Issues in Radiation Pressure Acceleration

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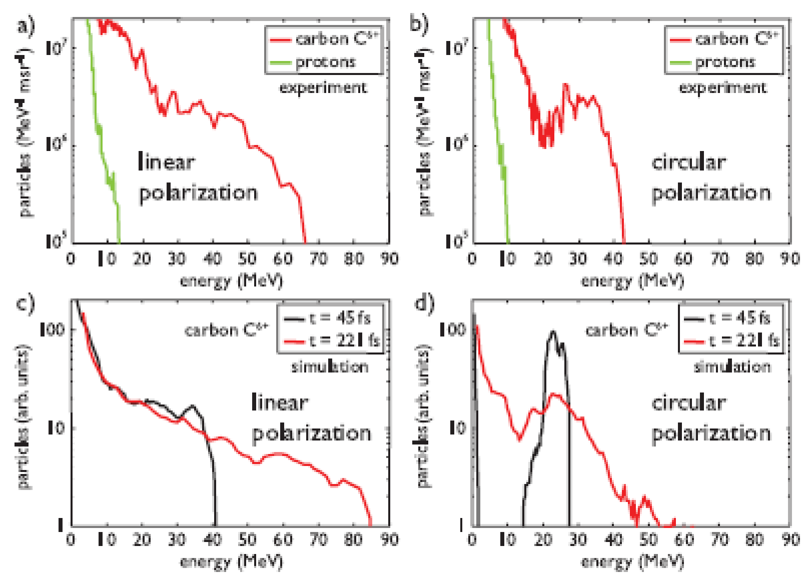
Why RPA using Circular Polarization?

Using CP and normal incidence (*an experimentalist's nightmare*...) fast electron generation by the **jXB** force is strongly suppressed, maximizing radiation pressure and obtaining a “smooth” acceleration of the bulk target

Early study in “thick” targets:
A.Macchi et al, PRL **94** (2005) 165003

Use of CP-RPA with ultrathin foils has been later proposed to achieve effcient and monoenergetic acceleration:
X.Zhang et al, Phys. Plasmas **14** (2007) 073101 & 123108;
A.P.L.Robinson et al, New J. Phys. **10** (2008) 013201;
O.Klimo et al, Phys. Rev. ST-AB **11** (2008) 031301.

First experimental evidence reported recently:
A.Henig et al, PRL **103** (2009) 245003



CP-RPA appears to attract much theoretical interest...

Thick (semi-infinite) targets ("Hole Boring"):

T.V.Liseikina & A.Macchi, Appl.Phys.Lett. **94** (2007) 165003;
N.Naumova et al, Phys.Rev.Lett. **102** (2009) 025002;
T.Schlegel et al, Phys.Plasmas **16** (2009) 083103;
A.P.L.Robinson et al, Plasma Phys.Contr.Fus. **51** (2009) 024004 & 095006;
A.Macchi & C.Benedetti, Nucl.Inst.Meth.Phys.Res. A (2010), in press

Ultrathin (sub-wavelength) targets ("Light sail"):

X.Q.Yan et al, Phys.Rev.Lett. **100**, (2008) 135003 ;
B.Qiao et al, Phys.Rev.Lett. **102** (2009) 145002;
V.K.Tripathi et al, Plasma Phys.Contr.Fus. **51** (2009) 024014;
B. Eliasson et al. New J. Phys. **11** (2009) 073006;
X.Q.Yan et al, Phys.Rev.Lett. **103** (2009) 135001;
A.Macchi et al, Phys.Rev.Lett. **103** (2009) 085003;
A.Macchi et al, New J. Phys. (2010) in press.

Results presented in this poster

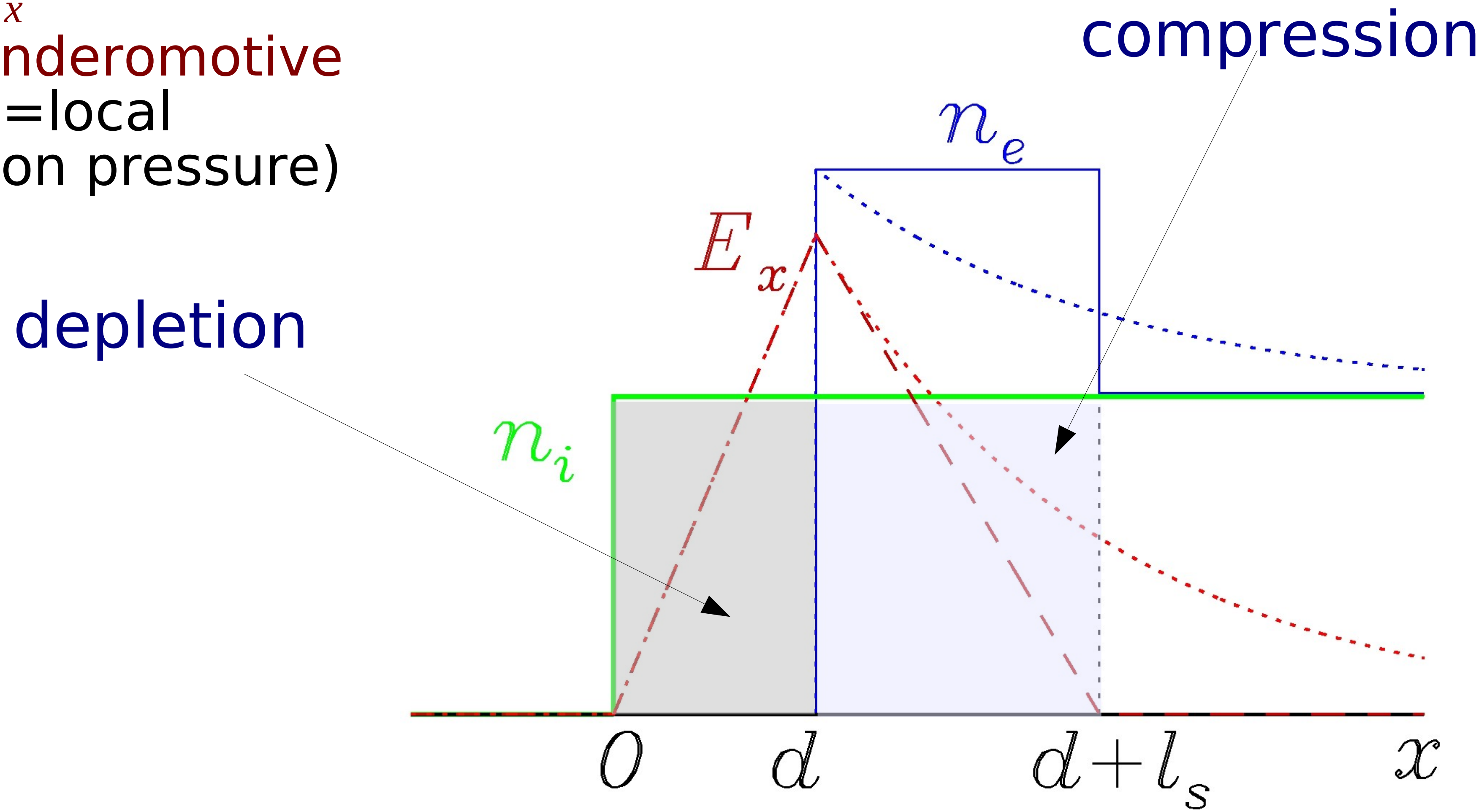
Variations on the theme (side effects, structured targets, ...)

T.V.Liseikina et al, Plasma Phys.Contr.Fus. **50** (2008) 124033;
S.G.Rykovanov et al., New J. Phys. **10**, (2008) 113005;
L.Ji et al, Phys.Rev.Lett. **101** (2008) 164802;
Y.Yin et al, Phys.Plasmas **15** (2008) 093106;
A.R.Holkundkara and N.K.Gupta, Phys.Plasmas **15** (2008) 123104;
M.Chen et al, Phys.Plasmas **15** (2008) 113103;
X.Zhang et al, PRST-AB **12** (2009) 021301;
A.A.Gonoskov et al, Phys.Rev.Lett. **102** (2009) 145002;
M.Chen et al, Phys.Rev.Lett. **103** (2009) 024801

RPA dynamics and thick vs. thin targets - I

The laser pulse penetrates into the target creating electron depletion ($0<x<d$) and compression ($d<x<d+l_s$) layers.

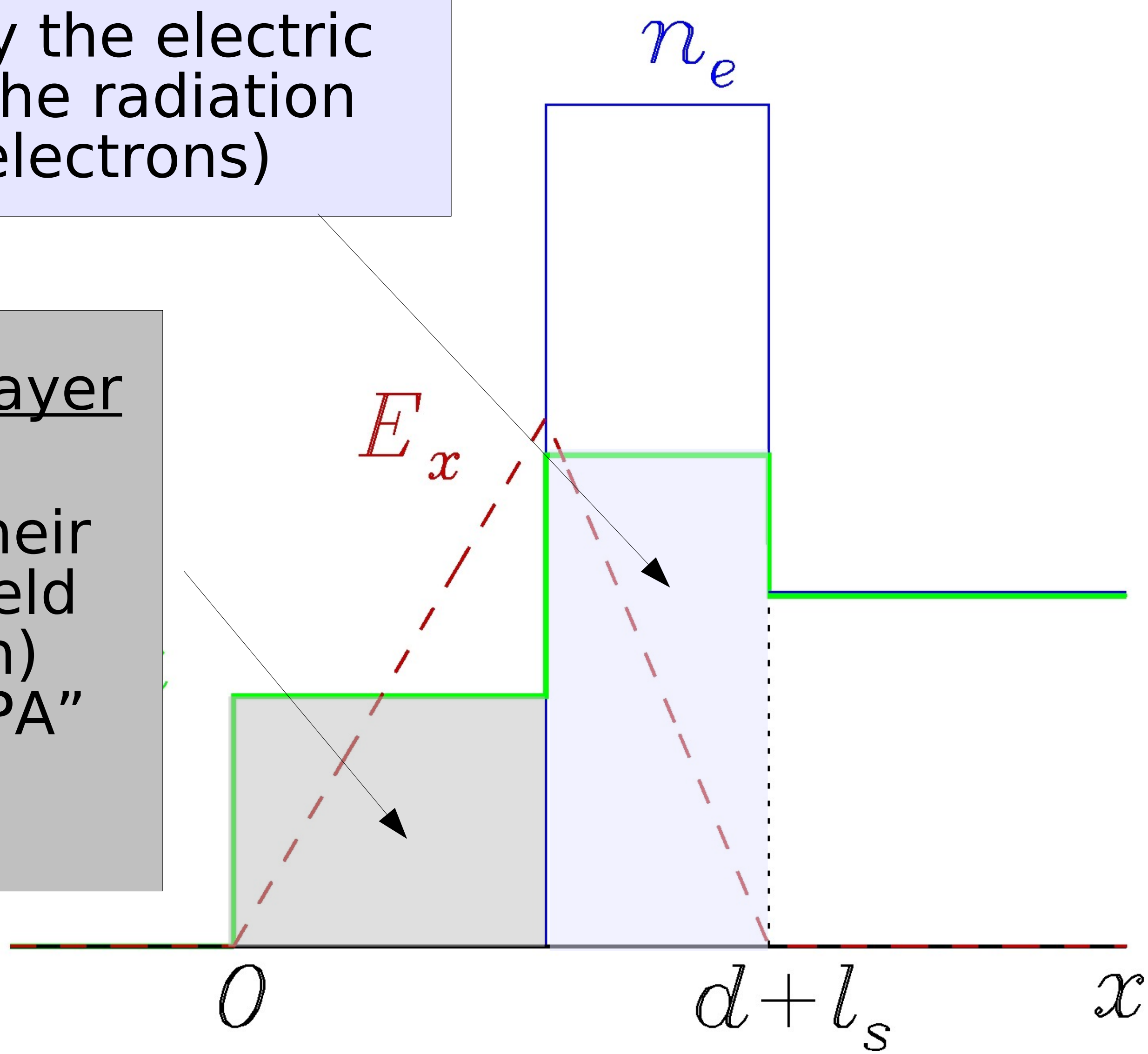
The electrostatic field E_x balances the ponderomotive force (=local radiation pressure)



RPA dynamics and thick vs. thin targets - II

Ions in <u>compression layer</u> $d<x<d+l_s$ are accelerated “by RPA” (actually by the electric field balancing the radiation pressure on electrons)

Ions in the <u>depletion layer</u> $0<x<d$ are accelerated by their own space-charge field (Coulomb explosion) and do not reach “RPA” ions



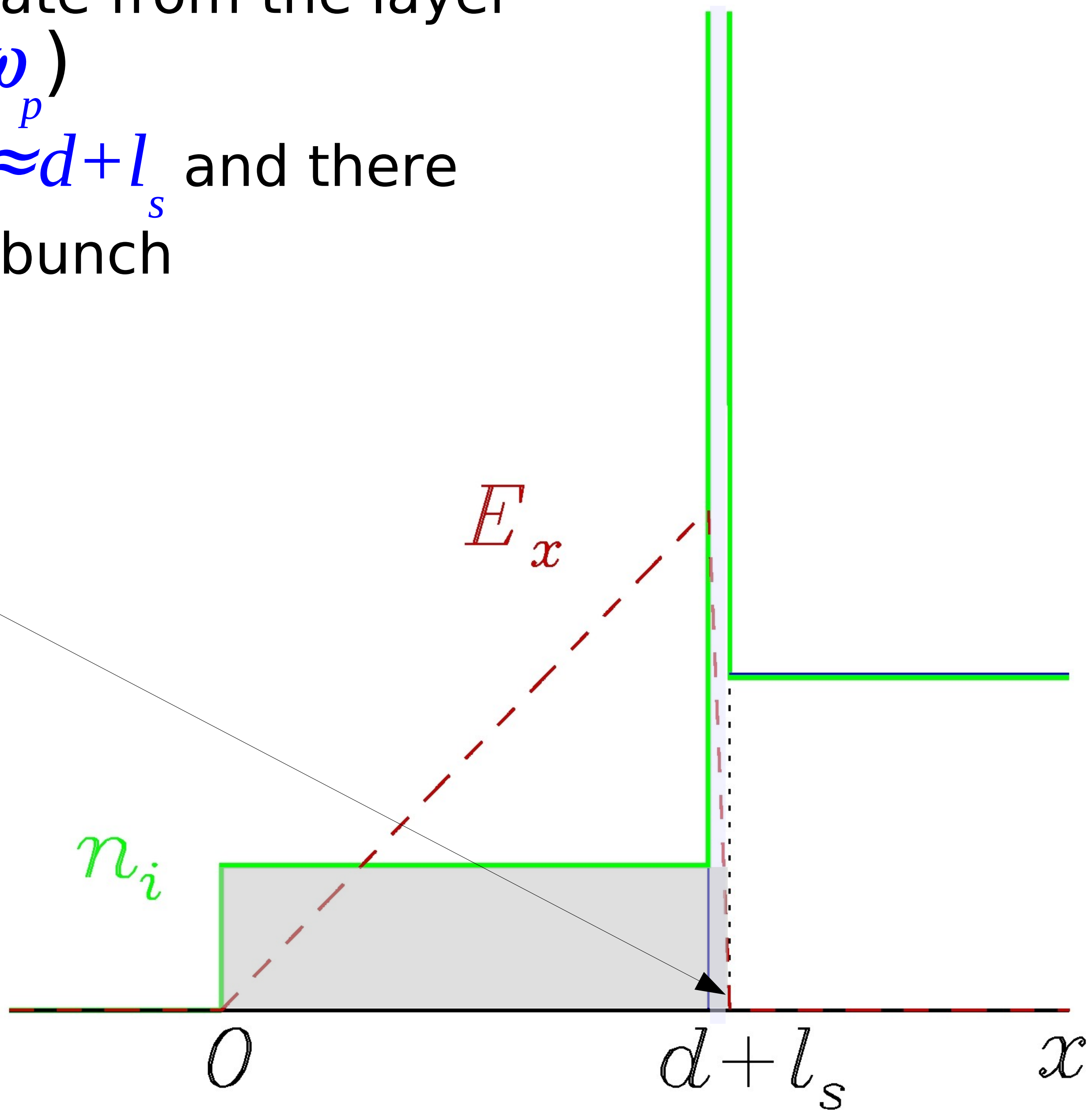
RPA dynamics and thick vs. thin targets - III

The faster ions originate from the layer $d<x<d+l_s \quad (l_s \approx c/2\omega_p)$

The ions pile up at $x \approx d+l_s$ and there "wavebreaking" and bunch formation occurs.

A "thin" target should end <u>here</u>,

i.e have a thickness $\ell \approx d+l_s$ in order to allow "repeated" acceleration of the "fast" ion layer



Scaling laws in the hole boring regime

"Piston parameter"

$$\Pi \equiv \frac{I}{\rho c^3} = \frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}a_0^2$$

Cut-off velocity and energy for non-relativistic ions
[A.Macchi et al, PRL **94** (2005) 165003]

$$\frac{v_{i,m}}{c} = 2\sqrt{\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}}a_0 = 2\sqrt{\Pi}$$

$$E_{i,m} = 4Zm_ec^2\left(\frac{n_c}{n_e}\right)a_0^2 = 2m_ic^2\Pi$$

Relativistic corrections accounting for laser energy depletion in the Lab frame
[A.P.L.Robinson et al, PPCF **51** (2009) 024004]

$$\frac{v_{i,m}}{c} = \frac{2\sqrt{\Pi}}{1+\sqrt{\Pi}}$$

$$E_{i,m} = 2m_ic^2\frac{\Pi}{1+2\sqrt{\Pi}}$$

Hole Boring: Pro et Contra

CONTRA

- Ion energy scales with pulse intensity, not energy

- For solid-densities only a few MeV energies may be obtained (maybe not sufficient to cross the target!)

PRO

- with respect to LS (requiring ultrathin targets) HB seems less prone to prepulse effects: it works in low density "preplasma" achieving higher ion energy [Liseikina et al, PPCF **50** (2008) 124033]

- with moderately overdense gas or liquid jet higher energies and high repetition rate may be obtained

Option: liquid hydrogen jet with Ti:Sa laser

$n_e = 4.2 \times 10^{22}\ \mathrm{cm}^{-3} = 25 n_c$, $25\,\mu\mathrm{m}$ diameter

[Toleikis et al, High Energy Density Physics **6** (2010) 15]

Hole Boring Acceleration with Few-Cycle Pulses

Future laser systems may produce few-cycle pulses with intensities $>10^{22}$ W/cm^{-2} and high repetition rate

Such short pulses could “concentrate” all their energy into the acceleration of a single ion bunch

In combination with a liquid hydrogen jet they could provide an efficient, high repetition rate source of multi-MeV protons

Case study:

Hydrogen slab with $n_e = 50 n_c = 8.6 \times 10^{22}$ cm^{-3}

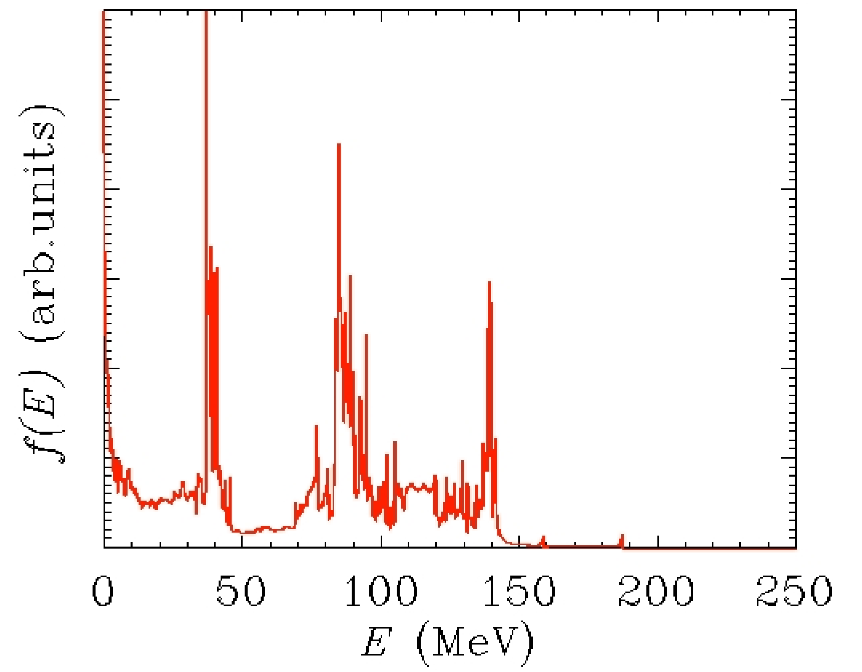
CP laser pulse with $\lambda = 0.8\mu$m and 2 cycles duration (FWHM)
Peak intensity $I = 4.9 \times 10^{22}$ W/cm^{-2} ($a_0 = 106$)

(*suggestion by M.Borghesi & M.Zepf, QUB, Belfast*)

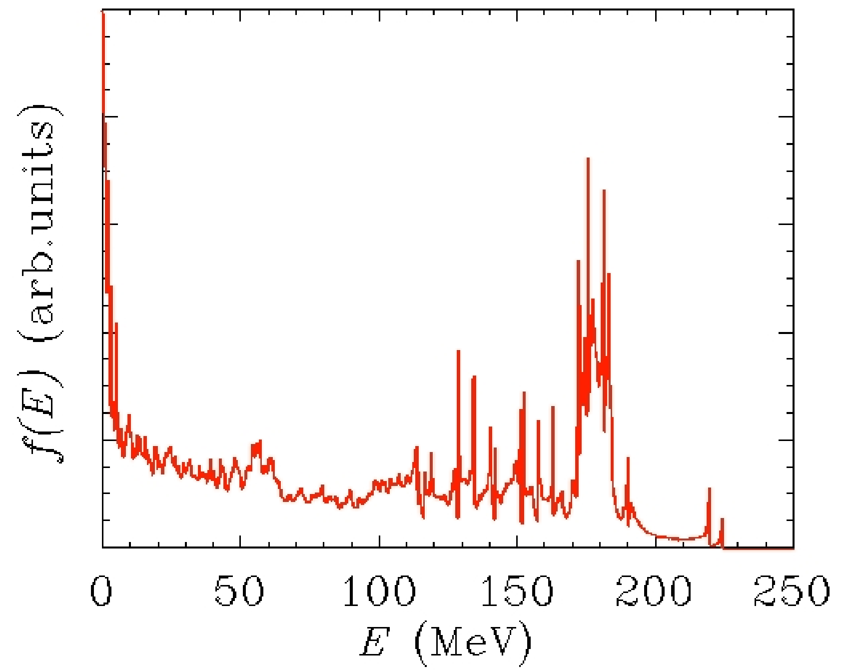
The ion spectrum is improved by a density gradient

Step-like density profiles:
- multiple ion bunches
- multiple peaks in the ion spectrum, cut-off energy at ~140 MeV

(bunch production time is less than laser cycle)



Inhomogeneous density profile (3μm preplasma):
- single bunch produced
- spectrum dominated by single peak at ~180 MeV, <10% energy spread



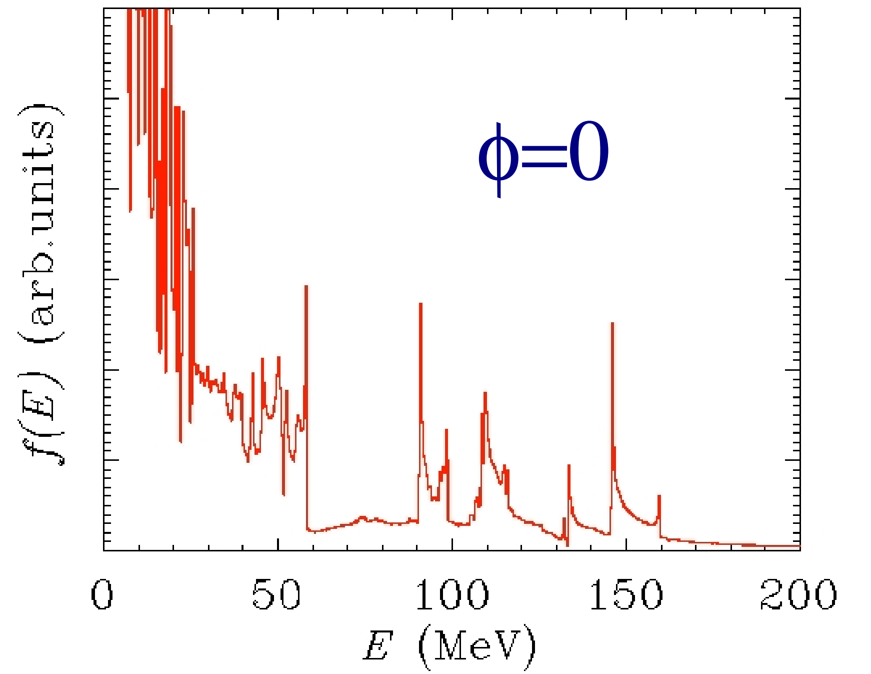
Circular Polarization stabilizes CE phase effects

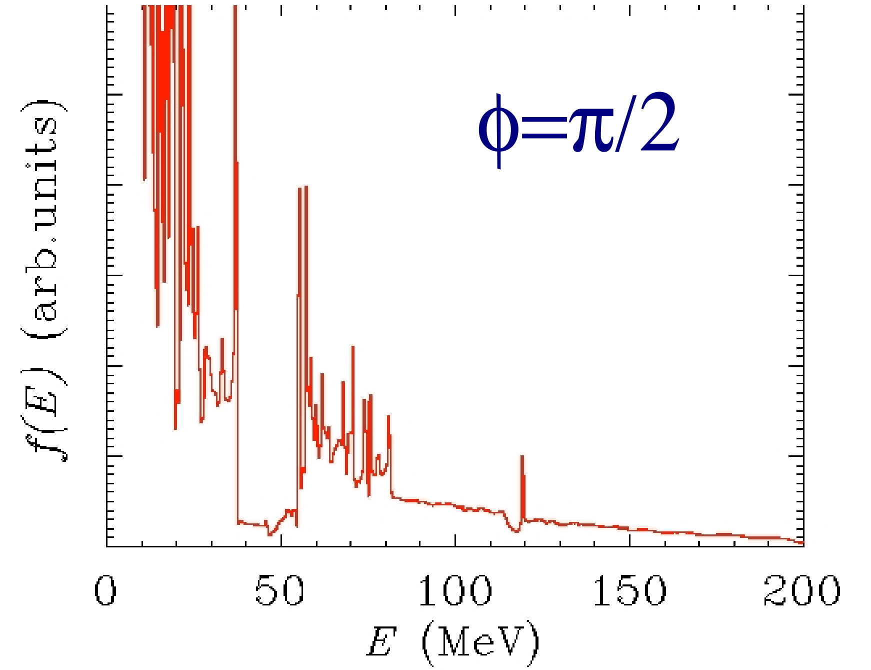
Laser-matter interaction with few-cycle pulses is sensitive to the Carrier-Envelope phase ϕ:

$$E(t)=f(t)\sin(\omega t+\phi)$$

For linearly polarized pulses the ion spectrum is broad and strongly dependent on ϕ:

For circular polarization, there is almost no dependence on ϕ because $|E(t)|^2$ is constant in this case

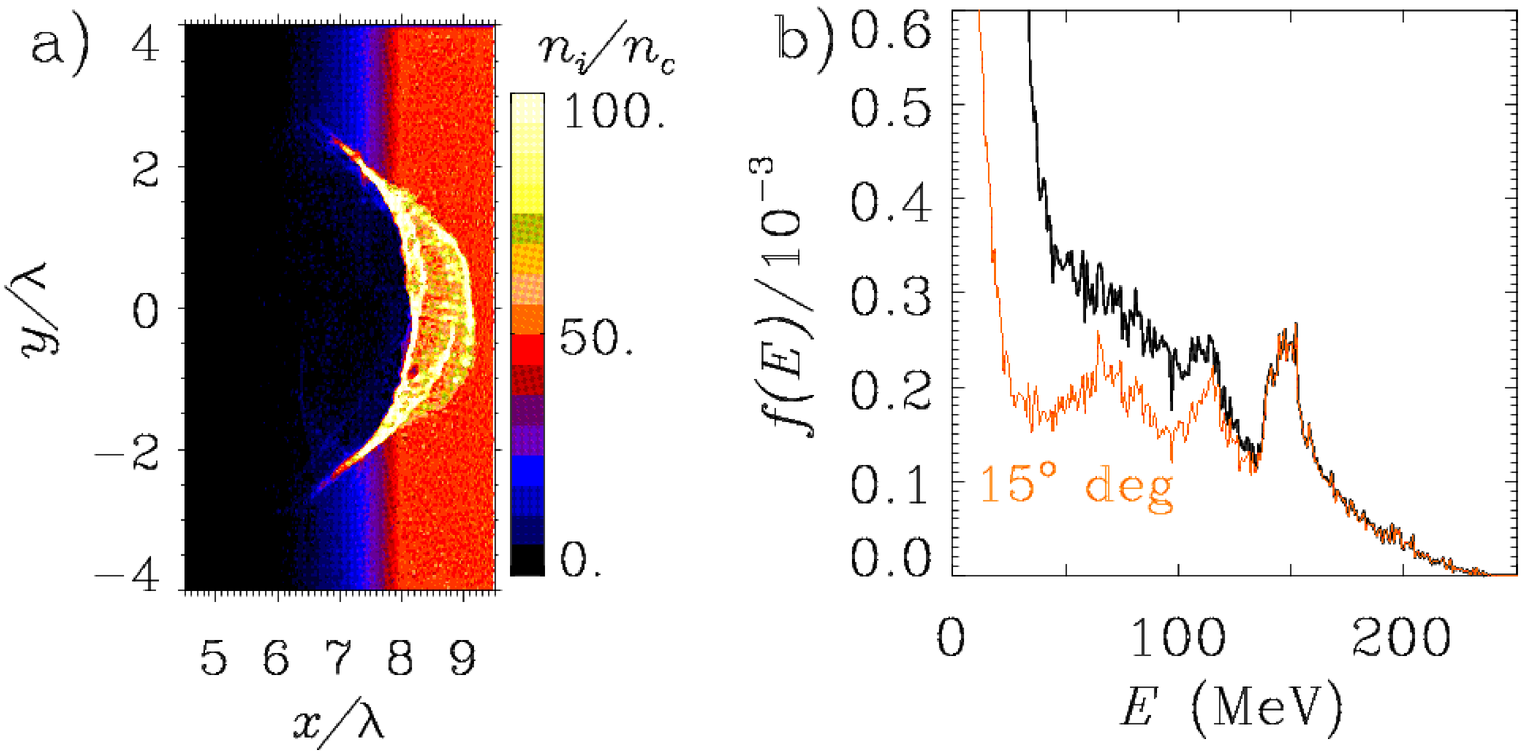




2D simulations with the ALaDyn[1] code - I

$n_e = 50 n_c$ H slab, 4λ preplasma, CP Gaussian pulse

2λX2λ , $a_0 = 106$

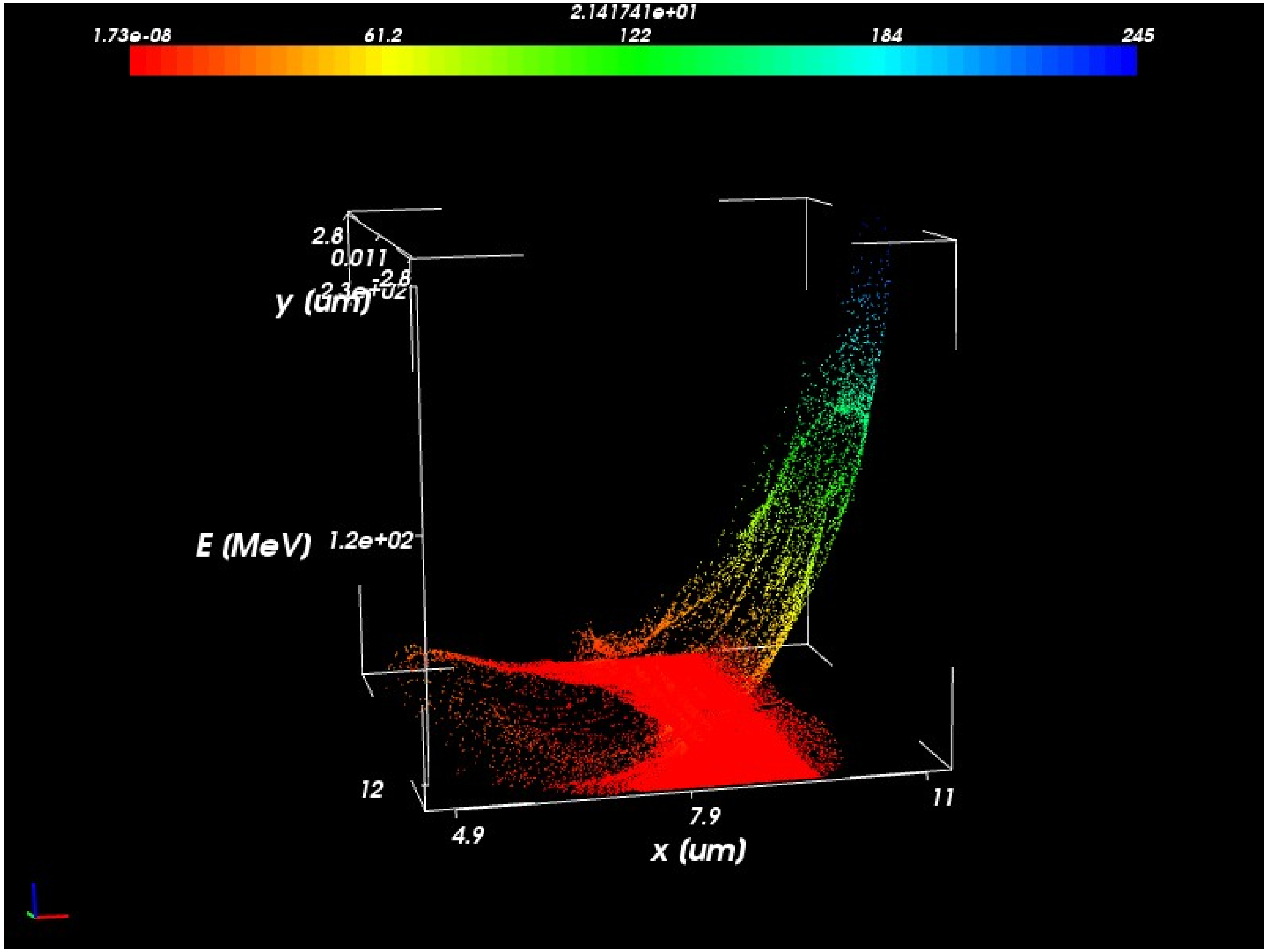


A. Macchi, C. Benedetti, Nucl.Inst.Meth.Phys.Res. A (2010), in press

[1]C.Benedetti et al., IEEE Trans. Plasma Sci. **36** (2008) 1790.

2D simulations with the ALaDyn[1] code - II

Ion spectrum is sensitive to focal position: "best" spectrum found with waist inside the plasma

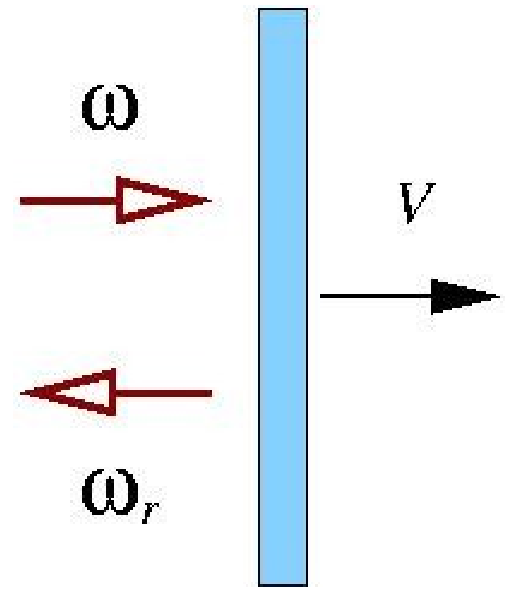


[1]C.Benedetti et al., IEEE Trans. Plasma Sci. **36** (2008) 1790.

The "Light Sail" or (Accelerating Mirror) model-I

Model: a perfectly reflecting, rigid mirror of mass $M=\rho\ell S$ boosted by a plane light wave

Mirror velocity as a function of the laser pulse intensity I and duration τ and of the surface density $n_e\ell$ of of the target:



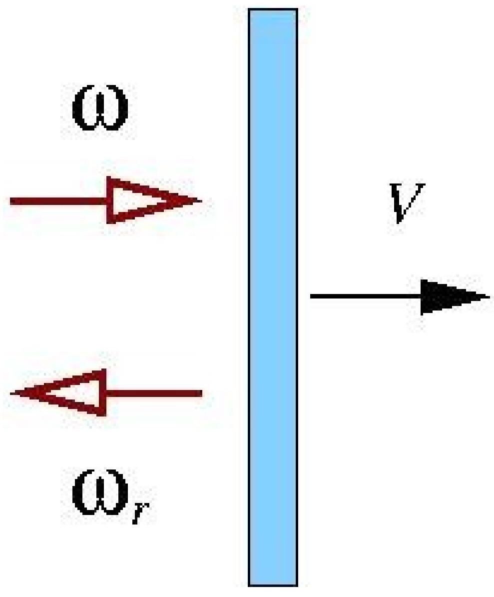
$$\beta(t) = \frac{(1+\mathcal{E})^2 - 1}{(1+\mathcal{E})^2 + 1}, \qquad \mathcal{E} = \frac{2F(t)}{\rho\ell c^2} = 2\pi \frac{Z}{A}\frac{m_e}{m_p}\frac{a_0^2\tau}{\zeta}$$

$$F(t) = \int_0^t I(t')dt' \propto a_o^2\tau, \qquad \zeta = \pi\frac{n_e}{n_c}\frac{\ell}{\lambda}$$

G.Marx, Nature **211**, 22 (1966)
J.F.L.Simmons and C.R.McInnes, Am.J.Phys. **61**, 205 (1993)

The "Light Sail" or (Accelerating Mirror) model-II

The efficiency of the acceleration process can be obtained by a simple argument of conservation of "number of photons" plus the Doppler shift of the reflected light:



$$N = \frac{IS\tau}{\hbar\omega}, \qquad \omega_r = \omega\frac{1-\beta}{1+\beta}$$

$$\eta = \frac{\mathcal{E}_{\rm abs}}{\mathcal{E}_{\rm laser}} = \frac{N\hbar(\omega-\omega_r)}{IS\tau} = \frac{2\beta}{1+\beta}$$

$$\beta \to 1 \Rightarrow \eta \to 1$$

100% efficiency in the relativistic limit

G.Marx, Nature **211**, 22 (1966)
J.F.L.Simmons and C.R.McInnes, Am.J.Phys. **61**, 205 (1993)

Comparison of LS model with 1D PIC simulations-I

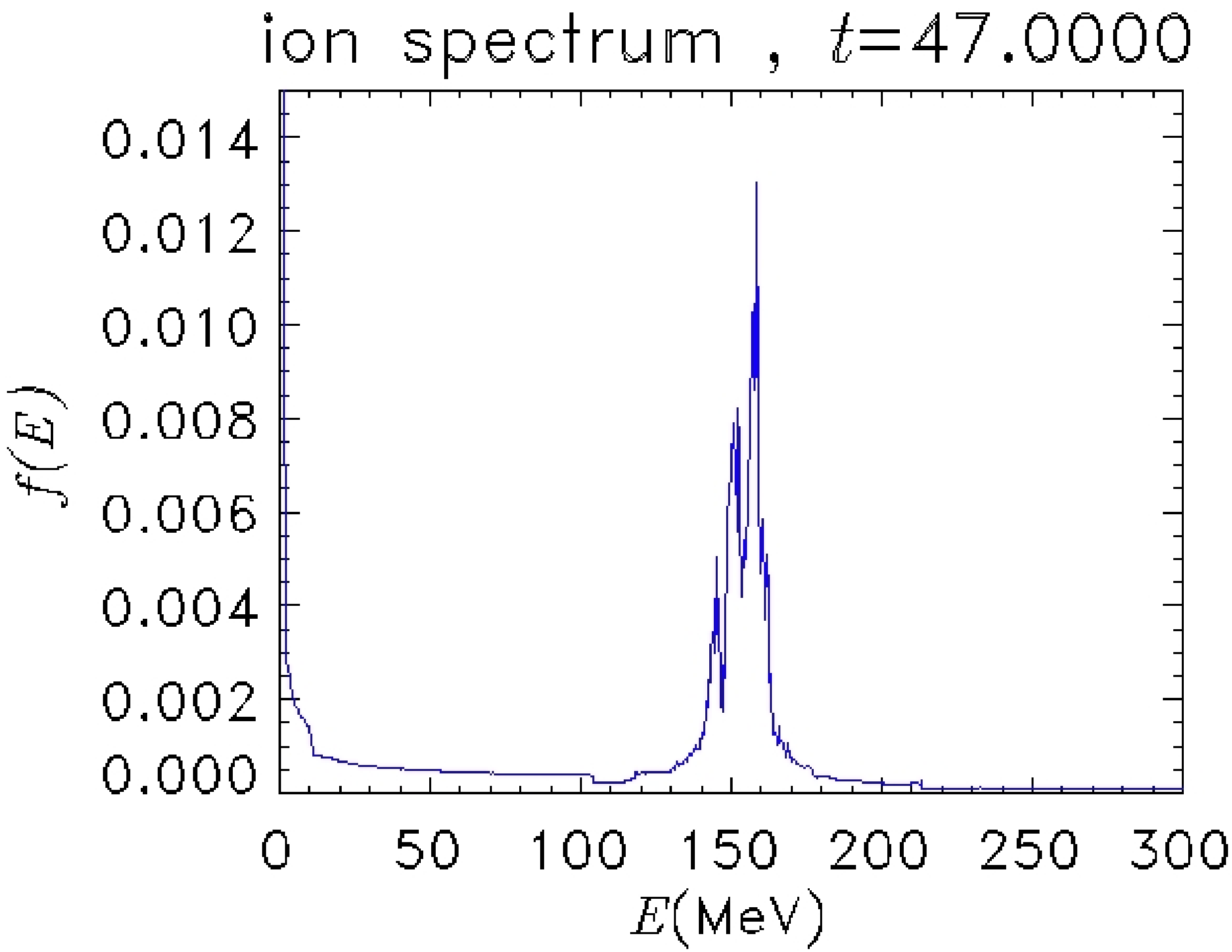
Laser pulse: a_0=**5-50**, τ=8 cycles ("flat-top" envelope)

Thin foil target: n_e=250n_c, ℓ=**0.01-0.1**λ (ζ=**7.8-78.5**)

A narrow spectral peak is observed for $a_0<\zeta$.

The energy of the peak is in good agreement with the LS formula

For $a_0>\zeta$, the dynamics is dominated by a Coulomb explosion of the foil

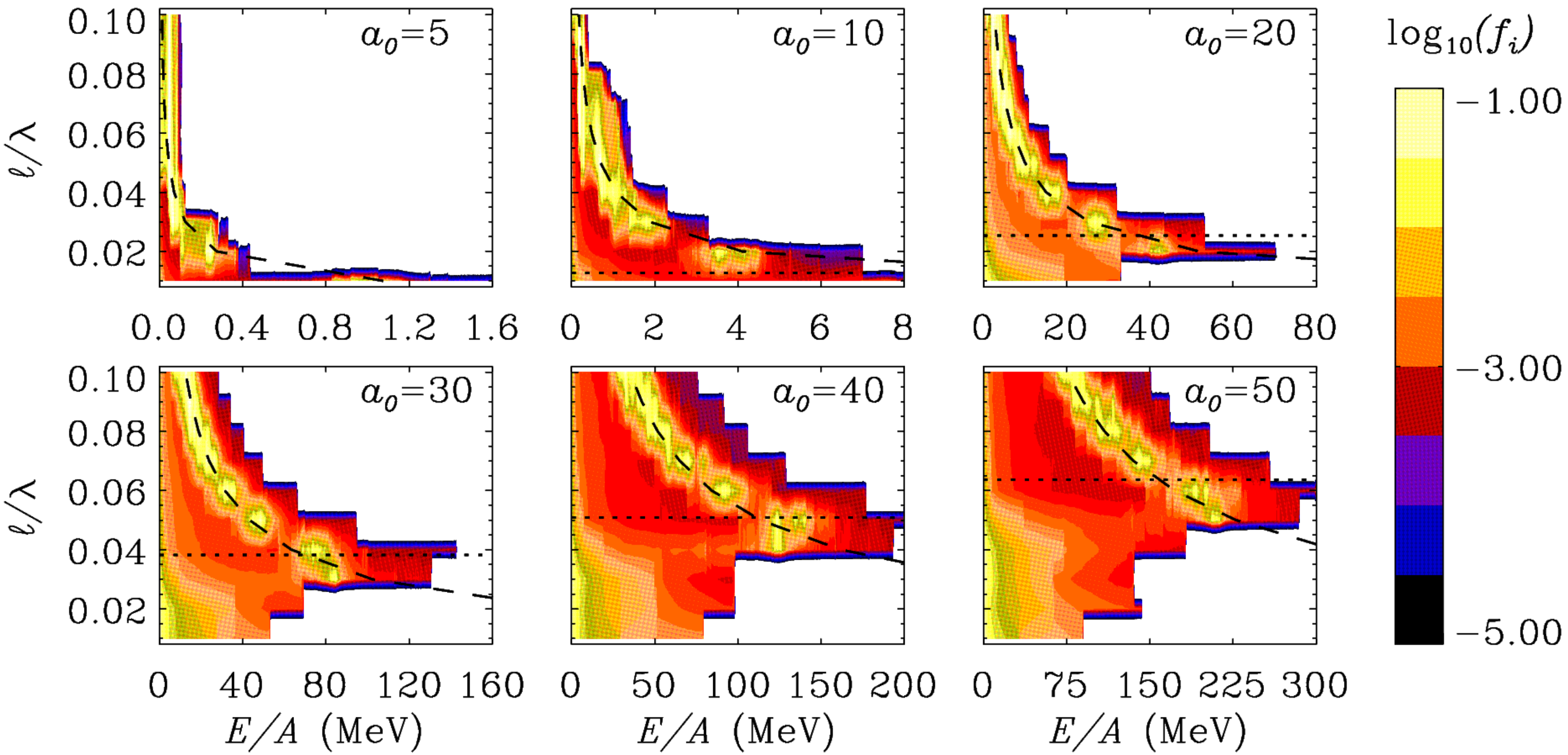


A.Macchi, S.Veghini, F.Pegoraro, PRL **103** (2009) 085003

Comparison of LS model with 1D PIC simulations-II

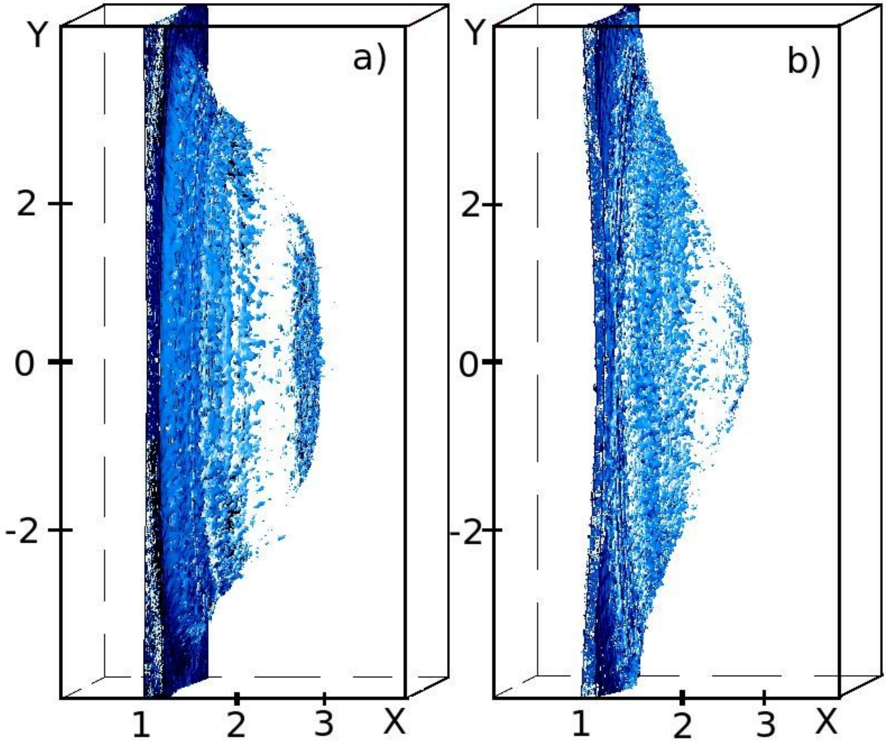
Energy spectra vs. a_0 and ℓ:

Dashed line: LS model prediction, dotted line: $a_0 = \zeta$.

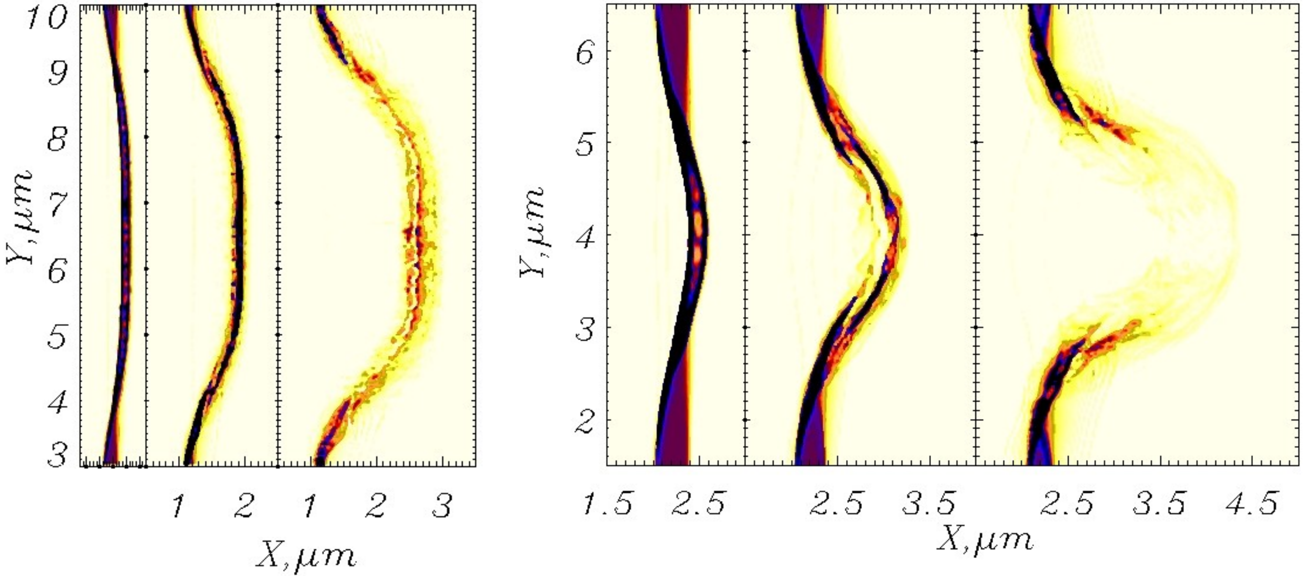


A.Macchi, S.Veghini, F.Pegoraro, PRL **103** (2009) 085003

3D simulations “support” 1D modeling



Gaussian intensity profiles lead to early “burnthough” due to lateral expansion of the target
Supergaussian “flat-top” profiles, keeping a “quasi-1D geometry” are needed for efficient acceleration and to ensure high collimation and monoenergeticity



[T.V.Liseikina et al, PPCF **50** (2008) 124033]

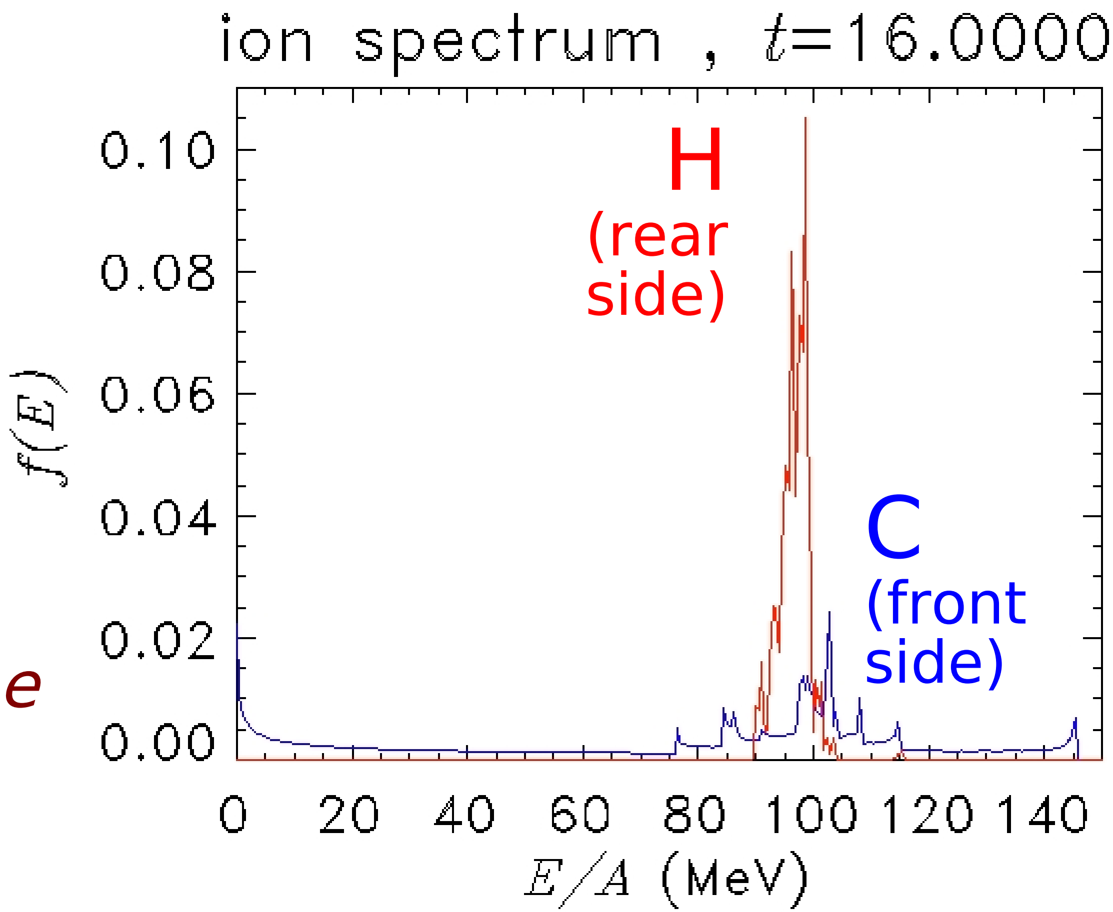
However, some questions remain...

- What determines the "optimal thickness" condition $a_0 < \zeta$?
- Does the foil remain neutral after the acceleration?

- A "puzzle": the CPA peak contains only ~30% of all the ions (and ~64% of their energy)

Only the rear side of the foil is accelerated (thus LS RPA may work for double-layer targets!)

→ *Why there is very good agreement of the energy with the LS formula when using the whole mass of the target (and not ~30% of it)?*

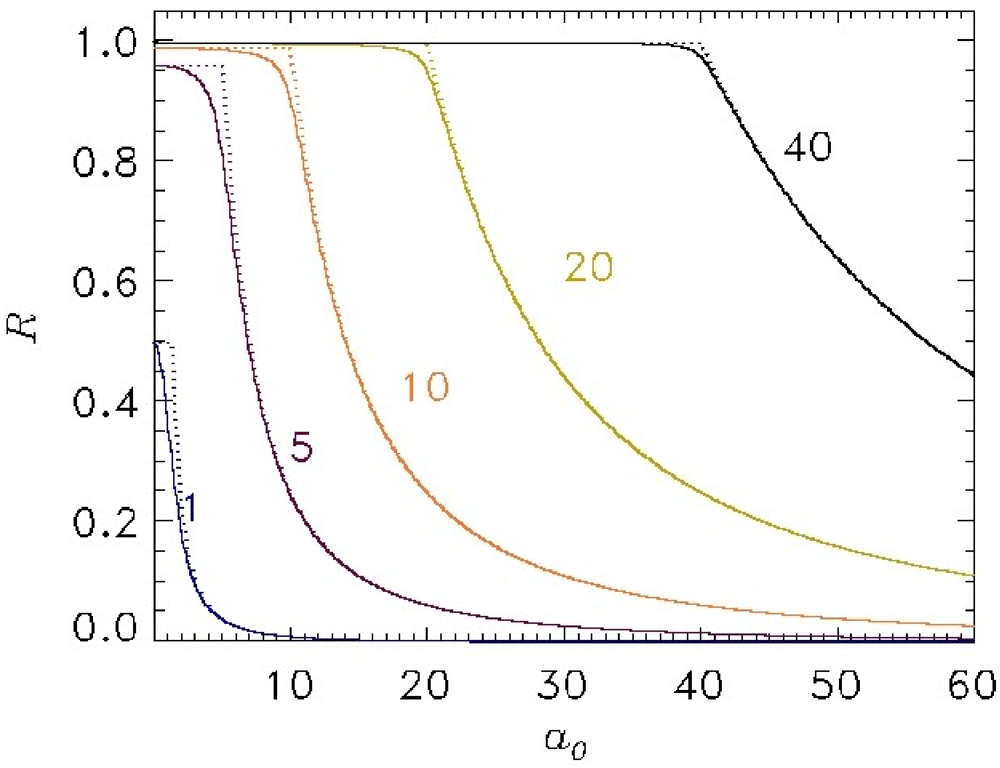


Nonlinear reflectivity accounts for optimal thickness

Ultrathin slab model: $n_e(x)=n_0 \ell \delta(x)$, foil thickness $\ell << \lambda$

Total radiation pressure in rest frame $P_{rad} = (2I/c)R$

Nonlinear reflectivity $R=R(\zeta,a_0)$ can be computed analytically



approximated (but rather precise) formula:

$$R \approx \zeta^2/(\zeta^2+1) \quad \text{for } a_0 < \zeta$$

$$R \approx \zeta^2/a_0^2 \quad \text{for } a_0 > \zeta$$

P_{rad} does not depend on a_0 for $a_0 > \zeta$! (since $I \sim a_0^2$)

The maximum boost of the foil is at $a_0 \approx \zeta$

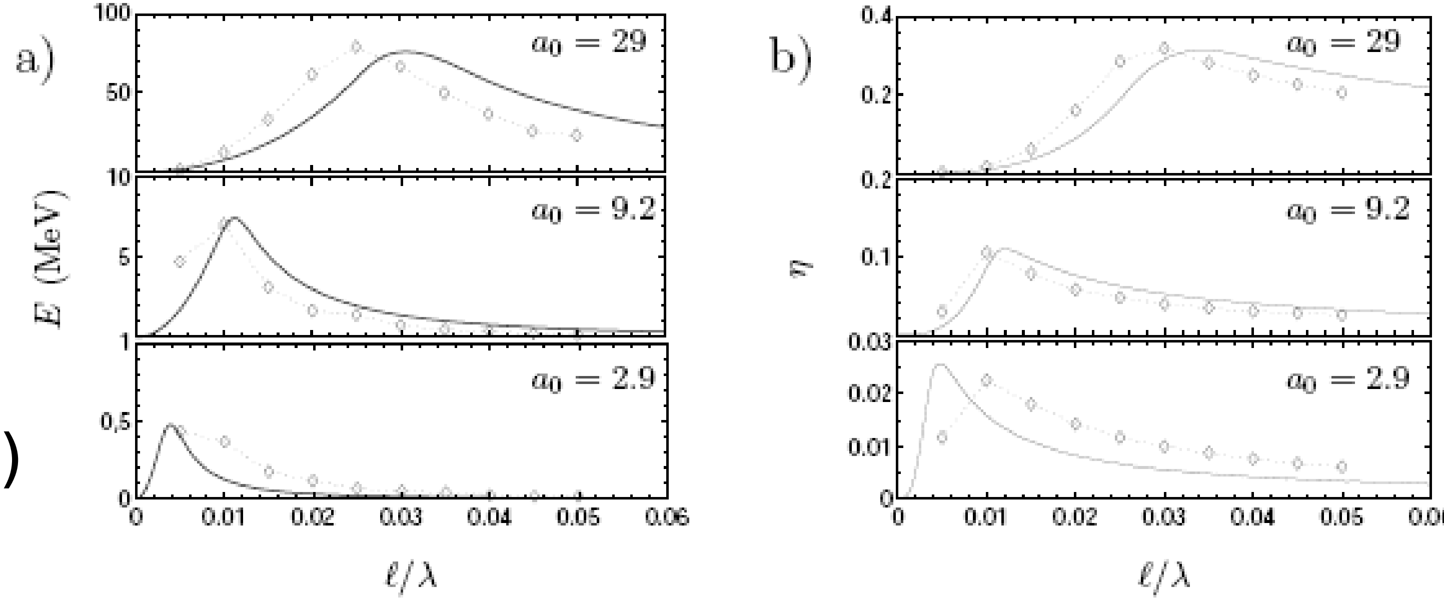
LS with self-induced transparency included

Modified energy formula for $R<1$, $a_0<\zeta$

$$\beta(t) = \frac{(1+\mathcal{E}-\zeta^{-2})^2 + (1+\mathcal{E}-\zeta^{-2})\sqrt{(1+\mathcal{E}-\zeta^{-2})^2+4\zeta^{-2}} + 2\zeta^{-2} - 2}{(1+\mathcal{E}-\zeta^{-2})^2 + (1+\mathcal{E}-\zeta^{-2})\sqrt{(1+\mathcal{E}-\zeta^{-2})^2+4\zeta^{-2}} + 2\zeta^{-2} + 2}$$

$$\mathcal{E} = \frac{2F(t)}{\rho \ell c^2} = 2\pi \frac{Z}{A}\frac{m_e}{m_p}\frac{a_0^2 \tau}{\zeta}$$

Ion energy and conversion efficiency vs. intensity and thickness (solid: theory, points: PIC sims.)



9 cycles pulse, $n_e=250n_c$

A.Macchi et al, New J. Phys. **12** (2010) in press

Balance of radiation and electrostatic pressures

For $a_0 < \zeta$ the maximum electrostatic pressure P_{es} (corresponding to complete electron depletion) exceeds the radiation pressure; electrons are held back (for circular polarization and quasi-equilibrium conditions!)

$$P_{rad} = (2I/c)R < P_{es} = 2\pi(en_0\ell)^2 \quad \text{for } a_0 < \zeta$$

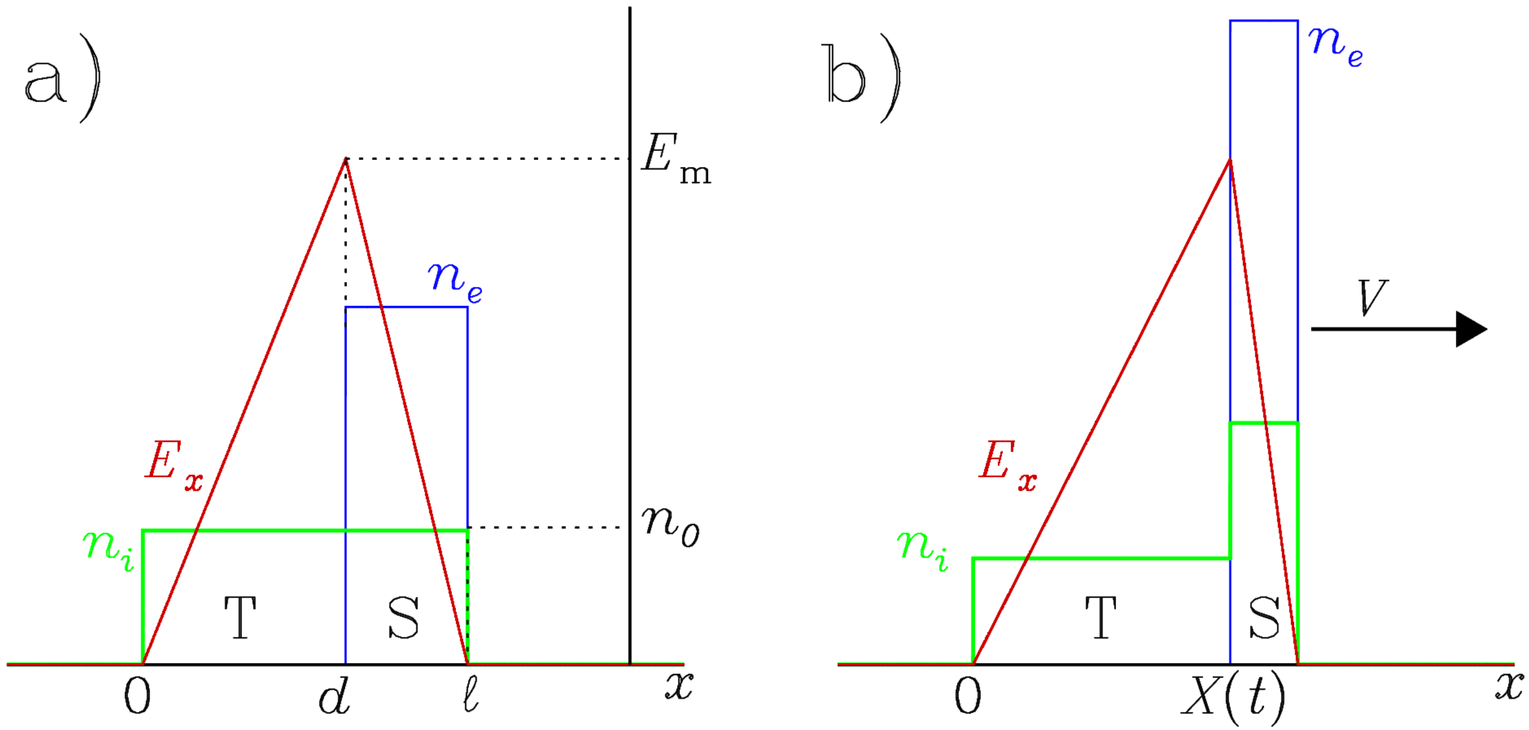
$$P_{rad} = P_{es} \quad \text{for } a_0 = \zeta$$

If $a_0 < \zeta$ and $\zeta >> 1$, $R \approx 1$ and no electrons are pushed away (the ponderomotive force at the rear surface is zero)

For $a_0 \rightarrow \zeta$ all the electrons must pile up near the rear surface in order to establish the equilibrium between P_{rad} and P_{es} .

→ the compression layer is much thinner than the foil
→ only a fraction of the foil is accelerated

Origin of two ion populations: "Tail" and "Sail"



Sail (S): ions are bunched accelerated by $E_x = f_p / e$ and move coherently as a "foil" : monoenergetic component

Tail (T): ions are accelerated by their own space-charge field and "Coulomb explode": broad spectrum component

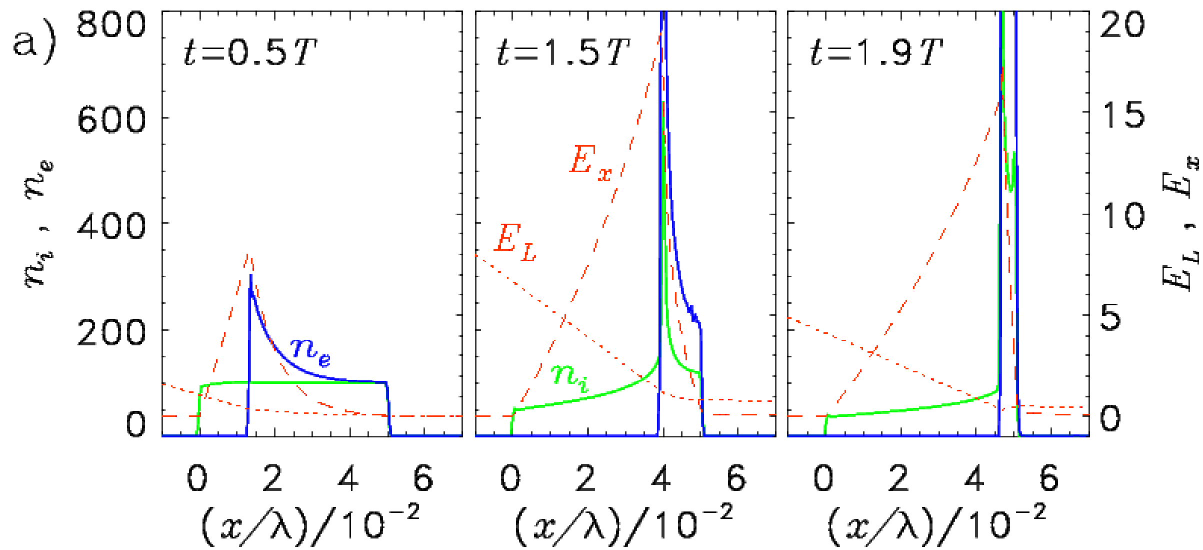
A.Macchi et al, New J. Phys. **12** (2010) in press

1D PIC simulations confirm model suggestions

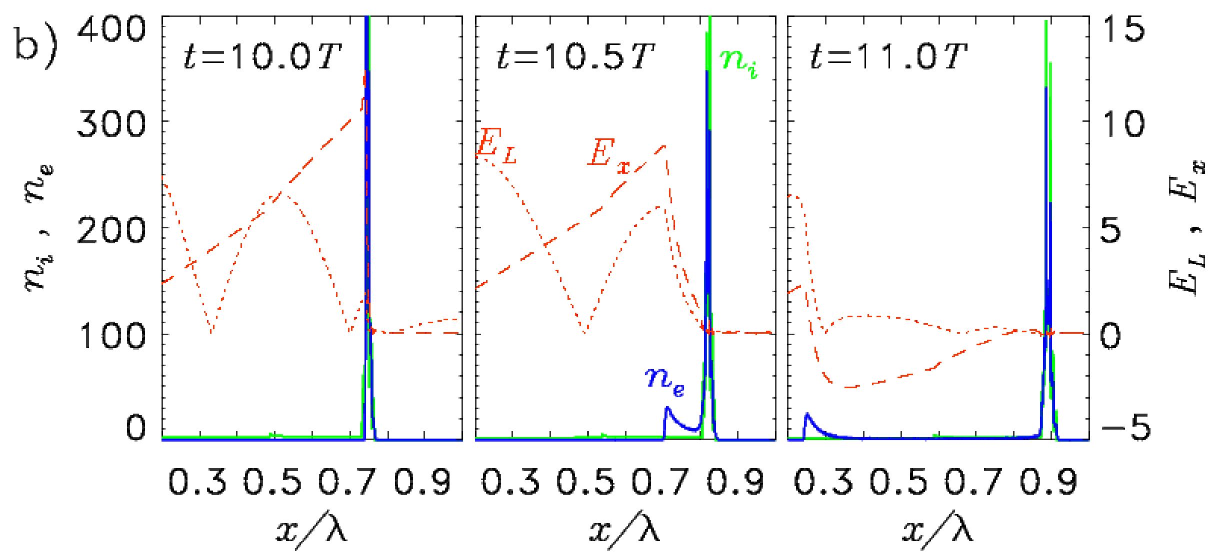
Laser pulse: a_0=30, τ=8 cycles ("flat-top" envelope)

Thin foil target: n_e=250n_c , ℓ=0.04λ , ζ=31.4,

The ions in the compression layer form a "sail" thinner than the original foil and negatively charged (excess of electrons)



The excess electrons "detach" from the sail near the end of the laser pulse, moving backwards and leaving a neutral bunch



Reduced pressure on ions balances missing inertia

Equilibrium between radiation and electrostatic pressure on *electrons*:

$$P_{\mathrm{rad}} \doteq \int (-e) n_e E_x dx = \int n_e f_p dx$$

Electrostatic pressure on *ions*:

$$P_{\mathrm{es}} = \int Zen_i E_x dx < P_{\mathrm{rad}} \qquad (Zn_i < n_e)$$

Calculation on equlibrium profiles yields:

$$P_{\mathrm{es}} = \frac{M_{\mathrm{Sail}}}{M_{\mathrm{Foil}}} P_{\mathrm{rad}}$$

Resulting equation of motion:

$$P_{\mathrm{es}} = \frac{d}{dt}(M_{\mathrm{Sail}}\mathbf{V}) \Longleftrightarrow P_{\mathrm{rad}} = \frac{d}{dt}(M_{\mathrm{Foil}}\mathbf{V})$$

$\rightarrow$ The Sail moves as if it had the total mass of the foil

Note: there is a mass flow from M_{tail} to M_{sail} to balance the decrease of P_{rad} with velocity in the Lab $(P_{\mathrm{rad}})^{\mathrm{L}}=(1-\beta)/(1+\beta)P_{\mathrm{rad}}$

A.Macchi et al., PRL **103** (2009) 085003; New J. Phys **12** (2010), in press

Energy balance

Efficiency (=total percentage of laser energy "absorbed" by the system) depends only on β

But the kinetic energy of the Sail is less than the total!

Energy stored in the electrostatic field E_x :

$$U_{es} = U_{es}(t) = \int_0^{X(t)} \frac{E_x^2(x,t)}{8\pi} dx$$

"Conversion efficiency" into electrostatic energy η_{es} :

$$\frac{dU_{es}}{dt} = \frac{1}{8\pi} E_x^2[X(t),t] \frac{dX}{dt} = \frac{1}{8\pi} E_0^2 \beta c$$

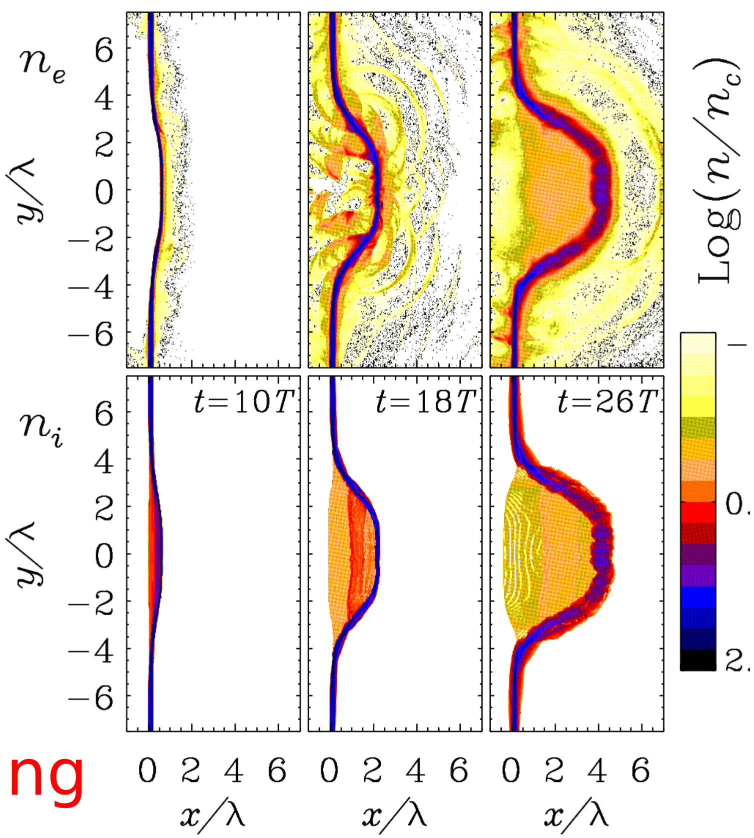
$$\eta_{es} = \frac{1}{I}\frac{dU_{es}}{dt} = 2\beta \left(\frac{d}{\ell}\right)^2 \left(\frac{\zeta}{a_0}\right)^2$$

For $a_0 = \zeta$, the depletion width $d \approx \ell$ thus $\eta_{es} \approx 2\beta$:
most of the stored energy is converted into electrostatic energy and eventually goes to Tail ions

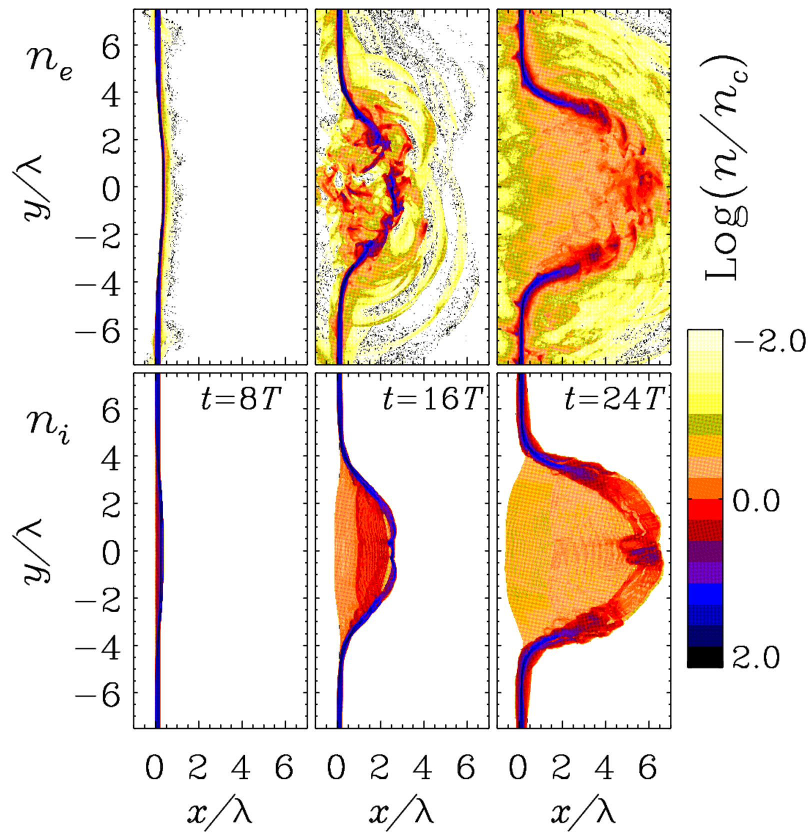
Two-dimensional simulations

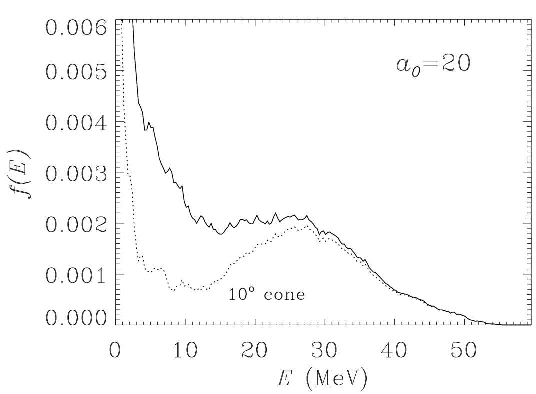
2D sims
for ζ=31.4
and two
different
amplitudes

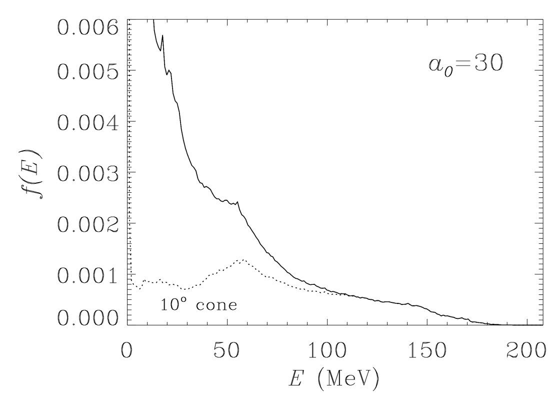
a_0 =20



a_0 =30







stronger electron heating and lower “penetration” threshold with respect to 1D: ion spectrum is broad

Other issues

At ultrahigh intensities, is RPA affected by
Radiation Friction effects?

N.Naumova et al, PRL **102** (2009) 025002;
T. Schelegel et al, Phys.Plasmas **16** (2009) 083103
M. Chen et al, arXiV:0909.5144

In particular what about the "Laser Piston" regime where, in addition, RPA should be dominant anyway (i.e. also for Linear Polarization)?

T.Esirkepov et al, PRL **92** (2004) 175003; **96** (2006) 105001

- See Poster by M. Tamburini