Sailing Before the Light: Laser-Plasma Acceleration Driven by Radiation Pressure

Andrea Macchi

[1]National Institute of Optics, National Research Council (CNR/INO), Pisa, Italy

[2]Department of Physics "Enrico Fermi", University of Pisa, Italy

Plasma Physics Colloquium, Dept. of Applied Physics and Applied Mathematics, Columbia University, New York, USA, July 2013

Outline

- a brief history of laser-plasma acceleration of matter
- the concept of “light sail” radiation pressure acceleration
- experimental evidence
- simulations of high gain regimes: towards relativistic ions

Main coworkers for this talk

A. Sgattoni[1,2], A. Singh Nindrayog[1,3,†], M. Tamburini[1,3,*], F. Pegoraro[1,3], M. Passoni[2], T. V. Liseykina[4], P. Londrillo[5], S. Sinigardi[6], S. Kar[7], M. Borghesi[7]

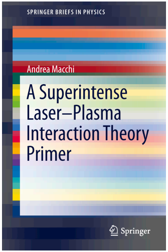
[1]CNR/INO, Pisa, Italy
[2]Dipartimento di Energia, Politecnico di Milano, Milan, Italy
[3]Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa, Italy
[4]Institut fuer Physik, Universitaet Rostock, Germany
[5]INAF and INFN, Bologna, Italy
[6]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[7]Center for Plasma Physics, Queen's University of Belfast, UK
[†]presently at Lyallpur Khalsa College, Jalandhar, India
[*]presently at MPI-K, Heidelberg, Germany

Recent ion acceleration reviews (parochial selection)

A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. **85** (2013) 571

A. Macchi, A. Sgattoni, S. Sinigardi, M. Borghesi, M. Passoni,
Advanced Strategies for Ion Acceleration using High Power Lasers,
EPS 2013 arXiv:1302.1775

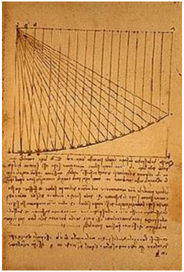
A. Macchi,
A Superintense Laser-Plasma Interaction Theory Primer (Springer, 2013)
Chap.5 "Ion Acceleration" (for absolute beginners)



Focused light interaction with matter: an old story

Archimedes' mirror burning Roman ships. Giulio Parigi, ab. 1600. Uffizi Gallery, *Stanzino delle Matematiche*, Florence, Italy

Leonardo da Vinci: Studies on reflection by burning mirrors. Codex Arundel (1480-1518), British Library, London.



First attempts to "strongly" modify matter with intense light (heating, phase transition, ionization . . .)

Intensity of Sunlight: $I \simeq 1.4 \times 10^3$ W m^{-2}

with "ultimate" concentration $\sim 10^4 \rightarrow I \simeq 10^7$ W m^{-2} at focus

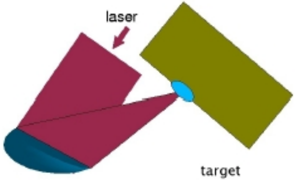
The dawn of laser-plasma physics (1964)

"*The laser is a solution looking for a problem*" (D'Haenens to Maiman, 1960)

Q-switched lasers (1962):

10 GW on $\sim 10^{-4}$ m spot

$\rightarrow I \simeq 10^{17}$ W m^{-2}



THE PHYSICS OF FLUIDS VOLUME 7, NUMBER 7 JULY 1964

On the Production of Plasma by Giant Pulse Lasers

John M. Dawson
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey
(Received 10 October 1963; final manuscript received 10 March 1964)

Calculations are presented which show that a laser pulse delivering powers of the order of 10^{10} W to a liquid or solid particle with dimensions of the order of 10^{-2} cm will produce a hot plasma with temperatures in the range of several hundred eV. To a large extent the plasma temperature is held down by its rapid expansion and cooling. This converts much of the energy supplied into ordered energy of expansion. This ordered expansion energy can amount to several keV per ion. If the expanding plasma can be caught in a magnetic field and its ordered motion converted to random motion this might be utilized as a means for filling controlled thermonuclear fusion devices with hot plasma. Further, it should also be possible to do many interesting plasma experiments on such plasmas.

Modern ultraintense laser-matter interactions

Short (~ 10 fs $= 10^{-14}$ s) pulses of Petawatt (10^{15} W) power focused near diffraction limit ($w \sim 1\ \mu$m): $I \simeq 10^{26}$ W m^{-2}
(Hercules Laser, CUOS, University of Michigan Ann Arbor, US)

Proposed ELI laser: 100 PW, 15 fs, $I > 10^{27}$ W m^{-2}
A future vision: multi-fibre laser
[Mourou et al, Nature Photonics **7** (2013) 258]

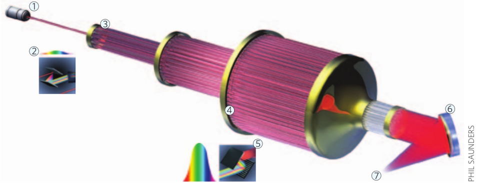
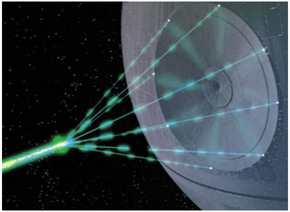


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined coherently, compressed (5) and focused (6) to produce a pulse with an energy of >10 J at a repetition rate of ~10 kHz (7).

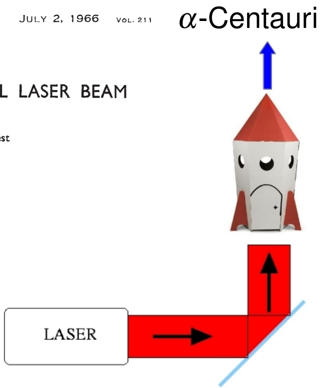


Early vision of radiation pressure acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

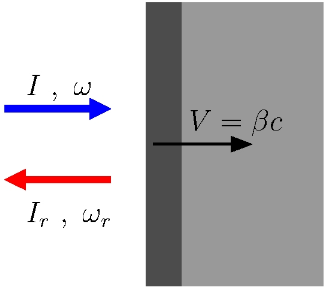
By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest



A solution to "Fermi's paradox": "*Laser propulsion from Earth . . . would solve the problem of acceleration but not of deceleration at arrival . . . no planet could be invaded by unexpected visitors from outer space*"

The "accelerating mirror" paradigm

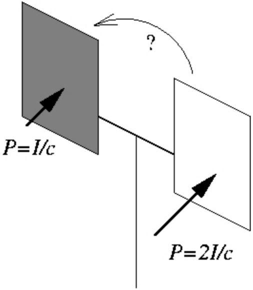
Perfect mirror boosted by a plane wave: mechanical efficiency η and momentum transfer to mirror derived by Doppler shift and photon number conservation



$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

High efficiency but slow gain as $\beta \longrightarrow 1$

How to make radiation pressure dominant?



The “Optical Mill” rotates in the *opposite* sense to that suggested by radiation pressure balance: due to imperfect vacuum *thermal* pressure due to heating dominates

Enforcing radiation pressure dominance requires to suppress heating of the surface

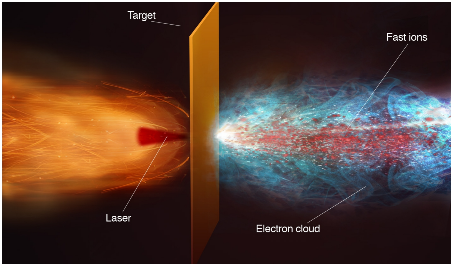
The vision of "coherent" acceleration: Veksler (1957)

V. Veksler, At. Energ. **2** (1957) 525

- accelerating field on each particle proportional to the number of accelerated particles
- automatic synchrony between the particles and the accelerating field
- field localization in the region where the particles are
- acceleration of quasi-neutral bunches with large numbers of particles
- These features are realized in laser-plasma acceleration of ions

Laser-plasma acceleration of ions (2000–)

Clark et al, PRL **84** (2000) 670
Maksimchuk et al, *ibid.* 4108
Snavely et al, PRL **85** (2000) 2945



State of the art (2013):
- up to $\simeq 70$ MeV protons observed
- $> 10^{13}$ protons, $> 10^{11}$ C ions accelerated in single shots (as charge neutralized bunches)
- very low emittance measured ($< 0.1\pi$ mm mrad)
- proofs-of-principle of spectral manipulation and beam focusing

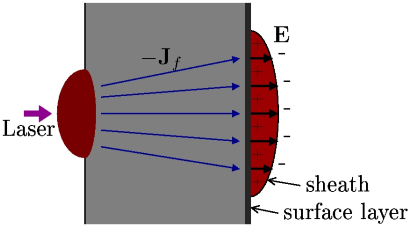
Basic processes of ion acceleration

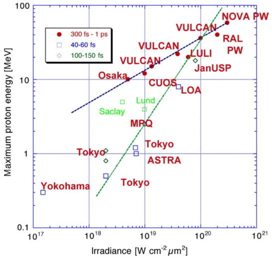
Coupling to ions is always mediated by electrons:

- Sheath Acceleration / Plasma expansion :
  - ions are dragged in the charge separation field produced by “hot” electrons (multi–MeV for intense lasers)
- Shock wave acceleration:
  - ions are accelerated by the moving fronts of laser-driven collisionless shock waves
- Light/Radiation Pressure Acceleration:
  - the charge separation field is directly sustained by the pressure of laser light ($\sim I/c \to 10^{18}$ N m$^{-2} = 10^{13}$ atm)

Target Normal Sheath Acceleration

TNSA is driven by “fast” electrons generated in thin solid targets: protons from surface contaminants are accelerated in the rear sheath





TNSA observed in many laboratories and wide range of parameters: up to ~ 70 MeV observed

Why going from TNSA to RPA?

- Maximum energy per nucleon $\mathscr{E}_{\max}$ in TNSA still far from "Holy Graal" goals:
  - (60-250 MeV for proton hadrontherapy, >1 GeV for particle physics)
- slow scaling of energy and efficiency observed with increasing intensity
- broad "thermal" spectra observed while monoenergetic spectra are desirable

$\longrightarrow$ explore alternative mechanisms

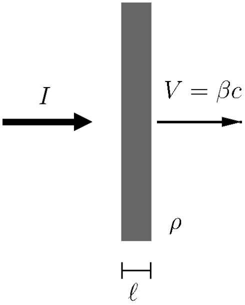
Light Sail formulas: thin, plane moving mirror model

$$\mathscr{E}_{\text{max}} = m_p c^2 \mathscr{F}^2/(2(\mathscr{F}+1))$$
$$\simeq m_p c^2 \mathscr{F}^2/2 \qquad (\mathscr{F} \ll 1)$$

$$\mathscr{F} = 2(\rho\ell)^{-1}\int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$

$$\mathscr{E}_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3}$$

(for $t \gg \rho\ell c^2/I$, $\mathscr{E}_{\text{ion}} > m_p c^2$)



Favorable scaling with dimensionless laser pulse fluence $\mathscr{F}$
"Perfect" monoenergeticity for "rigid", coherent sail motion
Limits: "slow" energy gain, foil transparency and deformation

Experimental requirements for Light Sail acceleration

→ matching laser amplitude and target areal density as trade-off between reduced mass and transparency

$$a_0 = \left(\frac{I}{m_e c^3 n_c}\right)^{1/2} \quad \simeq \quad \zeta = \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$$

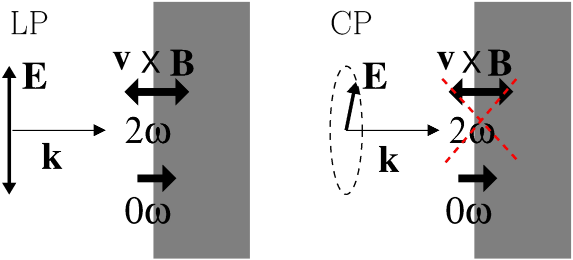
- Diamond-Like Carbon ultrathin (nm) targets

→ avoid “prepulses” to cause early target disruption

- ultrahigh-contrast systems, “plasma mirror” technology
- wide spots (and large energy), supergaussian intensity profiles to avoid strong deformation

Reducing electron heating in laser-target interactions

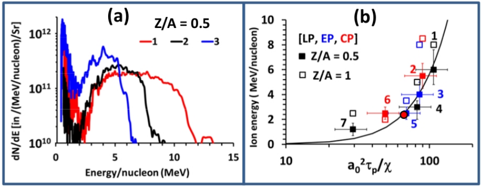
Suppress electron longitudinal oscillations and heating using Circular Polarization at normal incidence



Ions respond “smoothly” to steady component:
RPA dominance at “any” intensity
[Macchi et al, PRL **95** (2005) 185003]

$\mathscr{F}^2$ scaling experimentally observed

VULCAN laser, RAL/CLF:
Laser pulse: $t_p \simeq 800\ fs$
3×10^{20} W cm^{-2}
$\sim 10^9$ contrast
Target: $\sim 0.1\ \mu$m metal foil

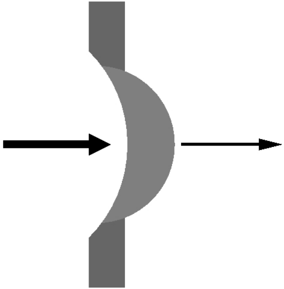


Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/amu observed at high flux
Simulations suggest > 100 MeV/nucleon are within reach

Kar, Kakolee, Qiao, Macchi, Borghesi et al PRL **109** 185006 (2012)

see also: Steinke et al, PRST-AB **16**, 11303 (2013);
Aurand et al, NJP **15**, 33031 (2013)

Pushing LS forward: “unlimited” acceleration?



Transverse expansion of the target reduces surface density $\rho\ell$

$\Rightarrow$ “unlimited” acceleration possible at the expense of the number of ions

[Bulanov et al, PRL **104** (2010) 135003]

“Faster” gain $E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{3/5}$ predicted

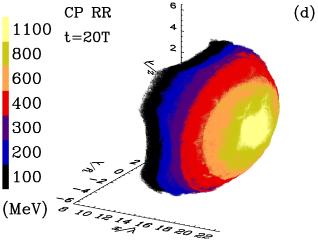
Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

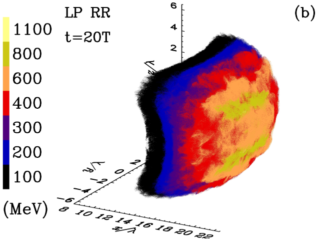
Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$

Relativistic increase of λ in “sail” frame delays breakthrough

3D simulations of RPA-LS with “extreme” pulses

Laser: 24 fs, 8 μm spot, $I = 1.7 \times 10^{23}$ W cm^{-2}, $U = 1.5$ kJ
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $Z/A = 1$, $\zeta \simeq a_0 \simeq 200$





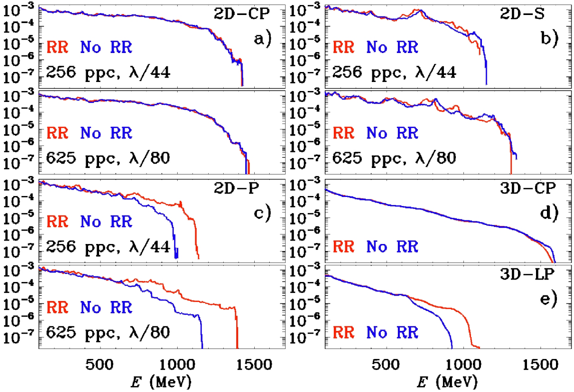
Circular Polarization (CP)
symmetric, collimated distribution
higher energy

Linear Polarization (LP)
asymmetric two-lobe distribution
lower energy

[Tamburini, Liseykina, Pegoraro, Macchi, PRE **85** (2012) 016407]

3D, radiation friction, and numerical resolution effects

Comparison of spectra for 3D vs. 2D for S/P polarization (LP), same/higher resolution, with/without radiation friction (RR)

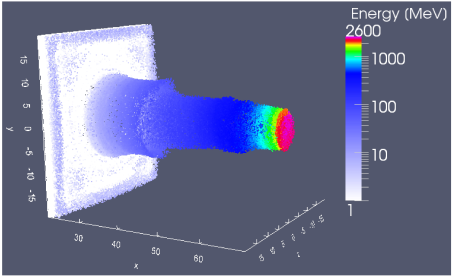


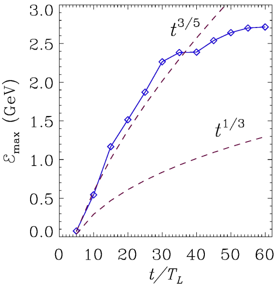
Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

The “optimal” CP case is the most robust (Ion energy is **higher** in 3D than in 2D **!**)

High energy gain in 3D RPA-LS simulations - I

Simulation with ALaDyn PIC code on CINECA/FERMI super-computer up to longer times: $60\ T$ vs $20\ T$



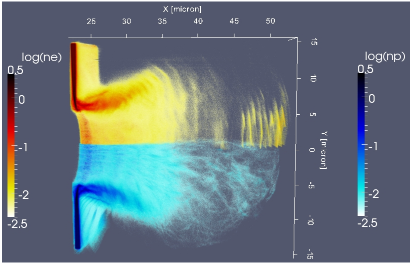


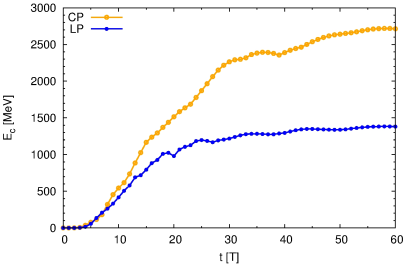
CP pulse: $\mathscr{E}_{\rm max} \simeq 2.6$ GeV > 4 times 1D model prediction

Most energetic ions collimated in 10° cone

High energy gain in 3D RPA-LS simulations -II

Simulation with ALaDyn PIC code on CINECA/FERMI super-computer up to longer times: $60\ T$ vs $20\ T$





Energy increase stopped by the onset of transparency

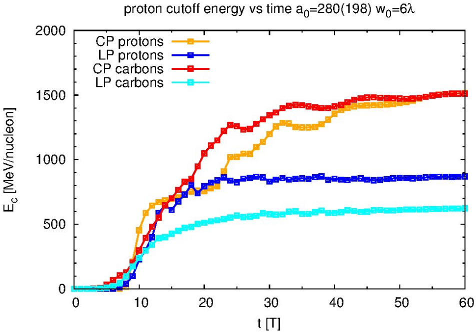
Higher gain (2X) with CP with respect to LP

High energy gain in 3D RPA-LS simulations -III

Simulation with ALaDyn PIC code on CINECA/FERMI super-computer up to longer times: $60\ T$ vs $20\ T$

More "realistic" target:
C $(Z/A = 1/2)$ foil
with H $(Z/A = 1)$ layer

$\mathscr{E}_{\text{max}} \simeq 1.5$ GeV
~ 2.5 times 1D model prediction



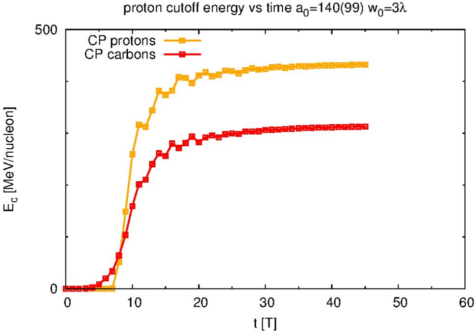
C and H reach same energy/nucleon asymptotically for CP case

High energy gain in 3D RPA-LS simulations -IV

(Preliminary) Simulation with reduced energy:
4 μm spot, $I = 4 \times 10^{22}$ W cm^{-2}, $\zeta \simeq a_0 \simeq 100$, $U = 100$ J

- Energy still higher than in 1D case, but lower gain with respect to fully relativistic regime

- Separation of species in energy spectrum



Conclusions and open issues

- experimental evidence for fast scaling and peaked proton/C spectra
- predicted high gain in relativistic ion (GeV) regime: promising for next-generation ELI class lasers
- “delicate” ultrathin targets required
- wide spots (and large energy) probably needed
- spectrum not monoenergetic as hoped

Acknowledgments

- Work sponsored by the FIRB-MIUR, Italy (project SULDIS – "Superintense Ultrashort Laser-Driven Ion Sources")
- Use of supercomputing facilities at CINECA (Italy) via grant awards:
  - IBM-SP6, ISCRA award (project TOFUSEX – "TOwards FUll-Scale simulations of laser-plasma EXperiments" N.HP10A25JKT-2010)
  - FERMI BlueGene/Q$^{\text{TM}}$, PRACE award (project LSAIL – "Large Scale Acceleration of Ions by Lasers")

EXTRA SLIDES

Simple criteria for RPA “dominance” - I

Heuristic criterion:
ions must respond promptly to charge separation
(before electrons heat up too much $\rightarrow$ expansion dominates)

Ions become promptly (nearly) relativistic sticking to electrons when:

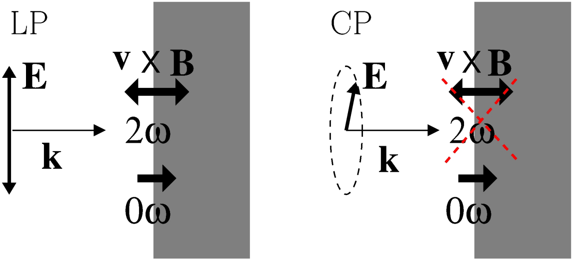
$$v_i/c = 1/2 \quad \longrightarrow \quad a_0 \simeq 30 \left(\frac{n_e}{n_c}\right)^{1/2} > 300$$

$$\longrightarrow \quad I\lambda^2 > 10^{23}\ \mathrm{W\ cm^{-2}}\mu\mathrm{m}^2$$

[see also: Esirkepov et al, PRL **92** (2004) 175003]

Simple criteria for RPA "dominance" - II

Suppress electron longitudinal oscillations and heating using Circular Polarization at normal incidence



Ions respond "smoothly" to steady component:
RPA dominance at "any" intensity
[Macchi et al, PRL **95** (2005) 185003]

Simple criteria for RPA "dominance" - III

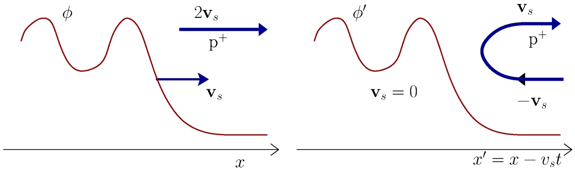
Ions move across the skin layer within a laser halfcycle: prompt "cancellation" of charge separation

$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{2a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{30}{a_0} < 1$$
$$\longrightarrow \quad I\lambda^2 > 1.2 \times 10^{21} \text{ W cm}^{-2}\mu\text{m}^2$$

Consequence: important RPA effects in current experiments (also for Linear Polarization)

Collisionless Shock Acceleration

- Concept: Collisionless Shock Wave of velocity $v_s = Mc_s$ ($M > 1$, $c_s = \sqrt{ZT_e/Am_p}$) driven by the laser pulse into an overdense plasma



- Ion acceleration in the plasma bulk by *reflection* from the shock front: $v_i \simeq 2v_s$

$\rightarrow$ *monoenergetic*, multi–MeV ions if v_s is constant and $T_e \simeq T_{\text{pond}}$ at $a_0 > 1$

Monoenergetic CSA in CO_2 laser-H gas interaction

Proton spectra:

$\mathscr{E}_{\text{max}} = 22$ MeV $\quad \Delta\mathscr{E} \lesssim 10^{-2}\mathscr{E}_{\text{peak}}$

Laser: 100 ps train of 3 ps pulses

$I = 6.5 \times 10^{16}$ W cm^{-2}, $(a_0 = 2.5)$,

linear pol.

Target: H_2 gas jet, $n_0 \leq 4n_c$

Interpretation: shock driven by fast electron pressure

Number of protons is very low: is efficiency of CSA incompatible with monoenergetic spectra?

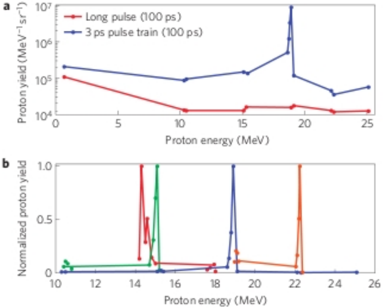


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within the monoenergetic peak was 2.5×10^5. **b**, The details of the energy spectra on four different laser shots with different macropulse structures (number of pulses and a_0 values ranging from 1.5 to 2.5).

Haberberger et al Nature Phys. **8** (2012) 95

Shock "loading" and spectral broadening

- shock wave loses part of its energy to accelerated ions
- decrease of shock kinetic energy leads to decrease of velocity v_s
- velocity $2v_s$ of reflected ions also decreases: spectrum broadens towards low energy

$\rightarrow$ weak loading necessary for monoenergetic spectrum

$\rightarrow$ limited number of accelerated ions

Demonstration in 1D simulation: vary the number of accelerated ions by varying the background ion temperature T_i

Shock loading in 1D simulation with warm ions - I

Parameters:

$a_0 = 1$

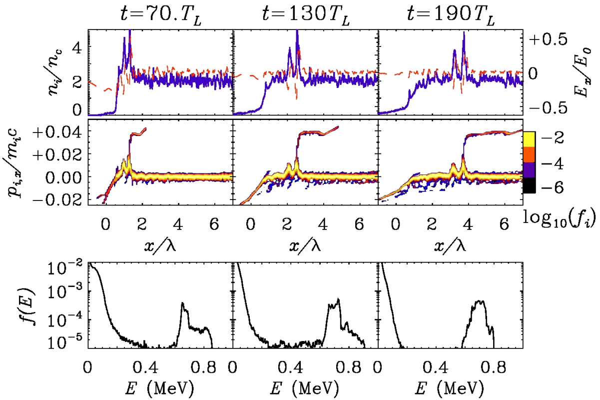
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 0.5$ keV

$\Delta x = \lambda/400$

800 particles/cell



A few ions in the tail of the warm distribution are reflected as a monoenergetic beam (v_s is constant)

Shock loading in 1D simulation with warm ions - II

Parameters:

$a_0 = 1$

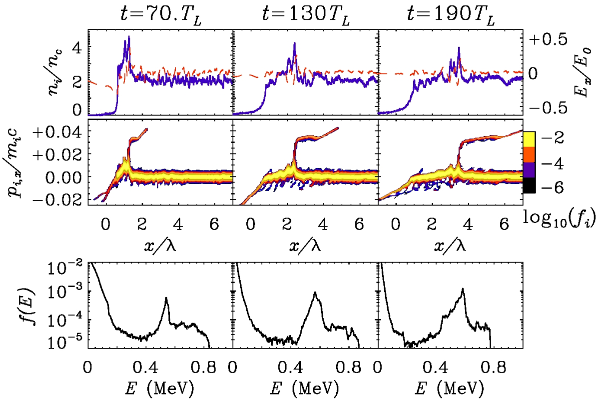
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 2$ keV

$\Delta x = \lambda/400$

800 particles/cell



At higher T_i more ions are reflected $\rightarrow v_s$ decreases and the spectrum broadens towards low energies

Macchi, Nindrayog, Pegoraro, PRE **85** (2012) 046402