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Theoretical scaling of fast isochoric heating for laser fusion

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ABSTRACT

- In order to understand a contribution of a thermal diffusion to the fast ignition scheme, we leveraged our theoretical scaling equation of the thermal diffusion and solved one-dimensional (1D) energy equation numerically.
- Based on some optimistic assumptions, we estimate the lower limit of the required input energy by the heating laser light for the ignition scale as high as 200 kJ.
- By considering the contribution of the thermal diffusion may mitigate the amount of injected laser energy required for the ignition rather than taking account into relativistic electron beam (REB) only.

BACKGROUND

- The heat transport mechanism of laser fusion has been changing with the development of laser devices. Recently, kilojoule/ps lasers such as LFEX have been accessible.
- Matsuo *et al.* applied the LFEX laser to heat the implosion core and achieve the electron temperature about 2 keV at the core region with an energy density of 2 PPa [1].
- This highly efficient heating is difficult to explain only by REBs. The experimental and the simulation results in that paper suggest the thermal diffusion launched from the hot preformed plasma region contributes to heat the core in addition to the REB heating.
- The author *et al.* have recently developed a theoretical model of the propagation speed of the thermal diffusion at keV temperature to clarify the parameter dependency of thermal diffusion and benchmarked it via a series of PIC simulations [2].

CHALLENGES / METHODS / IMPLEMENTATION

CHALLENGES

- Clarifying the contribution of the thermal diffusion, which has not received much attention so far, to the "ignition".
- It is challenging to directly exteriorize the theoretical scaling equation we have developed to the ignition scale.

METHODS

- Solving numerically the partial differential equation (PDE) for the 1D electron energy equation. PDE solver can assess the fast ignition in the ignition scale indirectly through the theoretical model.
- Interpreting the results of theoretical scaling to determine the PDE parameters.

IMPLEMENTATION

- The governing eq. is the 1D electron energy eq. with the energy transfer term (electrons -> ions) and the bremsstrahlung radiation loss term.

1D electron energy equation w/ radiation loss & energy transfer to ions

$$\frac{3}{2}\bar{n}_{\mathrm{e}}\frac{\partial \bar{T}_{\mathrm{e}}}{\partial \bar{t}} = \frac{3}{2}\frac{\bar{n}_{\mathrm{h}}\bar{T}_{\mathrm{h}}}{\bar{\tau}_{\mathrm{e}}(\bar{T}_{\mathrm{h}})} + \frac{\bar{j}_{\mathrm{h}}^{2}}{\bar{\sigma}(\bar{T}_{\mathrm{e}})} + \frac{\partial}{\partial \bar{x}}\left(\bar{\kappa}\left(\bar{T}_{\mathrm{e}}\right)\frac{\partial \bar{T}_{\mathrm{e}}}{\partial \bar{x}}\right) - \frac{3}{2}\bar{P}_{\mathrm{Br}} - \frac{3}{2}\bar{n}_{\mathrm{e}}\,\bar{\nu}_{ei}\frac{2m_{\mathrm{e}}}{m_{\mathrm{i}}}\left(\bar{T}_{\mathrm{e}} - \bar{T}_{\mathrm{i}}\right)$$

drag heating, Joule heating, thermal diffusion, radiation loss, energy transfer to ions

1D ion energy equation

$$\frac{3}{2}\bar{n}_{\mathrm{i}}\frac{\partial \bar{T}_{\mathrm{i}}}{\partial \bar{t}} = -\frac{3}{2}\bar{n}_{\mathrm{i}}\,\bar{\nu}_{ei}\frac{2m_{\mathrm{e}}}{m_{\mathrm{i}}}\left(\bar{T}_{\mathrm{i}} - \bar{T}_{\mathrm{e}}\right)$$

energy transfer from electrons

- Solved by method of lines and the 4th order Runge-Kutta scheme.
- The fast electron density is constant in time.

OUTCOME

NUMERICAL CALUCULATION FOR THERMAL DIFFUSION TO VERIFY THE THEORETICAL MODEL

- Confirm that PDE can reproduce the results of the theoretical model, which has already successfully explained the simulation results.
- As a consequence of the theoretical model, if the same focused intensity can be applied regardless of different wavelengths, the shorter wavelength is more advantageous for the thermal diffusion.

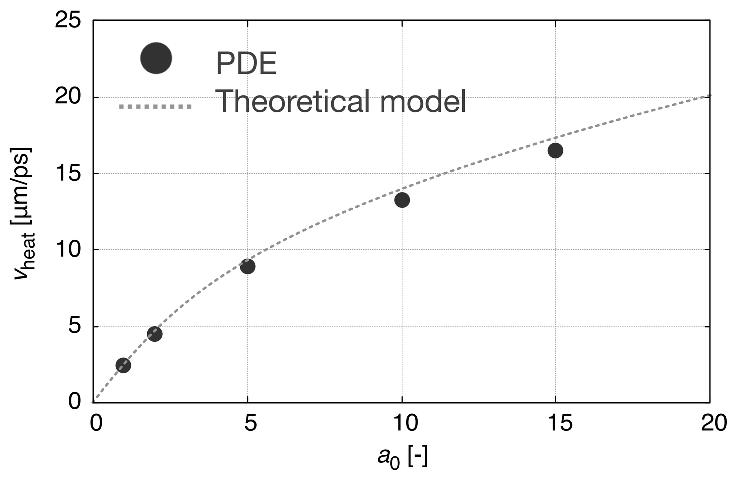

Fig. 1 model vs. PDE

$$\bar{v}_{\mathrm{heat}} = \left(\frac{8}{9}\alpha_{\mathrm{SH}}\,f_{\mathrm{NL}}\right)^{\frac{1}{2}}\left(\frac{\bar{n}_{\mathrm{h}}}{\bar{n}_{\mathrm{e}}}\right)^{\frac{1}{2}} \times \bar{v}_{\mathrm{h}}$$

$$= \sqrt{\frac{8\,\alpha_{\mathrm{SH}}\,f_{\mathrm{NL}}}{9\,\bar{n}_{\mathrm{b}}}\frac{\gamma^{2}-1}{\gamma}} \quad \gamma \equiv \sqrt{1+\chi_{\mathrm{ab}}\frac{a_0^{2}}{2}}$$

Scaling formula for the propagation speed of the thermal diffusion [2]

NUMERICAL CALCULATION TO ASSESS THE FAST IGNITION IN THE IGNITION SCALE

- As a result of the numerical calculation of the PDE, taking into account the boundary condition that the heat flow comes from hot pre-plasma regions and assuming the parameters as shown in the Table 1, the thermal diffusion front reaches to the region of the imploded core (300 g/cc deuterium plasma) within about 20 ps, leading to the "ignition". This corresponds to an input energy of at most 200 kJ. Neglecting the fluid motion of the expanding plasma seems to make the results optimistic.

target	material	deuteron
	mass density [g/cc]	300
laser	wave length [μm]	0.5 (2ω)
	a_0	10
	ab. ratio [%]	80
	pulse duration [ps]	20
	spot radius [μm]	20
	energy [kJ]	< 200

Table. 1 parameters for PDE

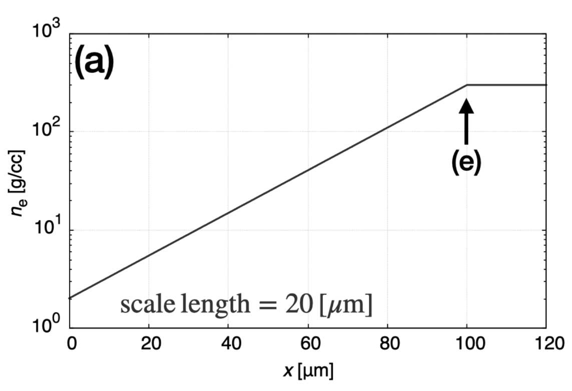

Fig. 2(a) n_e profile

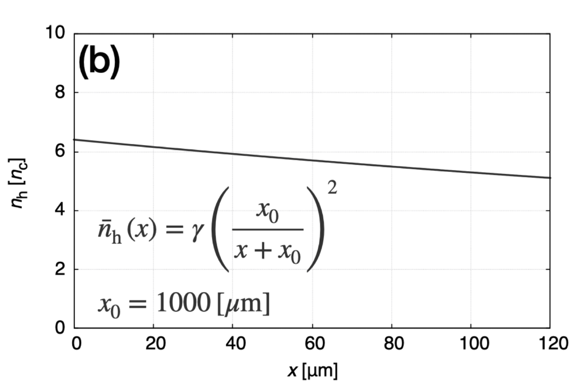

Fig. 2(b) n_h profile

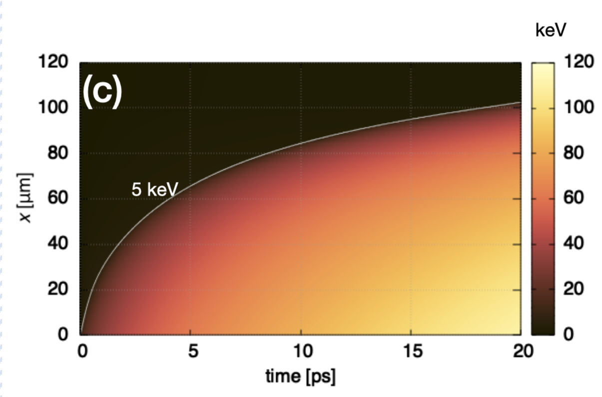

Fig. 2(c) t-x diagram of T_e

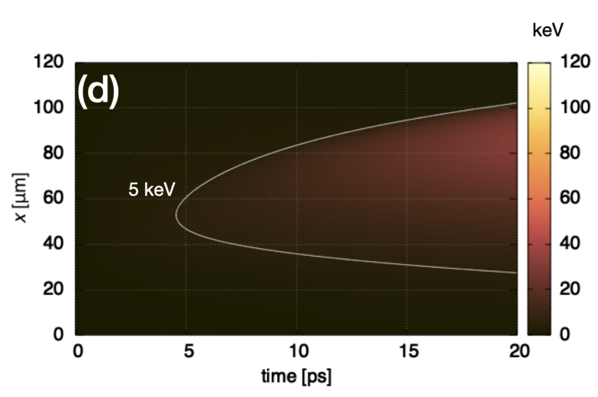

Fig. 2(d) t-x diagram of T_i

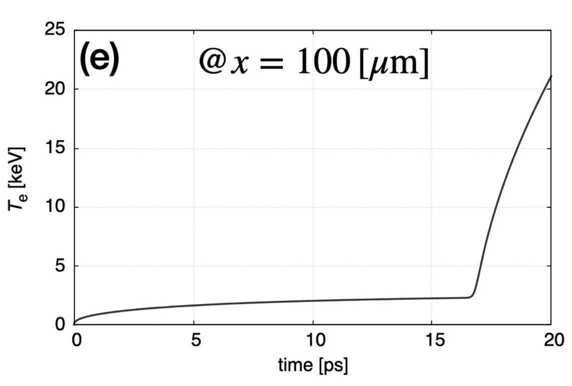

Fig. 2(e) temporal evolution of T_e

CONCLUSION

- The theoretical model and numerical calculation revealed that if the same focused intensity can be applied regardless of different wavelengths, the shorter wavelength is more advantageous for the thermal diffusion.
- Although this is an optimistic result having the limitation in 1D situation, we are able to estimate the minimum required energy for "ignition".
- In the future, we will develop a model that takes into account the effects of multidimensional results.

REFERENCES

[1] Matsuo et al., PRL, **124**, 035001 (2020).
[2] Higashi et al., under preparation (2021).

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