Advanced strategies for ion acceleration using high power lasers

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Outline

A quick review of the state-of-the-art and recent results on some “advanced” schemes for ion acceleration

- Mostly an update of our recent review of the field:

A. Macchi, M. Borghesi, M. Passoni, *Ion Acceleration by Superintense Laser-Plasma Interaction*,
Rev. Mod. Phys. **85**, 751-793 (2013)

(see also: H. Daido, M. Nishiuchi, A. S. Pirozhkov, *Review of laser-driven ion sources and their applications*,
Rep. Prog. Phys. **75**, 056401 (2012)

Preprint of invited paper: arXiv:1306.6859

Main coworkers for this talk

A. Sgattoni[1,2], A. Singh Nindrayog[1,3,†], M. Tamburini[1,3,*], F. Pegoraro[1,3], M. Passoni[2], T. V. Liseykina[4], P. Londrillo[5], S. Sinigardi[6], V. Floquet[7], T. Ceccotti[7], S. Kar[8], M. Borghesi[8]

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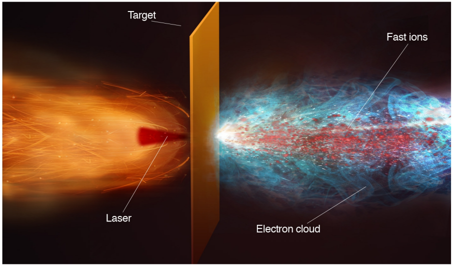
The vision of “coherent” acceleration: Veksler (1957)

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

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

- These features are realized in laser-plasma acceleration of ions

Laser-plasma acceleration of ions (2000–)



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

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

Many open challenges for ion acceleration . . .

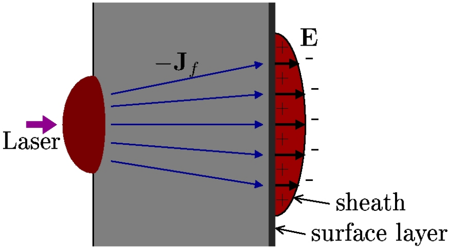
- increase maximum energy per nucleon $\mathscr{E}_{\text{max}}$
  - (60-250 MeV for proton hadrontherapy, >1 GeV for particle physics)
- increase efficiency (e.g. $> 10\%$ for fast ignition ICF)
- enable high repetition rate
- achieve monoenergetic spectra
- beam control and focusing, post-acceleration
- . . .

. . . and many mechanisms at play

- Target Normal Sheath Acceleration (TNSA)
  - solid targets (nm-μm thickness)
- Radiation Pressure Acceleration (RPA)
  - Hole Boring RPA: thick, low density targets opaque to laser light (gas jets for CO_2 lasers)
  - Light Sail RPA: ultrathin (nm) solid targets
- Collisionless Shock Acceleration (CSA)
  - thick overdense low density targets
- Break-Out Afterburner (BOA)
  - ultrathin, *relativistically transparent* targets
- . . .

TNSA: enhancing fast electron generation

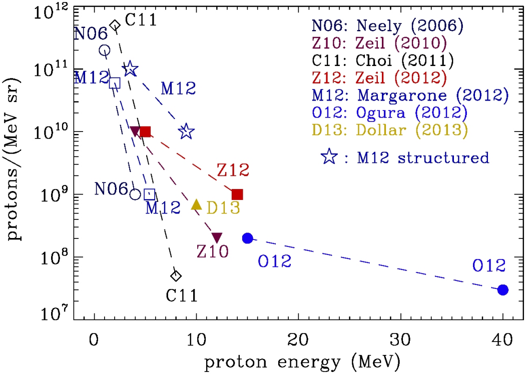
Target Normal Sheath
Acceleration (TNSA)
is driven by *fast* electrons
generated at the
front surface of solid targets



Key issue:
increase number and energy of fast electrons

Question: how much can be obtained with "table-top" lasers (<10 J energy, <100 fs duration)?

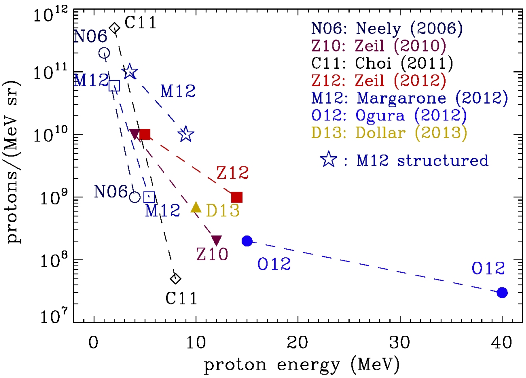
A survey of “sub-10 J” data



Neely et al APL **89** 21502 (2006) [LLC Lund]
Zeil et al NJP **12** 45015 (2010) [DRACO@HZDR]
Choi et al APL **99** 181501 (2011) [LiFSA@GIST/APRI]
Zeil et al Nat.Comm. **3** 874 (2012) [DRACO@HZDR]
Margarone et al PRL **109** 234801 (2012) [LiFSA@GIST/APRI]
Ogura et al Opt.Lett. **37** 2868 (2012) [JKAREN@JAEA/PSI]
Dollar et al PoP **20** 56703 (2013) [HERCULES@CUOS]

All data in ultrahigh laser contrast and tight focusing conditions
All spectra well approximated by $N_p(\mathscr{E}) = N_{p0}\exp(-\mathscr{E}/T_p)$

A survey of “sub-10 J” data



Intensity range:

$I = (1-5)\times 10^{19}$ W cm^{-2}

$a_0 = 2.4 - 5.4$

(empty symbols)

$I = (0.8-2)\times 10^{21}$ W cm^{-2}

$a_0 = 22 - 34$

(filled symbols)

Pulse duration range:

$\tau = 25 - 40$ fs

Target thickness range:

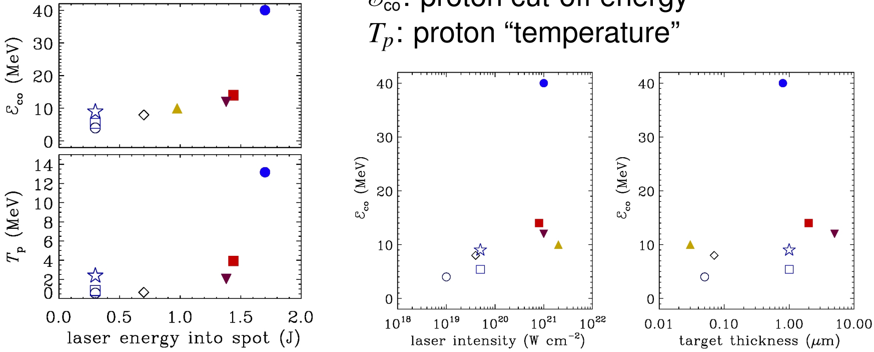
$\ell = 0.05 - 4.0\ \mu$m

$a_0 = 0.85(I\lambda^2/10^{18}$ W cm$^{-2})^{1/2}$ “relativistic” interaction parameter

Proton energy scaling with laser/target parameters

$\mathcal{E}_{co}$: proton cut-off energy

T_p: proton "temperature"



"Fast" scaling of $\mathcal{E}_{co}$ and T_p with laser energy *on spot*

Weaker scaling with intensity, no clear trend with thickness

"Anomalous" data • Ogura (2012): high energy at low proton number

Energy limit for < 2 J pulses?

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

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

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

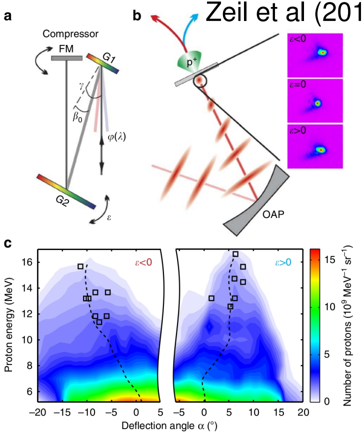
$$\mathcal{E}_{\text{beam}} \doteq T_{\text{pond}} = m_e c^2 [(1 + a_0^2/2)^{1/2} - 1] \qquad (2)$$

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 $\simeq$65 MeV limit for $<$2 J pulses [d'Humieres et al, PoP **20** (2013) 023103]

TNSA out of equilibrium

Zeil et al (2012)



Zeil et al, Nature Comm. **3** (2012) 874: "pre-thermal" TNSA and proton beam "steering" by laser pulse
Veltcheva et al, PRL **108** (2012) 075004: TNSA with 5 fs pulses

Our simple modeling of "prompt" TNSA yields for proton energy $\mathscr{E}_p$:

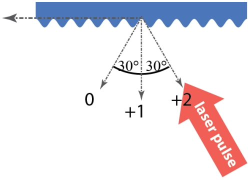
$$\mathscr{E}_p = m_e c^2 a_0^2 \left(\frac{m_e}{m_p}\right) \begin{cases} 2(\tau/T_L)^2 & (n_f \gtrsim n_c) \\ 1 & (n_f \ll n_c) \end{cases}$$

τ/T_L: duration in cycles n_f: fast electron density n_c: cut-off density

Fast scaling $\mathscr{E}_p \propto a_0^2 \propto I$ counterbalanced by (m_e/m_p) factor

Grating targets for surface-wave enhanced absorption

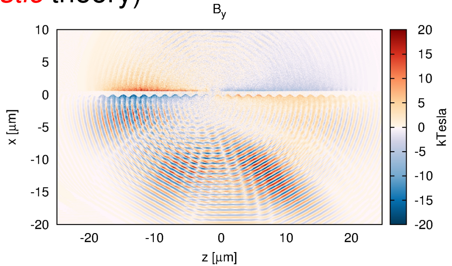
Irradiating grating targets at resonant angle



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

leads to surface wave (SW) excitation
(according to *linear*, *non-relativistic* theory)

Simulations suggest SW excitation to occur also in the relativistic, nonlinear regime and to enhance fast electron generation and TNSA



TNSA enhancement in grating targets: experiment

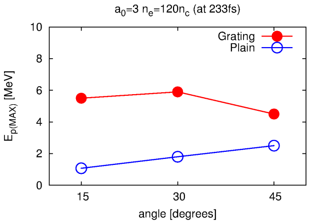
LaserLAB EU experiment at SLIC facility, CEA Saclay (F)

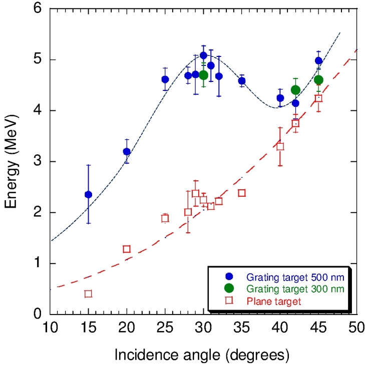
(laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{-12}$)

Increase of $\mathscr{E}_{\rm co}$ by ~ 2.5X

in a broad aperture around $\theta_{\rm res} = 30^\circ$

Fair agreement with 2D simulations



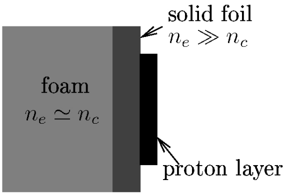


A. Sgattoni et al, talk 5.209

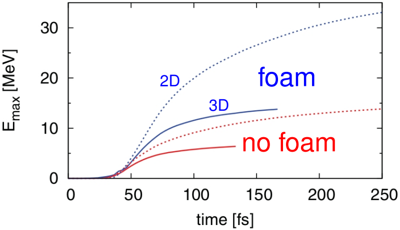
Foam targets for low density-enhanced absorption

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

With low-density layer at $n_e \simeq n_c$
$\mathscr{E}_{co}$ doubles with foam up to 15 MeV in 3D simulation with 25 fs, 1 J energy pulse

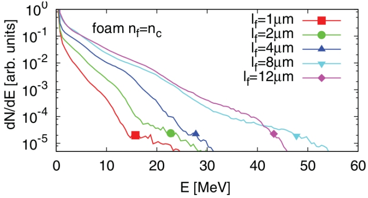


Foam target manufacturing and experimental results: Passoni, Prencipe et al, poster P4.204

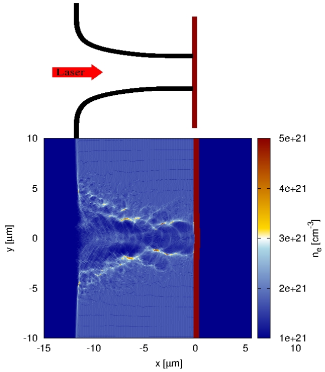


Notice: $\mathscr{E}_{co}$ is lower by a factor of ~ 2 in 3D vs 2D

Foam-enhanced fast electron generation



Absorption in fast electrons maximized for optimal foam areal density $n_e\ell$



Fast electron temperature

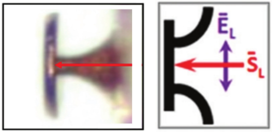
$T_f \gtrsim 3T_{\text{pond}}$

Coupling of P-component of $\mathbf{E}$ with channel walls accelerates electrons:

similarity with cone targets

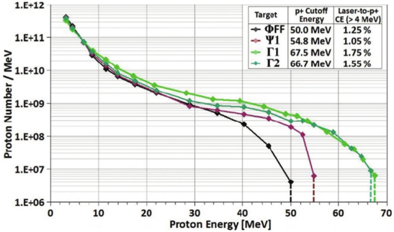
Enhanced TNSA in microcone targets

[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]

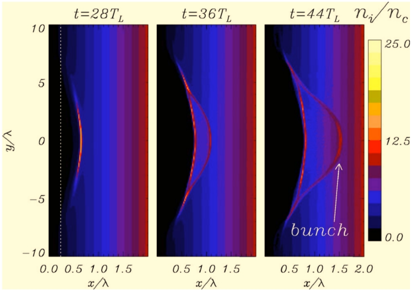
Some partial conclusions and perspectives: TNSA

- TNSA with ultrashort < 10 J pulses shows a promising scaling
- highest energies observed (40 MeV) need independent confirmation
- how to break the 66 MeV theoretical barrier?
- structured targets lead to enhanced TNSA and "better-than-ponderomotive" scaling for T_{fast}
- little recent progress in tailoring the energy spectrum
- "best" modeling still unclear (static, dynamic or both?)
- large 3D simulations needed for quantitative estimates

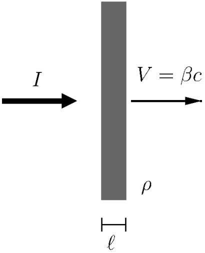
Radiation Pressure Acceleration

Light pressure effects dominate over TNSA either for $I > 10^{23}$ W/cm^{-2} or with Circular Polarization (CP) instead of Linear Polarization (LP) (less fast electrons with CP)

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



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



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 $n_e = 4 - 8n_c$ using CP, $I = 6.5 \times 10^{15}$ W cm^{-2} CO_2 ($\lambda = 10\ \mu$m) pulses

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

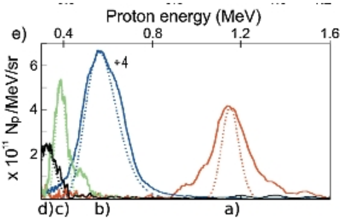


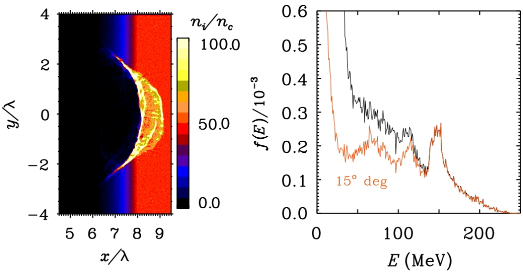
FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\text{max}} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{\text{cr}}$, (b)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

Hole Boring RPA with liquid H target and 0.8μm laser?

Proton spectra with peak at $\mathscr{E}_{\text{peak}} = 150$ MeV in 2D simulations for H liquid jet at $n_e = 50n_c$ using CP, $I = 5 \times 10^{22}$ W cm^{-2}, two-cycle pulse

A.Macchi, C.Benedetti, NIMA **620**, 41 (2010)

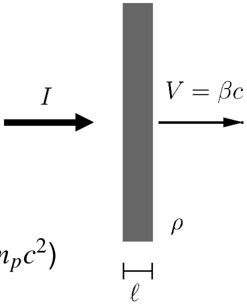


Promising scheme for next-generation “extremely” short lasers?

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

Light Sail "accelerating mirror" model

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



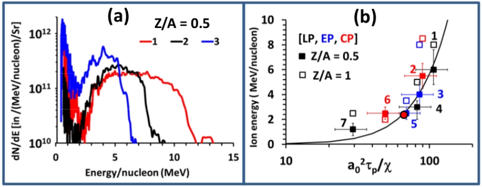
$$\mathcal{F} = 2(\rho\ell)^{-1} \int_0^\infty I(t')dt' \simeq 2I\tau_p/\rho\ell$$

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

Favorable scaling with laser pulse fluence $\mathcal{F}$
100% efficiency in the relativistic limit
"Perfect" monoenergeticity for "rigid", coherent sail motion
Need of ultrathin (nm) foils and ultrahigh contrast pulses
Limits: "slow" energy gain, foil transparency and deformation

Light Sail RPA: $\mathscr{F}^2$ scaling 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 $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
(Almost no laser polarization dependence observed . . .)

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

S. Kar, talk I1.203

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

Light Sail RPA: open issues

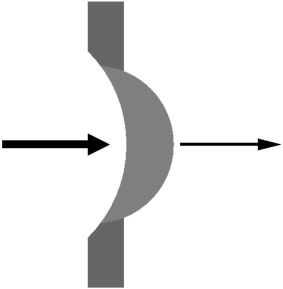
- spectra are not monoenergetic as in the “rigid mirror” model
- weak dependence on polarization and spectral separation of species with different Z/A
- overall weak signatures of LS-RPA for very tight focusing [Dollar et al, PRL **108** 175005 (2012)]

$\rightarrow$ important effects of target deformation and heating

- use of wide spots may lead to large energy requirement

More experimental work is needed . . .

Pushing LS forward: "unlimited" acceleration?



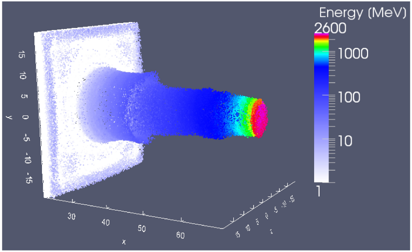
Transverse expansion of the target reduces surface density $\rho\ell$
$\Rightarrow$ "unlimited" acceleration possible at the expense of the number of ions
[Bulanov et al, PRL **104** (2010) 135003]

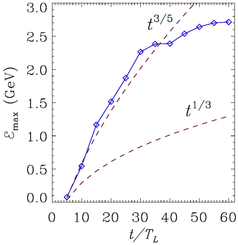
"Faster" gain $E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{3/5}$ predicted
Mechanism is effective for *relativistic* ions ($\mathscr{F} \gg 1$)

Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$
Optimal trade-off when $a_0 \simeq \zeta$

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}, $\zeta \simeq a_0 \simeq 200$





$\mathcal{E}_{\max} \simeq 2.6$ GeV > 4 times 1D model prediction
Higher gain in 3D vs 2D (stronger rarefaction)
Simulation with ALaDyn PIC code on CINECA/FERMI supercomputer

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

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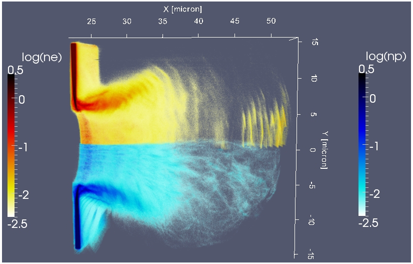
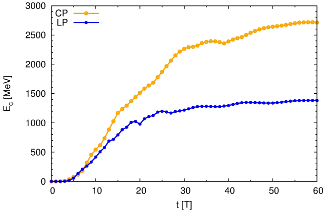




Energy increase stopped by the onset of transparency
Higher gain (2X) with Circular Polarization

Some partial conclusions and perspectives: RPA

Hole Boring RPA:

- evidence in CO_2 laser-gas jet interactions
- possible option for “extreme” pulses, not-so-prone to ultrahigh contrast
- requires development in low-density target preparation

Light Sail RPA:

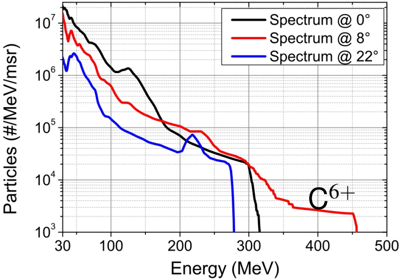
- evidence for fast scaling and peaked proton/C spectra
- predicted high gain in relativistic ion (GeV) regime: promising for next-generation ELI class lasers
- “delicate” ultrathin targets required, may need wide spot (and large energy), spectrum not monoenergetic as hoped

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



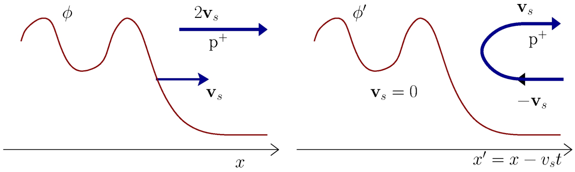
[Jung et al NJP **15** (2013) 023007]

Indication of > 100 MeV cut-off for protons [Hegelich, APS Conf. 2011]

Survey of results oriented to ion-driven fast ignition ICF: Hegelich et al, Nucl. Fus. **51** (2011) 83011

Collisionless Shock Acceleration

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



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

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

Monoenergetic CSA in CO_2 laser-H gas interaction

Proton spectra:

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

Laser: 100 ps train of 3 ps pulses

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

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

Interpretation: shock driven by fast electron pressure

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

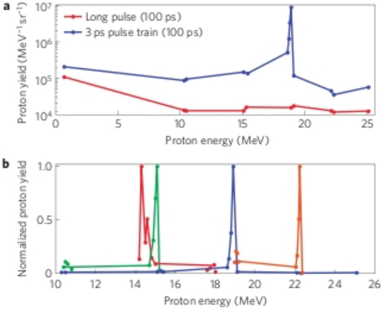


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within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

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

Shock "loading" and spectral broadening

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

$\rightarrow$ weak loading necessary for monoenergetic spectrum

$\rightarrow$ limited number of accelerated ions

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

Shock loading in 1D simulation with warm ions - I

Parameters:

$a_0 = 1$

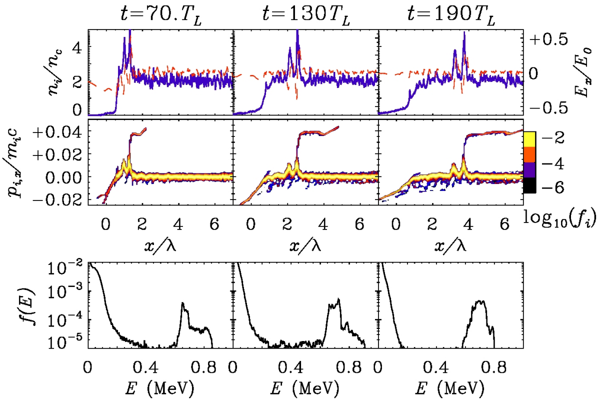
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 0.5$ keV

$\Delta x = \lambda/400$

800 particles/cell



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

Shock loading in 1D simulation with warm ions - II

Parameters:

$a_0 = 1$

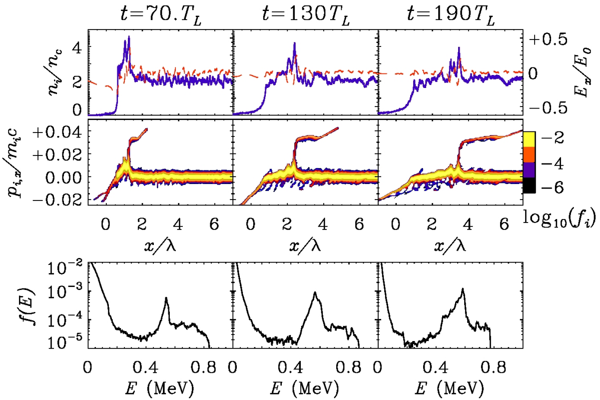
$\tau_p = 55T_L$

$n_e = 2n_c$

$T_i = 2$ keV

$\Delta x = \lambda/400$

800 particles/cell



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

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

Some partial conclusions and perspectives: CSA

- highly monoenergetic spectra observed
- “gas target plus gas laser”-based scheme suitable for high repetition rate
- efficiency might be too low and not compatible with monoenergetic spectra
- scalability to optical lasers and > 100 MeV to be demonstrated

  (targets with suitable density $\simeq 10^{21}$ cm^{-3} needed: see d’Humieres talk I1.204)

Some general 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
- Each mechanism may be more or less suitable for a future specific application depending on typical features and requirements
- Target development and engineering may strongly contribute to advance ion acceleration
- Large-scale simulations on supercomputers are needed for quantitative predictions (important for next-generation laser design)

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  - IBM-SP6, ISCRA award (project TOFUSEX – "TOwards FUll-Scale simulations of laser-plasma EXperiments" N.HP10A25JKT-2010)
  - FERMI BlueGene/Q™, PRACE award (project LSAIL – "Large Scale Acceleration of Ions by Lasers")

EXTRA SLIDES

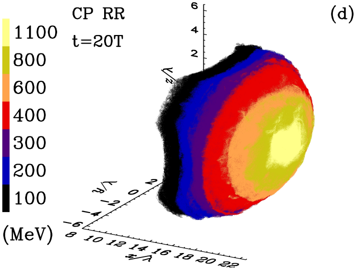
Set-up of 3D RPA simulations

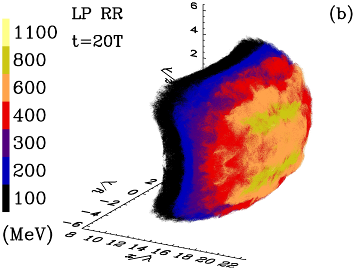
- Laser pulse: $(9T) \times (10\lambda)^2$ (FWHM) [$T = \lambda/c$]
  $\sin^2 \times$Gaussian shape, $a_0 = 280$ (198) for LP (CP),
  $\lambda = 0.8$ μm ($I = 1.7 \times 10^{23}$ W cm^{-2})
- Plasma: $\ell = 1\lambda$, $n_0 = 64n_c$, $Z = A = 1$
  Note: $a_0 \simeq \zeta = \pi(n_e/n_c)(\ell/\lambda)$
- RF included via Landau-Lifshitz force
- Numerical: $1320 \times 896 \times 896$ grid, $\Delta x = \Delta y = \Delta z = \lambda/44$,
  $\Delta t = T/80 = \lambda/80c$, 216 particles per cell (for both e and p),
  1.526×10^{10} in total

Runs performed on 1024 processors (1.7 GBytes each) of IBM-SP6 at CINECA (Italy)

3D simulations of RPA-dominant LS acceleration

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





CP: symmetric, collimated ion distribution, higher energy

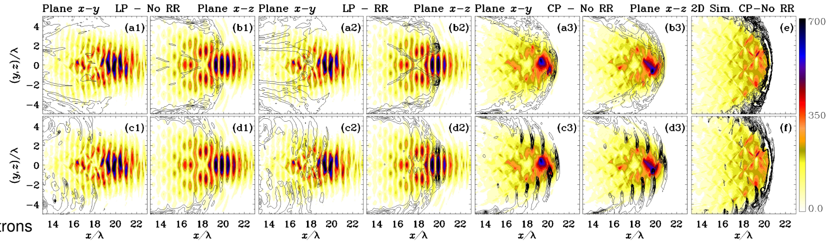
LP: asymmetric, two-lobe ion distribution, lower energy

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

Pulse self-wrapping by the foil

Sections of 3D fields [a1)-d3)] vs 2D simulations [e)-f)]

ions

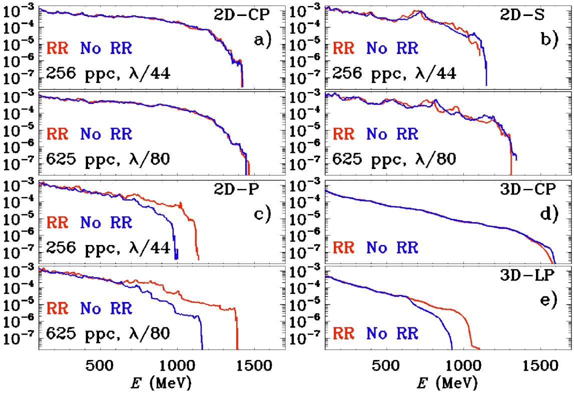


electrons

- Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]
- “Wrapping” and focusing effects are weaker in 2D vs 3D [see e)-f)]
- Breakthrough in the foil occurs for LP [see series -1)-2)]

Effects of 2D/3D, radiation and numerical resolution

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



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

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

Hints from Collisionless Shocks theory

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

- Collisionless shock may *not* form at all in the absence of reflected ions
- Background ions *must* have some energy spread otherwise they would *all* be either reflected or not
- Reflected ions are on the tail of the ion distribution ($v_i > v_s - \sqrt{2e\Phi_\mathrm{M}/m_i}$ with Φ_M shock potential barrier)
- Too many ions reflected may lead to shock loading

$\Rightarrow$ shock front slows down and energy spectrum is “chirped” towards low energy

- Search for optimal trade-off ion temperature T_i : energy spread vs. number of ions

CSA with warm ions: 1D simulation - II

Parameters:

$a_0 = 16$

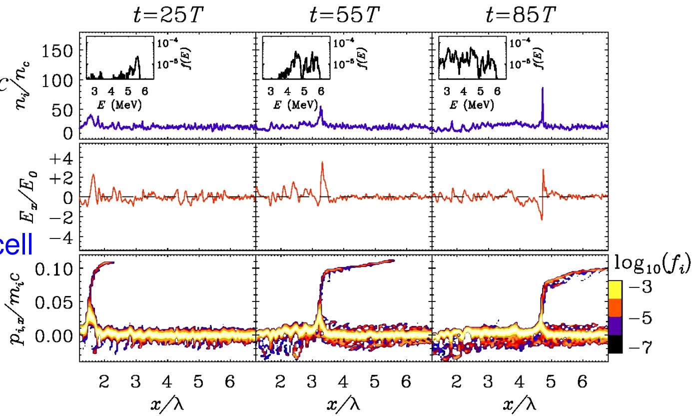
$\tau_p = 4T = 4\lambda/c$

$n_e = 20n_c$

$T_i = 1$ keV

$\Delta x = \lambda/400$

800 particles/cell

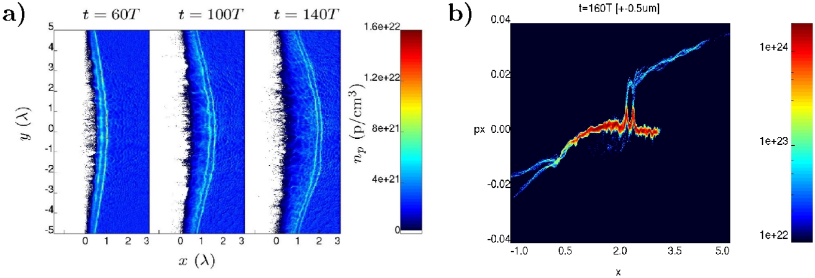


Too high T_i causes shock to slow down and spectrum to broaden

CSA with warm ions: 2D simulation

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

Same as 1D (on axis) except lower resolution ($\Delta x = \lambda/100$, 100 p/cell)



Strong "chirping" observed in 2D $\rightarrow$ no monoenergetic spectrum

Spectral broadening related with transverse "rippling"?

Need of larger simulations to simulate experimental regimes