

Control of burning wave propagation by strong magnetic fields toward end-on fast ignition

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Magnetized fusion has been used in various inertial confinement fusion concepts to relax ignition requirements. Strong magnetic fields would induce burning asymmetry, which may be usually harmful to the central ignition schemes. However, it could be utilized in some intrinsically asymmetric ignition schemes, such as the traditional fast ignition (FI) scheme and the double-cone ignition (DCI) scheme, in which the hot spots are located at the edge of the compressed fuel. In this paper, an analytical model and a three-dimensional MHD code are developed to study the asymmetric burning propagation and related effects in magnetic fields. It is found that the magnetic field can guide a directional and faster burning propagation along the parallel direction to the B-field by the anisotropic α -particle transport, providing a method to control the burning behavior. The B-field also leads to a faster increase in the hot spot temperature. Simulation shows that 10 kT B-fields, corresponding to the α -particle Hall parameter of $H_\alpha \sim 0.5$, would increase the hot spot temperature by 38% and the burning propagation speed by 44% in FI and DCI conditions, leading to an 87% increase of the fusion output energy and an 18% increase of hot spot mass. This study could also provide a direct reference for assessing the burning asymmetry in the magnetized ICF schemes.

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I. INTRODUCTION

The historical breakthrough of ignition [1–5] at the National Ignition Facility has inaugurated a new era toward commercial fusion energy of inertial confinement fusion (ICF). However, the intrinsically low heating efficiency and hydrodynamic instability at the inner interface of the pellet have been the obstacles to high gain operations. These have inspired the community to explore new ignition concepts with higher gain, such as fast ignition (FI) [6–9], magnetized central ignition [10–13], and double-cone ignition (DCI) [14–16]. Increasing attention has been drawn to the effects of magnetic fields in these new concepts. In FI, the magnetic field is usually used to collimate the relativistic electron beam (REB) to decrease the divergence angle and raise the energy deposition efficiency of the REB [17–19]. In magnetized laser fusion, the magnetic field can be used to relax the ignition conditions [11,20] and to mitigate mixing at the gas-ice interface [21,22].

Despite the considerable research on the role of magnetic fields in ICF, further studies would be required to clarify the

magnetic effects on the burning propagation. In isochoric fast ignition, the studies on the role of magnetic fields are usually limited to guiding the REB. Minimal research focuses on the effects of magnetic fields on the transport or deposition of α -particles, which are the dominant driver of the burning wave, but require a much stronger magnetic field to be affected due to their large mass. On the other hand, the current magnetized laser fusion studies use the central ignition scheme, in which the magnetic field introduces new asymmetry and degrades the spherical symmetry [23,24]. The magnetic effect on the burning asymmetry has not been fully discussed either. Moreover, current studies have often been limited to qualitative comparisons between the α -gyro radius and the hot spot size [11], relying solely on numerical simulations [25]. Therefore, it would be difficult to discuss the role of magnetic fields in a simple and quantitative manner.

The experimental achievement of 10 kT-level magnetic fields [13] has now made it feasible to utilize strong magnetic fields to influence α -transport or even control the burning propagation. Such control by magnetically induced burning asymmetry can be particularly advantageous in some intrinsically asymmetric ignition schemes, such as the traditional fast ignition (FI) scheme and the double-cone ignition (DCI) scheme. In these schemes, the hot spots are formed at the edge of the compressed isochoric fuel due to the external heating source, leading to additional energy loss and stricter ignition conditions [26]. More importantly, there is a geometric mismatch between the isotropic α -transport and the fuel

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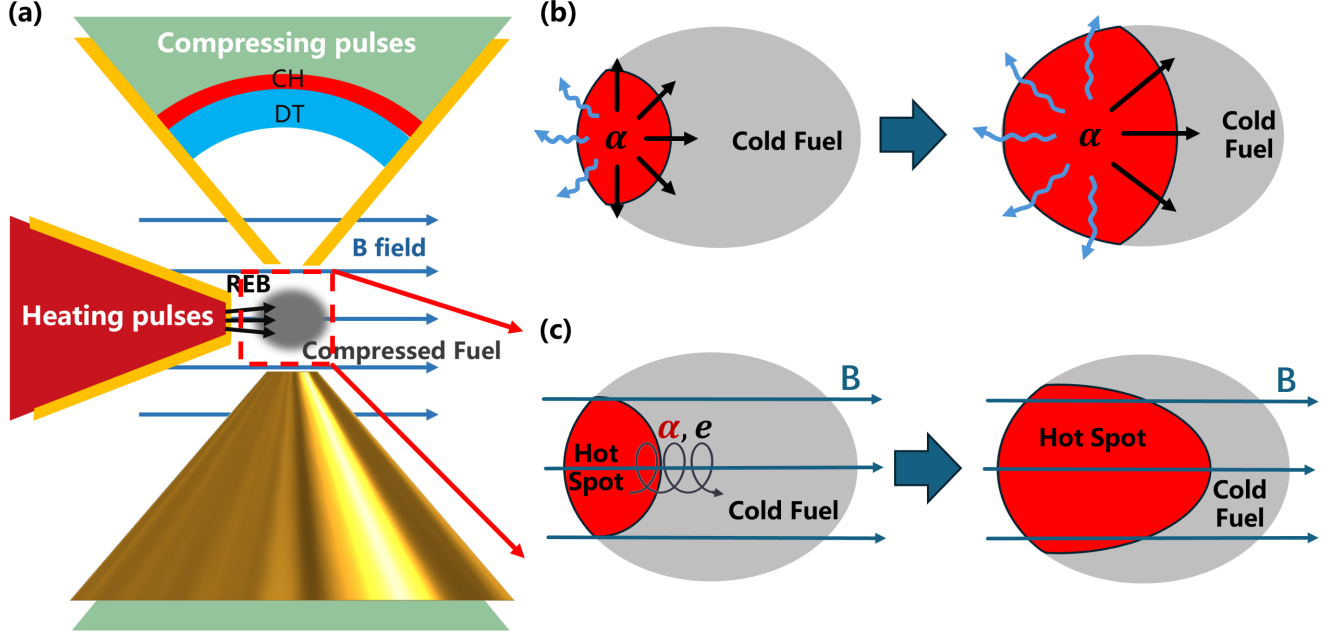


FIG. 1. (a) Schematic of DCI scheme with strong magnetic fields. The hot spot is formed at the edge of the compressed fuel. (b) The intrinsic geometric mismatch between the isotropic α -transport and the fuel configuration. (c) With strong magnetic field, the α -particles and electrons spiral along the magnetic line, driving a directional burning propagation to the other side.

configuration, as shown in Fig. 1. The mismatch results in a large number of α -particles escaping into the vacuum and being wasted during the burning propagation, rather than heating the cold fuel. Such defects must be overcome by directional burning propagation to achieve high fusion gain, where the magnetic control can play a vital role.

In this paper, an analytical model and a magnetohydrodynamic (MHD) code, O-SUKI-NM, are developed to investigate the asymmetric burning propagation in magnetic fields. The possibility of using magnetic fields to control the burning propagation is then investigated for the schemes such as FI and DCI.

The paper is organized as follows: In Sec. II, we present the analytical model and the numerical model of O-SUKI-NM. In Sec. III, we discuss the results of the analytical model and compare them with the simulation results. In Sec. IV, we demonstrate the advantages of using a magnetic field to control the burning propagation in the FI and DCI. In Sec. V, a conclusion is given.

II. MODELS OF ASYMMETRIC BURNING PROPAGATION IN MAGNETIC FIELDS

A. Analytical model

For simplicity, we consider a preassembled model consisting of a central spherical hot spot and infinite fuel in a uniform magnetic field, as shown in Fig. 2(a). The angle between the magnetic field and the burning propagation direction is θ . The model is developed based on two assumptions: (1) The burning propagation is driven by the outward energy flux from the hot spot into the cold fuel (hereafter referred to as the outward energy flux). (2) The magnitude of the burning propagation speed should be proportional to the outward energy flux. A simple proof of the second assumption is as follows:

Consider a spherical hot spot with radius R , and the burning wave propagates from R to $R + dR$. The burning propagation is to heat the layer of the dR fuel to the fusion temperature. Assuming the power of energy transport from the hot spot to the cold fuel is P , the specific heat capacity of the cold fuel is C_V , the density of the cold fuel is ρ , and the temperature difference between the cold fuel and the fusion temperature is ΔT . Then, we have

$$P \cdot dt = C_V \cdot \rho \cdot 4\pi R^2 dR \cdot \Delta T, \quad (1)$$

$$v_{\text{burn}} = \frac{dR}{dt} = \frac{P}{4\pi R^2 C_V \rho \Delta T} = F_E \frac{1}{C_V \rho \Delta T}, \quad (2)$$

where F_E is the magnitude of the outward energy flux, so we have $v_{\text{burn}} \propto F_E$.

The outward energy flux consists of three parts: the α -transport F_α , the electron thermal conduction F_e , and the ion thermal conduction F_i . For hot spot conditions that can start the burning propagation, we usually have $F_\alpha \gg F_e$, $F_\alpha \gg F_i$ [27]. Therefore, we only consider F_α in our model. This assumption is also verified by simulation results in Sec. III B.

Based on the two assumptions, the asymmetric burning propagation is determined by the asymmetry of F_α . The calculation of F_α can be divided into two parts: the magnitude of the total outward energy flux and the angular distribution. Both are affected by the magnetic field.

We first derive the total outward energy flux. In a strong magnetic field $\mathbf{B}$, the transverse α transport would be suppressed. Consequently, the fraction of the α -particle energy deposited inside the hot spot should increase, thereby reducing the total outward energy flux. Gus'kov [28] derived the fraction of α -deposition inside a spherical homogeneous

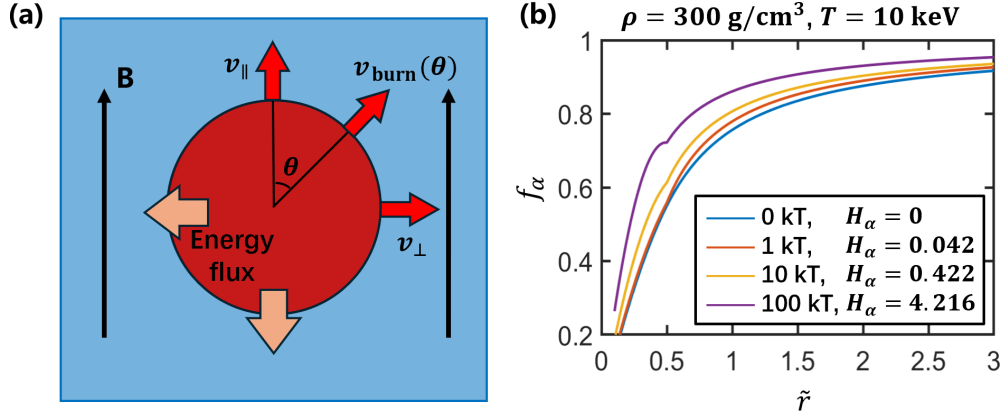


FIG. 2. (a) Schematics of asymmetric burning propagation driven by energy flux in magnetic fields. (b) The energy deposition fraction of α -particles f_α in the hot spot in strong magnetic fields. Here, $\tilde{r} = R_h/l_\alpha$ denotes radius of the hot spot relative to the α -particle range.

hot spot:

$$f_\alpha(H_\alpha, \tilde{r}) = \begin{cases} \left[\frac{3}{2} + \frac{71}{40} \left(\frac{H_\alpha}{H_\alpha+1} \right) \right] \tilde{r} - \left[\frac{4}{5} + \frac{27}{10} \left(\frac{H_\alpha}{H_\alpha+1} \right) \right] \tilde{r}^2, & \tilde{r} \leq 0.5 \\ 1 - \left[\frac{9}{40} - \frac{17}{160} \left(\frac{H_\alpha}{H_\alpha+1} \right) \right] \frac{1}{\tilde{r}}, & \tilde{r} \geq 0.5 \end{cases} \quad (3)$$

where $H_\alpha = \omega_\alpha \tau_\alpha = \frac{4 \times 10^{-4} T_e^{3/2} [\text{keV}] B [\text{T}]}{\rho [\text{g/cc}]}$ is the Hall parameter of α -particles, $\tilde{r} = R_h/l_\alpha = 45 \frac{\ln \Lambda}{5} \frac{\rho R}{T^{3/2}}$ is the hot spot radius R_h relative to the α -particle range l_α , $\ln \Lambda$ is the Coulomb logarithm. As expected, f_α increases as the B-field rises, as shown in Fig. 2(b). Then, we have the total outward energy flux as $P_\alpha \cdot (1 - f_\alpha)$. It should be noted that Eq. (3) is not smooth at $\tilde{r} = 0.5$, but the model does not rely on the specific form of f_α . A better formula may replace it if available.

The angular distribution of F_α is also influenced by the magnetic field, which is the immediate cause of the asymmetric burning propagation speed. The energy flux should be proportional to the α -diffusion coefficients in different directions, if we use the diffusion model. The diffusion coefficient perpendicular to the B-field is derived by Liberman [29] as Eq. (5), where we denote $h(H_\alpha) = \frac{1}{1+(H_\alpha)^2}$:

$$D_\parallel = \frac{1}{6} v_\alpha^2 \tau_\alpha, \quad (4)$$

$$D_\perp = D_\parallel \frac{1}{1 + (H_\alpha)^2} = D_\parallel \cdot h(H_\alpha), \quad (5)$$

where v_α is the speed of α particles. A Braginskii-like form is used to calculate the $\vec{F}_\alpha(\theta)$:

$$\begin{aligned} \vec{F}_\alpha(\theta) &= -D_\parallel \nabla_\parallel n - D_\perp \nabla_\perp n \\ &= -D_\parallel \frac{\partial n_\alpha}{\partial r} \cos \theta \vec{e}_\parallel - D_\perp \frac{\partial n_\alpha}{\partial r} \sin \theta \vec{e}_\perp, \end{aligned} \quad (6)$$

$$F_\alpha(\theta) = F_0 \sqrt{h(H_\alpha)^2 \sin^2 \theta + \cos^2 \theta} = F_0 \cdot g(H_\alpha, \theta), \quad (7)$$

$$g(H_\alpha, \theta) = \sqrt{h(H_\alpha)^2 \sin^2 \theta + \cos^2 \theta}. \quad (8)$$

The integral of the energy flux over the entire spherical surface should equal the total outward energy flux. So, $F_\alpha(\theta)$ satisfies

$$\begin{aligned} \int_0^\pi F_\alpha \cdot 2\pi r^2 \sin \theta \, d\theta &= P_\alpha \cdot (1 - f_\alpha), \quad (9) \\ F_0 &= \frac{P_\alpha (1 - f_\alpha)}{4\pi R_h^2} \frac{2\sqrt{-1 + 1/h^2}}{\sqrt{-1 + 1/h^2} + h \cdot \text{arcsinh}(\sqrt{1 - h^2}/h)}, \end{aligned} \quad (10)$$

where $0 < h \leq 1$. Since we have $F_\alpha(H_\alpha, \theta) = F_0 \cdot g(H_\alpha, \theta)$, we obtain

$$\begin{aligned} F_\alpha(H_\alpha, \theta) &= \frac{P_\alpha (1 - f_\alpha)}{4\pi R_h^2} \frac{2\sqrt{-1 + 1/h^2} \cdot \sqrt{h^2 \sin^2 \theta + \cos^2 \theta}}{\sqrt{-1 + 1/h^2} + h \cdot \text{arcsinh}(\sqrt{1 - h^2}/h)}. \end{aligned} \quad (11)$$

When $B = 0$, f_α reverts to the deposition fraction f_0 in the absence of B-field, $h = 1$, thus $\frac{2\sqrt{-1 + 1/h^2} \cdot \sqrt{h^2 \sin^2 \theta + \cos^2 \theta}}{\sqrt{-1 + 1/h^2} + h \cdot \text{arcsinh}(\sqrt{1 - h^2}/h)} = 1$. So, $F_\alpha = \frac{P_\alpha (1 - f_0)}{4\pi R_h^2}$, which is the α -energy flux without magnetic fields. The result is self-consistent.

The burning propagation speed is proportional to F_α . Therefore, we obtain

$$\begin{aligned} v_b(H_\alpha, \theta) &= v_0 \frac{1 - f_\alpha}{1 - f_0} \frac{2 \cdot \sqrt{-1 + 1/h^2} \cdot \sqrt{h^2 \sin^2 \theta + \cos^2 \theta}}{\sqrt{-1 + 1/h^2} + h \cdot \text{arcsinh}(\sqrt{1 - h^2}/h)}, \end{aligned} \quad (12)$$

where $v_0 \propto P_\alpha (1 - f_0) / 4\pi R_h^2$ is the burning propagation speed without B-fields. Since we do not assume an isochoric or isobaric model in the derivation, Eq. (12) is valid for both as long as v_0 is provided. Like the f_α , the model does not specify the form of v_0 .

B. Numerical model of O-SUKI-NM

To verify our model and further investigate the burning propagation process with magnetic fields, we developed an MHD code, O-SUKI-NM, based on the Eulerian part of the

three-temperature radiation hydrodynamic program, O-SUKI-N 3D [30]. The program, O-SUKI-NM, includes Braginskii anisotropic ion/electron thermal conduction [31], Braginskii-like anisotropic α diffusion [32], magnetic diffusion, Ohmic heating, and Nernst effect [33,34]. The control equations of O-SUKI-NM are

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (13)$$

$$\rho \left[\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} \right] = -\nabla \left(P + q + \frac{B^2}{\mu_0} \right) + \frac{1}{\mu_0} (\mathbf{B} \cdot \nabla) \mathbf{B}, \quad (14)$$

$$\begin{aligned} \frac{\partial T_i}{\partial t} = & -(\mathbf{u} \cdot \nabla) T_i - \frac{k_B}{C_V} \left(\frac{P_i + q}{\rho} \nabla \cdot \mathbf{u} \right) \\ & - \frac{1}{\rho C_{V_i}} \nabla \cdot (\mathbf{q}_i) - K_{ie} + Q_{\alpha i}, \end{aligned} \quad (15)$$

$$\begin{aligned} \frac{\partial T_e}{\partial t} = & -(\mathbf{u} \cdot \nabla) T_e - \frac{k_B}{C_V} \left(\frac{P_e}{\rho} \nabla \cdot \mathbf{u} \right) - \frac{1}{\rho C_{V_e}} \nabla \cdot (\mathbf{q}_e) + K_{ie} \\ & - K_{re} + Q_{\alpha e} + \frac{k_B}{\mu_0^2 \rho C_V} (\nabla \times \mathbf{B}) \cdot \boldsymbol{\eta} \cdot (\nabla \times \mathbf{B}), \end{aligned} \quad (16)$$

$$\frac{\partial T_r}{\partial t} = -(\mathbf{u} \cdot \nabla) T_r - \frac{k_B}{C_V} \left(\frac{P_r}{\rho} \nabla \cdot \mathbf{u} \right) + \frac{1}{\rho C_{V_r}} \nabla \cdot (\mathbf{q}_r) + K_{re}, \quad (17)$$

$$\frac{\partial (\varepsilon_\alpha)}{\partial t} = \langle \sigma v \rangle_{\text{DT}} n_{\text{D}} n_{\text{T}} E_\alpha - \nabla \cdot (\mathbf{F}_\alpha) E_\alpha - \omega_{\alpha c} \varepsilon_\alpha, \quad (18)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\tilde{\mathbf{u}} \times \mathbf{B}) - \frac{1}{\mu_0} \nabla \times (\boldsymbol{\eta} \cdot \nabla \times \mathbf{B}), \quad (19)$$

where q is the artificial viscosity, whose form can be found in Ref. [30]. μ_0 is the magnetic permeability of vacuum. k_B is the Boltzmann constant. $\boldsymbol{\eta}$ is the electrical resistivity tensor [33]. $E_\alpha = 3.5$ MeV is the energy of α particles and ε_α is the energy density of α particles. C_{V_k} is the heat capacity of ion, electron, and radiation; $\mathbf{q}_r$ is the radiation thermal conduction; K_{ie} and K_{re} represent the ion-electron and electron-radiation energy exchange [35]. $\mathbf{q}_i$ and $\mathbf{q}_e$ is the Braginskii thermal conduction [31]:

$$\mathbf{q}_k = -\kappa_{\parallel} \nabla_{\parallel} T_k - \kappa_{\perp} \nabla_{\perp} T_k + \kappa_{\times} \mathbf{b} \times \nabla T_k \quad (k = i, e). \quad (20)$$

$Q_{\alpha i}$ and $Q_{\alpha e}$ are the α -energy deposition in ion and electron [36]:

$$Q_{\alpha i} = f_i \frac{\varepsilon_\alpha \omega_{\alpha c}}{\rho C_{V_i}}, \quad (21)$$

$$Q_{\alpha e} = f_e \frac{\varepsilon_\alpha \omega_{\alpha c}}{\rho C_{V_e}}, \quad (22)$$

$$f_i = \frac{1}{1 + 32/T_e [\text{keV}]}, \quad f_e = 1 - f_i, \quad (23)$$

where $\omega_{\alpha c}$ is the collision frequency of α -particles with electrons and ions. $\mathbf{F}_\alpha$ is the anisotropic flux of α particles, which we use a Braginskii-like form [32]:

$$\begin{aligned} \mathbf{F}_\alpha = & -D_{\parallel} \nabla_{\parallel} n_\alpha - D_{\perp} \nabla_{\perp} n_\alpha + D_{\times} \mathbf{b} \times \nabla n_\alpha, \\ D_{\times} = & D_{\parallel} \frac{H_\alpha}{1 + H_\alpha^2}. \end{aligned} \quad (24)$$

$D_{\parallel}$ and $D_{\perp}$ are the same as Eqs. (4) and (5). The Nernst and cross-gradient-Nernst effects are also considered in the

evolution of the magnetic field [33,34]:

$$\tilde{\mathbf{u}} = \mathbf{u} - \gamma_{N\perp} \nabla_{\perp} T_e - \gamma_{N\wedge} \mathbf{b} \times \nabla T_e. \quad (25)$$

O-SUKI-NM uses a staggered mesh algorithm to calculate the evolution of magnetic fields, while the solution of fluid keeps the same as O-SUKI-N 3D. The details of the time-update strategy can be found in Ref. [37].

III. RESULTS AND DISCUSSIONS

A. Results of the analytical model

The result of the analytical model Eq. (12) can be rewritten as

$$v_b(H_\alpha, \theta) = v_0 \cdot g(H_\alpha, \theta) \cdot A(H_\alpha, \tilde{r}), \quad (26)$$

$$A(H_\alpha, \tilde{r}) = \frac{1 - f_\alpha}{1 - f_0} \frac{2 \cdot \sqrt{-1 + 1/h^2}}{\sqrt{-1 + 1/h^2} + h \cdot \text{arcsinh}(\sqrt{1 - h^2}/h)}. \quad (27)$$

The equation contains three parts: the burning propagation speed v_0 when $B = 0$, the angular distribution $g(H_\alpha, \theta)$, and the acceleration factor $A(H_\alpha, \tilde{r}) = v_{\parallel}/v_0$. Equation (26) indicates that the magnetic field not only induces asymmetric burning propagation, but also affects the burning speed along the direction of the B-field.

Figure 3(a) plots the burning propagation speed in different directions in magnetic fields. For a typical isochoric hot spot parameter, a notable asymmetry is observed with a magnetic field of ~ 10 kT.

By analyzing Eq. (26), it can be observed that there are two mechanisms through which magnetic fields can accelerate the burning wave in its parallel direction:

(1) The indirect acceleration: As indicated by Eq. (3), magnetic fields lead to an increase in f_α , thereby accelerating the hot spot temperature rise. A higher temperature, in turn, speeds up the burning propagation. This effect is reflected through v_0 , which increases with higher temperature.

(2) The direct acceleration: Magnetic fields can directly accelerate the burning propagation, which is reflected as $A(H_\alpha, \tilde{r})$. There exists an internal competition in this effect. On one hand, $\frac{1-f_\alpha}{1-f_0} < 1$, which means the magnetic field leads to a decrease in the total outward energy flux. On the other hand, $\frac{2 \cdot \sqrt{-1+1/h^2}}{\sqrt{-1+1/h^2} + h \cdot \text{arcsinh}(\sqrt{1-h^2}/h)} > 1$, which stems from the anisotropy of F_α . α -particles mainly spiral along magnetic field lines, thus enhancing the F_α parallel to the direction of the field.

The value of $A(H_\alpha, \tilde{r})$ in the parameter space is plotted in Fig. 3(b). When the hot spot conditions are within the region where $v_{\parallel}/v_0 > 1$, the magnetic field can directly accelerate burning propagation. It can also be observed that $v_{\parallel}/v_0$ varies steeply within $\tilde{r} < 0.5$, but approaches a constant value for $\tilde{r} > 0.5$. The reason is that $\tilde{r}$ only affects $(1 - f_\alpha)/(1 - f_0)$. For $\tilde{r} < 0.5$, f_α and f_0 vary steeply [Fig. 2(b)]. For $\tilde{r} > 0.5$, almost all α -particles are deposited in the hot spot and the variation of both f_α and f_0 are minimal with respect to $\tilde{r}$. Figure 3(b) also shows the positions of hot spots of $\rho = 300 \text{ g/cm}^3$, $B = 10 \text{ kT}$, $R_h = 20 \text{ }\mu\text{m}$, $T = 10 \text{ keV}$ (diamond) or 20 keV (pentagram) in the parameter space. It can be

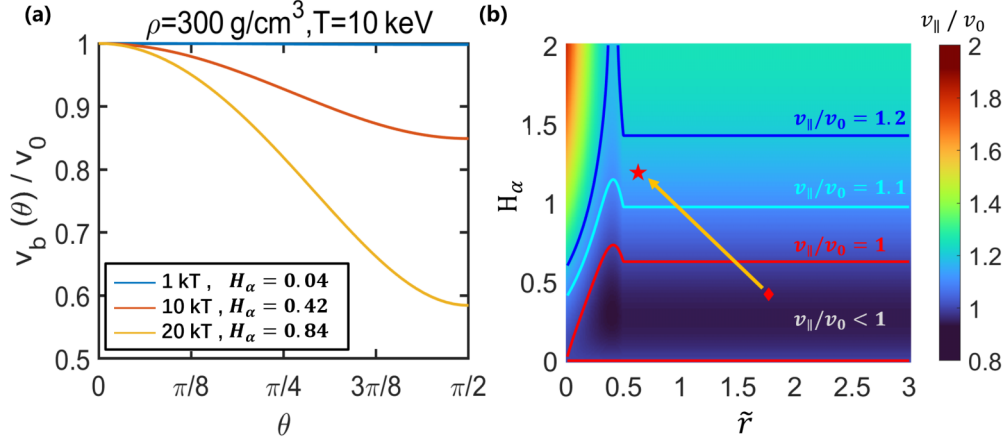


FIG. 3. (a) The ratio of burning propagation speed $v_b(\theta)/v_||$. (b) The value of $v_||/v_0$ in the parameter space. The region of $v_||/v_0 > 1$ marks the direct magnetic acceleration. The red diamond and pentagram represent the positions of hot spots for $T = 10$ keV (diamond) or 20 keV (pentagram). The nonsmoothness at $\tilde{r} = 0.5$ is caused by the nonsmoothness of f_α [Eq. (3)].

observed that in the initial phase of burning, $v_||/v_0 < 1$, where the magnetic field mainly accelerates the burning propagation through indirect effects by increasing v_0 . As the temperature rises, $v_||/v_0$ exceeds unity. The magnetic field directly accelerates the burning wave. Such phenomena originate from the longer α range and deposition time in high temperatures. First, the longer deposition time allows more magnetic gyrations in α -trajectories, reflecting through the increased H_α . Second, longer α range means lower f_α and higher F_α , thus enhancing $v_||$.

B. Simulations of the asymmetric burning propagation

With O-SUKI-NM, we performed a series of simulations of asymmetric burning propagation. The initial conditions of the spherical hot spot are $R_0 = 20$ μm , $T_0 = 9$ keV, $\rho = 300$ g/cm³, which corresponds to $\tilde{r} = 2$. For the surrounding cold fuel, $T_0 = 1$ keV, $\rho = 300$ g/cm³. The simulation length in (x, y, z) directions is 200 μm , and the total mesh number is $200 \times 200 \times 200$. The initial magnetic field along the z -axis ranges from 0 to 20 kT, corresponding to $H_\alpha \in [0, 0.72]$. The influence of B diffusion and Ohmic heating can be estimated

by dimensional analysis in the parameter space of interest. For B diffusion, the magnetic Reynolds number is 2.38×10^{10} and the B diffusion term is much smaller than the advection term. Similar analysis shows the Ohmic heating term is also negligible compared to mechanical work. For clarity, the B diffusion and Ohmic heating are turned off in the simulations.

An example is shown in Fig. 4. It is observed that an initial $B_0 = 10$ kT is enough to induce notable burning asymmetry, corresponding to $H_{\alpha 0} = 0.36$. During the simulation, the magnetic field decreases at the center of the hot spot and is compressed at the shock front in the transverse direction due to the density increase. This phenomenon is consistent with the frozen effect of B, indicating the results are reasonable. To prove that the α transport plays the main role instead of the electron or ion thermal conduction, a test case of $B_0 = 10$ kT is simulated without the anisotropic α transport. The averaged $v_\perp/v_|| = 0.96$, which shows little asymmetry. In contrast, the values of $v_\perp/v_||$ with anisotropic α transport given by the analytical model and simulations are 0.88 and 0.87 , respectively.

The simulation results were compared with the model, as shown in Fig. 5(a). The burning propagation speed is averaged

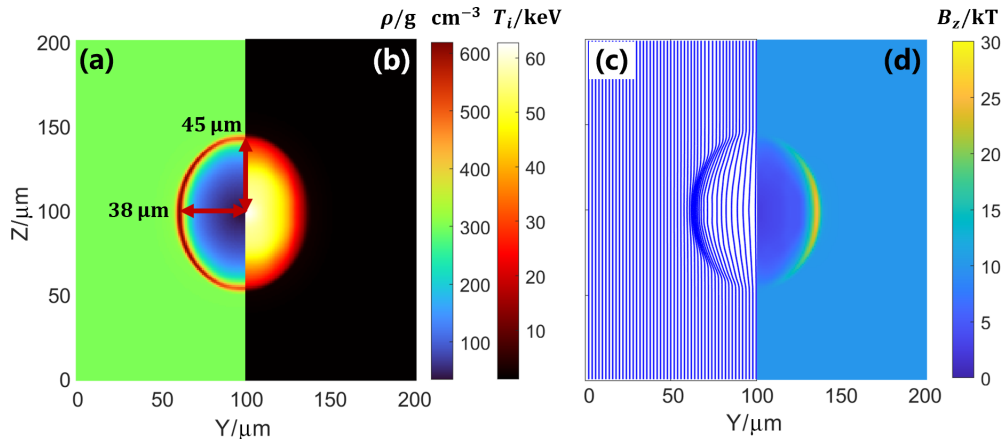


FIG. 4. The (a) density, (b) ion temperature, (c) B streamline, and (d) B_z of an isochoric asymmetric burning propagation at $t = 20$ ps. Notable burning asymmetry is observed.

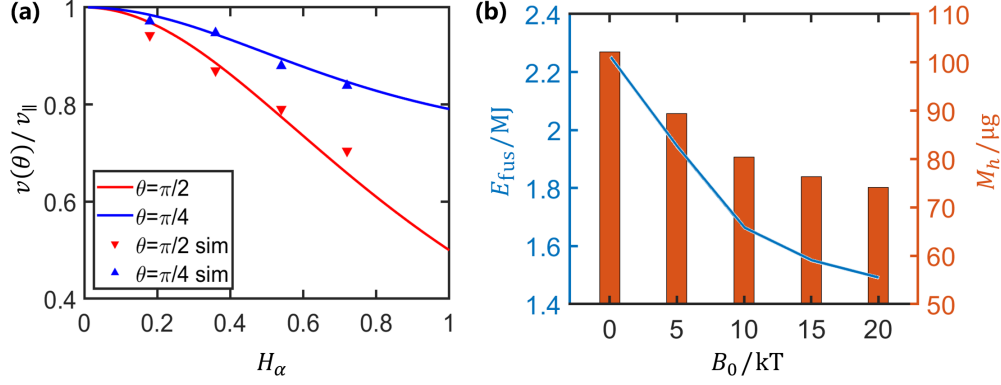


FIG. 5. (a) Comparison of angular distribution of burning propagation speed between the model and the simulations. (b) Fusion energy and hot spot mass ($T_i > 5$ keV) of different initial magnetic fields at 20 ps.

during the simulation. For angular distribution, the results agree well with the model. The most likely reason for the difference is the instantaneous α -deposition assumption in the analytical model, which implicitly comes from the usage of f_{α} . The fusion energy of different B_0 is plotted in Fig. 5(b). The E_{fus} decrease in spherical hot spot comes from the decrease in hot spot mass, which is mainly caused by the suppression of transverse burning propagation. Although the magnetic field can lower the ignition conditions [11], the magnetic burning asymmetry might be harmful for the central spherical hot spot to achieve high fusion gain, which is consistent with recent literature [38].

IV. CONTROLLING A DIRECTIONAL BURNING PROPAGATION BY MAGNETIC FIELDS

An intrinsic asymmetry exists in ICF concepts based on the FI. Because of the external heating source, the hot spots are formed at the edge of the compressed fuel (Fig. 1). The position of the hot spot leads to the energy loss mechanism named hot spot disassembly (or named hot spot collapse in Ref. [26]). Its competition with the burning propagation results in stricter ignition conditions. More significantly, there is a geometric mismatch between the isotropic α -transport and the fuel configuration, as shown in Fig. 1(b). The mismatch results in a large amount of α -particles escaping into the vacuum, rather than heating the cold fuel. If the burning wave continues to propagate symmetrically, it shall approach one-dimensional conditions, leading to a more severe wastage of α -particles. Such defects must be overcome to achieve high fusion gain. Using a magnetic field to guide a directional burning propagation can be a good method to mitigate the mismatch and reduce α -wastage [Fig. 1(c)]. Due to the non-spherical shape of the hot spot, f_{α} is different from Eq. (3). So, the analytical results cannot be simply applied, and we continue our discussion with simulations. However, the model can be extended if a proper f_{α} is found.

Simulations similar to Ref. [26] are performed with pre-assembled fuel consisting of a hemispherical hot spot and semi-infinite fuel. The initial condition of the hot spot is $T_0 = 9$ keV, $R_{h0} = 20$ μm , $\rho_0 = 300$ g/cm³ and that of the cold fuel is $T_f = 1$ keV, $\rho_0 = 300$ g/cm³. B_0 is along the z -axis and ranges from 0 to 10 kT. The region $Z < 100$ μm

is set to be a vacuum. The results are shown in Fig. 6. It is observed that with 10 kT applied, the hot spot exhibits a somewhat directional shape and the average temperature increases dramatically [Fig. 6(e)]. The average hot spot temperature increases from 12.9 keV to 17.8 keV at 45 ps. Figure 6(f) also shows the burning propagation speed along the z -axis, and the speed increases by 44%. The increased burning speed exceeds the disassembly speed earlier, which marks a sustainable burning propagation. The fusion energy and hot spot mass, unlike the previous spherical cases, increase by 87% from 1.77 MJ to 3.31 MJ and 18% from 96.3 to 114.2 μg within 50 ps. The results confirm that magnetic fields can be utilized to control and guide a directional burning propagation in FI or DCI, as well as increase the fusion energy.

Based on the simulation results, we summarize the advantages of burning propagation control that may contribute to a high fusion gain.

(1) Accelerating the burning propagation in its competition with the hot spot disassembly. The magnetic acceleration effect speeds up the burning wave, which makes the burning propagation easier to exceed the disassembly speed, as shown in Fig. 6(f).

(2) Reducing the geometric mismatch, as shown in Fig. 1(c). A strong magnetic field along the heating direction can guide a directional burning propagation toward the other side of the fuel, which has two benefits. (i) The entire fuel is ignited more rapidly within the confinement time, increasing the burn-up fraction. (ii) A properly designed magnetic field may guide the burning wave to reach fuel edges simultaneously, minimizing the wastage of α -particle energy.

(3) Providing a new dimension for optimization. In FI, a localized energy deposition of the REB is usually expected for higher hot spot temperatures, which requires a low-temperature REB. However, it is difficult to generate by ignition-scale picosecond lasers and usually leads to a small areal density and short confinement time of the hot spot. The faster temperature increase [Fig. 6(e)] allows the option of a slightly lower hot spot temperature with higher areal density. Therefore, the requirement of low REB temperature is relaxed. However, such a balance is delicate and highly relies on the configuration of the compressed fuel, so we only point out such a possibility here. Further investigation shall be included in the future work.

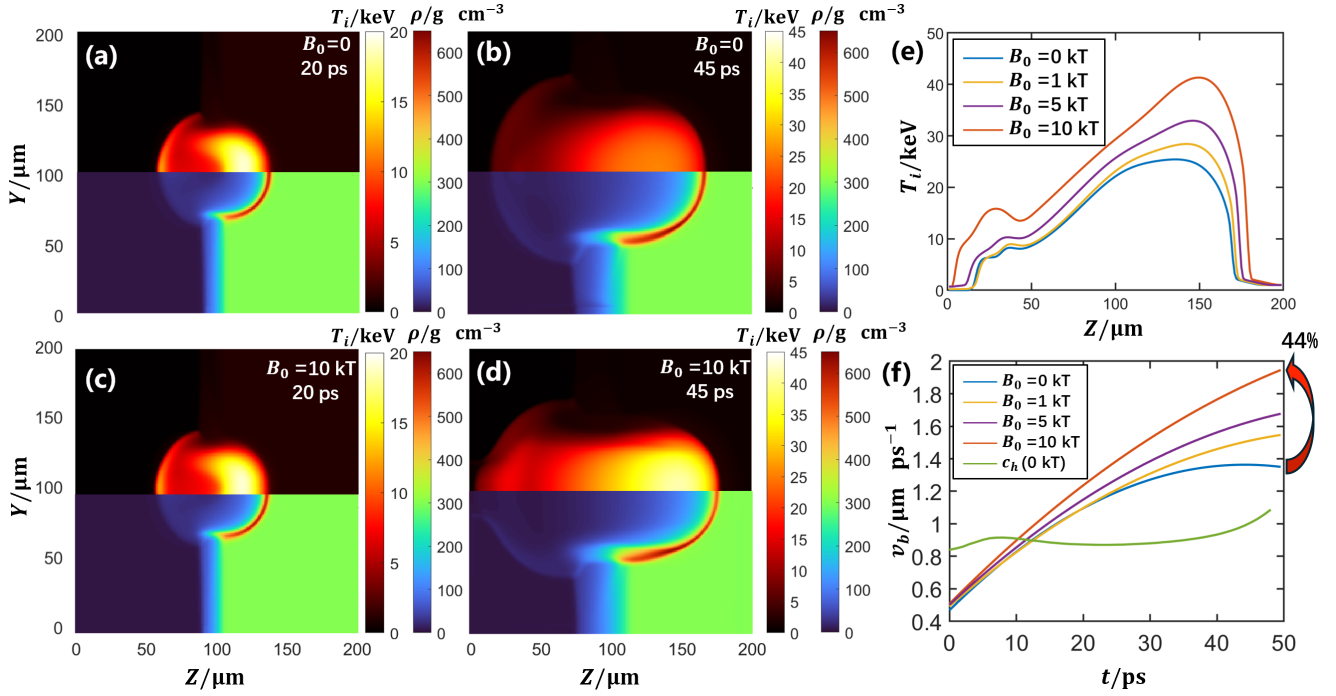


FIG. 6. (a)–(d) Ion temperature and density of preassembled fuel with hemispherical hot spot at $t = 20$ ps and 45 ps with $B_0 = 0$ and $B_0 = 10$ kT. The region of $Z < 100 \mu\text{m}$ is a vacuum at $t = 0$. (e) Ion temperature distribution along z -axis. (f) The burning propagation speed along z -axis. The hot spot disassembly speed c_h [26] with $B_0 = 0$ is also plotted.

V. CONCLUSIONS

In this paper, an analytical model is developed to discuss the asymmetric burning propagation in strong magnetic fields of ICF. The formula indicates that a 10 kT-level magnetic field would induce notable asymmetry in ICF parameter space, corresponding to α -particle Hall parameter $H_\alpha \sim 0.5$. The formula also suggests that the magnetic field accelerates the burning propagation in the parallel direction through direct and indirect effects. The direct effect originates from anisotropic α -transport. The indirect effect stems from faster temperature increase due to the suppressed transverse α -transport. An MHD program, O-SUKI-NM, was developed based on the code O-SUKI-N 3D. The simulation results agree well with the model.

The model shows the possibility of controlling burning propagation by magnetic fields in some intrinsically asymmetric concepts, such as fast ignition and DCI, where the hot spot is formed at the edge of the compressed fuel by external heating sources. A proper magnetic field can be applied to guide a directional burning propagation to the other side of the DT fuel. Simulation results have shown that a 10 kT-level B-field can increase the hot spot temperature by 38% and the burning propagation speed by 44% in FI conditions, leading to 87% more fusion energy. Advantages of directional burning propagation include reducing geometric mismatch and α -energy wastage, accelerating the burning propagation in its competition with the hot spot disassembly and introducing a

new dimension for optimization. These advantages can contribute to higher burn-up fraction and fusion gain. Despite the advantages, it remains challenging to generate such a strong and proper magnetic configuration. Such a process must be simulated from the beginning of the implosion. Concerns have been raised regarding the potential formation of a magnetic mirror configuration after the implosion process along the heating direction, which may prevent fast electrons from reaching the compressed core. However, the magnetic mirror may also bounce back the high-energy electrons (> 3 MeV) that would otherwise penetrate the plasma and enlarge their transport distance in the fuel, thereby enhancing energy deposition. The trade-off requires further investigation.

Future efforts will be focused on the design and generation of a magnetic field for controlling the burning propagation in the coming DCI experiments and maximizing the fusion gain. The effects associated with magnetic mirrors will also be investigated in realistic magnetic configurations.

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