An overview of recent results in laser-driven ion acceleration

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Outline

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

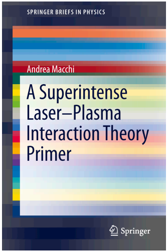
- Target Normal Sheath Acceleration (TNSA):
  - recent experiments with ultrashort (< 10 fs), low-energy (< 10 J) pulses: scalings and trends
  - enhanced TNSA using "special" targets: low-density foams, grating targets
- "Light Sail" Radiation Pressure Acceleration (LS-RPA):
  - recent experiments and current challenges
  - exploring "unlimited" regime in 3D simulations
- Collisionless Shock Acceleration (CSA):
  - monoenergetic spectra versus efficiency

Recent reviews on ion acceleration

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

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

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



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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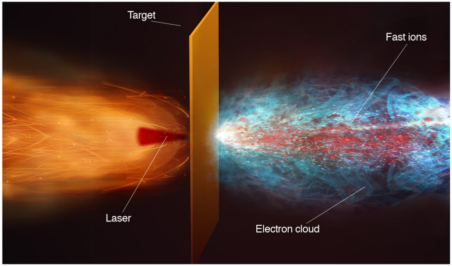
Open challenges for ion acceleration

- increase maximum energy per nucleon $\mathscr{E}_{\text{max}}$
- (>100 MeV for hadrontherapy, >1 GeV for particle physics)
- increase efficiency
- enable high repetition rate (for medical applications, . . .)
- achieve monoenergetic spectra
- beam control and focusing, post-acceleration
- . . .

TNSA: enhancing fast electron generation

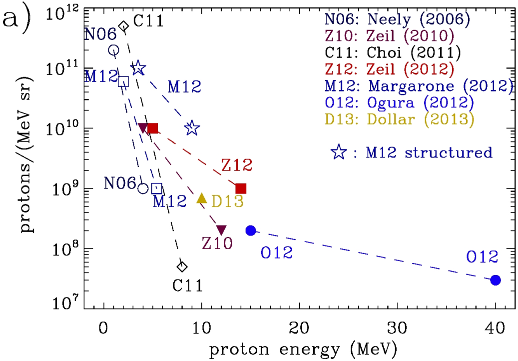
Target Normal Sheath Acceleration (TNSA) is driven by *fast* electrons generated at the *front* surface of solid targets



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)?

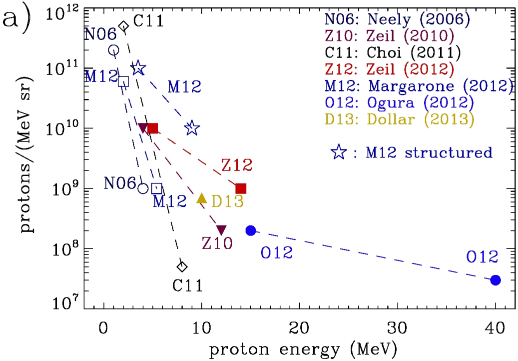
A survey of “sub-10 J” data



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 conditions

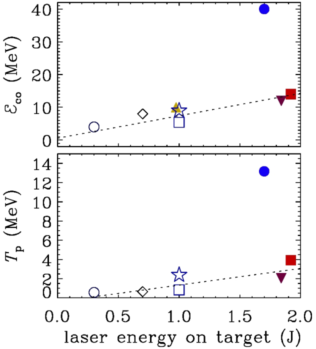
A survey of “sub-10 J” data



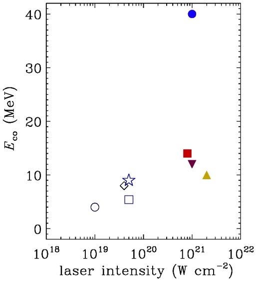
Intensity range:
$I = (1-5) \times 10^{19}$ W cm^{-2}
(empty symbols)
$I = (0.8-2) \times 10^{21}$ W cm^{-2}
(filled symbols)
Pulse duration range:
$\tau = (25-40)$ fs
Target thickness range:
$\ell = 0.05 - 4.0$ μm

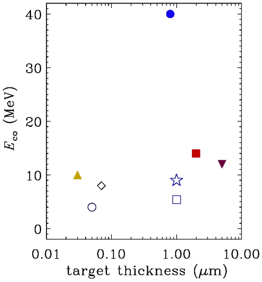
All spectra well approximated by $N_p(\mathscr{E}) = N_{p0} \exp(-\mathscr{E}/T_p)$
Ordering with cut-off energy $\mathscr{E}_{\text{co}}$ same as with T_p ($\sim \mathscr{E}_{\text{co}}/4$)

Proton energy scaling with laser/target parameters



Notice: *linear* scale for energy, *log* scale for intensity and thickness





Excluding "anomalous" data point • Ogura (2012):

Fairly clear (linear?) scaling with laser energy *on target*

Weak (log?) scaling with intensity, no clear trend with thickness

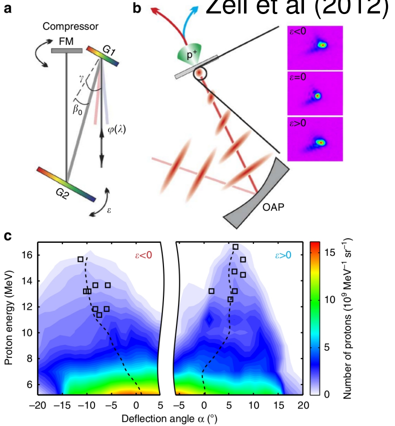
TNSA out of equilibrium

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

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

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

Zeil et al (2012)



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

Energy limit for < 2 J pulses?

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

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

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

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

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

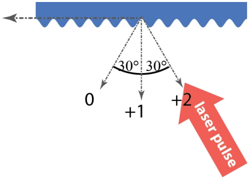
- 3D simulations find a $\simeq$65 MeV limit for $<$2 J pulses [d'Humieres et al, PoP **20**, 023103 (2013)]

Grating targets for surface-wave enhanced absorption

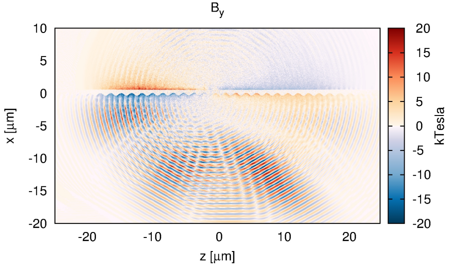
Irradiating grating targets at resonant angle

$$\sin\theta_{\text{res}} + \lambda/d = \sqrt{(1-n_e/n_c)/(2-n_e/n_c)}$$

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



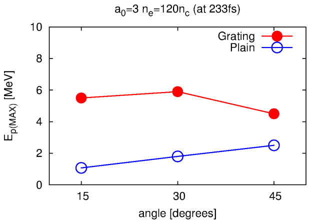
TNSA enhancement in grating targets: experiment

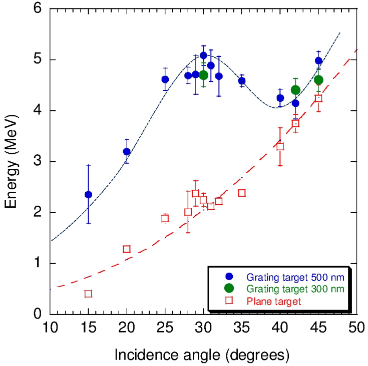
LaserLAB EU experiment at SLIC facility, CEA Saclay (F)
(laser UHI, 28 fs, 5×10^{19} W cm^{-2}, contrast $\sim 10^{-12}$)

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

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

Fair agreement with 2D simulations





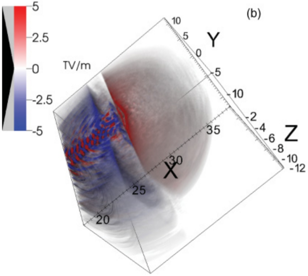
T.Ceccotti, V.Floquet, A.Sgattoni, A.Macchi et al, submitted to PRL

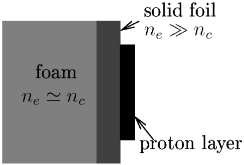
Foam targets for low density-enhanced absorption

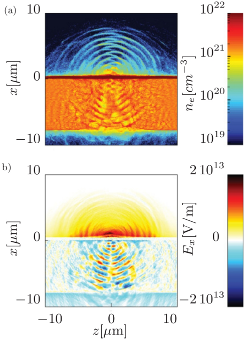
[Sgattoni, Londrillo, Macchi, Passoni, PRE **85** (2012) 036405]

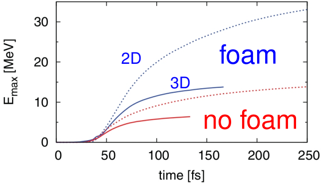
$\mathscr{E}_{\text{max}}$ doubles with foam up to 15 MeV in 3D simulation with 25 fs, 1 J energy pulse

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







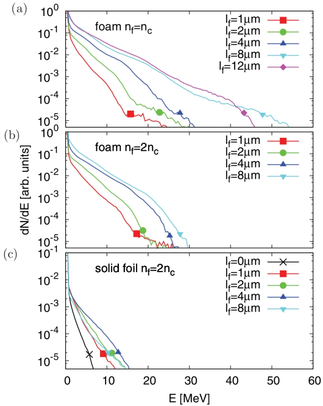


Foam-enhanced fast electron generation

2D parametric simulations:
Optimal foam mass density $n_e\ell$ exists
to enhance fast electron generation

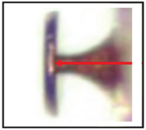
fast electron temperature $T_f \gtrsim 3T_{\text{pond}}$
where $T_{\text{pond}} = m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1\right)$

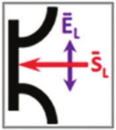
P-component of $\mathbf{E}$ accelerates electrons
(coupling with channel walls):
remarkable similarity with cone targets



Larger simulations needed to address longer, more energetic pulse for higher $\mathscr{E}_{\text{max}}$

Enhanced TNSA in microcone targets

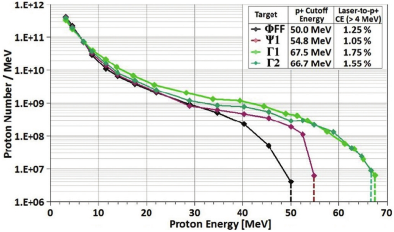




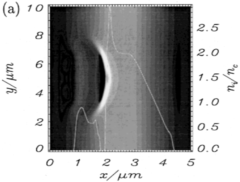
Gaillard et al, PoP **18** (2011) 056710

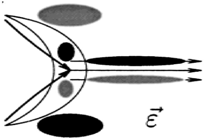
Up to $\mathscr{E}_{max}$=67.5 MeV protons with 80 J pulse energy in cone targets

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



Geometrical collimation (“funnel”) effect:
see also H.Ruhl, A.Macchi et al, PRL **82**, 2095 (1999)

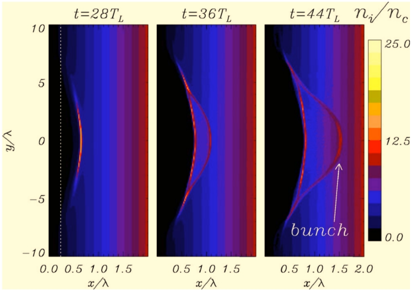




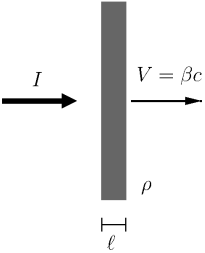
Radiation Pressure Acceleration

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): whole push of 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

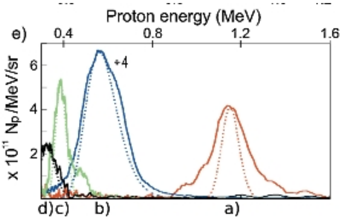


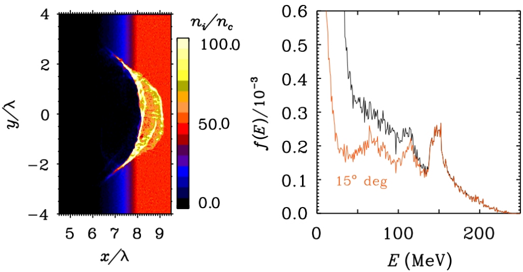
FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{\text{cr}}$, (b) $I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

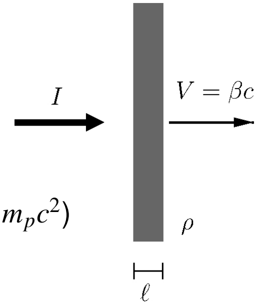
[see also: A.P.L.Robinson et al, PoP **18**, 056701 (2011); PPCF **54**, 115001 (2012)]

Light Sail "accelerating mirror" model

$$E_{\text{max}} \simeq m_p c^2 \mathscr{F}^2/(2(\mathscr{F}+1))$$

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

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



"Dream" features:

Favorable scaling with laser pulse fluence $\mathscr{F}$

100% efficiency in the relativistic limit

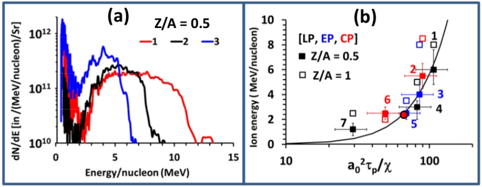
"Perfect" monoenergeticity for "rigid" coherent motion of the foil

Need of ultrathin (nm) foild and ultrahigh contrast pulses

Limits: "slow" energy gain, foil transparency and deformation

Light Sail RPA: $\mathscr{F}^2$ scaling observed

$\mathscr{E}_{\text{max}} \sim \mathscr{F}^2$ (for $\mathscr{F} \ll 1$)



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 ($Z/A = 1, 1/2$) peak observed with $\Delta\mathscr{E}/\mathscr{E} \simeq 20\%$
(Almost no laser polarization dependence observed . . .)
Experiment performed at VULCAN laser, RAL/CLF, UK

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

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

Light Sail RPA: open problems

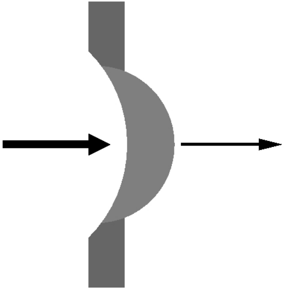
- spectra are not monoenergetic as suggested by the “rigid mirror” model
- weak dependence on polarization and spectral separation of species with different Z/A suggest important effects of target deformation and heating
- very tight focusing seems to destroy LS-RPA [Dollar et al, PRL **108** 175005 (2012)]
- use of wide spots leads to requirement of large energies: posing the “optimal thickness” condition

$$a_0 \simeq \zeta = \pi \frac{n_e}{n_c} \frac{\ell}{\lambda}$$

leads to 120 J on a 10 μm diameter spot

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

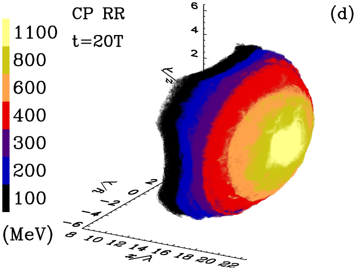


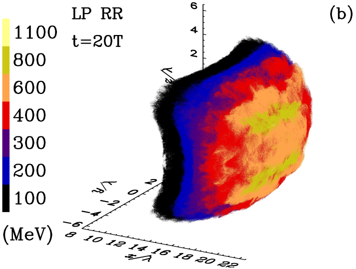
Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$
Optimal trade-off when $a_0 \simeq \zeta$

Notice: other mechanisms may be efficient in the transparency regime (e.g. “Break-Out Afterburner”)

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}, $Z/A = 1$





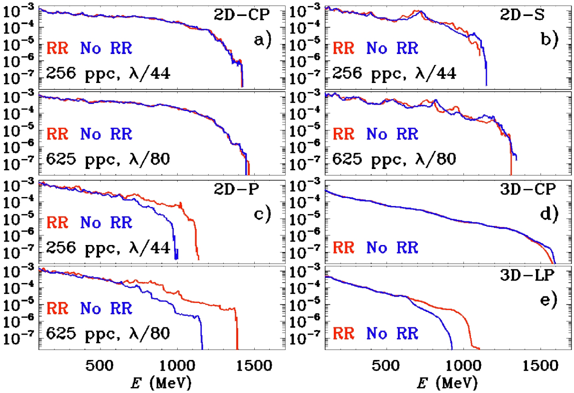
CP: symmetric, collimated ion distribution, higher energy

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

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

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

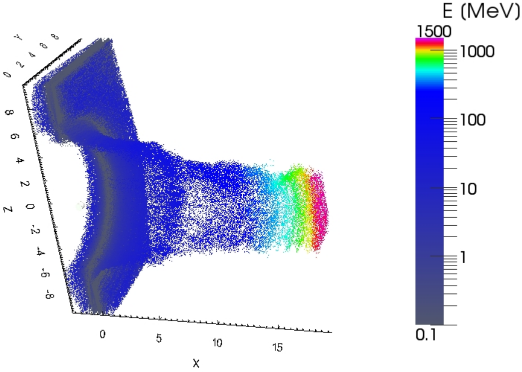
The "optimal" CP case is the most robust (Ion energy is **higher** in 3D than in 2D **!**)

RPA-LS: present understanding and work in progress

Energy increase in 3D vs. 2D attributed to effect of target rarefaction and laser self-wrapping by the deformed foil

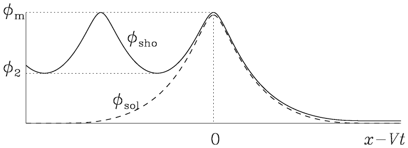
Need to push 3D simulation to longer times and distances for exploring the ultimate limit of RPA-LS

3D ALaDyn simulations on FERMI Tier0 (CINECA, Italy) sponsored by PRACE award



Collisionless Shock Acceleration

- Basic idea: a Collisionless Shock Wave of velocity $v_s = Mc_s$ with $M > 1$ ($c_s = \sqrt{ZT_e/Am_p}$) is driven into an overdense plasma by either piston-like push of radiation pressure or "suprathermal" pressure of fast electrons



- Ion acceleration occurs in the plasma bulk by *reflection* from the shock front: $v_i \simeq 2v_s$ ("moving wall" reflection)
- Reflected ions are *monoenergetic* if v_s is constant and have multi–MeV energy if $T_e \simeq m_e c^2 \left(\sqrt{1+a_0^2/2}-1\right)$

Monoenergetic protons from CO_2 laser-gas interaction

Proton spectra with $\mathscr{E}_{\text{peak}} = 14-22$ MeV ($\Delta\mathscr{E} \lesssim 10^{-2}\mathscr{E}_{\text{peak}}$) observed with 100 ps train of 3 ps pulses at $I = 6.5\times10^{16}$ W cm^{-2}

Target: H_2 jet, $n_0 \le 4n_c$ Pol.: Linear

Shock seems driven by hot electron pressure (rather than light pressure)

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

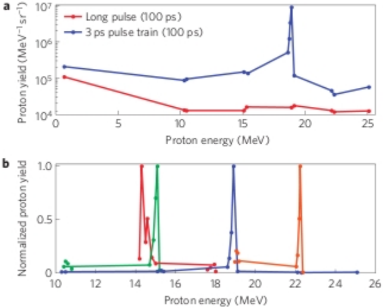


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within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

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 - I

Parameters:

$a_0 = 1$

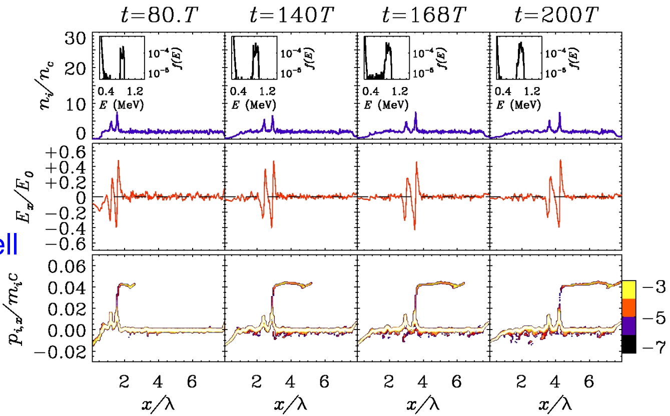
$\tau_p = 4T = 4\lambda/c$

$n_e = 2n_c$

$T_i = 100$ eV

$\Delta x = \lambda/400$

800 particles/cell



Steady ion reflection produces a narrow energy spectrum

CSA with warm ions: 1D simulation - II

Parameters:

$a_0 = 16$

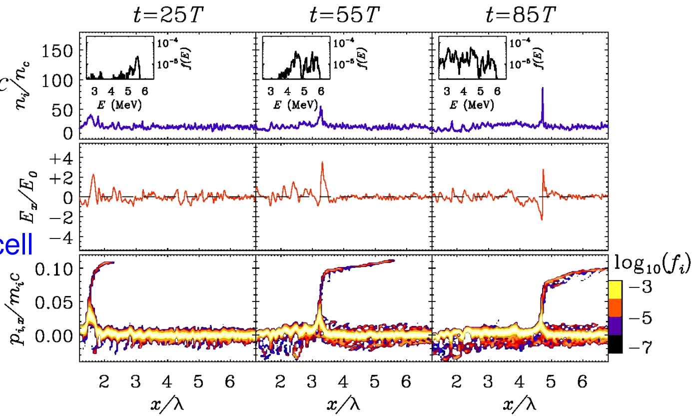
$\tau_p = 4T = 4\lambda/c$

$n_e = 20n_c$

$T_i = 1$ keV

$\Delta x = \lambda/400$

800 particles/cell

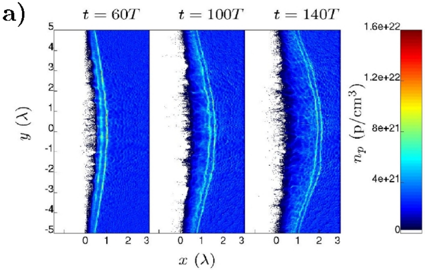


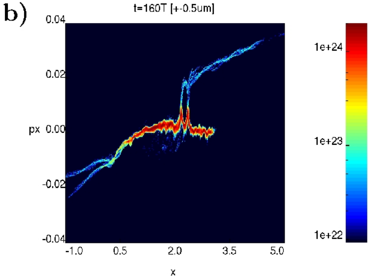
Too high T_i causes shock to slow down and spectrum to broaden

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

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 (but more investigation needed . . .)
- little recent progress in tailoring the energy spectrum
- "best" modeling still unclear (static, dynamic or both?)
- large 3D simulations needed for quantitative estimates

Some partial conclusions and perspectives: RPA

Hole Boring RPA:

- possible option for “extreme” pulses, not-so-prone to ultrahigh contrast
- requires development in low-density target preparation

Light Sail RPA:

- Fast scaling, prediction of energy enhancement by 3D effects
- “delicate” ultrathin targets required, may need wide spot (and large energy), spectrum not monoenergetic as hoped, slow gain with time/length

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

Acknowledgments

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

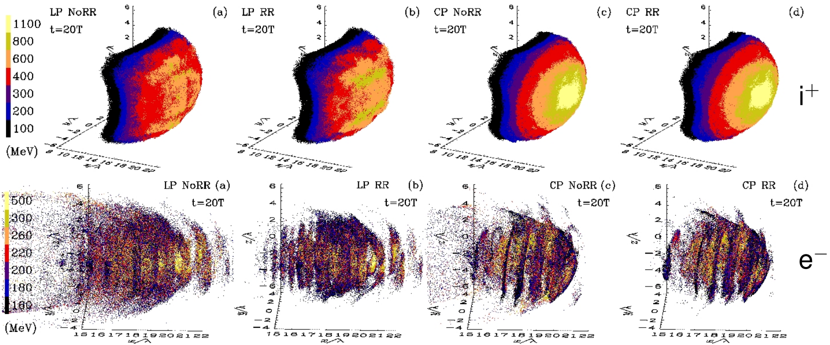
EXTRA SLIDES

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)

Space-energy distribution in 3D simulations



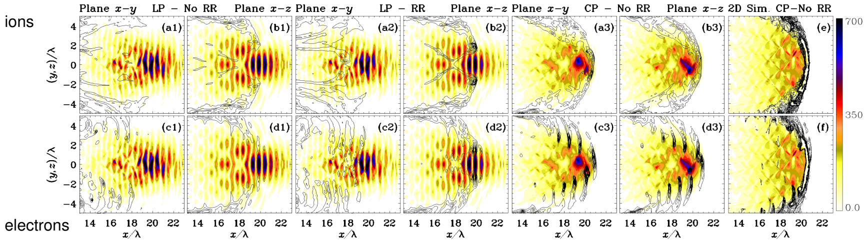
CP: symmetric, collimated ion distribution, weak RF effects

LP: asymmetric two-lobe ion distribution, strong RF effects

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

Pulse self-wrapping by the foil

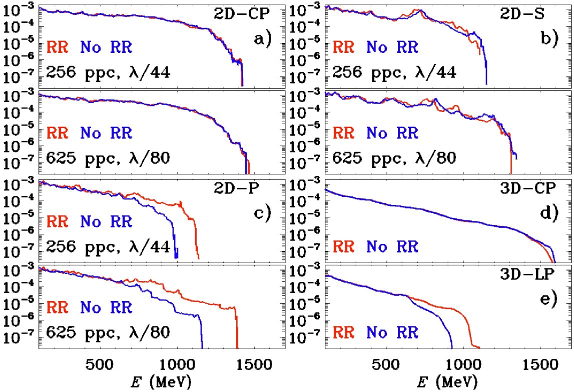
Sections of 3D fields [a1)-d3)] vs 2D simulations [e)-f)]



- 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 reduced dimensionality and resolution

Comparison of 3D ion spectra with 2D results (both S and P for LP) for both the same and higher resolution

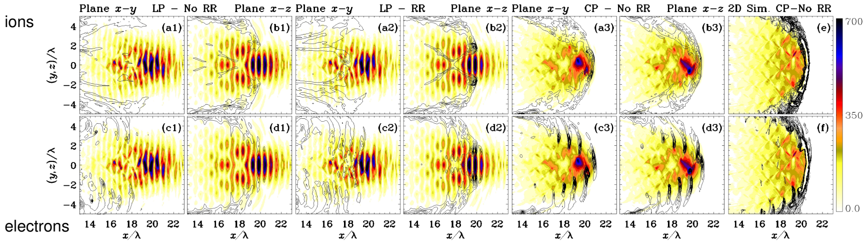


Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

The “optimal” CP case is the most robust (but energy is *lower* in 2D vs 3D !)

Pulse self-wrapping by the foil

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



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)]