Enhanced ion heating in short-pulse laser-driven buried-layers for NEET/NEEC

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Enhanced ion heating for NEET/NEEC

Motivation
• NEET/NEEC in high rep-rate short-pulse laser experiments
• **CONCEPT:** Enhanced heating in buried layers

Systematic study of enhanced ion heating
• Full solid density, self-consistent ionization, no numerical heating...
• Parameter dependence of energy transfer and ion heating at high laser intensity

Future work
• Simulation of optimized, high Z layers
• Characterization with XFEL at HIBEF
NEEC/NEET with Short Pulse Laser

- $^{169}\text{Tm}$ NEET/NEEC with 150 TW DRACO laser @ HZDR (4 J/30 fs/10 Hz)
- Isochoric heating to keV temperatures (Sentoku et al, PoP 14, 122701, 2007)
- Streaked spectroscopy at 8.4 keV
  → discriminate 4.1 ns nuclear decay from few-ps plasma emission

150 TW few Hz

Au / $^{169}\text{Tm}$ / Au target

atomic

nuclear

$^{169}\text{Tm}$

$\text{M} \to \text{L} \to \text{K}$

$E \to \text{G}$

$\lambda$

X-ray Streak

conical HOPG

A. Kritcher et al., JINA Workshop, London
March 13, 2011
Concept: isochoric heating in buried layers


- Electron pressure-gradient-driven pusher – calculated at 20 $n_{cr}$
- CD2 chosen, in order to use D-D fusion neutrons as ion diagnostic

$^{169}$Tm layer

4 J, 25 fs

< 10 Hz

Au layers

- few keV
- 10 g/cc
- few ps
Concept: isochoric heating in buried layers

"Isochoric heating in heterogenous solid targets with ultrashort laser pulses,"
Predicted Excitation Rates in $^{169}$Tm

• $kT \sim 1\text{-}2$ keV,
• solid density $\sim 9.3$ g/cm$^3$
• Peak Excitation rate $\sim 7 \times 10^7$ /s

G. Gosselin, CEA

M. Chen/A. Kritcher, LLNL

100 g/cm$^3$

$1 g/cm^3$
Signal rate predicted in short-pulse NEEC/NEET experiment

- Short-pulse separates excitation from decay
- High Repetition rate allows signal averaging & systematics
  - Verify excitation rates, and
  - resolve unknowns (e.g., Lifetime vs. Plasma Temperature)

- High-rep-rate 150 TW laser “Draco” at HZDR
- tamped targets – short-pulse isochoric heating
- large collection HOPG
- Fast X-ray streak, few ps (plasma emission)
- Slow X-ray streak, few ns (nuclear decay)

150 TW few Hz

\[ \text{Au} / ^{169}\text{Tm} / \text{Au target} \]

\[ \text{conical HOPG} \]

\[ \text{X-ray Streak} \]

\[ \lambda \]

\[ t \]

\[ \text{The half-life is predicted to decrease to 30 ps!} \]

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\[ \begin{align*}
  &\text{• } kT \sim 1-2 \text{ keV, } \sim \text{solid density, } \sim 10 \text{ } \mu\text{m}^3 \\
  &\text{• Rate } \sim 7.10^7 /\text{s}, \text{ Int. Conv. Coeff. } \alpha = 263.5 \\
  &N_\gamma \sim (4\times10^{11} \text{ nuclei})(7\times10^7)(10^{-12} \text{ s})(1/\alpha) \sim 10^5 \text{ per shot} \\
  &\text{HOPG efficiency } \sim \text{ few } 10^{-4}, \quad Q_E \sim 0.2 \\
  &\text{Signal: } (\text{few } \gamma / \text{ shot}) \times (\text{few shot / s}) \sim 10 \text{ s}^{-1}
\end{align*} \]
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  L. Huang et al, Phys. Plasmas 20, 093109 (2013)

Future work
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Particle in Cell simulation parameters

Laser parameters

<table>
<thead>
<tr>
<th>$\tau_{\text{FWHM}}$ [fs]</th>
<th>$I_0$ [W/cm²]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$2 \times 10^{19}$</td>
</tr>
<tr>
<td>500</td>
<td>3 J</td>
</tr>
<tr>
<td>400</td>
<td>2.4 J</td>
</tr>
<tr>
<td>300</td>
<td>1.8 J</td>
</tr>
<tr>
<td>200</td>
<td>1.2 J</td>
</tr>
<tr>
<td>100</td>
<td>0.6 J</td>
</tr>
</tbody>
</table>

Target configuration

- $\rho_{\text{CD}_2} = 1.1$ gcm$^{-3}$ (320$n_c$)
- $\rho_{\text{Al}} = 2.7$ gcm$^{-3}$ (780$n_c$)
- $\omega_{\text{FWHM}} = 5$ µm
- 2 µm 1 µm 2 µm

Numerical parameters

- $N_x \times N_y = 9000 \times 4500$
- $\Delta x \times \Delta y = \lambda_0 / 150 \times \lambda_0 / 150$
- $\Delta t = \Delta x / c$ (Directional splitting)
- $\omega_{\text{plasma}} \Delta t \approx 1.2 < 2$
- Deuteron / Carbon / Aluminum ion number per cell : 24 / 12 / 18
- maximum macro particle number : $\sim 0.5 \times 10^9$
- macro particle per real particle : $\sim 1000$
- interpolation order : 4

Particle in Cell simulation parameters

T.E. Cowan | Helmholtz International Beamline for Extreme Fields (HIBEF) at European XFEL | www.hzdr.de/hgbeamline

NIF to Stars, ACS, San Francisco, 10.08.2014
Ion heating dynamics in buried layer targets

Laser generated fast electrons propagate into target

Electrons $> 10$ keV and propagate quasi-ballistically into target

Velocity distribution for all electrons along laser axis

$100$ fs laser pulse

Hot forward electrons

\[ l_e = \frac{3(k_B T_e)^2}{4\sqrt{2\pi n_e e^4 \ln \Lambda}} \]
Ion heating dynamics in buried layer targets

Processes:
- Ionization dynamics
- e\textsuperscript- filamentation
- Hole-boring
- Channeling (hydro)
- Ion heating
- Interface "shocks"
- Colliding shocks
- Magnetic filaments

L. Huang, M. Bussmann et al., Phys. Plasmas 20, 093109 (2013)
Ion heating dynamics in buried layer targets

Net return current

Asymmetric electron velocity distribution (in laser propagation direction):
-0.2c < v_x < 0 indicates a net bulk return current.

Velocity distribution for all electrons in laser axis

100 fs laser pulse

Return Current

Collisional heating of electrons

- return e⁻
- e⁻ from ionization

Velocity distribution for all electrons in transverse direction

Collisional Effects

100 fs laser pulse

Symmetric distribution in z component
Ion heating dynamics in buried layer targets

Temporal evolution of bulk electron temperature

electron velocity distribution  →  electron thermal temperature

t=-1310.496fs
L(t)=7.9192e-007[10^{18} W/cm^2]

Temporal evolution of bulk electron temperature

Laser profile

T_{bulk} [keV]
Ion heating dynamics in buried layer targets

Ionization evolution: creates more free electrons

→ Collisional ionization of bulk as $T_e$ increases
→ At ~ -250fs, the target is almost fully ionized

Ion heating dynamics in buried layer targets

$\rightarrow$ CD$_2$
$\rightarrow$ Al
$\rightarrow$ CD$_2$

$x [\mu m]$
Ion heating dynamics in buried layer targets

Internal expansion driven by electron pressure gradient driven
Ion heating dynamics in buried layer targets

Ion collective motion driven by the internal electrostatic field

- Al layer acts like a piston pushing CD$_2$ layer forward
- Density of CD$_2$ layer compressed ~1.5x
- No mixing of Al ions with C and D C ions
- $\sim 10^{11}$ V/m electrostatic field associated with expansion front $\rightarrow$ accelerates ions inside target
- Expansion velocity is close to ion sound speed $\rightarrow$ not a shock wave
Enhanced ion heating by the internal expansion

Internal expansion region: ion beam kinetic energy transferred to ion thermal temperature → enhanced ion heating
Scaling of deuterium thermal temperature in the expansion region

- (a) $\tau_{\text{FWHM}} = 500$ fs
- (b) $\tau_{\text{FWHM}} = 400$ fs
- (c) $\tau_{\text{FWHM}} = 300$ fs
- (d) $\tau_{\text{FWHM}} = 200$ fs
- (e) $\tau_{\text{FWHM}} = 100$ fs

$T_D$ [keV] vs. $t$ [fs] for different fluences:
- Red: $2 \times 10^{19}$ W/cm²
- Green: $5 \times 10^{19}$ W/cm²
- Blue: $1 \times 10^{20}$ W/cm²
- Cyan: $2.8 \times 10^{20}$ W/cm²
- Pink: $5 \times 10^{20}$ W/cm²
Scaling of deuterium beam kinetic energy in the expansion region

(a) \( \tau_{\text{FWHM}} = 500 \, \text{fs} \)

(b) \( \tau_{\text{FWHM}} = 400 \, \text{fs} \)

(c) \( \tau_{\text{FWHM}} = 300 \, \text{fs} \)

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(e) \( \tau_{\text{FWHM}} = 100 \, \text{fs} \)

- Red: \( 2 \times 10^{19} \, \text{W/cm}^2 \)
- Green: \( 5 \times 10^{19} \, \text{W/cm}^2 \)
- Blue: \( 1 \times 10^{20} \, \text{W/cm}^2 \)
- Cyan: \( 2.8 \times 10^{20} \, \text{W/cm}^2 \)
- Magenta: \( 5 \times 10^{20} \, \text{W/cm}^2 \)
Ion heating dynamics in buried layer targets

Scaling of ion heating – fractional energy transfer rate, $R(t)$ from directed ion kinetic energy to transverse, thermal energy

$$\int_0^\infty E_{\text{shift}}(t) = \tau_{\text{FWHM}} + \text{const.}$$

$E_{\text{shift}}(t) = m_D v_{\text{shift}}(t)^2 / 2$

$R(t)$ is approximately independent of time. Decreases weakly with intensity:

$$R(t) \sim \text{const} \sim I^{-0.29}$$

A combination of several collisional processes, and collective plasma effects, appear to contribute to the enhanced deuteron heating... work in progress
Enhanced ion heating for NEET/NEEC

Summary

• Numerical stable (!) simulations of buried layer heating at solid-density (!)

• Self-consistent treatment of electron return current, collisional ionization and bulk electron heating, and collisional ion heating

• Dense plasma pusher – directed ion acceleration

• Collisional ion energy transfer to thermal motion

• Up to keV temperatures predicted (2D, but not optimized)

• Energy transfer rate decreases with increasing laser intensity (roughly consistent with ion collision frequency)

• Buried layer ion heating might be able to reach NEET/NEEC relevant conditions
Enhanced ion heating for NEET/NEEC

Future work

- Optimize layer thickness and elemental composition
- Extend to high Z, relevant for NEET/NEEC nuclides
- Use DD neutron yield to verify ion heating
- Use neutron energy versus angle to determine DD-beam fusion (shift), from thermal fusion (broadening).
- Combine NEET/NEEC with XFEL probing (coherent diffraction imaging, Thomson scattering), to simultaneously determine ion density and temperature

-- Example, HIBEF at European XFEL

Thank you for your attention....