Ion Acceleration

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Outline

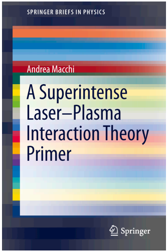
- The coherent (collective) acceleration paradigm (1957)
- The (re–)discovery of laser-driven proton beams (2000)
- Acceleration mechanisms: experiment & theory
- Target Normal Sheath Acceleration (TNSA)
- Radiation Pressure Acceleration (RPA)
- Collisionless Shock Acceleration (CSA)
- Other mechanisms

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,
Plasma Phys. Contr. Fus. **55** (2013) 124020

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



SPRINGER BRIEFS IN PHYSICS

Andrea Macchi

A Superintense Laser–Plasma Interaction Theory Primer

Springer

Other ion acceleration reviews

H. Daido, M. Nishiuchi, A. S. Pirozhkov,
Review of Laser-Driven Ion Sources and Their applications,
Rep. Prog. Phys. **75** (2012) 056401

J.C. Fernández, B.J. Albright, F.N. Beg, M.E. Foord, B.M. Hegelich, J.J. Honrubia, M. Roth, R.B. Stephens, and L. Yin,
Fast ignition with laser-driven proton and ion beams,
Nucl. Fusion **54** (2014) 054006

The vision of “coherent” acceleration: Veksler (1957)

V. I. 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

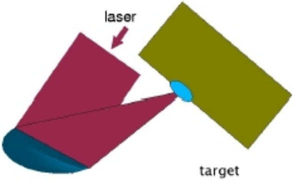
The dawn of laser-plasma physics (1964)

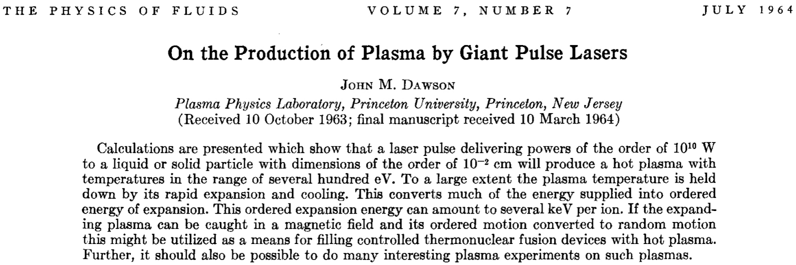
"*The laser is a solution looking for a problem*" (D'Haenens to Maiman, 1960)

Q-switched lasers (1962):

10 GW on $\sim 10^{-2}$ cm spot

$\rightarrow I \simeq 10^{13}$ W cm^{-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

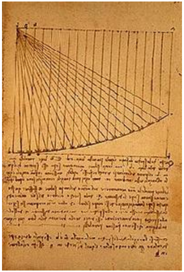
(Received 10 October 1963; final manuscript received 10 March 1964)

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.

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: $I \simeq 1.4 \times 10^{-1}$ W cm^{-2}
with "ultimate" concentration $\sim 10^4 \rightarrow I \simeq 10^3$ W cm^{-2} at focus

Modern ultraintense laser-matter interactions

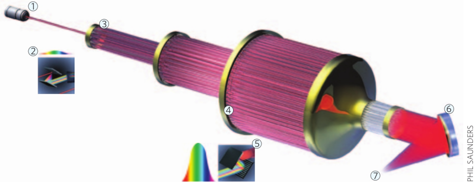
Short (~ 10 fs $= 10^{-14}$ s) pulses of Petawatt (10^{15} W) power focused near diffraction limit ($w \sim 1\ \mu$m): $I \simeq 10^{22}$ W cm^{-2}

(Hercules Laser, CUOS, University of Michigan Ann Arbor, US)

Proposed ELI laser: 100 PW, 15 fs, $I > 10^{23}$ W cm^{-2}

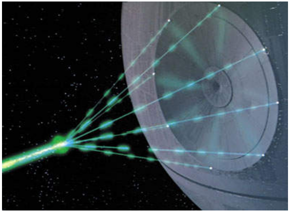
A future vision: multi-fibre laser

[Mourou et al, Nature Photonics **7** (2013) 258]



PHIL SAUNDERS

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).



Laser-plasma ion acceleration in general

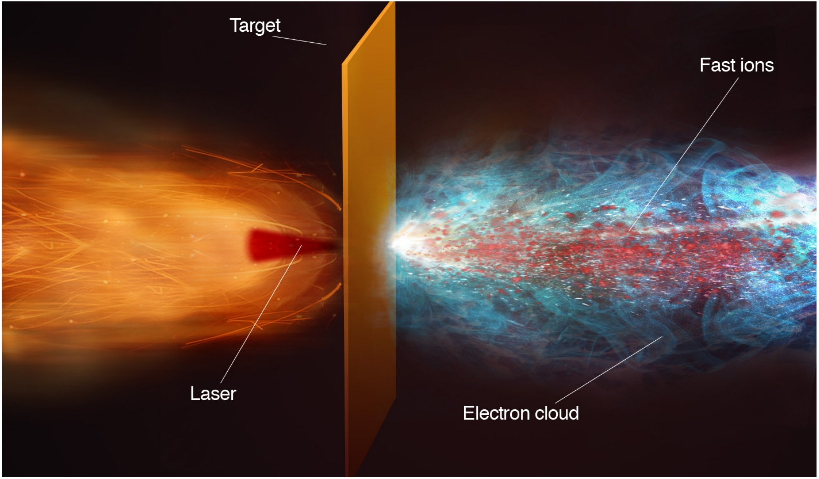
- Laser-plasma interaction (propagation, absorption, nonlinear effects . . .) is dominated by electrons

$$\mathbf{J}_a = q_a n_a \mathbf{v}_a \qquad \mathbf{v}_a = \frac{\mathbf{p}_a}{m_a \gamma_a} \propto \frac{\mathbf{E}_{\text{laser}}}{m_a \omega_{\text{laser}}}$$

$a = (e, i) \qquad m_i = A m_p = 1836 A \times m_e$

- The target (plasma) is globally neutral: if electrons are heated to high energy or directly "swept" by the laser, a strong charge separation buils up
- Ions are accelerated by the electrostatic field due to charge separation

Multi-MeV protons from solid targets (2000)



Multi-MeV protons from solid targets (2000)

Up to 58 MeV protons observed at LLNL (Livermore) Petawatt

Snavely et al, PRL **85** (2000) 2945

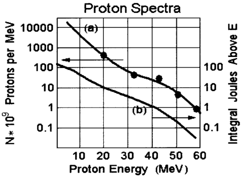
Other observations:

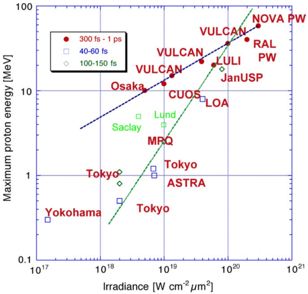
Clark et al, PRL **84** (2000) 670

Maksimchuk et al, PRL **84** (2000) 4108

Protons have been observed and characterized in a large number of laboratories and for different laser pulse regimes

Figure from Borghesi et al, Plasma Phys. Contr. Fus. **50** (2008) 124040

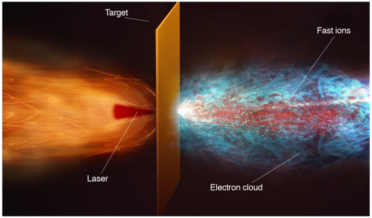


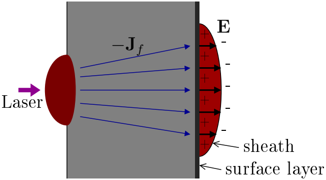


Target Normal Sheath Acceleration (TNSA)

Physics: sheath field generation by “fast” relativistic electrons at the rear surface of a solid target
Field lifetime:
$\sim (1-10)\times 10^{-12}$ s
→ ultrashort ion bunches

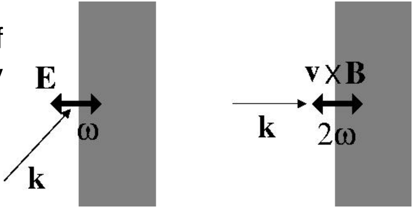
Protons originate from a surface impurity layer at the target rear: favorable initial position and Z/A ratio
(target cleaning → heavier ions acceleration)

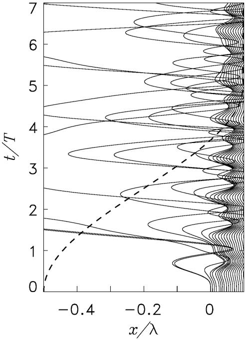




Fast electron generation: a simplified picture

Needs laser-driven push-pull of electrons across the density gradient



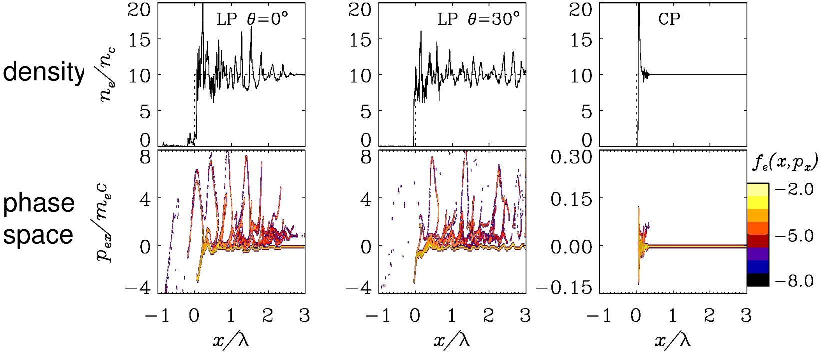


Electrons perform “half-oscillations” in vacuum and re-enter in the plasma with approximately the “quiver” energy

Oscillations driven by:

- $\mathbf{E}$ for P–polarization
- $\mathbf{v}\times\mathbf{B}$ for S–polarization or normal incidence

Fast electron generation: 1D simulations



Linear Polarization: fast electron bunches at rate ω (for $\theta = 30°$, P-pol.) or 2ω (for $\theta = 0°$)

Circular Polarization at $\theta = 0°$: *no fast electrons* ($(\mathbf{v} \times \mathbf{B})_{2\omega} = 0$)

Fast electron generation: typical parameters

- Typical energy (“ponderomotive scaling”)

$$\mathcal{E}_f = m_e c^2(\gamma - 1) \sim m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1\right)$$

a_0: “relativistic” amplitude parameter

$$a_0 = \left(\frac{I\lambda^2}{10^{18}\ \mathrm{W/cm^2}}\right)^{1/2} = \frac{eE_L}{m_e\omega c} = \frac{p_{\mathrm{osc}}}{m_e c}$$

- conversion efficiency $\eta_f \simeq 10^{-2} - 10^{-1}$
- density $n_f \simeq 10^{20} - 10^{21}\ \mathrm{cm}^{-3}$
- current density $\sim 10^{12}\ \mathrm{A/cm^2} \rightarrow 10\ \mathrm{MA}$ over the laser spot

Static modeling of TNSA

Assume fast electrons in Boltzmann equilibrium with density n_e and temperature T_e as the only parameters to evaluate sheath extension L_s and potential drop $\Delta\Phi$

$$L_s \simeq \lambda_D = (T_e/4\pi e^2 n_e)^{1/2}\,, \qquad \Delta\Phi \simeq T_e/e$$

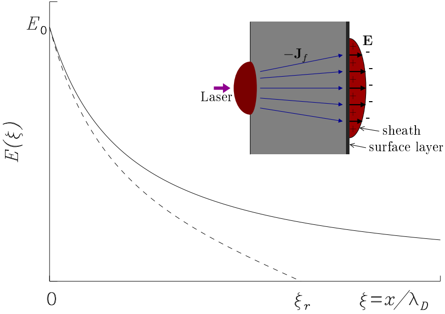
Energy gain by a “test” ion in the static sheath:

$$\mathscr{E}_{\text{max}} = Ze\Delta\Phi \simeq ZT_e$$

⚠ : exact treatment yields

$$L_s \to \infty \qquad \Delta\Phi \to \infty$$

if Boltzmann’s distribution is not “truncated” at high energy



Charging and “truncation” by electron escape

- An isolated, warm plasma in “real” 3D space gets charged due to the escape of N_{esc} electrons with energy $> U_{\text{esc}}$ (since the binding potential is limited)
- For a simple spherical emitter of radius R having N_0 electrons at T_e:

$$N_{\text{esc}} = N_0 \exp(-U_{\text{esc}}/T_e) \qquad U_{esc} = e^2 N_{\text{esc}}/R$$

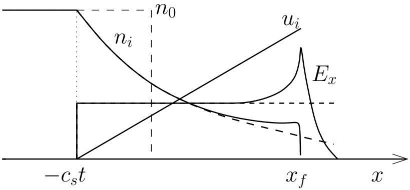
- Message: cut-off energy U_{esc} (hence $\mathcal{E}_{\text{max}}$) depends on target density, size, . . .
- ⚠: the system is neither steady nor in Boltzmann equilibrium, the target is neither isolated nor grounded, . . .

Dynamic modeling of TNSA

Plasma expansion model: isothermal rarefaction wave solution "patched" at the ion front where quasi-neutrality breaks down

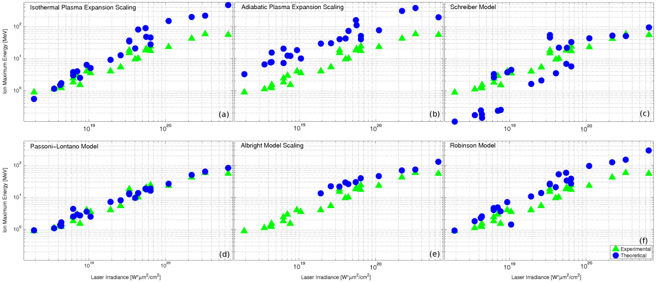
$$c_s = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \quad u_f \equiv u_i(x_f) = c_s[2\ln(\omega_{pi}t)+1], \quad \mathscr{E}_{\text{max}} = \frac{m_i}{2}u_f^2 \propto ZT_e$$

⚠: ion energy diverges due to infinite energy reservoir!
assume finite model (e.g thin foil expansion) with $T_e(t)$
assume finite acceleration time (extra patch)



Some models fit better than others

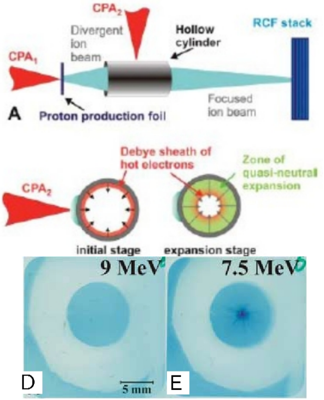
Comparison of several models with experimental energies [Perego et al, Nucl.Inst.Meth.Phys.Res.A **653** (2011) 89]

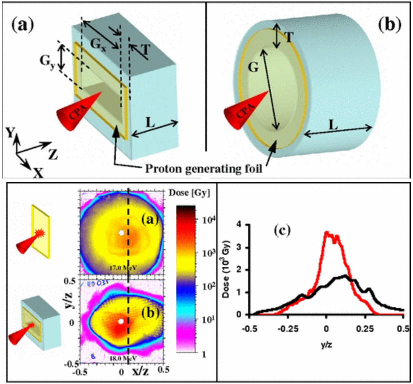


Fitting parameters: laser pulse energy, power, intensity, duration; fast electron energy, density, divergence; ion density and distribution; target thickness; . . . and various “phenomenological” quantities

Proton beam focusing and manipulation

TNSA-based “lenses” for spatial and spectral control of protons





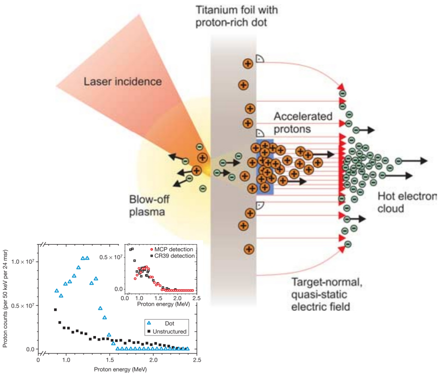
Toncian et al, Science **312** (2006) 410

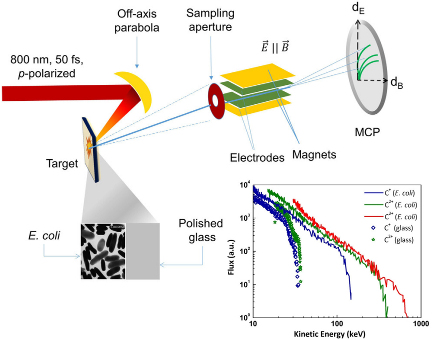
Kar et al, PRL **100** (2008) 105004

Engineering the initial distribution of ions

Hydrogen-rich microdot for monoenergetic acceleration

Use of *bacteria* as hydrogen-containing layer





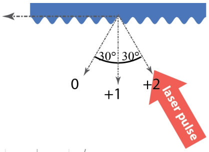
Schwoerer et al, Nature **439** (2006) 445

Dalui et al, Scient. Rep. **4** (2014) 1

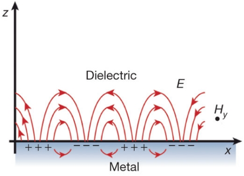
Structured targets for enhanced TNSA

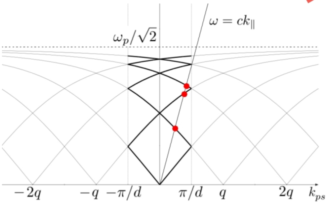
Fast electron production can be increased in targets with front side shaping or structuring (foams, microfunnels, . . . , gratings)

Periodic structures allow resonant excitation of surface waves → field enhancement and high absorption (“light caught by a grating”)



Matching possible at a plasma-vacuum interface if the grating is preserved (ultrahigh pulse contrast necessary!)





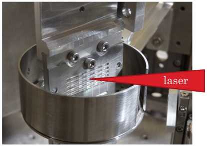
SW-enhanced TNSA: experimental results

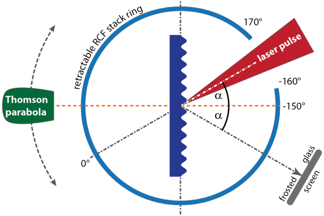
LaserLAB experiment at SLIC (CEA Saclay, F)

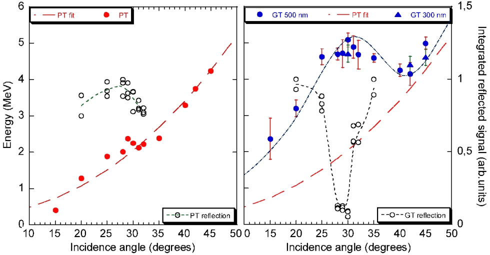
laser UHI, 28 fs, 5×10^{19} W cm^{-2}

contrast $\sim 10^{12}$ → grating survives prepulse!

Laserlab Europe







Enhancement observed in proton energy at resonant angle of incidence

T.Ceccotti et al, PRL **111** (2013) 185001

Beyond TNSA: searching for other mechanisms

Unresolved issues and limitations of TNSA:

- broad (~ exponential) energy spectrum
  (slow progress from engineered targets)
- slow scaling with laser intensity ($\mathscr{E}_{\text{max}} \sim I^{1/2}$)
- high repetition rate not easy with thin solid targets
- structured targets may be complex and/or expensive

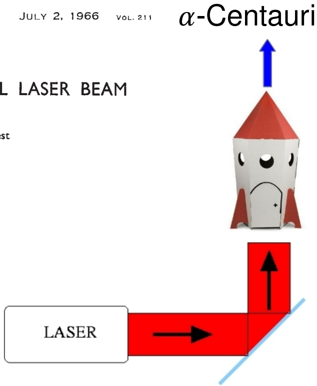
Early vision of radiation pressure acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By PROF. G. MARX

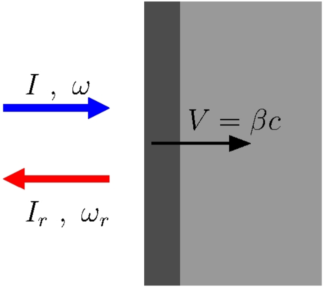
Institute of Theoretical Physics, Roland Eötvös University, Budapest



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 model of RPA

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



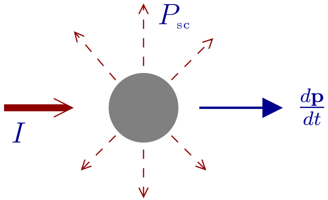
$$\frac{dp}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

High efficiency ($\eta \to 1$) but slow gain ($dp/dt \to 0$) as $\beta \longrightarrow 1$

Analogy with Acceleration by Thomson Scattering

Light Sail equations of motion have the same form as those of a particle undergoing Thomson Scattering

Landau & Lifshitz, *The Classical Theory of Fields*, ch.78 p.250 (1962).



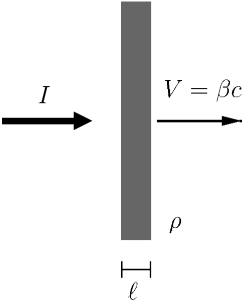
$$\frac{dp}{dt} = \sigma_T I \propto P_{sc}$$

Veksler's idea: coherent scattering by a cluster of radius $a \ll \lambda$ with N $(\gg 1)$ particles, $P_{sc} \to N^2 P_{sc} \Rightarrow \sigma_T \to N^2 \sigma_T$

Light Sail formulas and scaling

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

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

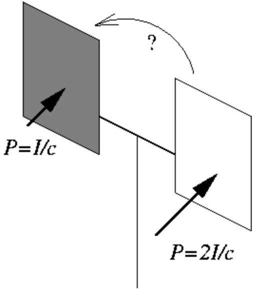


$$\mathscr{E}_{\text{ion}}(t) \propto \left(2It/\rho\ell c^2\right)^{1/3}$$

(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
Need of ultrathin (nm) foils and ultrahigh contrast pulses
Issues: slow energy gain, heating, transparency, deformation . . .

How to make radiation pressure dominant?



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

Enforcing radiation pressure dominance requires to suppress heating of the surface
Possible solution for ultraintense lasers: circular polarization

Relativistic transparency and optimal thickness

Thin plasma foil becomes transparent because of relativistic effects when

$$a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda} \qquad n_c = \frac{m_e\omega^2}{4\pi e^2} \text{ (cut-off density)}$$

→ optimal thickness as trade-off between reduced mass and transparency: $a_0 = \zeta$

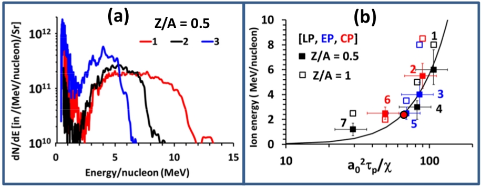
- Diamond-Like Carbon ultrathin (nm) targets

→ avoid “prepulses” to cause early target disruption

- ultrahigh-contrast systems
- wide spots (and large energy), supergaussian intensity profiles to avoid strong deformation ?

$\mathscr{F}^2$ 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

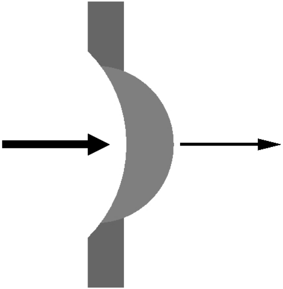


Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/amu observed at high flux
Simulations suggest > 100 MeV/nucleon are within reach

S.Kar et al PRL **109** (2012) 185006

Other recent expts: Steinke et al, PRST-AB **16** (2013) 11303;
Aurand et al, NJP **15** (2013) 33031

Pushing LS forward: “unlimited” acceleration?



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

⇒ “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

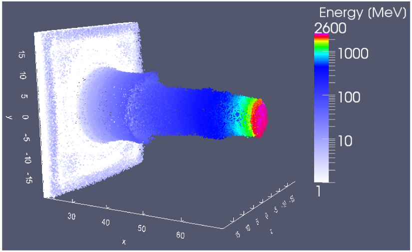
Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

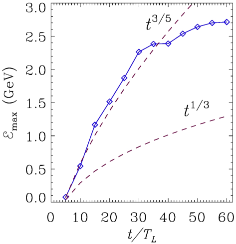
Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$

Relativistic increase of λ in “sail” frame delays breakthrough

High energy gain in 3D RPA-LS simulations

Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $\zeta \simeq a_0 \simeq 200$





$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction

Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020

Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Open Issues for Light Sail RPA

Experimental results show important “non-pure LS” effects:

- broad, non-monoenergetic peaks in energy spectrum
- species separation
- weak dependence on polarization (tight focusing and target deformation effects?)

High gain, relativistic regime (accessible with ELI) may be affected by Rayleigh-Taylor instabilities

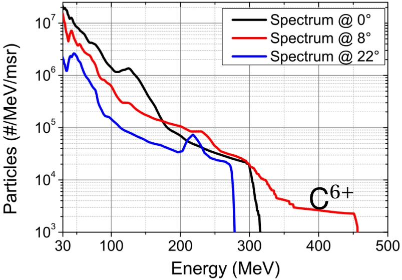
[Sgattoni et al, `arXiv:physics/1404.1260`]

Transparency regime: Break-Out Afterburner

Transition to transparency: strong instability and volumetric heating of electrons

Proton and C broad spectra at high energies and large number of particles (6% efficiency)

Highest energies observed off-axis



[Jung et al NJP **15** (2013) 023007]

Indication of > 150 MeV cut-off for protons!

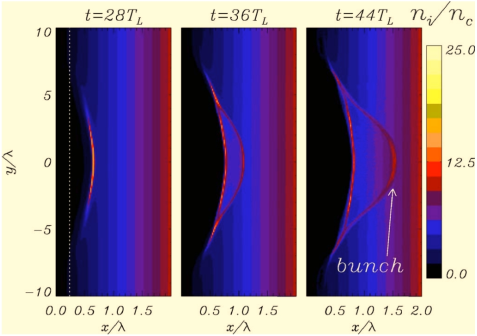
[Hegelich et al, APS Conf. 2011; `arXiv:physics/1310.8650`]

RPA in Thick Targets: “Hole Boring”

“Piston” push at a reflecting plasma surface bores a hole accelerating ions at velocity v_i
Momentum flow balance:

$$P_{\text{EM}} \doteq P_{\text{kin}}$$

(steady assumption)



$$I/c \sim (m_i n_i v_i) v_i \Rightarrow v_i \sim (I/m_i n_i c)^{1/2}$$

Energy scaling $\mathscr{E}_i \sim v_i^2 \sim n_i^{-1}$ suggests to use low densities $n_i \gtrsim n_c$ (cut-off density): possible with gas targets

Hole Boring RPA with gas H target and CO_2 laser

Narrow proton spectra at $\mathscr{E}_{\text{peak}} = 0.8 - 1.2$ MeV ($\Delta\mathscr{E}/\mathscr{E}_{\text{peak}} \simeq 20\%$ spread) observed from H gas jet at $n_e = 4 - 8n_c$

CO_2 ($\lambda = 10\ \mu$m) laser

$I = 6.5 \times 10^{15}$ W cm^{-2}

circular polarization

Scaling with I/n_e and number of protons consistent with HB acceleration

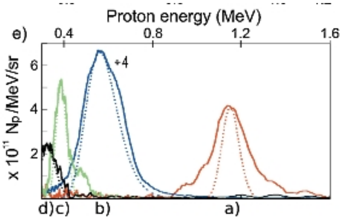
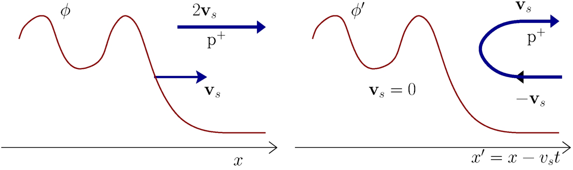


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{\text{cr}}$, (b) $I = 5.5$, $n = 6.1n_{\text{cr}}$, (c) $I = 5.9$, $n = 7.6n_{\text{cr}}$, (d) $I = 5.7$, $n = 8.0n_{\text{cr}}$ (I in units of 10^{15} W cm^{-2}). (e) Background subtracted (solid lines) and also corrected (dashed lines) spectra. Heights of corrected spectra adjusted to match those of raw lineouts. Lineout corresponding to (b) reduced 4× to fit on the same scale.

Palmer et al, PRL **106** (2011) 14801

Collisionless Shock Acceleration

- Concept: shock wave of velocity $v_s = Mc_s$ ($M > 1$, $c_s = \sqrt{ZT_e/Am_p}$) driven by the laser pulse into an ideal (collisionless) plasma



- Shock front is a moving potential barrier → *reflection* of some ions from the shock front: $v_i \simeq 2v_s$

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

Collisionless Shocks: Existence and Generation

Shocks do *not* exist in an *ideal* gas or plasma: some "dissipation" is necessary

→ ion reflection itself can provide dissipation in a collisionless plasma!

[Tidman & Krall, *Shock Waves in Collisionless Plasmas* (Wiley, 1971)]

Shock generation requires some "strong and sudden driver" (e.g. explosion): for laser-plasma interaction it may be driven by (a combination of)

- rapid heating of electrons at the interface
- "piston" effect of radiation pressure
- plasma instabilities (connection with astrophysics)

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?

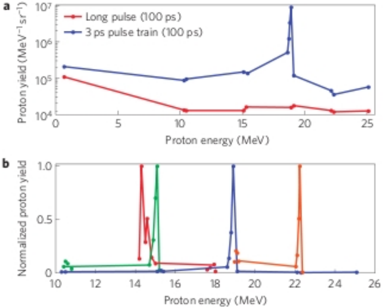
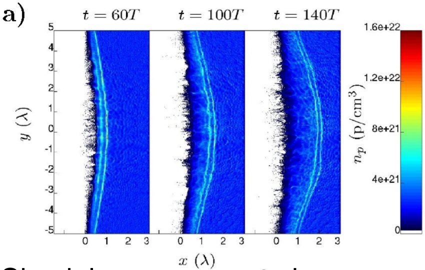


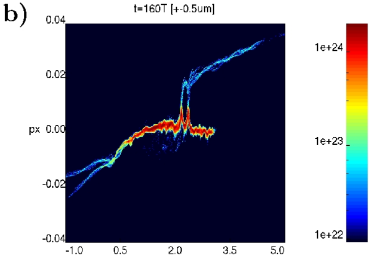
Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within 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 Energy Chirping (2D Simulation)

laser : $\tau_p = 45T,\ a_0 = 1,\ w = 5\lambda$; target: $n_e = 2n_c,\ T_i = 100$ eV, $Z/A = 1$





Shock loses energy to ions → v_s decreases → ions velocity $(2v_s)$ decreases → spectrum broadens towards lower energies

Density profile and energy distribution of background ions are crucial for monoenergetic CSA (too many ions cannot be reflected anyway)

Macchi et al, PRE **85** (2012) 046402; Sgattoni et al, Proc. Spie **8779** (2013)

Potential of Gas Jet Targets

- Flowing gas targets allow high repetition rate operation and pure hydrogen content
- CO_2 gas laser may also work at high rate

→ motivation for CO_2 laser development?

- Scaling to optical lasers needs target engineering (gas jets at high density)

Some conclusions and perspectives . . .

- Progress in ion acceleration has been obtained on various sides (cut-off energy, efficiency, energy spread . . .) in separate experiments with different mechanisms (more or less suitable for foreseen applications)
- Laser-driven ion beams already used for ultrafast plasma diagnostic and warm dense matter production
- Reaching required performance for other applications is still challenging:
- exploit new generation lasers
- improve target engineering
- develop large-scale simulations for experiment design