEX (Laser for Fusion EXperiment) has been commissioned. It consists of a 4-beam and 4-path Nd:glass amplifier system with a 40-cm square aperture in each beam. The design goal of LFEX is to deliver 10-kJ energy in 10-ps width at 1-µm wavelength. The focusing optics is an off-axis parabola mirror with f/10 speed in each beam. Currently, three among four beams are in operation, and the fourth beam will be commissioned by the end of 2014.

3. Magnetic Fast Ignition

It has been found in recent years that relativistic fast electrons as the energy carrier unfavorably diverge at high laser intensities necessary for significant heating [2]. Several approaches are considered and tested. A double cone with vacuum gap between the cones pulls back the divergent electrons by sheath potential in the gap [6]. Using high atomic-number material as a path of fast electrons suppresses cold return current and self-generates azimuthal magnetic field that pinches the divergent fast electrons [7]. Although these schemes are still attractive, the difficulty of the divergence can be overcome by super-strong external magnetic field along the path of the fast electrons. Such field has been created with a capacitor-coil target driven by a high power laser [3]: Two nickel disks are connected by a U-turn coil; Three beams of the GEKKO-XII laser irradiate the first disk through a hole in the second disk; fast electrons are generated via nonlinear laser-plasma interactions and escape from the first disk inducing a mega-Volt positive potential in the first disk; then, the mega-Ampere current flows in the U-turn coil. The resultant magnetic field was measured with Faraday rotation and B dot probe techniques to be 1 kilo Tesla with about 20% uncertainty at half mm away from the coil. This field is high enough to collimate fast electrons toward the compressed core, as the gyro-radius of the electrons is of the order of the compressed core size. The field was applied along the axis of fast electron transport, to collimate fast electrons along the magnetic field. The electron emission distribution was measured with a witness plate via transition radiation. It suggests therefore that the super-strong magnetic field collimates the fast electrons towards the compressed core, thereby increasing the energy coupling efficiency from the heating laser to the core, resulting in high temperature.

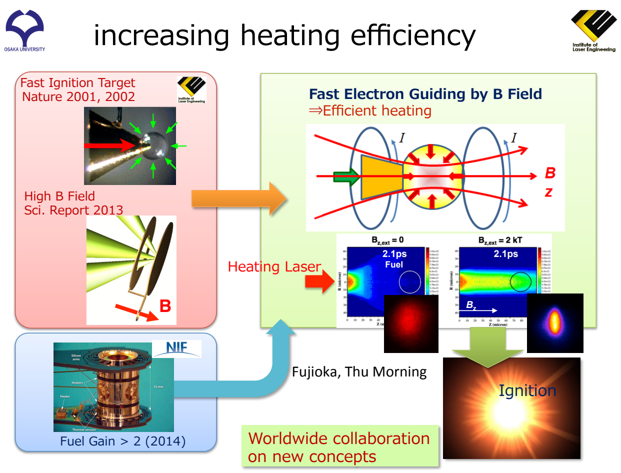


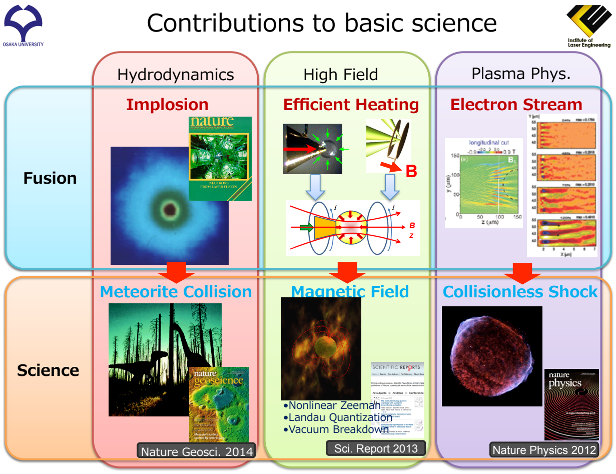
Fig. 1. Magnetic Fast Ignition: Super high magnetic field collimates hot electrons to the compressed core.

4. Prospects

Given the ignition temperature demonstration at the FIREX-I, we anticipate a next step toward inertial fusion energy: a laser fusion experimental reactor that demonstrates electrical power generation. Repetitive creation of fast ignition plasma has been demonstrated [4]. Further technology development includes high-efficiency high rep-rate lasers; target injection, and fusion chamber-and-blanket. Among these, high-rep lasers, have been demonstrated by using two technology breakthroughs: laser diodes for optical pumping increases the efficiency by a factor of a hundred; and cooled ceramic crystals for laser materials increase the thermal conductivity by a factor of three hundreds. Such technology breakthroughs have enabled much higher rep-rates (250 Hz) than that required by more than an order of magnitude [5]. These technologies would be converged into a laser fusion experimental reactor LIFT with the goal of demonstration of power generation.

5. High Energy-Density Science

While the laser fusion study gives purposes to high energy density science, the science brings breakthrough to the fusion study. Such mutual interaction is essential to sustain a long-term fusion study. We show in Fig. 2 recently achieved three such examples: Model experiment of meteorite collision that closes the question of the dynasors extinction [8]; Generation of super strong magnetic field, that open up unexplored science such as nonlinear Zeeman and Landau quantization [3]; Origin of Collisionless shocks that generate super energetic (10^{20} eV) cosmic rays [9].



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