Protons Acceleration with Laser: influence of pulse duration

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Summary

Influence of sub-ps pulse duration on proton acceleration*

- TNSA
  - Previous numerical studies
  - Simulations & Results

2 targets / 2 pulses configurations

TNSA and related parameters for proton acceleration

p-polarized EMW with oblique incidence

ponderomotive force + resonant absorption

plasma expansion

front side

rear side

increases absorption

E_field screening

N_hot

Thot

I_{ss}, T_p
Experimental deduction of early rear-side proton expansion for ps pulse*

I = 8*10^19 W/cm² is kept constant (E increases with the pulse)

Discrepancies with Mora’s isothermal model

Need for two phase in temperature:
1) Thot raises linearly (on T_p time scale)
2) e-cooling according to Mora’s model + 3D effects

*Robson et al., Nat. Phys, 3, 58 (2007)
Previous numerical studies have demonstrated lower proton energies with extended rear-surface gradients.

Andreev: 2D PIC simulations
I = 7*10e18 W/cm², 35 fs
Linear density profile created by a 10e10 W/cm², ns prepulse
front gradient density length = 2*back gradient density length

Grismayer: 1D fluid simulations
Thermal expansion (Te- = 1 MeV)
Adiabatic cooling of e-
Plasma slab with exponential density gradient

Numerical set-up for sharp-edge target studies

- dx = dy = 11 nm
- dt = 0.027 fs
- box size = 56*38 µm²
- plasma slab = 3 µm (e- + p)
- E = 0.14 J constant
- Spot size = 2.8 µm (at Imax/2)
- Duration: 30 to 300 fs i.e., I from 3.6.10e19 to 3.6.10e18 W/cm² @ 45°
- No prepulse

At high contrast, is the rising edge of the pulse able to preheat the target and modify the proton acceleration?

Variations of Epmax with the pulse duration?
**Sharp-edge absorption and $E_{p_{\text{max}}}$**

- Emax increases with Abs
- Abs saturates ~ 70 % and Emax decreases

For comparison between each pulse duration, we would like less variations in absorption (same coupled energy)

Preplasma at the front side
Numerical set-up for smooth-edge target & results

\[ n = 50n_c \exp\left(-x/l_{ss}\right) \]

\( l_{ss} = 200 \text{ nm} \)
\( E_{\text{max}} \) shifted to short pulses

Less variations in the absorption, which saturates at \( \sim 70\% \)
Why does $E_{p\text{max}}$ decrease while the absorption is constant?

Absorption is $\sim$ in each simulation → the same energy is transferred to e-

If $E_{p\text{max}}$ was directed by the $N_{\text{hot}} \cdot T_{\text{hot}}$ → same cut-off proton energy

What does make the proton not benefit from the e- energy from one simulation to another?

1) Intensity and Thot decreases according to Wilk's formula
2) Density gradient length at the back side
3) Acceleration time
Thot, Nhot and lss and how to link them?

Scaling laws

\[ l_{ss} \ll \lambda_D \quad E \propto \sqrt{N_{hot} \times T_{hot}} \]

\[ l_{ss} \gg \lambda_D \quad E \propto \frac{T_{hot}}{l_{ss}} \]
Measurement & scaling laws for Ex

Qualitative agreement that Ex at the back side is a combination of the two scaling laws!
The acceleration time mitigates the decrease of the rear-side accelerating field.

The decrease of $E_x$ cannot explain the decrease of $E_{\text{max}}$.

According to the most simple consideration for a proton, we have

\[ dv \propto E_x \, dt \quad \Rightarrow \quad E_{\text{max}} \propto \left( \int E_x \, dt \right)^2 \]

We approximate by \( E_{\text{max}} \propto (E_x \tau_p)^2 \) and plot \( \left( \frac{(E_x \tau_p)^2}{(E_x \tau_p)^2_{165\,\text{fs}}} \right) \).
$T_{\text{acc}}$ is the longest between the pulse duration and the characteristic energy exchange time.

Proton energy normalized to the 165 fs case.

This simple scaling is relevant when the acceleration time becomes proportionnal to the pulse duration.

Characteristic energy time exchange between the particles.
Conclusions

We study the effect of pulse duration on proton acceleration at constant laser energy, using kinetic numerical simulations.

The maximum proton energy results from a compromise between 3 effects:

1) the front expansion which enhances absorption

2) the early rear side expansion which becomes important for longer pulse and hampers proton acceleration

3) the acceleration time (longest between $T_p$ and energy exchange time) which increases with the pulse duration and mitigates the reduction in proton peak energy

Lead to an optimum pulse duration for proton acceleration

See A. Flacco et al., Tuesday morning
Needs for controlling the proton energy spectra: 2 targets / 2 pulses configuration

Modulate proton energy spectrum in the scope of isochoric heating

Potential to overcome

Accelerating field

Trailing protons

Leading protons

Use of different time-scale for proton acceleration: heavy substrate

Different time-scale: heavy substrate / thin layer

Gaussian pulse with $a = 4$

Delay between the 2 pulses: $2000 \, \omega_0^{-1}$

Reference case

Linear density gradient

T layer
After the interaction of the peak
1 source
**Conclusions**

With **DT layer**: less perturbation in the phase-space at the moment of the peak and real cut-off at low energy

With **linear gradient**: the repulsive field is increased (higher absorption) but the accelerating field is decreased (screening)

However:

- the accelerating field is limited in space and time
- the spectrum we collect is composed of P, C and T

In 2D, is it worth trying to «shape» the proton spectrum in the scope of isochoric heating?