Ion Acceleration

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Applications of Laser-driven Particle Acceleration (ALPA 2015)
Venezia, Italy, November 19, 2015

Outline

A short overview of laser-plasma ion acceleration with emphasis on recent results:

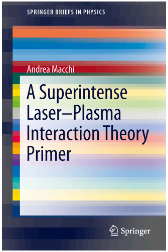
- Energy scaling in short pulse systems
- A new all-optical approach to beam post-acceleration and control
- Progress in radiation pressure acceleration

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

M. Borghesi, J. Fuchs, S. V. Bulanov, A. J. Mackinnon,
P. K. Patel, M. Roth,
Fast Ion Generation by High-Intensity Laser Irradiation of Solid Targets and Applications,
Fusion Science and Technology **49** (2006), 412

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

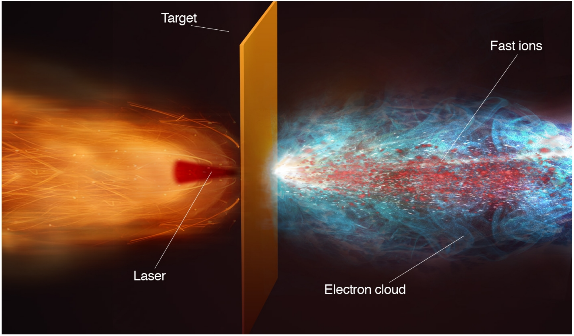
The vision of “coherent” acceleration: Veksler (1957)

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

Multi-MeV protons from solid targets (2000–)

Target Normal Sheath Acceleration (TNSA) model: ion acceleration at the rear side driven fast electrons generated in the laser-plasma interaction



Macchi et al, Rev. Mod. Phys. **85** (2013) 571

Features of laser-accelerated protons

- in metal targets protons originate from H impurities
- cut-off energy record: 67.5 MeV
  (Gaillard et al, Phys. Plasmas **18** (2011) 056710)
- mostly broad energy spectra (exponential-like)
- large numbers - e.g. $\sim 2 \times 10^{13}$ protons, ∼kA current
  (Snavely et al, PRL **85** (2000) 2945)
- charge neutralization by comoving electrons
  ("plasma beam")
- good collimation with energy-dependent spread $\sim 10° - 30°$
- low emittance i.e. $\sim 4 \times 10^{-3}$ mm mrad
  with proper definition for broadband spectra
  (Nuernberg et al., Rev. Sci. Instrum. **80** (2009) 033301)
- ultrashort duration at source (∼ laser duration, $\sim 0.1 - 10$ ps)

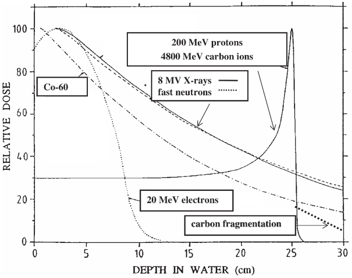
Applications of laser-accelerated protons

Energy deposition dominated by Bragg peak: optimal for localized heating of matter

figure from:

U. Amaldi, G. Kraft,

Rep. Prog. Phys. **68** (2005) 1861



Ongoing & foreseen applications:

- ultrafast probing of electromagnetic fields (M. Borghesi's talk)
- production of warm dense matter
- diagnostic of materials
- triggering of nuclear reactions, isotope production
- oncology: ion beam therapy (IBT)
- fast ignitor beam in inertial confinement fusion

Open challenges for applications

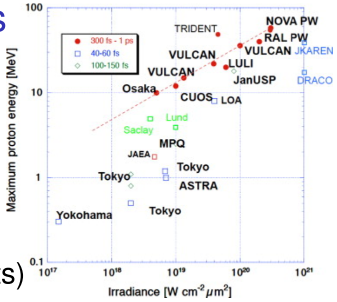
- increase maximum energy per nucleon
- (60-250 MeV for proton beam therapy, >1 GeV for particle physics)
- increase efficiency (e.g. $> 10\%$ for fast ignition ICF)
- enable high repetition rate
- spectral control, monoenergetic spectra
- beam control and focusing, post-acceleration
- …

The race to higher cut-off energies

Emphasis has been put on increasing the proton cut-off energy $\mathscr{E}_{\rm co}$ with the IBT window $(60-250$ MeV) as a goal

2000: $\mathscr{E}_{\rm co}$ ≃58 MeV at $\sim 10^9$ p/MeV (LLNL/Nova, 1 PW, 500 J)

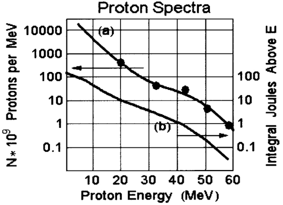
2011: $\mathscr{E}_{\rm co}$ ≃ 67.5 MeV at $\sim 10^7$ p/MeV (LANL/Trident, 200 TW, 80 J, cone targets)

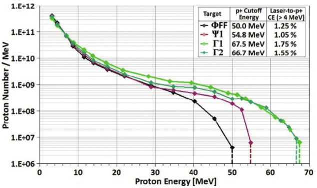


(Snavely 2000)

(Gaillard 2011)

One may argue that progress was slow (especially if not considering some unpublished claims of higher energies) ...



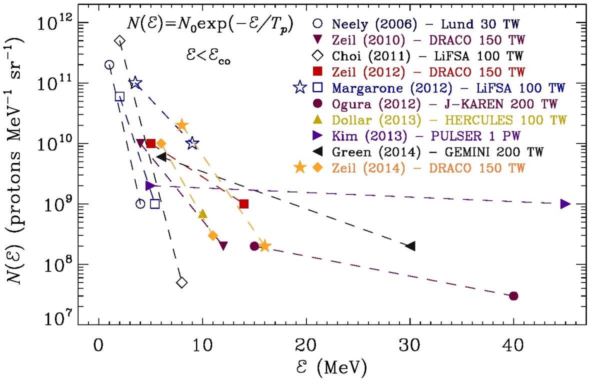


Considerations around the energy cut-off

- progress should be monitored on small-scale lasers with potential for high repetition rate and cost-effective applications
- $\mathscr{E}_{co}$ is dependent on several laser parameters (energy, intensity, duration, contrast, ...) and on target thickness and size as well: difficult to infer meaningful scaling laws
- unresolved issue of determining $\mathscr{E}_{co}$ from exponential-like spectra which may end into noise (need to establish common criteria); at least comparison should be made at equal particle numbers

→ Our approach: narrow the range of laser parameters (femtosecond lasers with few Joule energy on target) and compare whole spectra when available

Comparison of spectra from fs laser systems



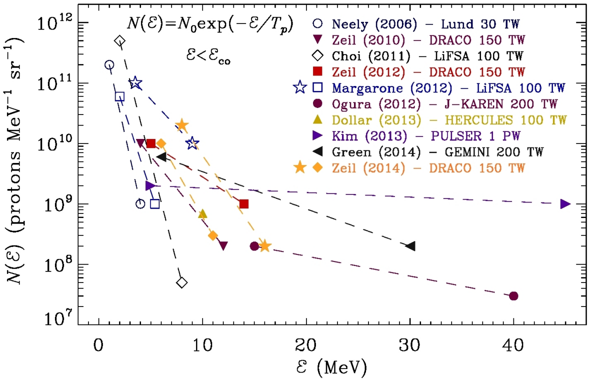
Neely (2006) APL **89** 21502
Zeil (2010) NJP **12** 45015
Choi (2011) APL **99** 181501
Zeil (2012) Nat.Comm. **3** 874
Margarone (2012) PRL **109** 234801
Ogura (2012) Opt. Lett. **37** 2868
Dollar (2013) PoP **20** 56703
Kim (2013) PRL **111** 165003
Green (2014) APL **104** 214101
Zeil (2014) PPCF **56** 084004

Pulse duration
$\tau = 25 - 40$ fs

All spectra well approximated by $N_p(\mathcal{E}) = N_{p0}\exp(-\mathcal{E}/T_p)$

All data in ultrahigh laser contrast and tight focusing conditions

Comparison of spectra from fs laser systems



Laser intensity range:
$I = (1-5)\times 10^{19}$ W cm^{-2}
$a_0 = 2.4-5.4$
(empty symbols)
$I = (0.3-2)\times 10^{21}$ W cm^{-2}
$a_0 = 12-34$
(**filled** symbols)

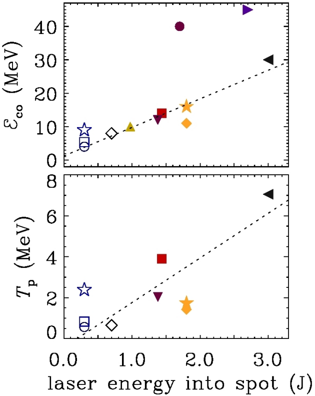
Target thickness range:
$\ell = 0.01-4.0\ \mu$m

$a_0 = 0.85(I\lambda^2/10^{18}$ W cm$^{-2})^{1/2}$ “relativistic” interaction parameter
“Starred” data: special targets
Margarone (2012): μ-spheres covered, Zeil (2014): mass-limited

Linear scaling with pulse energy?

$\mathscr{E}_{\rm co}$ and T_p vs laser energy in focal spot
(notice: linear scale!)
Weaker scaling with intensity
No clear trend with thickness

"Anomalous" data:
● Ogura (2012):
high energy at low proton number
no plasma mirror & metal target
$\rightarrow$ prepulse effects?
▶ Kim (2013):
large proton number & "flat" spectrum
ultrathin target $\ell = 0.01\ \mu$m
$\rightarrow$ new (hybrid) acceleration regime?

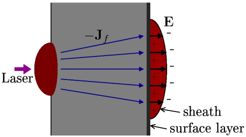


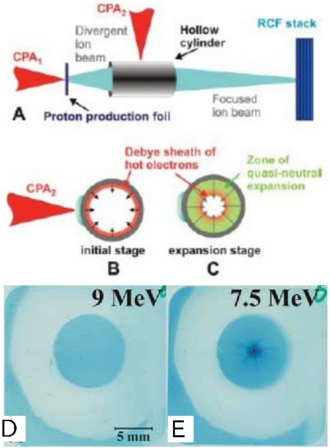
Beam post-acceleration and control

Applications of the proton beam need devices for beam focusing and spectral selection.
All-optical solutions look more compact and cost-effective

Example: chromatic focusing by a laser-irradiated cylinder

The experiment also demonstrates the fast spreading of sheath fields generated by fast electrons



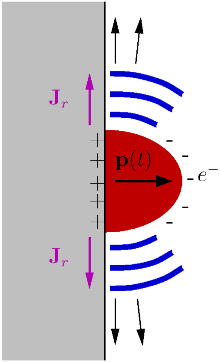


Toncian et al, Science **312** (2006) 410

Fast electron-driven unipolar surface waves

Fast-electron transient charge separation generates an electric dipole $\mathbf{p}(t)$
→ generation of EM waves by the transient sheath as an antenna

Surface waves should drive return current J_f for neutralizing negative charge loss (some $\sim 10^{10}-10^{12}$ electrons escape in vacuum)
→ "unipolar" current pulses propagate on the surface



First observation:
K.Quinn, P.A.Wilson, C.A.Cecchetti, B.Ramakrishna, L.Romagnani, G.Sarri, L.Lancia, J.Fuchs, A.Pipahl, T.Toncian, O.Willi, R.J.Clarke, D.Neely, M.Notley, P.Gallegos, D.C.Carroll, M.N.Quinn, X.H.Yuan, P.McKenna, T.V.Liseykina, A.Macchi, M.Borghesi, Phys. Rev. Lett. **103** (2009) 194801

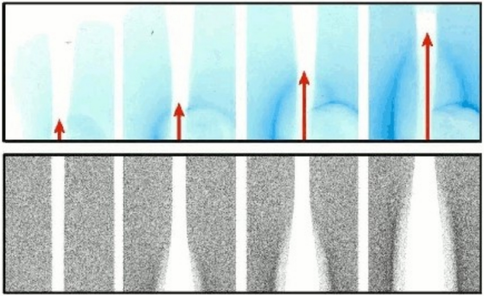
Imaging of field propagation along a wire target

Time-resolved imaging of the electric field via the proton probing technique

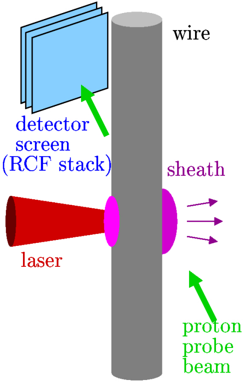
M. Borghesi et al, PoP **9** (2002) 2214

K. Quinn et al, RSI **80** (2009) 113506

Experimental proton images



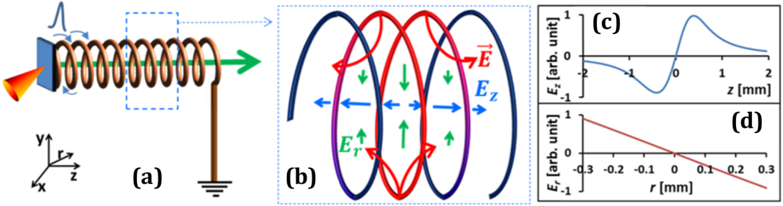
Proton tracing simulations



Field front propagates along the wire with velocity $v_f = 0.96 \pm 0.04c$

Application to post-acceleration of protons: design

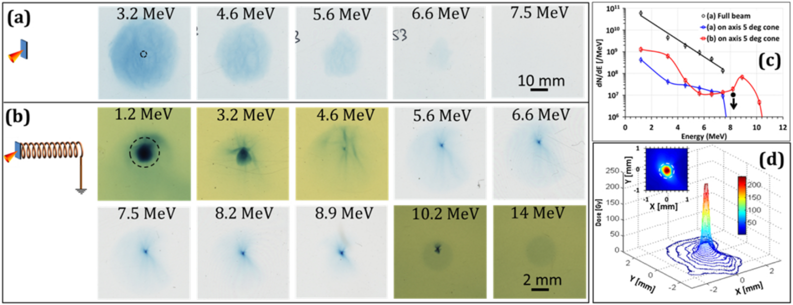
Idea: use current pulse as synchronized wave for proton focusing and post-acceleration
Sending the pulse along a coaxial coil generates an electric field both re-accelerating and focusing a part of the protons
Coil can be designed to achieve phase matching



S. Kar (QUB Belfast), UK patent

Application to post-acceleration of protons: results

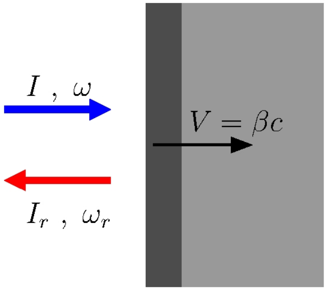
Tight beam focusing and 50% energy gain!



S.Kar, H.Ahmed, R.Prasad, M.Cerchez, S.Brauckmann, B.Aurand, G.Cantono, P.Hadjisolomou, C.L.S.Lewis, A.Macchi, G.Nersisyan, A.P.L.Robinson, A.M.Schroer, M.Swantusch, M.Zepf, O.Willi, M.Borghesi, “A laser-driven travelling-wave ion accelerator” (2015), submitted

Radiation Pressure Acceleration

Basic 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

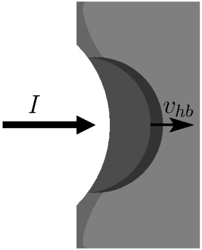


$$\frac{dP}{dt} = \frac{2I}{c}\frac{1-\beta}{1+\beta} \qquad \eta = \frac{2\beta}{1+\beta}$$

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

"Hole Boring" vs "Light Sail" RPA

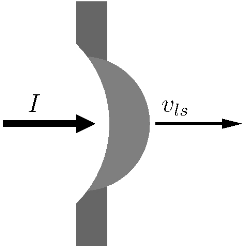
Hole Boring (HB): thick target, "piston" push of the plasma surface



Energy scaling with intensity

$\mathscr{E}_{\mathrm{HB}} \simeq 2m_p c^2 (I/\rho c^3)$

Light Sail (LS): push of whole thin foil target



Energy scaling with (fluence)^2

$\mathscr{E}_{\mathrm{LS}} \simeq 2m_p c^2 (I\tau_p/\rho\ell c^2)^2$

τ_p pulse duration, ℓ target thickness

(non-relativistic ions)

Theoretical conditions for RPA dominance?

RP push must overcome fast-electron effects

For linear polarization:

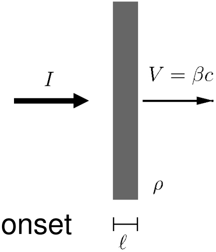
- Esirkepov et al, PRL **92** (2004) 175003 $I\lambda^2 > 10^{23}$ W cm$^{-2}\mu$m^2
  Ions must become promptly relativistic and "stick" to electrons
- Qiao et al, PRL **108** (2012) 115002 $I\lambda^2 > 10^{21}$ W cm$^{-2}\mu$m^2
  Energy from RPA > energy from TNSA in a thin foil
- Macchi, HPLSE **2** (2014) e10 $I\lambda^2 > 5 \times 10^{20}$ W cm$^{-2}\mu$m^2
  Ions move across skin layer fast enough to catch electrons

For circular polarization and normal incidence, RPA should dominate for any intensity because fast electron generation is quenched
Macchi et al, PRL **94** (2005) 165003

Light Sail RPA scaling

$$\mathcal{E}_{\rm LS} \simeq m_p c^2 \mathcal{F}^2/2 \qquad (\mathcal{F} \ll 1)$$

$$\mathcal{F} \simeq \frac{2I\tau_p}{\rho\ell} = 2\pi \frac{Zm_e}{Am_p}\frac{a_0^2}{\zeta}\frac{c\tau_p}{\lambda} \qquad \zeta = \pi\frac{n_e\ell}{n_c\lambda}$$



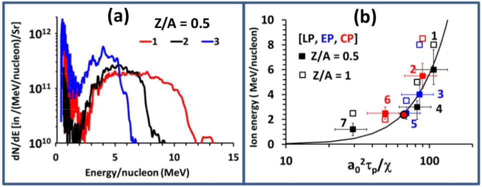
Trade-off between low mass and transparency onset $a_0 \simeq \zeta$ ($\rightarrow \ell \lesssim 10^{-2}\lambda$) gives an "optimized" scaling

$$\mathcal{E}_{\rm LS}^{\rm (opt)} = 2\pi^2 m_e c^2 \left(\frac{m_e}{m_p}\right)\left(\frac{Z}{A}\frac{c\tau_p}{\lambda}a_0\right)^2 \simeq 1.4\times 10^{-3}\ \text{MeV}\left(a_0\frac{c\tau_p}{\lambda}\right)^2$$

If $a_0(c\tau_p/\lambda) \simeq 3.3\times 10^2$ (40 fs, 10^{21} W cm^{-2}) $\rightarrow \mathcal{E}_{\rm LS}^{\rm (opt)} \simeq 150$ MeV
The optimal condition is accessible with nm targets, thus >100 MeV energy seems reachable with current lasers . . .

Evidence for $\mathscr{F}^2$ scaling (VULCAN)

Laser pulse: $t_p \simeq 800$ fs
3×10^{20} W cm^{-2}
$\sim 10^9$ contrast
Target: ~ 0.1 μm metal foil



Multispecies peaks observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
Up to $\simeq 10$ MeV/nucleon observed with $\mathscr{F}^2$-scaling on average
Kar, Kakolee, Qiao, Macchi et al, PRL **109** (2012) 185006

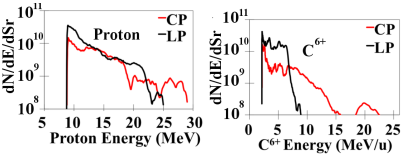
Significant "non-RPA" effects observed: broad spectra, species separation, weak dependence on polarization ...

See also:

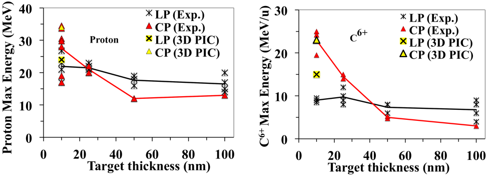
Henig et al, PRL **103** (2009) 245003; Dollar et al, PRL **108** (2012) 175005; Steinke et al, PRST-AB **16** (2013) 11303; Aurand et al, NJP **15** (2013) 33031

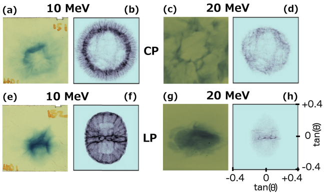
Circular vs. Linear polarization (Astra GEMINI)

Laser pulse: $t_p \simeq 45$ fs
3×10^{20} W cm^{-2} , $\sim 10^9$ contrast
Target: $10 - 100$ nm Carbon foils



Higher energy for CP
($\sim$ 30 MeV protons)
Different beam structures
between LP and CP
(instability signatures?)





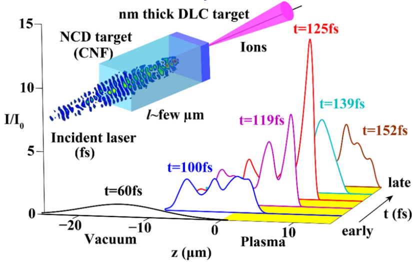
Good agreement with
3D PIC simulations
(C. Scullion, D. Doria, A. Sgattoni et al,
in preparation)

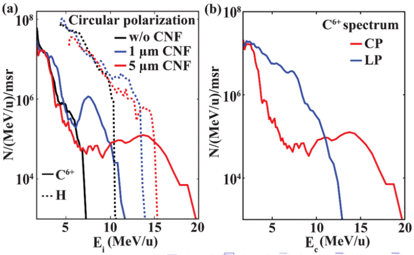
RPA with pulse shaping (Astra GEMINI)

Laser pulse: $t_p \simeq 45$ fs
2×10^{20} W cm^{-2} , $\sim 10^9$ contrast
Target: ~ 10 nm
Diamond-Like Carbon foils
covered with $\sim \mu$m low density
Carbon Nanotube Foams
for spatio-temporal
pulse steepening

Higher energies and
prominent RPA features
observed with CNF

Bin et al, PRL **115** (2015) 064801



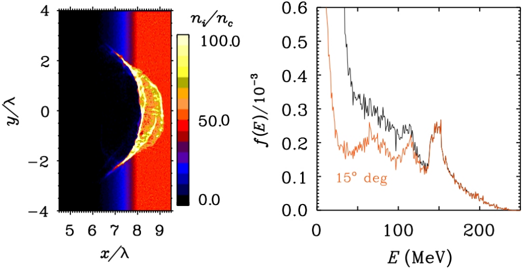


Perspectives for Hole Boring RPA?

Interesting as "bulk" acceleration mechanism: large number of ions (albeit at low energy)

Due to $\mathscr{E}_{\mathrm{HB}} \sim (I/\rho)$ scaling high energy may be obtained for extreme intensity pulses and reduced density targets

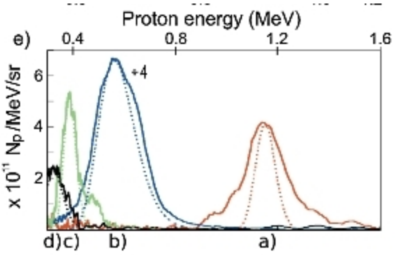
Proton spectra with peak at ~150 MeV in 2D simulations for H liquid jet at $n_e = 50 n_c$ using CP, $I = 5 \times 10^{22}$ W cm^{-2} two-cycle (~5 fs) pulses
A.Macchi & C.Benedetti, NIMA **620**, 41 (2010)



[see also Robinson et al, PoP **18**, 056701 (2011); PPCF **54**, 115001 (2012)]

Hole Boring RPA with gas H targets

Peaked proton spectra using circularly polarized, $I = 6.5 \times 10^{15}$ W cm^{-2} ($a_0 \simeq 0.7$) CO_2 ($\lambda = 10$ μm) pulses and H gas jet target at $n_e = 4 - 8n_c$ ($n_c = 10^{19}$ cm^{-3})



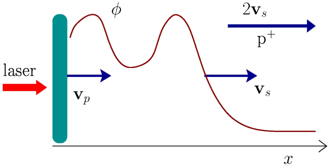
Scaling with I/ρ and number of protons consistent with HB acceleration

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

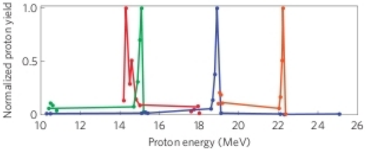
Testing HB with optical/near-IR lasers can exploit higher a_0 but requires suitable target developments (e.g. high density gas jets, $n_e > 10^{21}$ cm^{-3})

Collisionless Shock Acceleration

For linear polarization,
fast electron generation allows the propagation of collisionless shocks → ion acceleration by "reflection" from shock front



Monoenergetic spectra ~ 20 MeV observed at UCLA
Haberberger et al,
Nature Phys. **8** (2012) 95



Much lower energy (~1 MeV) observed at Brookhaven NL
Tresca et al, PRL **115** (2015) 094802

Achieving higher energy needs substantial CO_2 laser development and the efficiency of CSA is an issue
[see e.g. Macchi et al, PRE **85** (2012) 046402]

Summary and conclusion

- Evidence of linear scaling of proton cut-off with pulse energy in short-pulse interactions with solid targets ($\sim$10 MeV/J in spot)
- Can we reach $\sim$100 MeV by putting 10 J on target?
- Shall we abandon TNSA for other (possibly emerging) mechanisms?
- New promising schemes for all-optical post-acceleration and control
- Light Sail RPA has very favorable scaling but there is a long route to optimization
- Possible exploration of new mechanisms (HB-RPA, CSA, ...)
- Laser development and exploitation of petawatt facilities seems necessary in almost all cases

EXTRA SLIDES

Energy limit for < 2 J pulses?

- "Universal" electron distribution function proposed on the basis of simulation results [Sherlock, PoP **16** (2009) 103101]:

$$f(\mathscr{E}_e) = C \exp\left[-\frac{(\mathscr{E}_e - \mathscr{E}_{\text{beam}})^2}{(0.57\mathscr{E}_{\text{beam}})^2}\right] \exp\left[-\left(\frac{\theta}{\theta_{1/2}}\right)^4\right] \quad (1)$$

- Insertion of (1) in static TNSA theory for arbitrary distribution plus "ponderomotive" scaling

$$\mathscr{E}_{\text{beam}} \doteq T_{\text{pond}} = m_e c^2[(1 + a_0^2/2)^{1/2} - 1] \quad (2)$$

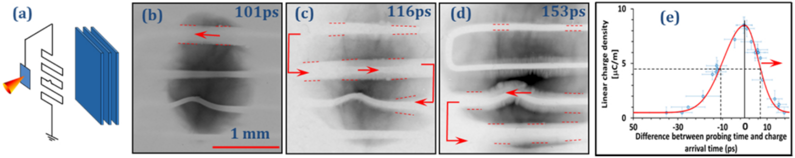
yields proton energy limit of 66 MeV for ultrashort pulses at 10^{21} W cm^{-2} [Schmitz, PoP **19** (2012) 083115]

- 3D simulations find a ≃65 MeV limit for <2 J pulses [d'Humieres et al, PoP **20** (2013) 023103]

Propagation along a folded wire

"Self-probing" target: current pulse and probe protons generated from the same sheath field

Efficient propagation on long distances along a bent structure



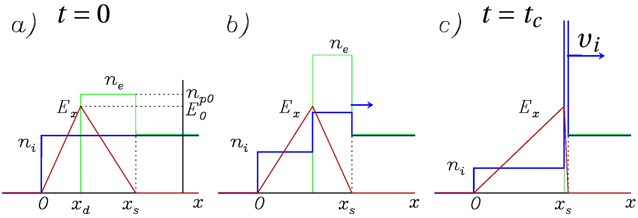
Idea: use current pulse as synchronized wave for proton focusing and (post-)acceleration

S.Kar, H. Ahmed, R. Prasad, M. Cerchez, S. Brauckmann, B. Aurand, G. Cantono, P. Hadjisolomou, C. L. S. Lewis, A. Macchi, G. Nersisyan, A. P. L. Robinson, A. M. Schroer, M. Swantusch, M. Zepf, O. Willi, M. Borghesi, "A laser-driven travelling-wave ion accelerator" (2015), submitted for publication

Beyond the mirror: charge separation effects

Real targets are not perfect rigid mirrors: radiation pressure separates electrons from ions

Electrostatic tension balances $P_{\text{rad}} \simeq 2I/c$ and accelerates ions [Macchi et al PRL **94** (2005) 165003; **103** (2009) 85003]

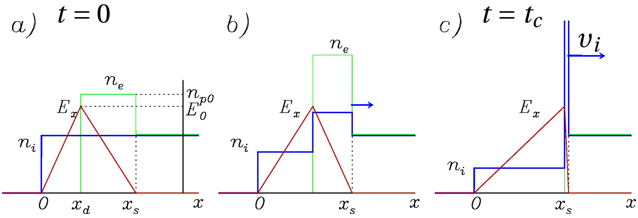


An ion bunch is formed as ions exit the skin layer

Ion motion in the skin layer

Simple model gives ion bunch velocity v_i at "overtake" time t_c

$$\frac{v_i}{c} \simeq \left(\frac{Zm_e n_c}{Am_p n_e}\right)^{1/2} a_0 \quad \text{at} \quad t = t_c \simeq \frac{c/\omega_p}{v_i} = \frac{1}{\omega_p a_0}\left(\frac{Am_p n_e}{Zm_e n_c}\right)^{1/2}$$



LS motion is the "average" of repeated ion bunch acceleration
[M.Grech et al, New J. Phys. **13** (2011) 123003]

Simple criteria for RPA "dominance" - I

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

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

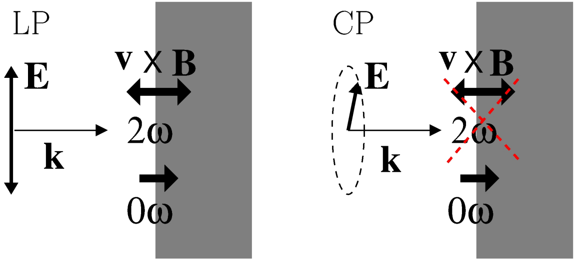
$$v_i/c = 1/2 \quad \longrightarrow \quad a_0 \simeq 30\left(\frac{n_e}{n_c}\right)^{1/2} > 300$$

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

→ RPA dominance expected at ultra-high intensities (yet to be reached!)
[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

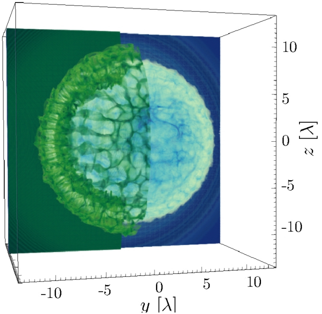
$$t_c < \pi/\omega \quad \longrightarrow \quad \frac{1}{\pi a_0}\left(\frac{Am_p}{Zm_e}\right)^{1/2} \simeq \frac{19}{a_0} < 1$$

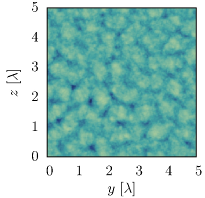
$$\longrightarrow \quad I\lambda^2 > 5 \times 10^{20} \text{ W cm}^{-2}\mu\text{m}^2$$

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

[A. Macchi, High Power Laser Science and Engineering **2** (2014) e10]

Light sail instability (3D simulations)





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

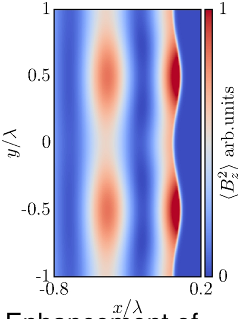
Interpretation: Rayleigh-Taylor instability (light fluid accelerates heavy plasma fluid)

Crab Nebula image, Hubble telescope

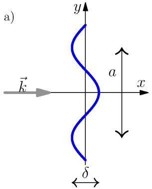
A.Sgattoni, S.Sinigardi, L.Fedeli, F.Pegoraro, A.Macchi, Phys. Rev. E **91** (2015) 013106

Plasmonic seed of Rayleigh-Taylor instability

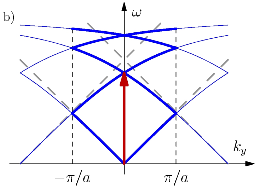
The EM field at a rippled surface (e.g. 2D reflecting, sinusoidal grating of period d) is modulated with plasmonic enhancement of the P-polarization component when $d \sim \lambda$



Enhancement of P-component in 2D simulations



Geometry



Matching with surface plasmons

The resulting self-modulation of laser light pressure provides a spatial seed for RTI
[A.Sgattoni et al, Phys. Rev. E **91** (2015) 013106]