Ion acceleration in plasmas

Lecture 6. Ion acceleration in solids

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1. Introduction: Laser driven ion acceleration in solid targets

2. Introduction: Target Normal Sheath Acceleration (TNSA)

3. Theoretical Model (TNSA)

4. Experiment and Results (TNSA)
Laser-driven Ion Acceleration in Solid Targets

A direct interaction of protons and heavier ions with laser beams of currently existing laser systems is by far not strong enough to accelerate these particles to MeV energies.

The relativistic threshold for electrons:

\[ I_e \lambda^2 = 1.37 \times 10^{18} \text{ W } \mu \text{m}^2/\text{cm}^2, \]

Similarly, the relativistic threshold for protons

\[ I_p \lambda^2 = \left( \frac{m_p}{m_e} \right)^2 I_e \lambda^2 \approx 5 \times 10^{24} \text{ W } \mu \text{m}^2/\text{cm}^2, \]

when the kinetic energy of an oscillating proton in the laser field is equal to its rest energy.

\[ I_p \lambda^2 \approx 5 \times 10^{24} \text{ W } \mu \text{m}^2/\text{cm}^2 \]

corresponds to a laser field amplitude \( a_0 = 1836 \), which is far beyond the present laser technology and might be feasible with new concept optical parametric amplification (OPA-CPA) in the future.
Energetic ions observed in the laser-matter interaction have been accelerated not directly by the laser fields but by the plasma fields.

Plasma fields are formed due to the laser heated electrons.

Plasma electrons can mediate the forces of laser fields on ions by generating quasi-static electric fields which arises from local charge separations.

The quasi-static fields (vary on a timescale comparable to the laser pulse duration) can be of same magnitude as that of the fast oscillating laser fields, giving the ions a significantly longer time to accelerate.
Laser-driven Ion Acceleration in Solid Targets

The laser energy can be efficiently transferred to the plasma electrons by various mechanisms leading to different ion acceleration regime, depending on:

Laser parameters, e.g. intensity and temporal contrast of pulse, target properties e.g. shape and size of the target.

There are three main ion acceleration scenarios, which are relevant here:

1. Target Normal Sheath Acceleration (TNSA)
2. Radiation Pressure Acceleration (RPA)
3. Shock Wave Acceleration (SWA)
Target Normal Sheath Acceleration

→ TNSA mechanism demonstrate the ion acceleration in solid targets at the rear side of the target.
→ Laser heated fast electron accelerates at the target front surface, crossing the bulk target and escape in vacuum from the rear side.
→ As a result a space-charge field in the form of thin Debye sheath generates and provides strong and stable electric field which accelerates ions.

Fig. 6.1: TNSA Mechanism: Electrons heated at front side pass through a thin target, escape to vacuum and form an electrostatic field at rear, which accelerates ions.
Radiation Pressure Acceleration (RPA)

In RPA mechanism, ions can be accelerated in the vicinity of the laser focus at the target front surface by the "ponderomotively" expelled electrons, leaving behind a positive space charge of ions.

RPA effects dominate over TNSA either for laser intensities $I > 10^{23} \text{ W/cm}^2$ or with Circularly Polarized (CP) laser field instead of Linearly Polarized (LP) (less fast electrons with CP)

In TNSA mechanism demonstrate the ion acceleration is solid targets at the rear side of the target.

Hole Boring (HB): thick target "piston" push of the plasma surface
Light Sail (LS): thin target whole push of thin foil target.

TÁMOP-4.1.1.C-12/1/KONV-2012-0005 projekt
Shock Wave Acceleration (SWA)

In SWA, when the laser intensity is of moderate range, i.e. $10^{18} - 10^{21}$ W/cm$^2$, the light pressure ranges up to terabar values, sweeps out and compresses the laser-produced plasma, pushing its surface at relativistic speeds. Such a strong compression and acceleration may generate strong shock waves propagating in the bulk of plasma which accelerate ions. In moderate overdense and hot plasmas, where the shocks are of collisionless nature, SWA leads to higher ion energy and narrow ion spectrum SWA can be dominant over TNSA and PRA.
Target Normal Sheath Acceleration (TNSA)

Introduction

According to TNSA model,

→ Very intense current of high energy "hot (fast)" electrons generated at the front side.

↓

Generated hot electrons cross the rear side boundary and attempt to escape in vacuum while ions due to their heavy mass almost remain at rest.

↓

Thus the charge imbalance generates a sheath field $E_s$, normal to the rear surface of solid target.

$$E_s \sim \frac{T_h}{eL_s}$$  \hspace{1cm} (6.1)

where $n_e$ — electron density

$T_h$ — electron temperature

$L_s$ — spatial extension of the sheath field
Target Normal Sheath Acceleration (TNSA)

Protons will be accelerated perpendicularly to the target into the rear side hemisphere until they compensate the electron charge.

Assuming a steep interface, $L_s$ can be roughly estimated as the Debye length of fast electrons,

$$L_s \sim \lambda_{Dh} = \sqrt{\frac{T_h}{4\pi e^2 n_h}}$$

(6.2)

For $I\lambda^2 = 10^{20}$ Wμm$^2$/cm$^2$, fractional absorption $\eta_h = 0.1$,

we find $n_h \sim 8 \times 10^{20}$ cm$^{-3}$,

$T_h = 5.1m_e c^2 = 2.6$ MeV

$\lambda_{Dh} = 4.2 \times 10^{-5}$ cm

$E_s \sim 6 \times 10^{10}$ V/cm
The large sheath field $E_s \sim 6 \times 10^{10}$ V/cm will backhold most of the escaping electrons, ionize atoms at the rear surface, and will accelerate ions.

Roughly a test ion particle crossing the above calculated sheath field would attain energy $\sim Z e E_s L_s = Z T_h$, resulting in MeV energies and scaled as $I^{1/2}$.

If $T_h = E_p$ as given by Equation holds.

**TNSA (Experimental results):** Hatchett et. al., *Phys. Plasmas* 7, 2076 (2000);
The huge electrostatic sheath field is much stronger than the electric field of the laser, thus the strong sheath field will backhold most of the escaping electrons, ionize the atoms at the rear side and start to accelerate ions.

Due to hydrocarbon or water contaminants on the surfaces of non-treated targets, the favorably accelerated ion species a proton, as they have the highest charge-to-mass ratio.

The heavy ions can be also efficiently accelerated from cleaned targets.

The accelerated ions leave the target together with comoving electrons forming a quasineutral plasma cloud. As the plasma density in this cloud quickly drops after the detachment from the target and as the temperature remains high in this cloud, recombination effects are negligible from propagation lengths in the range of several meters.

The accelerating electrostatic field is parallel to the normal vector of the target rear surface, therefore this mechanism of ion acceleration is called Target Normal Sheath Acceleration (TNSA).
In the one-dimensional model, assuming the ions at rest with the density

\[ n_i = n_{i0} \text{ for } x < 0 \]

and

\[ n_i = 0 \text{ for } x > 0 \]

The electron density \( n_e \) is continuous and follows the Boltzmann distribution,

\[ n_e = n_{e0} \exp(e\varphi/T_e) \]

\( n_e \) – electron density in the unperturbed plasma
\( T_e \) – constant electron temperature

The potential \( \varphi \) satisfies the Poisson equation,

\[ \frac{\partial^2 \varphi}{\partial x^2} = \frac{e}{\varepsilon_0} (n_e - Z n_i). \]
Basic Theoretical Model

The ion expansion into a vacuum is described by the hydrodynamic equations of continuity and motion,

\[
\left( \frac{\partial}{\partial t} + v_i \frac{\partial}{\partial x} \right) n_i = -n_i \frac{\partial v_i}{\partial x},
\]

(6.4)

\[
\left( \frac{\partial}{\partial t} + v_i \frac{\partial}{\partial x} \right) v_i = -\frac{z_e}{m_i} \frac{\partial \varphi}{\partial x},
\]

(6.5)

\( v_i \) – ion velocity.

Assuming the quasi-neutrality condition \((n_e = zn_i)\), the self-similar solution of this set of equations (depending on self-similar variable \(\xi = x/t\)) describes the rarefaction wave:

\[
zn_i = n_{e0} \exp(-\xi/c_s - 1), \quad v_i = c_s + \xi \quad e\varphi = -T_e(\xi/c_s + 1)
\]

(6.6)
Basic Theoretical Model

Here \( x = 0 \) is the sonic point and the original position of the plasma surface.

The solution is valid for, \( x > x_u = -c_s t \)

\( x_u \) – upstream front of the rarefaction wave propagating with the ion-acoustic velocity ion velocity \((c_s)\).

\[ c_s = \sqrt{z T_e / m_i} \]

By integrating the Poisson equation (6.3) from \( x = 0 \) to \( x = \infty \), the maximum accelerating electric field can be obtained as,

\[ E_{ac} = \sqrt{\frac{2}{e_N e \lambda_{D0}}} \frac{T_e}{e \lambda_{D0}} \approx \frac{T_e}{e \lambda_{D0}} = \sqrt{\frac{n_{e0} T_e}{\varepsilon_0}}. \] (6.7)

\( \lambda_{D0} \) – Debye length in the unperturbed plasma of electron density \( n_{e0} \).

\( e_N = 2.7182 \) (Euler number).
Basic Theoretical Model

The maximum velocity can be translated into the maximum (cut-off) energy of accelerated ions

$$E_{\text{imax}} \approx 2ZT_e \ln^2 \left( \tau + \sqrt{\tau^2 + 1} \right). \quad (6.8)$$

The self-similar solution predicts a number of ions per unit energy and unit surface (ion energy spectrum)

$$\frac{dN}{d\varepsilon_i} = \frac{n_i \varepsilon_i \tau_{\text{acc}}}{\sqrt{2 \varepsilon_i zT_e}} \exp \left(-\frac{\sqrt{2 \varepsilon_i}}{zT_e}\right), \quad (6.9)$$

$$\tau = \omega_{pi} t_{\text{acc}} / \sqrt{2e_N},$$

$$\omega_{pi} = \sqrt{n_i z^2 e^2 / m_i \varepsilon_0}, \text{ ion plasma frequency},$$

$$t_{\text{acc}} \text{-- ion acceleration time.}$$
The total energy of accelerated ions (by integrating the product of (6.9) with $\varepsilon_i$),

$$W_{tot} = \int \varepsilon_i \frac{dN}{d\varepsilon_i} \, d\varepsilon_i$$

$$= ZT_e n_{i0} c_s t_{acc}. \quad (6.10)$$

The laser-to-ion conversion efficiency can be defined as

$$\eta_i = \frac{W_{tot} \text{ (Total Energy of Accelerated Ions)}}{\varepsilon_{Ltot} \text{ (Laser Pulse Energy)}} \quad (6.11)$$
The maximum energy in Eq. (6.8) diverges logarithmically with time. The total energy in the fast ions Eq. (6.10) diverges linearly. To apply the model to the interpretation of experiments, we may determine the relevant time $t_{acc}$ where which the acceleration is stopped.

A natural choice for $t_{acc}$ is the laser pulse duration $t_L$, but in the experiment, the acceleration does not stop suddenly, and it goes on even for $t > t_L$.

The isothermal model assumes a constant electron temperature, which can be held a reasonable assumption during the laser pulse, but it is certainly violated for late times, as the electrons progressively give their energy to the ions and cool down in the expansion.
Two populations of Electrons

The second issue of the model is the assumption of a single electron temperature which is not appropriate for laser plasma interactions.

During the interaction, two populations of electrons can be considered – the background cold electrons and minority of hot electron. Then, the electron density is a sum of two Boltzmann distributions with cold \( T_c \) and hot \( T_h \) temperature.

In relativistic case – \( T_h/T_c \) is certainly well above the critical value \( \approx 10 \), for which the quasineutral fluid theory of the expansion of semi-infinite plasma predicts two corresponding ion populations – while the first expands slowly according to the cold electron temperature, the second expands according to the hot electron temperature.
The third issue of the isothermal model is that they do not include multidimensional effects.

Model considers a planar intense laser wave interacting with plasma which creates a population of homogeneously distributed hot electrons inside the initial plasma.

→ In relativistic experimental conditions the laser pulse is tightly focused, and
→ the hot electrons sheath spreads along the target surface, which decrease the efficiency of acceleration process.

→ Beam divergence is one of the important parameters of the accelerated laser beams, and cannot be predicted by one–dimensional models.
2D and 3D Effects

The ions are accelerated parallel to the normal vector of the target rear surface. If the multidimensional effects are taken into account, the initial planar surface gets curved due to gradual spread of the sheath layer.

Accelerating electric field decreases due to the expansion and sheath spread and most energetic ions are accelerated from the planar rear surface and lower energy ions from curved surface.

Thus,

Divergence of fastest ions should be lower than the divergence of ions with a lower velocity.
The **TNSA process** is a consequence of the large charge separation generated by hot electrons reaching the rear side of the target.

Thus a cloud of relativistic electrons is formed, extending out of the target for several Debye lengths, and giving rise to an extremely intense electric field, mostly directed along the normal to the surface.

Consequently ions are accelerated perpendicularly to the surface, with high beam collimation.

The electric field generated at the rear surface depends on parameters of the electron distribution (temperature, number, divergence) as well as of the surface (mostly its density profile).

**Wilks et.al., Phys. Plasmas 8, 542 (2001).**
The TNSA acceleration is most effective on protons. Protons can be presented either in the form of surface contaminants or among the constituents of the solid target as in plastic targets.

The heaviest ion populations provide a positive charge with much more inertia, thus creating the charge separation which generates the accelerating field. Part of the heavy population can also be effectively accelerated, on a longer time scale, if the proton number is not high enough to balance the charge of the escaping hot electrons, and especially if impurity protons are removed before the interaction, for example, by preheating the target. In this way, ions of several different species may be accelerated.

The rear side TNSA acceleration strongly observed through several experiments.

Proton emission from a wedge target effectively having two rear surfaces. Two separate spots are observed on the detector, which shows that most of the protons originate from the rear side of the target.

Problems

Q6.1. True or False. Direct acceleration of ions by the laser field is neglected in laser-solid interaction, since ions have a much greater inertia than electrons and tend to respond to the laser field on very long timescales.

A6.1. True.

Q6.2. Energetic Ions observed in the laser-matter interaction are accelerated not directly by the laser fields but by the plasma fields. How does plasma field respond to ions?

A6.2. Laser heated plasma electrons mediate the forces of laser fields on ions by generating quasi-static electric fields which arises from local charge separations. The most efficient energy chain is therefore from the laser pulse to high energy electrons, and from these to the ions.
Problems

Q6.3. In laser-solid interaction, the protons on the rear of target are accelerated quickly while ions from front of the target gains low energy.

A6.3. Since the protons on the back are in a sharp flat density gradient, they are accelerated quickly to high energies in the forward direction. On the front, the outermost ions are in a sphere, in a long scalelength plasma (due to prepulse) and therefore are accelerated to lower energies.

Q6.4. Calculate the TNSA sheath field for electron temperature of 500 keV and a density of $10^{21}$ cm$^{-3}$.

A6.4. 3 MV/μm.

Q6.5. True or False. The mechanism of ion acceleration through the electrostatic field is called Target Normal Sheath Acceleration (TNSA) since the laser field is parallel to the normal vector of the target rear surface.

A6.5. False.
Q6.6. Point out the true and false (from given a-d) for TNSA mechanism.
(a) The laser pulse coming from the left is focused into the preplasma on the target front side,
(b) main pulse interacts with the plasma and accelerates hot electrons into the target material,
(c) electrons are transported under a divergence angle through the target, leaving the rear side and forming a dense electron sheath. Stronging electric field generated by the charge separation is able to ionize atoms at the rear side.
(d) They are accelerated over a few μm along the target normal direction. After the acceleration process is over and the target disrupted (~ns), the ions leave the target in a quasi-neutral cloud together with comoving electrons.

A6.6. True (a-d).
Problems

Q6.7. Why protons are accelerated quickly than ions?
A6.7. Protons have higher charge to mass ratio.

Q6.8. With energetic protons via TNSA, the electrons are also present in large numbers (some of whom accompany the proton beam, charge neutralizing it) with energies up to several MeV. How can we discriminate the proton signal from the background?
A6.8 Plastic material CR-39, which is only sensitive to protons, heavy ions and neutrons. Macchi et.al., Review of Modern Physics 85, 751 (2013).

Q6.9. In TNSA mechanism, how ion maximum energy depends on the target thickness?
A6.9. By reducing the target thickness, TNSA ion maximum energy increases.

Q6.10. What are the demerits of energetic ion beam from TNSA mechanism?
A6.10. low particle density, large divergence and broad energy spread.
References


