Efficient fast isochoric heating process visualized with spatial-temporal-resolved x-ray imaging

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Abstract

Here we report the mechanism of plasma heating by fast-isochoric (FI) and magnetized fast-isochoric (MFI) heating schemes [1] with an ideal heating laser pulse. Intensity contrast of the heating laser pulse has been improved two orders of magnitude by implementation of plasma mirror device to LFEX laser system at Osaka University. The heating mechanism was visualized experimentally by combining several spectroscopic and spatially-resolved X-ray imaging techniques. The MFI scheme employs an external magnetic field for guiding a high-intensity relativistic electron beam (REB) generated by relativistic laser-plasma interactions to a small and dense fuel core along magnetic field line. This study reveals that the improvement of the pulse intensity contrast is essential to realize the efficient FI and MFI heating of a dense matter.

1. Introduction

The fast-isochoric (FI) heating may produce the ignition spark with avoiding ignition quench caused by the fluid mix between the spark and a cold fuel layer [2]. This mix is a crucial problem of the adiabatic compression heating in the central ignition scheme [3]. In the fast-isochoric heating scenario, a relativistic intensity laser, namely heating laser, generates the high-intensity relativistic electron beam (REB) [4]. The REB carrying a significant fraction of the heating laser energy travels in an overdense plasma from its generation zone to the pre-compressed fuel core. Part of the REB's kinetic energy is deposited in the pre-compressed core, and then the heated plasma core becomes the ignition spark. There are two major mechanisms in the fast-isochoric heating process as illustrated in Fig. 1. One is the drag heating mechanism, where energy is transferred from REB to the fuel core by particles binary collisions. The other is the diffusive heating mechanism, where energy is transferred by thermal conduction to a cold fuel from a high-temperature plasma that is heated by the resistive return current induced by the forward REB current, so-called resistive heating. Kilo-tesla magnetic field is required to guide the forward REB current and also the return current within a diameter of the pre-compressed core (~ 50 µm). A laser-driven capacitor-coil target was used to generate a kilo-tesla
magnetic field [5] in our MFI experiment.

Our previous studies clarified the followings: (i) the REB guiding resulted in doubling the drag heating efficiency [11], (ii) ultra-high-energy-density region having 2.0 keV of temperature and 2.2 Peta-Pascal of the pressure was created through the diffusive heating process, namely by heatwave propagating in the core with $10^{8.9}$ cm/s of the speed [12], (iii) MFI scheme can be a promising and alternative approach to create the fusion ignition spark because >15% of the coupling is achievable for an ignition-scale high area-density core (> 0.5 g/cm²) based on a simple model [19] that is fairly consistent with the experimental observations. This efficiency is > 3 times higher than that of the currently pursed central ignition scheme.

2. Visualization technique of FI and MFI heated region.

2.1 Resonance X-ray lines spectroscopy

In FI and MFI schemes, a characterization of the energy and spatial distribution of REB traveling in a pre-compressed plasma core are the most important parameters. A plasma containing tracer Cu ions enables us to visualize the spatial distribution of REB in the pre-compressed plasma. The drag-heating oriented laser-to-core energy coupling can be estimated from an absolute number of Cu-$K\alpha$ X-rays (8.05 keV) initiated by REB and ion collisions recorded with an X-ray spectrometer [6].

Highly oriented pyrolytic graphite (HOPG) is composed of a large number of small carbon crystallites, namely a mosaic crystal. Mosaic spread or mosaicity is defined as angular distribution of plane of crystallites relative to the HOPG bulk surface plane. The large mosaicity of HOPG results in high integral reflectivity of HOPG as a Bragg reflector. Therefore, HOPG provides us a significant signal intensity of Cu-$K\alpha$ X-rays with acceptable spectral resolution for our purpose.

Copper $K\alpha$ X-rays were imaged using a spherically bent quartz (2131) crystal to visualize the transport of the REB in a pre-compressed core from the direction perpendicular to the LFEX incident axis. The magnification, spatial resolution, and spectral bandwidth were 20, 13 μm (FWHM), and 5 eV (FWHM), respectively.

2.2 Fresnel Phase Zone Plate

Fresnel phase zone plate (FPZP) is an X-ray optics that converges a portion of a planar X-ray wave to a point at a distance $f$ behind the FPZP. This point is the focal position of the FPZP and $f$ is the focal length. The FPZP used in this study consists of multiple concentrated annular slits made of 1 μm thick tantalum membranes. The radial separation between each adjacent slit is designed to give a $2\pi$ radian of phase difference between the wavelets passing through each slit at the focal point. The thickness of the tantalum film is designed to give the transmitting wavelet a $\pi$-radian phase compared to the wavelet passing through the slit. Therefore, the phase difference between the wavelet passing through the membrane bar and the adjacent slit is $2\pi$ at the focal point. Finally, all wavelets that have passed through the FPZP constructively interfere with each other at the focal point. The focal length of FPZP is $f = a^2/\lambda$, where $a$ and $\lambda$ are the radius of the innermost annular slit and the wavelength of light, respectively. The focal length determines the relationship between the distance ($r$) from the objective to the FPZP and the distance from the FPZP to the image plane ($R$) as a standard lens. X-ray emitted from a plasma is not monochromatic but consists of multiple wavelength light. Position of FPZP image plane of targeted X-ray is different from that of untargeted one, thus the image of the untargeted X-ray is not formed on the targeted image plane, since the focal length is a function of the wavelength. FPZP provide us quasi-monochromatic X-ray images [7].

2.3 Filtered Pinhole Array Imaging

Spectral shape of continuum X-ray is determined by electron temperature of a plasma. Bremsstrahlung is the dominant process to generate continuum X-ray in a high temperature. In principle, the spectral shape of the continuum X-rays is independent from detailed atomic kinetics processes, namely excitation, deexcitation, ionization, recombination both by electrons and photons. Electron temperature of a high-density plasma can be derived more straightforwardly from the spectral shape of continuum X-ray by using the Bremsstrahlung formula in a plasma physics
compared to the resonance X-ray spectroscopy. The filtered-pinhole-array (FPA) technique [8,9] was used to obtain two-dimensional (2D) resolved rough spectral shapes or electron temperate based on the above mechanism. The 12 pinholes were used in this study to image 12 identical X-ray images of a plasma on an imaging plate. Each X-ray image passes each different X-ray filter located in the front of the imaging plate. Spectral shape of the continuum X-ray can be evaluated from X-ray intensities depending on material and thickness of X-ray filters with a reasonable assumption that the continuum X-rays are produced only by the Bremsstrahlung process.

3. Magnetic Field Generation and Diffusion

We have improved a previous analysis of the generation of a magnetic field with laser-driven capacitor-coil target and diffusion dynamics of pulsed magnetic field into the cone and the target. For the generation process, we calculated the temporal evolution of the coil current and laser-generated magnetic field in the laser-driven coil using the self-consistent circuit model [10]. The peak of the calculated magnetic field is delayed by 1.2 ns compared to that of the incident laser pulse. For the diffusion process, we calculated the electrical conductivity of warm dense gold over a wide temperature range (300 K - 100 eV) by combining ab initio molecular-dynamics simulation with the modified Spitzer model to estimate the magnetic diffusion into the guiding cone target with consideration of the temperature dependence of the electrical conductivity. The magnetic field that penetrates the gold cone reaches a maximum strength of 530 T at 5.5 ns. The maximum magnetic field that penetrates the cone is delayed by 2.5 ns with respect to the laser peak. In the MFI experiments performed by Sakata et al. [11] and Matsuo et al., [12], a heating laser was irradiated 1.88 - 2.22 ns after the incident laser peak of the laser-driven coil. The maximum coupling efficiency was observed at 2.2 ns after the incident laser. At this timing, our improved calculation shows that the field strength at the tip of the gold cone is 385 T, which is sufficiently strong to guide the REB to the fuel core.

4. Experiment

The experiment was conducted on the GEKKO-LFEX laser facility at the Institute of Laser Engineering, Osaka University [13]. The fusion fuel surrogate was made of a 200 μm-diameter solid Cu(II) oleate solid ball [Cu(C17H35COO)2] [14], whose surface was coated with a 25 μm-thick polyvinyl alcohol (PVA) layer to prevent the Cu atoms from being ionized directly by the compression laser beams. The Cu(II) oleate ball contains 9.7% Cu atoms in weight for visualization of the relativistic electron beam (REB) transport in the core and for measurement of the laser-to-core energy coupling. The fuel surrogate was attached to a Au cone, whose open angle, wall thickness, and tip diameter were 45 degrees, 7 μm, and 100 μm respectively. The outer surface of the Au cone was coated with a 50 μm-thick PVA layer to delay the cone breakup time [15]. Open-tip Au cones were used in the experiments; the tips of the closed cones were covered with a 7 μm-thick Au layer.

The solid ball was compressed by six of GEKKO-XII laser beams arranged in a quasi-cylindrical geometry, whose wavelength, pulse shape, pulse duration, and energy were 526 nm, Gaussian, 1.3 ns full width at half maximum (FWHM), and 175 ± 12 J/beam, respectively. The center of the nickel-made coil having a 500 μm diameter was located 230 μm from the center of the ball to apply a strong magnetic field near the REB generation zone and the solid ball. The first disk of the laser-driven capacitor was irradiated through the hole of the second disk by three tightly focused GEKKO-XII laser beams, whose wavelength, pulse shape, pulse duration, and energy were 1053 nm, Gaussian, 1.3 ns (FWHM), and 257 ± 24 J/beam, respectively, yielding \(2 \times 10^{15} \text{ W/cm}^2\) of the peak intensity. The tip of the cone was irradiated to produce a REB by four LFEX laser beams, whose wavelength, pulse shape, and pulse duration were 1053 nm, Gaussian, 1.8 ± 0.3 ps (FWHM), respectively.

In this study, plasma mirror (PM) was implemented to increase pulse contrast of the LFEX for understanding how the pulse contrast affects the heating efficiency. The PM configuration used in this experiment was fielded in the previous experiment in the LFEX laser system [16,17]. PM was made of a transplant quartz, and anti-reflection layers for 1.053-μm-light were coated on the both
sides of the quartz. A quartz is transparent for a low-intensity laser light, namely for foot pulse, prepulse and low-intensity pedestal of the LFEX pulse, whose intensities are $< 10^8 \text{ W/cm}^2$ on the quartz surface. The quartz becomes a plasma immediately for high-intensity laser light whose intensity is above the threshold intensity ($\sim 10^9 \text{ W/cm}^2$). This quartz plasma reflects the high-intensity laser light, namely high intensity pedestal and the main pulse. No foot pulse, prepulse, and low-intensity pedestal exist in the LFEX pulse after the PM reflection. Reflectivity of the PM for the main pulse depends on intensity of the main pulse on the PM. Average intensities of the LFEX main pulse on the PM were calculated from burn profiles on the retracted PMs and energy and pulse duration of the LFEX beams measured before the PM.

The total energy of the four LFEX beams on the tip was $367 \pm 33 \text{ J}$. The focal spot diameter was 50 $\mu\text{m}$ (FWHM) containing 30% of the total energy, yielding an intensity of $4 \times 10^{18} \text{ W/cm}^2$ at the maximum energy shot.

The diffusive heating area was visualized with the FPA. The internal energy of a heated plasma was obtained by combining 2D electron temperature profiles and 2D density ones that were measured with an X-ray backlight technique. The diffusive heating efficiency was calculated as a ratio between evaluated internal energy and heating laser energy. The diffusively heated area was observable only with PM. The diffusive efficiency was a few %, this not-so-high diffusive efficiency may be caused by the low intensity of heating laser. The energy source of the diffusive heating process is a high temperature plasma directly heated by the heating laser pulse. Lower intensity heating laser results in the lower diffusive heating, and the lower temperature of the heated area.
Fig. 3 the summary of the drag heating efficiency for the four different experimental conditions. Left (a) and right (b) graphs of Fig. 3 show the drag heating efficiencies without and with application of external magnetic field. Red cross and black solid squire marks are obtained with and without the implementation of PM.

Fig. 4 X-ray images obtained with filtered pinhole array (FPA) imager. Left image shows only x-ray emission from the coronal plasma produced by the compression laser beams. Heated region is clearly visualized with this imager in the middle image. The two-dimensional electron temperature profile is obtained with FPA imager.

Acknowledgement
The authors thank the technical support staff of ILE and the Cyber Media Center at Osaka University for assistance with the laser operation, target fabrication, plasma diagnostics, and computer simulations. This work was supported by the Collaboration Research Program between the National Institute for Fusion Science and the Institute of Laser Engineering at Osaka University (NIFS12KUGK057, NIFS15KUGK087, NIFS17KUGK111 and NIFS18KUGK118), and by the Japanese Ministry of Education, Science, Sports, and Culture through Grants-in-Aid, KAKENHI (Grants No. 24684044, 25630419, 15K17798, 15K21767, 15KK0163, 16K13918, 16H02245, and 17K05728), Bilateral Program for Supporting International Joint Research by JSPS, and Grants-in-Aid for Fellows by Japan Society for The Promotion of Science (Grant No. 14J06592, 15J00850, 15J00902, 15J02622, 17J07212, 18J01627, 18J11119, and 18J11354), the Matsuo Research Foundation, and the Re- search Foundation for Opto-Science and Technology.

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