Solitary- versus Shock-Wave Acceleration in Laser-Plasma Interactions

Andrea Macchi

[1]National Institute of Optics, National Research Council (CNR/INO), Pisa, Italy

[2]Department of Physics "Enrico Fermi", University of Pisa, Italy

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Coworkers

Amritpal Singh Nindrayog[1,2,*], Andrea Sgattoni[3,2],
Tatyana V.Liseykina[4], Francesco Pegoraro[1,2]

[1]Dipartimento di Fisica "Enrico Fermi", Università di Pisa, Pisa, Italy
[2]CNR/INO, Pisa, Italy
[3]Dipartimento di Energia, Politecnico di Milano, Milan, Italy
[4]Institut fuer Physik, Universitaet Rostock, Germany

[*]See also Amrit's poster 33 on these topics for more results and discussion

The basic idea of Shock Acceleration - I

A superintense ($a_0 > 1$), linearly polarized laser pulse incident on an *overdense* plasma ($\omega < \omega_p$ i.e. $n_e > n_c = m_e\omega^2/4\pi e^2$)

- heats up electrons up to high temperatures
- pushes the laser-plasma surface at the "hole boring" velocity (non-relativistic for simplicity)

$$v_{\text{hb}} \simeq a_0 c \left(\frac{1+R}{2}\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}\right)^{1/2} \qquad a_0 = 0.85\left(\frac{I\lambda^2}{10^{18}\ \text{W cm}^{-2}}\right)^{1/2}$$

High temperature + strong piston $\Longrightarrow$ *Collisionless Shock Wave*

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The basic idea of Shock Acceleration - II

- Ion acceleration occurs in the plasma bulk by *reflection* from the shock front: $v_i = 2v_s$
- If $v_s \gtrsim v_{\rm hb}$ the reflected ions have high ($>$ MeV) energy
- Reflected ions are *monoenergetic* if v_s is constant
- Shock acceleration invoked to explain very narrow spectra observed by Haberberger et al [Nature Phys.**8**, 95 (2012)] in CO_2 laser interaction with overdense Hydrogen jet

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Conditions for Shock generation ?

- Piston velocity should exceed sound velocity:

$$v_{\text{pis}} \simeq v_{\text{hb}} \simeq a_0 c \left(\frac{Z n_c m_e}{A n_e m_p}\right)^{1/2} > c_s \simeq \left(\frac{Z T_e}{A m_p}\right)^{1/2}$$

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

$$\Longrightarrow a_0 > \frac{1}{\sqrt{2}} \frac{n_e}{n_c}$$

- Caveat: $a_0 \gg n_e/n_c$ may bring into self-induced transparency regime and reduce piston action

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Collisionless Shocks in textbooks

A Collisionless Electrostatic Shock (CES) of velocity v_s is preceded by “reflected” ions of velocity $v_i = 2v_s$

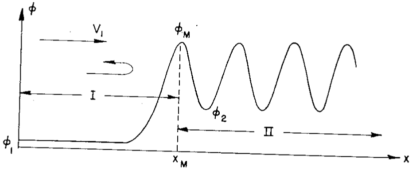

Fig. 6.2. An oscillatory electrostatic shock transition with some ions reflected from the leading pulse.

Tidman & Krall, *Shock Waves in Collisionless Plasmas* (Wiley, 1971), chap.6

necessary condition for ion reflection

$$e\Phi_{\mathrm{M}}(v_s) > m_i v_s^2/2$$

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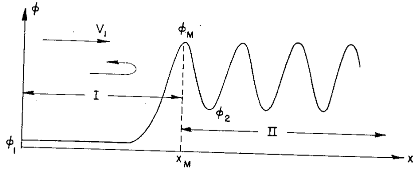

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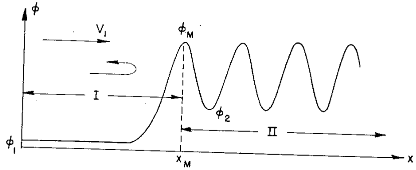

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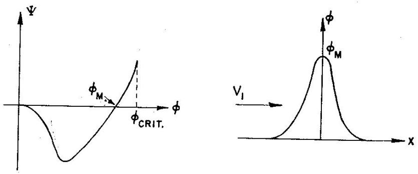

Fig. 6.1. Potential function $\Psi(\phi)$ for nonlinear ion-waves, and an example showing the variation $\phi(x)$ through an ion-wave soliton.

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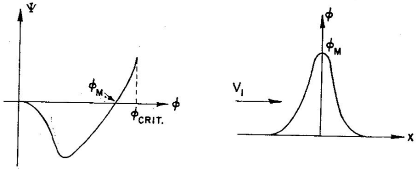

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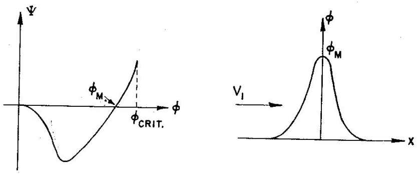

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Short-pulse driven "Solitary Acoustic Wave" (SAW)

1D PIC simulation: short ($\tau = 4T$), intense ($a_0 = 16$) laser pulse on an overdense ($n_e = 20n_c$), *cold* ($T_i = 0$) proton plasma slab

High resolution ($\Delta x = \lambda/200$, $N_p = 800$ part/cell)
to enforce accuracy and convergence of the results

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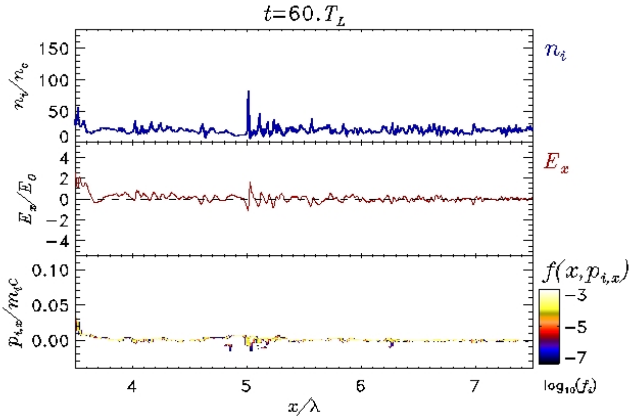

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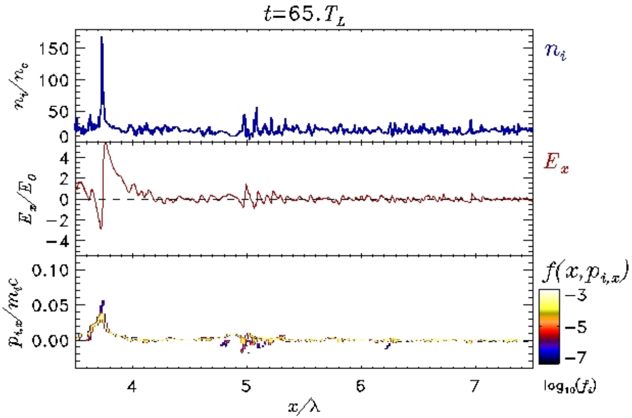

It looks like a soliton . . .

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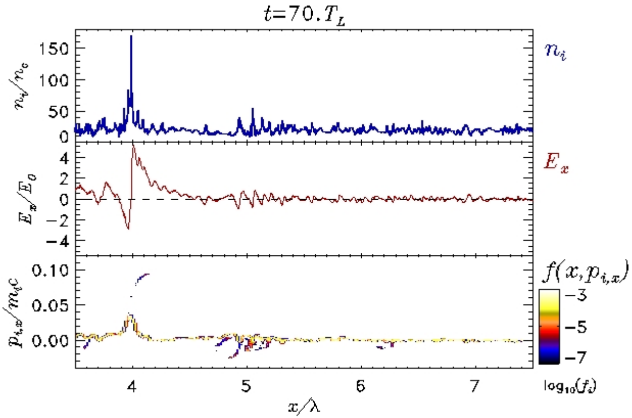

. . . but occasionally reflects a short bunch of ions!

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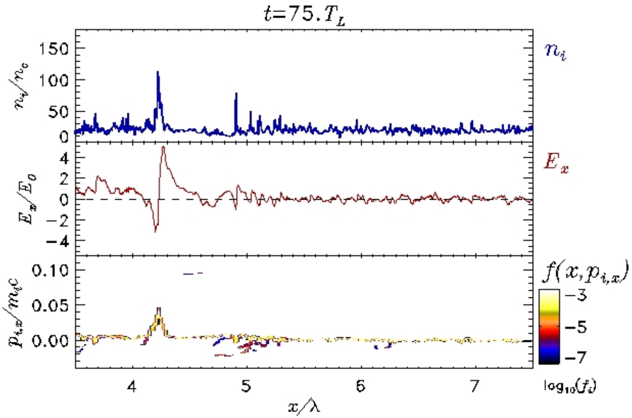

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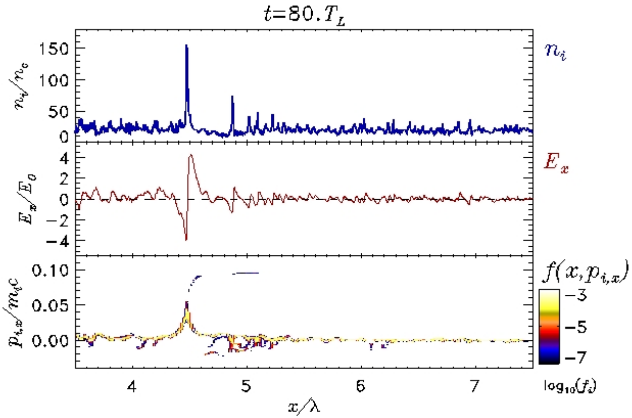

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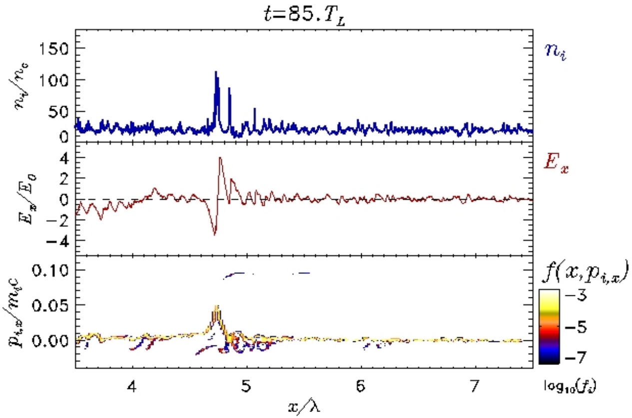
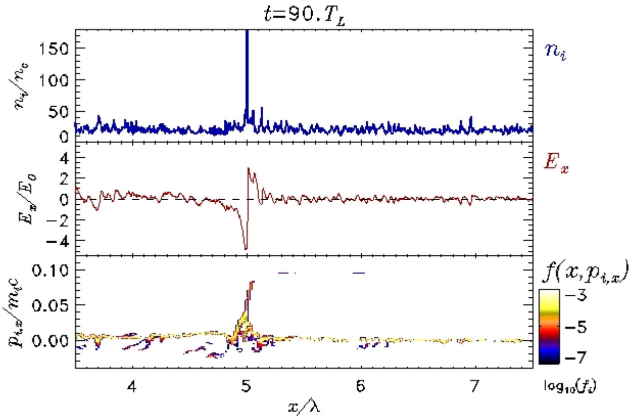


Acceleration is “pulsed”, solitary wave almost stays unchanged

Short-pulse driven “Solitary Acoustic Wave” (SAW)



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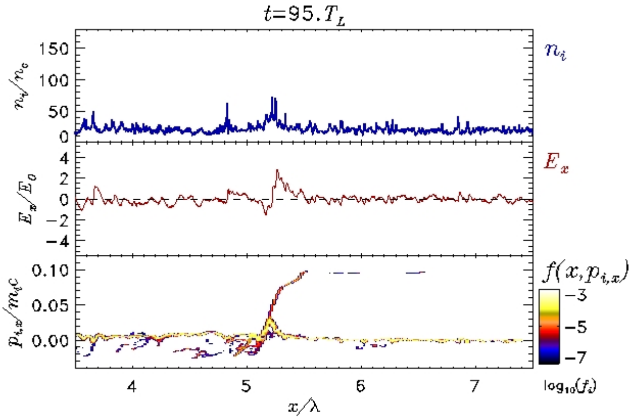

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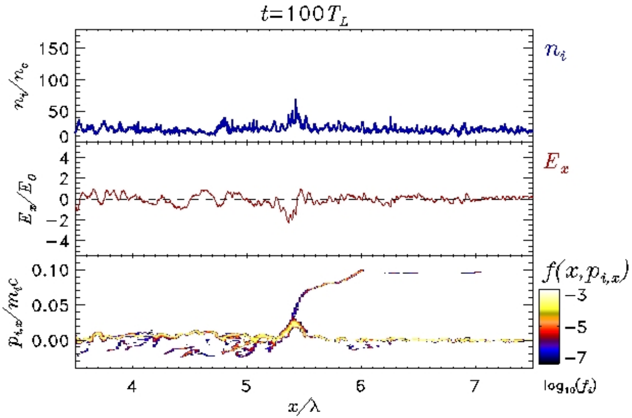

Eventually a long-lasting "shock-like" reflection occurs . . .

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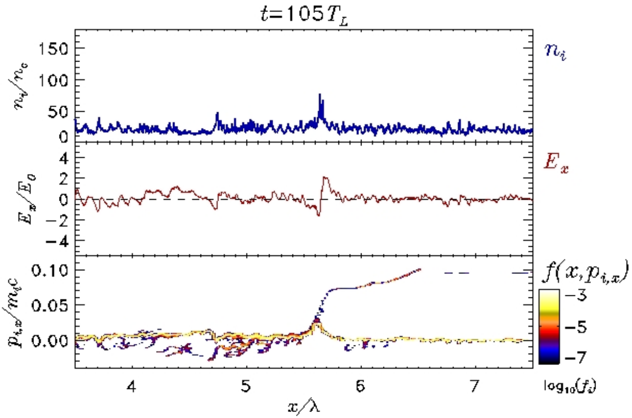

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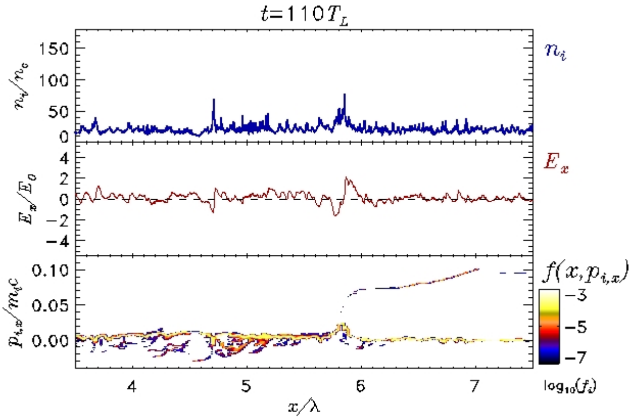


. . . and the solitary wave damps out

Evolution of ion spectrum

Peak: $\simeq 4.3$ MeV

$v_s \simeq 0.05c \Longrightarrow \frac{m_p}{2}v_s^2 = 4.7$ MeV

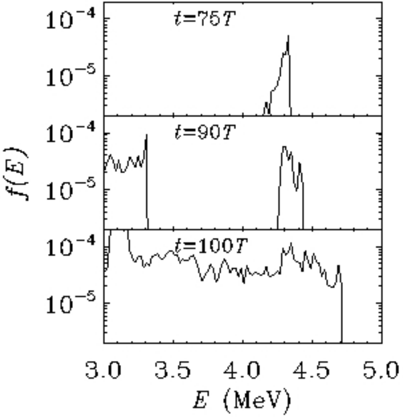
$v_{\text{hb}} \simeq 0.06c \quad (R \simeq 0.75)$

As the solitary wave damps

The “moving wall” slows down

$\Rightarrow$ broadening of

the monoenergetic peak



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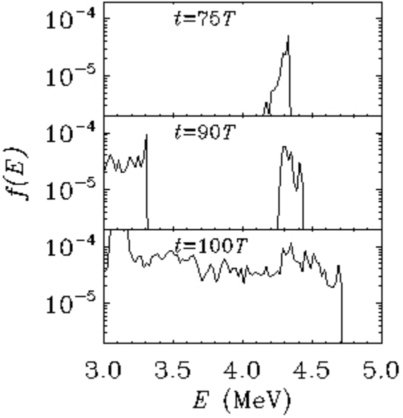


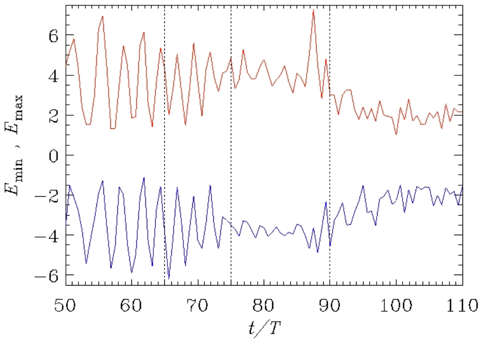
Solitary wave pulsations - I

Temporal oscillation of the electric field in the SAW

Dotted vertical lines: breaking and ion bunch acceleration events

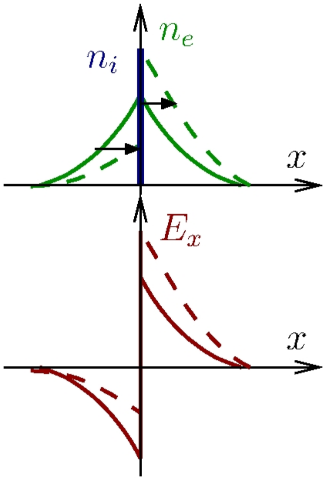
Φ_M exceeds threshold during the oscillation

max$(E_x) > 0$ min$(E_x) < 0$



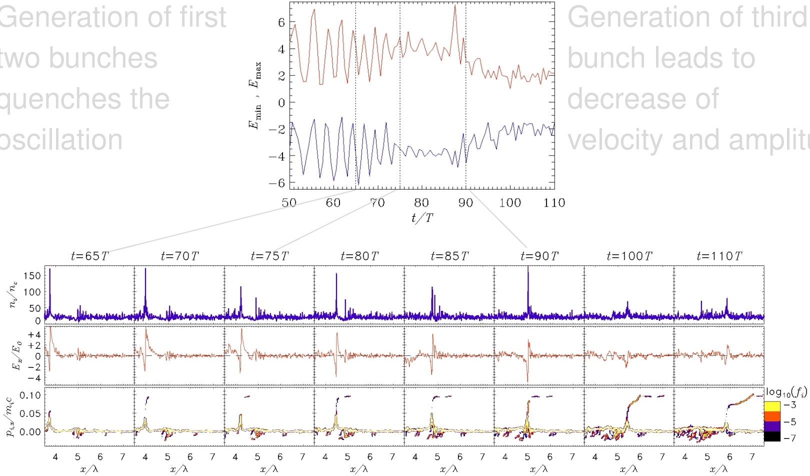
Solitary wave pulsations - II

Interpretation:
collective oscillation of the electron cloud around the ion density spike (consistent with $\Delta E_x = \max(E_x) - \min(E_x)$ remaining $\sim$ constant)



Solitary wave pulsations - III

Generation of first two bunches quenches the oscillation



Generation of third bunch leads to decrease of velocity and amplitude

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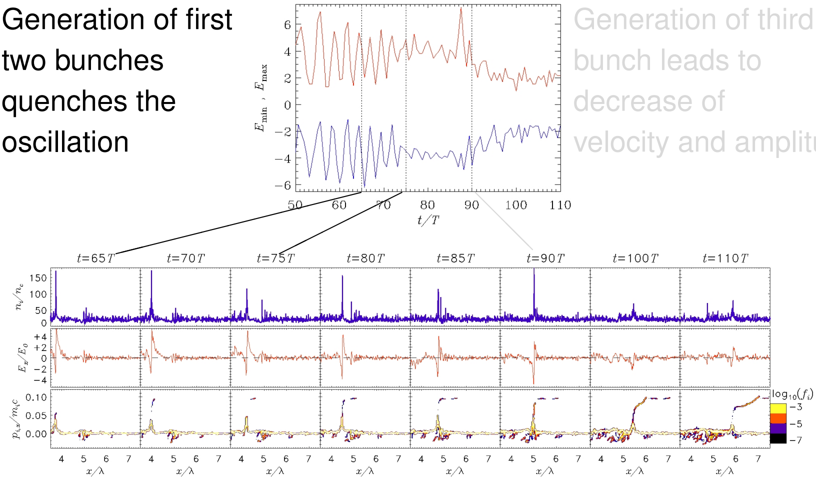

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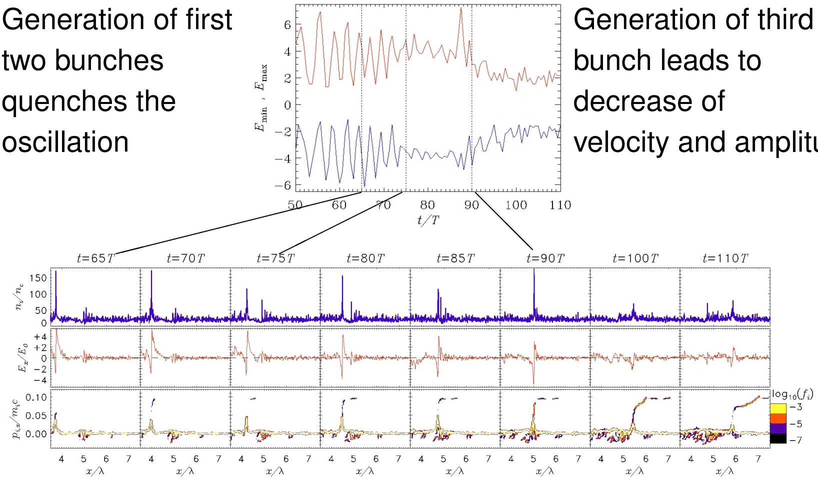


Generation of third bunch leads to decrease of velocity and amplitude

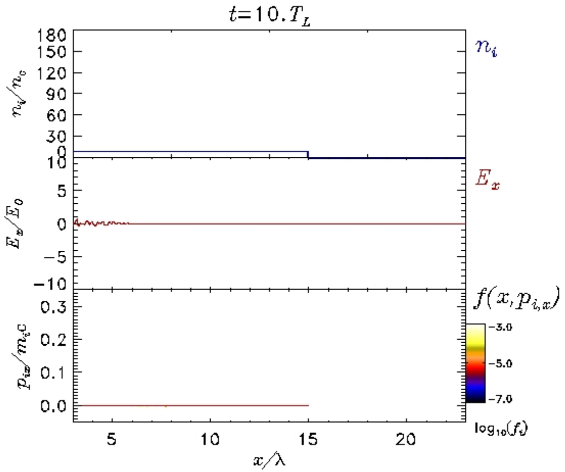
Long pulses: multipeak structures

1D PIC simulation: long ($\tau = 65T$), intense ($a_0 = 16$) laser pulse on an overdense ($n_e = 10n_c$), *cold* ($T_i = 0$) proton plasma slab

Same as preceding simulation, but *longer* pulse

Parameters very similar to Silva et al, PRL **92**, 015002 (2004)
Higher resolution reveal additional details in phase space

Long pulses: multipeak structures



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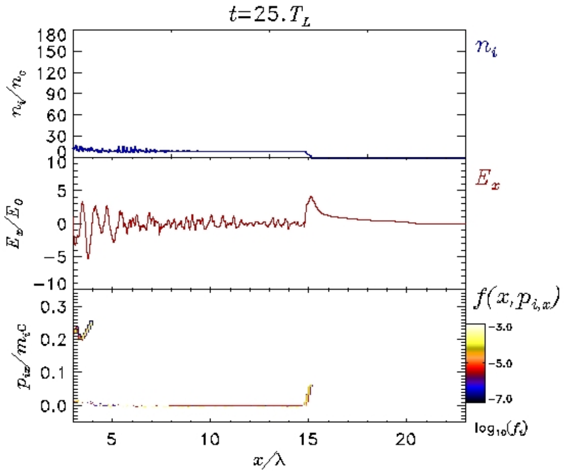

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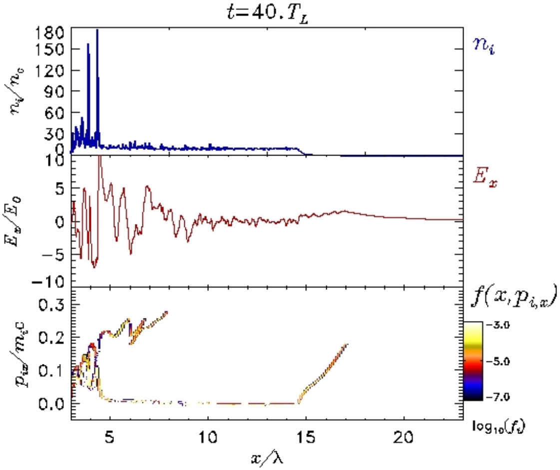

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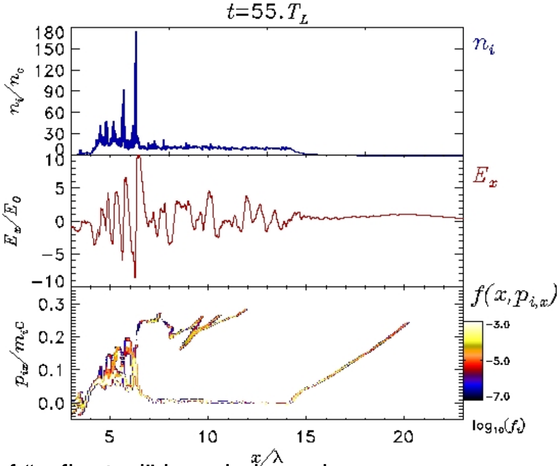
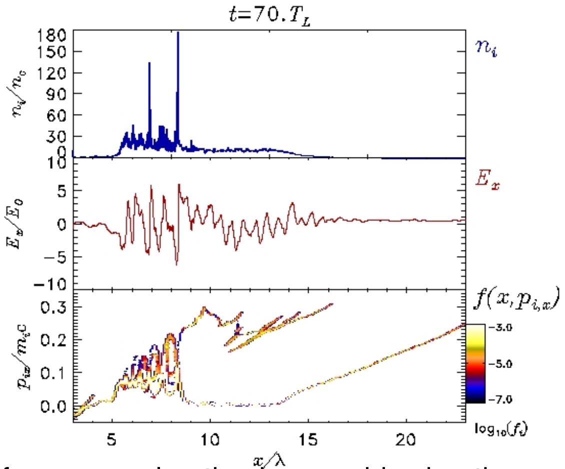


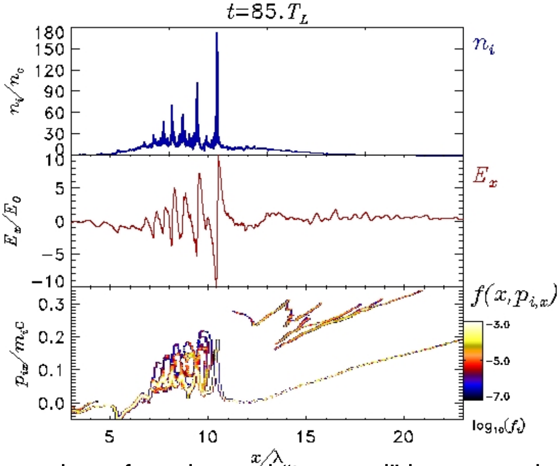
Spectrum of “reflected” ions is broad . . .

Long pulses: multipeak structures



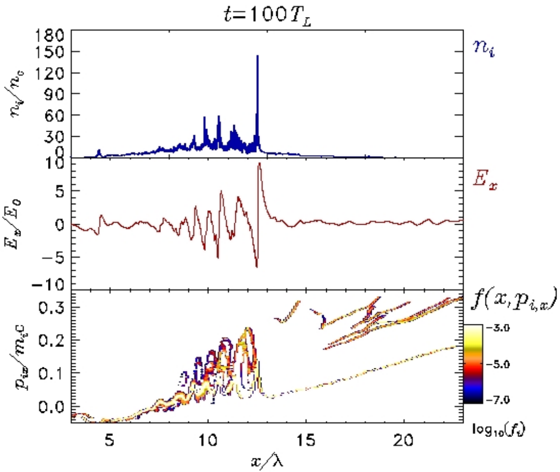
…even before re-acceleration in rear side sheath

Long pulses: multipeak structures



Velocity dispersion of peaks and “trapped” ions are observed

Long pulses: multipeak structures



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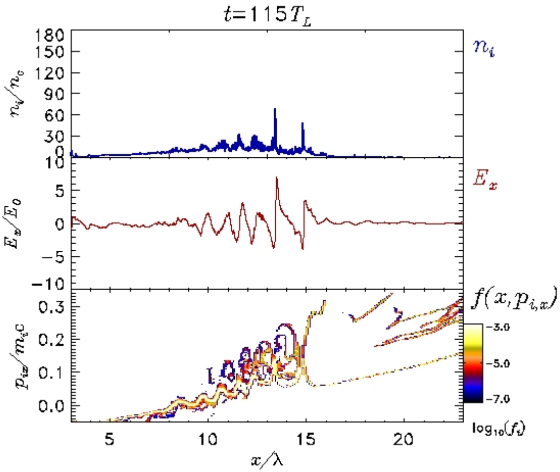

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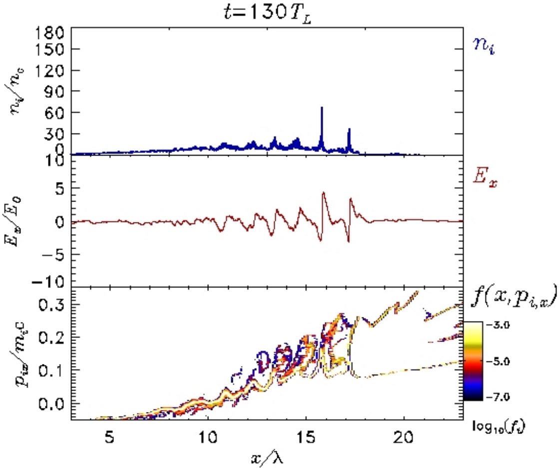
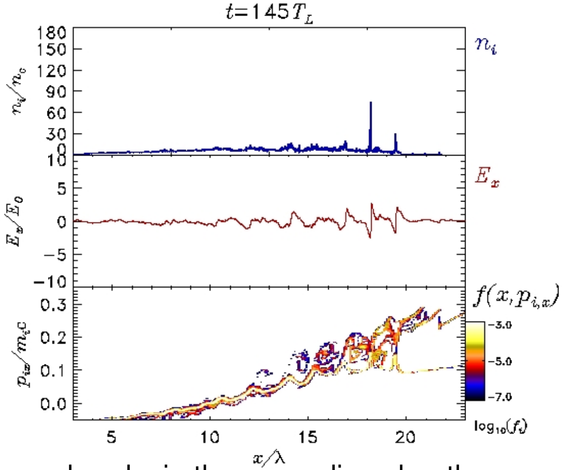
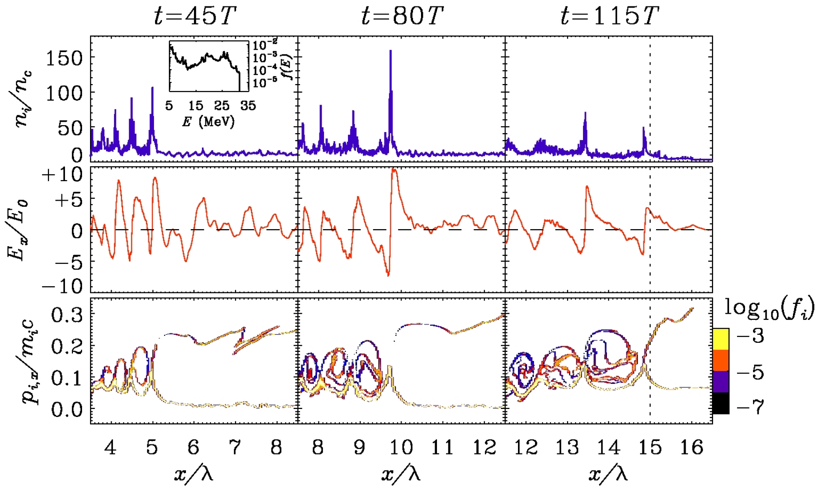


Long pulses: multipeak structures



Nonlinear wave breaks in the expanding sheath

Long pulses: multipeak structures



Effect of the initial ion distribution

- A "true" shock cannot form in a *cold ions*, quiescent plasma: all ions would be reflected by the front
  $\Rightarrow$ the wave quickly loses its energy and gets damped
- Solitary waves can be formed but seem not particularly stable ...
- In a *warm* ion plasma, ions in the tail of the distribution with $v_i > v_s - \sqrt{2e\Phi_{\mathrm{M}}/m_i}$ may be reflected
- If $T_i = m_i \langle v_i^2 \rangle /2$ is too high, too many ions are reflected
  $\Rightarrow$ the shock front slows down and monoenergeticity is lost again

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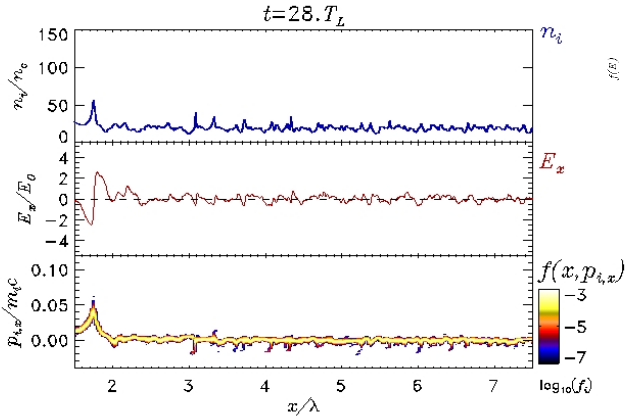
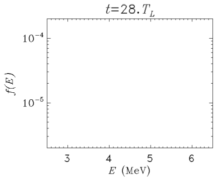
Warm ions: shock-like reflection

1D PIC simulation: short ($\tau = 4T$), intense ($a_0 = 16$) laser pulse on an overdense ($n_e = 20n_c$), *warm* ($T_i = 1$ keV) proton plasma slab

Same as "short pulse" simulation, but warm ions

Warm ions: shock-like reflection





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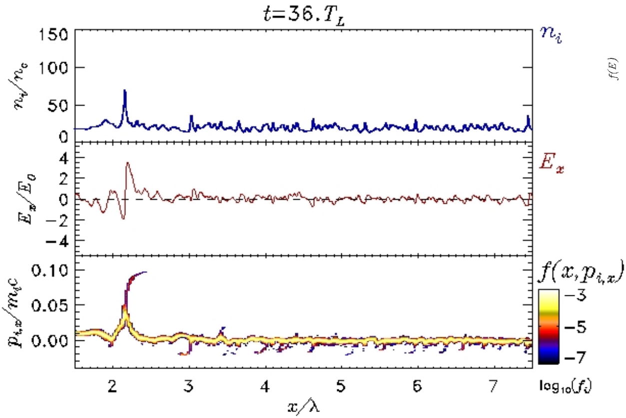

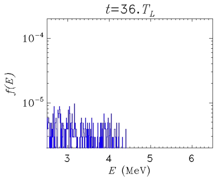

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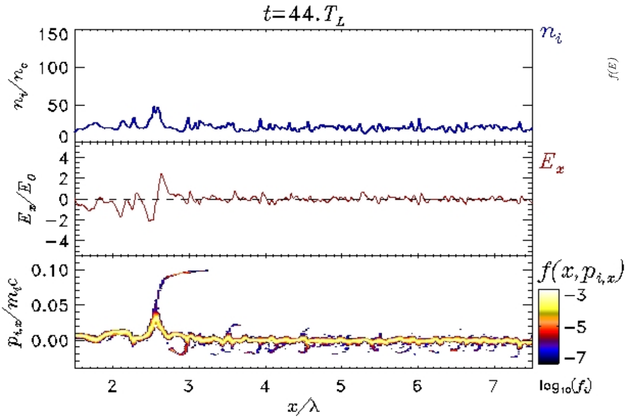

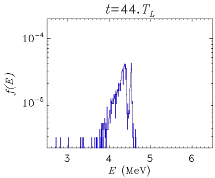

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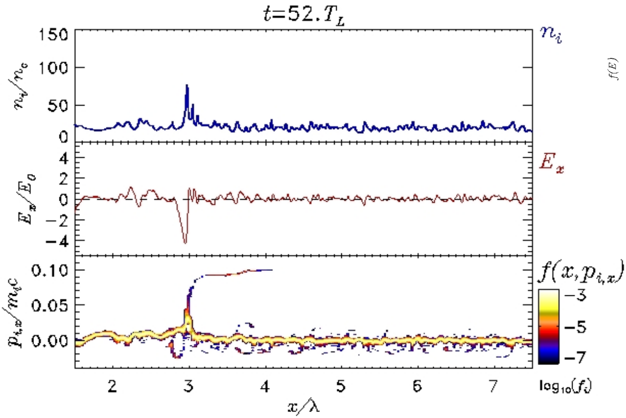
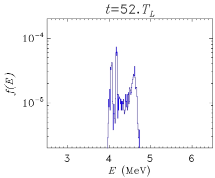
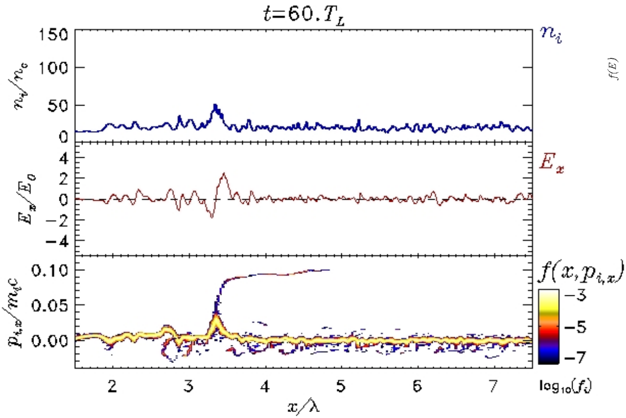
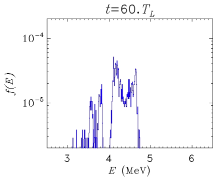




A steady reflection of quasi-monoenergetic ions is observed . . .

Warm ions: shock-like reflection





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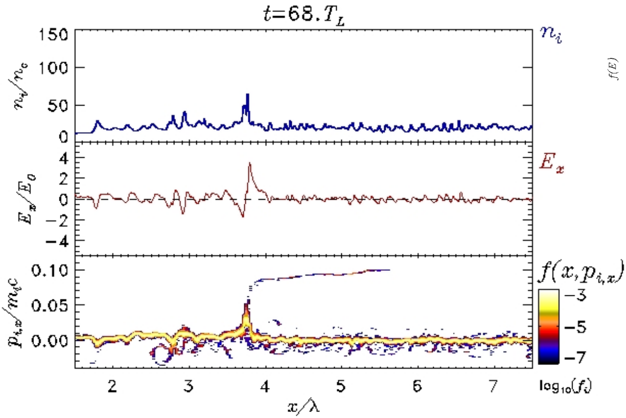

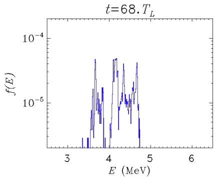

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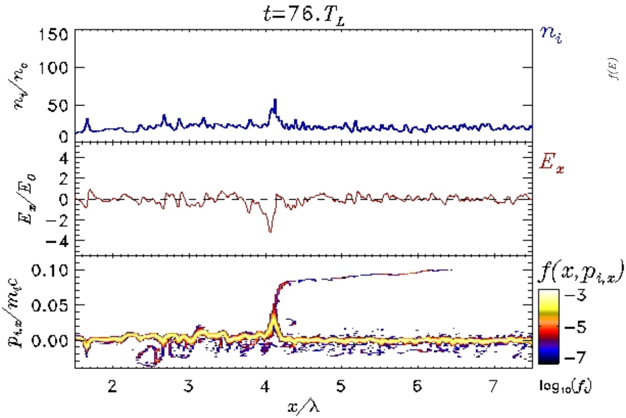

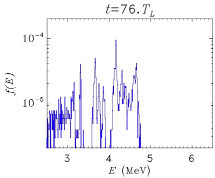

. . . but shock front slows down

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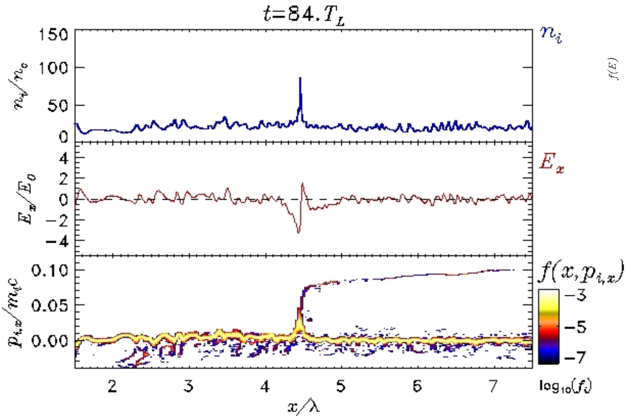

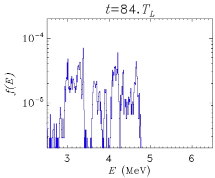

Energy spectrum shifts towards lower energies

Monoenergetic acceleration for warm ions -I

- In 1D finding a compromise between monoenergeticity and efficiency seems to be the point:
  - low numbers of reflected ions leave the shock velocity imperturbed and give a narrow spectrum
  - large numbers of reflected ions cause the shock front to slow down and give a broad spectrum
- we searched for an "optimal" value of T_i for given laser and plasma parameters (see poster for a survey of results)
- formation of monoenergetic spectra seem to be favored for moderate values of a_0 $(\sim 1-4)$

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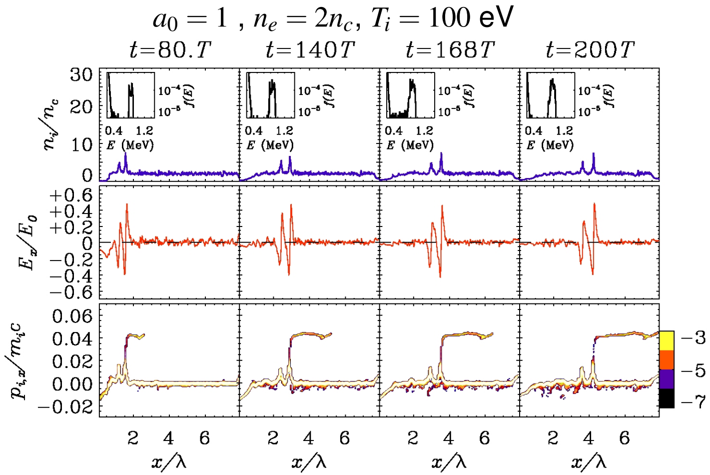
Monoenergetic acceleration for warm ions -II



Remarks on experiments - I

Haberberger et al
[Nature Phys. **8**, 95 (2012)]
observe very monoenergetic spectra
but with rather low number of ions

Is efficiency of shock acceleration
not compatible with
monoenergeticity?

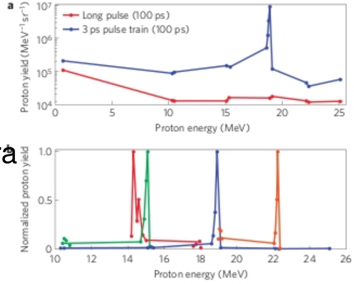


Figure 2 | Proton energy spectra. a, Proton spectra obtained with a 100-ps-long laser pulse (red) and a 100 ps macropulse consisting of a number of 3 ps micropulses (blue) both containing 60 J. The typical noise level on a single CR39 detector was 100 pits. The total number of protons contained within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

Remarks on experiments - II

Palmer et al
[PRL **106**, 14801 (2011)]
report on acceleration by a
"radiation pressure driven shock"
using *circular* polarization

But no "shock acceleration" in the bulk
is observed with circular polarization:
this may be described as "hole boring"
or "pure piston" acceleration
[Macchi et al, PRL **94**, 165003 (2005)]

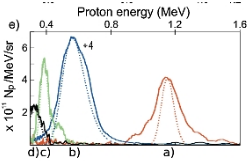
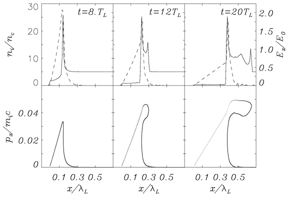


FIG. 1 (color online). Raw and processed proton spectra for varying peak density n and vacuum intensity I showing scaling of peak proton energy $E_{max} \propto I/nc$ [MeV]. Parameter I/n shown to the right of the respective raw images. Shots taken with (a) $I = 6.4$, $n = 6.1n_{cr}$, (b) $I = 5.5$,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

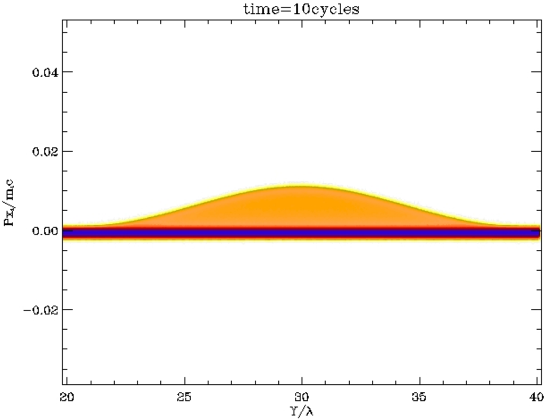


Two-dimensional simulations (preliminary)

2D PIC simulation: laser pulse $\tau = 45T$, $a_0 = 1$, $w = 5\lambda$
on an overdense ($n_e = 2n_c$), $T_i = 100$ eV) proton plasma slab

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

Two-dimensional simulations (preliminary)



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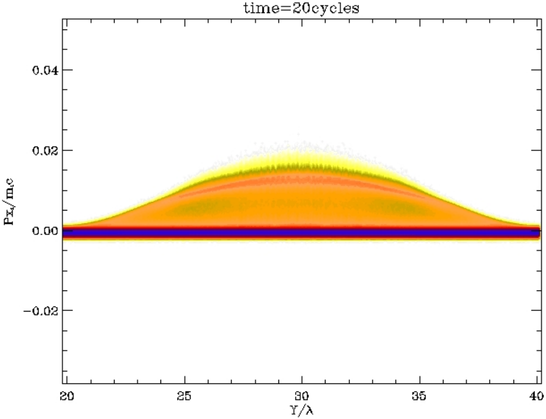

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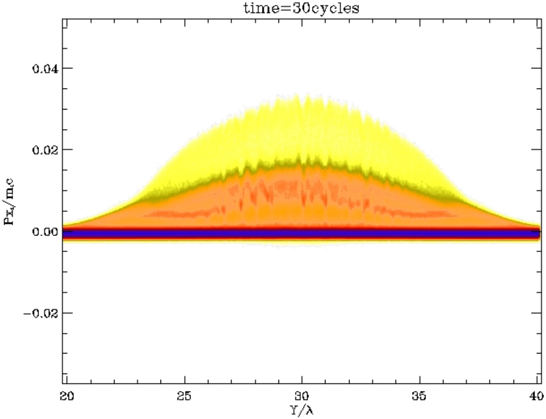

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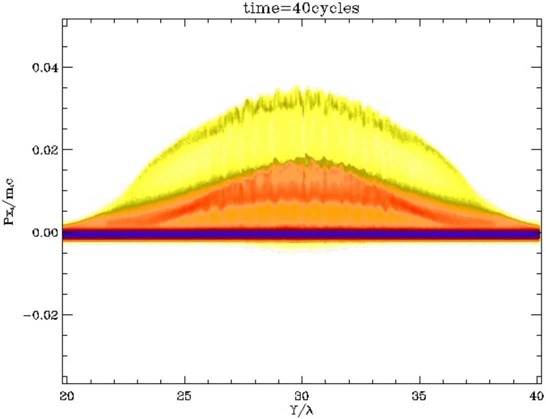

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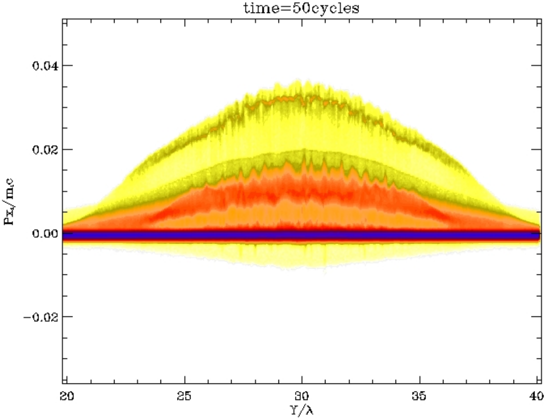
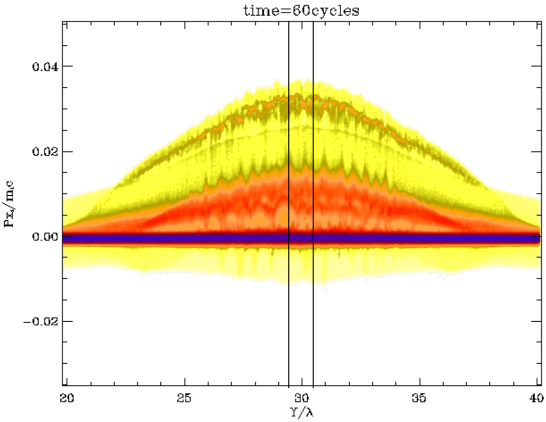


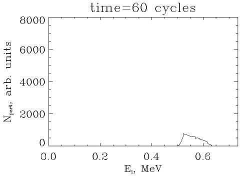
Development of transverse “ripples”

Two-dimensional simulations (preliminary)



Ion spectrum near axis

$29.4\lambda < y < 30.6\lambda$



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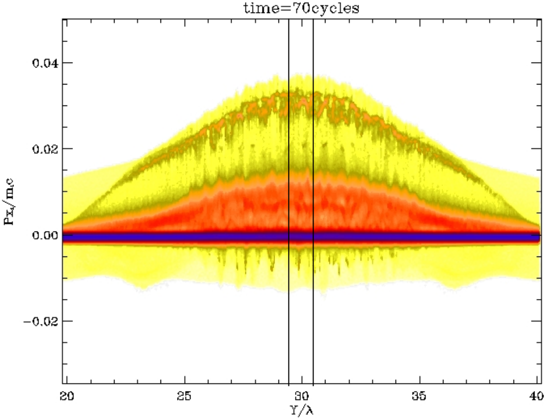

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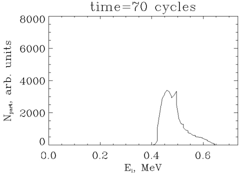

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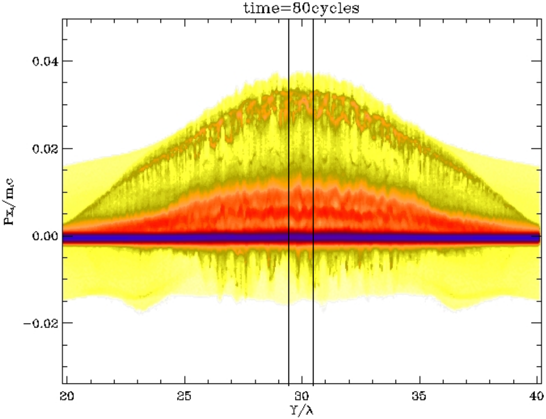

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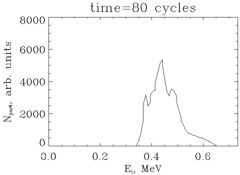

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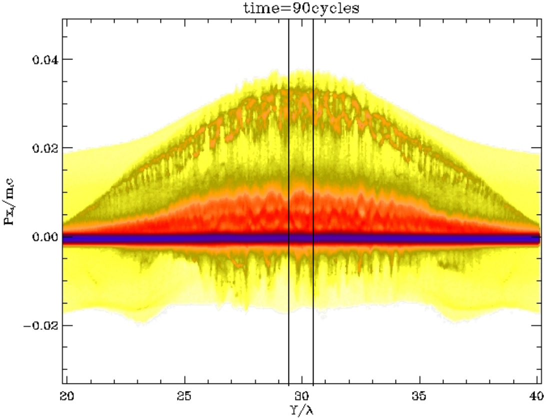

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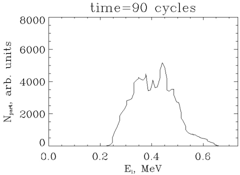

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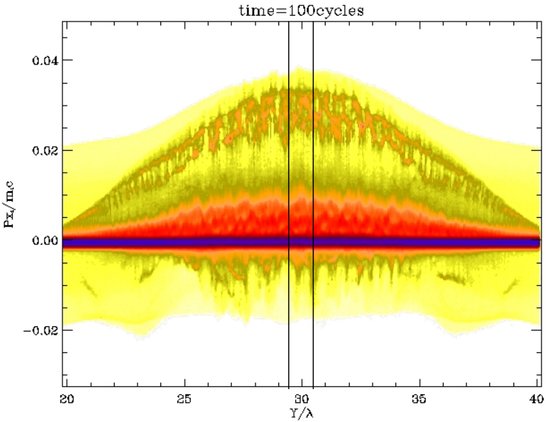

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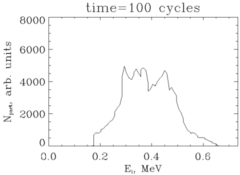

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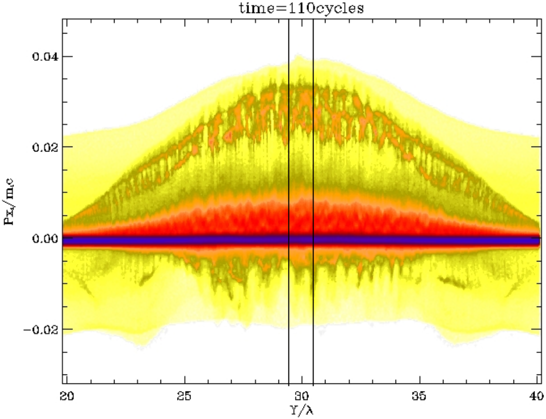

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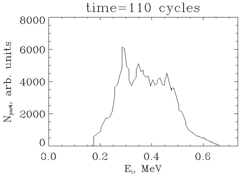

Reflected ions spectrum is much broader than in 1D

Open issues and work in progress . . .

- What causes the different evolution of the shock front and related acceleration in 2D vs 1D?
  - rippling of the shock front? (transverse electrostatic oscillations? Richtmyer-Meshkov-like instabilities? ... ?)
  - Insufficient numerical resolution? (In 1D the results failed to converge for $N_p < 100$ particles/cell)
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Conclusions

- "Shock acceleration" seems to be rather more complex than "reflection from a moving wall"
- Two possible regimes of monoenergetic acceleration found in 1D simulations:
  - short bunch generation by solitary wave "pulsation" (not easy to control)
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Reference and Acknowledgment

- A. Macchi, A. Singh Nindrayog, F. Pegoraro,
  Solitary versus Shock Wave Acceleration in Laser-Plasma Interactions,
  Phys. Rev. E **85**, 046402 (2012)
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  – see talk by Matteo Passoni