Laser acceleration of charged particles from low-density targets for nuclear and gamma sources

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Outline

• Synchronized acceleration by slow light (SASL) in low-density targets for protons with maximum energy; Pion production.

• Electron acceleration from low-density targets \( n_e \lesssim n_{cr} \) for maximization of total charge; Deep gamma radiography; Photoneutrons.

• Interaction with nano/micro-structured (nano-rods/plates) \( n_e \sim 0.1n_s \) targets; Thermonuclear (dd) (dt) neutrons.

• Rarefied plasma for hew diagnostic of intense laser pulses.
Ion acceleration by ponderomotive sheath

Stopping of the laser pulse at the front of the target and then accelerate the infiltrating intense part of the pulse inside a plasma

Laser pulse front (gray)
Front of the proton bunch
3D PIC simulation of SASL

I

30 J, 30 fs, 4μm
SASL regime: linear vs. circular polarization

- $30 \text{ J, } 3 \times 10^{21} \text{ W/cm}^2$
- $\tau = 30 \text{ fs}$
- $2 \rho = 4 \text{ \mu m}$
- linear/circular polarization

$5 \times 10^9$ protons with energy $> 200 \text{ MeV}$

$1.3 \times 10^{10}$ protons with energy $> 200 \text{ MeV}$

1.6 times maximum energy increase

Advanced low-density targets for SASL

Carbon nanotube planar targets: thickness = 10-1000 nm, ρ = (30-80) mg/cm³

Prokhorov General Physics Institute, Russian Academy of Sciences

E. A. Obraztsova & Co, GPI RAS, Moscow

A.V. Brantov et al., PHYS. REV. A&B 20, N6 (2017), Laser-triggered proton acceleration from hydrogenated low-density targets
Spectra of protons accelerated from 20nm contamination layers of solid C-foil ($200n_c$, $l = 0.012\lambda$) (black curve) and low-density C-target ($20n_c$, $l = 6\lambda$) (gray curve). The dashed curve shows proton spectrum from low-density C-target with the same number of protons distributed near both boundaries with linear decreased density.

Volumetrically dopped low density targets give similar result
Electron acceleration from low-density targets

Electrons for deep radiography

\[ l = 0.5 \pm 2 \times 10^{21} \text{W/cm}^2 \]
\[ t_{\text{FWHM}} = 30 \text{fs} \]
\[ \varnothing = 4 \mu\text{m} \]

FIG. 1: Total charge of accelerated electrons with energies > 30 MeV vs. target thickness for several electron plasma densities \( (n_e/n_c = 0.05, 0.1, 0.75, 1) \).
Electron acceleration from a low-density target of optimal density

Electron bunch (>30 MeV)

Electron spectrum

High conversion coefficient to MeV electrons 16%
Electron acceleration. Stochastic injection.

$N_{\text{max}} = ?$

$\varepsilon_e N_{\text{max}} \sim A E_{\text{las}}, \varepsilon_e = m_e c^2 A^2 / 4$

$N_{\text{max}} = \frac{A E_{\text{las}}}{\varepsilon_e} \Rightarrow n_e \sim n_c$

optimum target thickness:

$l_0 = v_g c \tau_L / (c - v_g) \approx c^2 \tau_L / (c - v_g)$

M.G.Lobok, A.V.Brantov, D.A.Gozhev, and V.Yu.Bychenkov
DOI: 10.1088/1361-6587/aaca79
Electron conversion to gamma emission

Deep $\gamma$-radiography (10-20 cm dense matter)
Single shot radiography:
150 nQ

Several-PW lasers

$8 \times 10^{20} W/cm^2, \lambda=1\mu m, 30fs, d=4\mu m, n_e=0.1n_c, Q=7nC$

polar angular diagram for high-energy $\gamma$
Ta of 16 mm thickness

Angular $\gamma$ distribution

$\gamma$ spectrum
Conversion from laser to gamma-rays of (1-10) MeV ~ 0.93% and (1-150) MeV ~ 1.06%
Electron conversion to neutron emission

- Laser pulse
- Electron beam
- Target
- Converter
- MeV neutrons

\[ A + B \sin^2 \theta \]

Giant dipole resonance

8 \times 10^{20} \text{W/cm}^2, \lambda = 1 \mu \text{m}, 30 \text{fs}, d = 4 \mu \text{m}, n_e = 0.1 n_e, Q = 7 nC

4 \times 10^{-3} \text{neutrons/electron}

Conventional method: e-beam \rightarrow \text{Bremsstrahlung} \rightarrow n^0

Ta irradiated with 25.5 MeV Bremsstrahlung

The neutron detecting bias energy is set at 7.4 MeV.


34 MeV Bremsstrahlung

Interaction with nano/micro-structured (nanoforest) target of high averaged density

J. J. Rocca et al., *Laser Focus World*, May 2017

Neuron source


Average density as high as 0.1-0.15 $n_{sd}$

TiD$_2$ wires, $T_e \sim 100$ keV, $Y \sim n^2$
An interesting physics of rods heating. Neutron production

The deuteron density distribution in nanoforest target for $t = 0$ (a) and $t = 200$ fs (b), momentum distribution in (px; py) plane at $t = 130$ fs (c) for 400nm diameter of nanorod.

A.V. Brantov et al.: WeR5-13, ICLO 2018
Target (Lebedev Physics Institute, Russia)

typical length of ~1-1.5 μm and half-maximum width of ~0.3-0.4 μm

SEM images of laser-induced self-organized Ni surface: top- (a –general, b –magnified) and side (30°, c –general, d – magnified) views

S. Kudryashov et al.
Neutron production from nanorod targets

3D simulation

(a) The energy distribution of deuterons ($r_0 = 0.15 \, \mu m$), (b) the cut-off deuteron energy for $r_0 = 0.15 \, \mu m$ and $r_0 = 0.2 \, \mu m$, (c) the energy spectrum for $t = 240 \, fs$ along with theoretical fit for $T_h = 160 \, keV$, $T_c = 1 \, keV$ and $n_h/n_c = 0.01$.

Ti-rods with 25% D, or 12.5% D and 12.5% T

$I = 10^{18} \, W/cm^2$ for DT
$I = 10^{19} \, W/cm^2$ for DD

1 PW laser pulse yields $10^7$ neutrons per 1J of laser pulse energy (30 J, 30 fs)
Nanoplate targets as alternative

Target (Lebedev Physics Institute, Russia), S. Kudryashov et al.
Laser proton acceleration for laser intensity measurement

Energy spectrum of accelerated protons

$t_{FWHM} = 30 \text{ fs, } D_F = 1.3 \lambda$

Cut-off proton energy

Off-axis parabolic mirror

Focusing in diffraction limit

In collaboration with CUOS UoM, USA (A.M. Maksimchuk, A.G. Thomas)
Conclusions

• The new mechanism of synchronized ion acceleration by ultra-intense slow light (SASL) from low-density targets of the order of relativistic critical density maximizes ion cut off energy, that is useful for elementary particle production with laser accelerated protons.

• Low-density targets of sub-critical density are the best for production of electron bunches with maximum total charge.

• Several-PW lasers is needed for single shot deep $\gamma$-radiography by using low density targets.

• High-rep fs lasers of $10^{18} – 10^{19}$ W/cm$^2$ of several J irradiating nanorod/nanoplate targets will be competitive with conventional neutron sources.

• Direct proton acceleration from low-pressure gas can be used for laser intensity measurements in ultra-intense regime.
Thank you