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An Alternative Fast Ignition Scheme by Standing Whistler-Wave Heating

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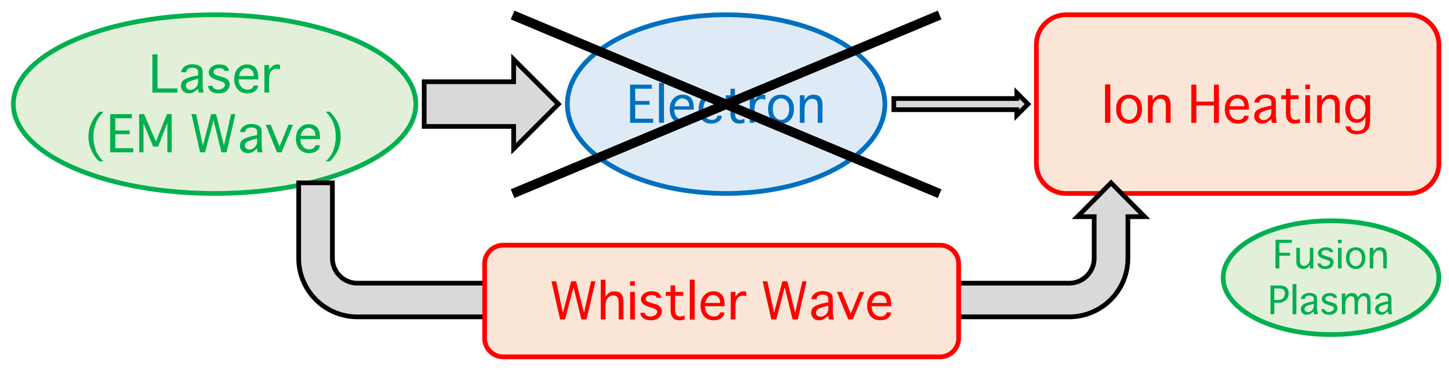
References: Sano et al. PRE, 96, 043209 (2017) ; Sano et al. RRE, 100, 053205 (2019) ; Sano et al. PRE, 101, 013206 (2020)

1. Direct energy transfer from lasers to ions may solve the ion-heating problem in ICF.



Fusion Plasma Generation by "Standing Whistler Wave Heating"

1. Efficient Neutron Source
2. Alternative Fast Ignition Scheme
3. "Ultraclean" pB Fusion Reaction

2. Motivation of this work is to find an efficient mechanism of ion heating in solid density plasmas.

- No Cutoff Feature of Whistler Wave
  - Strong B Field + CP Laser
  - Requirement

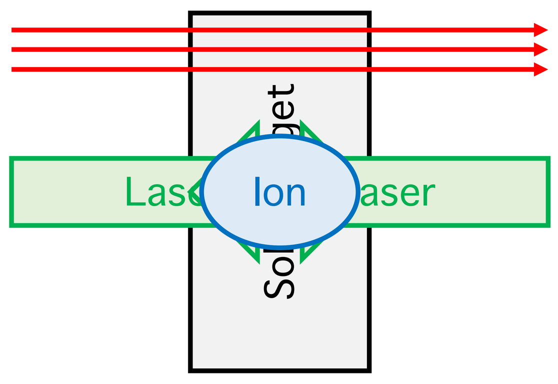
$$\omega_{ce} > \omega_0$$

$$B_{\rm ext} > \frac{m_e \omega_0}{e} \equiv B_c$$

  - Critical Field Strength

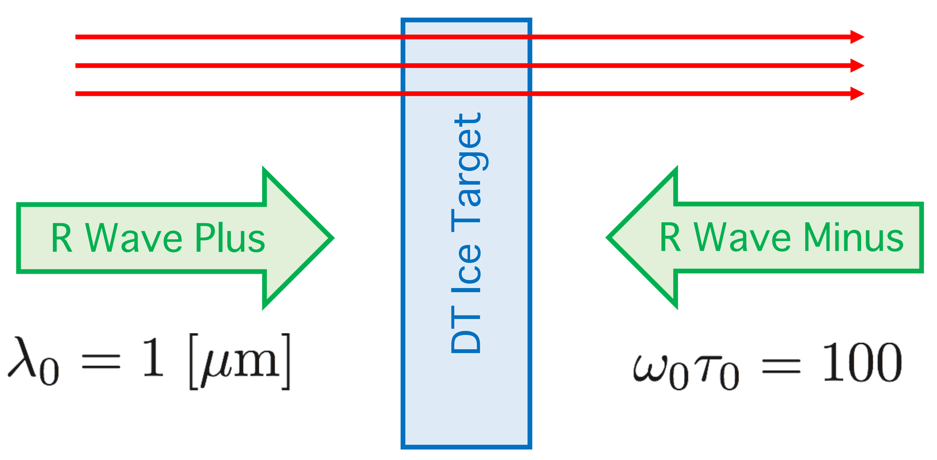
$$B_c = 13\left(\frac{\lambda_0}{0.8\ \mu{\rm m}}\right)^{-1}\ [{\rm kT}]$$

- New Concept
  - Standing Whistler Wave Formed by Counter Beams
  - Laser -> Ion Directly
  - Ultrafast Generation of Thermal Fusion Plasma



3. DT solid target is irradiated by circularly-polarized R-waves from both sides to generate thermal fusion plasmas.

- Initial Setup for 1D & 2D PIC Simulation by PICLS



$\lambda_0 = 1\ [\mu{\rm m}]$ $\quad \omega_0\tau_0 = 100$

$$L_x/\lambda_0 = 15$$

$$(D_x/\lambda_0, D_y/\lambda_0) = (25, 3)$$

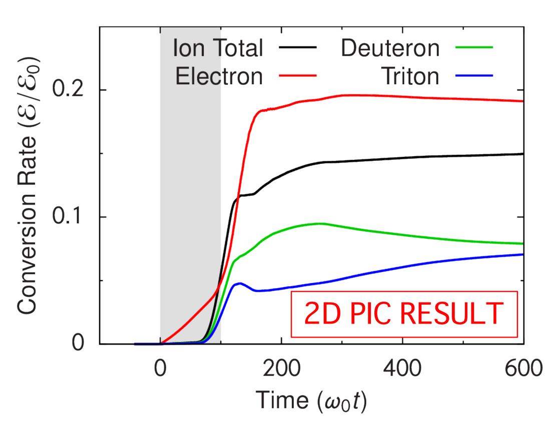
Key Parameters

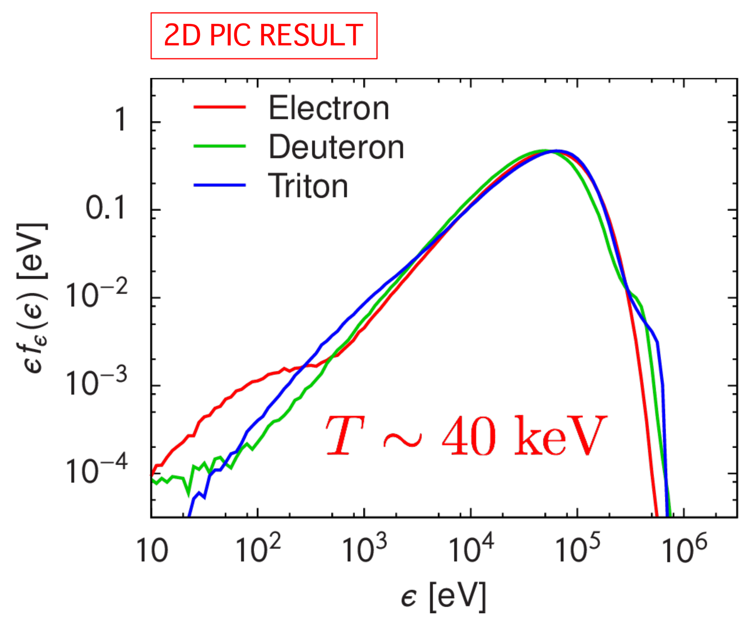
$$\tilde n_{e0} = 50$$
$$\tilde B_{\rm ext} = 20$$
$$a_0 = 4$$

$$\tilde n_e \equiv \frac{n_e}{n_c}$$
$$\tilde B_{\rm ext} \equiv \frac{B_{\rm ext}}{B_c}$$

4. Thermal DT fusion plasma of the temperature 40 keV is generated by standing whistler wave heating.

- DT Ice Target
- Ion Evolution in 2D = 1D
- Energy Conversion = 15%
- Relax to Isothermal State





- Maxwellian Fit of Whole Range

5. We found an interesting feature of the standing whistler wave which affects ion motions significantly.

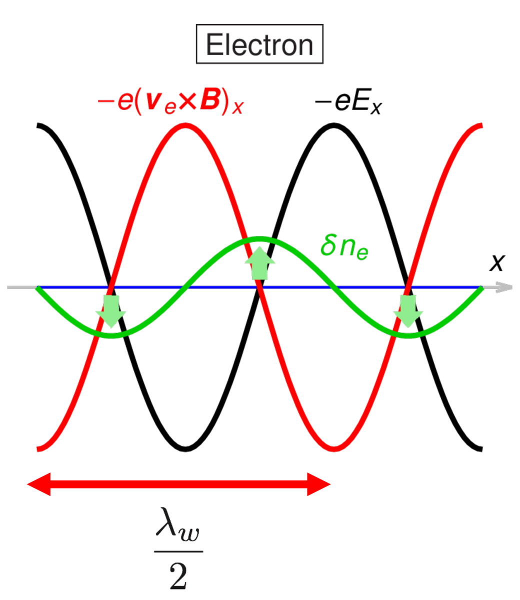
- For Each Whistler Wave... No Longitudinal Force to Electrons

$$(\boldsymbol{v}_w^+ \times \boldsymbol{B}_w^+)_x = (\boldsymbol{v}_w^- \times \boldsymbol{B}_w^-)_x = 0$$

- In a Standing Whistler Wave...

$$(\boldsymbol{v}_e \times \boldsymbol{B})_x = [(\boldsymbol{v}_w^+ + \boldsymbol{v}_w^-) \times (\boldsymbol{B}_w^+ + \boldsymbol{B}_w^-)]_x \neq 0$$

- Periodic Structure with a Half of the Whistler Wavelength
- Constant with Time



6. Static electric field can be evaluated from the force balance in the equation of motion for electrons.

- Electron Eq. of Motion

$$m_e n_e \frac{\partial v_{xe}}{\partial t} = -\frac{\partial P_e}{\partial x} - e n_e [E_x + (\boldsymbol{v}_e \times \boldsymbol{B})_x]$$

- Formula of the Static E Field ... Constant with Time

$$eE_x = -e(\boldsymbol{v}_e \times \boldsymbol{B})_x$$
$$= \left[\frac{2N a_w^+ a_w^-}{\tilde B_{\rm ext} - 1} m_e c\omega_0\right] \sin(2k_w x)$$
$$= \left[\frac{8Na_0^2}{(N+1)^2(\tilde B_{\rm ext} - 1)} m_e c\omega_0\right] \sin(2Nk_0 x) \propto t^0$$

$$k_w = Nk_0 \qquad a_w^\pm = \frac{2}{N+1} a_0$$

7. The longitudinal E field can be comparable to the whistler wave field.

- When a_0 is of the order of unity, the longitudinal electric field becomes comparable to the laser E field.

$$E_x \approx \frac{8Na_0^2}{(N+1)^2(\tilde B_{\rm ext} - 1)} \frac{m_e c\omega_0}{e}$$

$$\frac{m_e c\omega_0}{e} = 4.01 \times 10^{12} \left(\frac{\lambda_0}{0.8\mu{\rm m}}\right)^{-1}\ [{\rm V/m}]$$

- Then ions can be accelerated up to 0.01c in a few laser periods.
- If they were thermalized, the ion temperature could be 100keV.

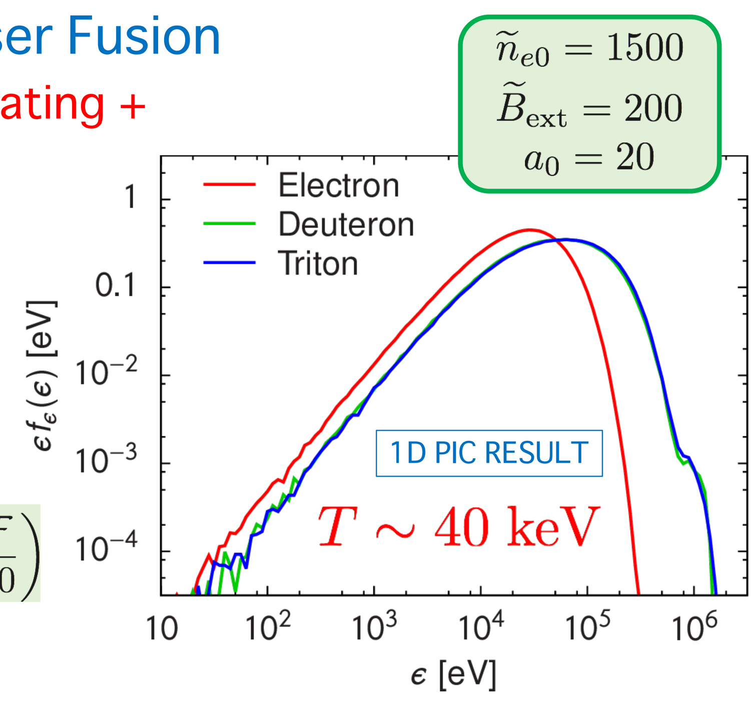
8. To increase the energy gain, enhancement of the target density and field strength by implosion is inevitable.

- Magnetically Confined Laser Fusion
  - Standing Whistler Wave Heating + Cylindrical Implosion
  - 30 Times Compression

$$50n_c \to 1500n_c$$
$$70\ {\rm kT} \to 2\ {\rm MT}$$

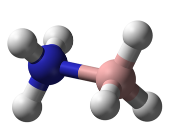
  - Energy Gain > 1

$$G \approx 2.4\lambda_{\mu m}^{-1}\tilde v_g^2 \left(\frac{\tilde n_{e0}}{1500}\right)^2 \left(\frac{a_0}{20}\right)^{-2} \left(\frac{\tilde \tau_0}{200}\right) \left(\frac{\mathcal{F}}{10}\right)$$



9. Aneutronic pB reaction will be realized by counter laser irradiation to Ammonia Borane Target.

- Ammonia Borane

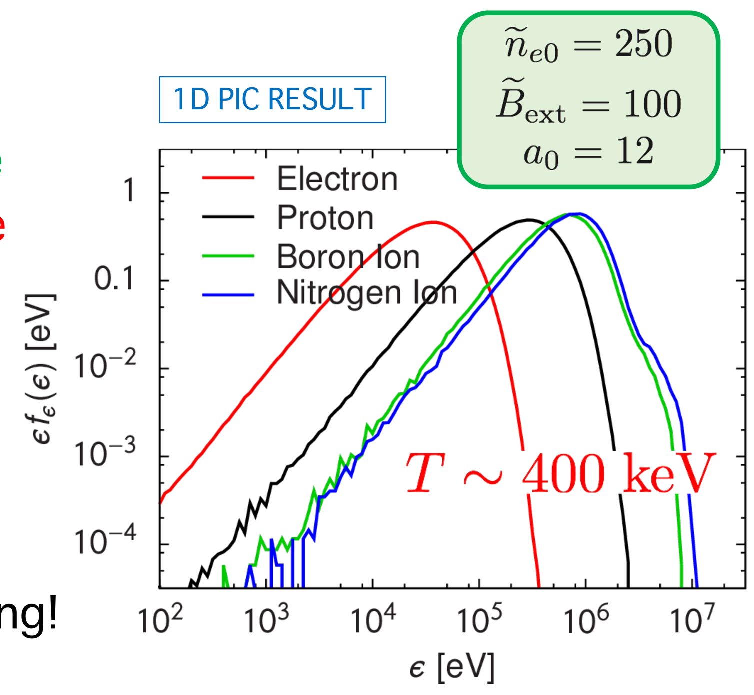


  - H_3B-NH_3
  - Higher H Density than H Ice
  - Solid at Room Temperature
- Proton-Boron Reaction

$${\rm p} + {}^{11}{\rm B} \to 3\alpha + 8.7\ {\rm MeV}$$

  - "Ultraclean" Reaction
  - Require over 400 keV

... but it's no problem for standing whistler wave heating!



10. Summary

"Standing Whistler Wave Heating" can generate thermal fusion plasmas over 10 keV.

1. Efficient Neutron Source
2. Alternative Fast Ignition Scheme
3. Aneutronic Proton-Boron Reaction

What's Next

- Quest for Mega-Tesla Field (Maybe by Self-Generated Field)
- PIC (or MHD) with Nuclear Reactions
- Optimization of Laser-Plasma Parameters for Efficient Ion Heating (Magnetosphere, Tokamak, ...)