Recent results in laser-driven ion acceleration

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Outline

An ultrashort review of the state-of-the-art and some recent contributions from our group, mostly based on Particle-In-Cell simulations of “advanced” schemes for ion acceleration:

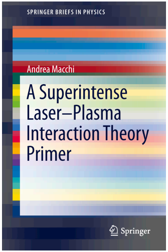
- enhanced proton energy in Target Normal Sheath Acceleration (TNSA) with foam-covered targets
- “Light Sail” Radiation Pressure Acceleration (LS-RPA) of thin foils: exploring “unlimited” regime in 3D
- monoenergetic spectra and efficiency in Collisionless Shock Acceleration (CSA)
- A common point: larger computational resources are needed!

Recent reviews on ion acceleration

A. Macchi, M. Borghesi, M. Passoni,
Ion Acceleration by Superintense Laser-Plasma Interaction,
Rev. Mod. Phys. (2013), in press (**May issue ?**), arXiv:1302.1775

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,*]
T. V. Liseykina[4], P. Londrillo[5], S. Sinigardi[6], M. Borghesi[7],
M. Passoni[3], F. Pegoraro[1,3]

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[*]presently at MPI-K, Heidelberg, Germany

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
- . . .

Ion acceleration for ICF

- ion-driven fast ignition
  [Tikhonchuk et al, Nucl. Fusion **50** (2010) 045003;
  Hegelich et al, Nucl. Fusion **51** (2011) 083011]
  - needs $\simeq 10$ kJ in ion beam, $> 10\%$ efficiency
  - acceleration of $A > 1$ ions (besides protons) **?**
- time-resolved proton radiography for ICF implosions
  - needs high energy protons (> 50 MeV) to resolve imploded core regions
- production and probing of Warm Dense Matter
- laser-driven neutron sources for material studies **?**

Some recent results - I

- proton energy cut-off:

  67.5 MeV with microcone targets, 80 J laser pulse
  [LANL/TRIDENT: Gaillard et al, PoP **18** (2011) 056710]

  40 MeV with 800 nm foil targets , <10 J
  [JAEA/JKAREN: Ogura et al, Opt. Lett. **37** (2012) 2868]

  120 MeV with 10 nm, relativistically transparent foils
  [LANL/TRIDENT: Hegelich et al, to be published]

- energy spread:

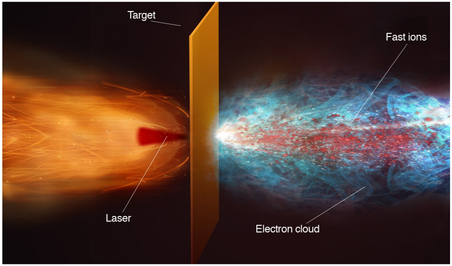
\- CO_2 laser interaction at $\simeq 10^{16}$ W cm^{-2} with Hydrogen jets:
$< 10\%$ at 1.2 MeV [1], $< 1\%$ at 22 MeV [2]
[1] Palmer et al, Phys. Rev. Lett. **106** (2011) 014801
[2] Haberberger et al, Nature Phys. **8** (2012) 95

Some recent results - II

- scaling with laser parameters:
  - Fast scaling with laser fluence $\mathscr{E}_{\text{peak}} \propto (I\tau_p)^2$ of C and H ions from $\sim 10^2$ nm targets
    [VULCAN: Kar et al, Phys. Rev. Lett. **109** (2012) 185006]
  - Transition from $\mathscr{E}_{\text{max}} \propto I^{1/2}$ to $\mathscr{E}_{\text{max}} \propto I$ scaling at $I \simeq 10^{20}$ W cm^{-2} for $\sim 10^1$ nm targets
    [GIST/APRI/PULSER: Kim et al, arXiv:1304.0333]
- Overall scenario: several promising results, different regimes of pulse/target, more than one mechanism in action . . .

TNSA: enhancing fast electron generation

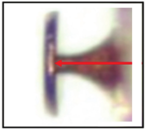
Target Normal Sheath Acceleration (TNSA)
is driven by *fast* electrons generated at the *front* surface of solid targets

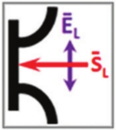


Key issue:
increase conversion efficiency of laser energy in fast electrons

A strategy: special targets (mass-reduced, microstructured, low-density, . . .)

Enhanced TNSA in microcone targets





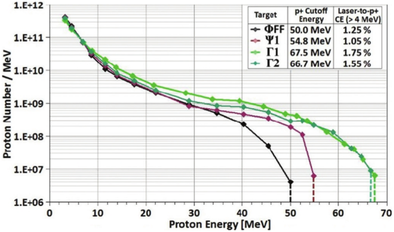
Gaillard et al, PoP **18** (2011) 056710

Use of cone target leads to

- effective grazing incidence

$\Longrightarrow$ more efficient fast electron generation

- geometrical collimation of fast electrons (“funnel” effect)

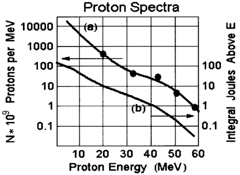


Up to $\mathscr{E}_{max}$=67.5 MeV protons with 80 J pulse energy

2000 LLNL Petawatt experiments:

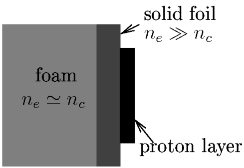
$\mathscr{E}_{max}$=58 MeV

[Snavely et al. PRL **85** (2000) 2945]

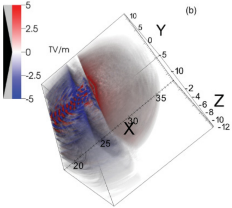


Enhanced TNSA in foam-covered targets

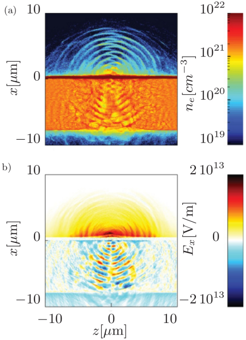
[Sgattoni, Londrillo, Macchi, Passoni, PRE **85** (2012) 036405]



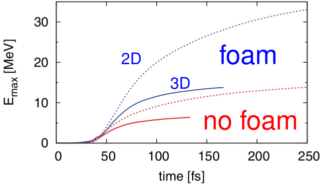
Self-generated channel behaves similar to cone



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



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



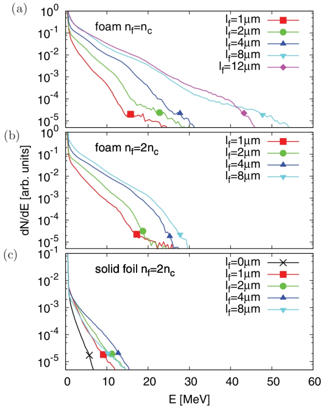
Foam-enhanced fast electron generation

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

fast electron temperature $T_f \gtrsim 3T_p$

where $T_p = m_e c^2 \left(\sqrt{1 + a_0^2/2} - 1\right)$

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

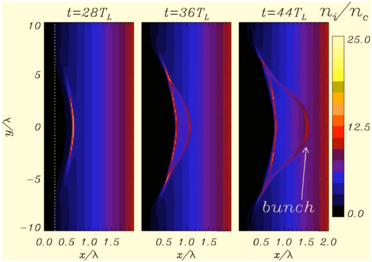


Larger simulations needed to address longer, more energetic pulse for higher $\mathscr{E}_{\text{max}}$

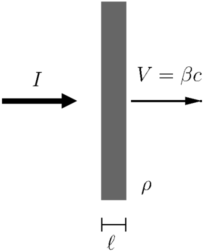
Radiation Pressure Acceleration

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

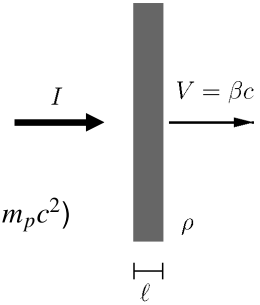


Light Sail "accelerating mirror" model

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

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

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



"Dream" features:

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

100% efficiency in the relativistic limit

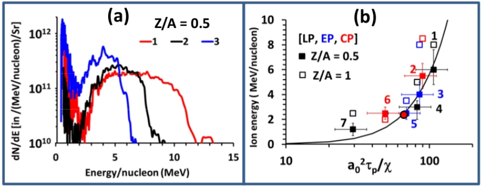
"Perfect" monoenergeticity for "rigid" coherent motion of the foil

Need of ultrathin (nm) foild and ultrahigh contrast pulses

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

RPA-LS: $\mathscr{F}^2$ scaling observed

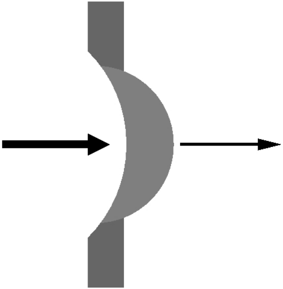
$\mathscr{E}_{\max} \sim \mathscr{F}^2$ (for $\mathscr{F} \ll 1$)



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
S.Kar, K.F.Kakolee, B.Qiao, A.Macchi, M.Borghesi et al.,
Phys. Rev. Lett. **109** (2012) 185006

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

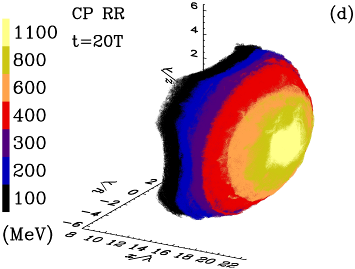
Limitation: relativistic transparency when $a_0 > \zeta \equiv \pi \frac{n_e}{n_c}\frac{\ell}{\lambda}$

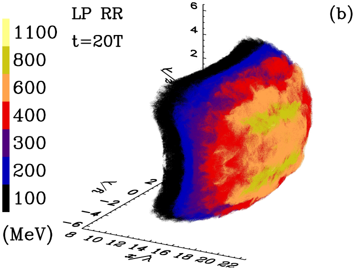
Optimal trade-off when $a_0 \simeq \zeta$

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}, $Z/A = 1$





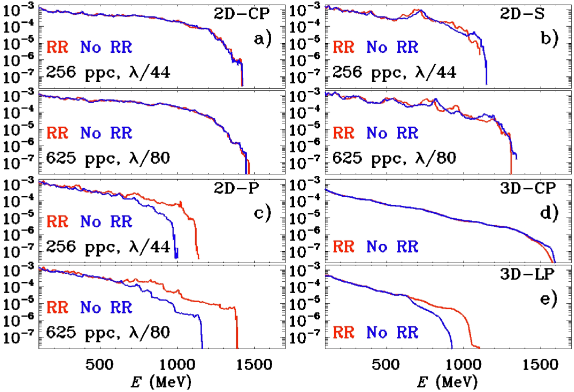
CP: symmetric, collimated ion distribution, higher energy

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

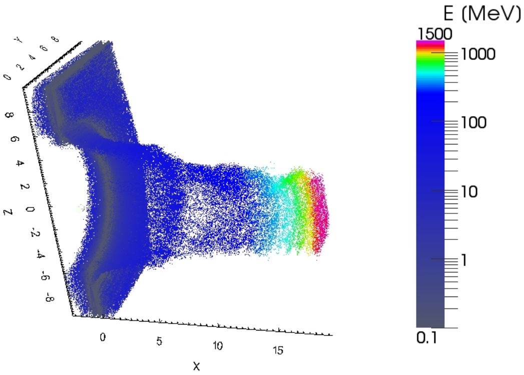
The "optimal" CP case is the most robust (Ion energy is **higher** in 3D than in 2D **!**)

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



HB and CSA in CO_2 laser-gas jet interaction

- laser-driven "piston" velocity $v_{\text{hb}} = (I/\rho c)^{1/2} \propto (n_c/n_e)^{1/2} a_0$
  - ion "reflection" from surface yields $v_{\text{max}} = 2v_{\text{hb}}$: Hole Boring (HB) or "piston" acceleration
- in a plasma with hot electrons such that $c_s = (ZT_h/m_pA)^{1/2} \approx v_{\text{hb}}$ the density perturbation may detach and propagate as a collisionless shock wave (or soliton) with velocity $v_{\text{sho}} = Mc_s$ with $M > 1$
  - ion "reflection" in the bulk from the shock front yields $v_{\text{max}} = 2v_{\text{sho}}$: Collisionless Shock Acceleration (CSA)
- Scaling with density suggests use of CO_2 laser + gas jets to produce a slightly overdense plasma $n_e \gtrsim n_c$

Hole Boring Acceleration with CP pulses

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 jet at $n_e = 4 - 8n_c$ using CP, $I = 6.5 \times 10^{15}$ W cm^{-2} pulses

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

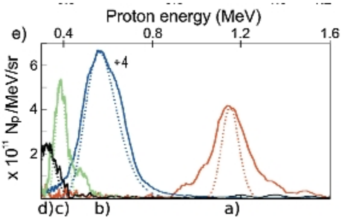


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{\max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{cr}$, (b) $I = 5.5$, $n = 6.1n_{cr}$, (c) $I = 5.9$, $n = 7.6n_{cr}$, (d) $I = 5.7$, $n = 8.0n_{cr}$ (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 $4\times$ to fit on the same scale.

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

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 $I = 6.5 \times 10^{16}$ W cm^{-2} and with LP
(Target: H_2 jet, $n_0 \leq 4n_c$)

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

Number of ions appears very low: is efficiency of CSA incompatible with monoenergeticity?

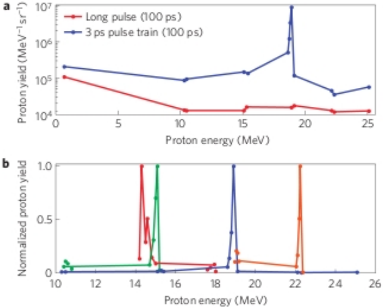


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within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

$a_0 = 1$

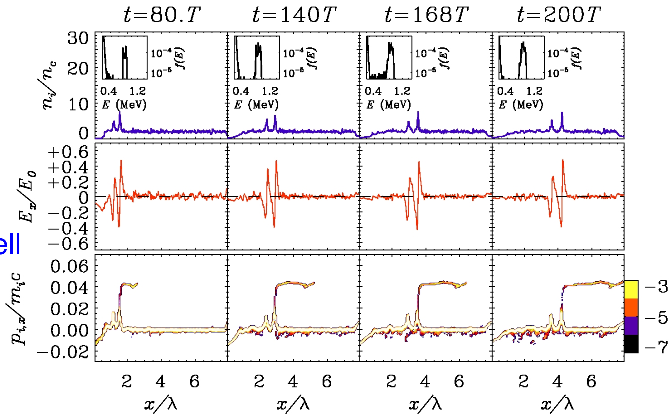
$\tau_p = 4T = 4\lambda/c$

$n_e = 2n_c$

$T_i = 100$ eV

$\Delta x = \lambda/400$

800 particles/cell



Steady ion reflection produces a narrow energy spectrum

CSA with warm ions: 1D simulation - II

Parameters:

$a_0 = 16$

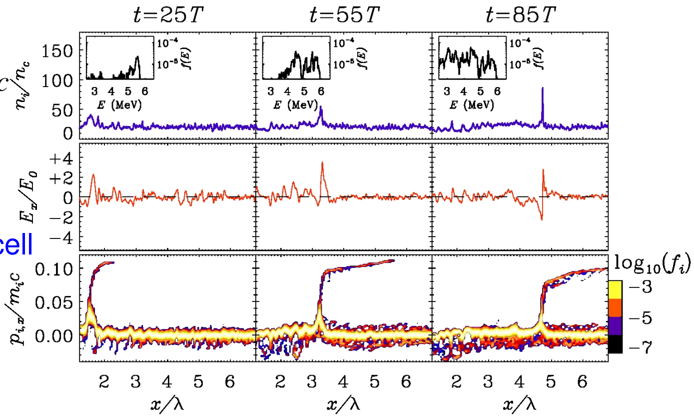
$\tau_p = 4T = 4\lambda/c$

$n_e = 20n_c$

$T_i = 1$ keV

$\Delta x = \lambda/400$

800 particles/cell

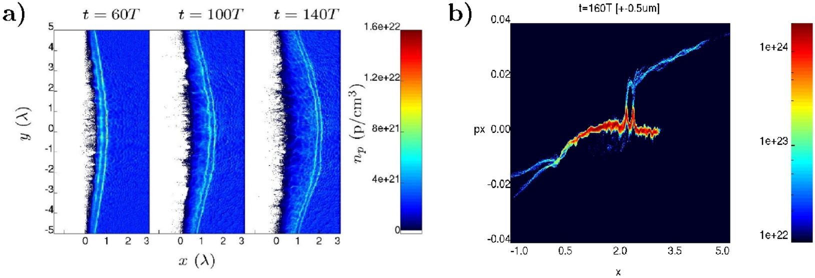


Too high T_i causes shock to slow down and spectrum to broaden

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: pros and cons ...

TNSA: Most tested mechanism, robust and reliable

- possibly slow scaling with laser energy/intensity, enhancement requires complex targets (cones, foams, ...)

RPA-LS: Fast scaling, promising for acceleration to >1 GeV

- "delicate" ultrathin targets required, spectrum not monoenergetic as hoped, slow gain with time/length

CSA: Monoenergetic spectra, gas-based scheme suitable for high repetition rate

- low efficiency? Scalable to optical lasers and > 100 MeV?

▶ General issue: larger simulations are needed!

"*Plasma physics is just waiting for bigger computers ...*"

. . . and my 2 cents for fast ignitION

- Although some parameters (energy, spread, efficiency) have been “demonstrated in separate experiments” with ultrathin foil targets [Hegelich et al, NF **51** (2011) 83011], this approach needs complex assembly of ignitor and fuel targets . . .
- HB-RPA *in situ* [Tikhonchuk et al, NF **50** (2010) 45003] appears to be simpler and in principle has potential to meet several specifications

  (a constraint: ion acceleration efficiency $\eta \simeq 2v_i/c$, i.e. $\eta \simeq 60\%$ for D-T ions with $\mathscr{E}_i \simeq 10$ MeV)
- Of course the approach remains very challenging . . .

Acknowledgments

- Work sponsored by the FIRB-MIUR, Italy (project SULDIS – “Superintense Ultrashort Laser-Driven Ion Sources”)
- Use of supercomputing facilities at CINECA (Italy) via grant awards:
  - IBM-SP6, ISCRA award (project TOFUSEX – “TOwards FUll-Scale simulations of laser-plasma EXperiments” N.HP10A25JKT-2010)
  - FERMI BlueGene/Q$^{\text{TM}}$, PRACE award (project LSAIL – “Large Scale Acceleration of Ions by Lasers”)

EXTRA SLIDES

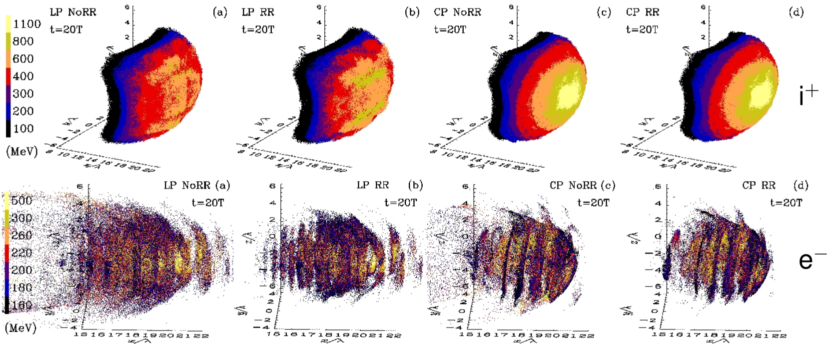
Set-up of 3D RPA simulations

- 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



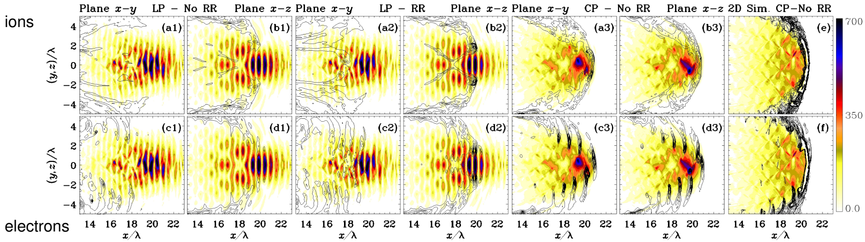
CP: symmetric, collimated ion distribution, weak RF effects

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)]



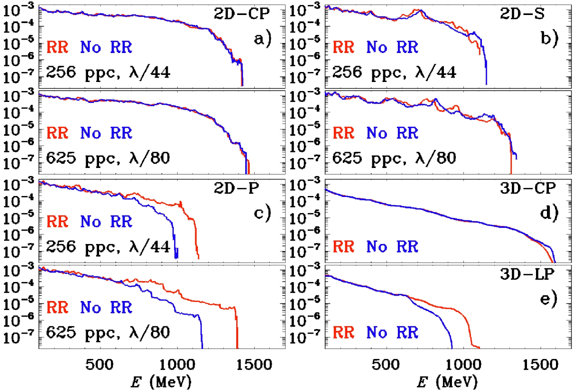
Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]

"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

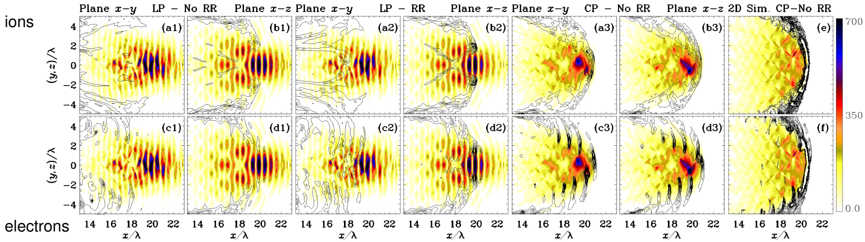


Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

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)]



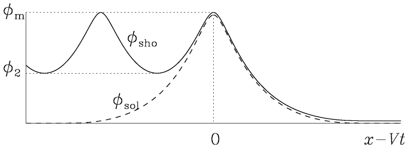
Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]

“Wrapping” and focusing effects are weaker in 2D vs 3D [see e)-f)]

Breakthrough in the foil occurs for LP [see series -1)-2)]

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 $T_e \simeq m_e c^2 \left(\sqrt{1+a_0^2/2}-1\right)$