Multi-Stage Laser Ion Acceleration

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Presentation Outline:

1. Purpose & Issues
2. Background – Previous studies in Laser foil interaction
3. Multi-stage laser ion acceleration
   in laser gas plasma interaction
1. Conclusions
**Ion Accelerator and Ion Beam**

/ Ion fusion  
/ Ion cancer therapy  
/ material procession, ...

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**Issues of Laser Ion Accelerator**

1. Ion beam quality  
   --- transverse divergence  
   --- energy & spectrum control  
2. Low energy efficiency from laser to ion beam  
   ~ a few % or less  
3. Total number of ions accelerated  
   ~ $10^{12}$ particles or so  
4. Low laser efficiency
Background: Collimated Ion Beam

Origin of ion beam divergence:
/ Edge fields of ion source & electron clouds
/ Ion beam temperature

Suppression of transverse proton divergence
by shielding edge fields of electron cloud & ion source.

Simulation Results

Target density \( n_F = 2 \times n_c = 2.01 \times 10^{21} \text{ cm}^{-2} \)

Proton

Maximum Kinetic Energy of Proton
Forward: 3.73 MeV  Backward: 2.89 MeV
Collimated Ion Beam

High-density plasma shields the edge field.

Laser
Thin Foil

Initial Target Profile

Target of Case A is the conventional slab foil plasma.
Target of Case B has a hole at the opposite side of the laser illumination.

Gradation part in figures mean density gradient.
Simulation Model of 2.5D PIC Simulations

- Gaussian pulse: 20fs
- Target Density: Solid Double Layer Target: consists of Al and H

**Incident laser**
- \( I_L = 1.0 \times 10^{20} \text{ [W/cm}^2 \text{]} \)

**Double Layer Target:** consists of Al and H

**Initial Parameter Values**

- **Intense laser pulse**
  - Wave length: \( \lambda_L = 1.053 \text{[\mu m]} \)
  - Gaussian laser duration: \( t_L = 20 \text{[fs]} \)
  - Laser intensity: \( I_L = 1.0 \times 10^{20} \text{[W/cm}^2 \text{]} \)
  - Laser spot diameter: \( r_L = 4\lambda_L \text{ (FWHM)} \)

- **Target**
  - Double layer target consists of Al and H
  - Initial density: solid
  - Initial distribution: Partial balance-Maxwell
    - distribution (temperature \( T_e=1.0, T_i=1.0 \text{[KeV]} \))

- **Calculation conditions**
  - The calculation mesh size \( \Delta x=\Delta y \) is 0.02\( \lambda \)
  - The integration time step \( \Delta t \) is 0.04 \( \times \Delta x/c \)
  - We employ about 1.6-million super particles in our simulations

No. 22
Proton Distribution in X-Y Space in Case A

![Proton Distribution in X-Y Space in Case A](image)

Proton Distribution in X-Y Space

![Proton Distribution in X-Y Space](image)

The proton beam transverse divergence of Case B is suppressed successfully by the shaped target and the electron cloud localization.
Robust hole target against laser alignment

Hydrogen
Aluminum

The laser illumination pattern B
pattern A

Robust hole target against laser alignment

(a) Pattern A  (b) Pattern B

Hydrogen
Aluminum

The laser illumination pattern B
pattern A

[(Graphs and diagrams showing distribution and analysis related to hydrogen and aluminum with labels Pattern A and Pattern B. Diagrams illustrating laser illumination patterns.)]
Energy Efficiency Enhancement
From Laser to Ion Beam

2. Low energy efficiency from laser to ion beam
   ~ a few % or less
⇒
/ jaggy or rough surface target
/ cluster, amorphous, many-holes. ...
/ long life of electrons

Energy Efficiency Enhancement
From Laser to Ion Beam

2. Low energy efficiency from laser to ion beam
   ~ a few % or less
⇒
/ long life of electrons
⇒ long life of acceleration E-field
Ion Acceleration

Target density \( n_F = 2 \times n_c = 2.01 \times 10^{21} \text{cm}^{-2} \)

Electrons oscillate in a potential well of the ESF with a high frequency

The number of the electrons to sustain the ESF wave depends on the energy of the electrons

Energy Efficiency Enhancement

From Laser to Ion Beam

2. Low energy efficiency from laser to ion beam
   \( \sim \) a few % or less
   ☑️ long life of electrons
Laser absorption and ion acceleration in micro-structured targets

Figure 5. a) Scanning electron microscope (SEM) image of the target surface covered by monolayer of polystyrene spheres with the diameter of about 0.9 µm. b) SEM image of a thin mylar foil (100 mm) covered by polystyrene-spheres (0.26 µm). Image is taken at the border of the foil, where the spheres are not regularly arranged due to the cutting process. c) Atomic force microscope image of the surface of a commercial commercially available (supplied by Goodfellow SARL) thin Aluminum foil (2 µm thick).

Figure 11. The energy distribution of protons accelerated from the rear side of targets A and C (from table 2) and the targets with density profiles plotted in figure 10. The distributions are compared 0.2 ps after the laser target interaction. (b) The energy distributions of protons accelerated out of the target from its front side. The distributions for thin and bulk targets are compared 1.3016 after the laser target interaction.
**Intense laser pulse**
- Wave length: $\lambda_L = 1.053\mu m$
- Gaussian laser duration: $t_L = 100[fs]$
- Laser intensity: $I_L = 5.0 \times 10^{20}[W/cm^2]$
- Laser spot diameter: $r_L = 4\lambda_L$ (FWHM)

**Target**
- Double layer target consists of Al and H
- Initial density: solid
- Initial distribution: Maxwell distribution (temperature $T_e=1.0, T_i=1.0[KeV]$)

**Calculation conditions**
- The calculation mesh size $\Delta x = \Delta y$ is 0.02$\lambda_L$
- The integration time step $\Delta t$ is $0.04 \times \Delta x / c$
- We employ about 1.6-million super particles in our simulations
Laser -> protons
1.5%

Laser -> protons
9.3%
Problems of Laser Ion Accelerator

1. Ion beam quality
   --- transverse divergence
   --- energy & spectrum control <=

2. Low energy efficiency from laser to ion beam
   ~ a few % or less

3. Total number of ions accelerated
   ~ $10^{12}$ particles or so

Energy Spectrum Control

1. Ion beam quality
   --- energy spectrum control
   / very thin ion source < skin depth
   / double layer – flying or fixed

[Diagrams showing Ambipolar Field, Virtual Cathode, grid, C and H ions, flying and fixed]
Laser: intensity $10^{20}$ W/cm$^2$
  wavelength 1 µm
  duration 15 fs
  pulse shape $\sin^2$
  polarization P
  spot size 3 µm
  incidence angle 0°

Foil: thickness 300 nm
  density 0.4 g/cm$^3$
  composition CH$_2$
  ion charge state C$^6+$, H$^+$ initial temperature 1 eV
  profile step-like boundary conditions
  thermalization of fast electrons

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case 3 periodic array with structure composed of boxes of 60 nm × µm separated by 0.25 µm,
material composition C$^6+$, density 0.35 g/cm$^3$

⇒ Flat target: 2.8% (Laser -> ions)
  Structured target: 26% (Laser -> ions) case 3 (20% C, 6% Protons)
Problems of Laser Ion Accelerator

1. Ion beam quality
   --- transverse divergence
   --- energy & spectrum control <=

2. Low energy efficiency from laser to ion beam <=
   ~ a few % or less

3. Total number of ions accelerated
   ~ $10^{12}$ particles or so

Multi-stage laser ion acceleration

Control of ion energy & enhancement of energy efficiency

Near-critical-density Plasma target for multi-stage acceleration
これまでの研究において、薄膜ターゲットに多数の穴を設けたマルチホールターゲットを考案し、レーザーからプロトンへのエネルギー変換効率を飛躍的に上昇させることに成功した。また、ターゲット後方にウォールを設けることでプロトンの発散を抑制できることが可能である[1,2]。


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**Laser particle acceleration mechanisms**

- **TNSA (Target Normal Sheath Acceleration)**
  - Laser → electron current → $B_\theta$
  - $\frac{\partial B_\theta}{\partial t} \rightarrow E_{//}$

- **RPA (Radiation Pressure Acceleration)**
  - Laser photon pressure accelerates a very thin foil

- **Inductive field acceleration**

- **Coulomb explosion**

......, etc
Laser accelerates electrons

→

Strong electron current generates a strong magnetic field.

→

At the increase phase of the magnetic field, ions are accelerated.

→

The acceleration field moves forward. Ions could be accelerated for a longer time.

Synchronization of ion beam with acceleration electric field motion enhances controllability of ion energy & spectrum.
**Laser plasma Interaction**

Electric field (Ex) $t = 130\text{fs}$

Magnetic field $t = 130\text{fs}$

1st & 2nd stages: TNSA + little inductive acceleration
3rd & 4th stages: Inductive acceleration + little TNSA

**Target model**

Plasma Target density : $0.7n_c$

- Density profile
- Laser parameter:
  - Intensity $I_L = 1.0 \times 10^{20} \text{ W/cm}^2$
  - Pulse duration $\tau_L = 40 \text{ fs}$
  - Spot diameter $r_s = 10.0\lambda$
  - Wave length $\lambda_L = 1.053 \mu\text{m}$

$\eta_c$ : Critical density
$N$ : refraction index
Multi-stage laser ion acceleration

Energy efficiency from laser to ions

<table>
<thead>
<tr>
<th>Energy Efficiency [%]</th>
<th>800fsにおけるエネルギー変換効率 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton</td>
<td>35.5</td>
</tr>
<tr>
<td>Electron</td>
<td>27.8</td>
</tr>
<tr>
<td>Proton and Electron</td>
<td>63.3</td>
</tr>
</tbody>
</table>

Multi-hole target 16.7%
**Speed of inductive acceleration field**

<table>
<thead>
<tr>
<th>Target density [$n_c$]</th>
<th>Speed of inductive field [m/s]</th>
<th>Speed of inductive field</th>
<th>Group speed $V_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>$1.504 \times 10^8$</td>
<td>0.501$c$</td>
<td>---</td>
</tr>
<tr>
<td>0.7</td>
<td>$1.872 \times 10^8$</td>
<td>0.624$c$</td>
<td>0.548$c$</td>
</tr>
<tr>
<td>0.5</td>
<td>$2.212 \times 10^8$</td>
<td>0.740$c$</td>
<td>0.707$c$</td>
</tr>
<tr>
<td>0.1</td>
<td>$2.874 \times 10^8$</td>
<td>0.957$c$</td>
<td>0.949$c$</td>
</tr>
</tbody>
</table>

$v_g = c \sqrt{1 - \omega_{pe}^2 / \omega^2}$

Synchronization of ions with the inductive E field speed enhances ion energy & controllability of ion energy & spectrum

**Proton distribution in space**

1st acceleration

Ion beam accelerated is transferred to the second stage.
Proton distribution in space
2nd post-acceleration

Laser

2nd post-acceleration

Target and Ion beam t=0fs
(a)

Target and Ion beam t=600fs
(b)

Ion beam t=0fs
(c)

Ion beam t=600fs
(d)

[MeV]

Proton distribution in space
3rd post-acceleration

Laser

3rd post-acceleration

Target and Ion beam t=0fs
(a)

Target and Ion beam t=500fs
(b)

Ion beam t=0fs
(c)

Ion beam t=500fs
(d)

[MeV]
Proton distribution in space
4th post-acceleration

Maximal proton energy history

1st & 2nd: TNSA
3rd & 4th: Inductive acceleration + TNSA

<table>
<thead>
<tr>
<th>Proton max energy [MeV]</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
<th>4th</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>38.9</td>
<td>89.9</td>
<td>149</td>
<td>254</td>
</tr>
</tbody>
</table>
4th stage: Acceleration E field on the axis & ions

90fs<t<160fs: inductive acceleration
160fs<t: TNSA

Ions between 20λ < x < 30λ.
Conclusions

Efficient controllable laser ion acceleration

1. Ion beam quality
   --- transverse divergence
       => Collimator (larger (>λ) hole structure)
   --- energy & spectrum control
       => Synchronization / multi stage acceleration / post acceleration, ...

2. Low energy efficiency from laser to ion beam
   ~ a few % or less
       => sub λ fine structure / synchronization for a longer acceleration period

3. Total number of ions accelerated
   ~ \(10^{12}\) particles or so
       => larger spot size, larger laser energy, ...