Ion Acceleration in Superintense Laser Interaction with Ultrathin Targets

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Protons from Metallic targets observed in 2000 by three experimental groups


- high number (up to $10^{14}$)
- good collimation
- ultra-low emittance
  (4 x $10^3$ mm mrad)
- maximum energy and efficiency observed (*):
  58 MeV, 12% of laser energy @ $I=3 \times 10^{20}$ W/cm$^2$
TARGET NORMAL SHEATH ACCELERATION

TNSA physical mechanism: acceleration in space-charge electric fields generated at the rear surface by escaping high-energy ("fast") electrons


Connection with the "classic" problems of sheath dynamics and plasma expansion into vacuum

Protons originate from impurities: TNSA of heavier ions can be achieved by target engineering
APPLICATIONS AND CHALLENGES

Foreseen applications:
- Ignitor or diagnostic beam in Inertial Confinement Fusion
- Oncological hadrontherapy & isotope production in Medicine
- Probing of laser-plasma interactions

Challenging tasks:
- Reaching >150MeV/A: scaling at higher intensities?
- Improve and control proton/ion beam properties (monoenergeticity, collimation, repetition rate, ...)
- Reaching relativistic ion regimes (>1 GeV/A); what happens at ultrahigh intensities? (ELI project: intensities up to $10^{26}$ W/cm²)
RUNNING PROJECTS ON ION ACCELERATION

FIRB “Futuro in Ricerca” project SULDIS ("SUperintense Laser-Driven Ion Sources") 2010/14
National coordinator: Matteo Passoni (Politecnico Milano)
Local coordinator: AM

Italian SuperComputing Resource Allocation (ISCRRA) project TOFUSEX at CINECA (Bologna)
(“TOwards Full-scale Simulations of laser-plasma EXperiments) Principal Investigator: AM
Collaborators: G.Turchetti, P.Londrillo, A.Sgattoni (Bologna)
ULTRATHIN TARGETS (1-100 nm)

Advantages:
- Concentration of laser pulse energy in small volume: higher electron temperature $\rightarrow$ higher ion energy?
- Significant (or even dominant) effect of direct Radiation Pressure Acceleration (RPA)

Possible to use thanks to:
- advanced target manufacturing (e.g. Diamond-Like Carbon foils)
- pulse cleaning techniques (e.g. plasma mirrors) to generate prepulse-free ultrashort pulses avoiding early target disruption
Target: thin (0.1-1 µm) **Cu** foil with **C** and **H** impurities

Laser pulse: 1ps, up to $3 \times 10^{20}$ W/cm$^2$

various polarizations

Modulated, “complementary” spectra for **C** and **H** (**H dip** at **C peak**)

Collimated plasma jet observed via interferometry

Data from VULCAN-TAP@RAL, UK (S.Kar)
Target: 0.1 $\mu$m Cu foil with 10nm CH layers
electron density $10^{23}$ cm$^3$
Laser pulse: 0.5ps, $1.4 \times 10^{20}$ W/cm$^2$
linear polarization

The scaled down model problem
qualitatively reproduces the experiment

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Target: 0.1µm **Cu** foil with 10nm **CH** layers 
electron density $10^{23}$ cm$^{-3}$
Laser pulse: 0.5ps, $1.4 \times 10^{20}$ W/cm$^2$
linear polarization

The scaled down model problem qualitatively reproduces the experiment

$t = 50$ cycles
Target: 0.1µm Cu foil with 10nm CH layers
electron density $10^{23}$ cm$^{-3}$
Laser pulse: 0.5ps, $1.4 \times 10^{20}$ W/cm$^2$
linear polarization

The scaled down model problem qualitatively reproduces the experiment

$t=75$ cycles
Target: 0.1 μm Cu foil with 10nm CH layers
electron density $10^{23}$ cm$^{-3}$
Laser pulse: 0.5ps, $1.4 \times 10^{20}$ W/cm$^2$
linear polarization

The scaled down model problem qualitatively reproduces the experiment

t=100 cycles
2D SIMULATIONS FOR THE EXPERIMENT

Target: 0.1\,\mu m Cu foil with 10nm CH layers
electron density $10^{23}$ cm$^{-3}$
Laser pulse: 0.5ps, $1.4 \times 10^{20}$ W/cm$^2$
linear polarization

The scaled down model problem
qualitatively reproduces the experiment

$t=125$ cycles

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Extension of the classic model of plasma expansion in vacuum to a multispecies plasma predicts the formation of shock fronts due to spatial separation between light and heavy species and formation of spectral peaks and dips.

[see e.g. Kemp & Ruhl, PoP 12 (2005) 033105; Tikhonchuk et al, PPCF 47 (2005) B869]

Possible additional effects in this experiment characterized by unprecedented intensity and ultrathin substrate target:
- nearly full relativistic electron population
- instabilities (two-stream, Buneman) in the blow-off plasma
- significant boost by radiation pressure acceleration (RPA)

[see e.g. Kar et al, PRL 100 (2008) 225004]
INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By Prof. G. Marx
Institute of Theoretical Physics, Roland Eötvös University, Budapest

Unlimited Ion Acceleration by Radiation Pressure

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(Received 18 November 2009; published 2 April 2010)
Using the “Light Sail” model, i.e. a perfect mirror boosted by Radiation Pressure, it is shown that acceleration efficiency is 100% as $V \rightarrow c$. 

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Simulations at $I \geq 10^{23} \text{W/cm}^2$ suggest thin foil acceleration up to GeV/A energies.
Using CP and normal incidence fast electron generation is strongly suppressed, making radiation pressure dominant even at intensities lower than...
Peak ion energy (a) efficiency (b) & energy spectra (c) vs. laser pulse intensity and thickness:
very good agreement of analytical model with results of PIC simulations accounting for kinetic effects

Macchi et al,
PRL 103 (2009) 085003;
Stronger electron heating and lower “penetration” threshold with respect to 1D: ion spectrum broadens and monoenergetic peak tends to disappear as seen in experiment.

3D simulations
left: Supergaussian spot profile
right: Gaussian

Note that only in 3D angular momentum conservation is taken into account

Simulation set-up:
- 320 X 1050 X 1050 grid, 80 points per wavelength
- 27 particles per cell, \(\sim 1.5 \times 10^9\) in total
- 182 PEs, \(\sim 360\) Gbytes load

Lyseykina, Borghesi, Macchi, Tuveri, PPCF 50 (2008) 124033
Motivation: Radiation Reaction (RR) aka Radiation Friction is important for ultra-relativistic particles in EM fields and is thus expected to play a strong role in next generation experiments at ultra-high intensities.

The typical intensity for relevant RR effects is estimated to be $\sim 10^{23}$ W/cm$^2$. This corresponds, to the foreseen regime of RPA dominance (for Linear Polarization)

Our approach: inclusion of Landau-Lifshitz RR force in PIC simulations (plus suitable approximations)
RADIATION REACTION MODELING

\[ \frac{dp}{dt} = -e \left( E + \frac{v}{c} \times B \right) \]
\[ -e \tau_0 \left[ \gamma \left( \frac{dE}{dt} + \frac{v}{c} \times \frac{dB}{dt} \right) \right. \]
\[ -\frac{e}{mc} \left( \left( E + \frac{v}{c} \times B \right) \times B \right) + \left( \frac{v}{c} \cdot E \right) E \]
\[ -\gamma^2 \frac{e}{mc} \left( \left( E + \frac{v}{c} \times B \right)^2 - \left( \frac{v}{c} \cdot E \right)^2 \right) v \]
\[ \tau_0 = \frac{2e^2}{3mc^3} \]

EoM with Landau-Lifshitz force in non-covariant notation

(Landau & Lifshitz, *The Classical Theory of Fields*, par. 76)

Numerical implementation benchmarked with the exact solution in a plane wave

RP-dominated regime: $2.3 \times 10^{23} \text{ W/cm}^2$, 11 cycles pulse

1 um foil, 100$n_c$, circular polarization

Negligible RR effects on ion spectrum!

Higher energy than in LP case
RR EFFECTS ON ION SPECTRA – II (CP)

RP-dominated regime: \(2.3 \times 10^{23} \text{ W/cm}^2\), 11 cycles pulse

1 um foil, 100\(n_c\), circular polarization

Negligible RR effects on ion spectrum!

Higher energy than in LP case
RP-dominated regime: $2.3 \times 10^{23} \text{ W/cm}^2$, 11 cycles pulse

0.3 um foil, 100$n_c$, circular polarization

The pulse penetrates through the foil due to “relativistic” Self-Induced Transparency

RR effects are now important for CP and increase the ion energy, but the regime is not optimal for ion acceleration
CONCLUSIONS

- Impressive amount of experimental research on laser ion acceleration in the last 10 years
- Theory and simulation are able to support and promote experimental activities and developments
- Combining progress in laser systems (higher intensities, (cleaner) pulses with target engineering (ultrathin foils, structured/multispecies targets ...) offers new perspectives
- Increase of Supercomputing power allows more realistic, closer to experimental simulations

Lots of work remain to be done anyway...

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