Ion Acceleration to Therapeutic Energies in the Directed Coulomb Explosion Regime

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Outline:

- Introduction
- Directed Coulomb Explosion of ion acceleration
- Two-stage proton acceleration from hydrogen containing ultra-thin targets
- Relativistic plasma shutter
- Conclusions
Possible application of laser-driven proton accelerators

Nuclear Physics
- Ion beam of rare isotopes

High-Energy Physics
- Pion production

Warm dense matter
- Isochoric heating

Time resolved studies
- Radiography of dense plasmas

Medicine
- Hadron Radiotherapy
- Isotope production for PET

Fusion
- Fast ignitor
Ultrashort pulse Ti:S systems have high rep. rate advantage if the applications are considered.
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Regimes of Proton Acceleration

**Coulomb Explosion Regime**
- Requires high contrast which allows to use sub-micron targets transparent to the high-intensity laser
- Pulse propagates through the target
- Removes most of the electrons from the target
- Provides much larger charge separation at the rear
- Ions feel uncompensated charge and explode
- Best design is to use high-Z/low-Z layers (laser contrast has to be even higher)

**Target Normal Sheath Acceleration**
- Prepulse creates preplasma at the surface
- If the laser contrast is poor it requires thicker targets
- Main pulse is absorbed at the plasma critical surface
- Pulse drives some $e^-$ through the target
- Charge separation at the rear accelerates protons

- Laser
  - $10^{18}$-$10^{20}$ W/cm²
  - 30 fs, $10^{22}$ W/cm²
  - $10^{-11}$ Contrast

- L ~ 0.1 μm

- L ~ 1-10 μm
HERCULES power reaches 300 TW

V. Yanovsky et. al.
HERCULES reaches record focused intensity of $2 \times 10^{22}$ W/cm$^2$
HERCULES demonstrated the record ASE contrast of $10^{-11}$

Double plasma mirror setup is implemented on Hercules

![Diagram showing the setup with plasma mirrors, off-axis parabola, and interaction chamber](image)

Position of PM2 relative to the focus (cm)

- S-pol.
- P-pol.
- Al shots
Double layer target

- Heavy ion layer is ionized by the laser pulse
- Electrons are expelled from the target by the laser pulse
- Light ions are accelerated in the charge separation field
- Heavy ion layer explodes due to the Coulomb repulsion of excess positive charge
Directed Coulomb Explosion 1: Optimal target thickness

In order to expel all the electrons from foil with thickness $l$ and achieve Coulomb explosion:

$$a \geq \pi \frac{n_e}{n_{cr}} \frac{l}{\lambda}$$

$$a = 0.85 \left( I \left[ \frac{W}{cm^2} \right] \lambda^2 \left[ \mu m \right] 10^{-18} \right)^{1/2}$$

Electric field near the positively charged plasma layer of heavy ions:

$$E_0 = 2\pi n_i Z_i e l = 2\pi n_e e l$$

The longitudinal size of the region, where estimation for $E_0$ is valid, is of order of the focal spot $d$ and ion acceleration is 1D

Maximum proton energy in the field produced by heavy ions:

$$E_{\max} = \pi N_i Z_i e^2 l d$$

There is an optimum foil thickness to achieve highest possible $E_{\max}$
Directed Coulomb Explosion 2: the influence of light pressure

For thicker (but still submicron) foils there is one more mechanism of ion acceleration due to light pressure. It works for finite reflectivity of target. For very thin target laser just transmits through a foil without pushing it.

The transparency condition \( \frac{l}{\lambda} < \frac{\pi a n_e}{n_{cr}} \) coincides with Coulomb explosion condition.

When a foil is thicker laser light reflects and accelerates foil by the radiation pressure. In this case laser field acts like a piston driving a flow of heavy ions tearing foil across.
Directed Coulomb Explosion
Parameters of 2D PIC simulation

Regime of tight laser pulse focusing
Intensities $\sim 10^{22}$ W/cm$^2$

**Parameters of simulation**
Simulation box: $20 \lambda \times 10 \lambda$
Grid mesh size: $\lambda/200$
25 particles/cell
Laser pulse: 150-500 TW
Pulse duration 30 fs
Linearly polarized (z)
Focused: by $f/D=1.5$ to $1\lambda$
Foil: first layer Al$^{+13}$, electron density $400n_{cr}$
second layer H$^+$, electron density $30 \ n_{cr}$

Layers thickness: $L_{AL}=25$-200 nm
$L_{H}=40$ nm
Directed Coulomb Explosion: Optimal target thickness from PIC

![Graph showing proton energy vs. Al thickness for different TW values](image)
Directed Coulomb Explosion

Electron density

Ion density

500 TW, 100 nm


Energy scaling and spectrum

If laser repetition rate is \( \sim 10 \) Hz then for 2.5 s irradiation:

\[
N_p = 10^{10}
\]

For 500 TW and 75 nm target:

\[
E_{\text{max}} = 230 \text{ MeV}, \quad N_p = 4 \times 10^8/\text{pulse}
\]

Super-Gaussian Beams

(i) Flat-top beams evacuate electrons from a larger area on the foil, thus generating a stronger longitudinal electric field
(ii) prevent electrons from returning to the evacuated region due to higher ponderomotive force

500 TW, 0.1λ thick Al foil with a 50 nm second layer hydrogen

S. S. Bulanov et. al. PRE (2008)
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Experimental Setup

Deformable Mirror
X-ray Detector

leak through laser diagnostic

4x10^{20} \text{ W/cm}^2, f/2 parabola
Diffraction limited spot size 3 \mu m FWHM
10^{-11} ASE contrast, no plasma mirror

Diagnostics, CR-39
X-ray PIN diode, gamma-ray PMT

E_{\text{max}} = 8 \text{ MeV for few microns Al target}
Maximum proton energy from H vs. non-H containing targets materials

Protons from the back

Double sheath

Silicon Nitride $\text{Si}_3\text{N}_4$
and
CH thin foils $\text{C}_n\text{H}_{2n+2}$

Simulations track protons from the front layer and back layer separately.

Two layer simulations with a Gaussian Pulse for 30 TW, $\tau=30$ fs.

- 50 nm proton $n=10n_{cr}$
- 250 nm $H^+ \cdot n=400n_{cr}$

$H^+ + H^+$

$n=400n_{cr}$
PIC simulations

**Proton energy**
- Protons from the front surface
- Protons from the rear surface

**Electrostatic field**
- Electrostatic field from the front
- Electrostatic field from the rear

Graphs showing the maximum proton energy in MeV and the maximum electrostatic field in TV/m as functions of time in femtoseconds.
The importance of front and back protons depends on the target thickness.

Two sheath acceleration is more efficient for targets with thickness 200-600 nm.
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Relativistic induced transparency allows for the peak pulse to propagate through the shutter while rejecting the lower intensity pedestal.

$n_c < n_e < \gamma n_c$ where $\gamma = (1 + a_0^2 / 2)^{1/2}$
Relativistic plasma shutter – study of transmission

Near field beam transmission images

Transmission

- Average Laser Transmission
  - 50 nm thick targets are the transition thickness either giving high or low transmission

Shutter is -20 \( \mu \text{m} \) out of focus

- Trans = 100 %
  - 2400
  - Vacuum Reference

- Trans = 86 %
  - 2277
  - 20 nm Si\(_3\)N\(_4\)

- Trans = 44 %
  - 1331
  - 75 nm Si\(_3\)N\(_4\)

- Trans = 2 %
  - 300
  - 200 nm Si\(_3\)N\(_4\)

Percent Transmittance vs Target thickness [nm]
Hydrodynamic simulations of the laser prepulse

Short range laser contrast          Hyades simulated pulse

A.U.                              Laser Intensity (W/cm²)

-30 -20 -10 0 10 20 30            0 5 10 15 20 25 30

time (ps)                          Time (ps)

10^{12} W/cm²

10^{15} W/cm²

~ 10^{-20} W/cm²

1 mJ Energy
Hyades Results

Si$_3$N$_4$

Peak density drops over 30ps

Scale length increases $\rightarrow 0.6\lambda, 1.2\lambda, 4.3\lambda$ @ 9.7 $n_{\text{crit}}$

$L$aser

30 ps Prepulse

1 mJ

Electron Density ($n_c$)

Position ($\mu$m)

$11n_{\text{crit}}$

$3n_{\text{crit}}$

$n_{\gamma\text{cr}} = \langle \gamma \rangle n_{\text{cr}} = 9.66n_{\text{cr}}$
Protons Spectrum with Shutter

Setup insert magnet

Proton Spectrum measured At $0^\circ$, $10^\circ$, $20^\circ$

50 nm Si$_3$N$_4$ foil, no shutter  50 nm Si$_3$N$_4$ foil, 30 nm shutter

20 μm separation

Energy (MeV)

Proton #/ MeV/ Steradian

Normal

10 degrees

20 degrees

20 deg.
Proton Direction Shift

Asymmetric curvature

Conclusions

- Hercules power reaches 300 TW, record intensity of $2 \times 10^{22}$ W/cm$^2$ and the ASE contrast of $10^{-11}$. Further contrast improvement of $\sim 10^3$ is achieved by using 2 plasma mirrors with efficiency of 45%.

- We suggested to use the Directed Coulomb Explosion regime of ion acceleration which can produce quasi-monoenergetic protons of about 200 MeV with 500 TW, 30 fs prepulse free laser pulses.

- We observed 2x higher proton energy from H-containing dielectrics (4 MeV CH/Mylar) compared to non-H containing dielectrics (~2.0 MeV silicon nitride). We have shown that such results are consistent with two sheaths (front and rear) acceleration for H-containing materials.

- A relativistic plasma shutter was introduced. It removed the 30 ps foot of the laser - allowing 30 nm targets to generate 1.8 MeV protons and showed a direction shift toward the laser axis which is characteristic of a high contrast interaction.
Thank you