1. Introduction

In the fast ignition scheme of inertial confinement fusion, laser-accelerated particle beams (electron and/or ion beams) heat a pre-compressed fusion fuel up to the ignition temperature. More than 10% of the energy coupling efficiency of a heating laser to a compressed dense core plasma $\eta_{\text{laser} \rightarrow \text{core}}$ is essential so that fast ignition prevails against the conventional central ignition scheme. To demonstrate the efficient core heating, the Fast Ignition Realization Experiments project (FIREX project) is now being conducted using the Gekko XII (GXII) + LFEX laser system at the Institute of Laser Engineering, Osaka University [1]. The integrated simulations [2] and experimental data [3] showed a very low heating efficiency ($\eta_{\text{laser} \rightarrow \text{core}} < 1\%$). There are two crucial issues preventing efficient heating: the fast electron temperature is too hot, and the beam divergence is too large. By improving the contrast ratio of the heating laser pulse, we have eliminated the plasma formation inside the guiding cone before the main part of the heating pulse comes, and successfully reduced the energy (or temperature) of fast electrons by keeping the energy convergence from the laser to the relativistic electron beam (REB) as constant [4].

As for the beam divergence, instead of the control of laser-plasma interactions to suppress the angular spread of the fast electron distribution function, some guiding ideas for a fast-electron beam with large beam divergence have been proposed, e.g. guiding schemes using self-generated magnetic fields (resistive guiding [5–11] and vacuum gap guiding [2, 12, 13]) and using externally-applied magnetic fields [14–18]. In the present paper, the latter scheme is discussed.

The required magnetic field strength for REB guiding has been evaluated as a function of irradiating laser intensity by integrated simulation of magnetic-field-assist fast ignition laser fusion

T Johzaki¹, H Nagatomo², A Sunahara³, Y Sentoku²,⁴, H Sakagami⁵, M Hata², T Taguchi⁶, K Mima², Y Kai¹, D Ajimi¹, T Isoda¹, T Endo¹, A Yogo², Y Arikawa⁷, S Fujioka⁷, H Shiraga⁷ and H Azechi⁷

¹ Department of Mechanical Systems Engineering, Hiroshima University, Higashi-Hiroshima 739-8527, Japan
² Institute of Laser Engineering, Osaka University, Suita 565-0871, Japan
³ Institute for Laser Technology, Suita 565-0871, Japan
⁴ Department of Physics University of Nevada Reno, Reno, NV 89557, USA
⁵ National Institute for Fusion Science, Toki 509-5292, Japan
⁶ Department of Electrical and Electronics Engineering, Setsunan University, Neyagawa 572-8508, Japan
⁷ The Graduate School for the Creation of New Photonics Industries, Hamamatsu 431-1202, Japan

E-mail: tjohzaki@hiroshima-u.ac.jp

Received 30 June 2016, revised 18 August 2016
Accepted for publication 6 September 2016
Published 16 November 2016

Abstract

To enhance the core heating efficiency in fast ignition laser fusion, the concept of relativistic electron beam guiding by external magnetic fields was evaluated by integrated simulations for FIREX class targets. For the cone-attached shell target case, the core heating performance deteriorates by applying magnetic fields since the core is considerably deformed and most of the fast electrons are reflected due to the magnetic mirror formed through the implosion. On the other hand, in the case of a cone-attached solid ball target, the implosion is more stable under the kilo-tesla-class magnetic field. In addition, feasible magnetic field configuration is formed through the implosion. As a result, the core heating efficiency doubles by magnetic guiding. The dependence of core heating properties on the heating pulse shot timing was also investigated for the solid ball target.

Keywords: fast ignition, magnetic field, core heating, fast electron, integrated simulation

(Some figures may appear in colour only in the online journal)
2-dimensional (2D) collisionless particle-in-cell (PIC) simulations [17]. It was shown that the kilo-tesla-class magnetic field is needed for FIREX class experiments where the heating pulse intensity is of the order of $10^{19}$ W cm$^{-2}$. The generation of a kilo-tesla magnetic field and electron beam guiding by applying an external magnetic field have been experimentally demonstrated using a laser-driven capacitor-coil scheme [3,19,20]. Not only the strength of the magnetic field but also the field configuration is important. The externally applied magnetic field will be compressed by fuel implosion except for the region inside the guiding cone, which results in the formation of a mirror field configuration. Under the mirror field configuration, we will expect the beam to focus while at the same time being concerned about the mirror reflection. The effects of mirror configuration were also discussed on the basis of the 2D PIC simulations [18], which showed the sufficient guiding performance in collisional dense plasma by kilo-tesla-class external magnetic fields for the case with a moderate mirror ratio ($\leq 10$). These numerical and experimental investigations showed the potential of beam guiding by external magnetic fields. For further study, we conducted integrated simulations for magnetic-field-assist fast ignition laser fusion. In the following, we discuss the core heating properties for the dense core with the converging magnetic field configuration appearing in the implosion of cone-attached targets at FIREX class experiments.

2. Simulation model

In the integrated simulations, first, we carried out the implosion simulations to evaluate the imploled core and magnetic field profiles around the maximum compression, where a radiation-hydro code PINOCO [21] was used. PINOCO is a single-fluid two-temperature hydrodynamics code written in 2D spherical geometry ($r-\theta$) and includes the energy transports due to radiation (flux-limited multi-group diffusion model), thermal conduction (flux-limited spritzer-Harms model), and laser pulse (ray-trace model). To consider the magnetic field effects, it has been extended to be a resistive magnetohydrodynamic one [22]. We set the implosion parameters by assuming the GXII laser system conditions at ILE Osaka University, i.e. we assumed the laser energy of 1.5 kJ, the wavelength of 0.53 $\mu$m, Gaussian pulse with 1.3 ns FWHM and peak timing of $t = 1.5$ ns.

The following core heating simulations were carried out by using FIBMET [23], which is a hybrid-type code written in cylindrical geometry ($r-z$). The bulk plasma is treated by a fluid model and the transport of fast particles (such as an REB) is treated by a particle scheme. The resistive field model is adopted. The collision between the fast particles and the bulk plasma is treated by the Fokker–Planck collision model. In the core heating simulations, we used the imploled core and magnetic field profiles obtained from the implosion simulations. The REB was injected at the tip of the cone by assuming the experimentally observed profiles [4], where the energy spectrum $f(E) \propto 0.95\exp(-E/0.9) + 0.05\exp(-E/5)$ ($E$ is electron energy in MeV). The beam divergence is assumed as 45 degree half angle. For the temporal and spatial profiles, we assumed the Gaussian with 1 ps duration (FWHM) and the super Gaussian with 20 $\mu$m radius (HWHM), respectively. The REB peak intensity and the injected energy are $1.55 \times 10^{19}$ W cm$^{-2}$ and 410 J, respectively.

3. Simulation results

3.1. Spherical shell target

The initial profile of a fuel target is shown in figure 1(a). The deuterated polystyrene (CD) shell radius and thickness are 250 $\mu$m and 8 $\mu$m. For this shell a gold cone with an open angle of 45 degree (full angle) is attached. The cone tip with 7 $\mu$m thick and 40 $\mu$m diameter is located at 50 $\mu$m away from the shell center. The external magnetic field $B_{2,ext} = 200$ T is uniformly applied in the $z$-direction. Figure 1(b) shows the imploled core profile (upper) and magnetic field configuration (lower) at $t = 1.87$ ns. At this moment, the fuel does not yet reach the maximum compression. Due to the suppression of thermal flow perpendicular to the magnetic field lines, the pressure imbalance is imposed, which induces the hydrodynamic instability. As a result, the equator part of the shell, which is the region perpendicular to the $z$-axis in figure 1, falls into the shell center faster than the other region and collapses at the center. Thus, the strongly deformed core is formed [22]. This asymmetric implosion leads to the strongly deformed magnetic field configuration around the core center. In addition, the jet-like plasma flow generated due to the shell collapse pushes the magnetic field on the cone tip, and forms the magnetic field wall on the cone tip, where the magnetic field strength reaches ~20 kT, which is about 100 times higher than the initial value. On the other hand, the magnetic field strength inside the cone where the fast electrons are generated is kept as the initial value since the plasma does not move. Such a magnetic field configuration is not feasible to the fast electron beam guiding.

To evaluate the effects of the external magnetic field on the core heating process, we carried out the REB transport simulations using the core plasma and magnetic field profiles. The REB was injected at the tip of the cone with the profiles noted in section 2. Figure 2 shows the spatial profiles of the fast electron energy density at $t_{\text{tran}} = 3$ ps, where $t_{\text{tran}}$ is time in the transport simulation and $t_{\text{tran}} = 0$ is the start of the transport simulation. If the external magnetic field is neglected in the transport simulation (figure 2(a)), the fast electrons flow forward and spread throughout the simulation region. Because of the small core size and of the large beam divergence, the heating efficiency is small; the core heating efficiency, that is the ratio of the REB energy deposited in the dense core region ($\rho > 5$ g cm$^{-3}$) to the injected REB energy, is $\eta_{\text{REB-core}} = 1.9\%$. In the case of the simulation with the external magnetic field, since the magnetic field strength around the REB injected region (the cone tip), $B_{2,\text{ inj}} = 0.2$ kT, is too small to trap MeV electrons, we artificially intensified the magnetic field strength; the magnetic field strength was...
multiplied tenfold in the whole region to make $B_z = 2 \text{kT}$. The result of the simulation showed, as was predicted, that most of the fast electrons cannot overcome the magnetic field wall ahead of the cone tip and are reflected. As a result, the heating efficiency becomes much lower than that for the case without the external field, $\eta_{\text{REB-core}} = 0.0015\%$.

The above simulation results showed that in the shell implosion case, the application of an external field not only disturbs the high density core formation but also prevents the efficient core heating. To apply the magnetic field to the shell target, the applied magnetic field structure and applied timing
should be optimized. Otherwise, the external field negatively affects the implosion and core heating profiles.

3.2. Spherical solid target

A shell target is used in the conventional central spark ignition scheme to form the central hot spot and surrounding cold dense main fuel structure through the implosion. In the fast ignition scheme, since the implosion is needed only to form a high-density fuel core, but not to generate a hot spot for the initiation of fusion burning, an alternative implosion scheme is applicable. To generate the high-density core more stably than a shell implosion, we have proposed the use of a spherical solid target [3] where a fuel target is compressed to high density by a spherically-converging shock. The formation of a dense core using a simple solid ball target [3] and a solid target with a gold cone [24] has been experimentally demonstrated. In this section, we evaluate the implosion and core heating properties for a solid ball target with external magnetic fields.

3.2.1. Implosion simulations. The initial target configuration is shown in figure 3. The target is a spherical CD solid ball with 100 µm radius. A gold cone is embedded in the CD target to reduce the distance between the cone tip and the target center and also to prevent the cone tip from breaking due to the attack of converging shock. To protect the

![Figure 5](image)

**Figure 5.** Magnetic field line profiles at the maximum compression for $B_{z, \text{ext}} = 0, 0.5, 1.0, 2.0 \text{ kT}$. The line color shows the magnetic field strength (T).

![Figure 6](image)

**Figure 6.** Spatial profiles of fast electron energy density (erg cm$^{-3}$) at the peak intensity of REB ($t_{\text{tran}} = 3 \text{ ps}$) for $B_{z, \text{ext}} = 0, 0.5, 1.0, 2.0 \text{ kT}$.

![Figure 7](image)

**Figure 7.** Energy deposited by REB in the dense core region ($\rho > 5 \text{ g cm}^{-3}$) $E_{\text{dep}}$ as a function of $B_{z, \text{ext}}$. The right axis shows the energy coupling efficiency of the heating laser to the dense core by using the experimentally measured energy conversion efficiency of the heating laser to the REB, 31% [3].
cone wall against the ablated plasma, the radiation from the coronal plasma and the reflected laser light, the surface of the cone wall is coated by the CD layer with a thickness of 20 μm. For this target, the external magnetic field is uniformly applied in the z-direction with the strength of \( B_{z,\text{ext}} = 0 \) to 2 kT. The imploded core profiles at the maximum compression are shown for \( B_{z,\text{ext}} = 0 \), 0.5 1.0, 2.0 kT in figure 4. Here, the maximum compression is defined as the timing when the integral of mass density \( \rho \) for the fuel region along the z-axis at \( r = 0 \), \( \int_{\text{CD}} \rho(r = 0, z)dz \), becomes maximum. Compared with the shell target case, the effect of the external field is small for the solid target case. As is the case with a shell implosion, however, since the ablation pressure becomes higher for the equator region by increasing the external field strength, the incoming shock is stronger for the equator region. As a result, with an increase in \( B_{z,\text{ext}} \), the timing of maximum compression \( t_{\text{max}} \) becomes earlier (\( t_{\text{max}} = 1.88 \) ns for \( B_{z,\text{ext}} = 0 \) to \( t_{\text{max}} = 1.64 \) ns for \( B_{z,\text{ext}} = 2 \) kT), the maximum density \( \rho_{\text{max}} \) becomes larger (\( \rho_{\text{max}} = 34 \) g cm\(^{-3} \) for \( B_{z,\text{ext}} = 0 \) to \( \rho_{\text{max}} = 61 \) g cm\(^{-3} \) for \( B_{z,\text{ext}} = 2 \) kT), and the core shape becomes more elongated. The magnetic field line structures at the same timing as that in figure 4 are shown in figure 5. Compared with the shell implosion case, the magnetic field lines are much smoother and the mirror ratio (the ratio of magnetic field strength between the cone tip region and the dense core region) is smaller. The mirror ratio is 2.4, 2.9 and 3.8 for \( B_{z,\text{ext}} = 0.5 \), 1.0 and 2.0 kT, respectively. Compared to the density compression ratio, the compression of the magnetic field is small for all cases. As was discussed in [3], this is due to the small magnetic Reynolds number (close to unity), and then the compression of the magnetic field is not efficient compared with the ideal magnetohydrodynamics case. The smooth magnetic field line profile and the moderate mirror ratio obtained for the solid ball target are adequate for the REB guiding.

3.2.2. Core heating properties. Using the profiles of the imploded core and magnetic field at the maximum compression obtained from implosion simulations, we carried out the REB transport simulations to evaluate the guiding effects for the solid target case. The injected REB condition was discussed in section 2. Figure 6 shows the spatial profiles of fast electron energy density at the peak intensity of REB (\( t_{\text{max}} = 3 \) ps). In the case without an external field, the REB spatially diverges with its propagation due to the large angular spread. Around the central axis, there is a region where the beam energy density becomes low. This is due to the scattering of fast electrons by the magnetic field generated around the core by the Biermann battery effect. Due to the REB heating, the direction of the bulk electron temperature gradient \( \nabla T_e \) becomes non-parallel to that of the bulk electron density gradient \( \nabla n_e \) around the dense core edge [23], which causes the Biermann battery fields in the direction to scatter the fast electrons. For the case of \( B_{z,\text{ext}} = 0.5 \) kT, the guiding effect can be observed. The guiding by the external fields weakens the scattering effect due to the Biermann battery field. However, the magnetic field strength at the REB injection region (\( B_{z,\text{ext}} = 0.5 \) kT) is not strong enough to trap the MeV-class fast electrons. Besides, the core shape is elongated by the external field. Hence the pronounced enhancement of the core heating efficiency by applying an external field is not observed. For the case of \( B_{z,\text{ext}} = 1.0 \) kT, the guiding effect by an external field overcomes the scattering effect by the Biermann battery field. Although the fast electrons in the beam edge region (large r region) are not guided to the core, more fast electrons are guided to the core compared to the case of \( B_{z,\text{ext}} = 0.5 \) kT, and then the heating efficiency becomes clearly higher than that for the case without an external field. For the further higher \( B_{z,\text{ext}} \) case, the guiding becomes more remarkable.

In figure 7, the energy deposited by the REB in the dense core (\( \rho > 5 \) g cm\(^{-3} \)) \( E_{\text{dep}} \) is plotted as a function of \( B_{z,\text{ext}} \). The right axis shows \( \eta_{\text{Laser--Core}} \) which is the energy coupling efficiency from the heating laser to the dense core by using the experimentally measured energy conversion efficiency of a heating laser to the REB. \( \eta_{\text{Laser--REB}} = 31\% \) [25]. As was noted above, in the case of a solid ball CD target, we can enhance the heating efficiency by applying the longitudinal external field. To obtain clear enhancement, a kilo-tesla-class field is required, e.g. the application of a 1.5 kT external field doubles

![Figure 8](image_url)
the heating efficiency roughly (from $\eta_{\text{laser-core}} = 2.3\%$ for $B_{\text{ext}} = 0$ kT to $\eta_{\text{laser-core}} = 4.3\%$ for $B_{\text{ext}} = 1.5$ kT). This requirement for an external field is consistent with the evaluation of guiding performance by 2D PIC simulations [17, 18].

The neutron yields from D(d,3He)n reactions $Y_{\text{nDD}}$ and the neutron-averaged ion temperature $T_{i \text{nDD}}$ obtained from the core heating simulations are plotted as a function of $B_{\text{z,ext}}$ in figure 8. The definition of $T_{i \text{nDD}}$ is

$$T_{i \text{nDD}} = \frac{\int \int T_i(r, z, t)R_{\text{sDD}}(r, z, t) dV dt}{\int \int R_{\text{sDD}}(r, z, t) dV dt},$$

where $R_{\text{sDD}}(r, z, t)$ is the D(d,3He)n fusion reaction rate. The values for the case without REB heating are indicated by dot-and-dash lines. For the case without REB heating, $Y_{\text{nDD}}$ is less than $10^5$ and $T_{i \text{nDD}}$ is less than 0.4 keV. When the REB is injected, both values increase; but, for the case without an external field case, the enhancements are very low. By increasing the applied field strength, the enhancements become remarkable. When the applied magnetic field strength is $B_{\text{z,ext}} = 2$ kT, $Y_{\text{nDD}} \sim 10^7$ and $(T_{i \text{nDD}} = 1.1$ keV are obtained; $Y_{\text{nDD}}$ is enhanced by more than 2 orders of magnitude and enhancement of $(T_{i \text{nDD}})$ is about 0.7 keV.

3.2.3. Heating pulse shot timing. In the fast ignition scheme, the heating pulse shot timing is important to heat the fuel and initiate the fusion burning. Unfortunately, the energy of implosion and heating lasers used at the FIREX-class experiments is not large enough to initiate the fusion burning. In such a case, the margin of the heating shot timing may be limited by the lifetime of the dense core. In a practical case, there is uncertainty in the control of shot timing. So the sensitivity evaluation is important for practical purposes. Also, it is interesting how the shot timing affects the hydrodynamics of the core. So we carried out the REB transport simulations by changing the REB injection timing. Figure 9 shows the
temporal evolution of the imploded core for $B_z = 1.0 \, kT$. In figure 9(a), $\rho_{Rz,\text{max}}$ and $\rho_{Rr,\text{max}}$ are defined as

$$
\rho_{Rz,\text{max}} = \max [\rho(r,z)] = \frac{1}{2} \max \left[ \int_{\text{CD}} \rho(r,z) \, dz \right],
$$

$$
\rho_{Rr,\text{max}} = \max [\rho(r,z)] = \max \left[ \int_{\text{CD}} \rho(r,z) \, dr \right],
$$

where $\int_{\text{CD}} \rho(r,z) \, dz$ and $\int_{\text{CD}} \rho(r,z) \, dr$ mean the integral over the CD plasma region. The maximum compression is achieved at $t = 1.68 \, ns$. Before this timing, the incoming shock does not reach the center. After the maximum compression ($t = 1.73 \, ns$), the fuel disassembly has already started.

The REB transport simulations were carried out for the timing from $t = 1.43 \, ns$ (250 ps before the maximum compression) to $t = 1.73 \, ns$ (50 ps after the maximum compression), every 50 ps. The core heating energy $E_{\text{dep}}$, neutron yields $Y_{\text{add}}$ and averaged ion temperature $T_{\text{i,add}}$ are plotted as a function of shot timing $t_{\text{shot}}$ in figure 10. The core heating energy $E_{\text{dep}}$ becomes maximum when the REB is injected at 50 ps before the maximum compression ($t_{\text{shot}} = 1.63 \, ns$) since the size of the core in the radial direction is larger at $t = 1.63 \, ns$ than at $t = 1.68 \, ns$ in spite of the small differences in $\rho_{Rz,\text{max}}$ and $\rho_{Rr,\text{max}}$. Though the coupling efficiency is not so sensitive to the shot timing (e.g. the shot timing window for $\eta_{\text{laser-core}} > 3\%$ is about 200 ps, $t = 1.53 \, ns$–$1.73 \, ns$), the heating pulse should be shot around the maximum compression to maximize the core heating energy. On the other hand, the REB injection earlier than the maximum compression results in the higher $Y_{\text{add}}$ and $T_{\text{i,add}}$ compared to those obtained at the REB injection at the maximum compression. This is due to the intensification of incoming shock by the REB heating. The pressure profiles before (upper) and after (lower) the REB heating are shown in figure 11. Figure 12 shows the temporal evolution of the spatial profiles of ion temperature and fusion reaction rate. Due to the REB injection, the low density plasma in front of the incoming shock, where the density is kept as the initial value (solid density), is pre-heated. The REB heating of high dense plasma behind the shock is much higher than that in front of the shock, which intensifies the incoming shock. Thus, after the REB heating, the intensified incoming shock collapses at the central axis, which hydro-dynamically heats the pre-heated low-density plasma. This shock collapse heating leads to a neutron flash from the locally-heated region. In such a case, most of the neutrons come from this locally-heated central region, and then the neutron-weighted average ion temperature is dominated by the temperature around there. This effect can be expected when the REB (or other heating pulse) is injected before the maximum compression. This heating scheme is the combination of direct REB heating and shock-collapse heating. Usually, the REB heats the bulk electron, and the bulk ion is heated by the collisional relaxation process. This relaxation time is not so small for the FIREX-class relatively low density plasma. Before the sufficient
relaxation is achieved, the fuel disassembly will start, which results in insufficient ion heating. However, the present shock collapse heating does not require the temperature relaxation. The shock intensification is caused by an increase in the pressure of the bulk electron heated by the REB, and the ion is hydrodynamically heated due to the collapse of the intensified incoming shock. So a high heating efficiency for bulk ion can be expected in this scheme.

4. Conclusion

To enhance the core heating efficiency in REB driven fast ignition laser fusion, we have proposed the application of an external longitudinal magnetic field for REB guiding to the dense core. On the basis of integrated simulations, we evaluated the effects of the application of an external field on implosion and core heating processes for a cone-attached spherical CD shell and solid ball targets in FIREX-class experiments.

In the case of a shell target, it is found that the inhibition of thermal flow perpendicular to the magnetic field lines results in significant deformation of a fuel core. In addition, the magnetic wall is formed ahead of the cone tip, which reflects almost all the fast electrons. As a result, the application of a magnetic field negatively affects the implosion dynamics and core heating properties.

On the other hand, for the solid ball target case, the implosion is more stable though the deformation due to the application of a magnetic field occurs to a certain extent (i.e. the core shape is elongated). In addition, the magnetic field configuration feasible for REB guiding is formed through the implosion such that the magnetic field lines are so smooth and the mirror ratio is moderate ($R_m \sim 3$). The core heating simulations showed that the application of a kilo-tesla-class magnetic field enhances the core heating efficiency, and the kilo-tesla-class field is required to obtain the clear enhancement. Also, we evaluated the dependence of core heating properties on the heating pulse shot timing. In FIREX-class experiments, the heating pulse should be shot around the maximum compression to obtain the high coupling efficiency and the shot timing window is about 200ps. The earlier shot timing than the maximum compression leads to a higher neutron yield and neutron-average ion temperature since the incoming shock is intensified by REB heating.

The experimental demonstration will be carried out in the near future experiments at GekkoXII+LFEX laser systems, ILE Osaka University. The ignition and high gain design using a solid ball target with an external field is of intrinsic importance to drive the fast ignition research, and now we are engaged in the ignition design on the basis of integrated simulation.

Acknowledgments

This work is partially conducted under the joint research projects of the ILE, Osaka University (FIREX-project), and with the support of the NIFS Collaboration Research program (NIFS12KUGK057, NIFS15KUGK087, NIFS15KUGK093, NIFS15KUGK094, NIFS14KNS0504) and JSPS KAKENHI (25400539, 25400534, 26400532, 15H03758, 16H02245, 16K05638, 15K17798). We are grateful for the support of the computer room of ILE and the cybermedia center, Osaka University.

References

[1] Azechi H and the FIREX Project 2006 Plasma Phys. Control. Fusion 48 B267
[2] Johzaki T, Nagatomo H, Sunahara A, Cai H-B, Sakagami H, Nakao Y and Mima K 2011 Nucl. Fusion 51 073022
[3] Fujikawa S et al 2015 Phys. Rev. E 91 063102
[4] Fujikawa S et al 2016 Phys. Plasmas 23 056308
[5] Robinson A P L and Sherlock M 2007 Phys. Plasmas 14 083105
[6] Robinson A P L, Sherlock M and Norreys P A 2008 Phys. Rev. Lett. 100 025002
[7] Johzaki T, Nagatomo H, Nakamura T, Sakagami H, Mima K and Kodama R 2008 J. Phys.: Conf. Ser. 112 042048
[8] Robinson A P L, Key M H and Tabak M 2012 Phys. Rev. Lett. 108 125004
[9] Robinson A P L and Schmitz H 2013 Phys. Plasmas 20 062704
[10] Johzaki T, Sunahara A, Fujioka S, Nagatomo H, Sakagami H and Mima K 2013 EPJ Web Conf. 59 03010
[11] Johzaki T, Sunahara A, Nagatomo H, Sakagami H, Fujioka S, Shiraga H and Mima K 2013 J. Plasma Fusion Res. 59 456
[12] Nakamura T, Mima K, Sakagami H and Johzaki T 2007 Phys. Plasmas 14 103105
[13] Cai H-B, Mima K, Zou W-M, Johzaki T, Nagatomo H, Sunahara A and Mason R J 2009 Phys. Rev. Lett. 102 245001
[14] Tabak M, Shay H, Strozzi D J, Divol L, Grote D P, Larson D, Nuckolls J and Zimmerman G 2010 52nd Annual Meeting of the APS Division of Plasma Physics (Chicago, Illinois, 8–12 November 2010) vol 55 (Bulletin of the American Physical Society) p 182
[15] Strozzi D J, Tabak M, Larson D J, Divol L, Kemp A J, Bellei C, Marinak M M and Key M H 2012 Phys. Plasmas 19 072711
[16] Robinson A P L, Strozzi D J, Davies J R, Gremillet L, Honrubia J J, Johzaki T, Kington R J, Sherlock M and Solodov A A 2014 Nucl. Fusion 54 054003
[17] Johzaki T, Mima K, Fujioka S, Sunahara A, Nagatomo H and Shiraga H 2016 J. Phys.: Conf. Ser. 688 012041
[18] Johzaki T, Taguchi Y, Sentoku Y, Sunahara A, Nagatomo H, Sakagami H, Mima K, Fujioka S and Shiraga H 2015 Nucl. Fusion 55 053022
[19] Fujioka S et al 2013 Sci. Rep. 3 1170
[20] Santos J J et al 2015 New J. Phys. 17 083051
[21] Nagatomo H, Johzaki T, Nakamura T, Sakagami H, Sunahara A and Mima K 2007 Phys. Plasmas 14 056303
[22] Nagatomo H, Johzaki T, Asahina T, Sunahara A, Sano T, Sakagami H, Mima K, Fujioka S, Shiraga H and Azechi H 2015 Nucl. Fusion 55 093028
[23] Johzaki T, Nakao Y and Mima K 2009 Phys. Plasmas 16 062706
[24] Sawada T et al 2016 Appl. Phys. Lett. 108 254101
[25] Arikawa Y et al 2015 Optimization of Hot Electron Spectra by Using Plasma Mirror for Fast Ignition, presented at IFSA2015 (9th Int. Conf. on Inertial Fusion Sciences and Applications, Seattle, WS 2015)