Advanced schemes for laser-plasma ion acceleration

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Main coworkers for this talk

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...and many colleagues from several institutes abroad (Queen's University – Belfast, LULI Ecole Polytechnique – Palaiseau, CEA/LyDyL – Saclay, Technical University –Prague, ...)

Outline

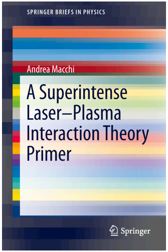
- Some history: from the coherent (collective) acceleration paradigm (1957) to the (re–)discovery of laser-driven proton beams (2000)
- Acceleration mechanisms: theory & experiment
- Target Normal Sheath Acceleration (TNSA): use of structured targets and high-field plasmonics
- Radiation Pressure Acceleration (RPA): “Light Sail” acceleration, high gai regimes and instability
- Collisionless Shock Acceleration (CSA): conditions for mononergetic spectra, Vlasov simulations

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)



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

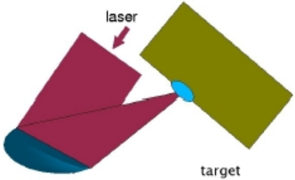
The dawn of laser-plasma physics (1964)

"*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.

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]

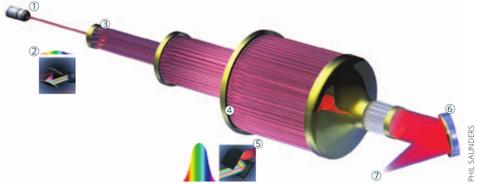
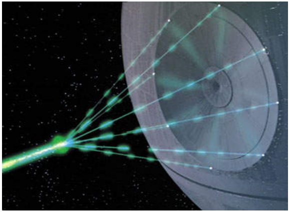
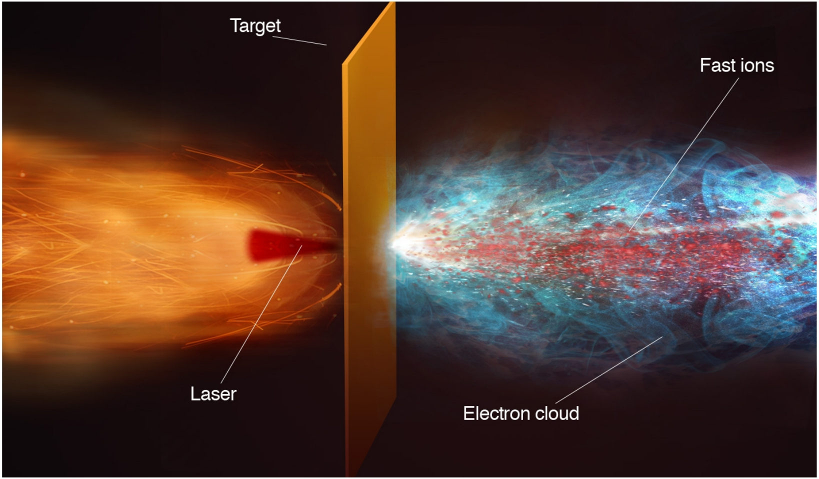


Figure 1 | Principle of a coherent amplifier network. An initial pulse from a seed laser (1) is stretched (2), and split into many fibre channels (3). Each channel is amplified in several stages, with the final stages producing pulses of ~1 mJ at a high repetition rate (4). All the channels are combined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



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

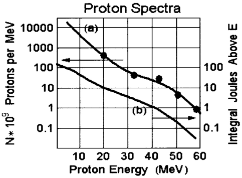
Other observations:

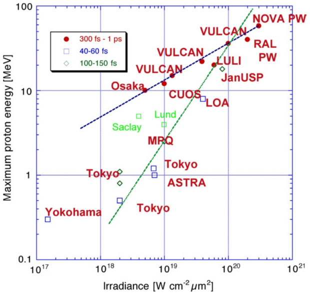
Clark et al, PRL **84** (2000) 670

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

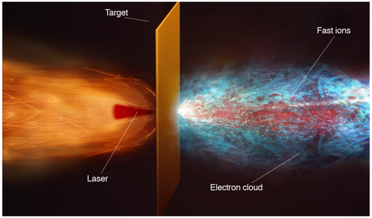
Figure from Borghesi et al, Plasma Phys. Contr. Fus. **50** (2008) 124040



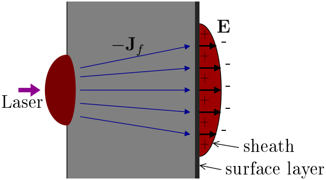


Target Normal Sheath Acceleration (TNSA)

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

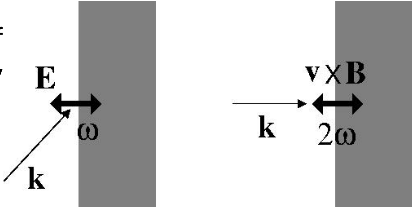


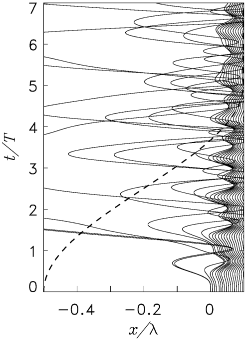
Protons originate from a surface impurity layer at the target rear: favorable initial position and Z/A ratio
(target cleaning → heavier ions acceleration)



Fast electron generation: a simplified picture

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

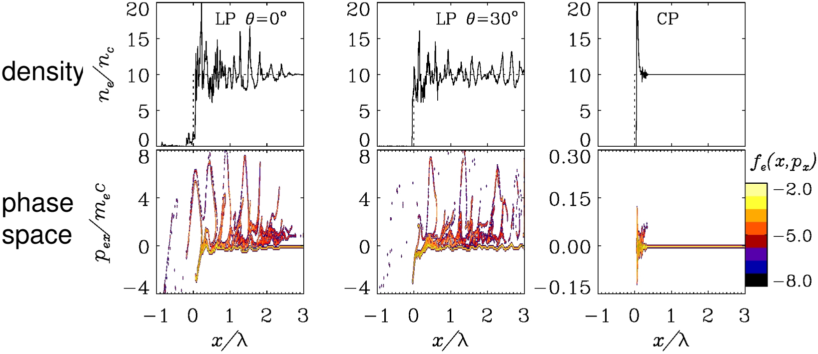




Electrons perform "half-oscillations" in vacuum and re-enter in the plasma with approximately the "quiver" energy

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

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

- conversion efficiency $\eta_f \simeq 10^{-2} - 10^{-1}$
- density $n_f \simeq 10^{20} - 10^{21}\ \text{cm}^{-3}$
- current density $\sim 10^{12}\ \text{A/cm}^2 \rightarrow 10\ \text{MA}$ 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 $\Delta\Phi$

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

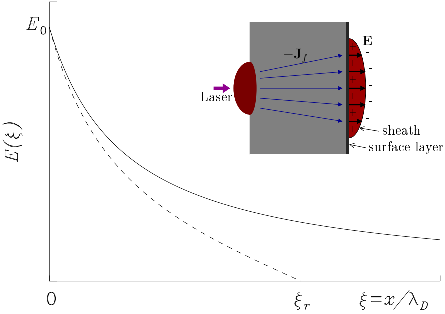
Energy gain by a "test" ion in the static sheath:

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

⚠ : exact treatment yields

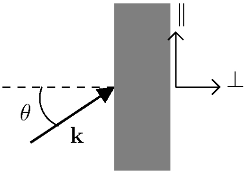
$$L_s \to \infty \qquad \Delta\Phi \to \infty$$

if Boltzmann's distribution is not "truncated" at high energy



Looking for resonant coupling at the surface

Idea: enhancement of the surface field and of absorption by exciting a normal mode of the target plasma



Resonant coupling requires matching of the phase $\varphi = \mathbf{k}_\parallel \cdot \mathbf{r} - \omega t$ between the laser and the resonant mode characterized by $(\omega_m, \mathbf{k}_m)$:

$$\omega \doteq \omega_m \qquad k_\parallel = k\cos\theta \doteq (k_m)_\parallel$$

Normal modes of step boundary metal/plasma: surface waves

SW: building blocks of **plasmonics** (at low fields)

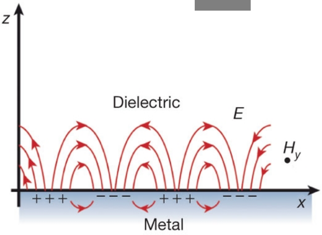


Fig.: Benson, Nature **480**, 193 (2011)

Surface wave coupling: the matching problem

Plasma-vacuum interface

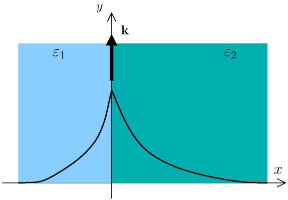
$$\varepsilon_1 = 1 \quad \varepsilon_2 = 1 - \frac{\omega_p^2}{\omega^2} = 1 - \frac{n_e}{n_c}$$

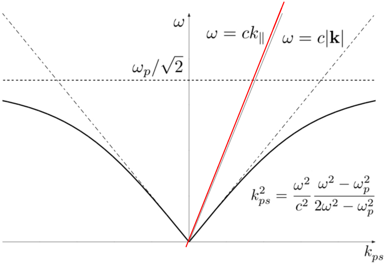
Dispersion relation $\omega = \omega(k)$

$$k = \frac{\omega}{c}\left(\frac{\omega_p^2 - \omega^2}{\omega_p^2 - 2\omega^2}\right)^{1/2}$$

$$\omega < \omega_p/\sqrt{2} \qquad v_{\text{ph}} < c$$

No matching with $\omega = ck_\parallel$

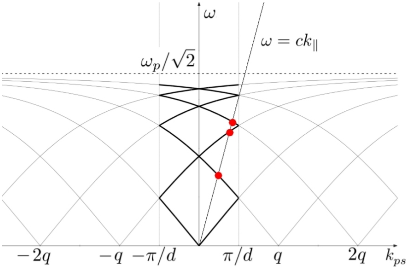




Surface wave matching in periodic structures

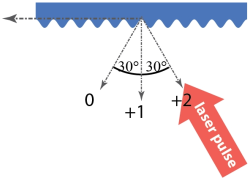
In a spatially periodic medium with period d, folding of $\omega_{SW}(k)$ in the Brillouin zone $|k| < \pi/d$ (Floquet-Bloch theorem) allows phase matching

Figure: M.Lupetti, M.Sc. Thesis, 2011



Resonant coupling with EM wave is possible in a grating at an angle of incidence

$$\sin\theta_{\text{res}} + \lambda/d = \left(\frac{1-\omega_p^2/\omega^2}{2-\omega_p^2/\omega^2}\right)^{1/2}$$



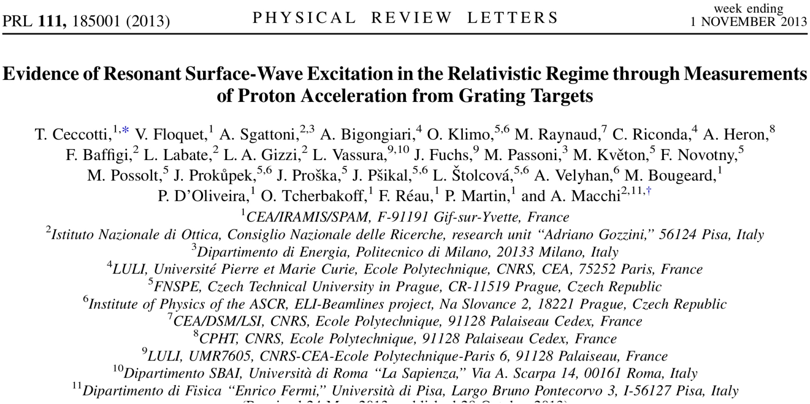
(provided $\omega_{SW}(k)$ does not change much)

Plasmonics at high fields?

Aim: exploit plasmonic field enhancement and surface wave excitation in sub-wavelength (periodic) structures at high intensity ($> 10^{18}$ W cm^{-2}, relativistic regime)

- hydrodynamics may wash target structuring out
  - use ultrashort pulses (10s of fs)
- prepulse effects may destroy structures at target surface
  - use high-contrast techniques (e.g. plasma mirrors)
- features of plasmonics and surface waves unknown in the high-field, nonlinear, relativistic regimes
  - hope for the best . . .

Experimental evidence: grating-enhanced TNSA


PRL **111,** 185001 (2013) PHYSICAL REVIEW LETTERS week ending 1 NOVEMBER 2013

Evidence of Resonant Surface-Wave Excitation in the Relativistic Regime through Measurements of Proton Acceleration from Grating Targets

T. Ceccotti,[1,*] V. Floquet,[1] A. Sgattoni,[2,3] A. Bigongiari,[4] O. Klimo,[5,6] M. Raynaud,[7] C. Riconda,[4] A. Heron,[8] F. Baffigi,[2] L. Labate,[2] L. A. Gizzi,[2] L. Vassura,[9,10] J. Fuchs,[9] M. Passoni,[3] M. Květon,[5] F. Novotny,[5] M. Possolt,[5] J. Prokůpek,[5,6] J. Proška,[5] J. Pšikal,[5,6] L. Štolcová,[5,6] A. Velyhan,[6] M. Bougeard,[1] P. D'Oliveira,[1] O. Tcherbakoff,[1] F. Réau,[1] P. Martin,[1] and A. Macchi[2,11,†]
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[10]Dipartimento SBAI, Università di Roma "La Sapienza," Via A. Scarpa 14, 00161 Roma, Italy
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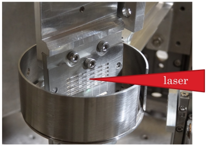
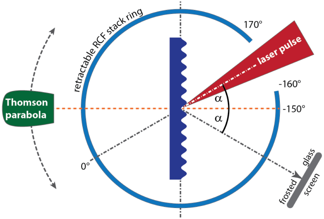
Experimental evidence: grating-enhanced TNSA

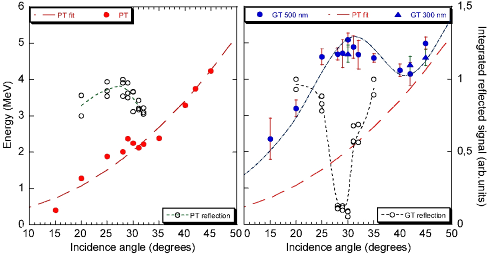
LaserLAB experiment at SLIC, CEA Saclay

laser UHI, 28 fs, 5×10^{19} W cm^{-2}

contrast $\sim 10^{12}$





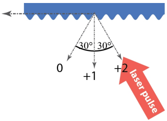


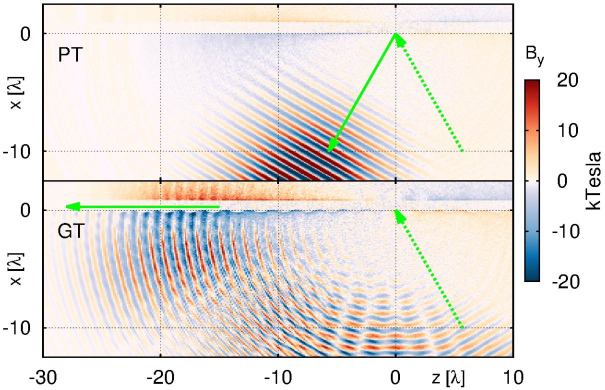
3X increase observed in proton energy at resonant angle

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

Surface wave in PIC simulations

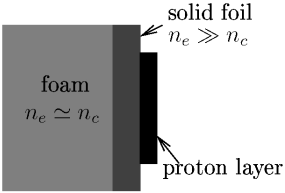
Snapshots of EM fields show localized wave propagating along the surface at resonant angle of incidence (plus reflection at various diffraction orders)





Foam targets for low density-enhanced absorption

Deposit layer at $n_e \simeq n_c$ on thin foil
→ proton energy doubles up to 15 MeV
(3D simulation, 25 fs pulse, 1 J energy)



Sgattoni, Londrillo, Macchi, Passoni,
PRE **85** (2012) 036405

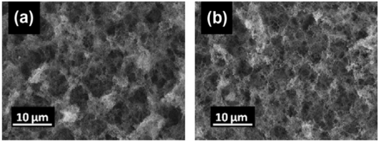
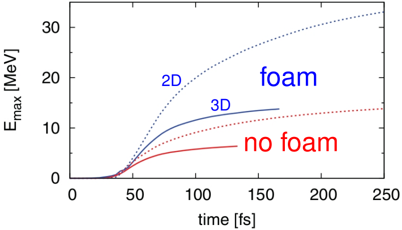
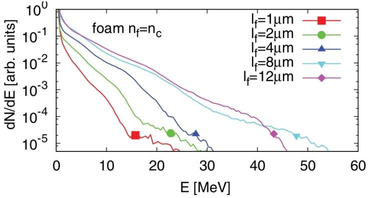


Fig. 8 – SEM plane view images of foam samples deposited, respectively, with 0.03 mg/s (1 sccm) (a) and 3 mg/s (100 sccm) (b) longitudinal gas flow.

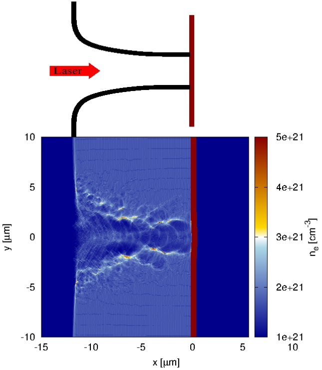


Low-density foam production and characterization:
Zani et al, Carbon **56** (2013) 358

Foam-enhanced fast electron generation



High absorption and fast electrons temperature $T_f \gtrsim 3T_{\text{pond}}$ for optimal foam areal density $n_e\ell$

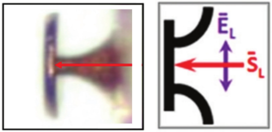


Coupling of P-component of $\mathbf{E}$ with channel walls accelerates electrons: similarity with cone targets (→)

Experiment recently performed on Petawatt laser at GIST, Gwangju, South Korea (data analysis in progress)

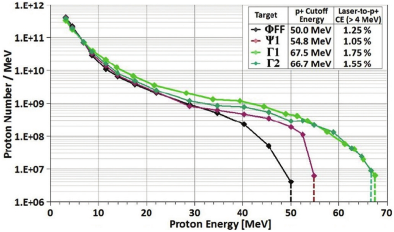
Enhanced TNSA in microcone targets

[Gaillard et al, PoP **18** (2011) 056710]



Up to $\mathscr{E}_{co}$=67.5 MeV protons with 80 J pulse energy in cone targets

Efficient coupling to side walls as in the channel case:
similar mechanism in action



[Kluge et al, New J. Phys. **14** (2012) 023038]

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

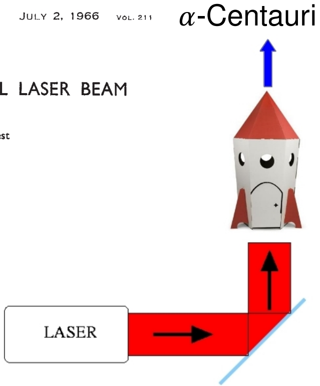
Early vision of radiation pressure acceleration (1966)

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

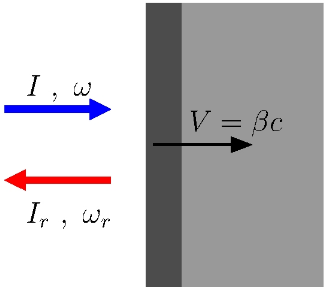
By PROF. G. MARX
Institute of Theoretical Physics, Roland Eötvös University, Budapest

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



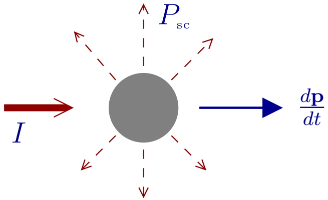
$$\frac{dp}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

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).



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

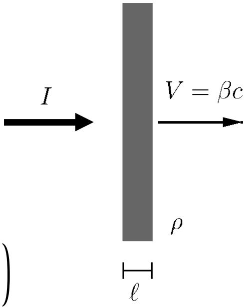
Veksler's idea: coherent scattering by a cluster of radius $a \ll \lambda$ with N $(\gg 1)$ particles, $P_{sc} \to N^2 P_{sc} \Rightarrow \sigma_T \to N^2 \sigma_T$

Light Sail formulas, scaling, and needs

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

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

$$\mathcal{E}_{\text{ion}}(t) \propto \left(\frac{2It}{\rho\ell c^2}\right)^{1/3} \qquad \left(t \gg \frac{\rho\ell c^2}{I}, \mathcal{E}_{\text{ion}} > m_p c^2\right)$$



Favorable scaling with normalized fluence $\mathcal{F}$
"Perfect" monoenergeticity for "rigid", coherent sail motion
Need of ultrathin (nm) foils and ultrahigh contrast pulses
Circular polarization to reduce undesired heating
Issues: slow energy gain, heating, transparency, deformation . . .

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

PRL **109,** 185006 (2012) PHYSICAL REVIEW LETTERS week ending 2 NOVEMBER 2012

Ion Acceleration in Multispecies Targets Driven by Intense Laser Radiation Pressure

S. Kar,[1,*] K. F. Kakolee,[1] B. Qiao,[1,†] A. Macchi,[2,3] M. Cerchez,[4] D. Doria,[1] M. Geissler,[1] P. McKenna,[5] D. Neely,[6] J. Osterholz,[4] R. Prasad,[1] K. Quinn,[1] B. Ramakrishna,[1,‡] G. Sarri,[1] O. Willi,[4] X. Y. Yuan,[5,§] M. Zepf,[1,7] and M. Borghesi[1,8]

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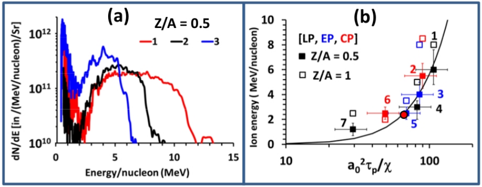
(Received 23 February 2012; published 2 November 2012)

$\mathscr{F}^2$ 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



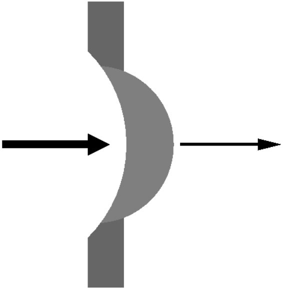
Multispecies ($Z/A = 1, 1/2$) peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/amu observed at high flux
Simulations suggest > 100 MeV/nucleon are within reach

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 $\rho\ell$
$\Rightarrow$ "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 simulation campaign: LSAIL project

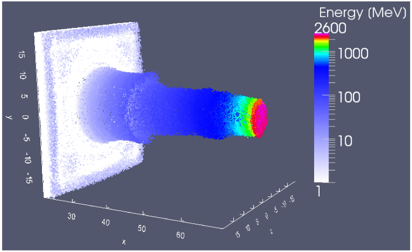
(Large Simulations of ion Acceleration by Intense Lasers)

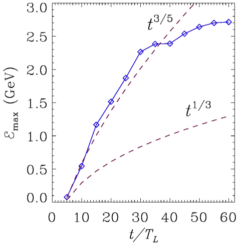
- PRACE award for access to FERMI BlueGene/Q at CINECA, Italy
- Typical set-up: 4096×1792^2 grid points, 2×10^{10} particles, 16384 cores used
- Particle-In-Cell (PIC) codes:

  - ALADYN: C. Benedetti, A. Sgattoni, G. Turchetti, P. Londrillo, IEEE Trans. Plasma Science **36** (2008) 1790
  - PICCANTE: Open Source code
    (L.Fedeli, A.Sgattoni, S.Sinigardi, et al)
    `github.com/ALaDyn/piccante`

High energy gain in 3D RPA-LS simulations

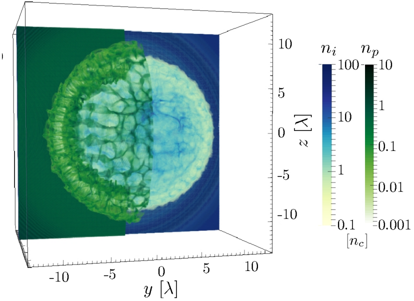
Laser: 24 fs, 4.8 μm spot, $I = 0.85 \times 10^{23}$ W cm^{-2} $\Longrightarrow$ **1.5 kJ**
Target: 1 μm foil, $n_e = 1.1 \times 10^{23}$ cm^{-3}, $\zeta \simeq a_0 \simeq 200$



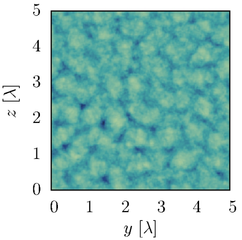


$\mathcal{E}_{\text{max}} \simeq 2.6$ GeV > 4 times 1D model prediction
Macchi et al, Plasma Phys. Contr. Fus. **55** (2013) 124020
Sgattoni et al, Appl. Phys. Lett. **105** (2014) 084105

Sructures in ion density: Rayleigh-Taylor instability?



Formation of net-like structures with size $\sim \lambda$ (laser wavelength) and $\sim$ hexagonal shape



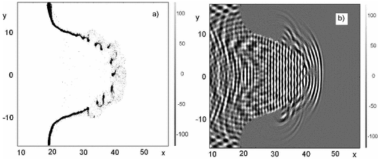
Interpretation: Rayleigh-Taylor instability driven by radiation pressure

Symmetry analysis of nonlinear RTI in 3D:
S. I. Abarzhi, Phys. Rev. E **59** (1999) 1729

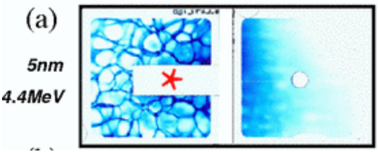
Sgattoni, Sinigardi, Fedeli, Pegoraro, Macchi, arXiv:1404.1260

RTI in Radiation Pressure Acceleration

Thin foil target of areal density σ accelerated by a laser of intensity I is unstable with growth rate $\gamma = (P_0 q/\sigma)^{1/2}$ with $P_0 = 2I/c$ and q the wavevector [Ott, PRL **29** (1972) 1429]



2D simulation
[F.Pegoraro & S.V.Bulanov, PRL **99** (2007) 065002]

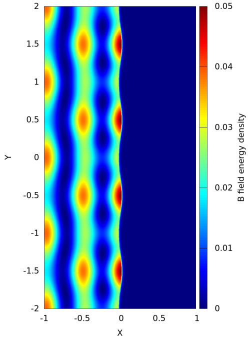


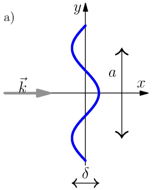
Experimental indication from accelerated ion beam profile structures [C.Palmer et al, PRL **108** (2012) 225002]

Question: what sets the dominant wavevector q (and spatial scale of structures $\sim q^{-1}$?)

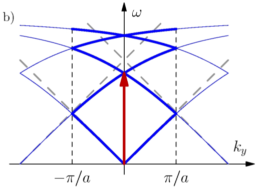
Plasmonic modulation of radiation pressure

The EM field at a rippled surface (e.g. 2D reflecting, sinusoidal grating of period d) is modulated with plasmonic enhancement of the P-component when $d \sim \lambda$





Geometry



Matching with surface plasmons

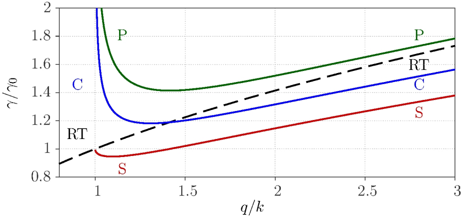
The resulting modulation of laser light pressure provides a spatial seed for RTI

Thin foil RTI with self-consistent pressure modulation

Model: reflection from shallow 2D grating of depth δ (first order in δ/λ) + modified Ott's theory with modulated pressure:

$$P \simeq P_0(1+K(q)\delta\cos qy)\,, \qquad K(q) = \begin{cases} -(q^2-k^2)^{1/2} & (S) \\ k^2 q(q^2-k^2)^{-1/2} & (P) \\ (k^2-q^2/2)(q^2-k^2)^{-1/2} & (C) \end{cases}$$

$$\gamma = (P_0/\sigma)^{1/2}\left[\left(q^2+K^2(q)/4\right)^{1/2} + K(q)/2\right]^{1/2}$$



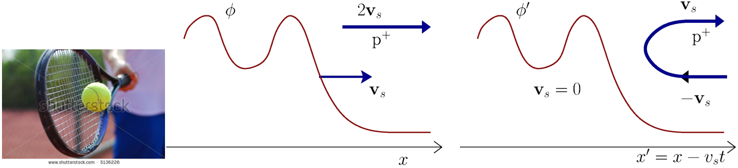
S-polarization
P-polarization
C-ircular polarization
RT: no modulation ($\delta = 0$)

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?)
  - Rayleigh-Taylor instabilities
- Use of ultrathin foil targets may be not optimal for high repetition rate operation

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 (low density, high temperature)



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

→ acceleration of *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 polarization
Target: H_2 gas jet, $n_0 \leq 4n_c$
Claim: shock driven by fast electron pressure

- monoenergetic spectrum
- suitability for high repetition rate (flowing target)
- low efficiency

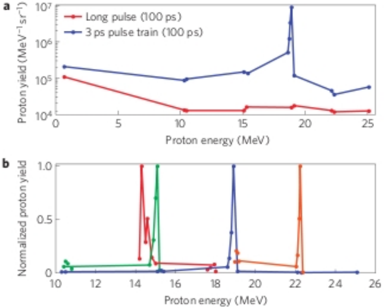


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within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

Efficiency vs. monoenergetic spectrum

Reflected ions are on the tail of the ion distribution

$$v_i > v_s - (2e\Phi_m/m_i)^{1/2} \qquad (\Phi_m \text{ potential jump})$$

Shock must lose part of its energy to accelerate ions

→ shock's kinetic energy and velocity v_s decrease

→ velocity $2v_s$ of reflected ions decreases and spectrum broadens ("chirps") towards low energy

→ small loss is necessary for monoenergetic spectrum

→ number of accelerated ions must be small

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

Shock loading in 1D simulation with warm ions - I

Parameters:

$a_0 = 1$

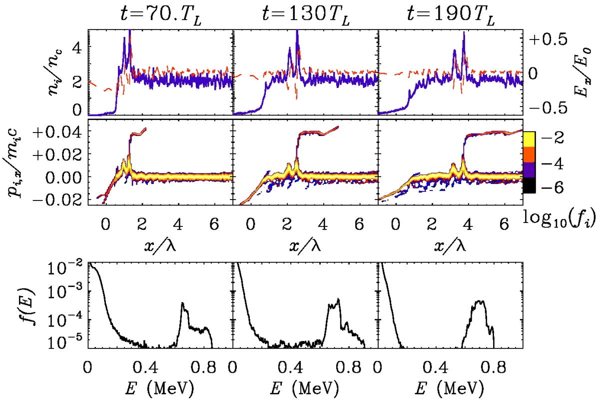
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 0.5$ 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:

$a_0 = 1$

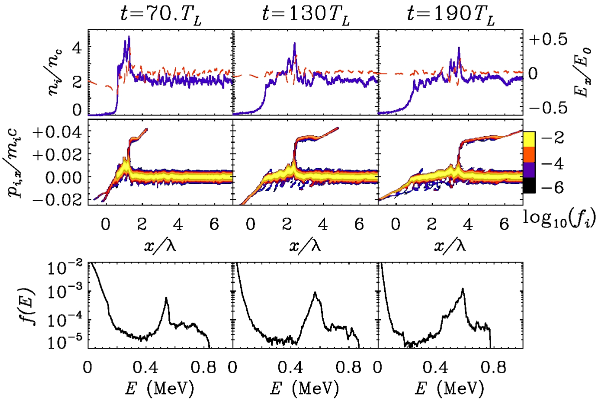
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 2$ keV

$\Delta x = \lambda/400$

800 particles/cell

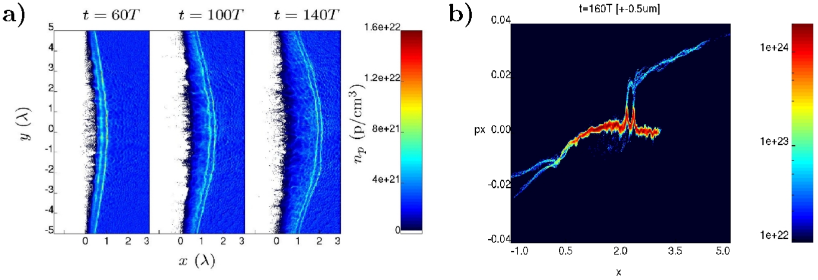


At higher T_i more ions are reflected $\rightarrow v_s$ decreases and the spectrum broadens towards low energies

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

Shock Loading and Energy Chirping in 2D

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



Sgattoni et al, Proc. Spie **8779** (2013)

Resolution of low-density tail in the ion distribution is crucial
→ challenge for PIC codes (high number of particles needed)

“Vlasov” simulations of collisionless shocks

Alternative approaches to Vlasov equation for $f(\mathbf{r},\mathbf{p},t)$

$$\partial_t f + \mathbf{v}\cdot\partial_{\mathbf{r}} f + q\left(\mathbf{E} + \frac{\mathbf{v}}{c}\times\mathbf{B}\right)\cdot\partial_{\mathbf{p}} f = 0 \qquad (+\text{Maxwell eqs.})$$

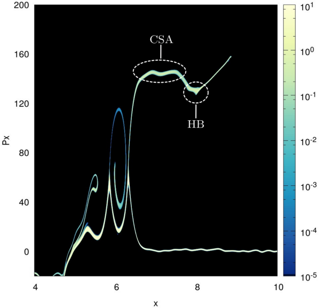
- Particle-In-Cell: Lagrangian, discrete momentum space
- “Vlasov”: Eulerian , continuum phase space

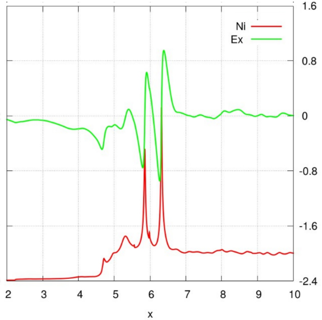
Pro et contra for Vlasov:

- fine resolution of low-density tails
- no numerical noise
- computational effort much greater than PIC

CSA in 1D Vlasov simulations

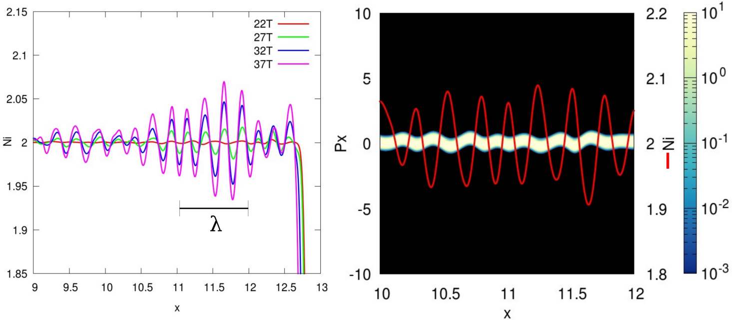
$a_0 = 2$
$n_e = 2n_c$
$T_i = 1$ eV
$L = 10\lambda$
HB ("hole boring"): direct "piston" acceleration





For cold ions no reflection from the shock should occur (unless the shock becomes a "snowplow" and cannot propagate)
BUT quite stable ion reflection is observed: what causes the necessary energy spread?
(Anna Grassi, M.Sc. Thesis, University of Pisa, 2013)

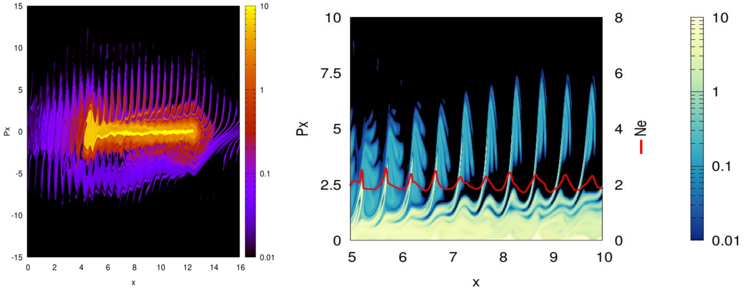
Ion turbulence



Quasi-static ($v_f \simeq 0$), very low-frequency ion density modulation with $\simeq \lambda/4$ wavelength (λ: laser) originating from the target rear boundary (opposite to the laser interaction side)

→ velocity spread for ion reflection

Origin of ion turbulence from “fast electron beats”



Fast electron bunches accelerated by $\mathbf{v}\times\mathbf{B}$ force have 2ω frequency, velocity $\sim c$ and are *coherent*

→ nonlinear plasma wave with $\lambda_p \simeq \lambda/2$

Reflection from the rear side causes “beating” of incident and reflected waves generating $\lambda_p/2 \simeq \lambda/4$ modulation

Model for ion turbulence - I

Pulsed electron bunches as “pump waves” ($\omega_\pm \simeq 2\omega$, $k_\pm \simeq \omega_\pm/c$):

$$(n_e^{(p)}, v_e^{(p)}) = \frac{(n_+, v_+)}{2} e^{ik_+x - i\omega_+t} + \frac{(n_-, v_-)}{2} e^{-ik_-x - i\omega_-t} + \text{c.c.}$$

Nonlinear coupling to background electrons and ions:

$$\partial_t n_e^{(NL)} + n_0 \partial_x v_e^{(NL)} \simeq -\partial_x (n_e^{(p)} v_e^{(p)}) \qquad \partial_t n_i \simeq -n_0 \partial_x v_i$$

$$\partial_t v_e^{(NL)} \simeq -\frac{e}{m_e} E^{(NL)} - v_e^{(p)} \partial_x v_e^{(p)} \qquad \partial_t v_i \simeq +\frac{e}{m_i} E^{(NL)} - \frac{T_e}{m_i} \frac{\partial_x n_i}{n_0}$$

Low frequency component $E^{(NL)} = \tilde{E} e^{iKx - i\Omega t}$ etc.:

$$\Omega = \omega_+ - \omega_- \ll \omega \qquad K = k_+ + k_- \simeq 2\frac{2\pi}{\lambda/2} = \frac{2\pi}{\lambda/4}$$

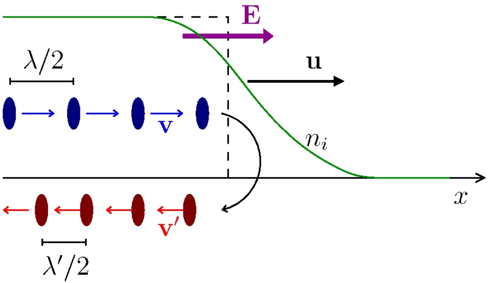
Model for ion turbulence - II

Reflection of electron bunches from expanding sheath at rear side

$\mathbf{v}' \simeq \mathbf{v} - 2\mathbf{u}$

$\lambda' \simeq \lambda(1 - u/v)$

$\Omega \simeq 2\omega(u/v) \simeq Ku$



Ion density oscillations

$$\tilde{n}_i = n_0 \frac{ie\tilde{E}}{m_i} \frac{K}{\Omega^2 - K^2 c_s^2} \qquad \tilde{v}_i = \frac{ie\tilde{E}}{m_i} \frac{\Omega}{\Omega^2 - K^2 c_s^2}$$

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

Funding acknowledgments

- LASERLAB-EUROPE, grant No. 284464, EU's 7th Framework Programme, proposal n.SLIC001693.
- PRACE supercomputing award, project LSAIL, for access to resource FERMI BlueGene/Q™ at CINECA (Italy)
- MIUR (Italy):
  - FIR project "Superintense Ultrashort Laser-Driven Ion Sources"
  - PRIN project "Laser-Driven Shock Waves"

EXTRA SLIDES

Charging and "truncation" by electron escape

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

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

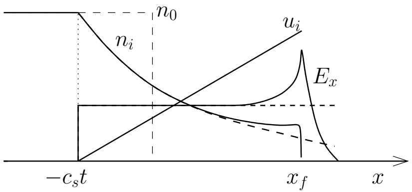
- Message: cut-off energy $U_{\rm esc}$ (hence $\mathscr{E}_{\rm max}$) depends on target density, size, ...
- ⚠: the system is neither steady nor in Boltzmann equilibrium, the target is neither isolated nor grounded, ...

Dynamic modeling of TNSA

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

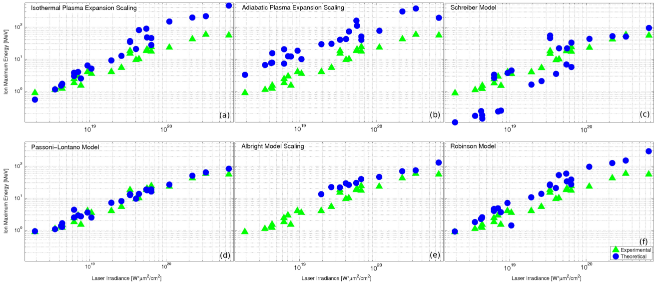
$$c_s = \left(\frac{ZT_e}{m_i}\right)^{1/2}, \quad u_f \equiv u_i(x_f) = c_s[2\ln(\omega_{pi}t)+1], \quad \mathcal{E}_{\text{max}} = \frac{m_i}{2}u_f^2 \propto ZT_e$$

⚠: 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

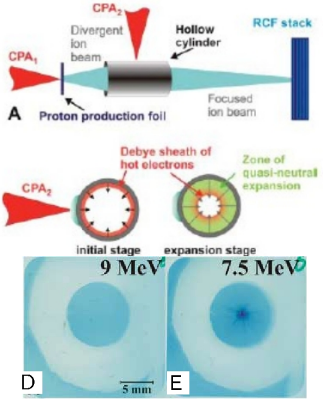
Comparison of several models with experimental energies [Perego et al, Nucl.Inst.Meth.Phys.Res.A **653** (2011) 89]



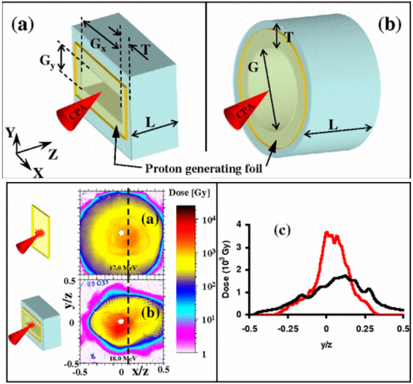
Fitting parameters: laser pulse energy, power, intensity, duration; fast electron energy, density, divergence; ion density and distribution; target thickness; . . . and various "phenomenological" quantities

Proton beam focusing and manipulation

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



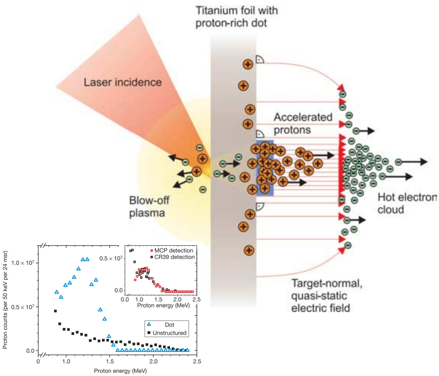
Toncian et al, Science **312** (2006) 410



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

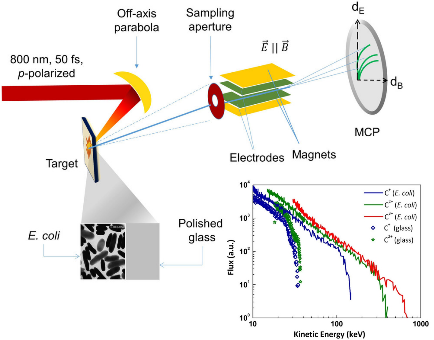
Engineering the initial distribution of ions

Hydrogen-rich microdot for monoenergetic acceleration



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

Use of *bacteria* as hydrogen-containing layer

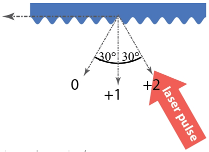


Dalui et al, Scient. Rep. **4** (2014) 1

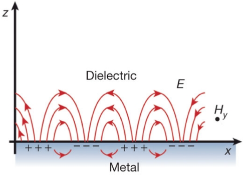
Structured targets for enhanced TNSA

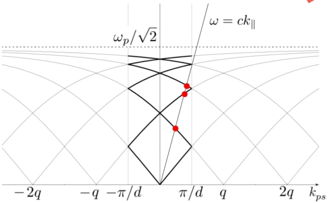
Fast electron production can be increased in targets with front side shaping or structuring (foams, microfunnels, . . . , gratings)

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



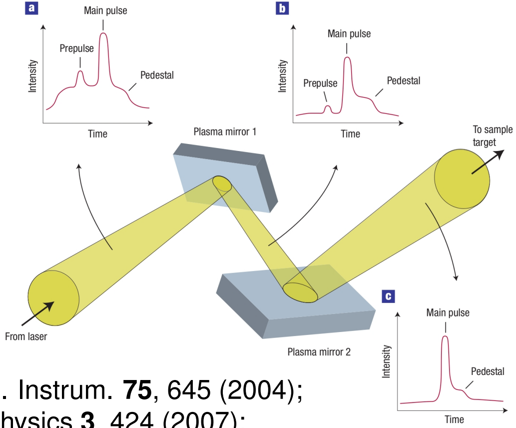
Matching possible at a plasma-vacuum interface if the grating is preserved (ultrahigh pulse contrast necessary!)





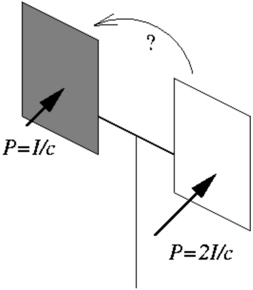
Need for ultraclean pulses: plasma mirrors

Plasma mirrors
yielding $\sim 10^{12}$ pulse-to-prepulse contrast allow to preserve target structuring until the short pulse interaction



B. Dromey et al, Rev. Sci. Instrum. **75**, 645 (2004);
C. Thaury et al, Nature Physics **3**, 424 (2007);
figure from P. Gibbon, *ibid.*, 369.

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

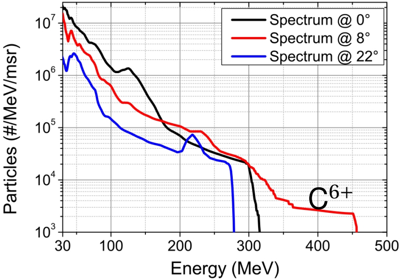
Enforcing radiation pressure dominance requires to suppress heating of the surface
Possible solution for ultraintense lasers: circular polarization

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!

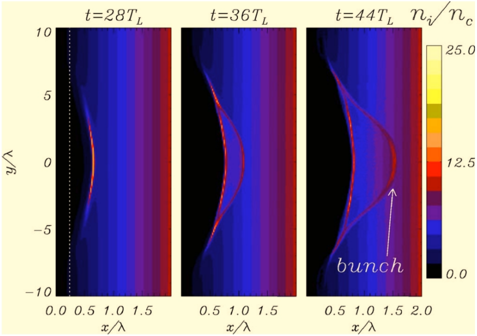
[Hegelich et al, APS Conf. 2011; arXiv:physics/1310.8650]

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

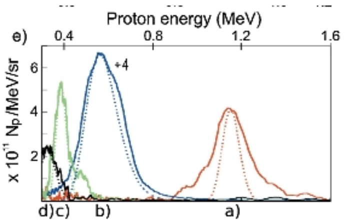


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{\text{cr}}$, (b) $I = 5.5$, $n = 6.1n_{\text{cr}}$, (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