Cascaded laser acceleration of carbon ions from double-layer nanotargets

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Acceleration of energetic heavy ions

- 5 MeV/u F\textsuperscript{7+} obtained by heating the targets

Status of heavy ion acceleration in TNSA

![Graph showing the relationship between laser pulse energy and maximum ion energy for various elements. The graph highlights the TNSA region.]
Why heavy ion acceleration is inefficient in TNSA

1. Contamination problem
   - acceleration field built by dilute hot electrons ($\sim n_c$)
   - 1 nm*(10um)$^2$ contamination layer contains $10^9$ protons, which can easily diminish the field

2. Ionization and injection problem
   - sheath field/collisional ionization is evolving
   - Ions with highest stage-of-charge are injected only after the peak of the intensity

3. Acceleration time problem
   - Heavy ions can not gain the full potential energy before the fade of the sheath field if the pulse duration is too short

\[
E_{\text{sheath}} \approx \sqrt{4\pi n_h k_B T_h}
\]
BOA & Relativistic Transparency


- Maximum ~83 MeV/u C$^{6+}$
- ~80 J, 550fs


- Peak at 18.3 MeV/u C$^{6+}$
- ~80 J, 550fs
Heavy ion acceleration in RPA

1. Contamination problem
   - Acceleration driven by bulk electrons instead of dilute thermal electrons

   **Superior to TNSA**

2. Ionization and injection problem
   - Additional optical field ionization happens at the laser-plasma interface

   **Superior to TNSA**

3. Acceleration time problem
   - Hole-boring and plasma instability lead to early end of the acceleration process
   - Fast fade of acceleration field after the reflection of laser pulses

   **Inferior to TNSA**

\[ E_{\text{separation}} \approx 4\pi \rho \epsilon_0 d \]

\[ N_e^{\text{sep}} \sim N_i^{\text{all}} \]
Heavy ion acceleration in RPA regime


- Maximum ~5 MeV/u C⁶⁺
- ~0.7 J, 45 fs

C. Scullion, PRL 119, 054801 (2017)

- Maximum ~25 MeV/u C⁶⁺
- ~6 J, 50 fs
Protons by RPA

Heavy ions by RPA

Maximum ion energy (MeV/u)

Laser pulse energy (J)
Plasma lens enhanced RPA

- ~20 MeV/nucleon quasi-monoenergetic $C^6^+$ generated
- $2 \, n_c$ near-critical density plasma lens
- ~5 J, 50 fs

Near-critical-density (NCD) plasma lens

With the propagation of laser pulse within NCD plasma, it becomes shorter, front-steepened, and strongly self-focused. If we use such shaped laser pulse in ion acceleration, the acceleration field will increase because of the enhanced intensity, and the major acceleration process can be finished before the break of the plasma thin slab.

3D simulation showing the pulse shaping process in $2n_c$ plasma

Intensity increased by 10
Pulse duration reduced by 50%.

Key targets: Carbon nanotube foams

Carbon nanotube foam (CNF): ~1% solid density, highly homogenous at um scale, as thin as a few um, will become homogenous plasma with density around critical density, can be used as plasma optics.
Hydrodynamic simulations on the expansion of CNTs
Step 1: Catalysts Sublimation

CNF sample on Si wafer

Step 2: Nanosized Catalysts Sprayed out

Step 3: Short Tubes Form in the Air and Grow

Step 3: Deposition

Microbalance

Optical profiler
Cooper spheres
D=1-3um

Height of the imaging plane

Mass vs deposition time

thickness vs deposition time

density vs deposition time
Parameters scan for double-layer targets

\[ a=21, \text{FWHM}=45\text{fs} \]

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Sub-classification of near-critical-density plasma

Zone I: relativistic transparent

\[ 1 < n_e < \gamma n_c \]

Strong pulse shaping


Zone II: slightly sub-critical

\[ 0.1 < n_e < 1 \]

Moderate pulse shaping, high-energy electron generation

Simulation results

\[ a=15, \, n_{e1}=0.2n_c, L_1=60 \, \text{um} \]

\[ (\gamma_e - 1)n_e \]

Laser field

Longitudinal E field

ultrathin foil
Cascaded acceleration

Laser shaping and electron flow generation

Stage 1:
Radiation pressure acceleration
Sheath field acceleration

Stage 2:
ultrathin foil
ultrathin foil
ultrathin foil

ultrathin foil

ultrathin foil
ultrathin foil

ultrathin foil

ultrathin foil
Energy spectra of electrons and ions after the RPA stage

$a=15, \, n_{e1}=0.2n_c, L_1=60\, \mu\text{m}$
Instant energy increment for tracked carbon ions

![Graph showing energy distribution over time](image)

- **Energy increase (MeV/fs)**
- **Energy Distribution**

**Axes:**
- Y-axis: Energy increase (MeV/fs)
- X-axis: Time (fs)

**Legend:**
- Black line: 0 µm
- Red line: 60 µm
- Blue line: 120 µm
- Purple dashed line: 2 $n_c$

**Timeline markers:**
- Laser arrival
- Laser reflected
Energy distribution among laser, particles and fields

70% energy of carbon ions comes from sheath acceleration stage.
1.5 PW laser (PULSE) in Center for Relativistic Laser Science (IBS), Korea

Experimental results

25fs-30fs,
Double plasma mirror,
9.2J on targets for LP,

I = 5.45 \times 10^{20} \text{ W/cm}^2 , a_0 = 16

CNF density fixed to 0.3 \pm 0.1 n_c
Raw data from Thomson parabola spectrometer

Single layer target
20 nm DLC

Double-layer target
20 nm DLC+80 um CNF (optimal parameters)
Energy spectra of the best shot

- Proton
- Carbon

CNF thickness scan

- Maximum energy (MeV/u) vs. CNF thickness (μm)
- Simulation vs. Experimental data
Cascaded acceleration

\[ E \propto I^{0.6} \]

- ~8.5 J, 30fs


- ~7.4 J, 30fs
Laser accelerator team at Peking university
CLAPA Laser Parameters

**Pulse Energy:** 5 J /5Hz

**Pulse Duration:** < 25 fs

**Wavelength:** 800 nm

**Contrast Ratio:**
- $10^{10}$:1 @ 100 ps
- $10^9$:1 @ 20 ps
- $10^6$:1 @ 5 ps
- $10^3$:1 @ 1 ps
The first proton Beam test

1) Position 1: Chamber
2) Position 2: Quadrupole
3) Position 3: Before BM
4) Position 4: After BM
5) Position 5: Radiation Platform

(3-15MeV)
Proton Beam before beam-line

Layout of target chamber

Laser parameters:

Energy 1.8J
Duration 30fs
Intensity $8.3 \times 10^{19}$ W/cm$^2$
Angle: 30 degree
Spot: 4.5μm×5.3μm
Proton Beam before beam-line

Shooting nanometer foils, without using plasma mirror, very good contrast can be confirmed!

- 15MeV
- 0.02-1.2μm plastic foil
Proton energy stability <3% in ~10 shots, 1.8J/30fs on target

Thanks to:
- Target flatness
- Laser (2%)
- Beam target coupling (3μm)

Ultra Stable acceleration

Proton energy stability <3%
Proton Emittance is measured by Pepper pot

A.L.Zhang, et al., submitted
Components of the beam-line

overview

Dipole magnet

Biomedical Irradiation platform

On-cite fluorescence microscope
Proton Beam at Position 2: Quadrupole

The proton charge on MCP was Significantly enhanced:

- 3.5 MeV × 7
- 4.5 MeV × 20
- 5.5 MeV × 20

energy spectrum with Angular resolution

B=0

Focusing 3 MeV

Focusing 4 MeV

Focusing 5 MeV
Beam at Position 3: before Bending Magnet

Very good proton beam pointing

70 (2.75MeV) 70 (2.75MeV)
70 (2.75MeV) 140 (4.3MeV)
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