ultrashort PW lasers pulse interaction with target and ion acceleration

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ion acceleration

- protons / ions

General interest in the field

- physics of laser driven radiation sources and their possible applications
- High energy phenomena and transport
- Knowledge of physics has impact on:
  1. fundamental physics – cosmology
  2. high-field laser physics
  3. fusion
  4. light and particle sources
- Laboratory astrophysics

aim:

to develop laser-driven sources of high energy protons, ions (and gammas) as a reliable, generic technology for applications
what will bring the laser development in the near future?

$I^a < \text{Scaling, } a > 1$

$I^{0.5} < \text{Scaling} < 1$

experiments
- 300fs – 1 ps
- 40-60 fs
- 100-150 fs
- simulations

maximum proton energy (MeV)

$I\lambda^2 \ (\text{Wcm}^{-2} \cdot \mu\text{m}^2)$


**using PW, short laser pulse for ion acceleration**

**Research Goals**

1. To achieve high proton energies via laser and target parameters optimisation.

2. Scaling and optimisation of proton beams driven by TNSA mechanism for applications.

- TNSA regime - is the only virtually stable and reliable way to accelerate ions

**We aim to investigate:**

- irradiation conditions
- proton acceleration
- proton source and beam properties
proton beams for applications

\[ \Delta \tau \sim 30 \text{ fs} \]
\[ \varepsilon = 30 J \]
\[ I \sim (0.5 - 5) \times 10^{21} \text{ W/cm}^2 \]

Contrast \( > 10^{12} : 1 \) at ns
\[ 10^8 : 1 \text{ at 4ps} \]

Targets - 0.2 – 6 \( \mu m \) Al

\( \sim 2 \times 10^{20} \text{ W/cm}^2 \) 7 J
50 nm C

Ion spectra

Contrast > 10^{12} : 1 at ns
\[ 10^8 : 1 \text{ at 4ps} \]

Targets - 0.2 – 6 \( \mu m \) Al
back reflex of PW, fs laser pulse at oblique incidence on the target

(0.1 - 1.2) \times 10^{21} \text{ W/cm}^2

incident angle 30 degree,

Al targets:

The energy and the spectrum of back reflected radiation were monitored throughout the experiments

2D PIC simulations

(simulation by Alexander Andreev)

\[ I = 2 \times 10^{21} \text{ W/cm}^2 \text{ in 4 \( \mu \text{m}, 30 \text{ fs, Gaussian, p- pol.}, \) target - 2 \( \mu \text{m} \) Al}^{+13} \]

incident angle 30 degree, no pre-plasma

**electron density profile on the target during the laser pulse**

PIC simulations have demonstrated:

- due to the light pressure the reflecting surface is curved
- the generation of regular structure in the electron density profile.

This structure can act as a grating and a significant amount of laser energy is reflected back.
back reflection coefficient

the grating period $d = \lambda / \sin \theta$ gives the diffraction peak of second order ($n = 2$) in the backward direction.

**The observed phenomena can have serious consequences when using PW laser systems in the interaction experiments.**

proton ion acceleration

"best" shots

laser intensity (W/cm²)

proton max energy (MeV)

Al Foil

1.5 μm
6 μm
2 μm
1.5 μm
0.4 μm
0.2 μm

proton max energy (MeV)

laser intensity (W/cm²)

protons

laser

RSTN

FSTN

protons

proton ion acceleration

~I 1

~I 0.5

laser intensity (W/cm²)

proton max energy (MeV)
intensity scaling of proton-energy

1.5 μm Al

forward-proton-E-max (MeV)

Backward-proton-E-max (MeV)

Laser Intensity (W cm\(^{-2}\))

defocusing effect

laser energy effect

steeper intensity dependence
proton acceleration by High contrast, relativistic laser pulse

The electrostatic field within the positively charged cavity cratered at the target front accelerates the ions to high energy

conclusions

- Rear side protons energy scaling $\sim 1$
- Front side energy scaling $\sim 0.5$
- It is also unclear why the intensity scaling is different when the focusing is changed and the energy is changed (??)
- almost independent on target thickness(??)

There is still life in the established TNSA mechanism
Proton source and beam properties
• propagation of protons is ballistic
• no ion interaction within the beam

The size and relative change of “virtual source” position dependant on proton energy

3 MeV

4 MeV

5 MeV

6 MeV

25 µm

20 µm

10 µm

8 µm

For any projection imaging experiments, e.g., in proton radiography or deflectometry, source size largely affects the spatial resolution of the image.
Mesh image as a pepper pot emittance probe was used to measure the transverse emittance of the ion beams:

\[ \varepsilon_{nt} < 0.05 \pi \text{ mm mrad} \]

the emittance of the beam is preserved in the whole measured spectral range

emission characteristics along and perpendicular to the laser polarisation direction:

in laser polarisation direction:
- the proton beams at different energies have the same divergence.

in perpendicular to laser polarisation direction:
- the divergence is increasing when particle energy is increasing.

the protons “virtual source” position was changing towards to the target when particles energy is increased.

These findings show the complex dynamic of the ion acceleration process which differs in parallel and perpendicular to laser polarisation direction.
the momentum distribution of protons in phase space

at the distance 50 μm from the target

- the protons with different energies exhibit different transverse momentum and therefore different divergence

- During further propagation the transvers momentum stays unchanged.

simulated proton image of the mesh

• mesh image formed by 4 MeV and 9 MeV beams are the same
temporal evolution of the transvers and longitudinal electric fields created by electron cloud around proton beam

- The transvers electric field at any time step is weak
- longitudinal electric contributes to the divergence of the beam

Fig. 5.
the duration of proton bunch is increased during the propagation

- the proton bunch width is shown for different energies

- high energies are affected more than low energies
particles trajectories are ray-traced from their given momentum values

the transvers and longitudinal el. fields in the beam have direct impact on the virtual source position at each energy
conclusions

in the determination of the field evolution

- the ultra-short burst duration ensures high temporal resolution (~ps),
- the laminarity, ultra-low emittance and small source size ensure high spatial resolution (~µm)

- moving source, which exhibit also different characteristics dependent on laser polarization direction may affect the quantitative analyses of the data

Further development of “proton deflectometry”

for continuous and 3D recording

of transient plasma fields

with sub-ps temporal resolution