Ion Acceleration by Circularly Polarized Pulses

Physics and Possible Applications

Andrea Macchi

www.df.unipi.it/∼macchi

polyLAB, CNR-INFM, University of Pisa, Italy

Coworkers

Federica Cattani[1], Fulvio Cornolti, Tatiana V. Liseykina[2]

Department of Physics, University of Pisa, Italy

[1]) Now at Chalmers University of Technology, Gothenburg, Sweden

[2]) Permanent address: Institute for Computational Technologies, Novosibirsk, Russia

Outlook

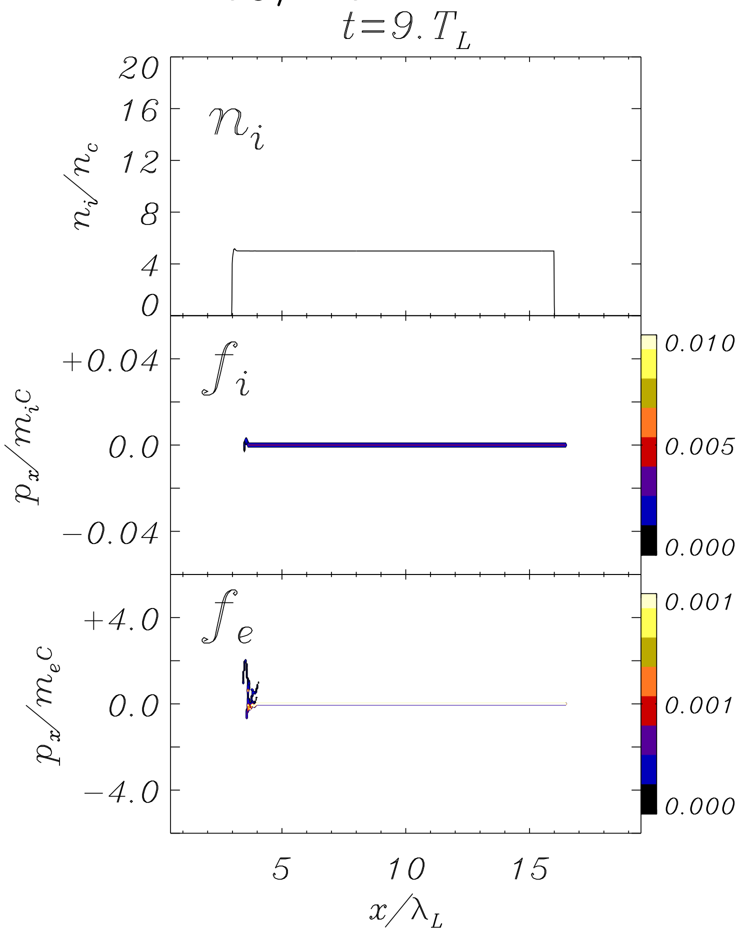
- (Ultra-)Short review of ion acceleration
- Acceleration with circularly polarized pulses: ion "bunches"
  - Simulations
  - Analytical modeling
  - Characteristics of ion bunches
- An application: ultrashort neutron sources
  - Concept
  - Simulations
  - A sub-fs source of fusion neutrons?

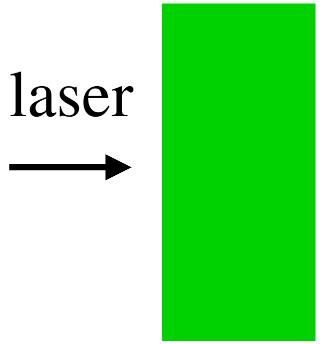
Ion acceleration: rear vs. front side

- There is now direct evidence of rear side acceleration (RSA) by sheath electric fields generated by fast electrons expanding in vacuum:
  L. Romagnani et al., PRL **95**, 195001 (2005)
- There are also experimental indications of front side acceleration (FSA) by possibly more than one mechanism:
  - acceleration by (collisionless) shock fronts:
    Habara et al, PRE **70**, 046414 (2004);
    Wei et al, PRL **93**, 155003 (2004)
  - "skin-layer ponderomotive acceleration":
    Badziak et al, PPCF **46**, B541 (2004)
- What is the role of fast electrons in FSA?

A simulation example

1D PIC simulation, “long” pulse,
normal incidence, linear polarization,
$a = 2.0$, $n_{e0}/n_c = 5$.





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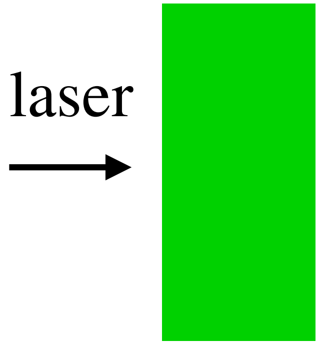

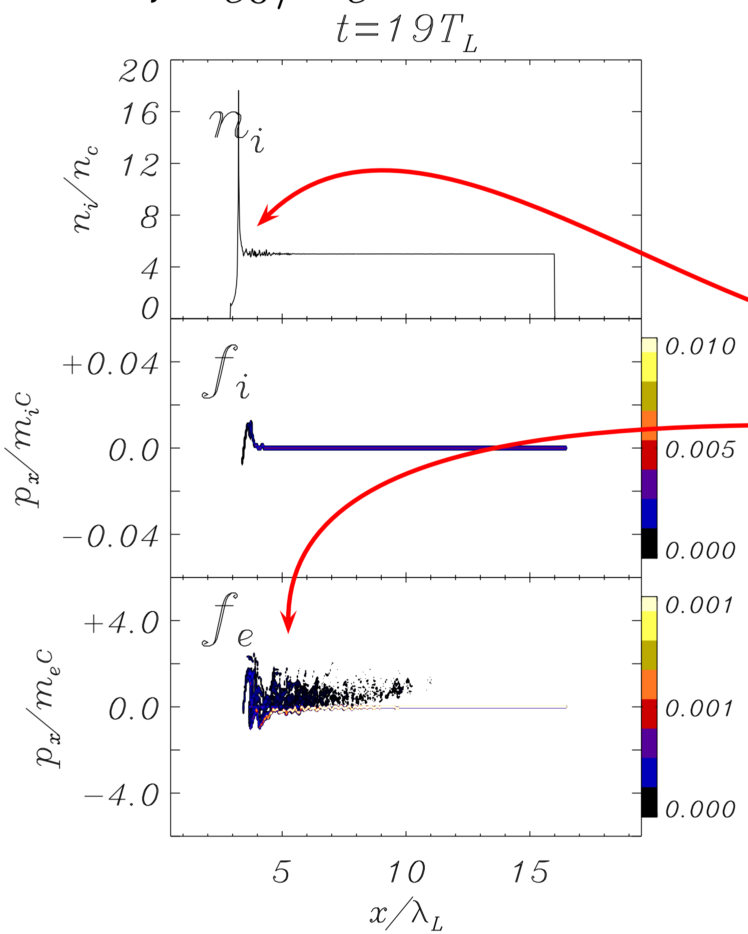

- Interaction starts
- generation of ion spikes + fast electrons

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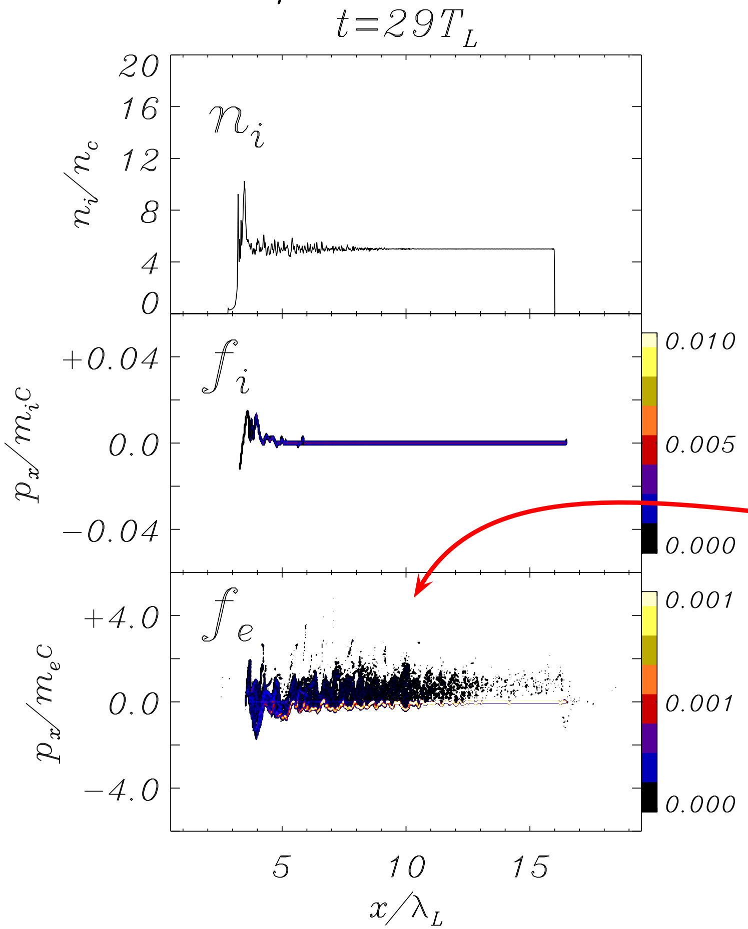

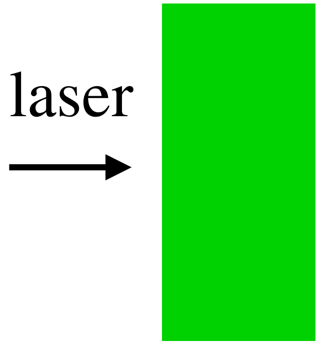

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- target heating to ~MeV

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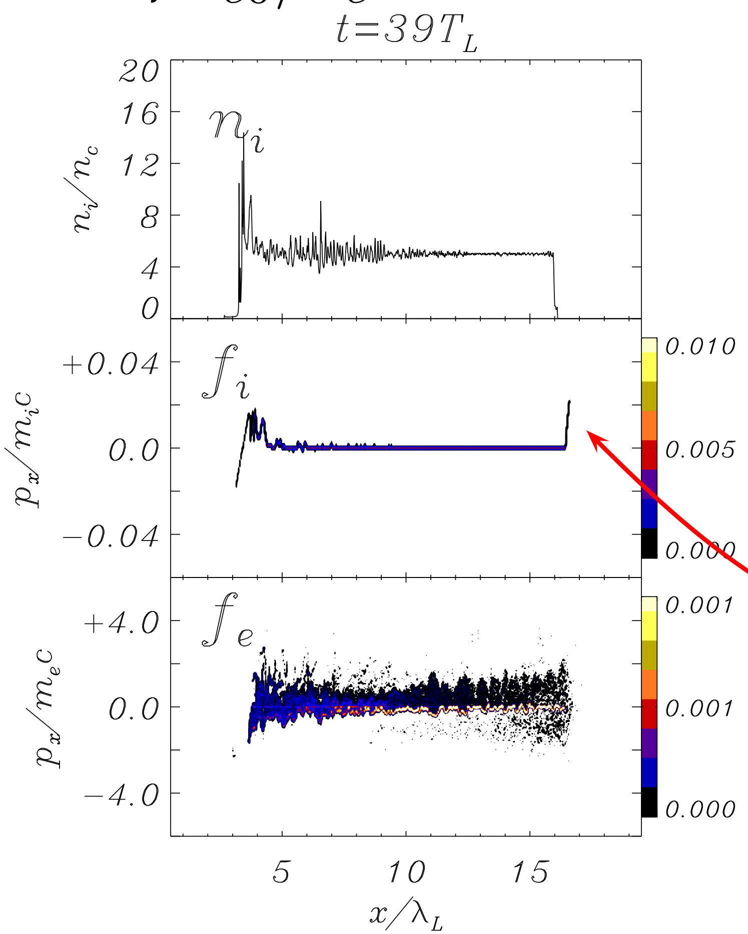

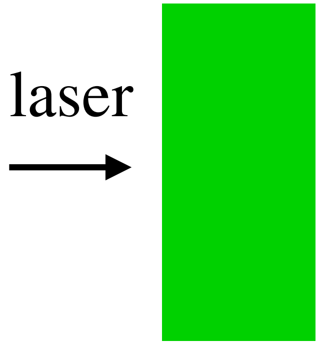

- Interaction starts
- generation of ion spikes + fast electrons
- target heating to ∼MeV
- RSA starts

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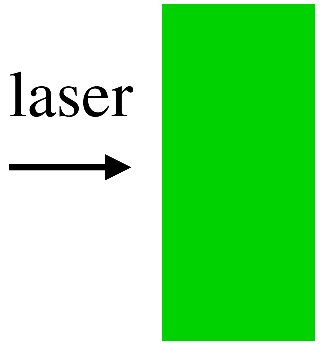

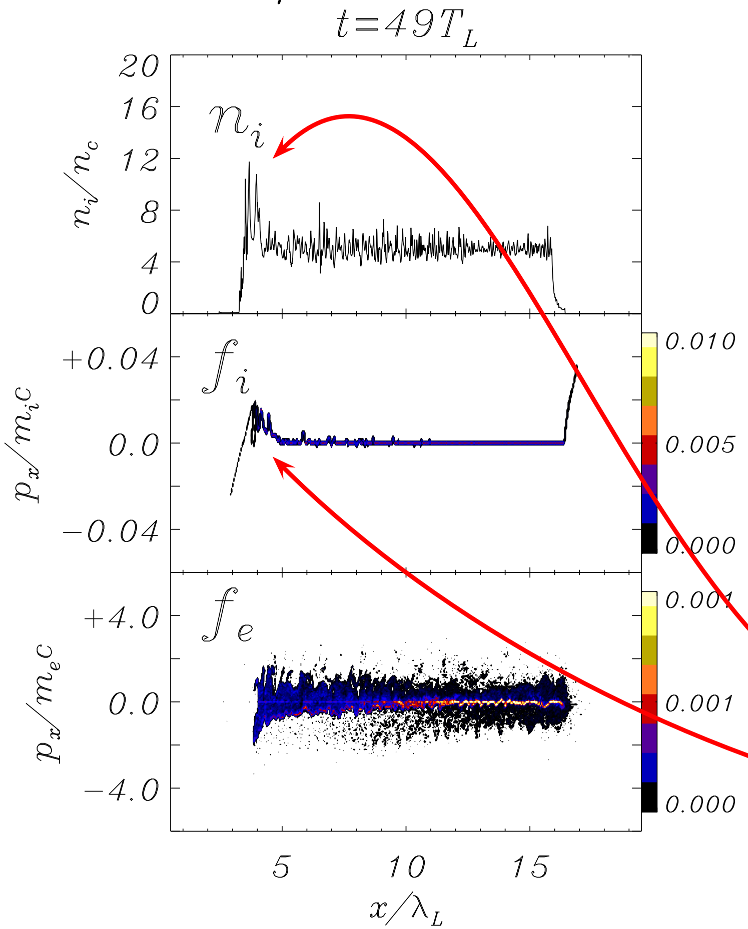

- Interaction starts
- generation of ion spikes + fast electrons
- target heating to $\sim$MeV
- RSA starts
- multiple ion spikes, FSA

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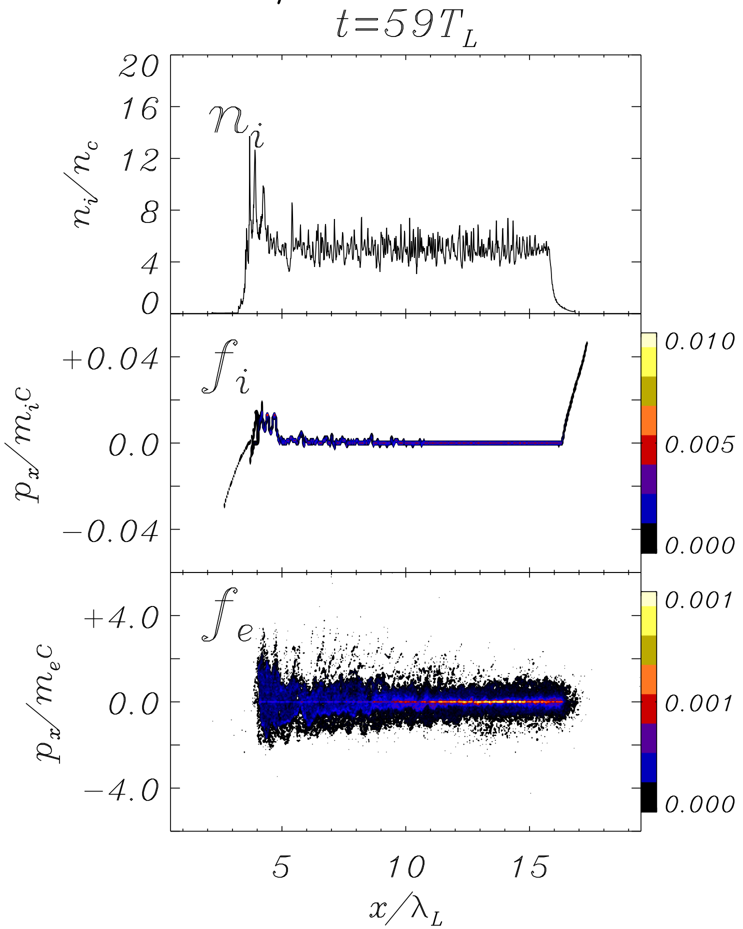
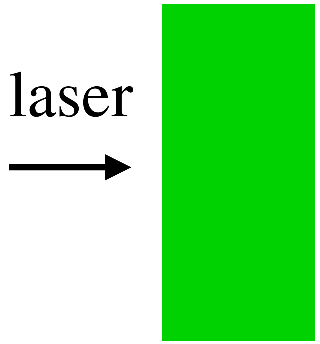
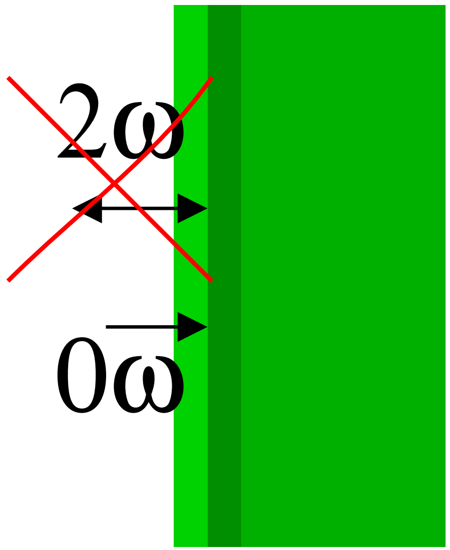




- Interaction starts
- generation of ion spikes + fast electrons
- target heating to ∼MeV
- RSA starts
- multiple ion spikes, FSA
- RSA & FSA coexist

Switch fast electrons off

- Fast electron generation at a steep laser-plasma interface requires an oscillating force across the boundary.
- For normal incidence, it is the $2\omega_L$ component of the $\mathbf{v} \times \mathbf{B}$ force.
- For circular polarization, the $2\omega_L$ component vanishes; only the secular component remains (radiation pressure).
- Does ion acceleration occur for circular polarization, and how does it look like?



Ion bunches

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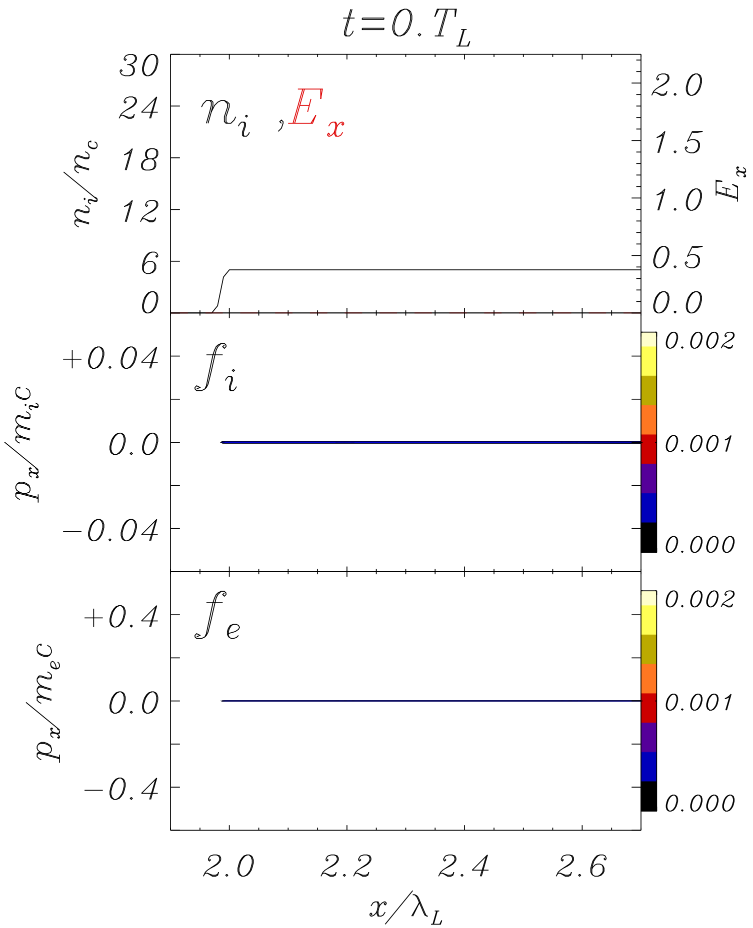

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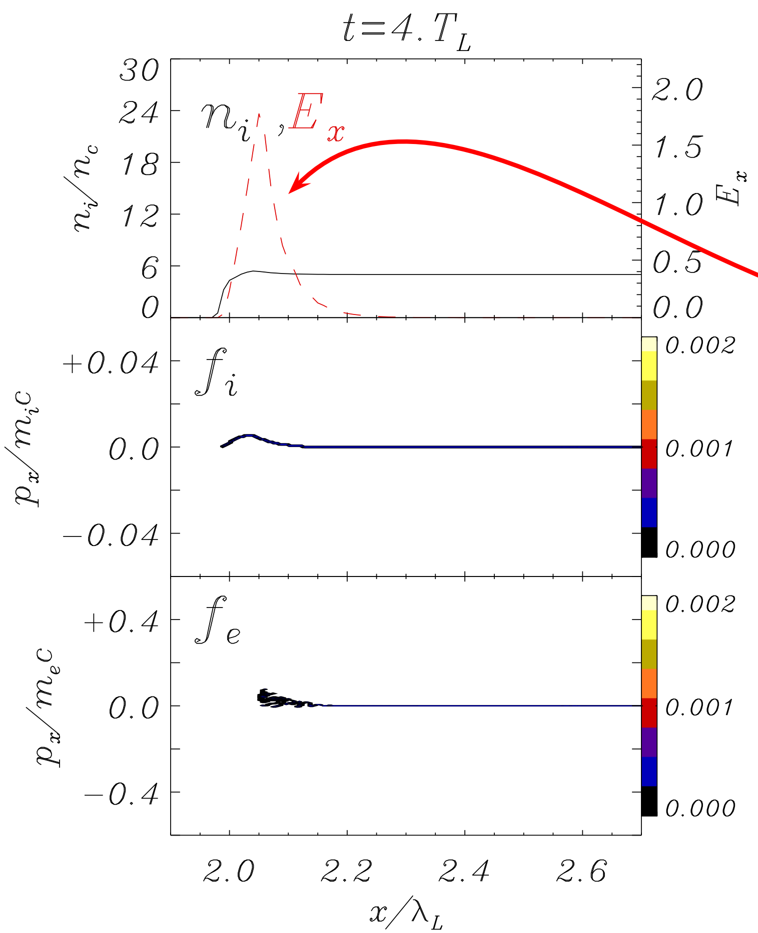

- interaction starts
- electrostatic field created

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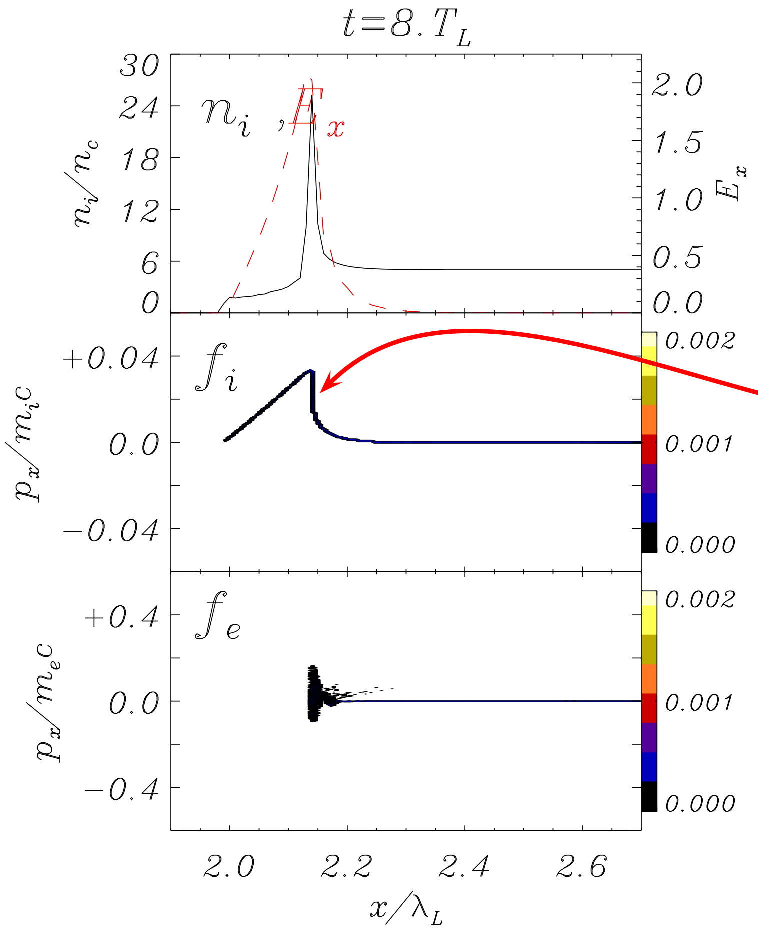

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- ion profile driven to “breaking”

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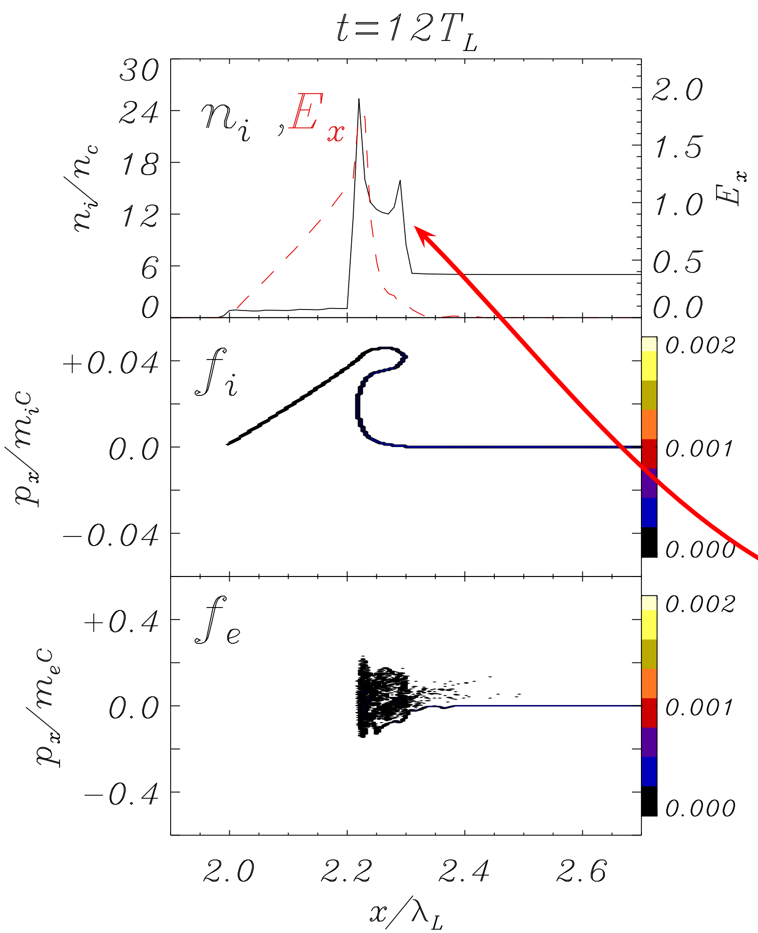

- interaction starts
- electrostatic field created
- ion profile driven to “breaking”
- ion “bunch” appears

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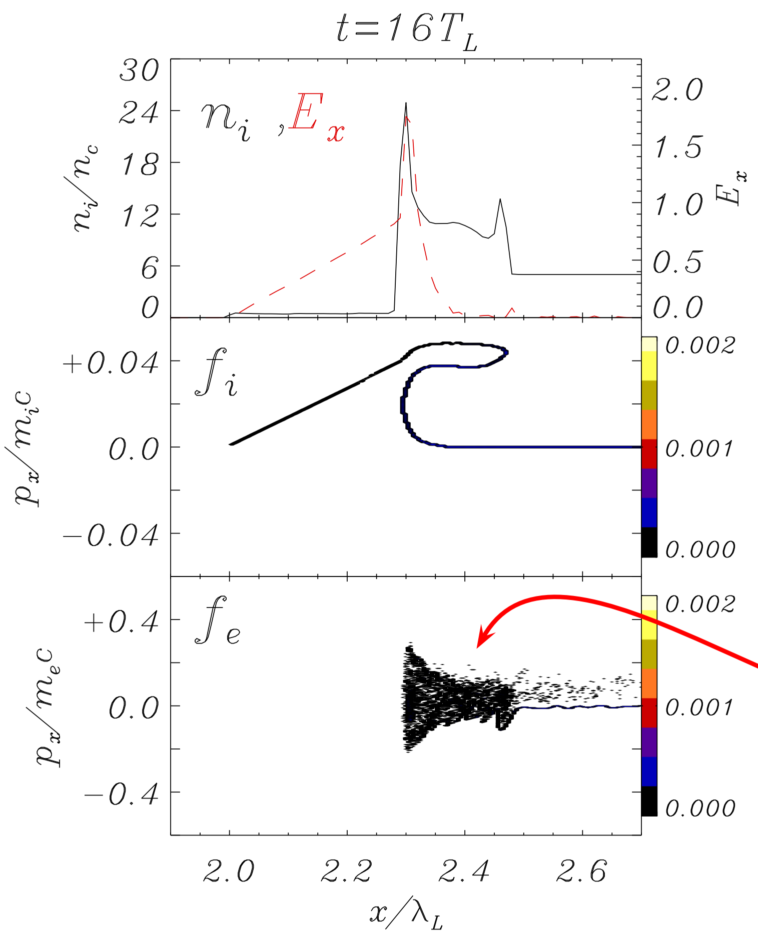

- interaction starts
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- electron energy $\sim$ keV

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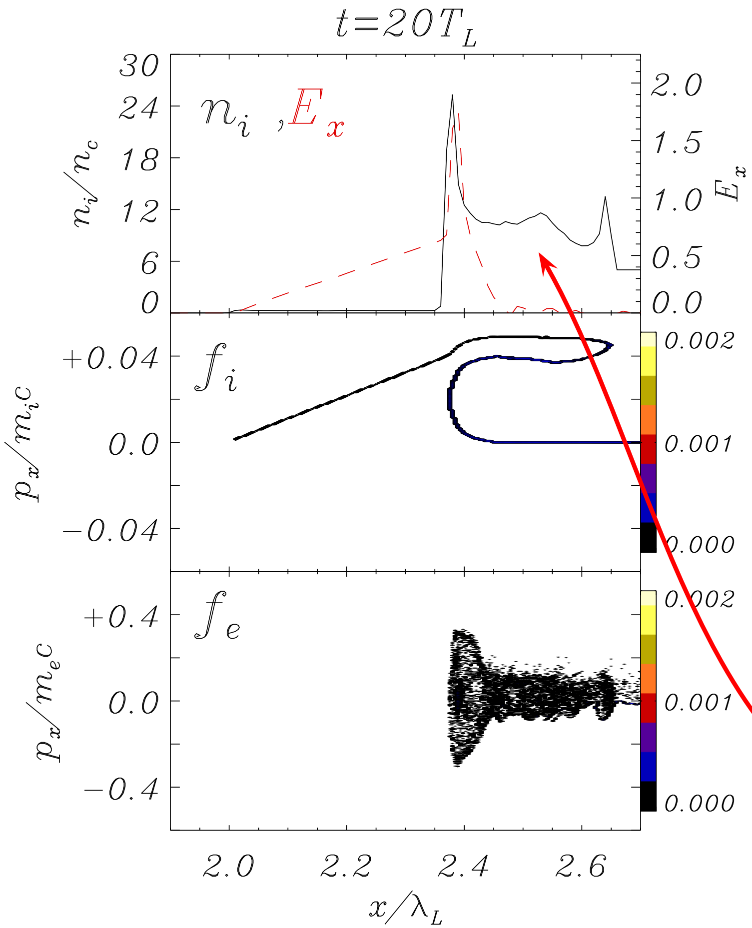
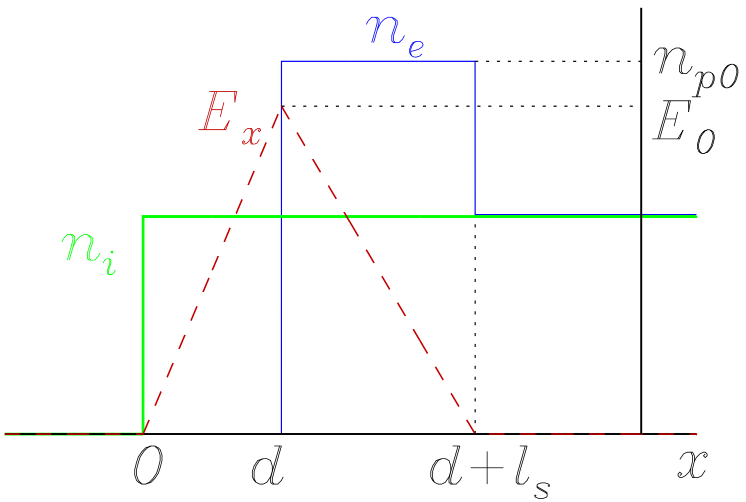


- interaction starts
- electrostatic field created
- ion profile driven to “breaking”
- ion “bunch” appears
- electron energy $\sim$ keV
- secondary bunches may appear

Simple model - I

Basic idea: electrons pile up leading to a quasi-equilibrium between the electrostatic field and the ponderomotive force. Ions are accelerated by the electrostatic field until breaking.

- Assume simple profiles . . .



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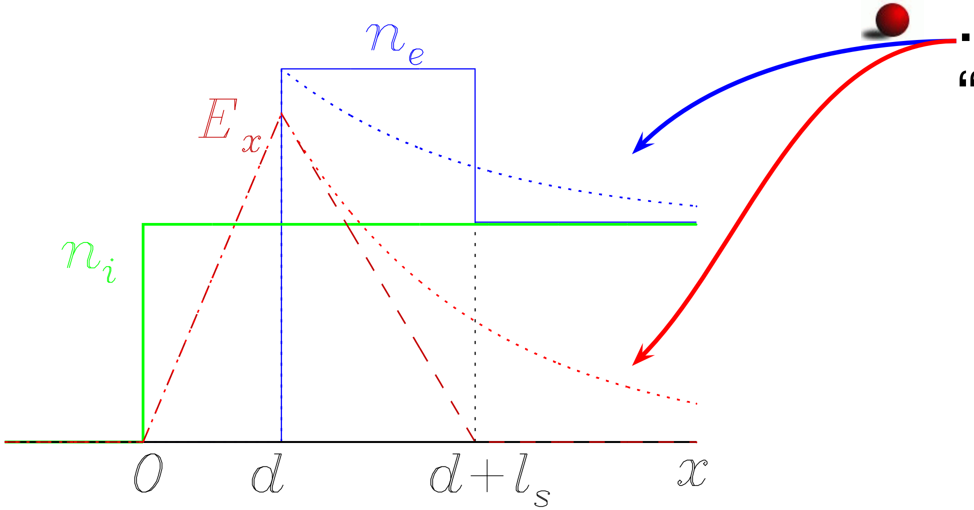

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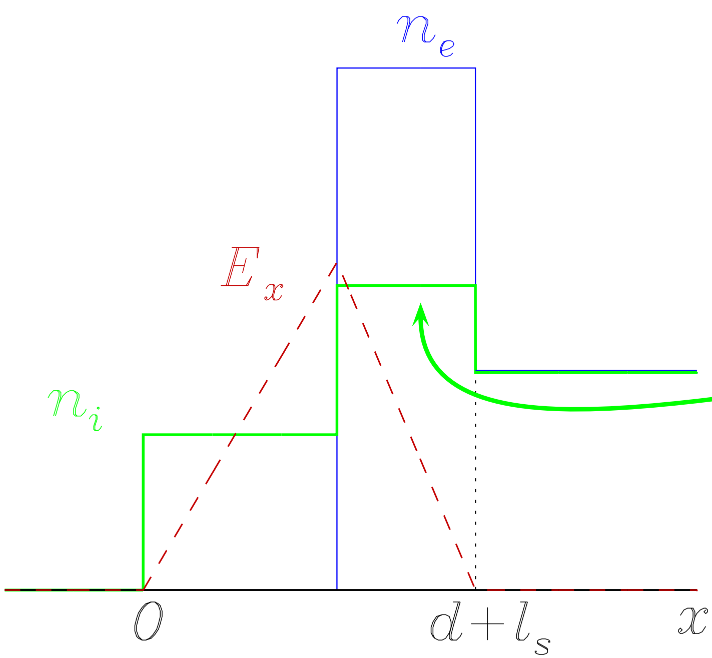

- Assume simple profiles . . .
- . . . which crudely approximate "real" ones
- ion profile is compressed

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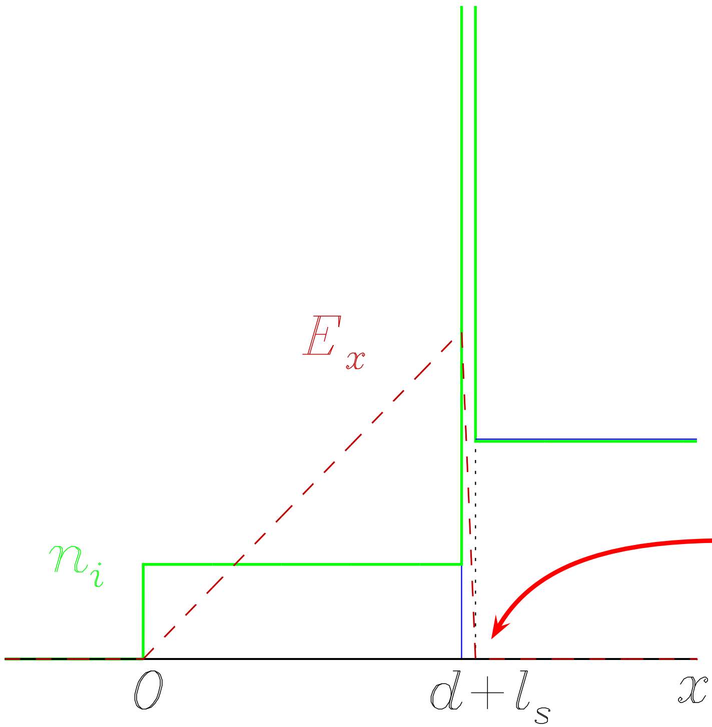


- Assume simple profiles . . .
- . . . which crudely approximate "real" ones
- ion profile is compressed
- "breaking" at the time when all ions reach the evanescence point

Simple model - II

- Input parameters d, E_0, n_{p0} are related by the Poisson equation and the constraints of charge conservation and total radiation pressure $P_{rad} = 2I_L/c$:

$$E_0 = 4\pi e n_0 d \,, \qquad n_0(d+l_s) = n_{p0} l_s \,, \qquad \frac{1}{2} e E_0 n_{p0} l_s \simeq \frac{2}{c} I_L$$

- Equations of motion are easily solved to yield maximum ion velocity and breaking time, assuming $l_s \simeq c/\omega_p$:

$$v_m = 2c\sqrt{\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}a_L} \qquad \tau_i \simeq T_L \frac{1}{2\pi a_L}\sqrt{\frac{A}{Z}\frac{m_p}{m_e}} \,.$$

- The average ion front velocity $v_f = v_m/2$ is the "hole boring" speed.

! To be NOT confused with shock acceleration!

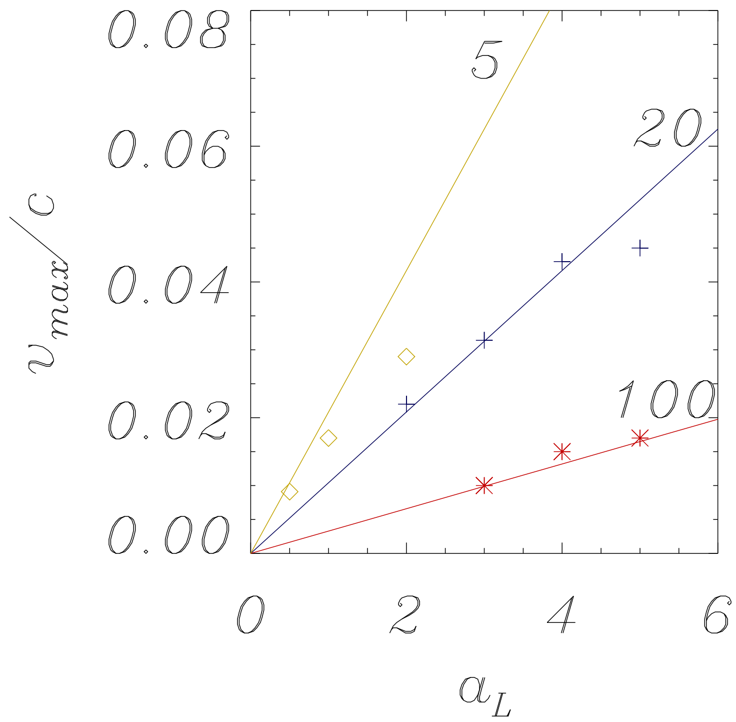
Model evaluation

The model is very simple , however, when compared to simulations, it gives:

- a correct scenario of the dynamics ion bunch formation

- a good scaling for the maximum ion velocity v_m vs. intensity and density

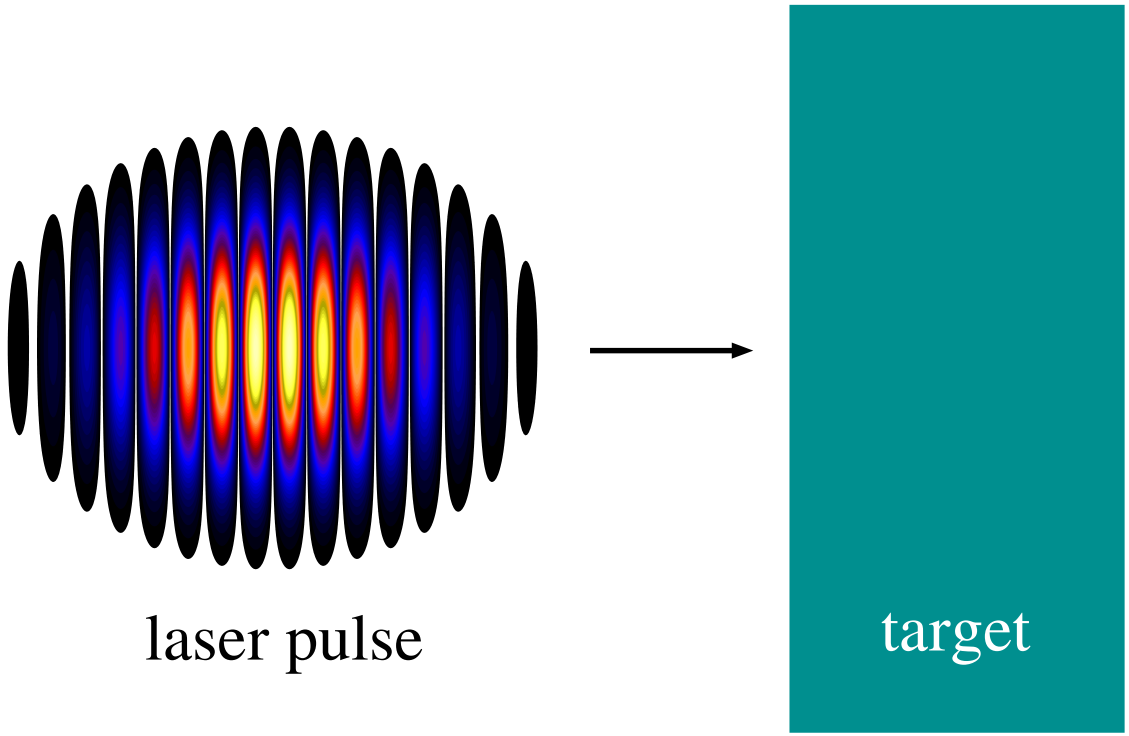
- fair estimates for the acceleration time (τ_i), the number of accelerated ions ($n_{i0}l_s$), and the conversion efficiency $\sim v_m/c$.



Other simulation features (e.g. non-white spectrum) are understood on a qualitative basis.

Two-dimensional simulations

In 2D simulations, the laser pulse profile imposes a smooth transverse modulation



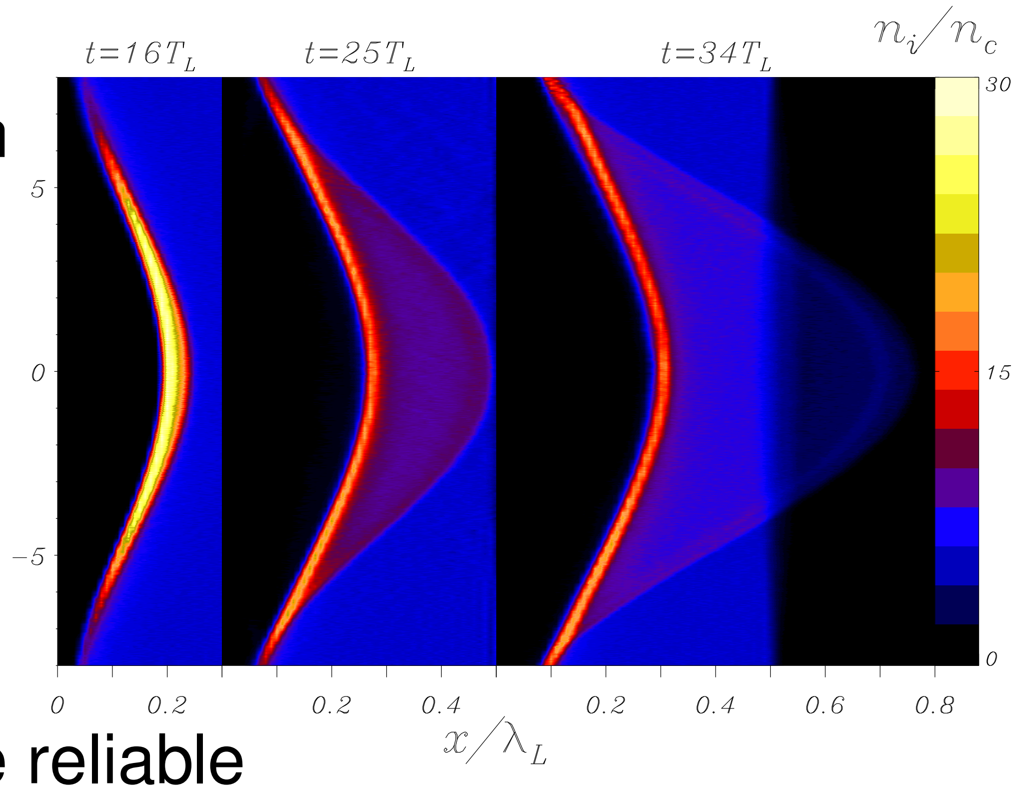
Two-dimensional simulations

In 2D simulations, the laser pulse profile imposes a smooth transverse modulation

$t = 16$: surface compression

$t = 25$: ion bunch formed

$t = 34$: ion bunch leaves target



1D scenario & modeling are reliable

Rippling of the laser-plasma interface is weak or absent

Ion “beam” characteristics

Ion bunches produced by circularly polarized pulses ($\tau_L \sim 5 \div 50$ fs, $I_L \sim 10^{18} \div 10^{20}$ W/cm^2) may have:

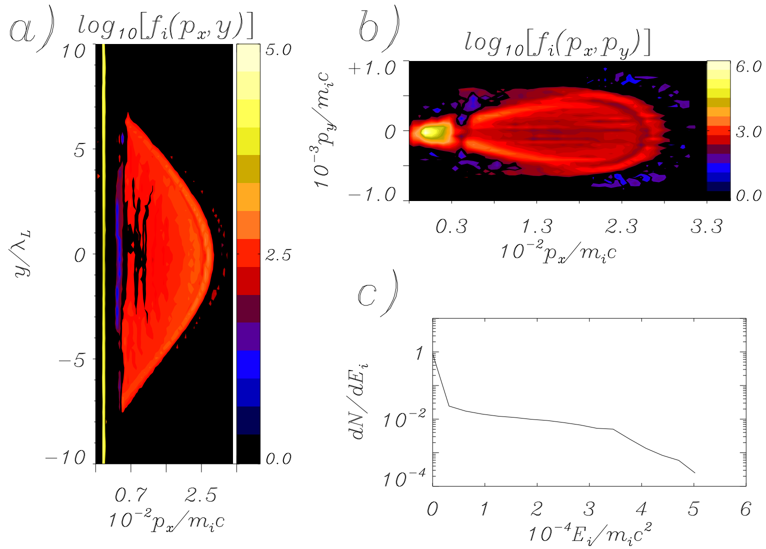
- modest energies ($0.1 \div 1$ MeV)

- high density ($n_b = 10^{21 \div 23}$ cm^{-3})

- ultrashort duration ($\tau_b \ll l_s/c$, can be $\tau_b < T_L = \lambda_L/c$)

- low divergence ($\sim 4 \times 10^{-2}$)

- good efficiency ($\simeq (2/3) v_m/c \sim 10^{-2}$)



Are these features useful for some application?

Application: neutron burst production

Idea: use the ion bunches to drive beam fusion reactions to produce neutrons.

- Fusion rate (two-beam scheme): $R = n_1 n_2 \langle \sigma v \rangle / (1 + \delta_{12})$
- n_1, n_2 may have solid-density values
- Approximated cross-section formula ($\mathcal{E}$: c.m.f. energy)

$$\sigma \simeq \frac{S_0}{\mathcal{E}} e^{-\sqrt{\mathcal{E}_G/\mathcal{E}}}$$

Maximum around the Gamow energy
$\mathcal{E}_G \approx 1$ MeVm_r/m_p $\qquad m_r = m_1 m_2/(m_1 + m_2)$.

$\Rightarrow$ One may obtain a significant neutron yield within the bunch duration.

D-T, single bunch scheme

D + T $\rightarrow \alpha$ + n $(14$ MeV$)$

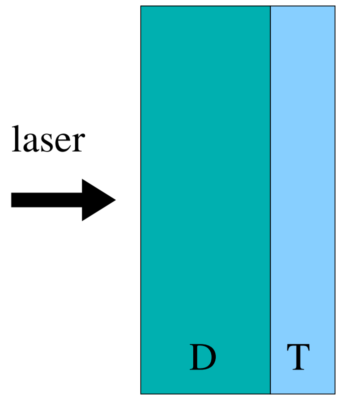
Assume $l_D \simeq l_s$ for optimal "projectile"

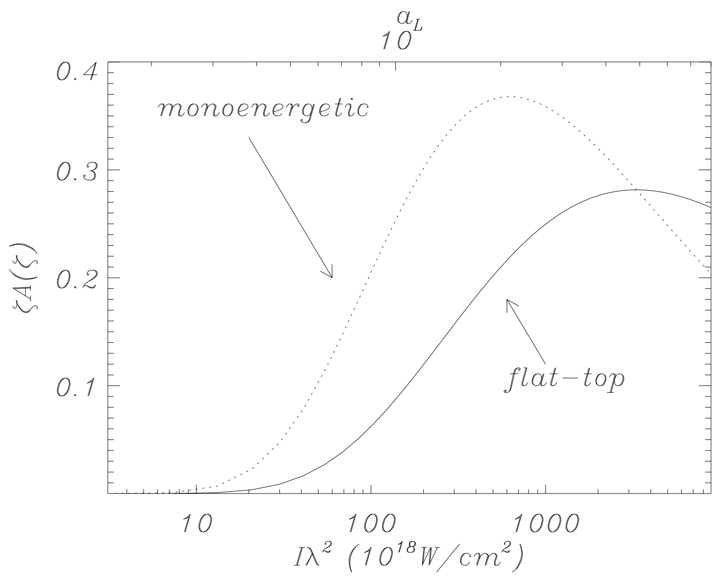
Shortest attainable duration
$\tau_n \simeq l_b/v_m$ if $l_T < l_b$

Neutron yield estimated analytically
$N \simeq 1.3 \times 10^{11}$ cm$^{-2}\kappa^{-1}\zeta\mathcal{A}(\zeta)$
$\zeta \equiv \sqrt{\mathcal{E}_g/\mathcal{E}}$
(monoenergetic or flat-top spectra)

$\sim 10^8$ neutrons in $\tau_n \sim 1.2$ fs
at $I\lambda^2 \geq 10^{19}$ W/cm^2

Double layer target:



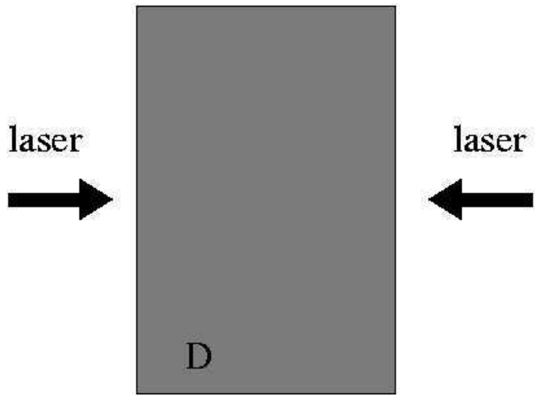


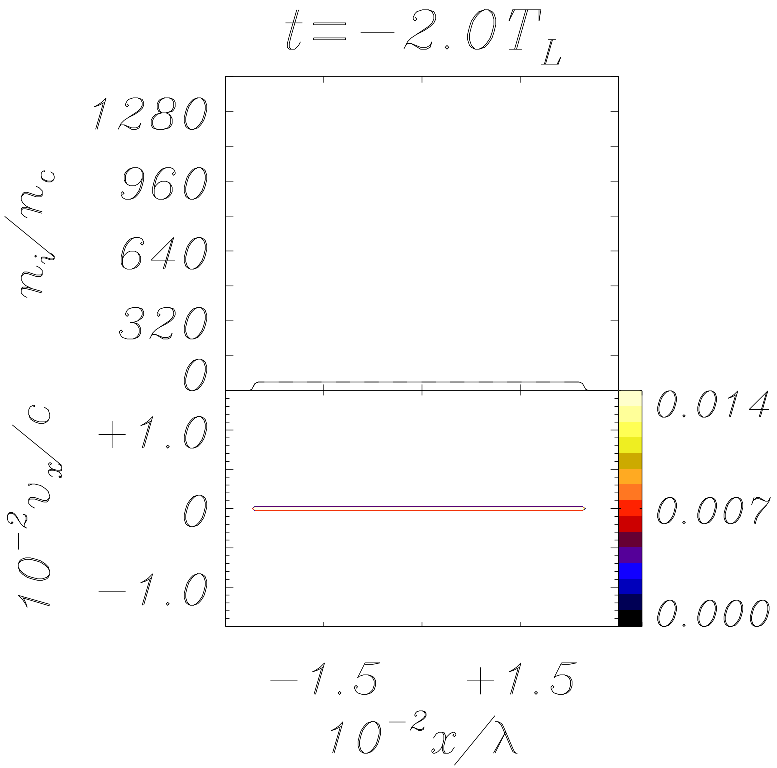
D-D, colliding bunches scheme

$\text{D} + \text{D} \rightarrow {}^3\text{He} + \text{n}\ (2.45\ \text{MeV})$

Two-side irradiation
to minimize duration and
maximize the center-of-mass energy
Optimal thickness $\ell = 2l_s$

Dynamics of colliding bunches
from PIC simulation:





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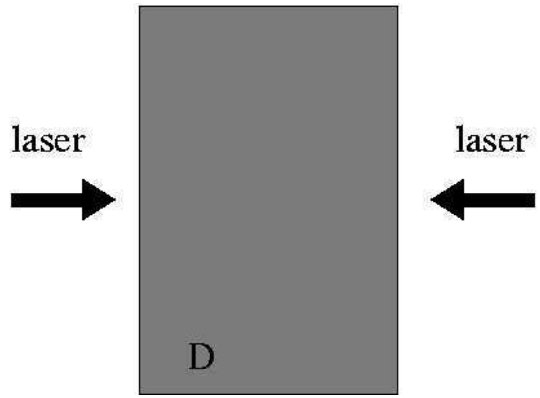

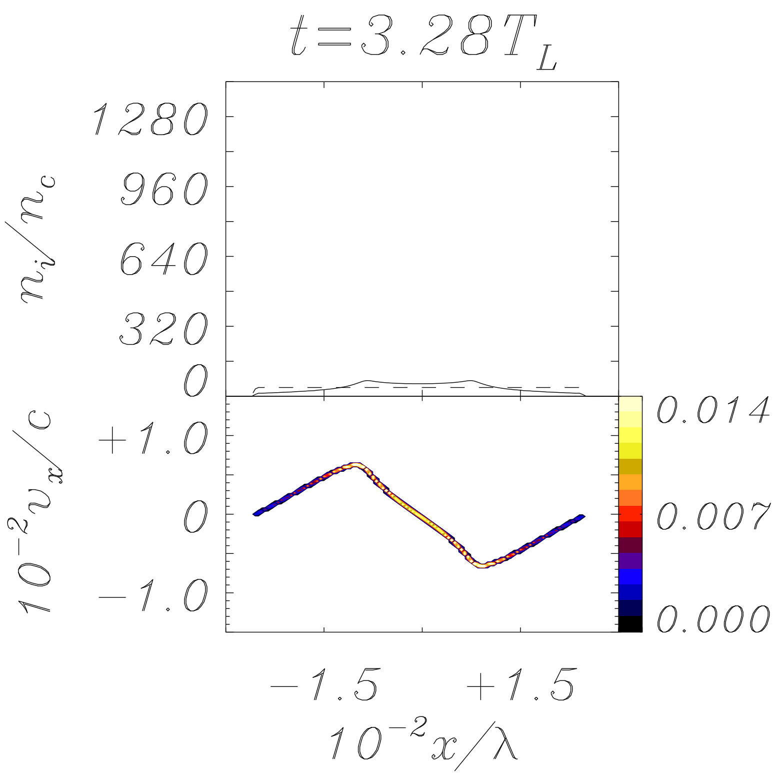

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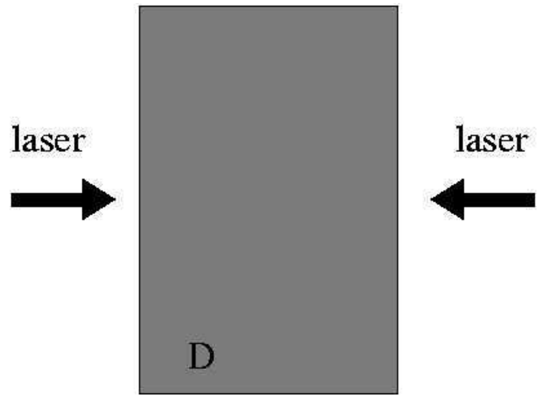

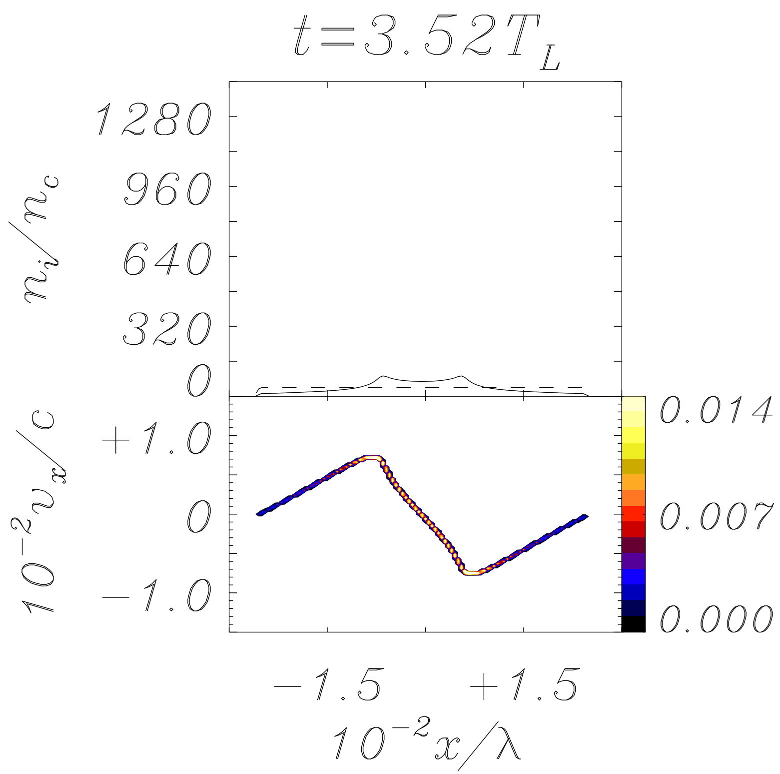

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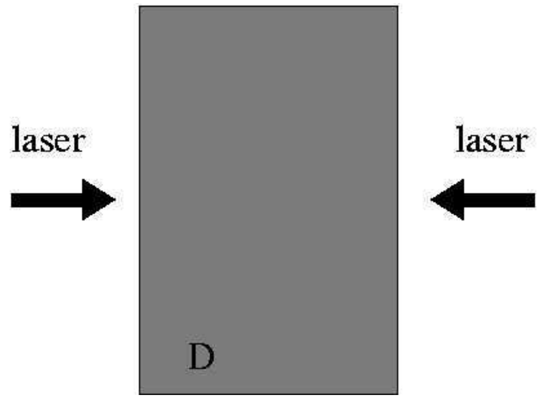

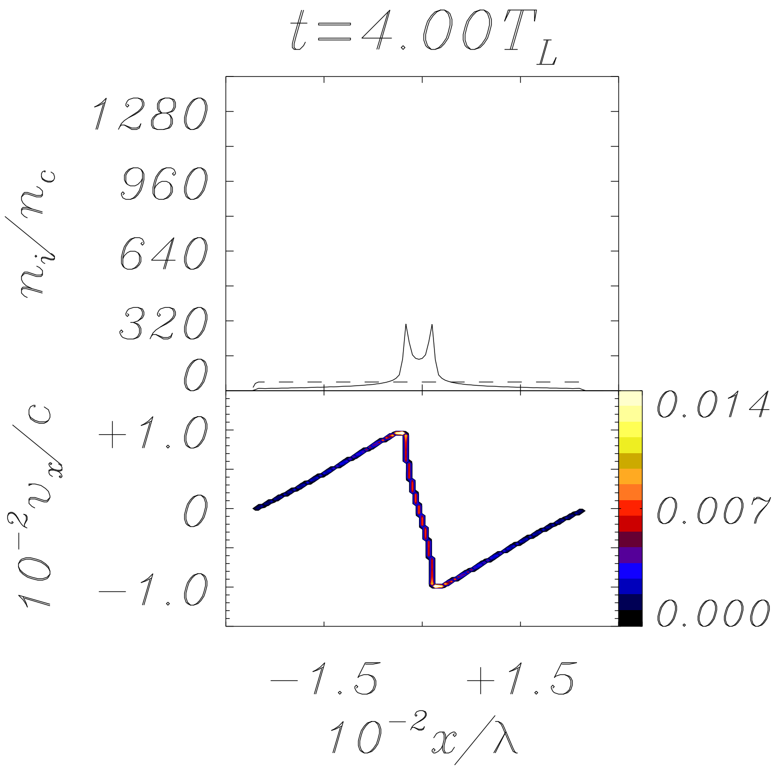

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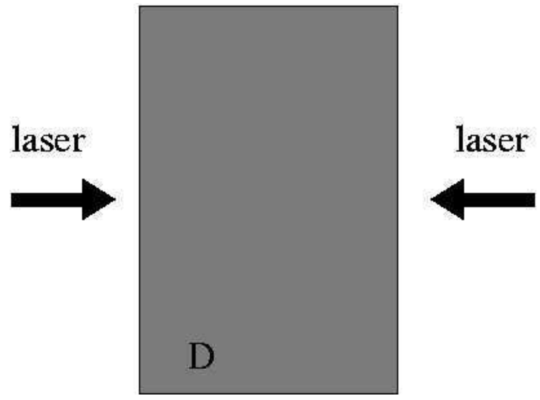

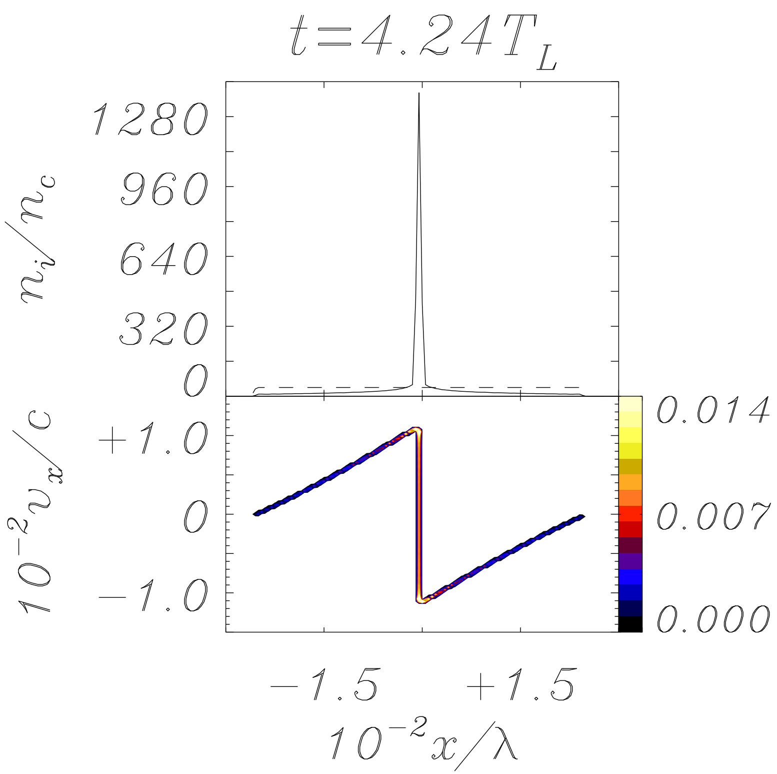

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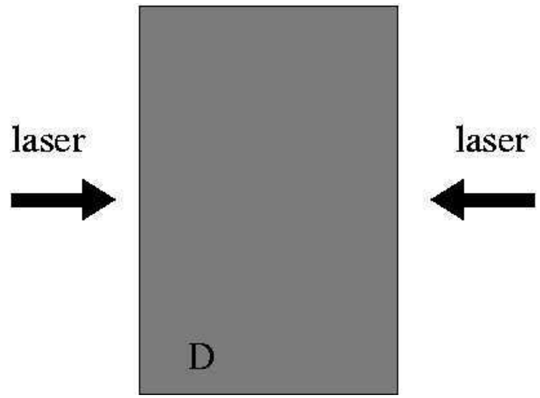

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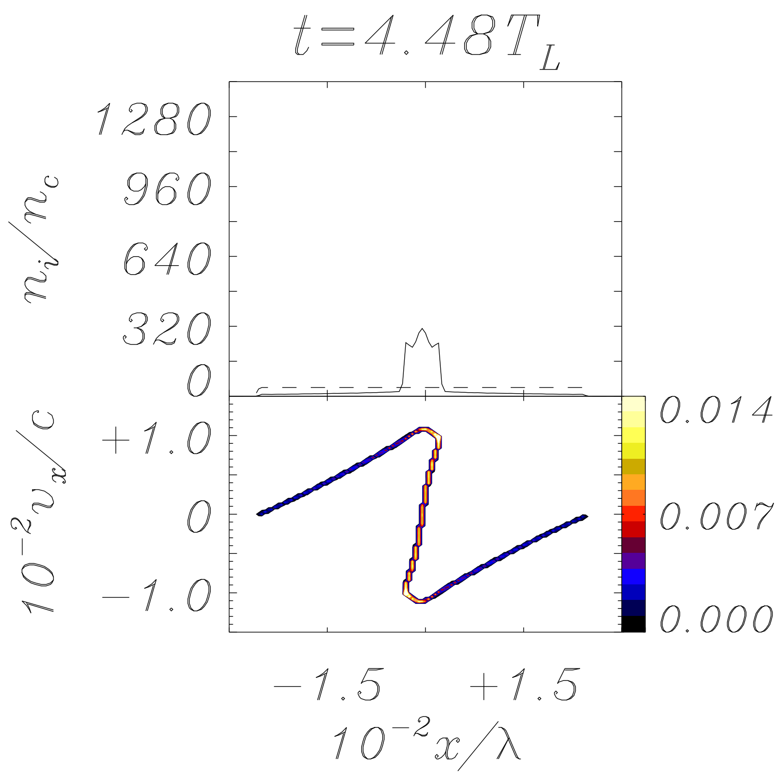

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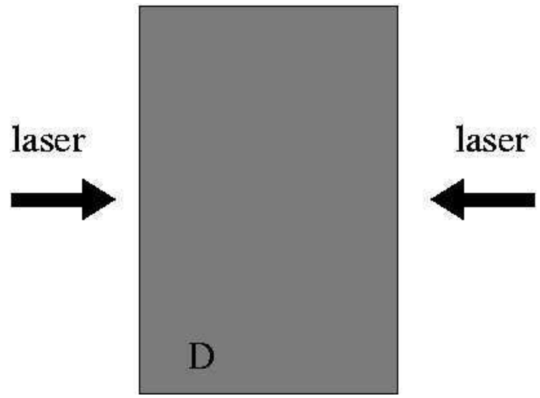

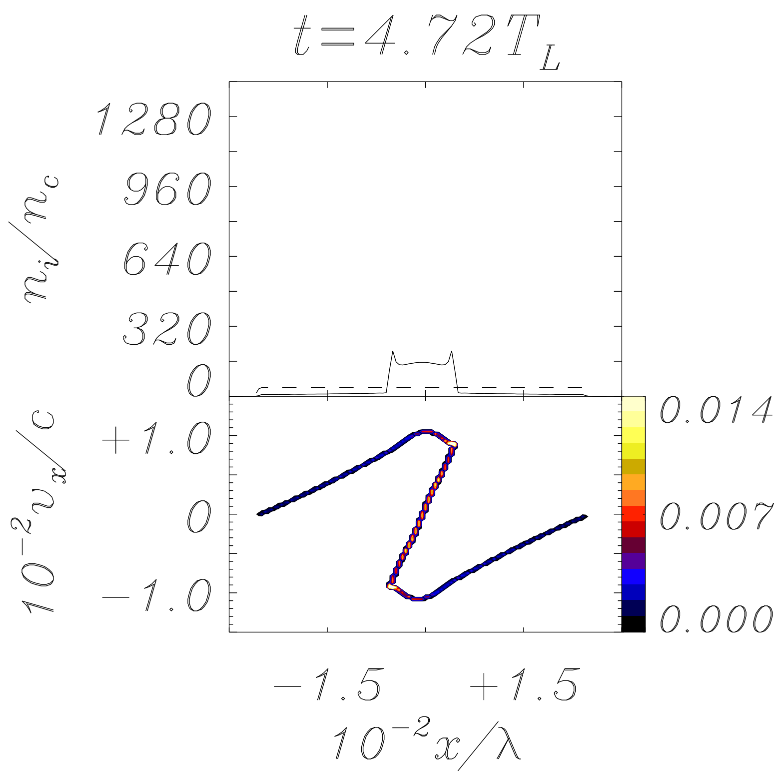

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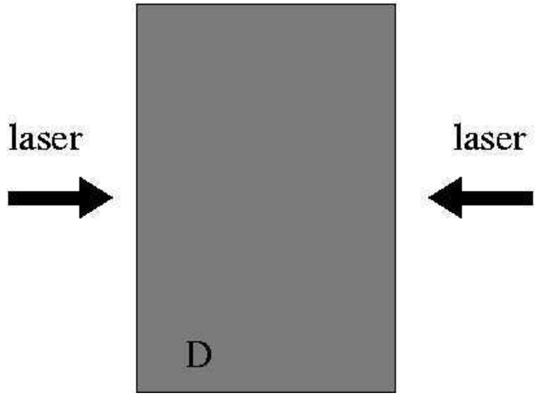

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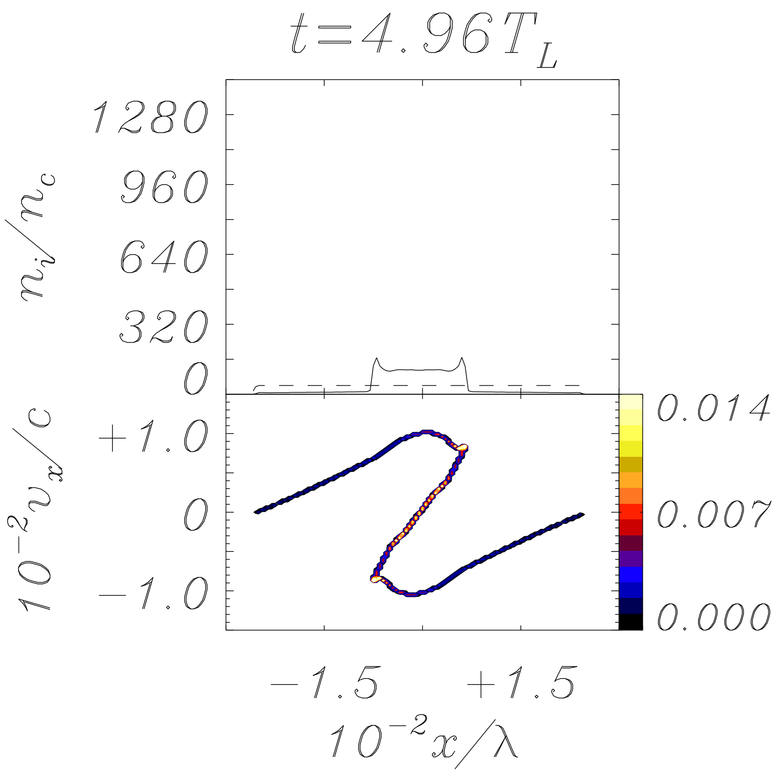


Thin foil of pure frozen D would be optimal (low $n_e/n_c \simeq 40$)
but $C_{\text{x}}D_{\text{y}}$ foil ($n_e/n_c \simeq 250$) is more realistic

Ultrashort neutron burst

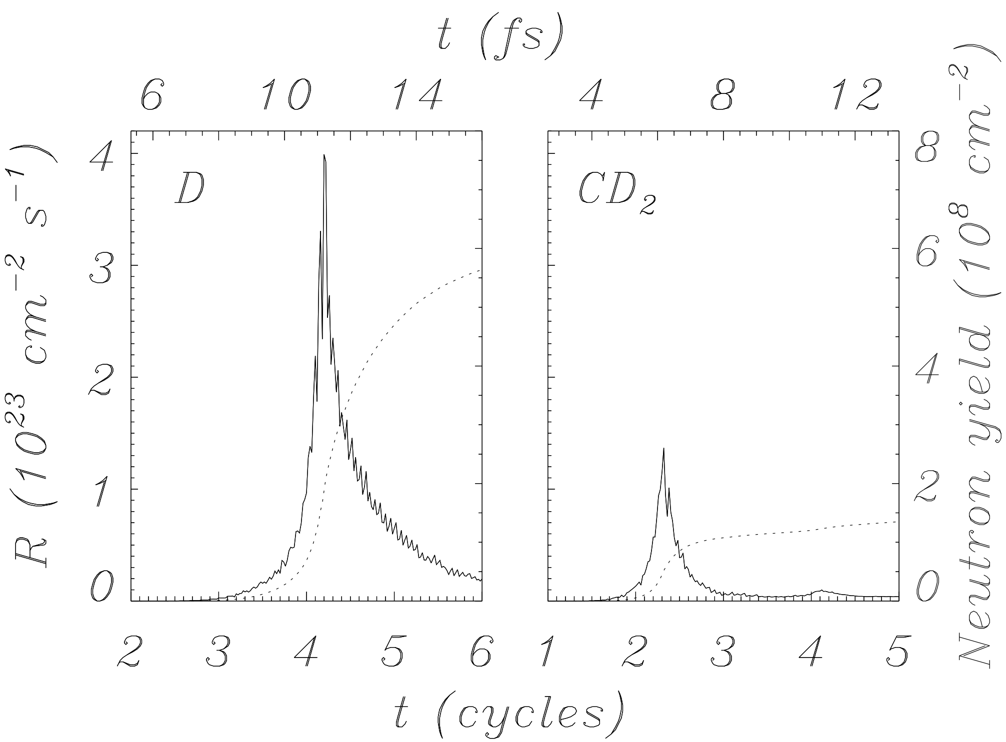
Neutron rate estimated from the simulation data.

Pulse duration: 15 fs

D: $n_i =$, $n_e/n_c = 40$,
$I_L = 1.3 \times 10^{19}$ W cm^{-2}

CD$_2$: $n_i =$, $n_e/n_c = 250$,
$I_L = 1.3 \times 10^{20}$ W cm^{-2}

Neutron burst duration:
$\simeq 0.7$ fs (FWHM)



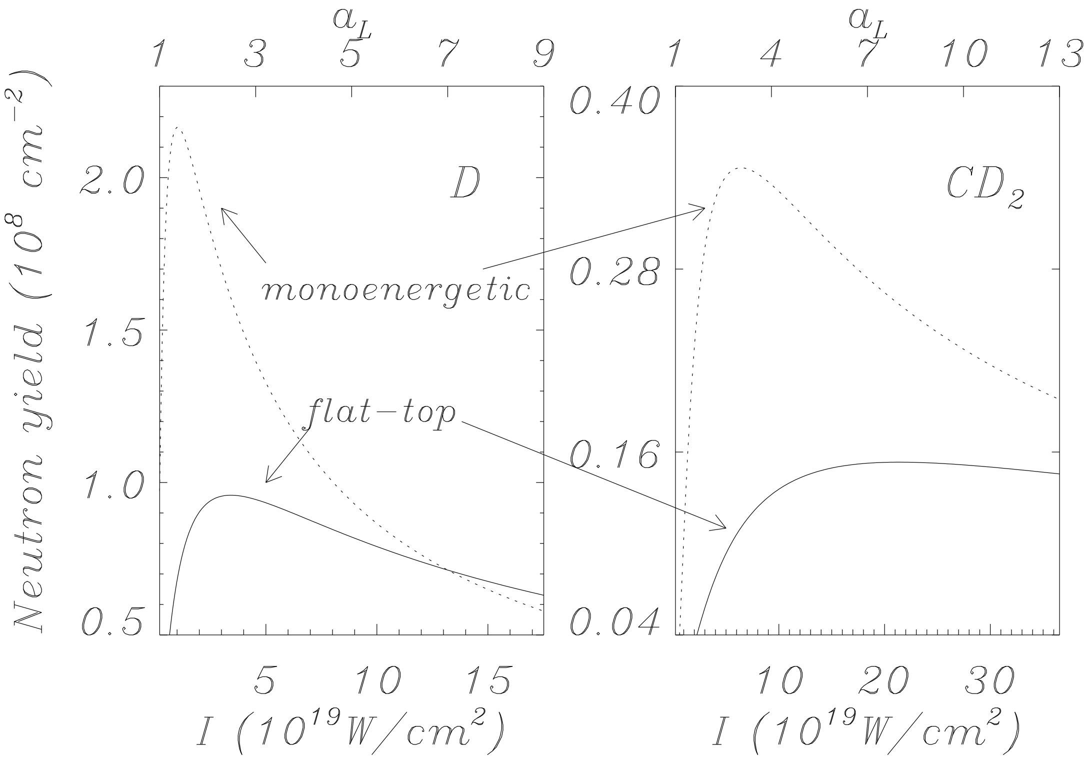
Neutron yield: $\sim 10^3$ J^{-1} (D), $\sim 10^2$ J^{-1} (CD$_2$)

Neutron yield vs. intensity

Analytical estimate of the neutrons produced *within the ultrashort* ($\tau \simeq l_b/2v_m$) *burst*:

$$N \simeq N_0 \zeta \mathcal{M}(\zeta)$$
$$\zeta \equiv \sqrt{\mathcal{E}_g/\mathcal{E}}$$

D: $N_0 \simeq 2 \times 10^8$
CD_2: $N_0 \simeq 3 \times 10^7$
(neutrons/cm^2)



Maximum rate reached in the range $I_L = 10^{19} \div 10^{20}$ W/cm^2

Comparison with other work

- Fusion neutrons have been observed in experiments with "T^3", fs laser systems using solid targets, gas jets, clusters and microdroplets
- (see e.g. Madison *et al.* [PRA **70**, 053201 (2004)] for partial summary and references)

→ Typical efficiency $10^3 \div 10^5$ neutrons/Joule

→ Duration of neutron emission not measured, but likely to be of the order of pulse duration

- Shen et al. [PRE **71**, 015401(R) (2005)] proposed a double-sided irradiation of a DT foil

→ concept based on foil confinement and thermonuclear fusion; requires "long" pulses

Experimental challenges

Apart form the usual “requirements” of high(er) intensity, short(er) duration, no prepulse . . .

- very thin foil target required ($\simeq 0.02\ \mu$m for “D-D”)
- Synchronization of the two pulses is critical to achieve a sub-fs neutron burst (but the burst duration remains in the few fs range anyway).
- Energy spectrum has to be quasi-monochromatic to preserve ultrashort duration
- Angular spread may lead to low brilliance
- Measurement of neutron burst duration is challenging (indirect measurement via “attosecond spectroscopy” techniques?)

Who needs a fs neutron source?

A femtosecond neutron source is *a solution looking for a problem . . .*

It might open a perspective for:

- ultrafast control and imaging of nuclear reactions by laser pulses

  [N. Milosevic, P. B. Corkum, and T. Brabec, PRL **92**, 013002 (2004); S. Chelkowski, A. D. Bandrauk, and P. B. Corkum, PRL **93**, 083602 (2004).]

- diagnostic of fast nuclear processes, e.g. nuclear spin-mixing oscillations with period ~ 1 fs

  [K. Pachucki, S. Wycech, J. Żylicz, and M. Pfützner, Phys. Rev. C **64**, 064301 (2001).]

Conclusions

- Studying ion acceleration by circularly polarized pulses
  - helps the understanding of the ion acceleration dynamics
  - suggests a novel regime of ion acceleration
- The ion bunches produced in this regime may open a perspective to bring the duration of neutron sources down in the sub-femtosecond regime

References

- ion acceleration: A. Macchi, F. Cattani, T. V. Liseykina, F. Cornolti, Phys. Rev. Lett. **94**, 165003 (2005)
- fs neutron source: A. Macchi, Applied Physics B, in press [preprint: http://arxiv.org/abs/physics/0505140.]
- Download this talk: http://www.df.unipi.it/∼macchi/talks.html
- Visit also http://www.df.unipi.it/∼macchi/research.html for movies, further details, or updates

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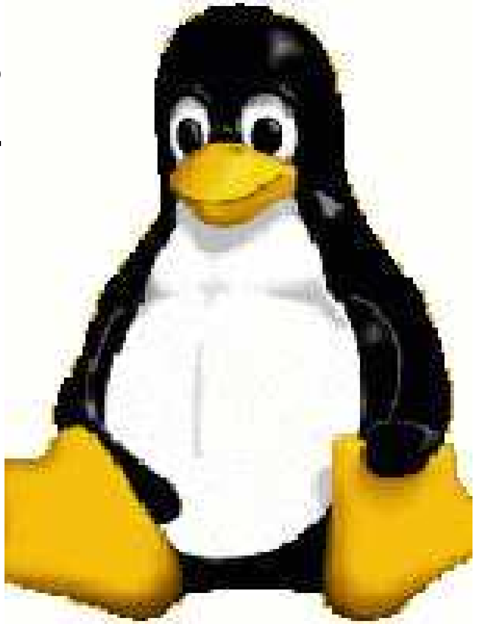
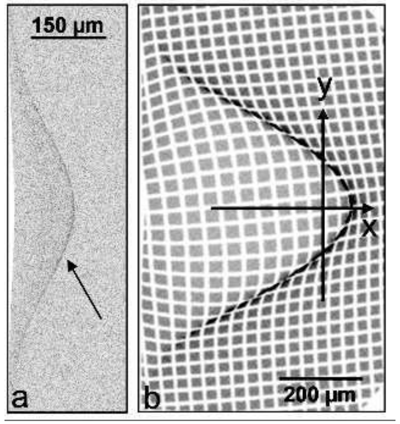


EXTRA SLIDES

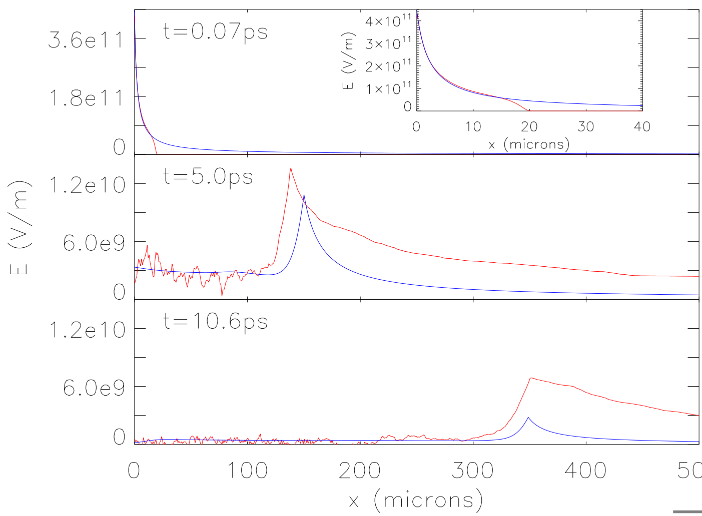
Rear sheath acceleration (RSA)

Acceleration of ions (protons) at the rear side is now well understood on the basis of the sheath acceleration model: fast electrons expanding in vacuum drive ion acceleration.



Experiment:
L. Romagnani et al.,
PRL **95**, 195001 (2005)

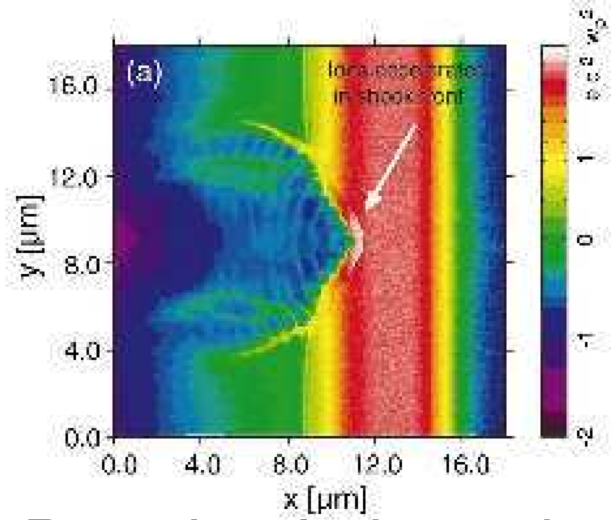
Modeling:
Fluid:
Mora, PRL **90**, 185002 (2003)
PIC:
Betti, Ceccherini, Cornolti, Pegoraro,
PPCF **47**, 521 (2005)



Front shock acceleration (FSA)

Recent experiments and related modeling indicate that acceleration of ions at the front side is due to (collision-less) shock fronts:

[Habara et al, PRE **70**, 046414 (2004); Wei et al, PRL **93**, 155003 (2004)]



2D simulation by Habara et al.

"Reflection" law $v_i \simeq 2v_s$

from momentum balance

$v_s \approx v_{hb} \simeq \sqrt{2I/m_i n_i c}$

[Silva et al, PRL **92**, 015002 (2004).]

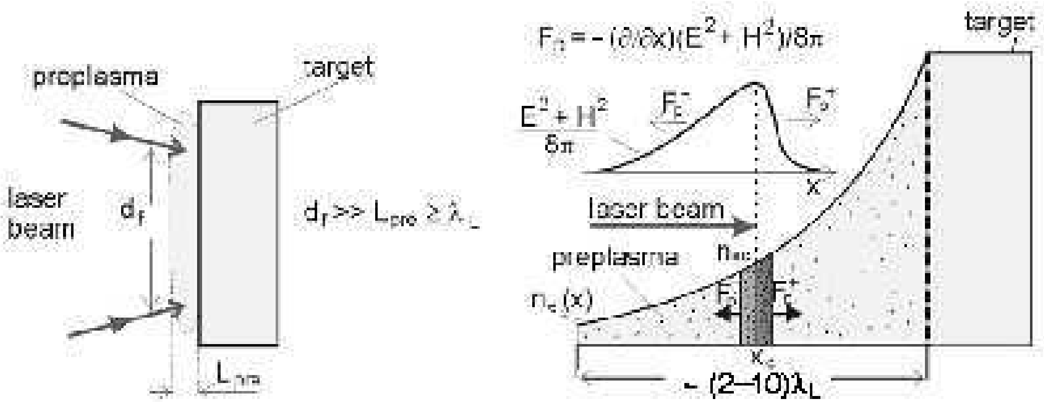
Is FSA also related to fast electrons?

S-LPA: another acceleration mechanism?

Skin-Layer Ponderomotive Acceleration (S-LPA)

Theory: Hora, Czech. J. Phys. **53**, 199 (2003)
Experiment: Badziak et al, PPCF **46**, B541 (2004)
(1 ps, $\leq 2 \times 10^{17}$ W/cm^2 pulses)

Concept: the steady ponderomotive force accelerates “plasma blocks” of high density and moderate energy ($\sim$ 0.01 MeV/nucleon) at the critical surface.



Role of prepulse and fast electrons, scaling to higher intensity, competition/overlap with FSA are yet to be understood.

Diagnostics of ion bunch acceleration

Ion acceleration using circular polarization at normal incidence should be characterised by:

- Ion cut-off energy:
$\mathcal{E}_m \simeq 0.5\ \text{MeV}\, Z\,(n_c/n_e)\,a_0^2 \simeq 0.4\ \text{MeV}(Z I_{18}/n_{e,21})$

- Number of ions (per unit surface):
$\simeq n_0 l_s \simeq 1.7 \times 10^{-16}\ \text{cm}^{-2}\sqrt{n_{e,21}}/Z$
(does *not* depend on intensity)

- low ($\sim 10^{-2}$) and energy-dependent angular spread (similar to RSA)

- almost no fast electrons ($\mathcal{E}_e \ll m_e c^2 a_0$)

$n_{e,21} = n_e/10^{21}\ \text{cm}^{-3}\,; \qquad I_{18} = I/10^{18}\ \text{W cm}^{-2}.$