Simple Analysis of the Laser-to-Core Energy Coupling Efficiency with Magnetized Fast Isochoric Laser Heating^{*)}

Shohei SAKATA^{*a*}, Tomoyuki JOHZAKI¹, Seungho LEE, Hiroki MORITA, Kazuki MATSUO, Ryosuke KODAMA, Yasunobu ARIKAWA, Yasuhiko SENTOKU and Shinsuke FUJIOKA

Institute of Laser Engineering, Osaka University, 02-06 Yamada-Oka, Suita, Osaka 565-0871, Japan ¹⁾Department of Mechanical Systems Engineering, Hiroshima University, Higashi-Hiroshima, Hiroshima 739-8527, Japan

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In this study, we have demonstrated the enhancement of laser-to-core energy coupling using magnetized fast isochoric laser heating on the GEKKO-LFEX laser facility. We achieved a maximum coupling of 8% by applying an external magnetic field, and the coupling gradually degraded with increasing energy of the heating laser, maintaining the pulse duration and the spot diameter constant. The obtained energy couplings are consistent with those obtained using simple calculation models. The models predict that an energy coupling of 20% - 35% can be achieved by an ignition-scale core exhibiting a moderate guiding field and heating laser intensity.

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1. Introduction

The outer surface of a few-millimeter-scale spherical capsule containing a deuterium-tritium (DT) ice layer in a high-Z-material enclosure is irradiated with X-rays in case of the indirect-drive approach to inertial confinement fusion (ICF) [1,2]. X-rays result in a converging shock wave, which compresses the fuel to become 1000 times the solid density. Adiabatic compression heats the DT gas that initially fills the capsule interior, resulting in an ignition spark during the final stage of compression. Scientific breakeven, where the energy released by the fusion reactions exceeds the energy contained in the compressed fusion fuel, has been achieved at the National Ignition Facility (NIF) [3]. However, the mixing of fuel caused by hydrodynamic instabilities quenches the ignition of ICF.

Fast isochoric heating, also known as fast ignition [4], of a precompressed core has been proposed as an alternative approach to ICF ignition. This method avoids the ignition quenching caused by fuel mixing because a hot spark is generated not by the adiabatic compression but by the injection of external energy on a timescale shorter than the hydrodynamic timescale (<100 ps). The interactions between a high-intensity laser and a solid material produce a relativistic electron beam (REB) [5, 6] that deposits its kinetic energy into the compressed core; the heated region becomes the hot spark that triggers fusion ignition. The invention of the cone-in-shell target [7] enables a heating laser to interact with close to the dense core without affecting the plasma surrounding the compressed fuel. However, only a small portion of the REB collides with the core because of its large divergence of the REB [8].

The application of a strong magnetic field along the REB path has been proposed as a mechanism for guiding the diverging REB into the dense core [9]. A kilo-tesla magnetic field can radially confine MeV electrons within the dense core because the gyroradius of the MeV electrons (a few μ m) is smaller than the typical core radius (a few tens of μ m). Magnetic field strengths of 600 - 700 T have been achieved using a laser-driven capacitor/coil target [10,11] and a 1.5-ns full-width at half-maximum (FWHM) pulse duration [12,13]. Guiding an REB using such a laser-produced external magnetic field has been experimentally demonstrated in a planar geometry [14].

A solid sphere target has been introduced for use with magnetized fast isochoric laser heating to produce a stable core [15] and a moderate guiding field [16–18]. We have achieved a maximum laser-to-core energy coupling of 8% [19] even with a relatively small-areal-density core when compared with that used in previous integrated experiments without the application of an external magnetic field [20].

Further, we compare the measured energy coupling and two simple models.

2. Laser-to-Core Energy Coupling Measurement

We conducted an integrated experiment at the

author's e-mail: sakata-s@waseda.jp

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^{*a*)} Current affiliation: Administration and Technology Center for Science and Engineering, Technology Management Division, Waseda University

GEKKO-LFEX laser facility at the Institute of Laser Engineering, Osaka University [21, 22]. The experimental configuration has been schematically described in a previous study [19]. We attached a fuel surrogate to an Au cone with a 45° opening angle, 7-µm wall thickness, and 100-µm tip diameter. Further, we coated the outer surface of the Au cone with a 50-µm thick polyvinyl alcohol (PVA) layer to delay the cone breakup. We fabricated the fusion fuel surrogate using a 200-µm diameter solid ball of Cu (II) oleate $[Cu(C_{17}H_{33}COO)_2]$ [23], whose surface was coated with a 25-µm thick PVA layer to prevent the Cu atoms from being directly ionized by the compression-laser beams. The solid ball was irradiated by six of the GEKKO-XII laser beams arranged in a quasi-cylindrical geometry. Each laser beam had a wavelength of 0.526 µm, a Gaussian pulse shape, a 1.3-ns FWHM pulse duration, and an energy of 240 ± 15 J. The center of a 500-µm diameter nickel coil was located 230 µm from the center of the ball to apply a strong magnetic field near both the REB generation zone and the solid ball. The first disk of the laser-driven capacitor was irradiated through a hole in the second disk using three tightly focused GEKKO-XII laser beams, each with a 1.053 µm wavelength, Gaussian pulse shape, 1.3-ns FWHM pulse duration, and 600 ± 20 -J energy, yielding a peak intensity of 7×10^{15} W cm⁻². Four LFEX laser beams were focused on the tip of the cone to produce an REB; the wavelength, pulse shape, and FWHM pulse duration were $1.053 \,\mu\text{m}$, Gaussian, and $1.8 \pm 0.3 \,\text{ps}$, respectively. The time origin (t = 0 ns) is hereafter defined as the peak of the compression-laser pulse. The peak of the magnetic-fieldgeneration laser pulse was set at t = -1.5 ns; therefore, the magnetic field strength reaches its maximum value before irradiation by the compression beam. We injected the heating lasers (the four LFEX beams) around the time of maximum compression (t = 0.38 - 0.72 ns). We monitored the injection timings using an X-ray streak camera having an accuracy of ± 0.02 ns.

We positioned an X-ray spectrometer with a planar highly oriented pyrolytic graphite (HOPG) [Advanced Ceramic brand of HOPG Grade ZYB $12 \times 12 \times 2$ mm produced by Momentive Performance Materials company] located at 40° from the LFEX incident axis to measure the absolute Cu-K α yield. We measured the energy distribution of the laser-accelerated electrons using an energy analyzer containing a permanent magnet [24], which was placed on the axis of incidence.

The cross-sections for electron-impact K-shell ionization have a similar dependence on electron energy when compared with that on collisional energy loss. The two are essentially the same but with a different threshold energy. Therefore, the collisional deposition of REB energy (J) in a Cu-containing core can be obtained from the number of Cu-K α photons (photons/sr) emitted from the core using a correlation factor [20].

3. Results and Analysis

We observed a factor-of-two enhancement in the number of Cu-K α photons when an external magnetic field was applied [19]. This significant enhancement indicates that the REB was guided by the external magnetic field. In the integrated experiment, we observed 9×10^{11} /sr K α photons when we injected a laser having an energy of 630 J. The energy deposited into the core can be evaluated from Eq. (1) using the detected K α photons, denoting a coupling efficiency of 8%.

An example of the REB energy distribution at the time of maximum compression is depicted in Fig. 1 (a). We fitted the energy distribution of the escaping electrons exhibiting a two-temperature Boltzmann distribution function, $f(E) = A \exp(-E/T_{\text{REB1}}) + (1 - A) \exp(-E/T_{\text{REB2}})$, where A and E denote the intercept and electron energy, respectively, and $T_{\text{REB1}} < T_{\text{REB2}}$. The lower slope temperatures T_{REB1} are plotted as red circles in Fig. 1 (b). The black solid and blue dashed lines are Wilks's scaling [5] and Beg's scaling [6], respectively. The obtained results are larger than the conventional scalings, which are generally used to derive energy coupling.

We define the correlation factor C as the ratio between the stopping power and the K-shell ionization cross-section



Fig. 1 (a) An example of the REB energy distribution measured at the time of maximum compression. (b) The lower slope temperatures T_{REB1} for various laser intensities. The red circles and squares represent the compression times of t = 0.4 and 0.72 ns, respectively. The black solid and blue dotted lines are Wilks's scaling [5] and Beg's scaling [6], respectively. The red dotted line is the fitted line, which can be considered to be $I_{\text{laser}}^{2.3}$.

$$(C [J photons^{-1} sr]).$$

$$C = \frac{\int_{0}^{L} \int_{10 \, \text{keV}}^{1 \, \text{GeV}} \varepsilon_{\text{dep}}(E, x) dE dx}{\int_{0}^{L} \int_{10 \, \text{keV}}^{1 \, \text{GeV}} P_{K_{\alpha}}(E, x) dE dx}$$

=
$$\frac{\int_{0}^{L} \int_{10 \, \text{keV}}^{1 \, \text{GeV}} v(E, x) f(E, x) S(E, \rho) dE dx}{\int_{0}^{L} \int_{10 \, \text{keV}}^{1 \, \text{GeV}} v(E, x) f(E, x) n_{\text{Cu}} \sigma_{K_{\alpha}}(E) / 4\pi dE dx}.$$
(1)

Here, $\varepsilon_{dep}(E, x)$, $P_{K\alpha}(E, x)$, v(E, x), f(E, x), and n_{Cu} denote the energy deposited collisionally by the REB into the dense core [J s⁻¹], the probability of Cu-K α emission [photons $s^{-1} sr^{-1}$], the relativistic electron velocity [m s^{-1}], the REB energy distribution, and the number density of Cu atoms in the core $[m^{-3}]$, respectively, where E is the electron kinetic energy. The initial REB energy distribution at the generation zone (x = 0) is a Boltzmann function $f(E,0) = \exp(-E/T_{\text{REB}})$. We calculate the distribution f(E, x) at position x by considering the collisional deceleration during beam transport. The quantity $S(E, \rho)$ [J s⁻¹] is the stopping power obtained using the Solodov-Betti model [25]. We calculated the electron-impact K-shell ionization cross-section $\sigma_{K\alpha}(E)$ [m⁻²] using the Davies [26] and Hombourger [27] models. We describe our analyzed results in the following section.

4. Discussion

The dependence of the measured laser-to-core energy coupling on the intensity of the heating laser is depicted in Fig. 2. The red filled circles are the experimental data at the time of maximum compression (t = 0.72 ns). The vertical error corresponds to 16% spatial non-uniformity of the integral reflectance of the HOPG crystal; we achieved a maximum coupling of 8% when a magnetic field was applied. The coupling gradually degraded when the energy of the heating laser was increased while keeping both the pulse duration and the spot diameter unchanged (1.8 ps and 50 µm, respectively). A high laser intensity produces a



Fig. 2 Dependence of the laser-to-core energy coupling on the heating-laser intensity at the time of maximum compression. The red filled circle, blue triangle, and black filled diamond represent the experimental data, the simplified model, and the slowing-down model, respectively.

high-energy REB, leading to reduced energy deposition.

$$\eta = \eta_{\text{REB}} \cdot \eta_{\text{col}} \cdot \eta_{\text{dep}}.$$
(2)

The laser-to-core coupling η can be written as in Eq. (2), where η_{REB} , η_{coll} , and η_{dep} denote the laser-to-REB energy conversion efficiency, the REB collision probability, and the rate of REB energy deposition in the core, respectively.

$$\eta_{\rm dep} = \frac{AT_{\rm REB1}^2}{AT_{\rm REB1}^2 + (1 - A)T_{\rm REB2}^2} \cdot \frac{\rho L}{0.6T_{\rm REB1}} + \frac{(1 - A)T_{\rm REB2}^2}{AT_{\rm REB1}^2 + (1 - A)T_{\rm REB2}^2} \cdot \frac{\rho L}{0.6T_{\rm REB2}}.$$
 (3)

We assumed $\eta_{\text{REB}} = 0.4$ [28] and $\eta_{\text{coll}} = 1$, and we calculated η_{dep} from a simplified model [28] using the measured areal density at the time of maximum compression (t = 0.72 ns) and the REB slope temperatures [19].

We used the approximate relation R_{REB} [g/cm²] = 0.6 $f_{\text{R}} T_{\text{REB}}$ [MeV] from Eq. (11) in Ref. [29] to calculate R_{REB} from the experimentally measurable parameter T_{REB} . The quantity f_{R} is an adjustable parameter set to 1 in the standard model [31] plotted as a blue triangle in Fig. 2.

We also used the continuum slowing-down model to estimate the energy coupling. We calculated the energy deposited by an electron with a given initial energy in a finitesize core by integrating along a path through the core. We used the measured values for performing this analysis. This model does not consider the effects of Coulomb scattering or the gyro-motion of the REB. The calculated results are denoted in Fig. 2 as a black-filled diamond. Both the simplified models are in good agreement with the experimental results despite the complicated nature of the experiments. This indicates that our experimental conditions are close to the ideal case in which the REB is efficiently guided.

In addition, we used the continuum slowing-down model to investigate the energy coupling as a function of the REB slope temperature for high densities. The calculated results are depicted in Fig. 3. For these calculations, we assumed the DT core plasmas to have mass densities of 10 or 300 g/cm^3 but different areal densities. These results denote that a maximum energy coupling of 35% can be achieved by an ignition-scale core with a 1-MeV slope temperature. However, it is not easy to adapt our scheme to a fusion reactor because of the complicated target configuration. The usage of a self-generated magnetic field [30, 31] to guide an REB may become an alternative methodology to realize similar guiding conditions without the requirement of complicated target configurations.

5. Conclusions

We demonstrated an enhancement of laser-to-core energy coupling using magnetized isochoric heating and evaluated the dependence of the laser-to-core energy coupling on the laser intensity. A high laser intensity produces



Fig. 3 Energy coupling as a function of the REB slope temperature for two different mass densities and two different areal densities of a DT core plasma. The blue circles and red triangles denote our results for the same areal density but different mass densities.

a high-energy REB, leading to reduced energy deposition. The simple models denote a good agreement with the energy coupling obtained experimentally by the application of an external magnetic field. An energy coupling of 20% -35% can be achieved for an ignition-scale core with a moderate guiding field and heating laser intensity. A high laser energy is required for heating a high-density core. The laser pulse duration must be extended to sustain a highenergy coupling of greater than 20%. Recent theoretical and numerical investigations have denoted that a high slope temperature T_{REB2} results in the deposition of higher energy with increasing pulse duration when compared with that observed in case of short-pulse-duration (< 1 ps) laserplasma interaction [32, 33]. However, the low temperature T_{REB1} , which contributes dominantly to heating, does not change with the pulse duration. In addition, the contribution of the higher component T_{REB2} to heating is much less when compared with that of the lower component T_{REB1} . Therefore, the obtained scaling can be utilized in case of a reactor.

The investigation of the dependence of the REB energy distribution on the laser pulse duration is a key issue for realizing efficient energy deposition. An ignition-scale areal-density plasma can be achieved by pulse tailoring, as depicted in a previous study [34]. We intend to perform such investigations in the near future.

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