Radiation Pressure Acceleration with Circularly Polarized Light

Andrea Macchi

polyLAB/CNR/INFM
and INFN, sezione di Pisa
Dipartimento di Fisica “Enrico Fermi”, Università di Pisa,Italy

PHI, CEA-DSM/IRAMIS/SPAM,
Gif sur Yvette Cedex, April 9, 2008

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Max-Planck-Institut fuer Kernphysik, Heidelberg,
April 21, 2008

Contributors

Tatiana V. Liseykina* (research fellow)

Fulvio Cornolti, Francesco Pegoraro (faculty)

Domenico Prellino, Sara Tuveri, Silvia Veghini
(M.Sc. “Laurea” students)

Dipartimento di Fisica “Enrico Fermi”, Università di Pisa

**on leave from Institute of Computational Technologies, Novosibirsk, Russia presently at Max Planck Institute for Nuclear Physics, Heidelberg, Germany*

Outline

- Perspectives and goals for ion acceleration by laser
- Basics of Radiation Pressure Acceleration
- Why using circularly polarized pulses
- Simulation results:

➢ 1D: parametric studies (thin targets and preformed plasmas)

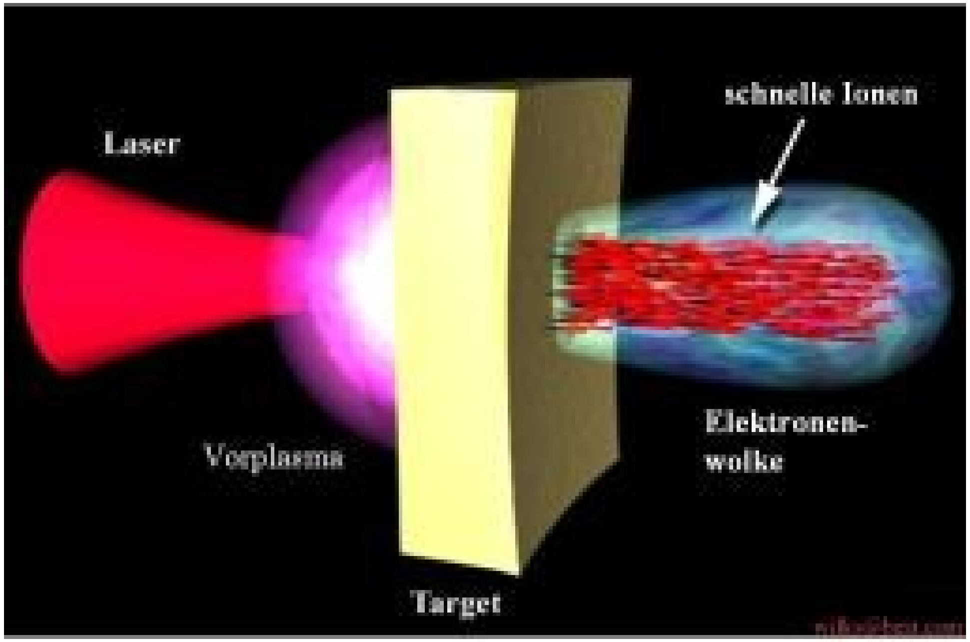
➢ 2D: ion beam properties and surface instabilities

➢ 3D: angular momentum absorption and magnetic field generation

The discovery of MeV proton emission in superintense interaction with *metallic* targets

Reported in 2000
by three experimental groups

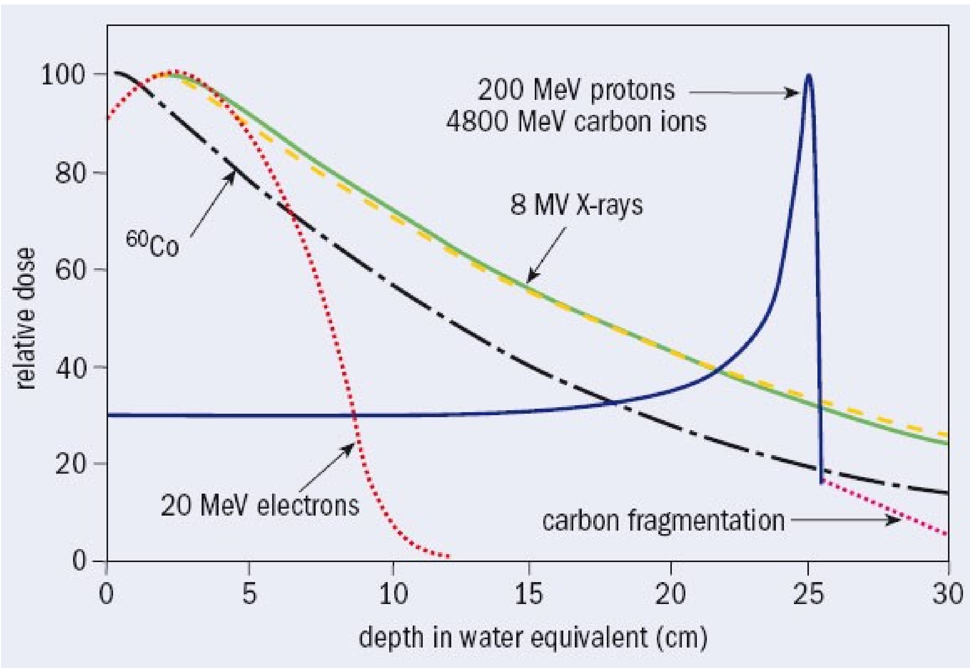
[Clark et al, PRL **84** (2000) 670;
Maksimchuk et al, *ibid.*, 4108;
Snavely et al, PRL **85** (2000) 2945 (*)]



Remarkable properties of the proton beam:

- **high number** (up to 10^{14})
- **good collimation**
- **ultra-low emittance** (4×10^{-3} mm mrad)
- maximum energy and efficiency observed (*):
  58 MeV , **12% of laser energy**
  @ $I = 3 \times 10^{20}$ W/cm^2

MeV protons (ions) are appealing for applications requiring localized energy deposition in matter



Sharp spatial maximum of deposited energy (Bragg peak)

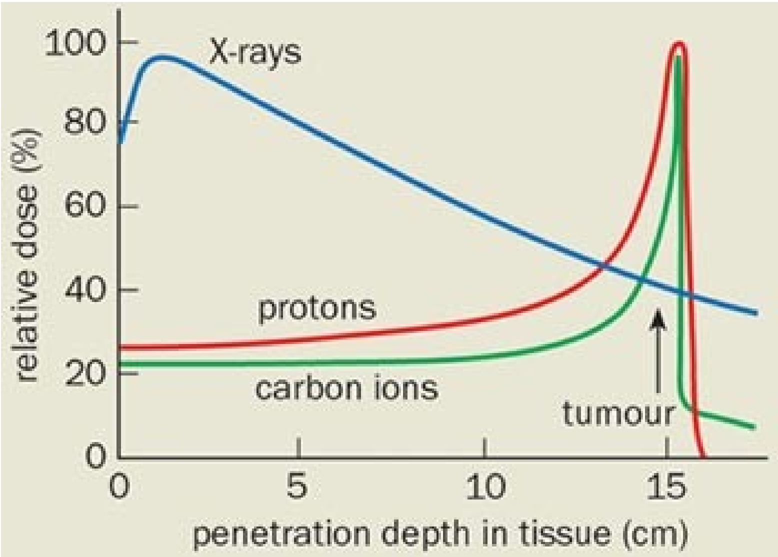
Peak location depends on energy

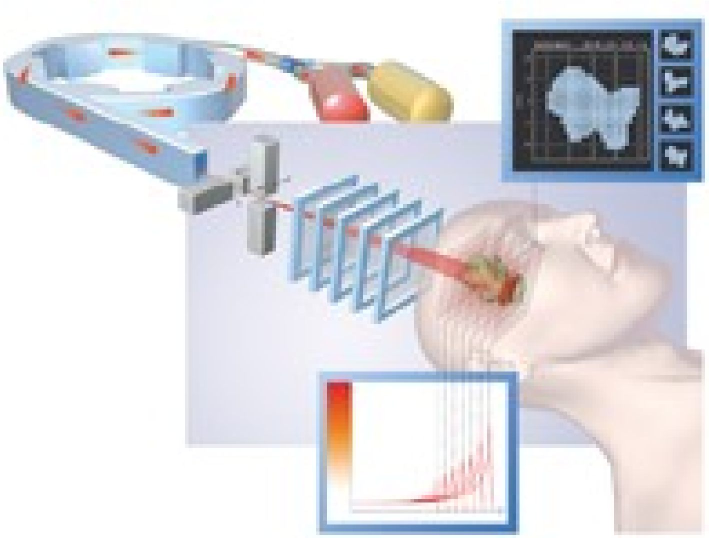
[U. Amaldi & G. Kraft, Rep. Prog. Phys. **68** (2005) 1861]

MeV protons (ions) are appealing for applications requiring localized energy deposition in matter

Medical Applications

ONCOLOGICAL HADRONTHERAPY





[K.Ledingham, Glasgow University, 2006]

If feasible with table-top, high repetition lasers,
cost can be reduced with respect to an accelerator facility

Other foreseen application in medicine:
isotope production (e.g. for Proton Emission Tomography)

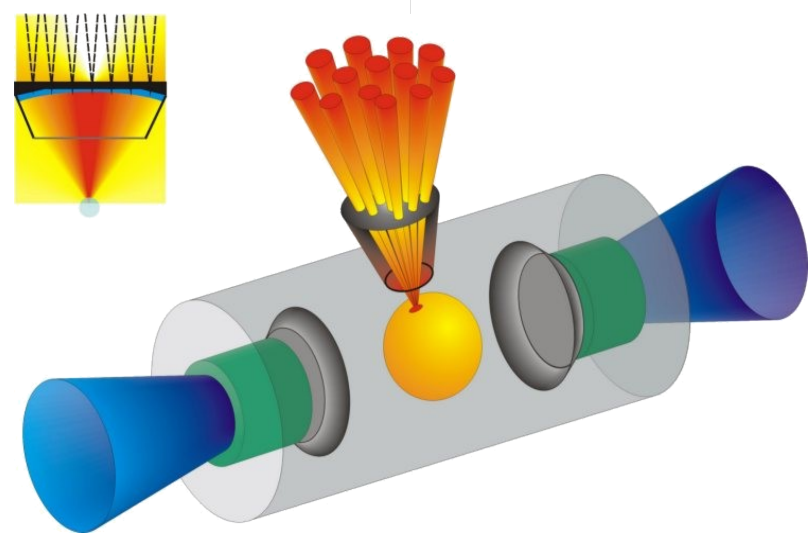
MeV protons (ions) are appealing for applications requiring localized energy deposition in matter

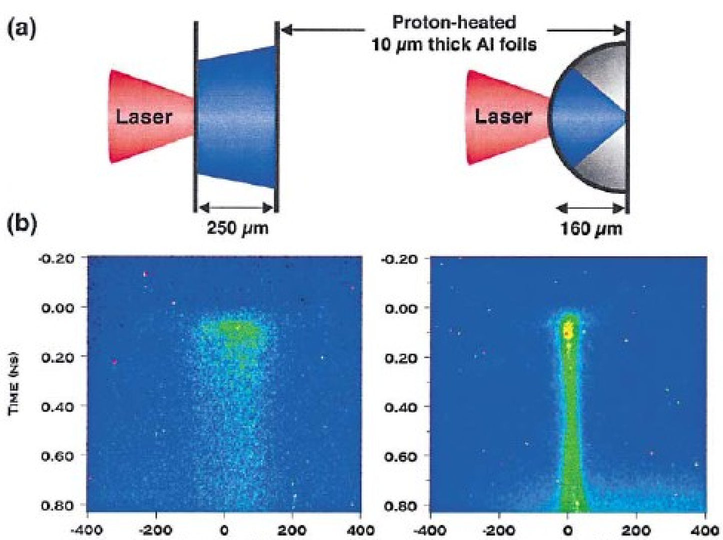
Inertial **C**onfinement **N**uclear **F**usion

FAST IGNITION

Protons can be used to create a “spark” in a pre-compressed ICF capsule achieving isochoric burn and high energy gain

[Roth et al, Phys. Rev. Lett. **86** (2001) 436;
Atzeni et al, Nuclear Fusion **42** (2002) L1;
Macchi et al, Nuclear Fusion **43** (2003) 362]





Geometrical focusing of laser-accelerated protons and localized isochoric heating has been demonstrated

[Patel et al, Phys. Rev. Lett. **91** (2003) 125004]

Fast ions seen in PIC simulations suggest several possible mechanisms of ion acceleration

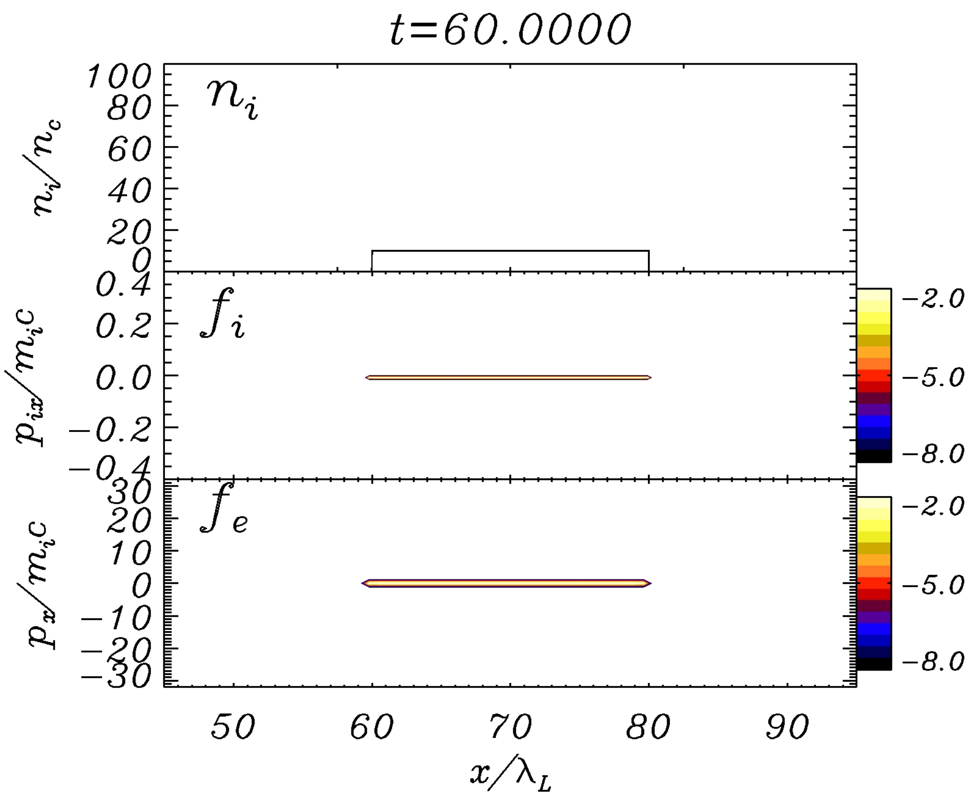
1D PIC simulation
I=3.5×10^{20}W/cm^2 ,
n_e=10^{22}cm^{-3}

Three fast ion populations, accelerated

- from rear side in forward direction

- from front side in forward direction

- from front side in backward direction



Which is the dominant “channel” for given conditions?

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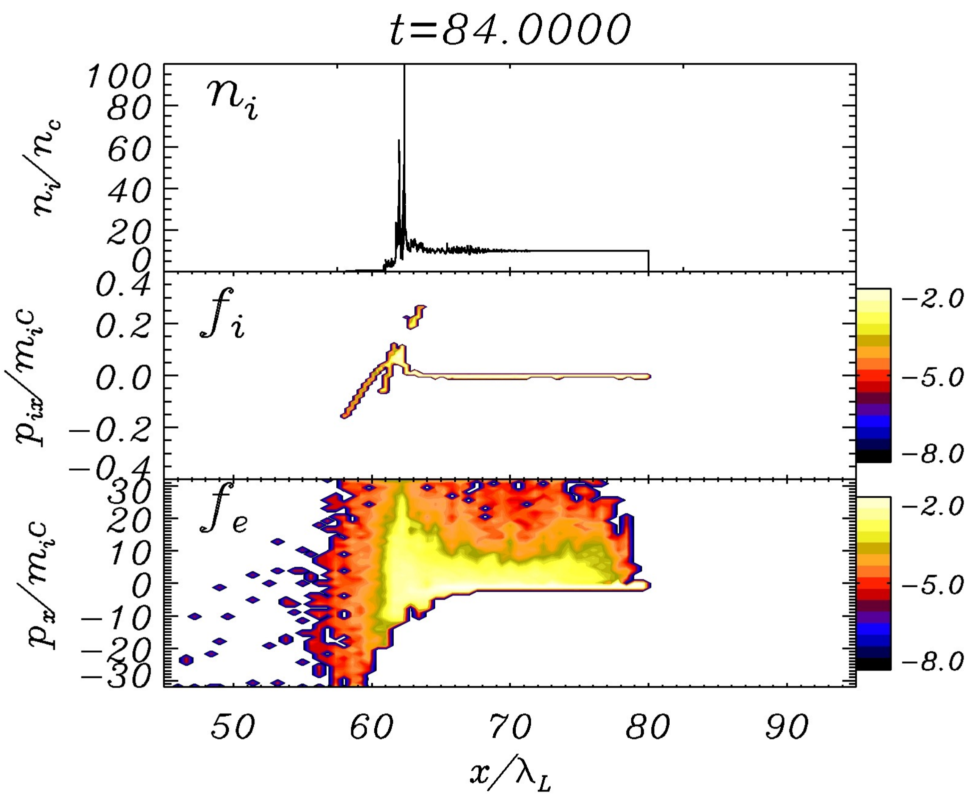

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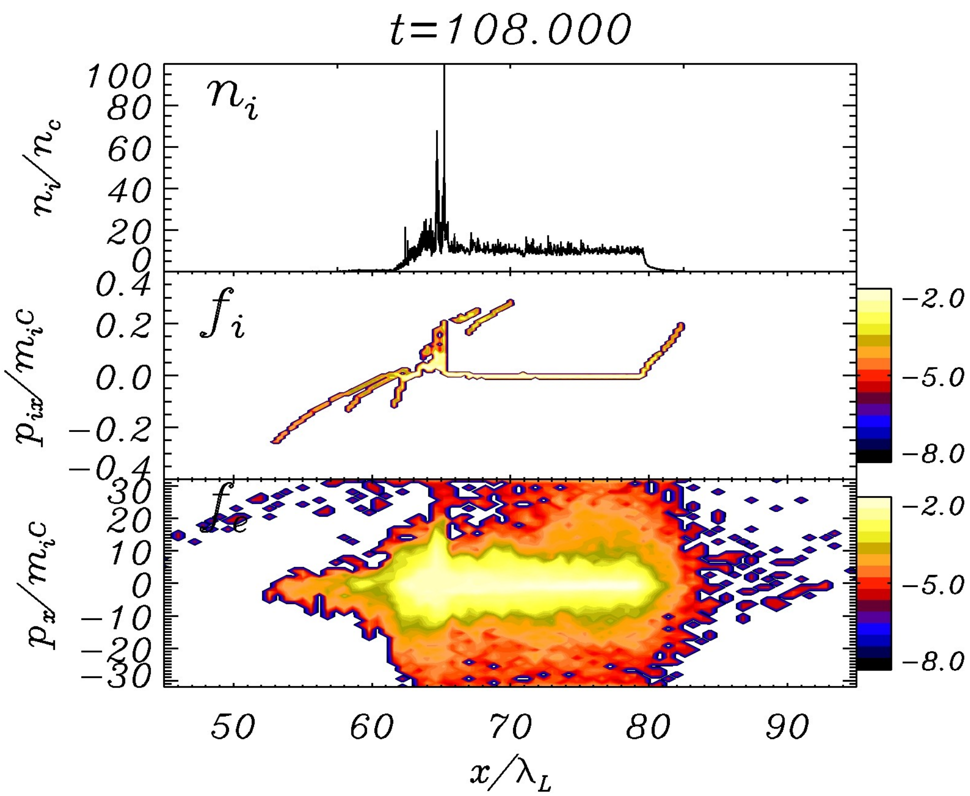

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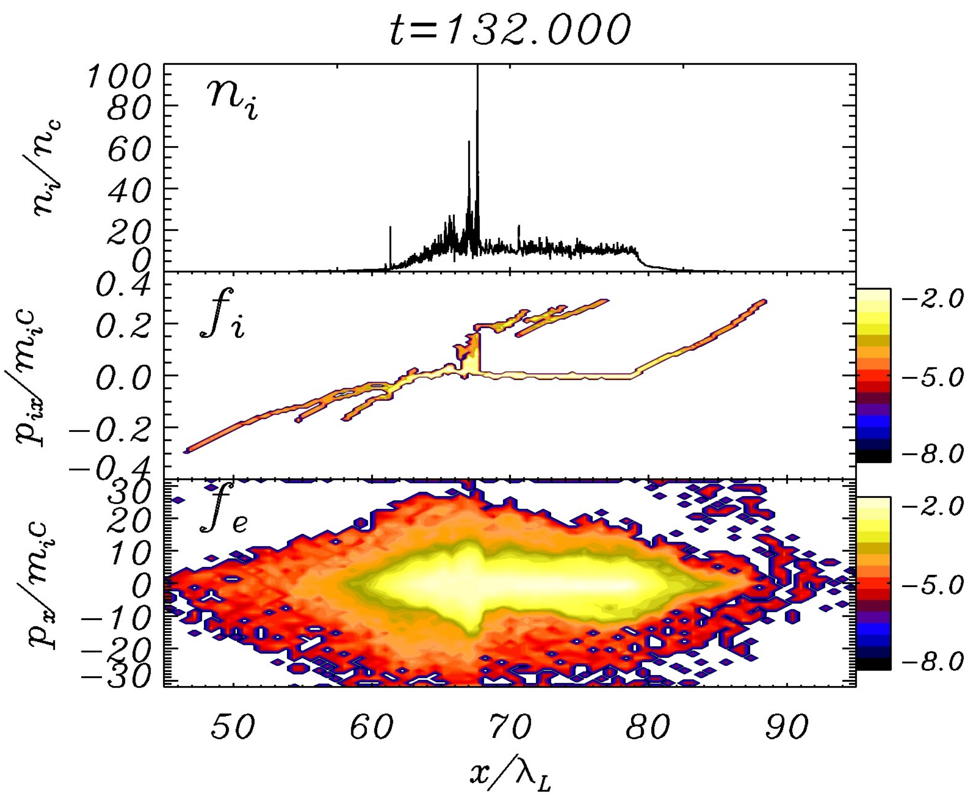

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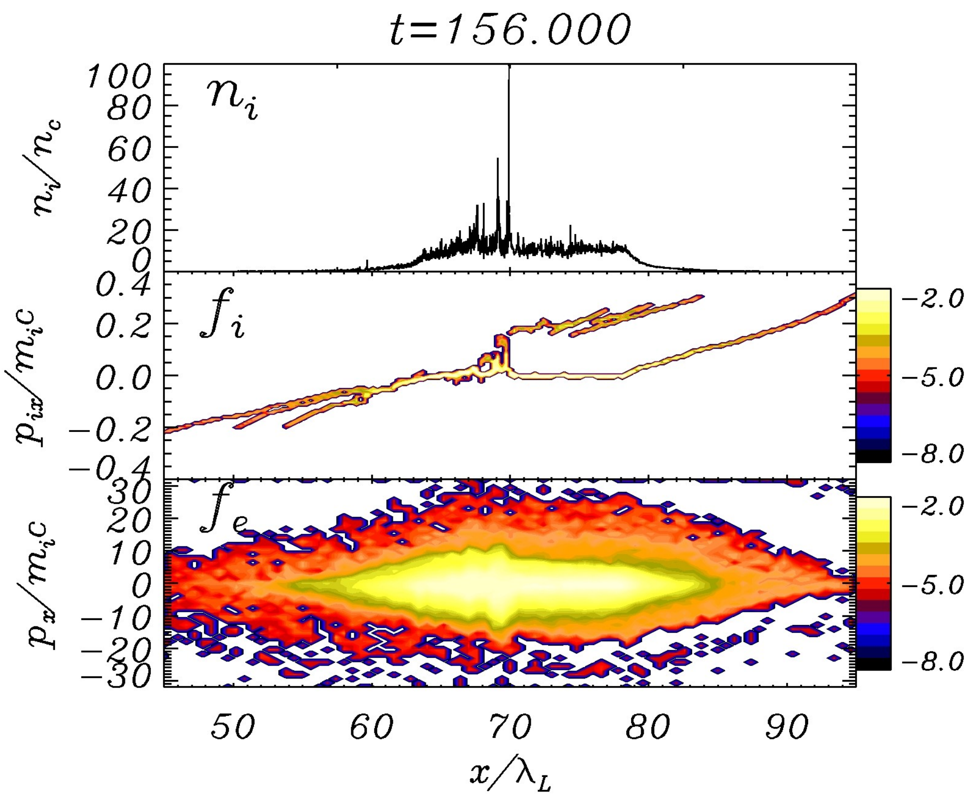
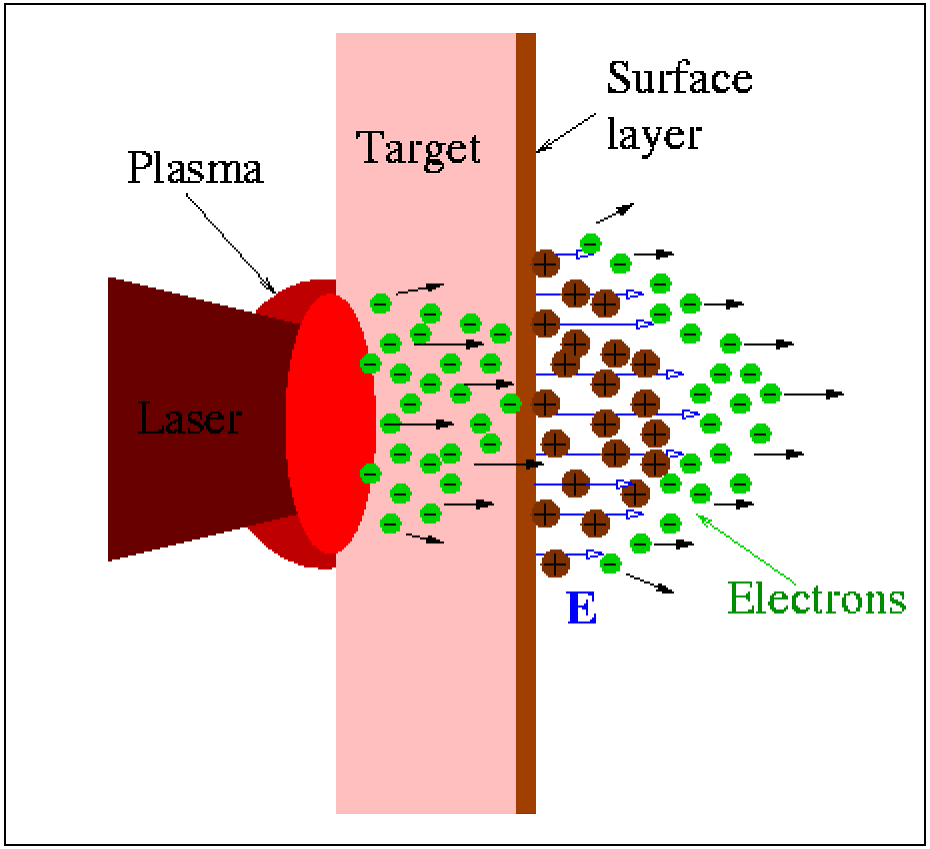
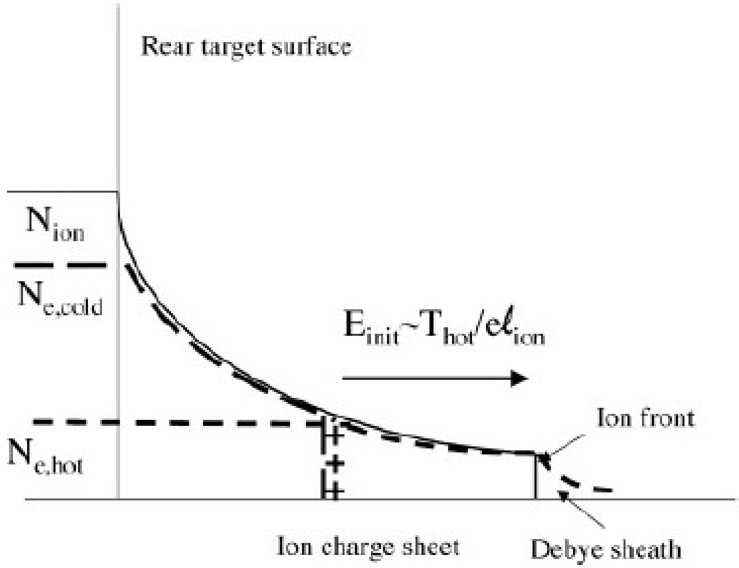


Which is the dominant “channel” for given conditions?

The Target Normal Sheath Acceleration model of proton acceleration

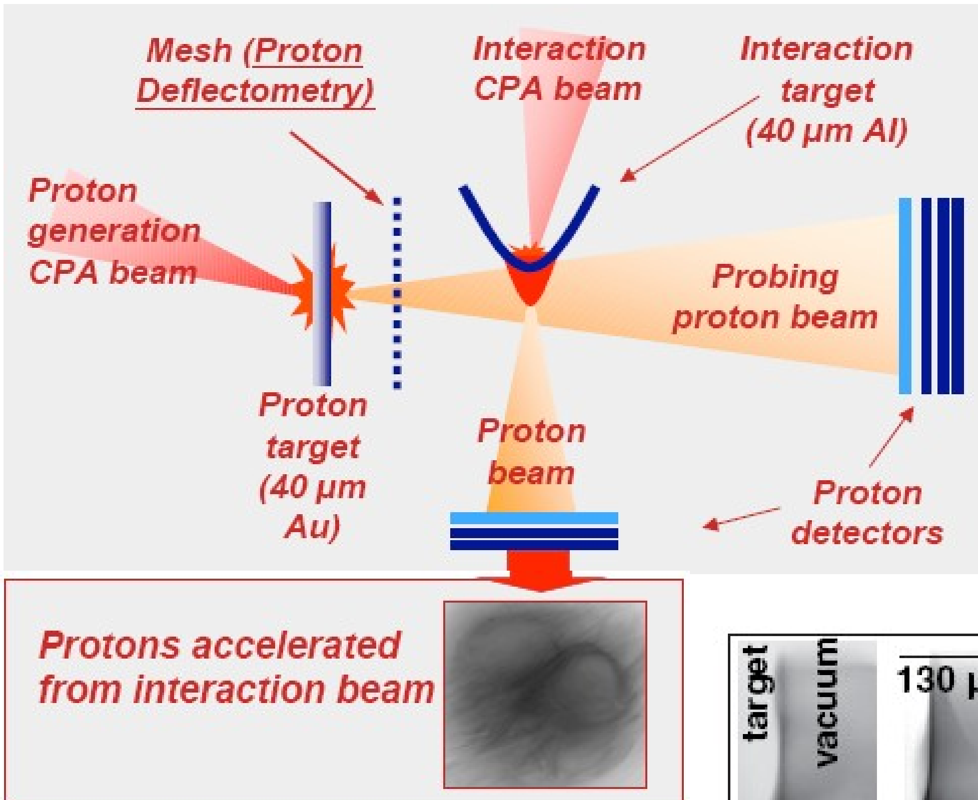
Physical mechanism:
acceleration in the space-charge electric field generated by "fast" electrons escaping from the target

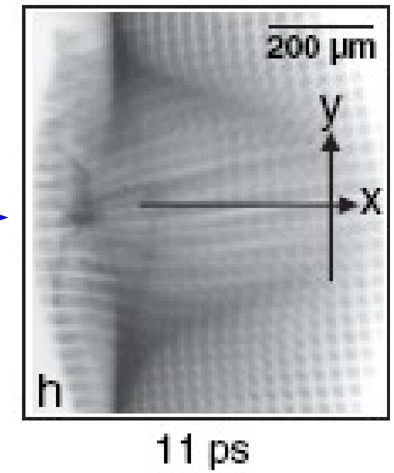


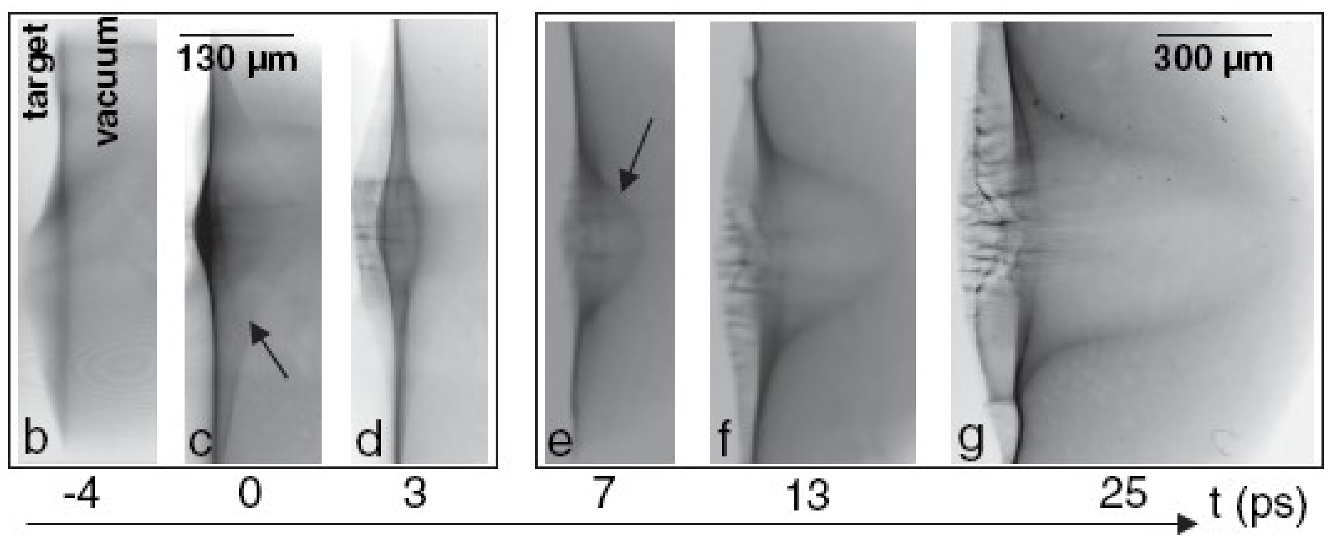


[S. Wilks et al, Phys. Plasmas **8** (2001) 542]

Experimental detection of sheath fields using the proton diagnostic





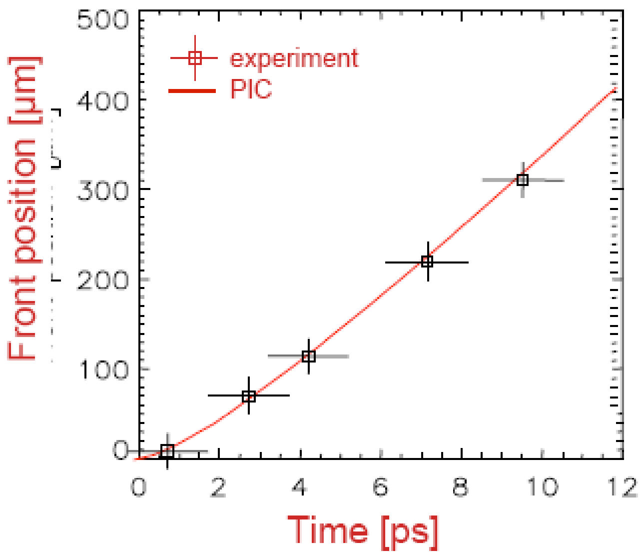


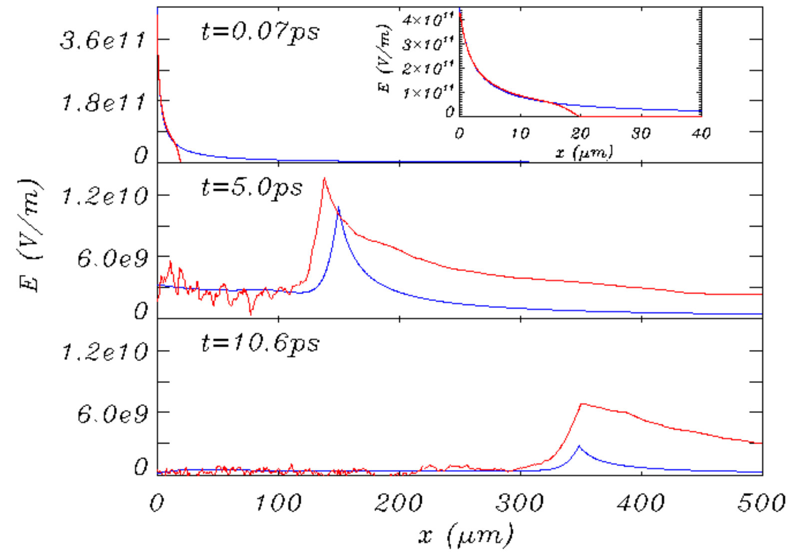
Expanding, bell-shaped electric field front observed in proton images and deflectograms

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

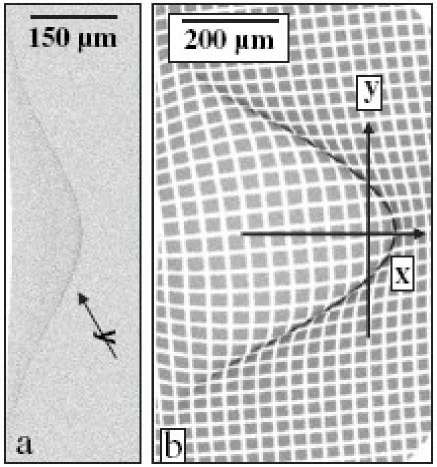
Experimental detection of sheath fields using the proton diagnostic

Experimental results have been compared with PIC simulations using the plasma expansion model.





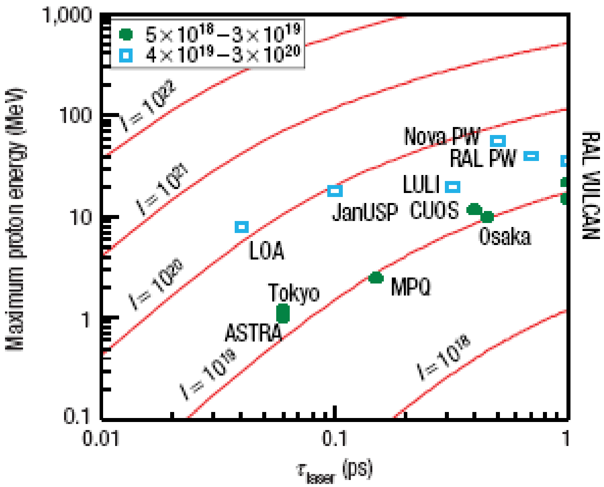
Particle tracing simulations of proton deflection in the PIC fields (plus an “heuristic” modeling of the 2D expansion) fit well experimental images and deflectrograms

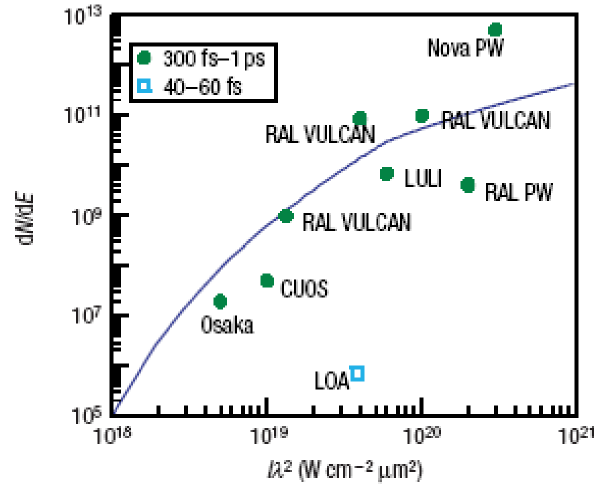


Comparison of fluid and kinetic (PIC) results show the importance of kinetic and non-thermal effects in the plasma expansion

L. Romagnani, J. Fuchs, M. Borghesi, P. Antici, P. Audebert, F. Ceccherini, T. Cowan, T. Grismayer, S. Kar, A. Macchi, P. Mora, G. Pretzler, A. Schiavi, T. Toncian, O. Willi, Phys. Rev. Lett. **95** (2005) 195001

Experimental State of the Art (quick look)





Scaling of ion energy and number vs. pulse duration and irradiance checked vs."modified" Mora's isothermal model

From: M.Borghesi et al, Fusion Science & Technology **49** (2006) 412;
J. Fuchs et al, Nature Physics **2** (2005) 48 .

A few recent results, all based on TNSA:

- narrow energy spectrum of protons from engineered double-layer target
[H. Schwoerer et al, Nature **439** (2006) 445]

- MeV carbon ions from pre-heated ("decontaminated") target
[B. Hegelich et al, Nature **439** (2006) 441]

- Ultrafast "laser-plasma microlens" for ion beam focusing and energy selection
[T. Toncian et al, Science **312** (2006) 410]

What about other ion populations? (I)

For prepulse-free measurement, the density profile is sharp also at the front side: TNSA in backward direction observed for thin targets (electrons have time to reflux back) and almost symmetrical with forward emission

T.Ceccotti et al, PRL **99** (2007) 185002

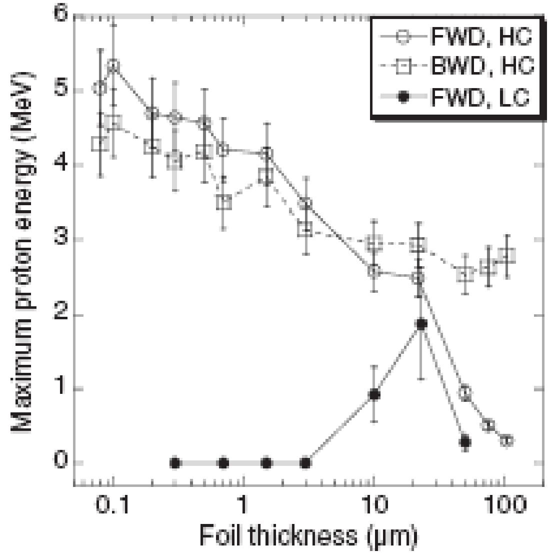


FIG. 1. Variation of maximum detectable proton energy as a function of target thickness. The FWD and BWD emissions for a laser contrast of 10^{10} (10^6) and intensity of 5×10^{18} W/cm^2 (10^{19} W/cm^2) are represented, respectively, by open (solid) circles and squares. Lines are a guide for the eye.

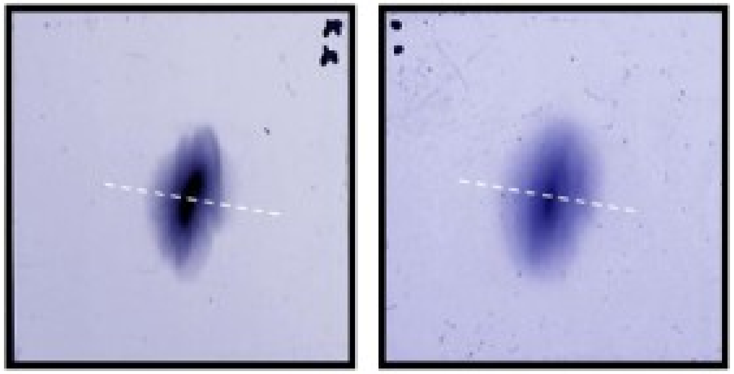
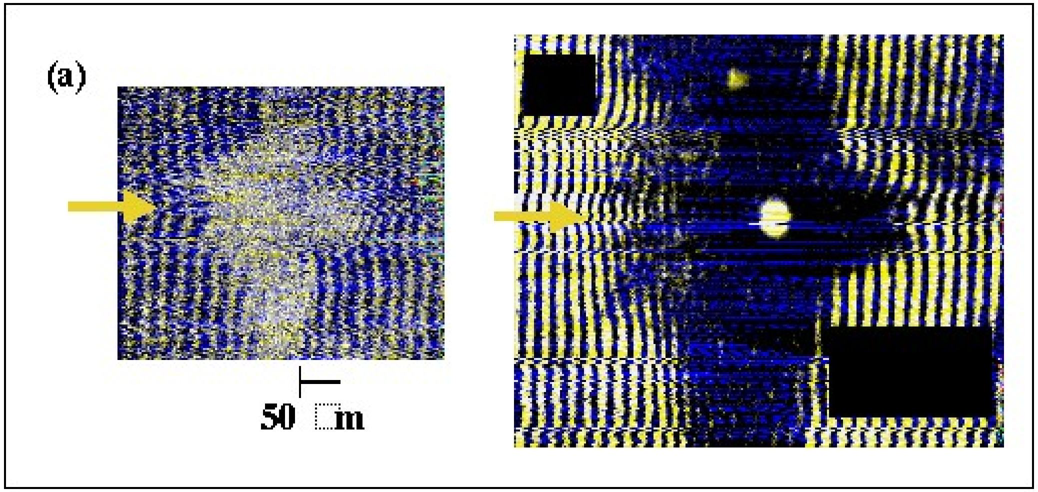


FIG. 2 (color online). Radiochromic films profiles in the FWD (left) and BWD (right) direction for the same shot. The estimated divergence along the dashed lines is around 4.5° for both proton beams.

What about other ion populations? (II)

In petawatt ($I \sim 10^{20}$ W/cm^2) experiments for "quite thin" targets a highly collimated dense plasma jet from the rear side is observed:
Is this due to front side ions accelerated by the Radiation Pressure?



(absence of jet for larger thickness ascribed to collisional ion stopping in the target)

S.Kar, M.Borghesi, S. V. Bulanov, A.J.MacKinnon, P.K.Patel, M.Key, L.Romagnani, A.Schiavi, T. V. Liseykina, A.Macchi, O.Willi,
RAL CLF annual report 2003-2004, p.24,
submitted to PRL

Simulations suggest regime transition at intensities ~ 10^{21} W/cm^2

Results from “multi-parametric” PIC simulations:

- for maximal ion energy an optimal areal density $n_e d$ exists for given intensity I

- ion energy scales with laser energy ε_L
  as $\varepsilon_L^{1/2}$ for $I<10^{21}$ W/cm^2
  as ε_L for $I>10^{21}$ W/cm^2

- transition is explained by the dominance of Radiation Pressure Acceleration

T.Esirkepov et al, PRL **96** (2006) 105001

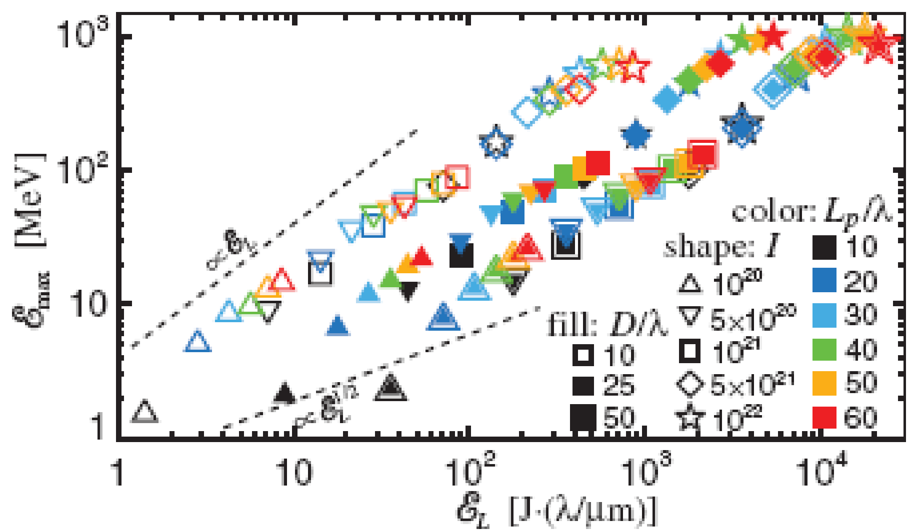
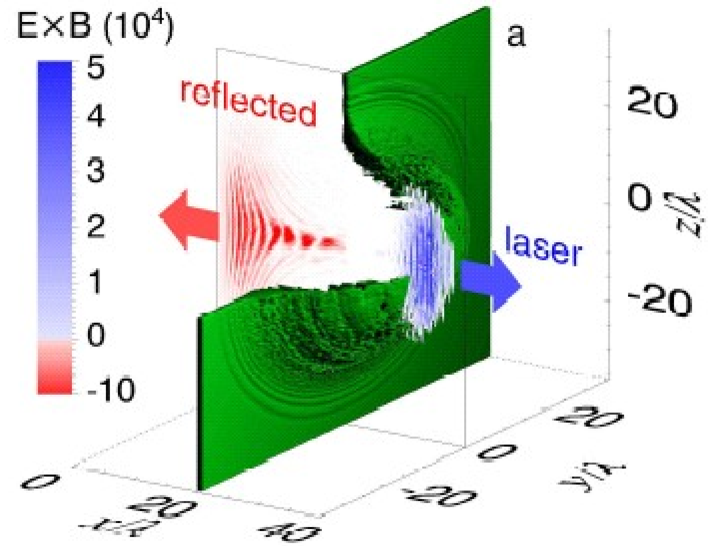


FIG. 3 (color). Proton maximum energy vs laser pulse energy for $l = \lambda$, $n_e = 100 n_{cr}$. The dashed lines exemplify possible scalings.

Relativistic ions: the "*Laser-Piston*" regime

Ultra-relativistic interaction regime
"dominated by radiation pressure"

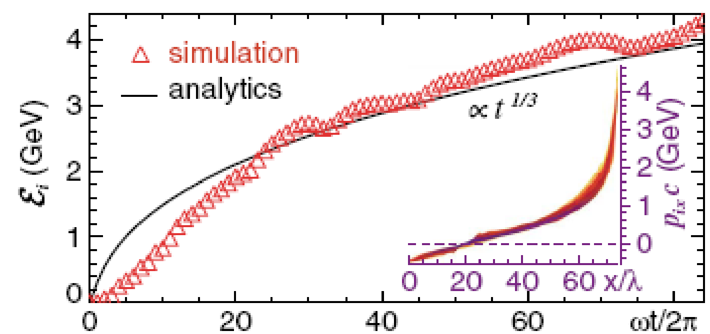
T.Esirkepov, M.Borghesi, S.V.Bulanov, G.Mourou, T.Tajima, PRL **92**, 175003 (2004)

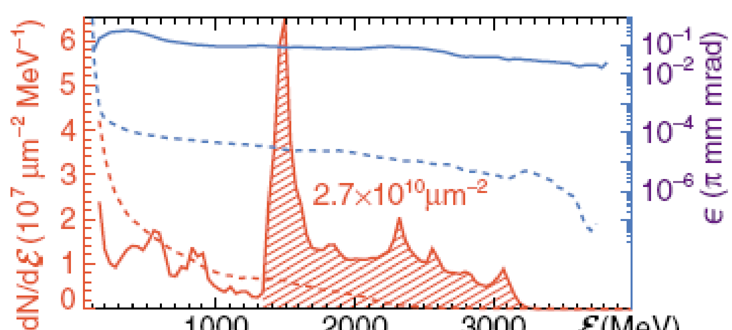


Required laser intensity

$I \geq 10^{23}$ W/cm^2

The foreseen ion beam parameters make this attractive as a driver of low-energy neutrino sources for studies of CP violation in $\nu_\mu \rightarrow \nu_e$ oscillations

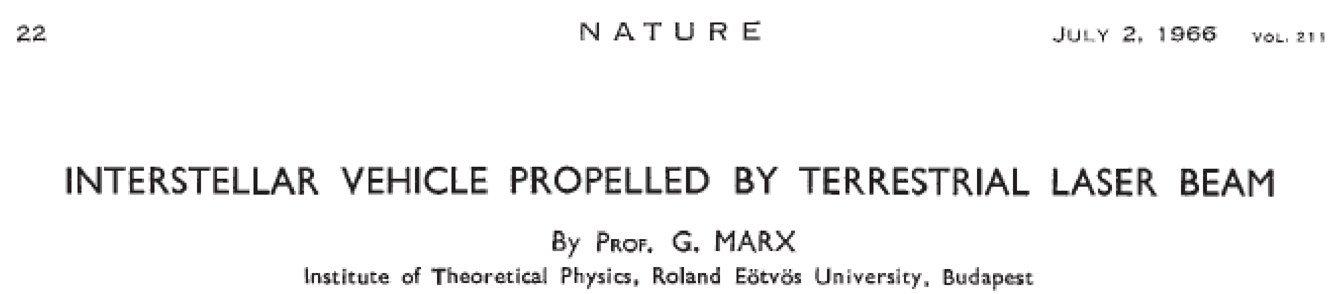




S.V.Bulanov, T.Esirkepov, P.Migliozzi, F.Pegoraro, T.Tajima, F.Terranova, NIM A **540**, 133 (2005);
F. Terranova, S.V.Bulanov, J.L.Collier, H.Kiriyama, F.Pegoraro, NIM A **558**, 430 (2006).

Radiation Pressure Acceleration: transfering the momentum of light to matter

The **acceleration of a massive mirror** by light pressure is particularly efficient when the velocity becomes close to the speed of light (this suggested the “visionary” application of a **laser-propelled rocket** 42 years ago:)

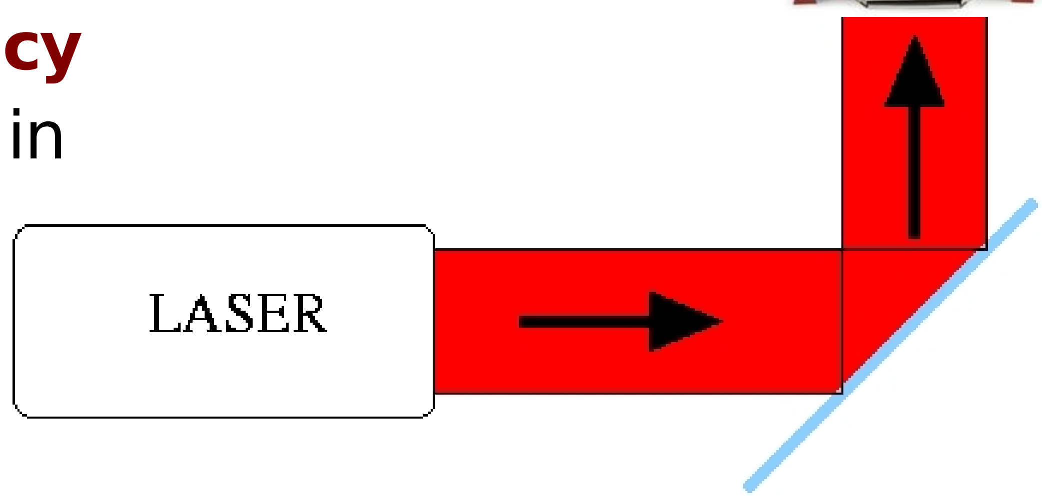

22 NATURE JULY 2, 1966 VOL. 211

INTERSTELLAR VEHICLE PROPELLED BY TERRESTRIAL LASER BEAM

By PROF. G. MARX

Institute of Theoretical Physics, Roland Eötvös University, Budapest

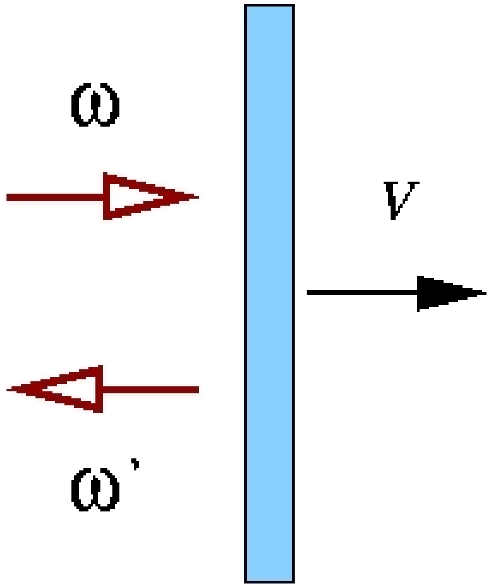
A **breakthrough in efficiency** is thus expected as we enter in the **relativistic regime**



Efficiency of RPA for a perfect mirror

Steady acceleration of a rigid mirror reaches 100% efficiency as

$$\beta = \frac{V}{c} \rightarrow 1$$



$$\beta(t) = \frac{(1+2\tau)^2 - 1}{(1+2\tau)^2 + 1}, \qquad \tau = \frac{ISt}{Mc^2}$$

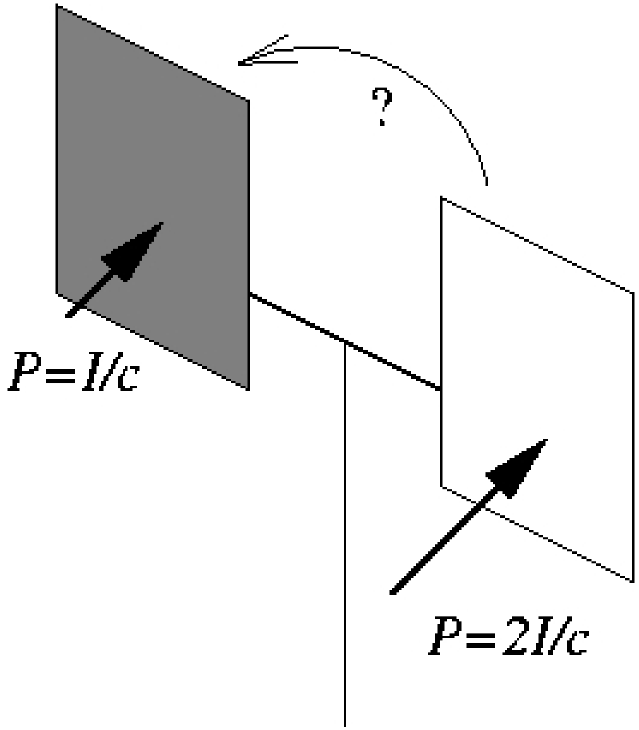
Simple argument:

conservation of "number of photons" plus Doppler shift of reflected light

$$N = \frac{IS}{\hbar}\omega = \frac{I'S}{\hbar}\omega', \qquad \omega' = \omega\frac{1-\beta}{1+\beta}$$

$$\frac{\Delta\mathcal{E}}{\Delta t} = N\hbar(\omega - \omega') = \frac{2\beta}{1+\beta} IS$$

Maximize the effect of Radiation Pressure: the "optical mill" (Solar radiometer) example



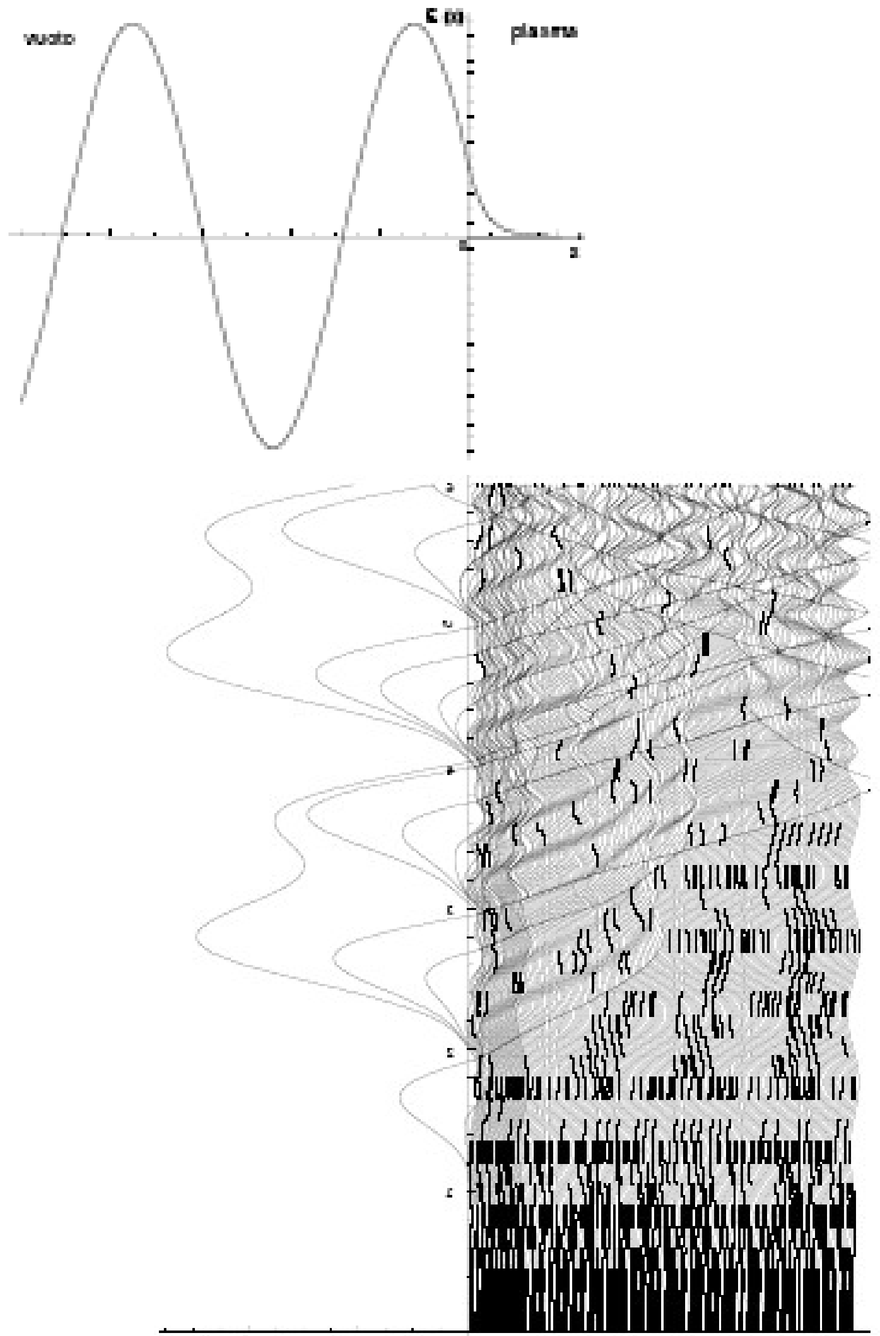
The mill spins in the opposite direction to what we'd expect thinking of P_{rad} only:

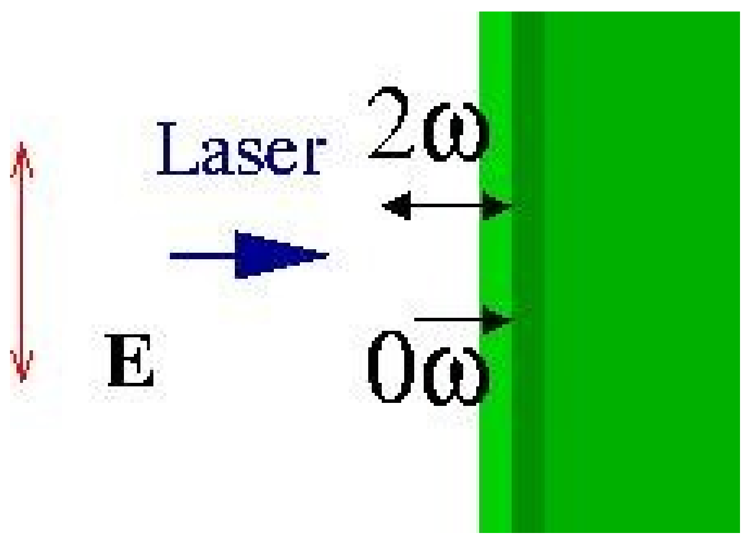
the heating of the **black** (absorbing) surface increased the thermal pressure of the background gas (imperfect vacuum!)

In the high-intensity irradiation of a solid-density (plasma) target, "heating" is due to energy absorption into electrons

How to "switch off" fast electrons

Forced oscillations of the electrons across the plasma-vacuum interface ($L << \lambda$) driven by the 2ω component of the **J**x**B** force (normal incidence) are non-adiabatic and lead to electron acceleration



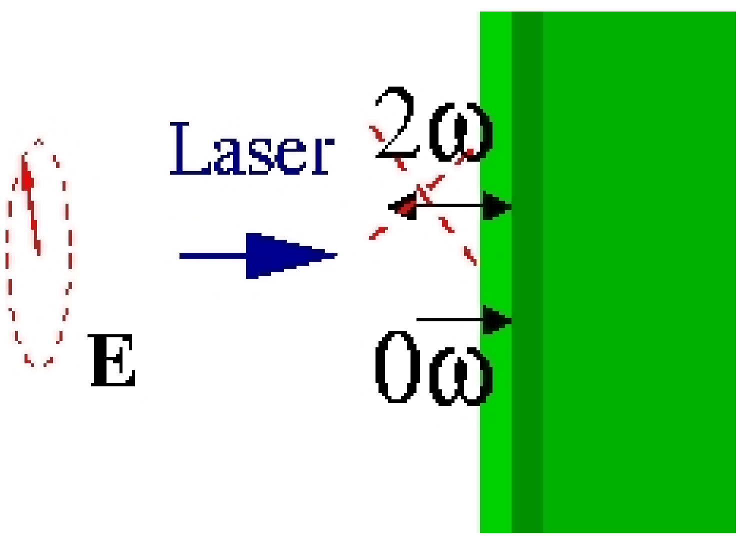


S. Tuveri, tesi di Laurea, 2006

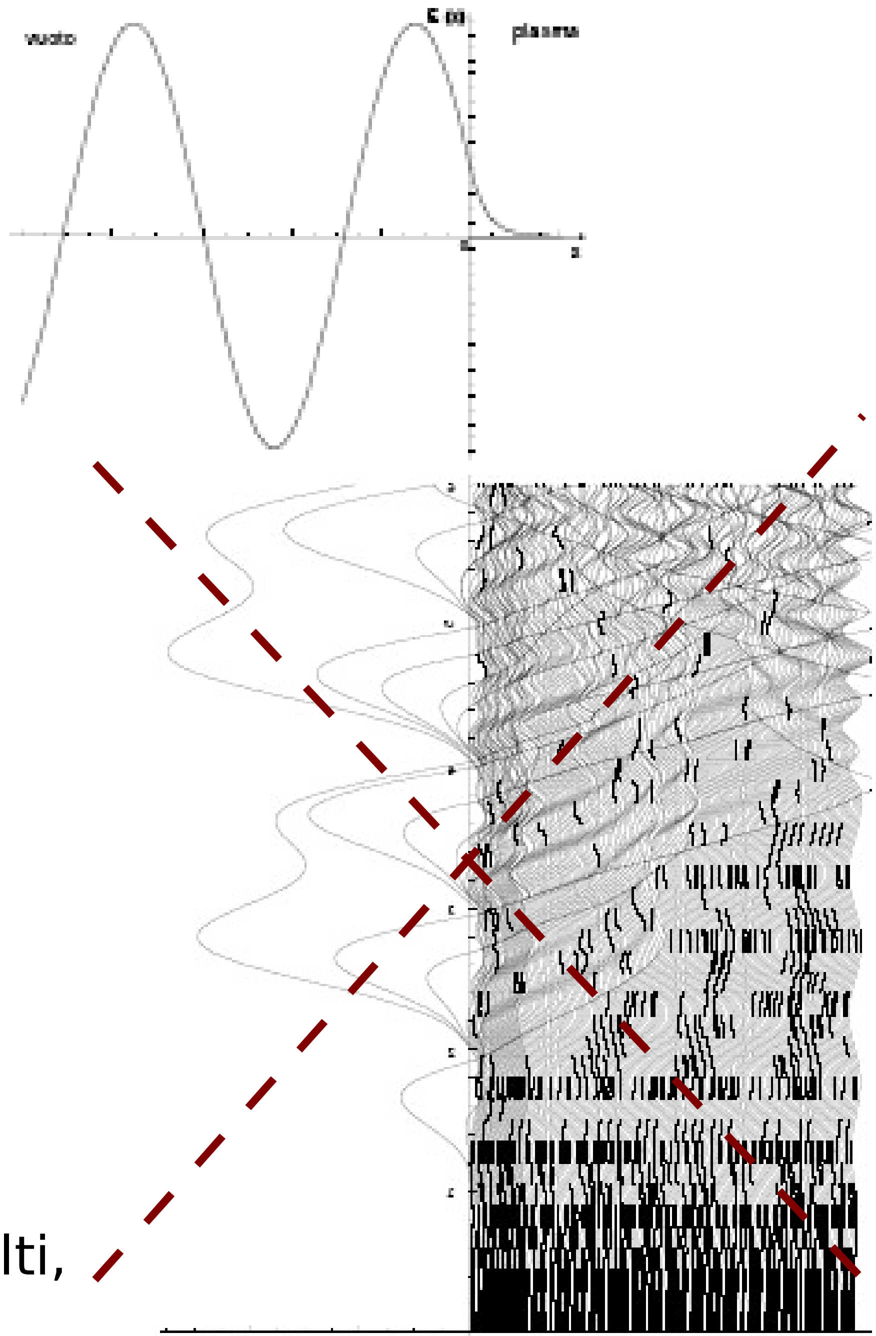
How to "switch off" fast electrons

For circular polarization,
the 2ω component of the **J**x**B** force vanishes:
- inhibition of electron acceleration
- **"direct" ion acceleration**

(i.e. "dominance" of Radiation Pressure)



A.Macchi, F.Cattani, T.V.Liseikina, F. Cornolti, Phys.Rev.Lett **94**, 165003 (2005)



S. Tuveri, tesi di Laurea, 2006

Ultrashort CP interaction with "thick" plasma: ion bunch acceleration without fast electrons

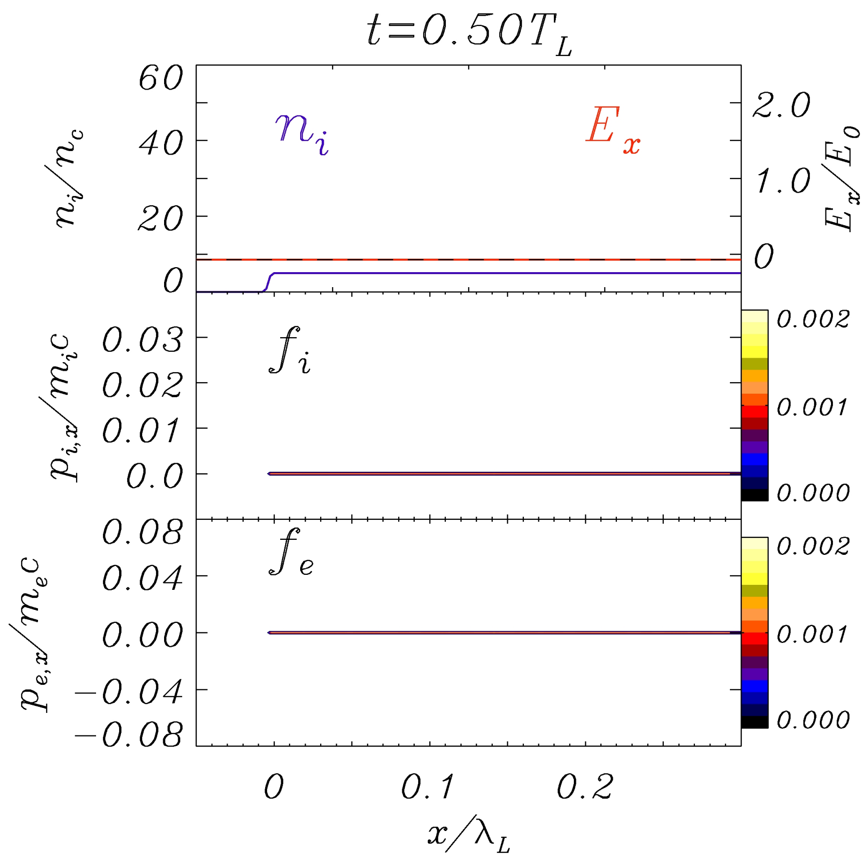
Circular polarization
I=8.6×10^{18}W/cm^2
t=7.5T=20fs
n_e=5n_c=8.6x10^{21}cm^{-3}

- Only one ion population (compared to three for LP)

- ion density spiking and breaking

- "fast" ion bunch in forward direction

- almost no "fast" electrons!



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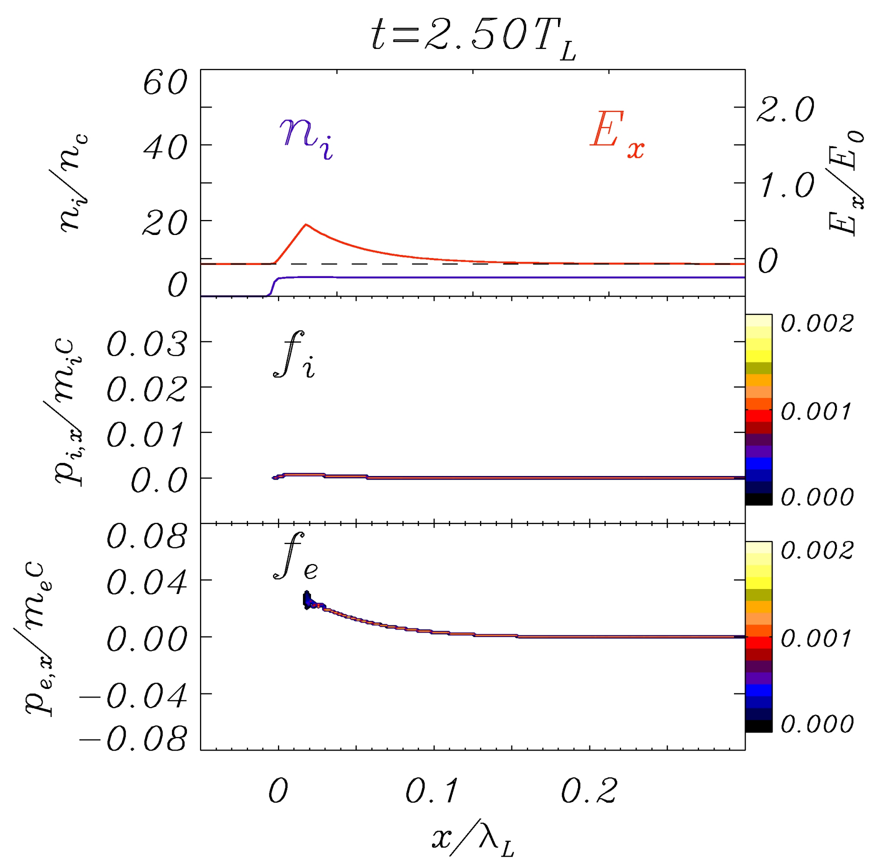

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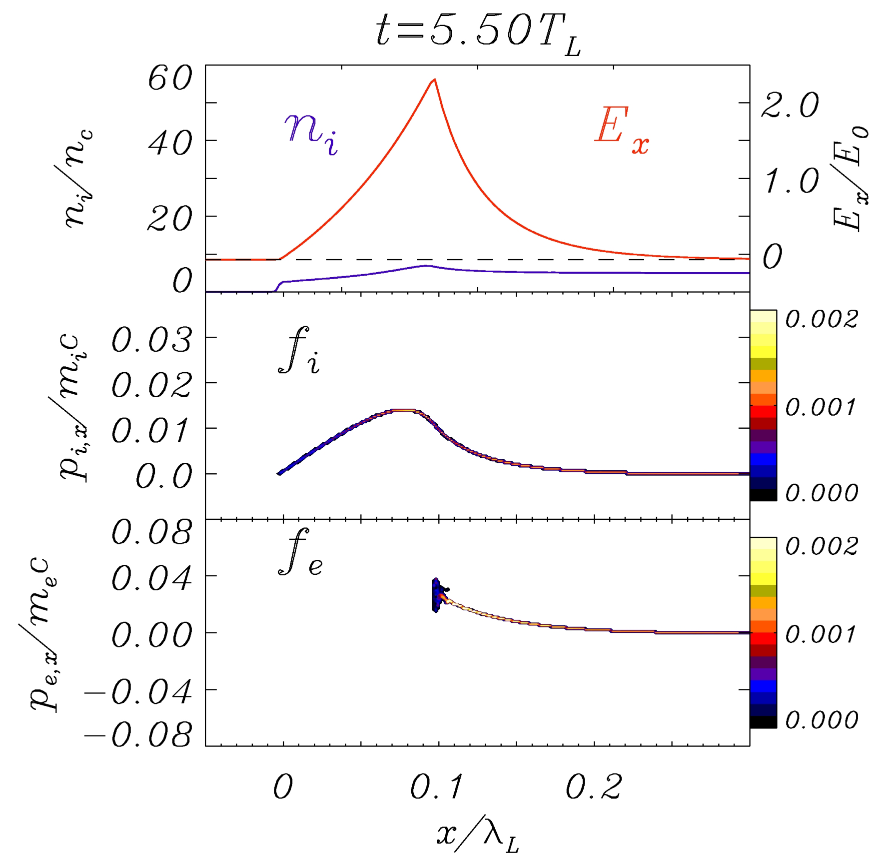

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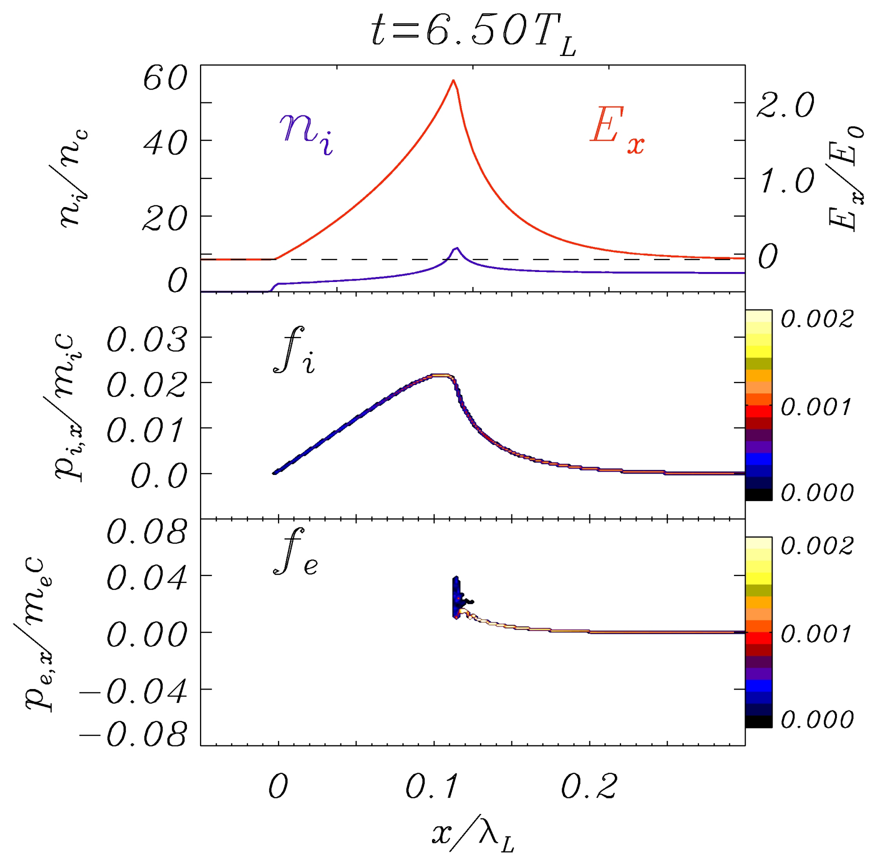


Ultrashort CP interaction with “thick” plasma: ion bunch acceleration without fast electrons

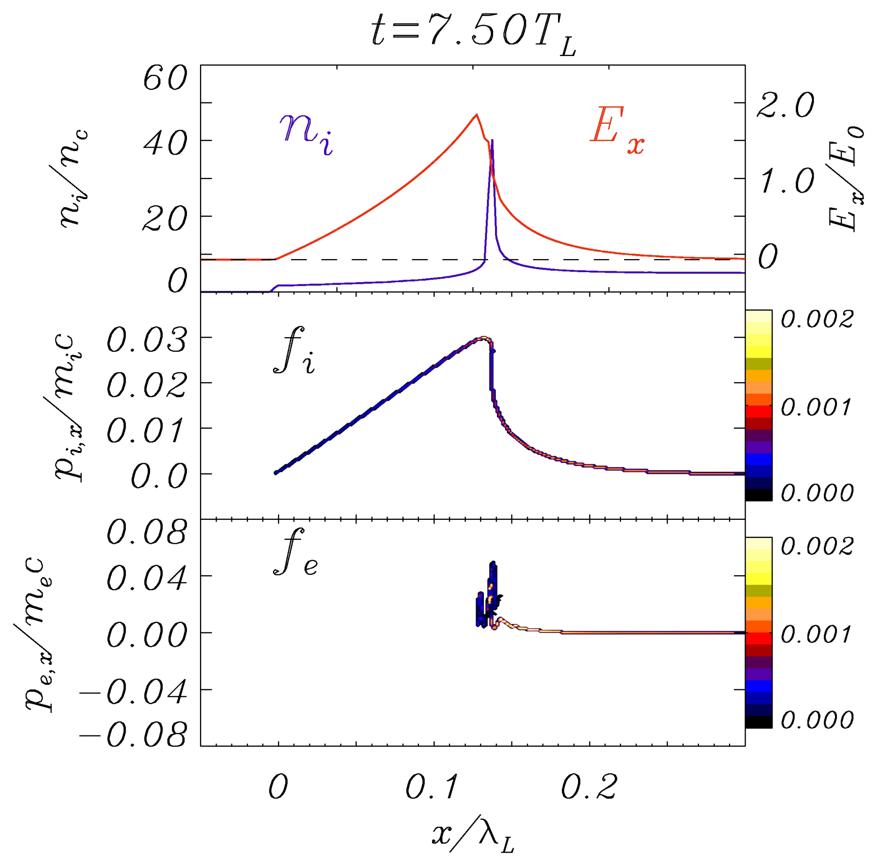
Circular polarization
I=8.6×10^{18}W/cm^2
t=7.5T=20fs
n_e=5n_c=8.6x10^{21}cm^{-3}

- Only one ion population (compared to three for LP)

- ion density spiking and breaking

- “fast” ion bunch in forward direction

- almost no “fast” electrons!



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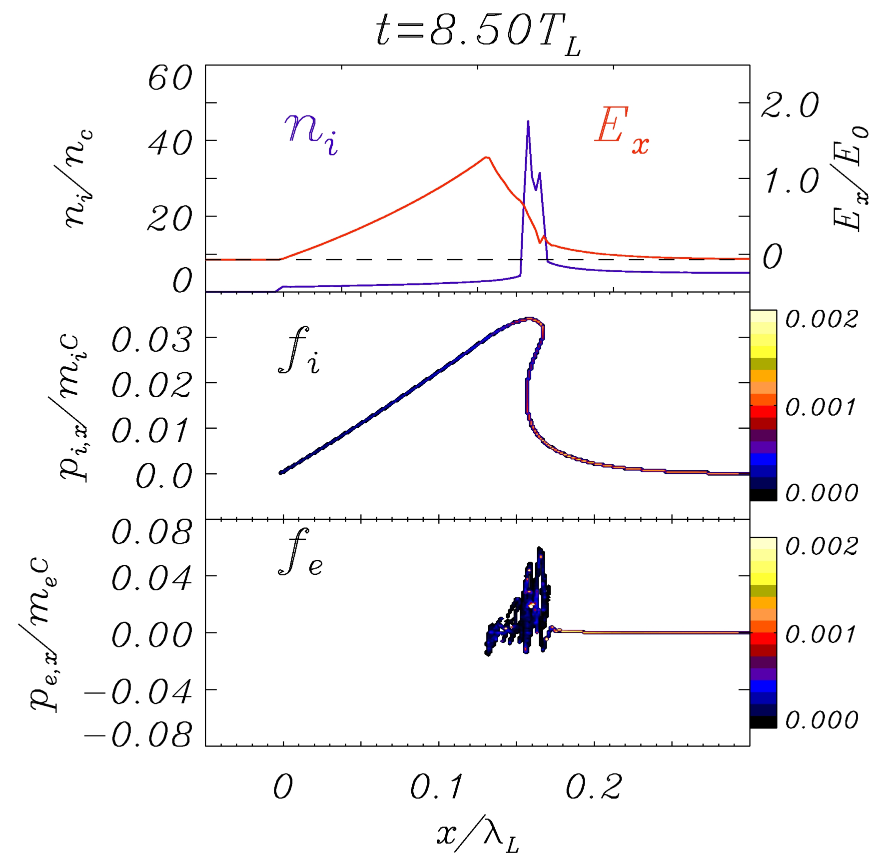

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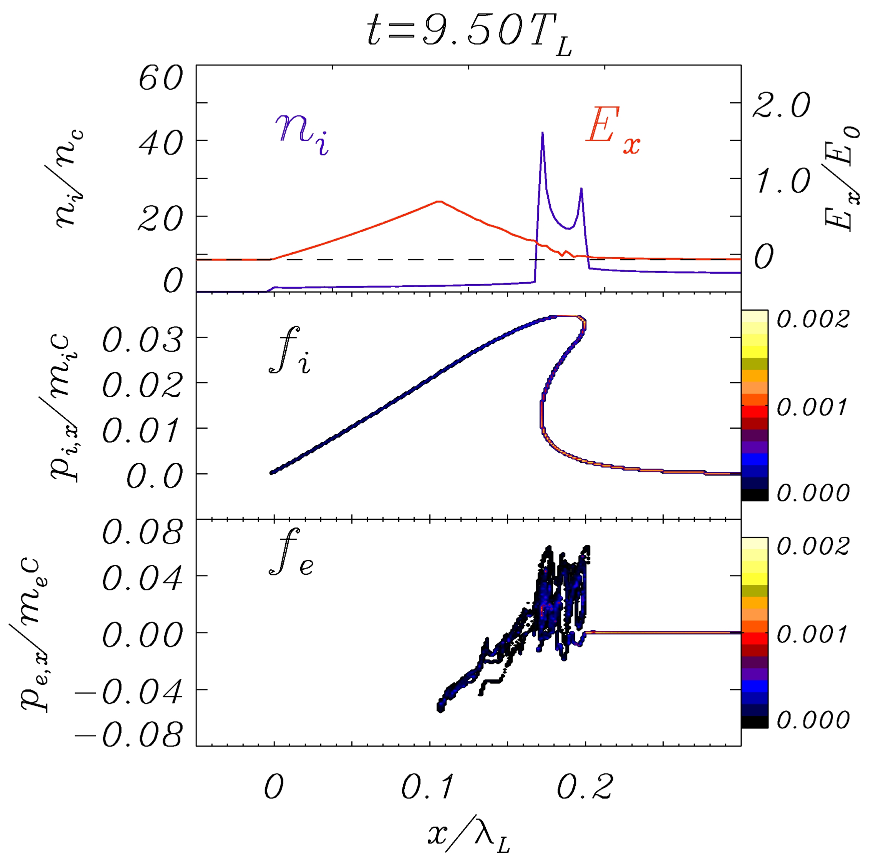

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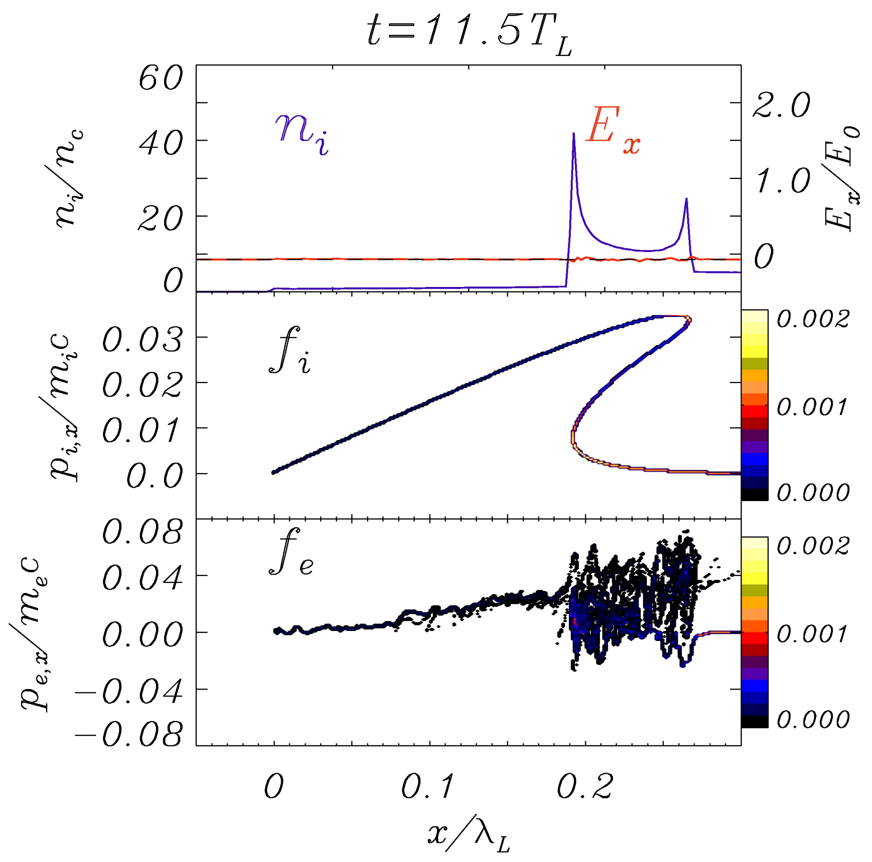

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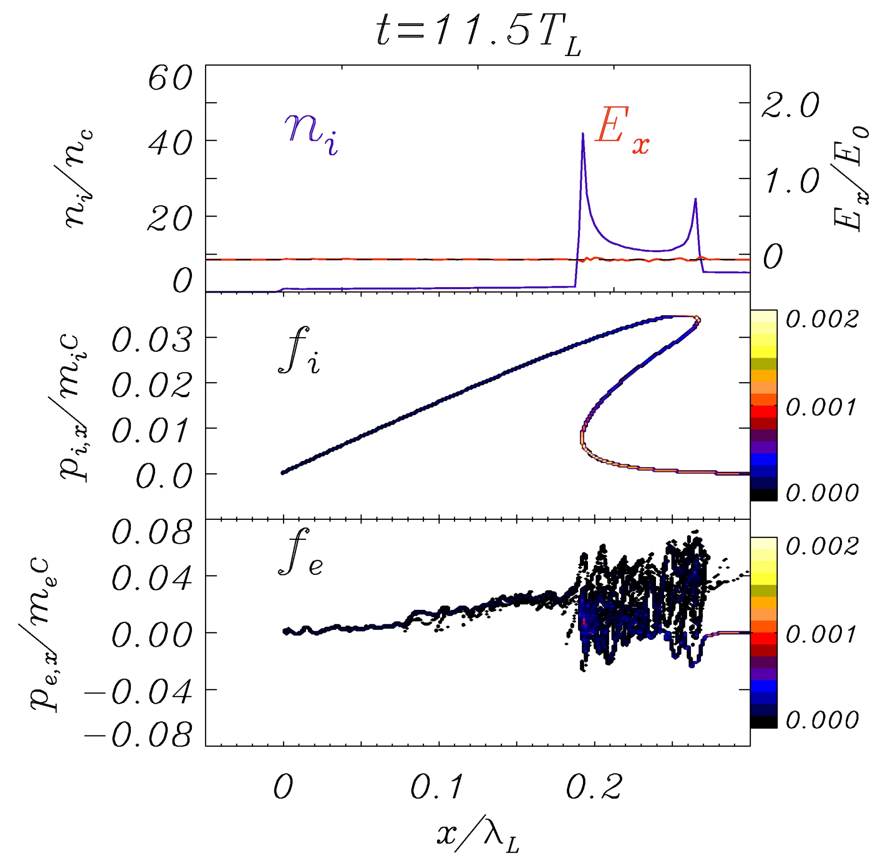
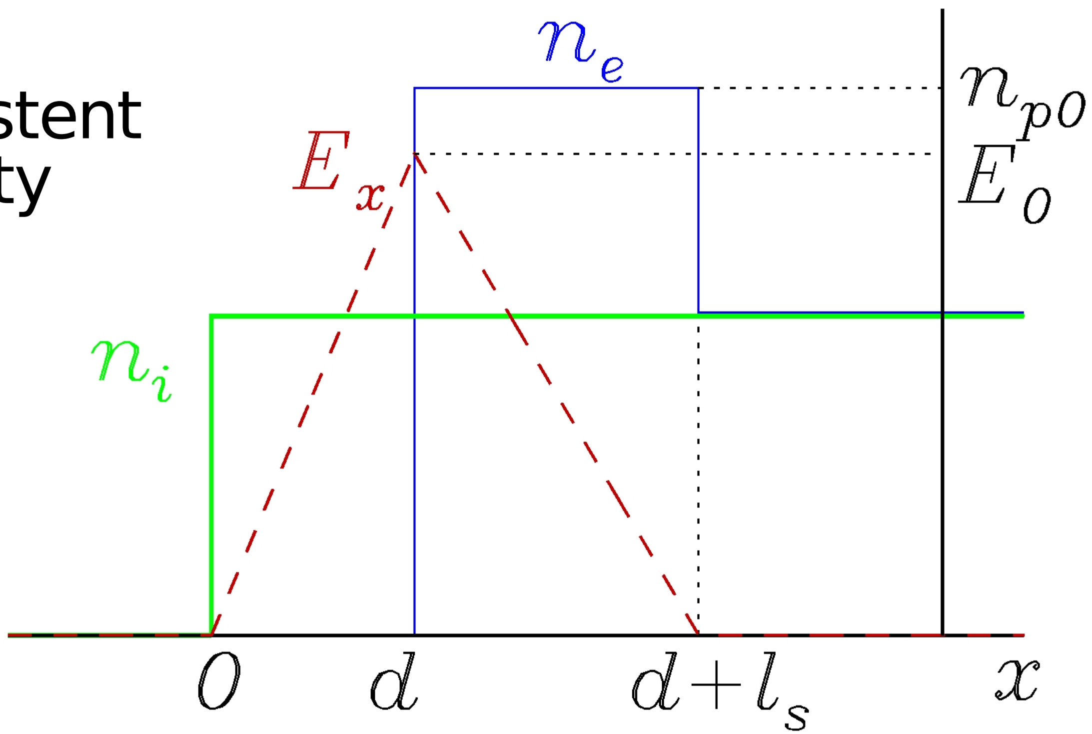


Simple model accounts for simulation results

Basic assumptions:
- electrons in quasi-mechanical equlibrium at any time (electrostatic field E_x balances the ponderomotive force)
- ions move accelerated by the electric field that evolves self-consistently

Approximating E_x by a "triangular" profile and n_i, n_e by "step" functions gives a self-consistent model accounting for density spiking and breaking

Macchi et al,
PRL **94** (2005) 165003



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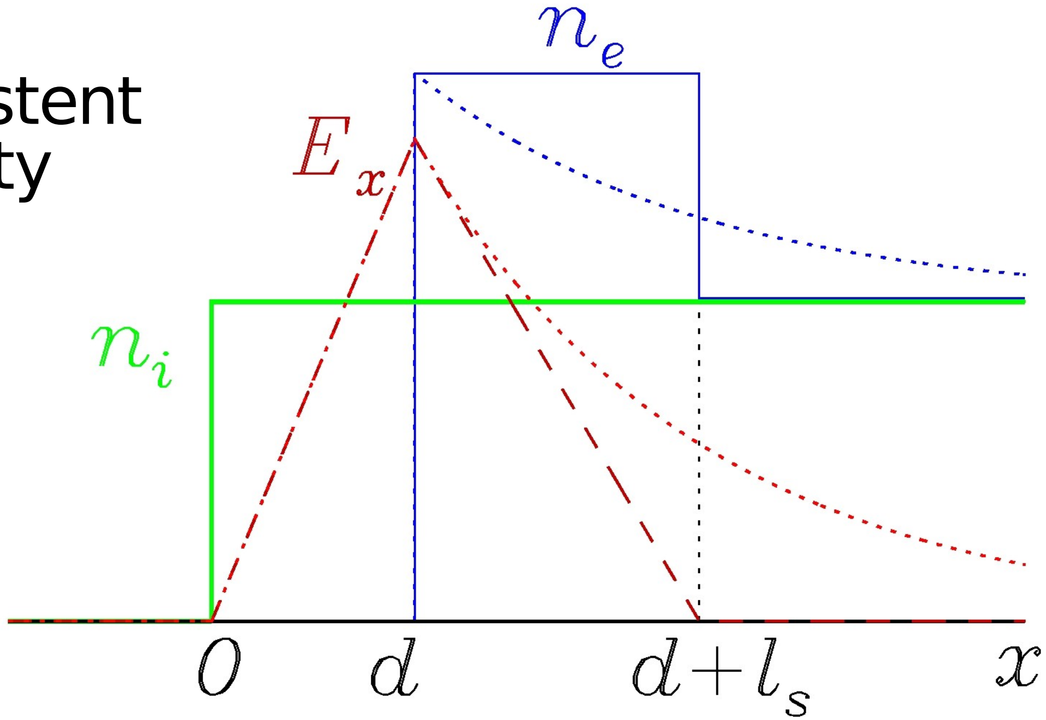

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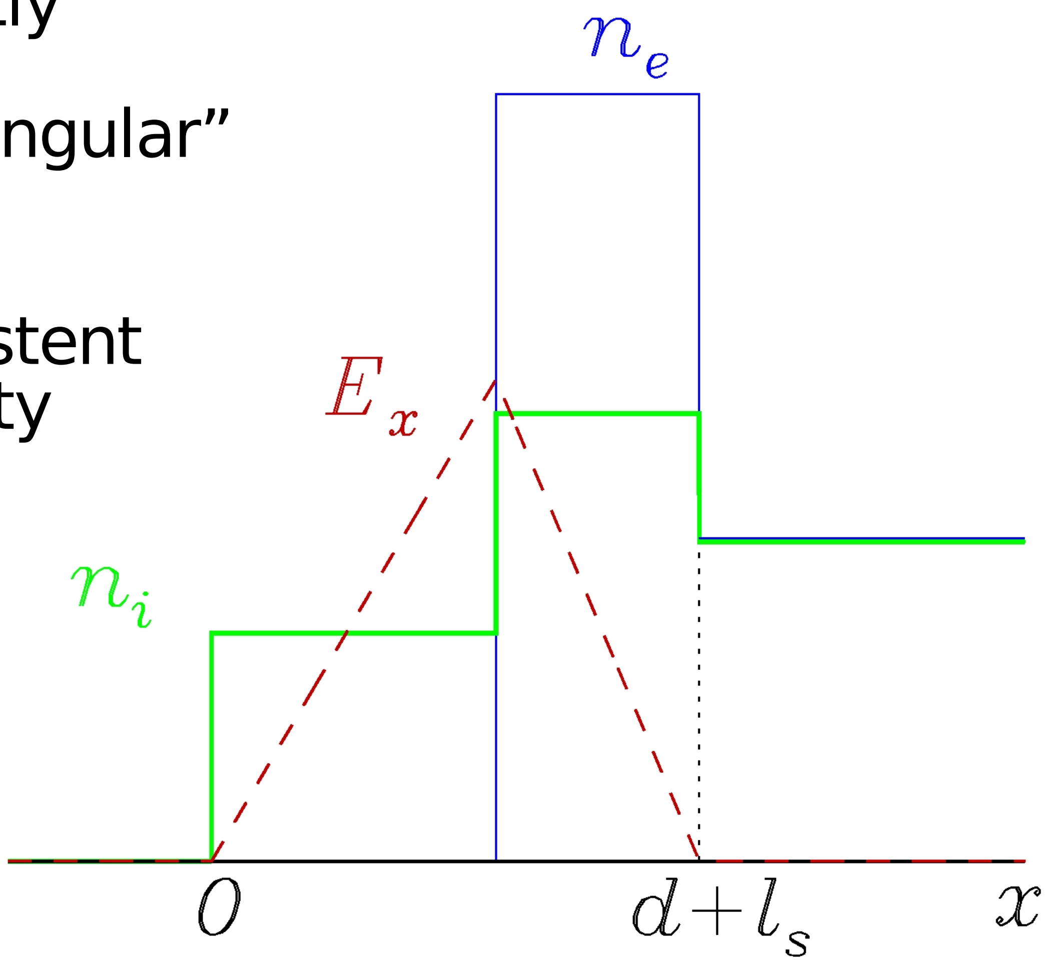

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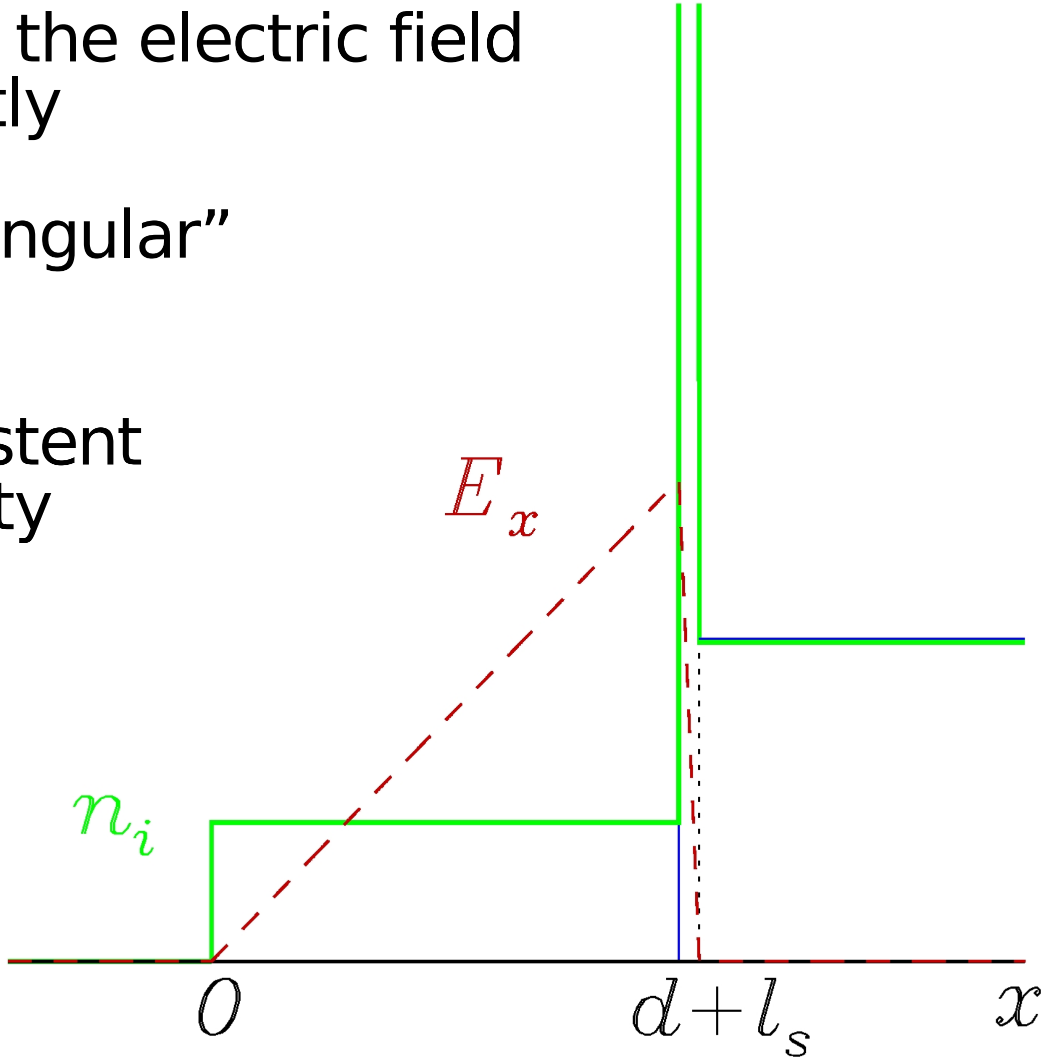
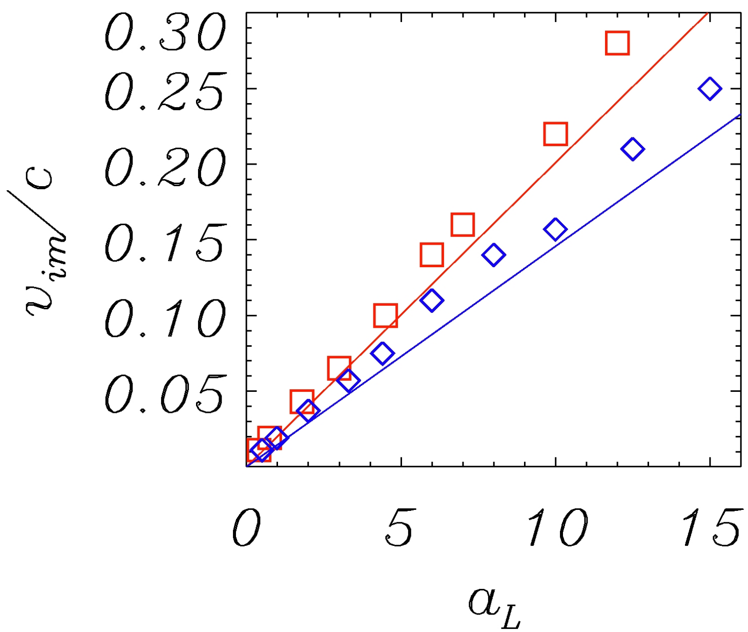
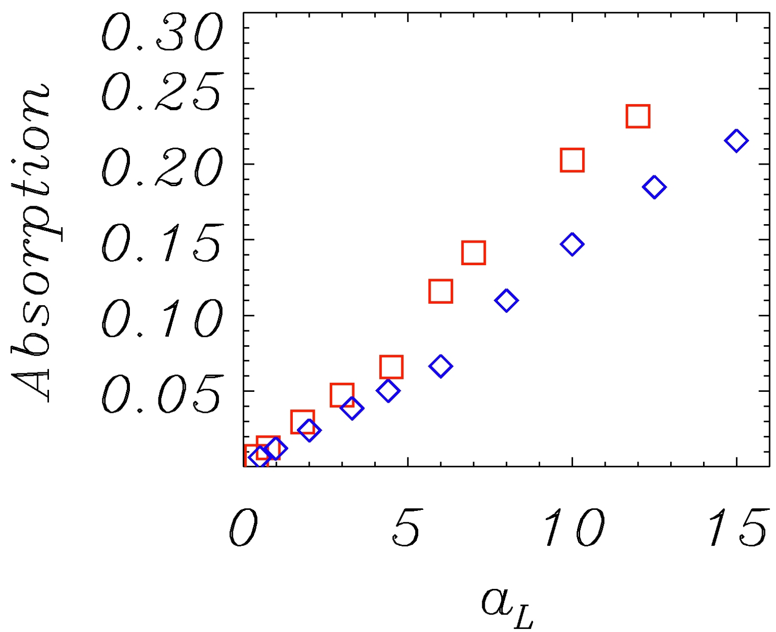


Scaling seen in simulations agrees with simple model

Bunch velocity

$$\frac{v_i}{c} = 2a_0\sqrt{\frac{Z}{A}\frac{m_e}{m_p}\frac{n_c}{n_e}}$$

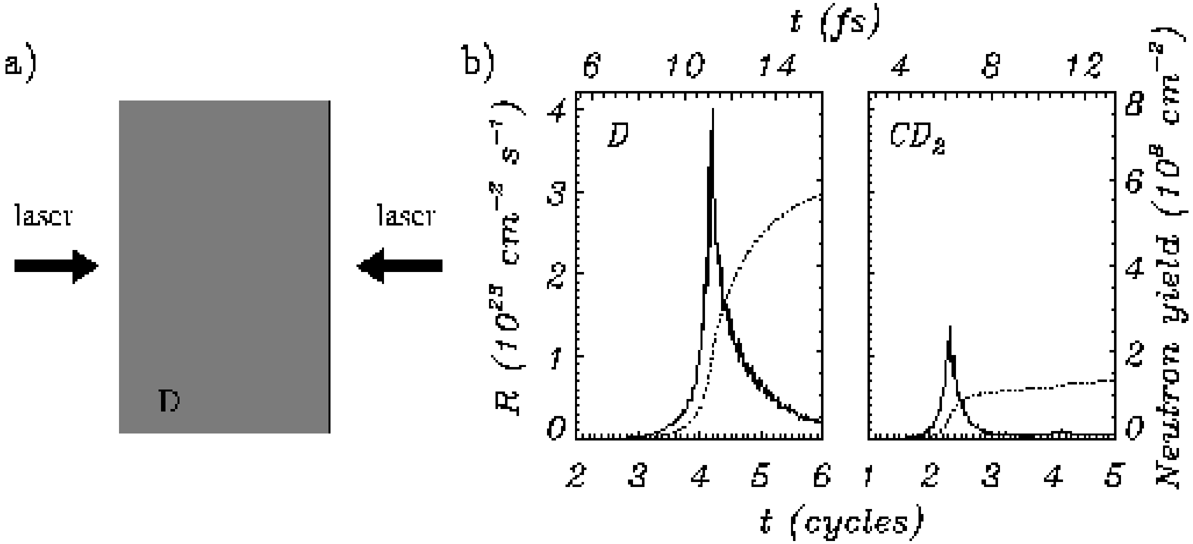




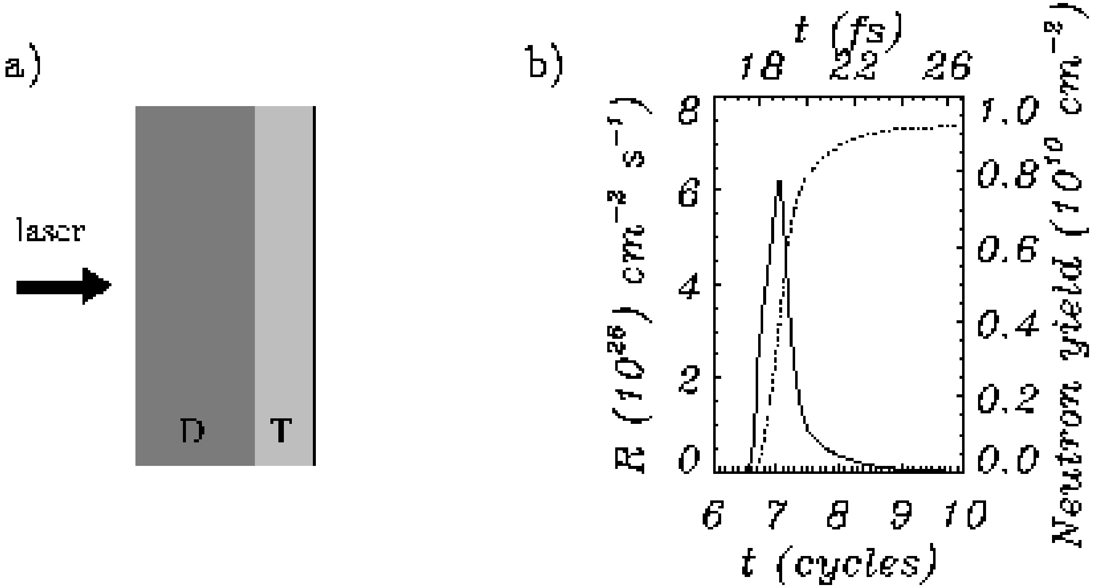
Lyseykina, Prellino, Cornolti, Macchi, IEEE Trans. Plasma Science, to be published

An application of circularly polarized LIA

Driver of beam fusion reactions in D or DT targets for a proposed scheme of a femtosecond source of MeV neutrons
[A. Macchi, Appl.Phys.B **82**, 337 (2006)]



A source for ultrafast control of nuclear processes and time-resolved spectroscopy of nuclei?



RPA with Circular Polarization of a thin foil; a route towards GeV ion energies?

- For target thickness $d < v_i t_p$ "repeated" or "multi-staged" RPA of all the target ions may occur: the laser pulse "follows" the ion bunch

- With appropriate thickness ALL ions are "bunched" and accelerated: the spectrum is monoenergetic "by construction"

- Circular polarization plus ultrathin targets (plus ultrahigh contrast?) is promising for high energy (GeV) with intensities $\sim 10^{21}$ W/cm^2

[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;
+
X.Q.Yan et al, PRL ***100****, 135003 (2008)* **?!? WHAT'S NEW?!?**]

- In this regime the ion energy scales with pulse duration t_p at given intensity (i.e. it scales with the pulse energy)

Simulation of thin foil acceleration with FLAME@INFN-Frascati parameters

- Carbon target, thickness d=0.04μm, $n_e=250n_c=4.3\times10^{23}$ cm^{-3}
- Laser: 26 fs pulse, $I=1.8\times10^{20}$ W/cm^2, relativistic param. $a_0 = 13$
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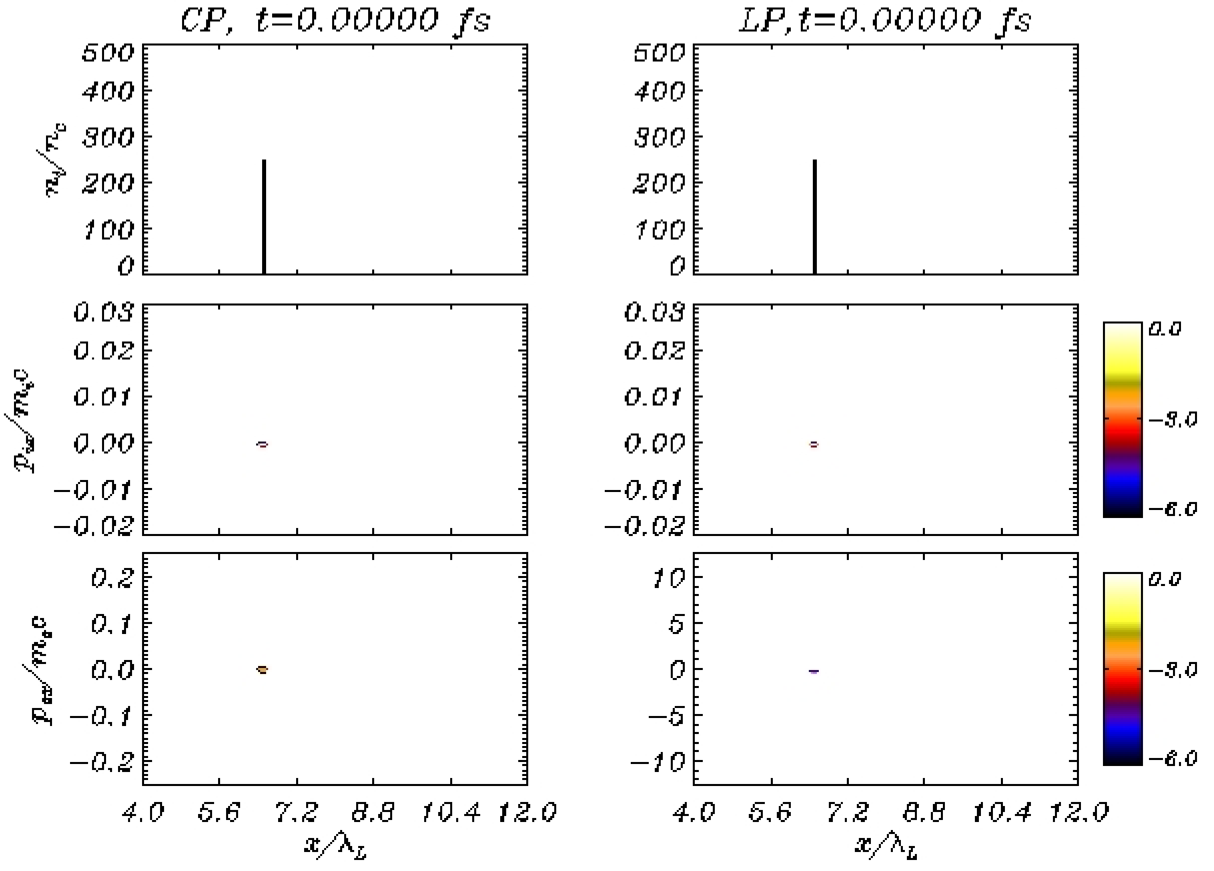

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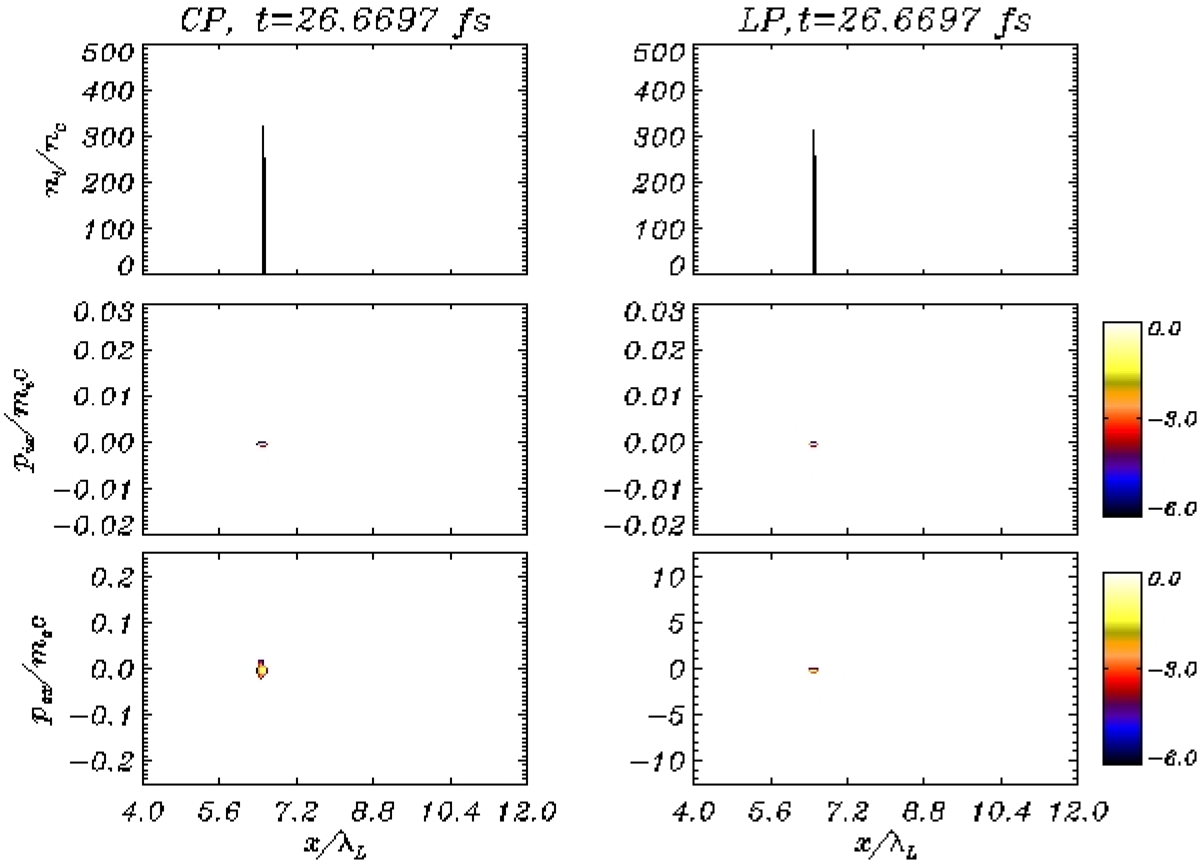

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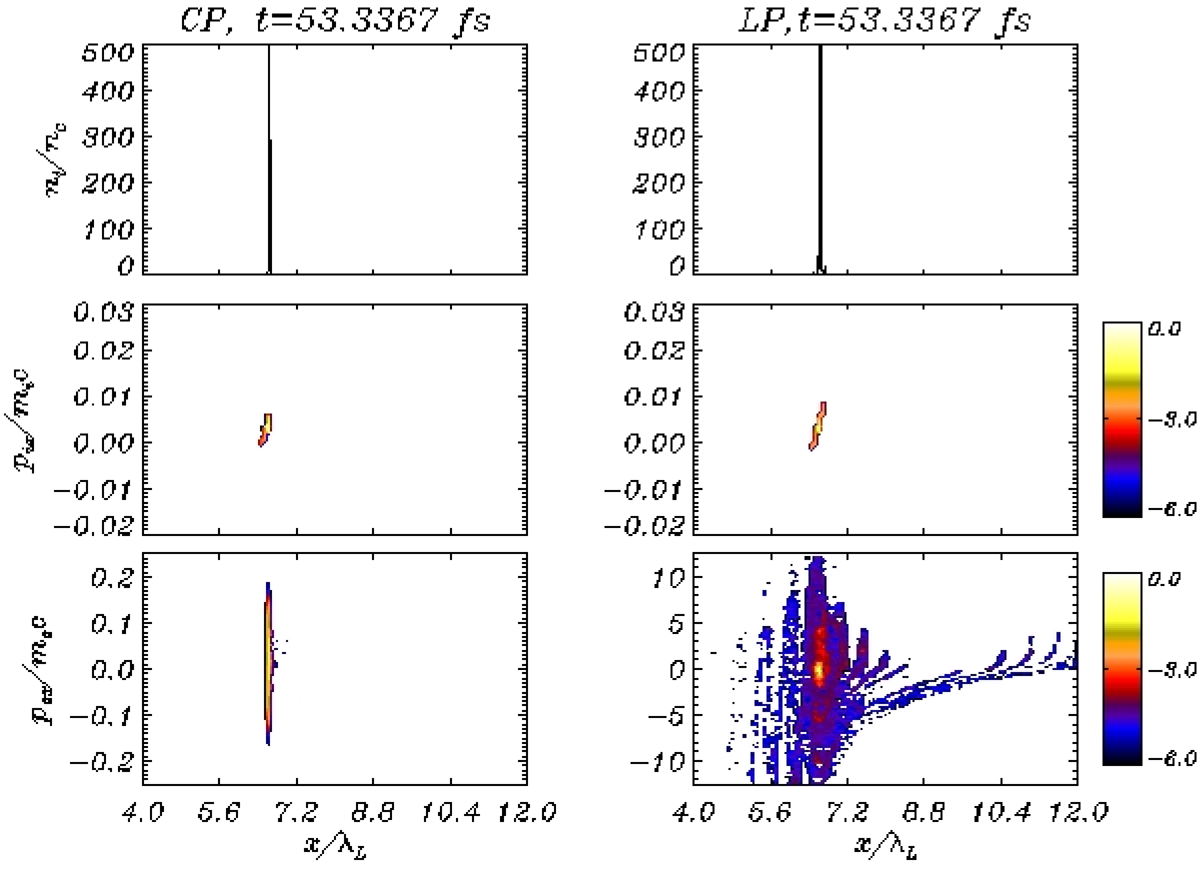

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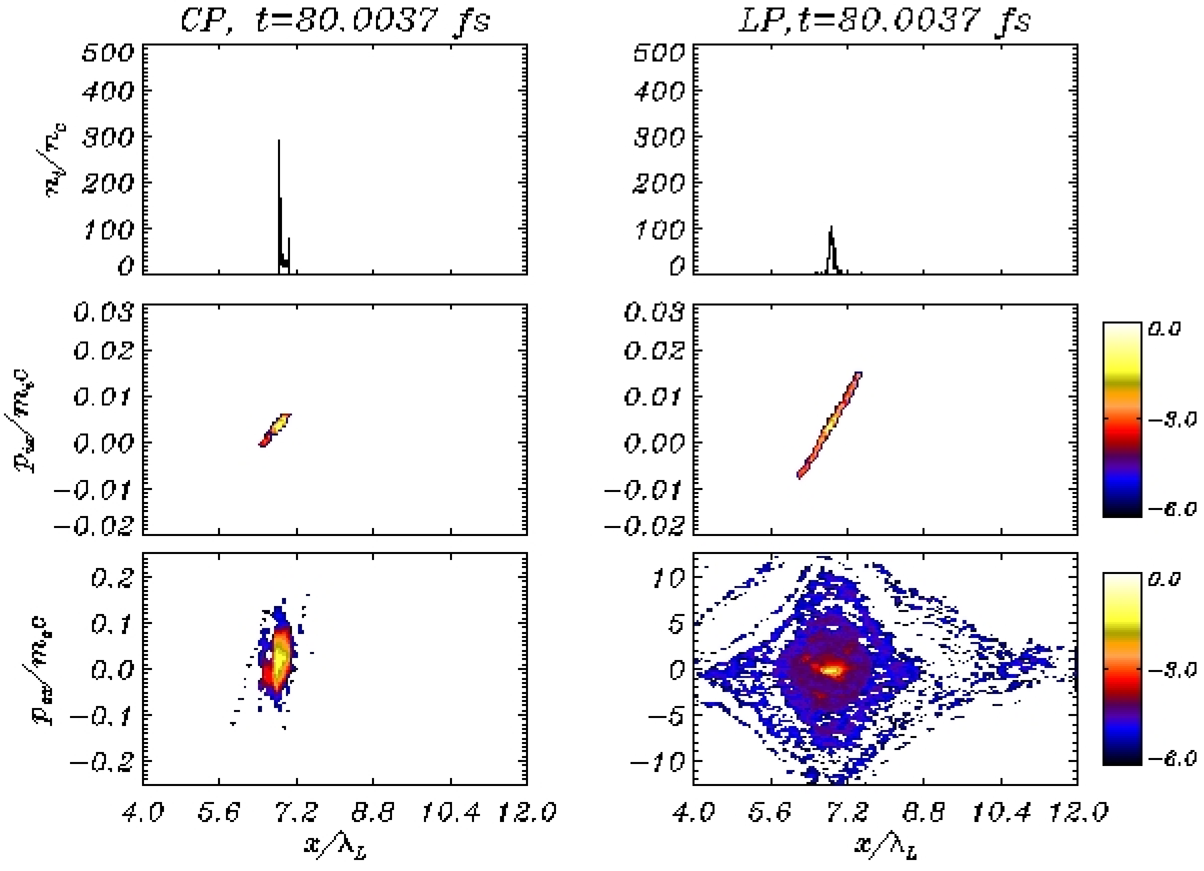

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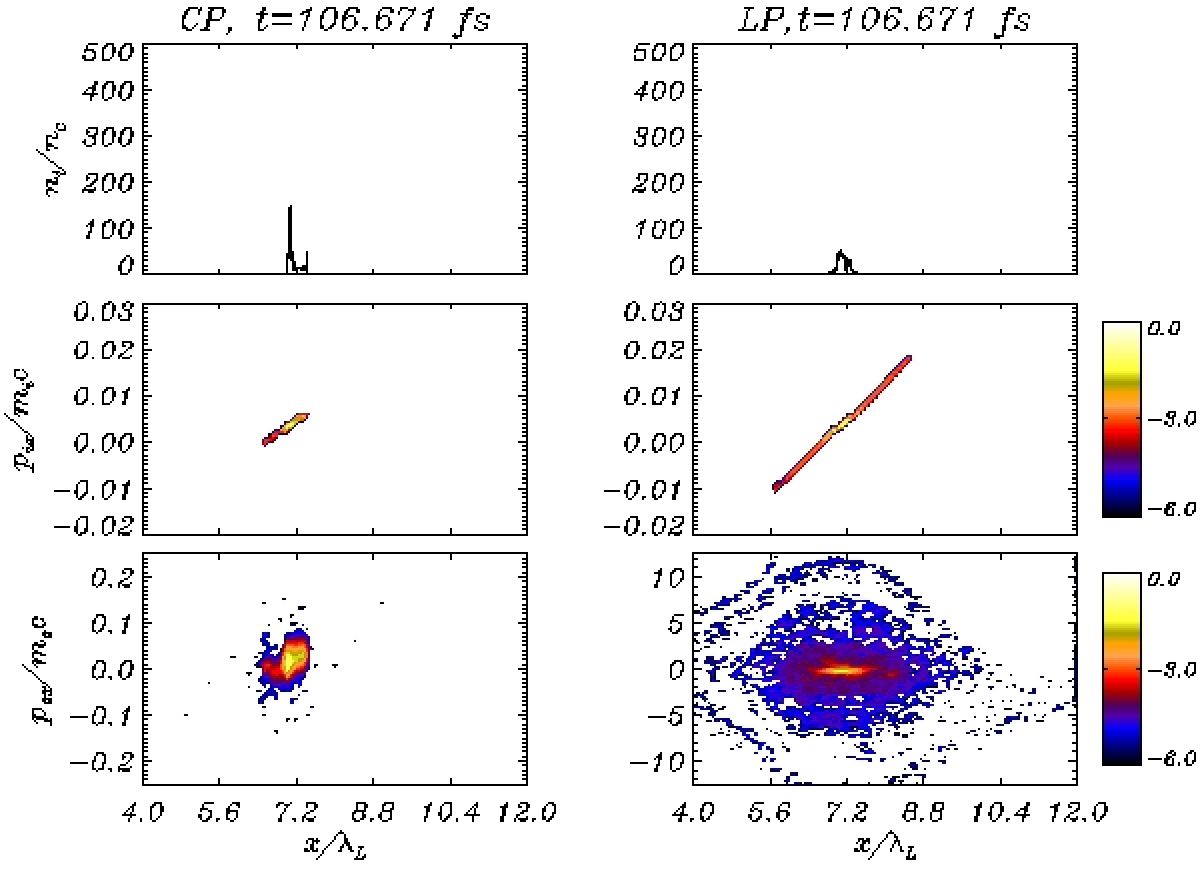

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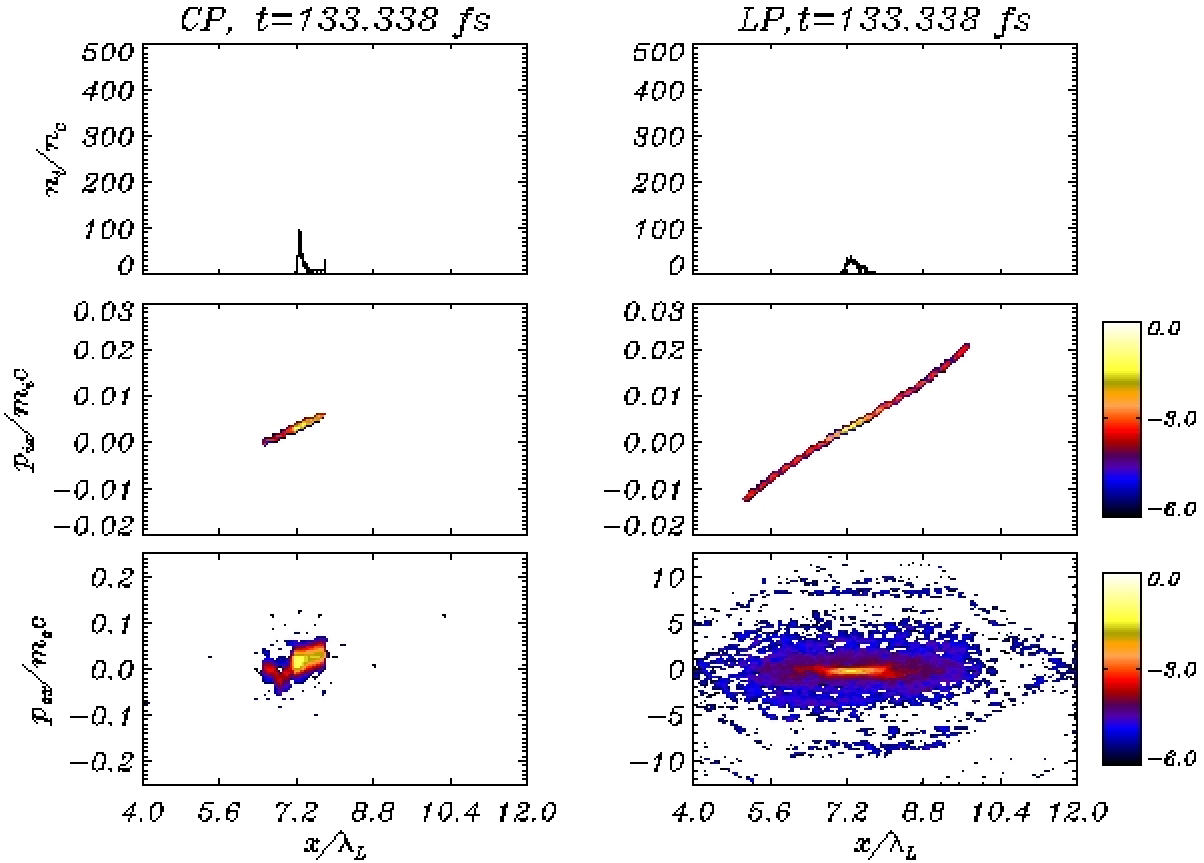

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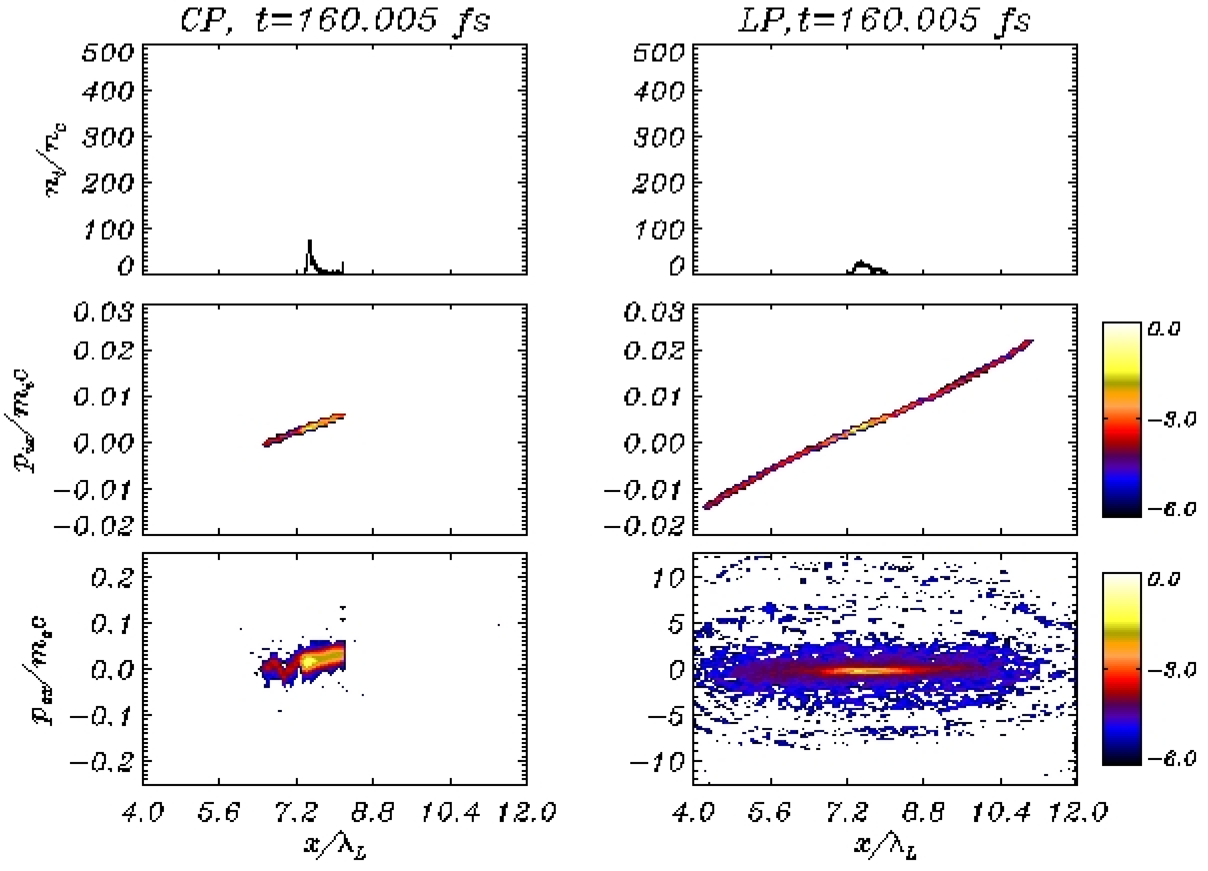

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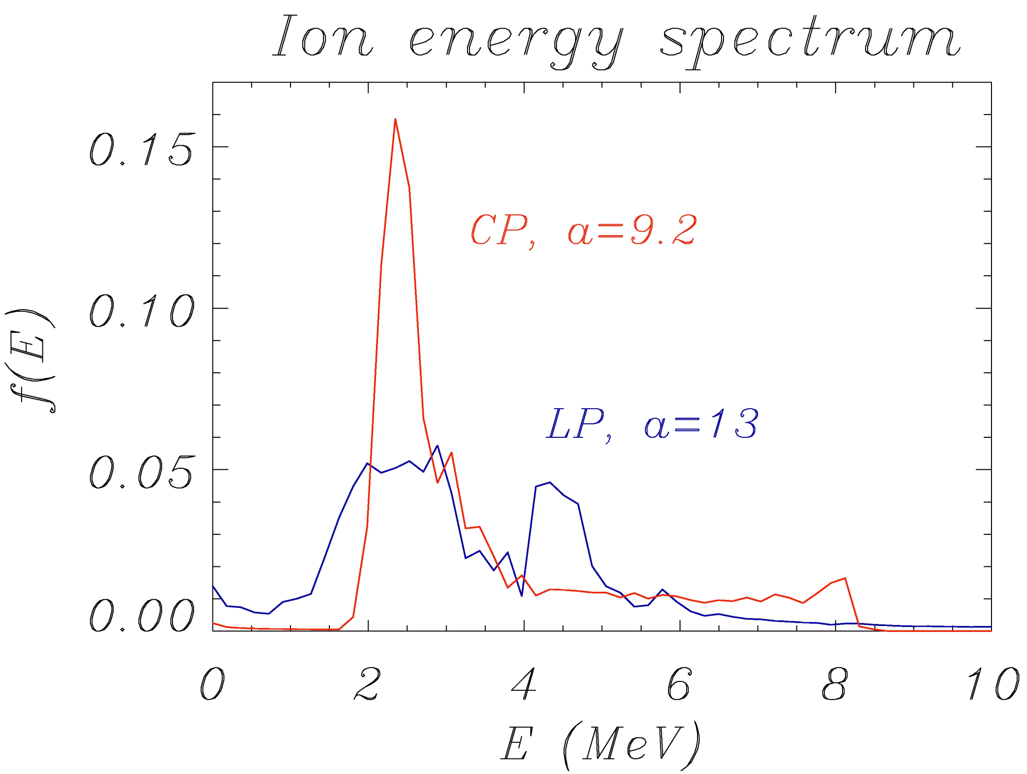
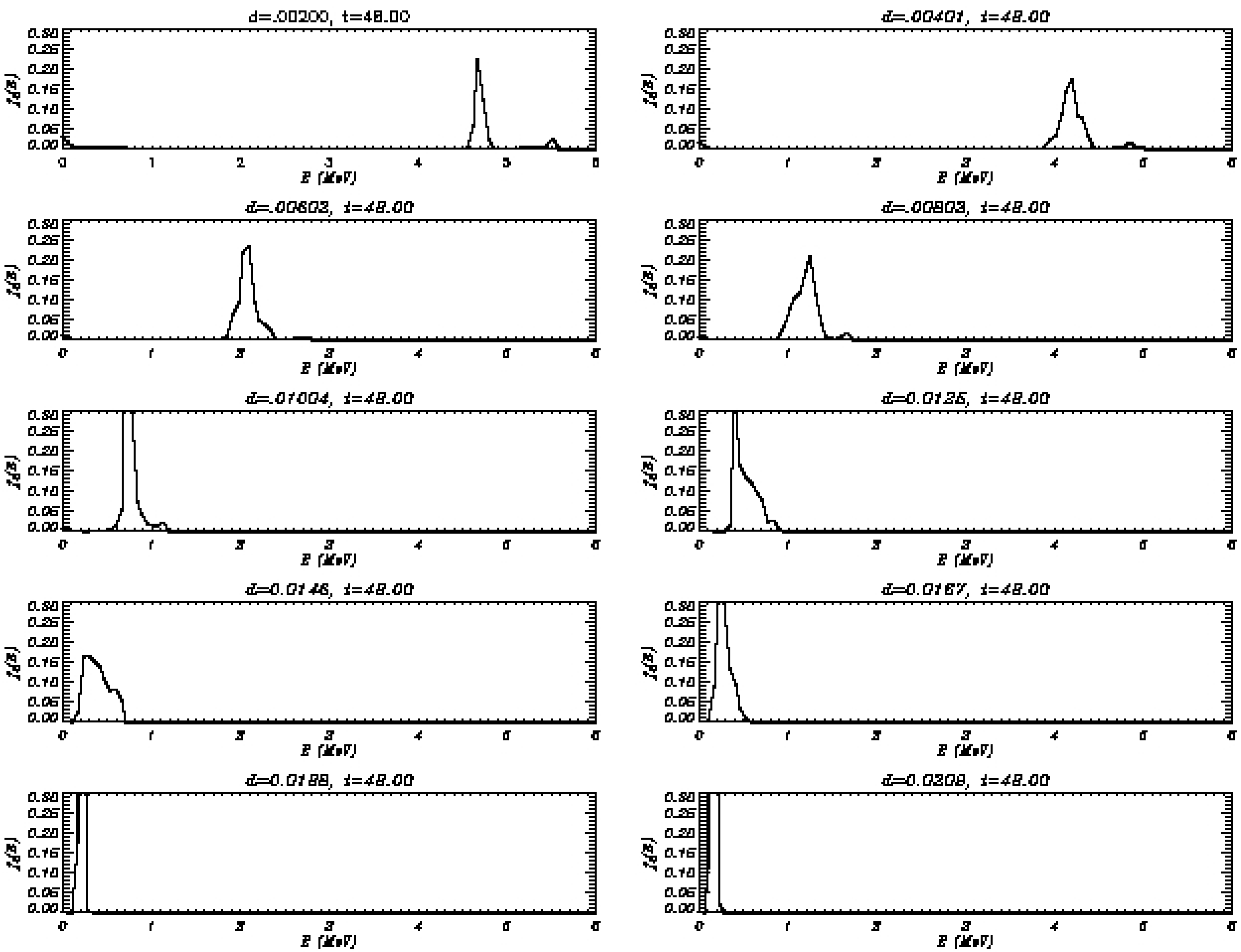


LP shows a broader "RPA peak" than CP and a low-density tail of multi-MeV ions due to TNSA

1D parametric study: ion energy vs. target thickness

- Carbon target, thickness d=0.02-0.002μm, $n_e = 250 n_c = 4.3\times10^{23}$ cm^{-3}
- Laser: 24 fs pulse, $I = 1.8\times10^{19}$ W/cm^2, relativistic param. a_0 = 2.9



highest ion energy

E=4.5 MeV

for (extremely) small target thickness

d=0.002um

target is “thin” for rocket-like RPA if d<0.01um

1D parametric study: absorption vs. target thickness

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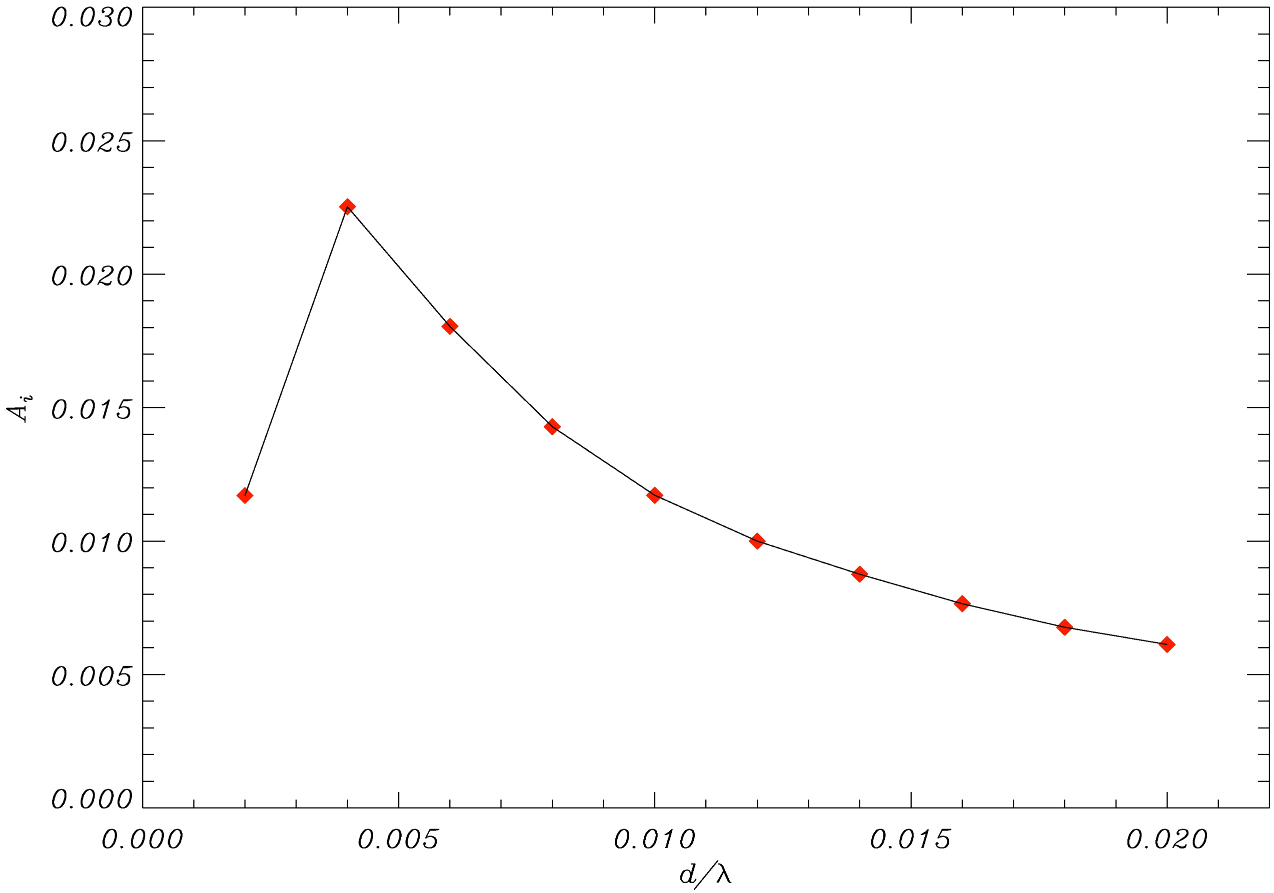

highest absorption

A=2.5%

for (extremely) small target thickness

d=0.004um

is there an optimal thickness? (compromise between low mass and induced transparency)

High energy ions require longer, stronger pulses ...

- Carbon target, thickness d=0.02μm, $n_e=250n_c=4.3\times10^{23}$ cm^{-3}
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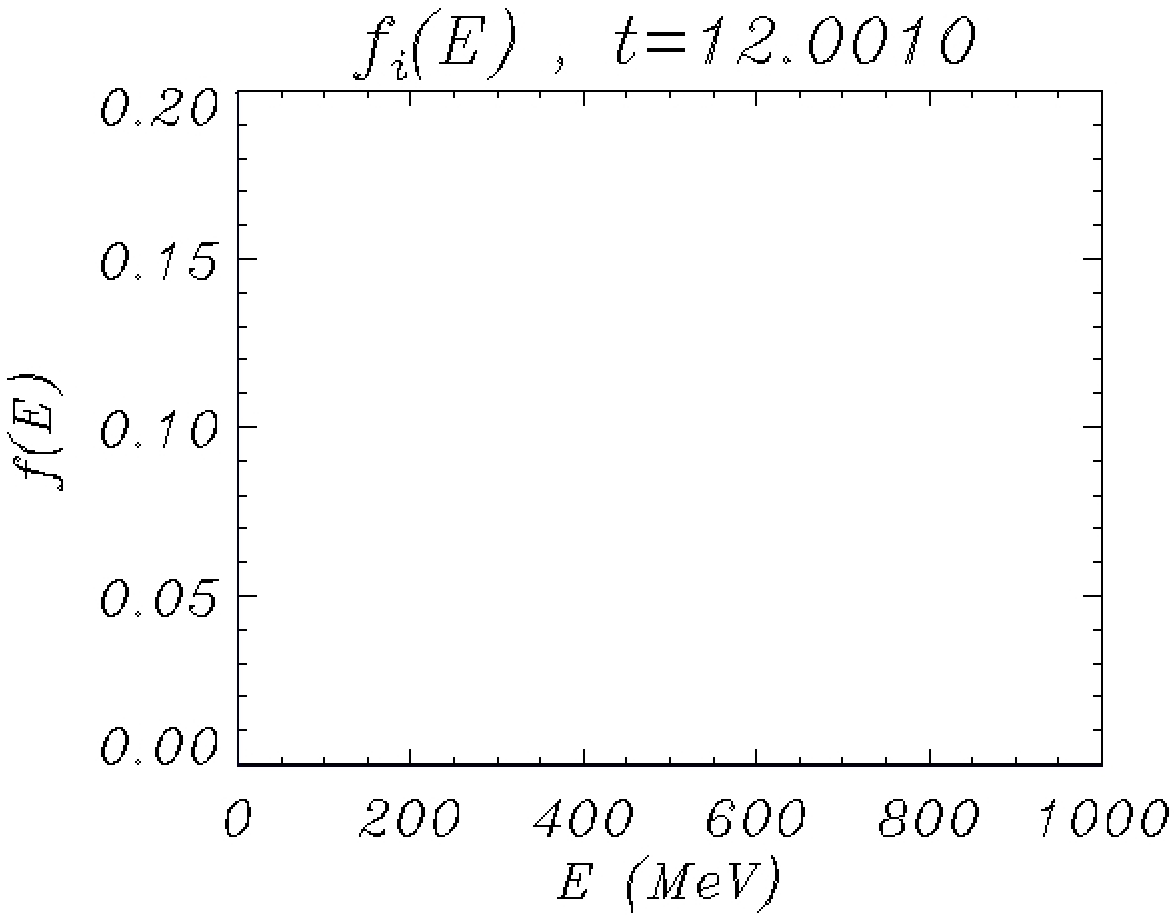

nice “monoenergetic” spectrum peaked at

E=600 MeV

some post-acceleration broadening (due to “late” electron heating)

attractive, but many (unknown) issues to be studied...

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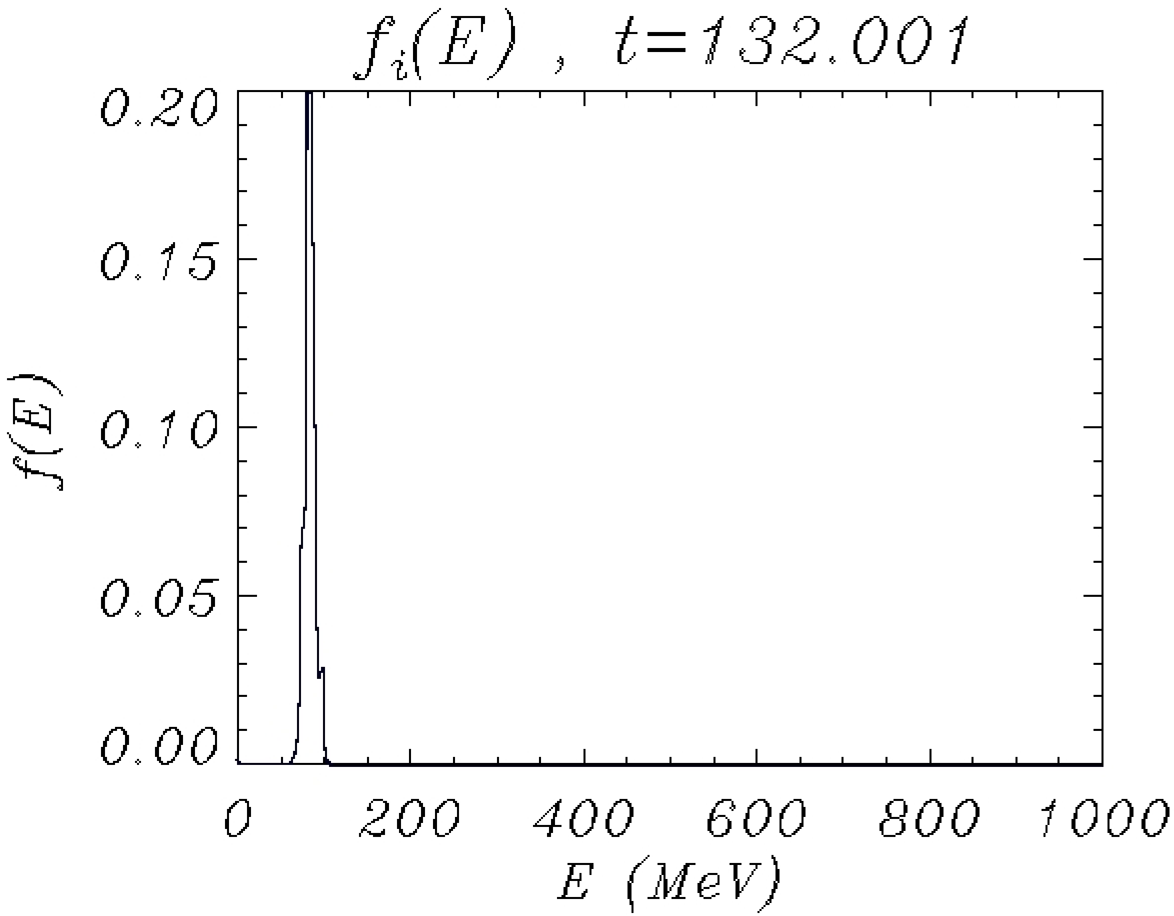

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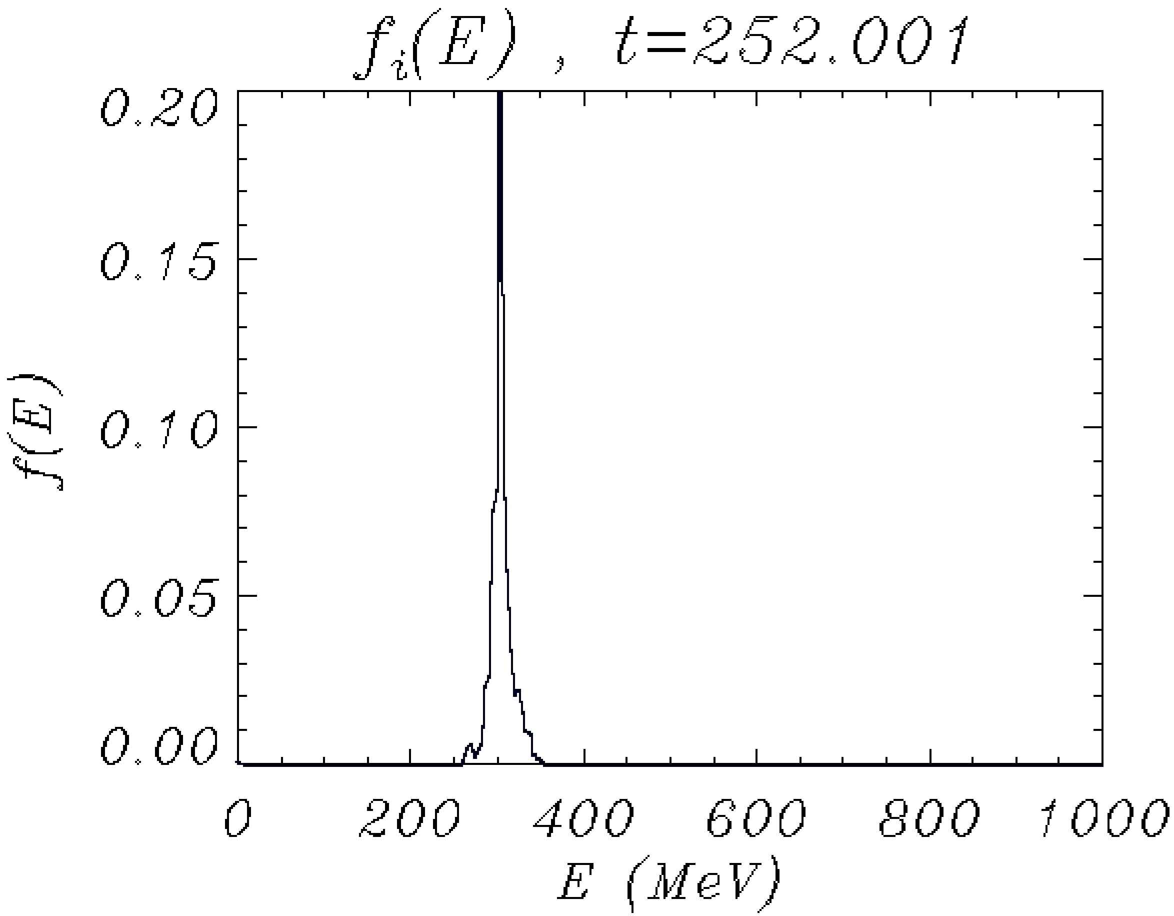

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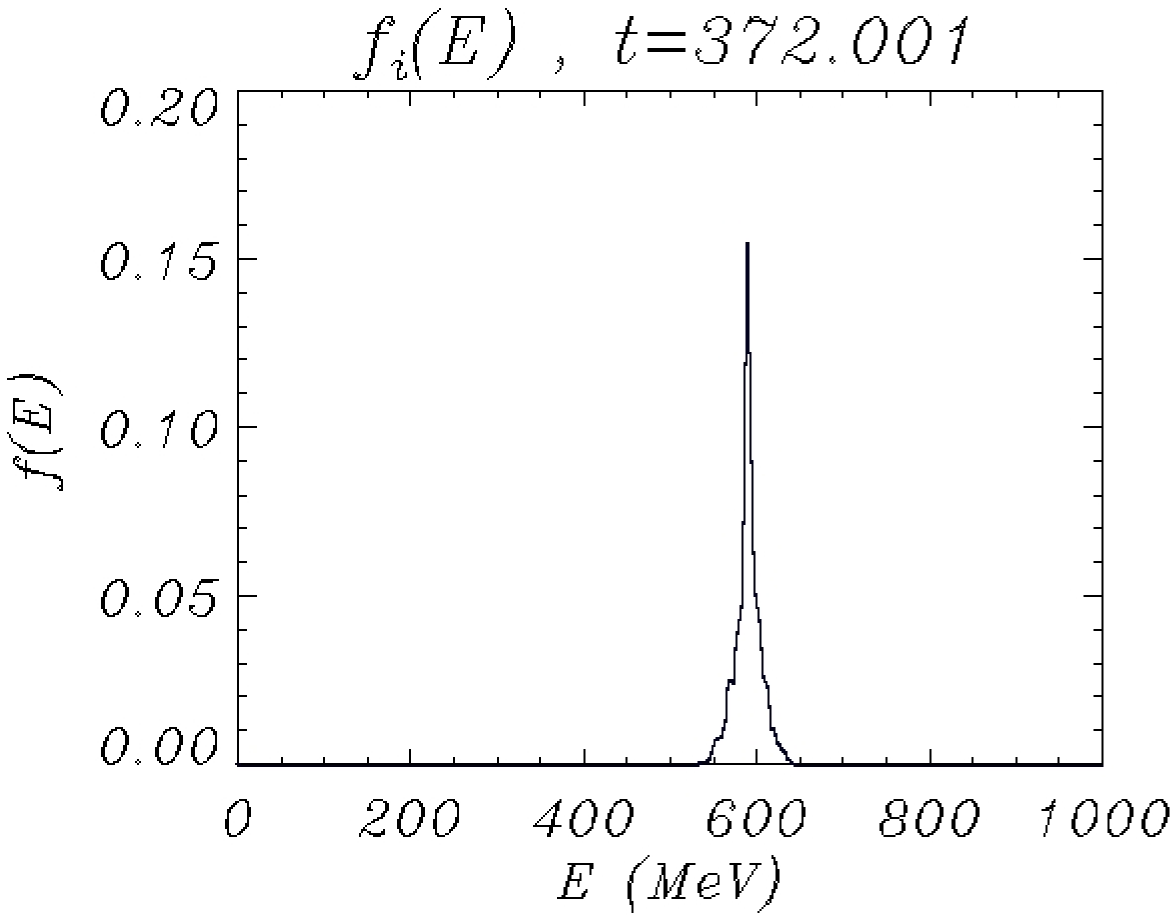

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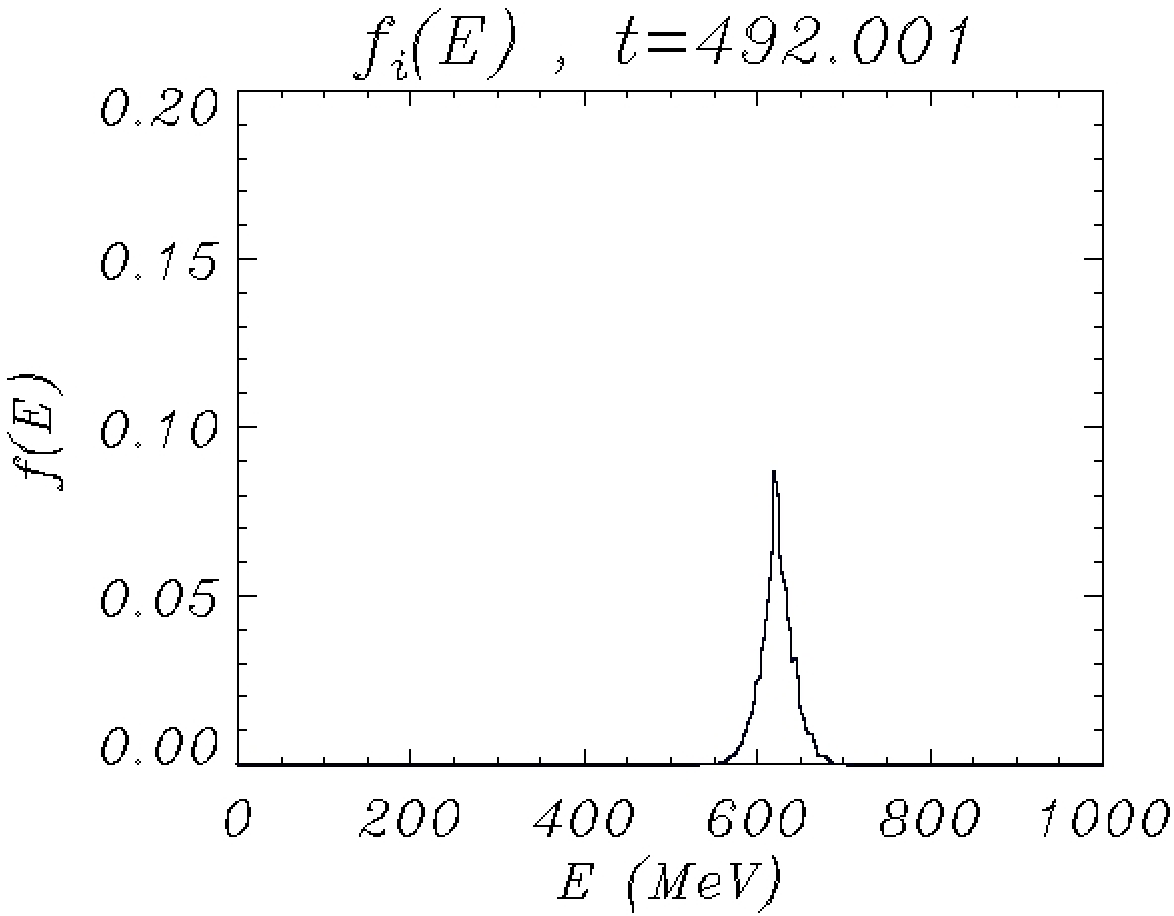

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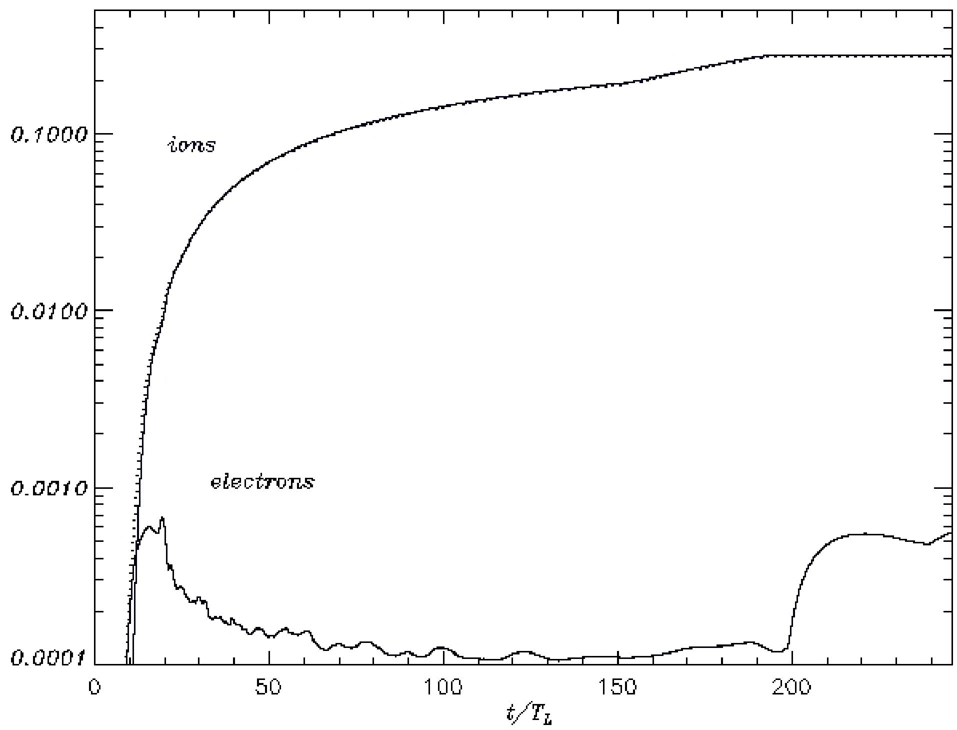

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Interaction with a short preplasma (preliminary)

- Carbon target, "power law" preplasma profile with short scalelength d=0.25-1.0μm, $n_{max}=10n_c=1.7\times10^{22}$ cm^{-3}

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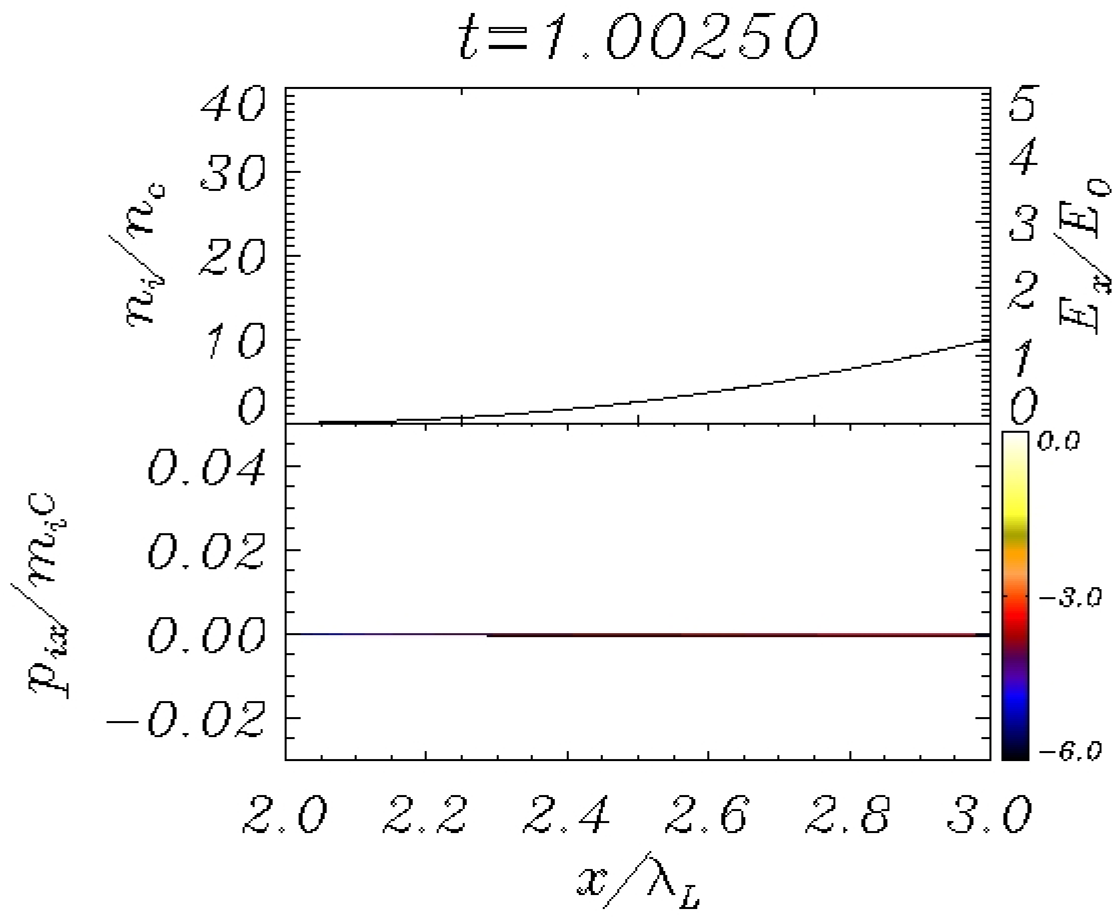

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- observed energy suggest "relevant" density is closer to n_c rather than n_{max}

-> **higher ion energy**

(but needs prepulse control + ability to cross the target bulk...)

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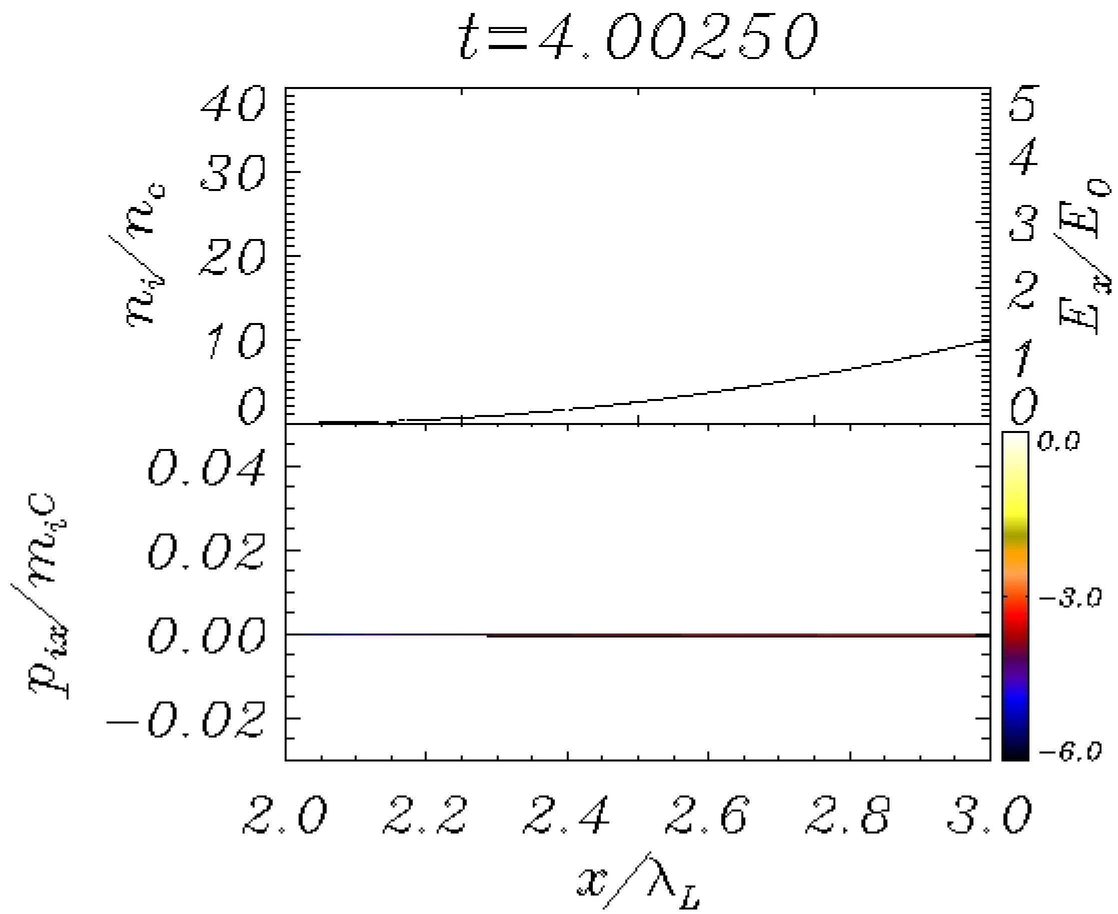

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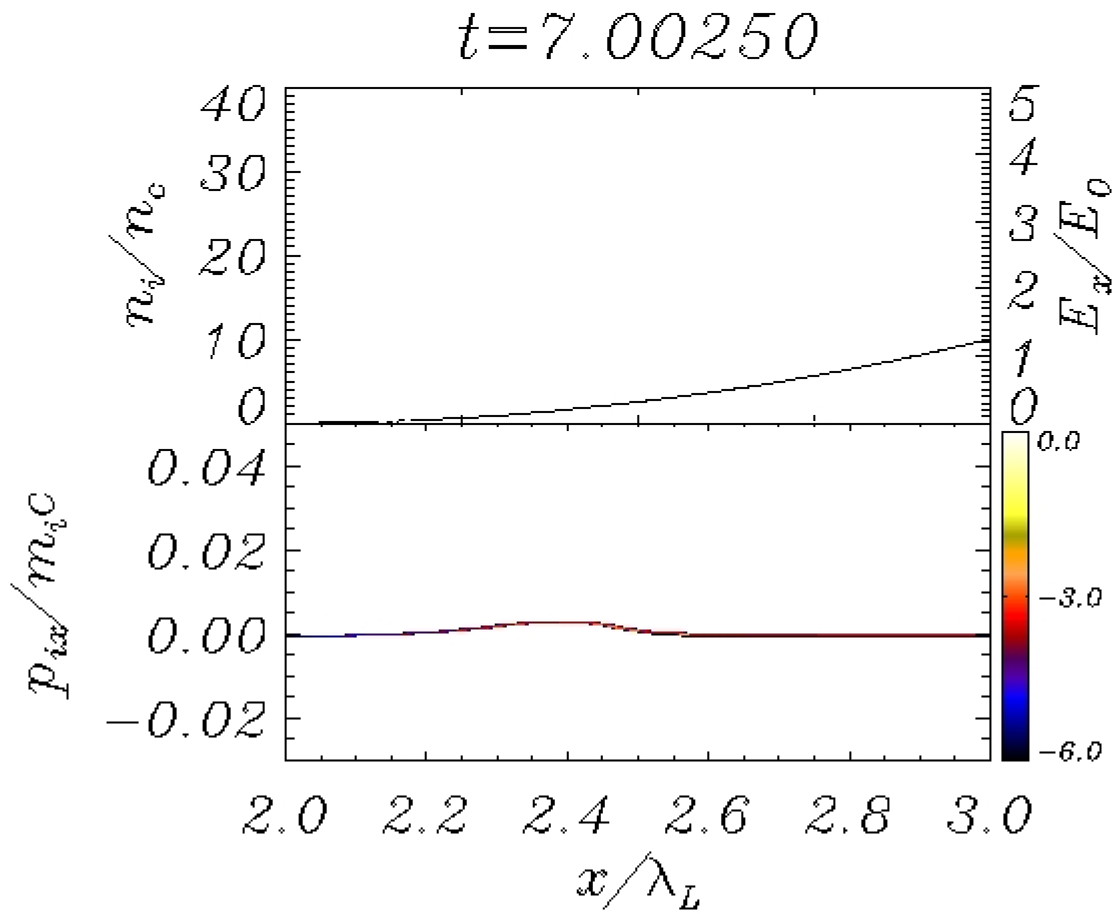

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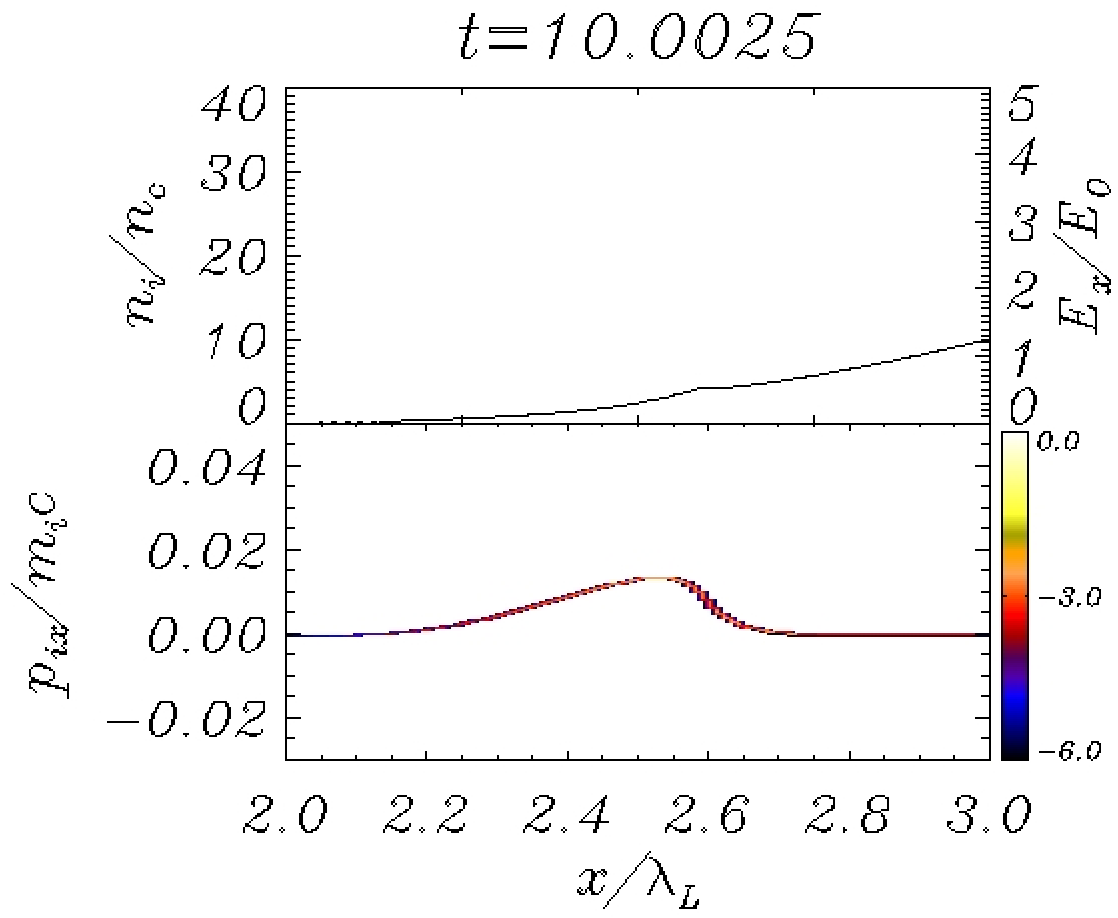

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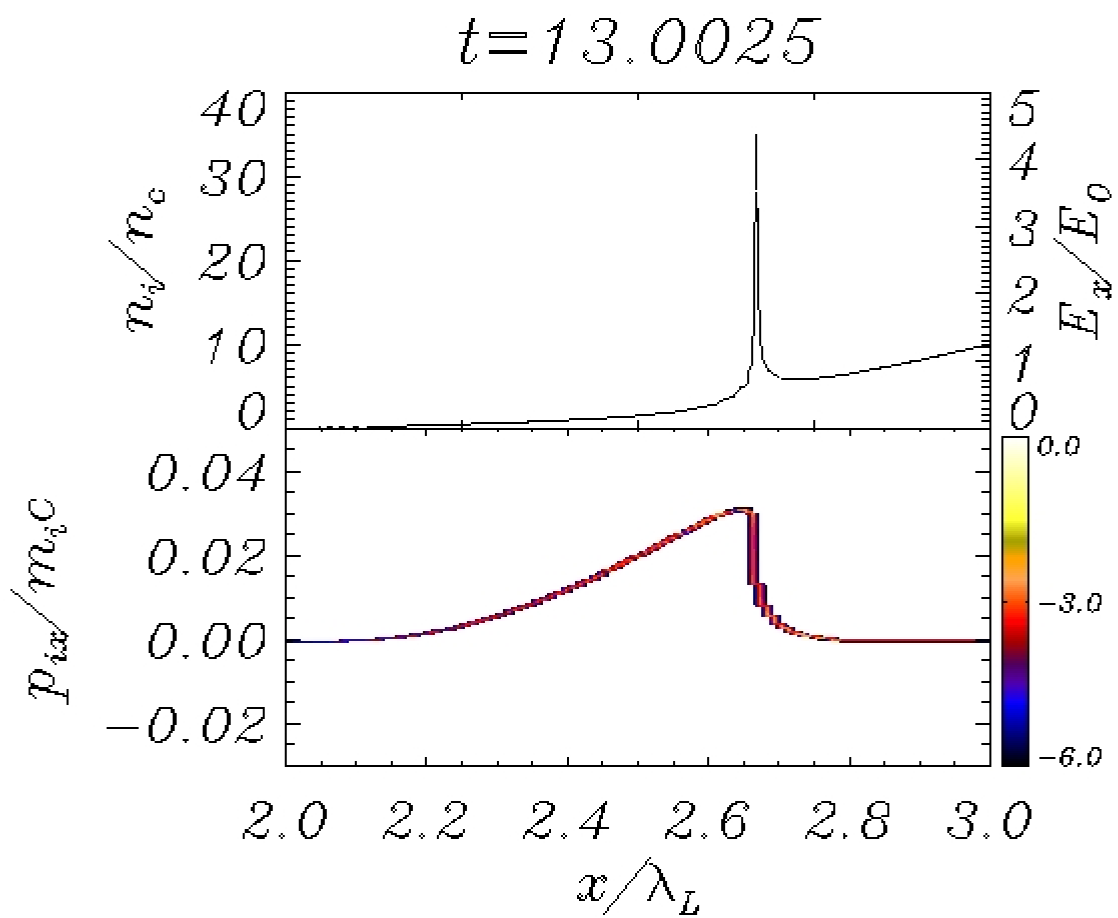

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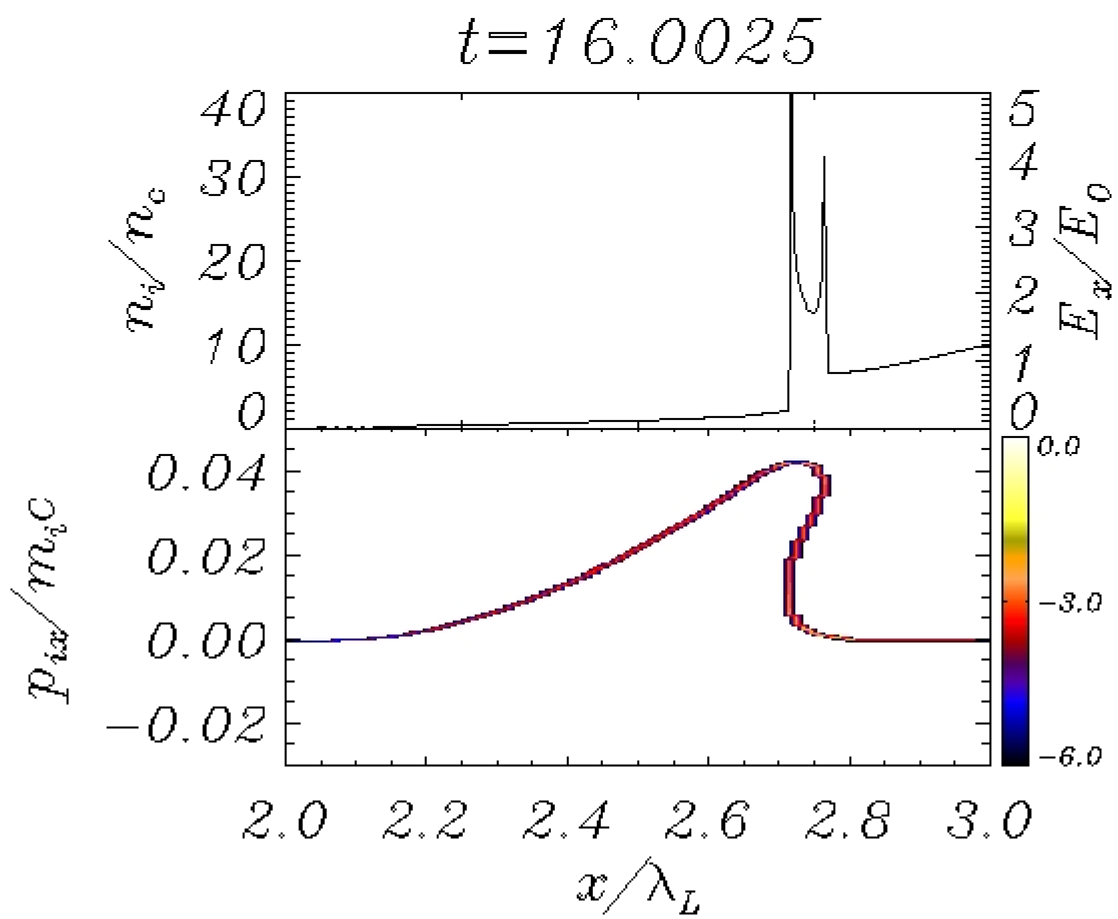

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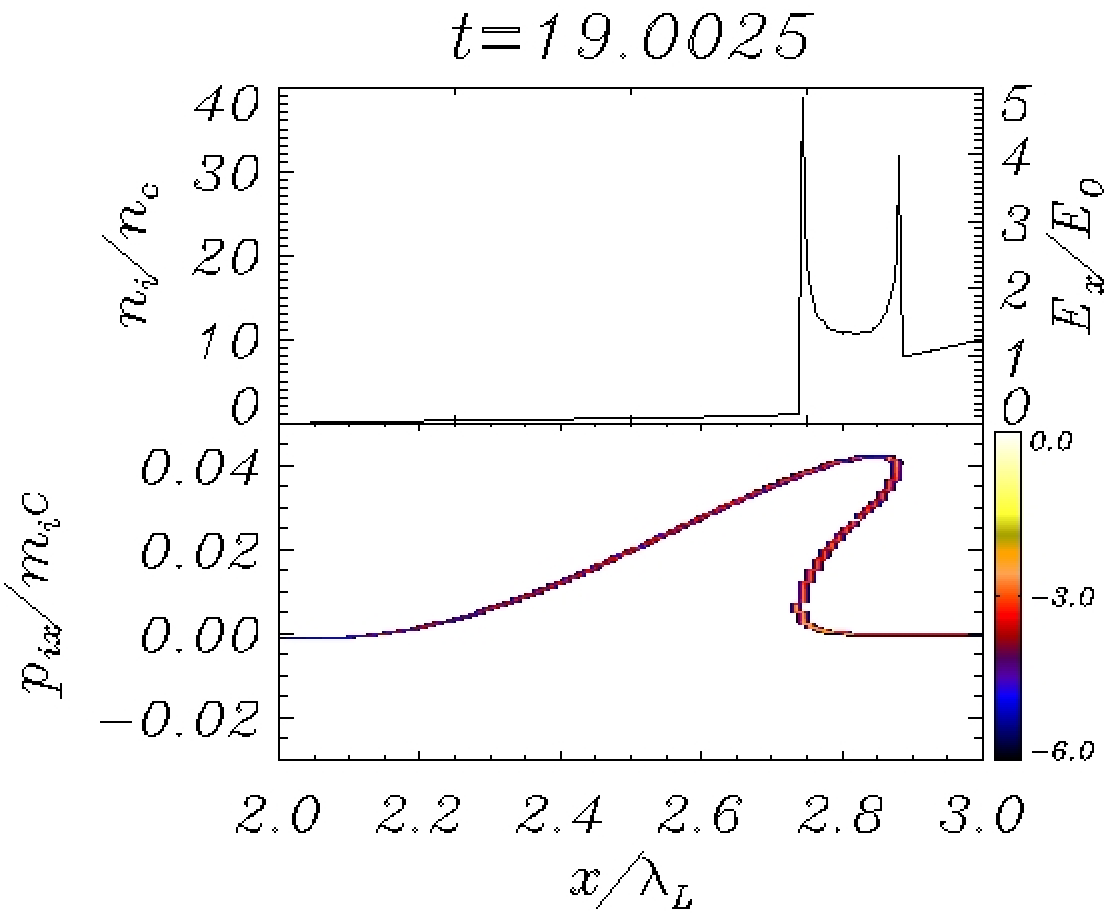
Interaction with a short preplasma (preliminary)

- Carbon target, "power law" preplasma profile with short scalelength d=0.25-1.0μm, $n_{max}=10n_c=1.7\times10^{22}$ cm^{-3}

- Laser: 24 fs pulse, $I=1.9\times10^{19}$ W/cm^2, relativistic param. a_0 = 3.0



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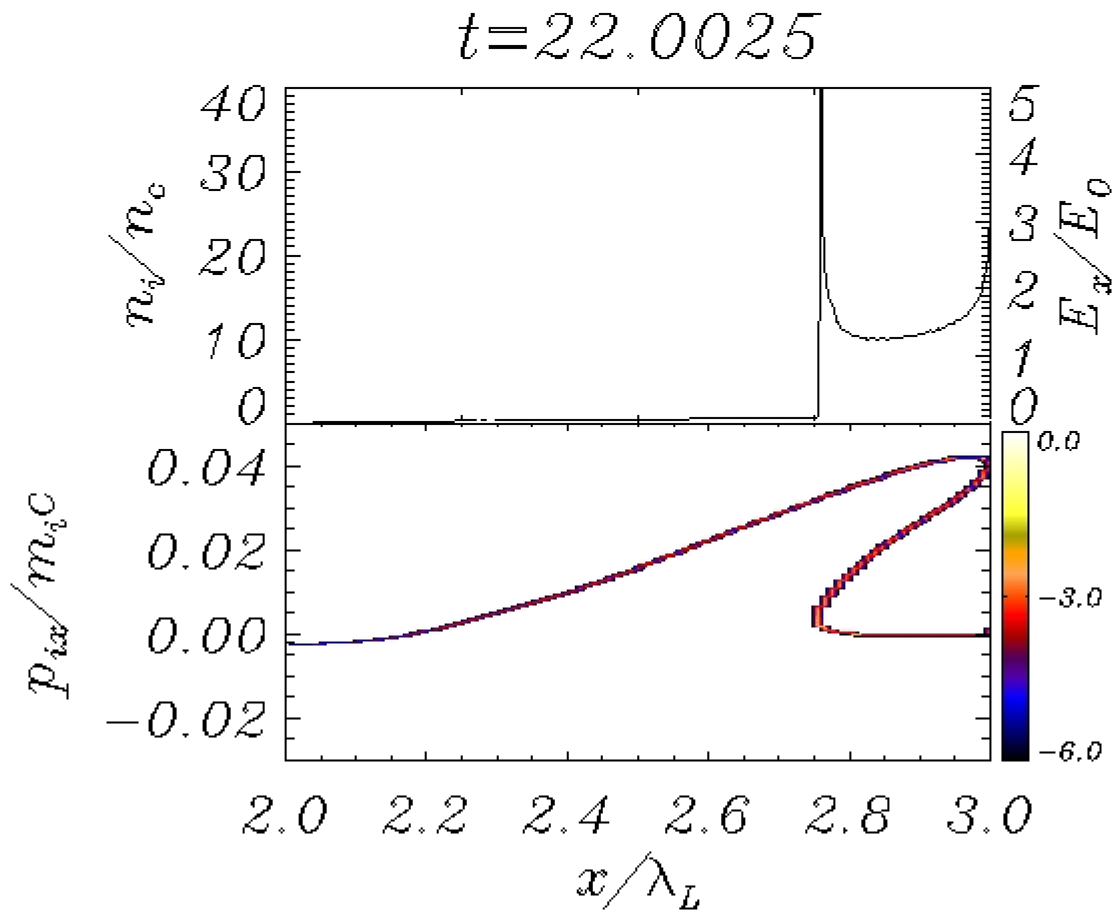

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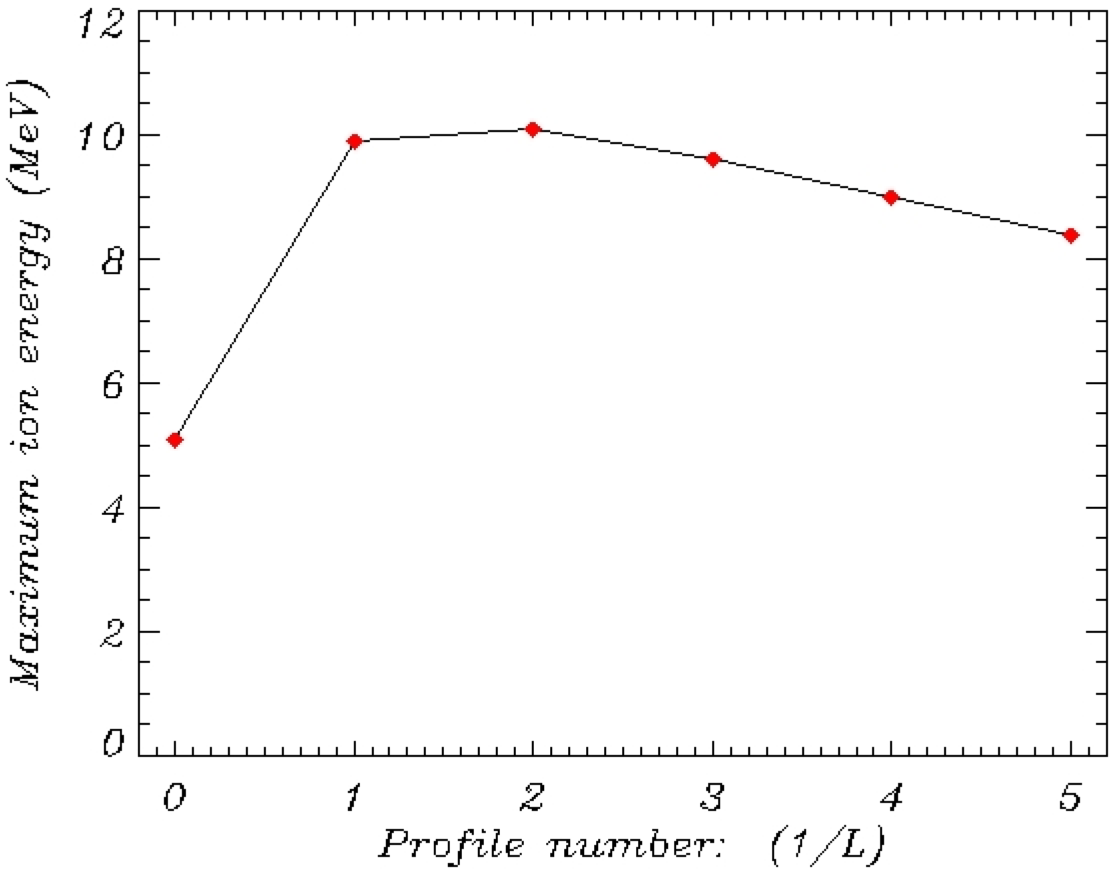

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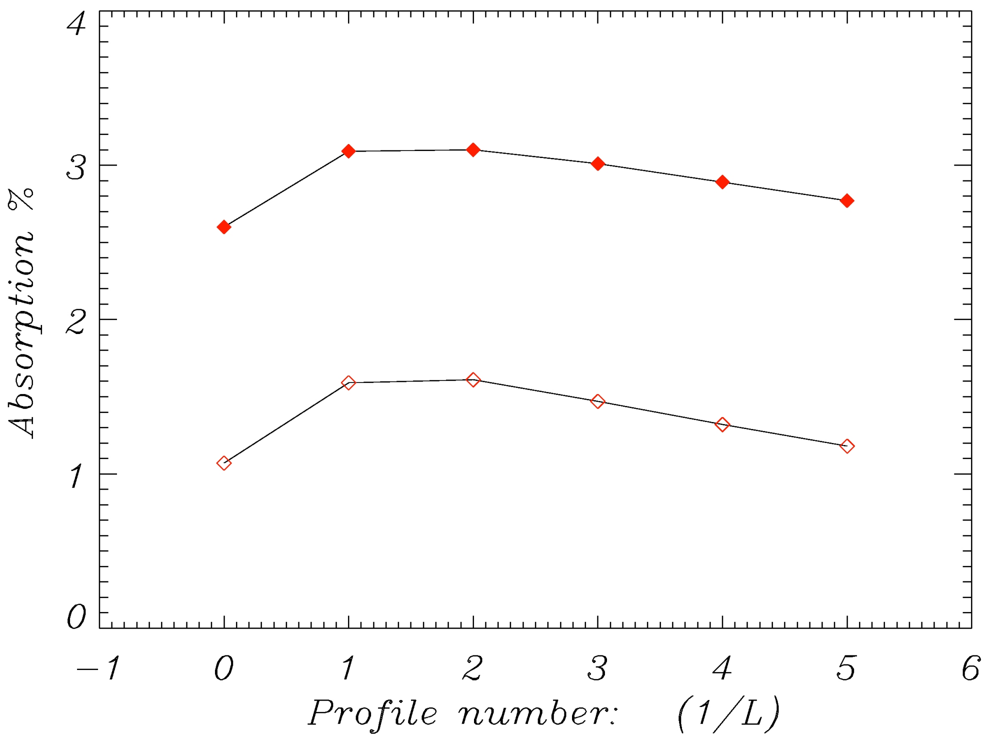

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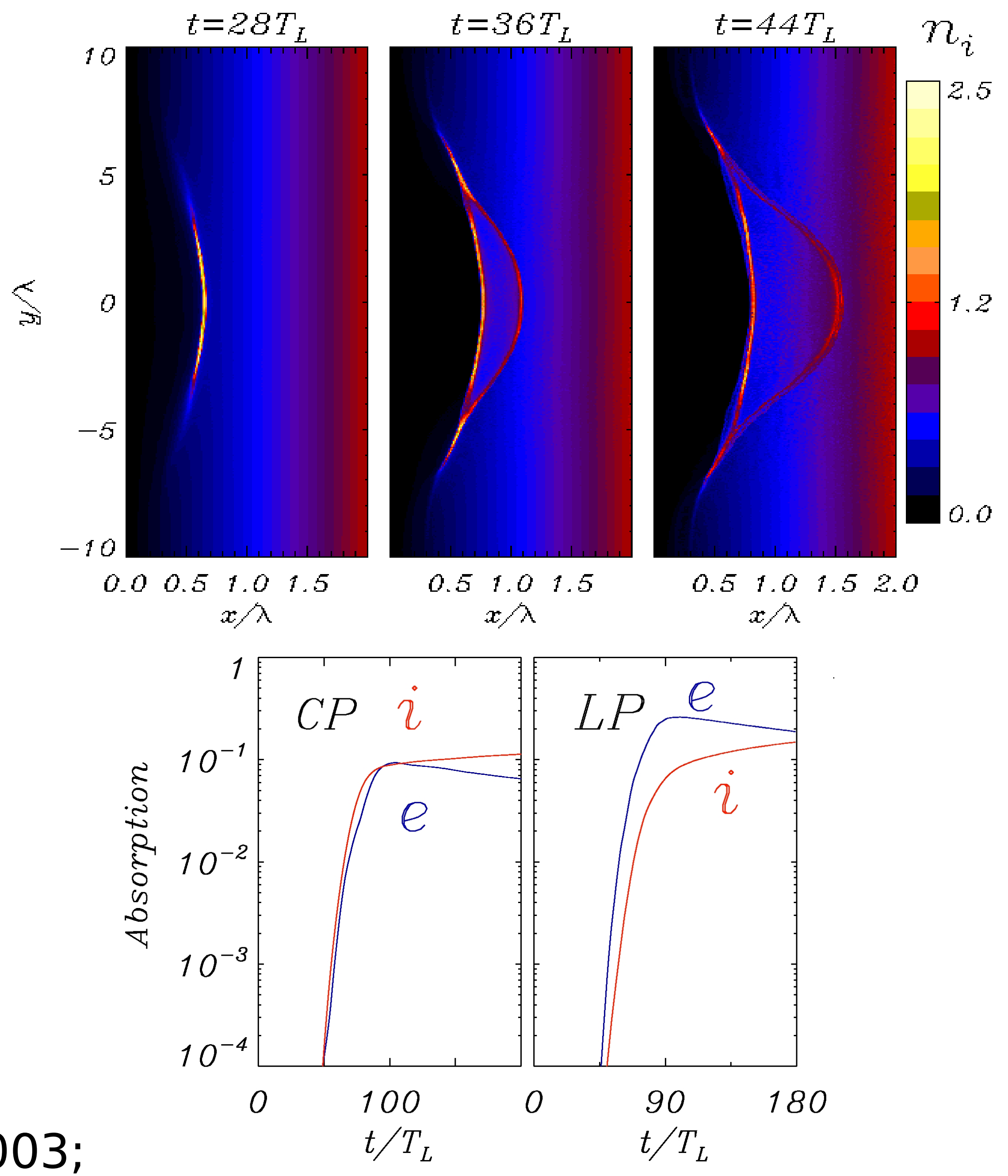
2D simulations ("thick" targets only)

The 1D ion "bunch" becomes a 2D "bent" front

For tight focusing, absorption into electrons grows because of longitudinal field components $E_x \sim (\lambda/D) E_y$ causing "vacuum heating"

For "non-flat-top" (e.g., Gaussian) profiles, ion energy varies with radial position due to the intensity distribution (analogous to TNSA)



[Macchi et al, PRL **94** (2005) 165003;
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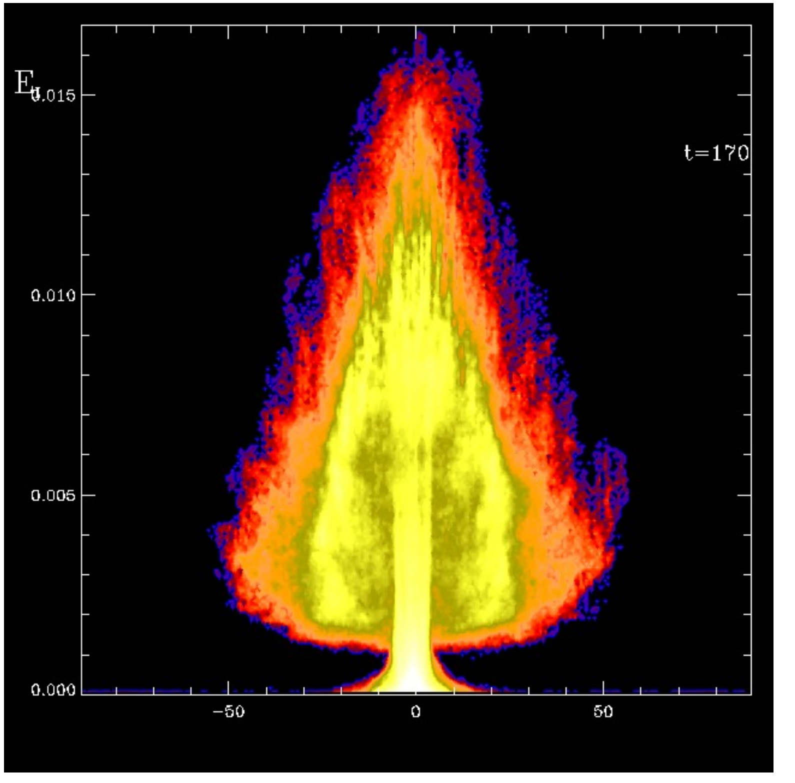

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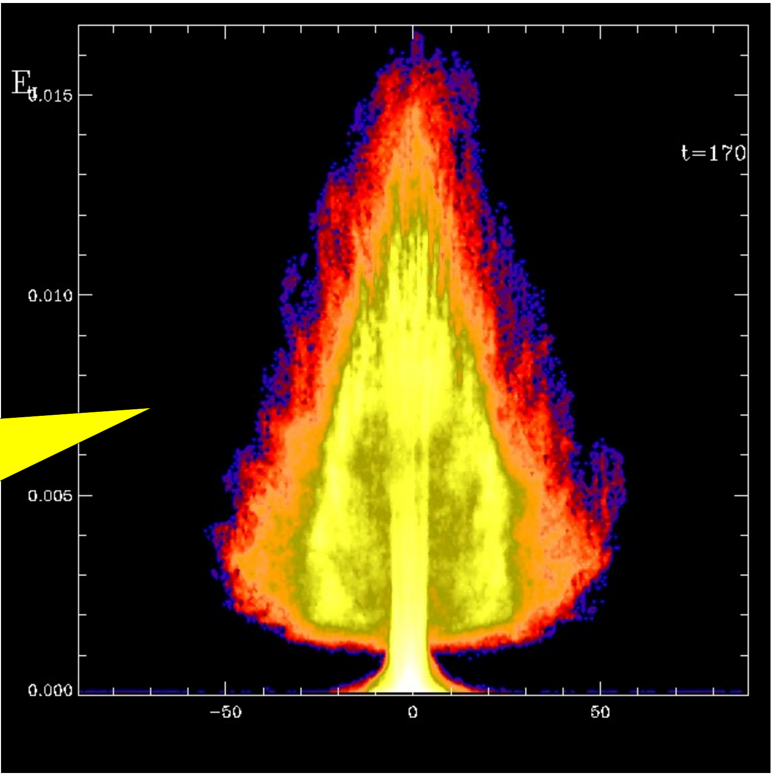

The "Xmas tree" is a contour plot of ion energy vs. emission angle, showing a high and energy-dependent collimation

(IEEE - Images in Plasma Science, in press)

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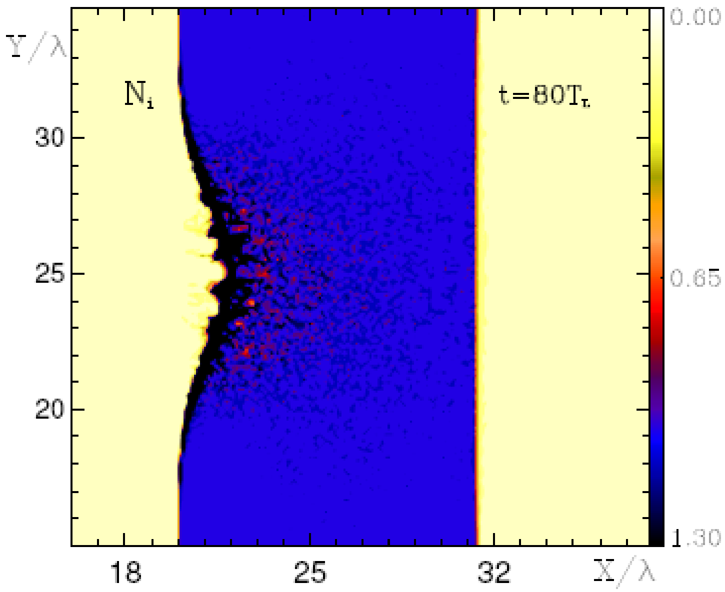
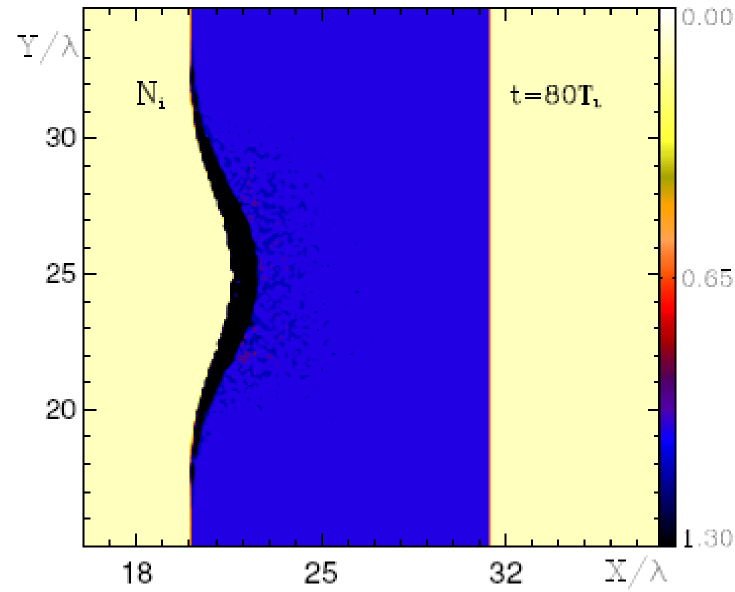
2D simulations, "Surface corrugation"





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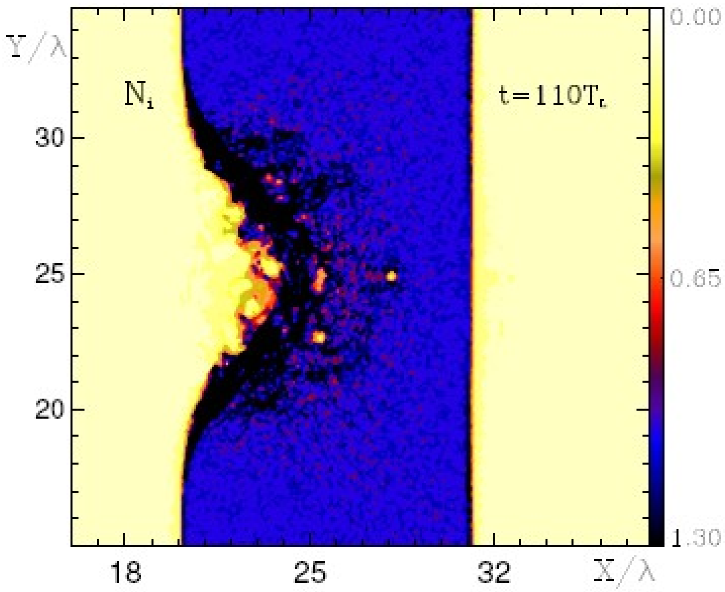

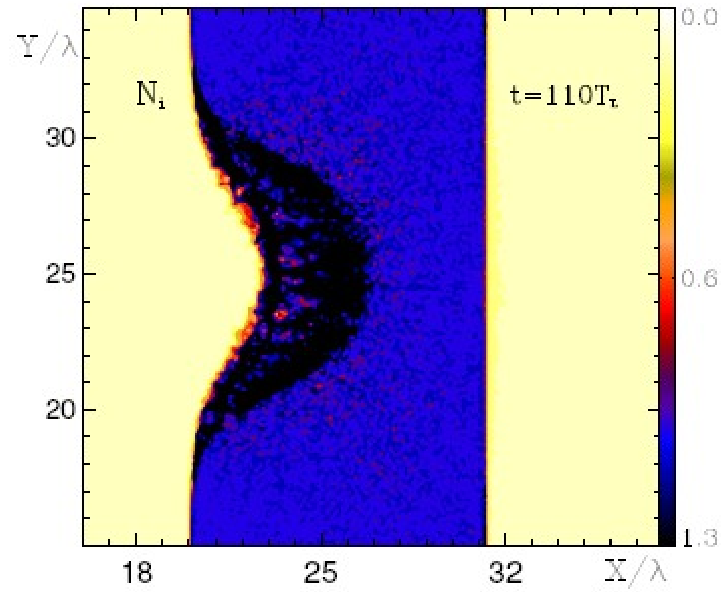

The front of ponderomotively accelerated ions almost diss-apear for later time

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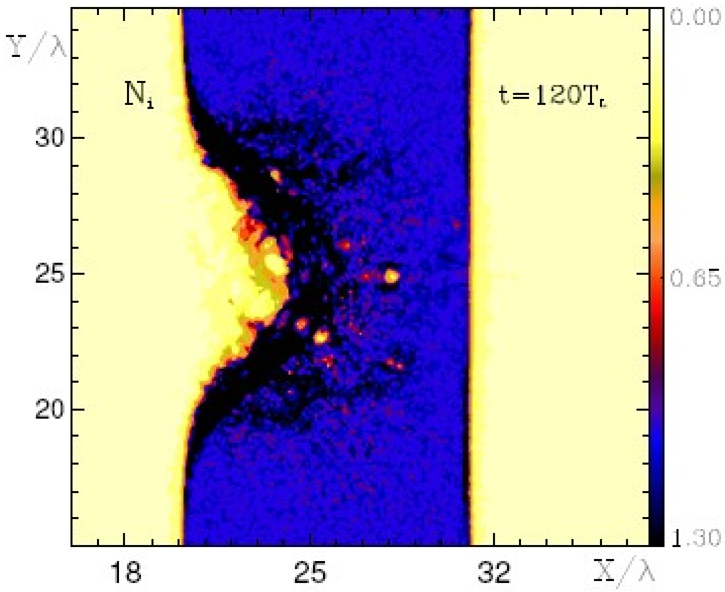

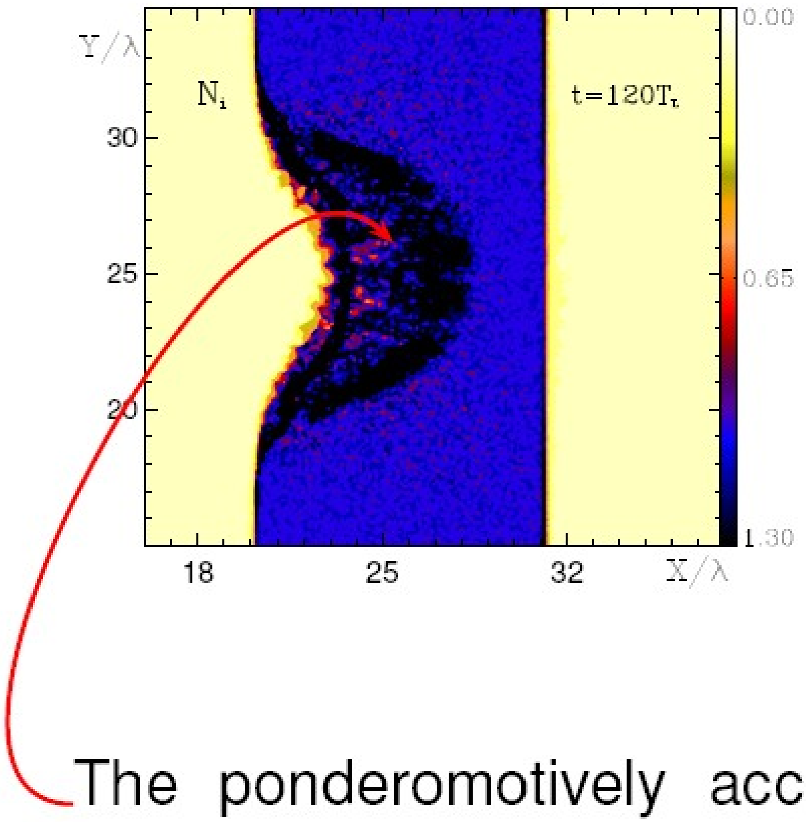

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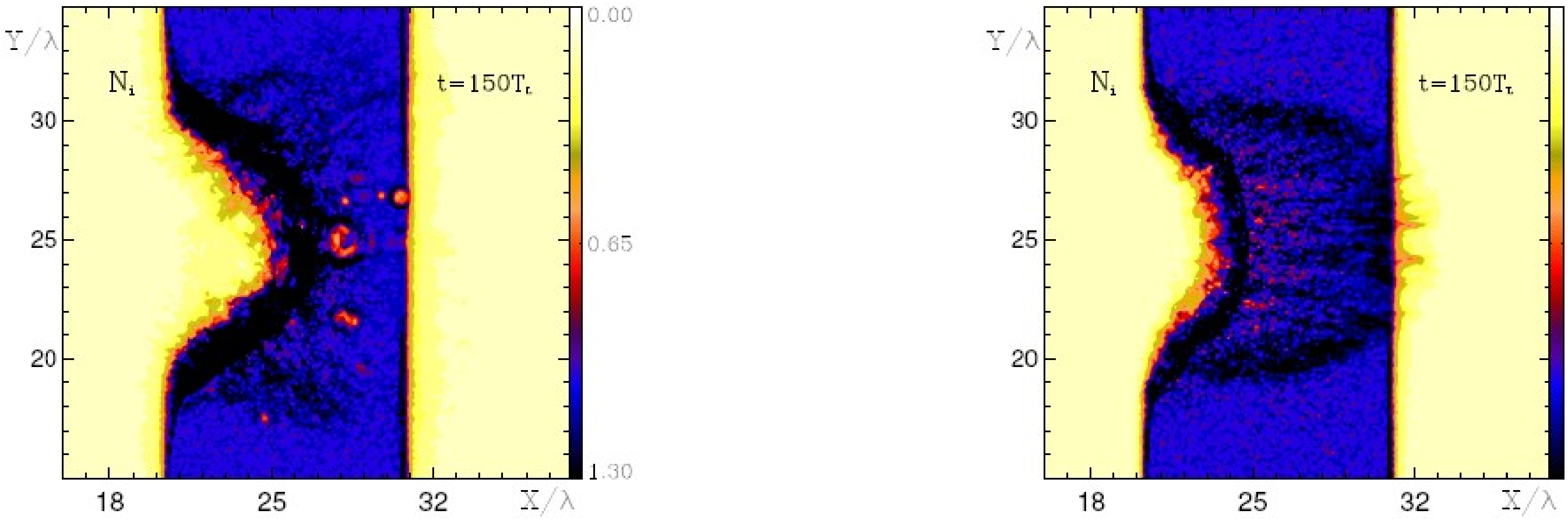

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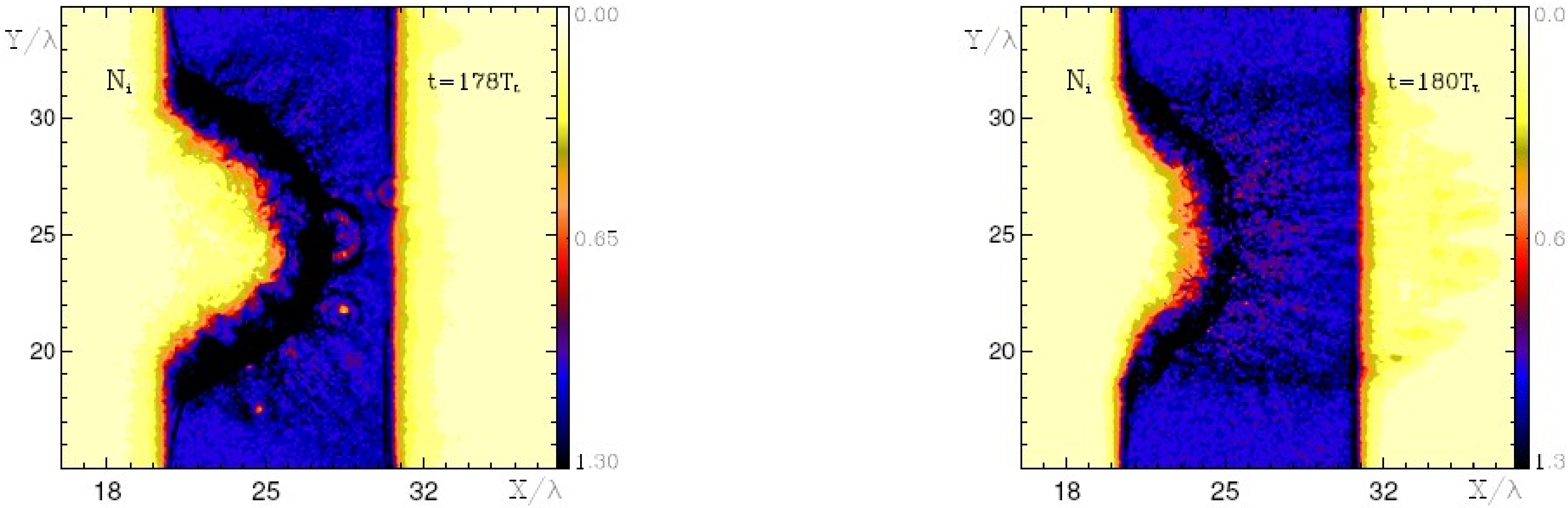
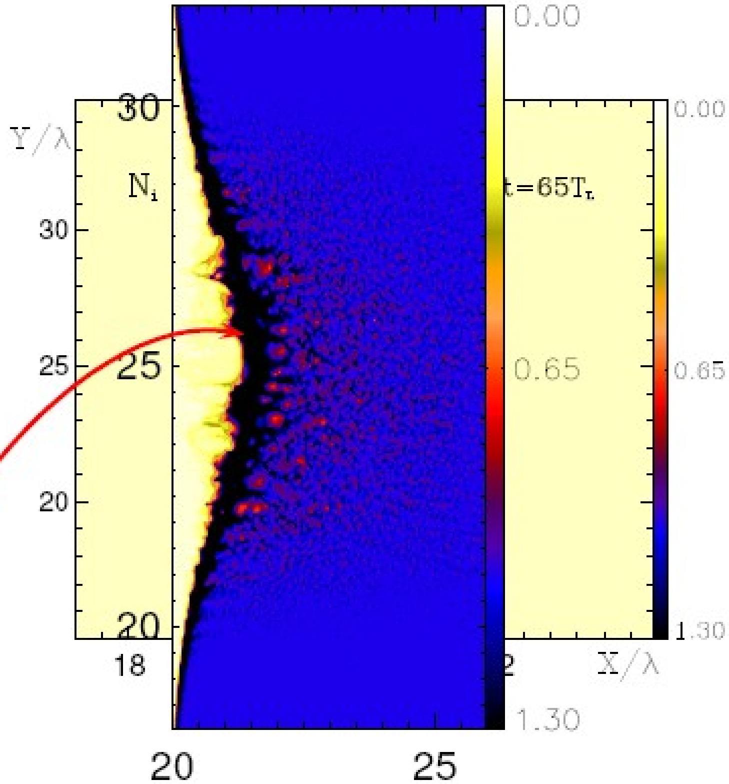
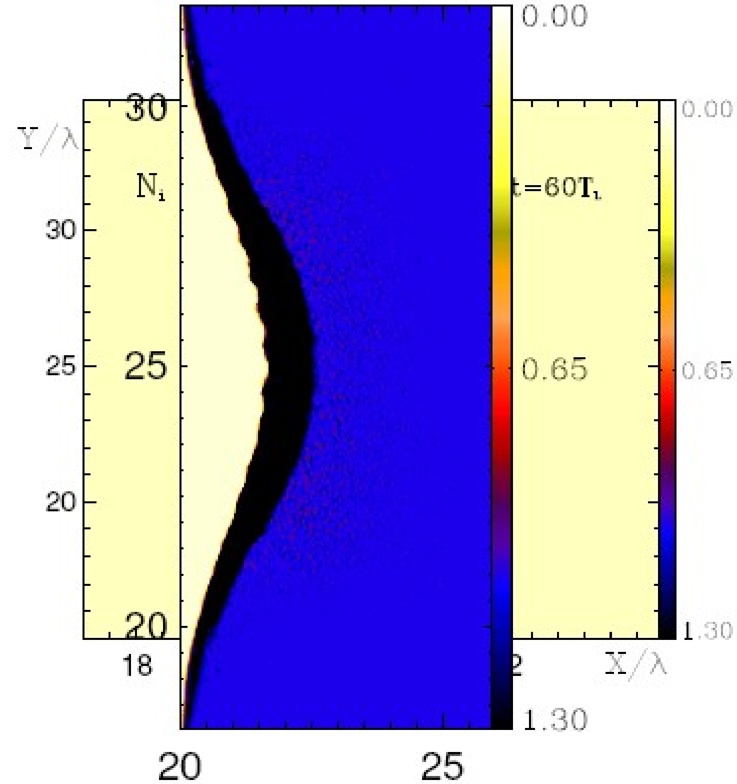


Fast (?) surface instabilities for the linear polarized pulse

$\Longrightarrow$ the depression of bunch formation?

2D simulations, "Surface corrugation"





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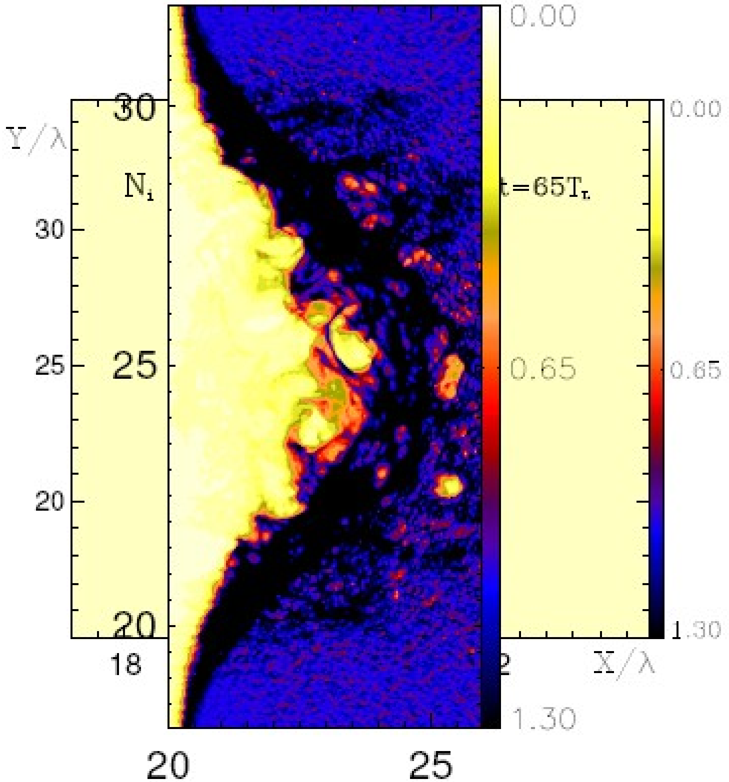

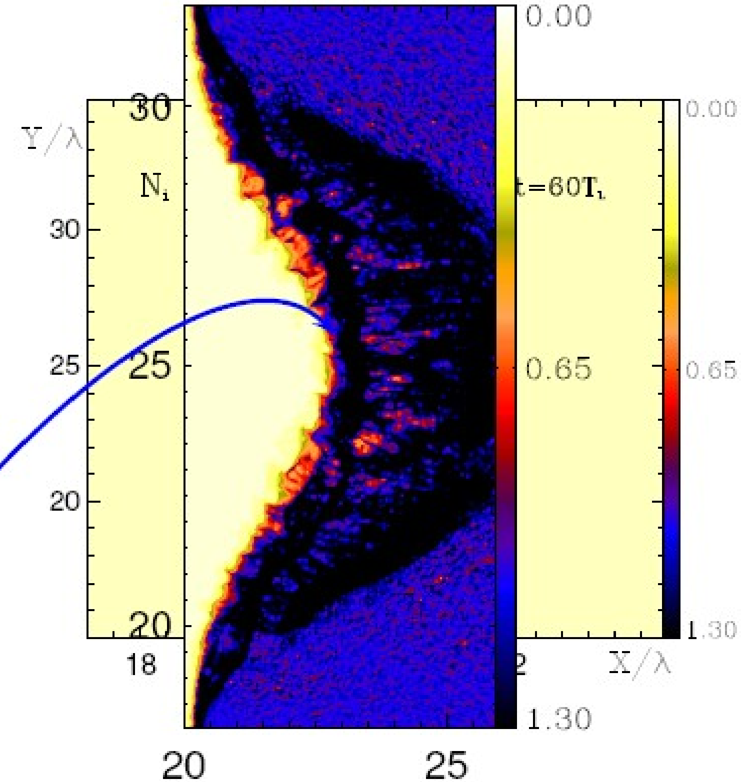

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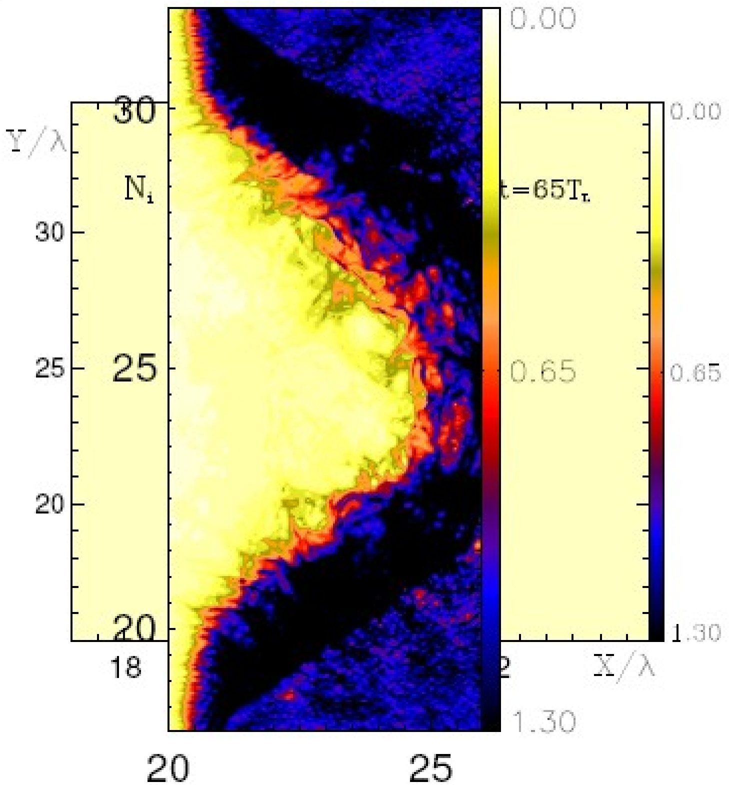
Even if the oscillating part of $\vec{j} \times \vec{B}$ is suppressed the rippling of the laser-plasma interface is present, but it is weak

2D simulations, "Surface corrugation"



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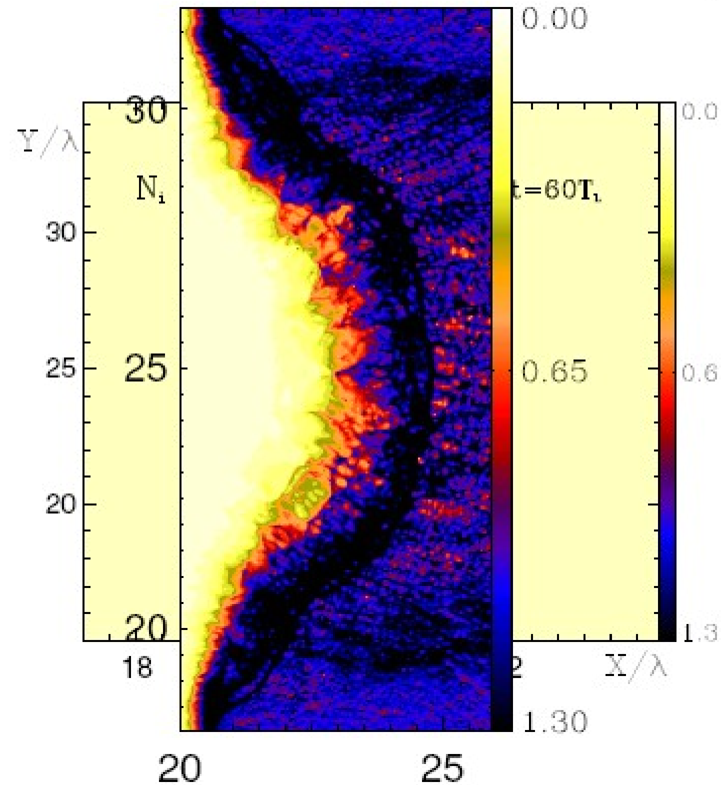


Radiation pressure dominant Rayleigh-Taylor mechanism (?)

(F. Pegoraro, S. Bulanov, RPL (2007)

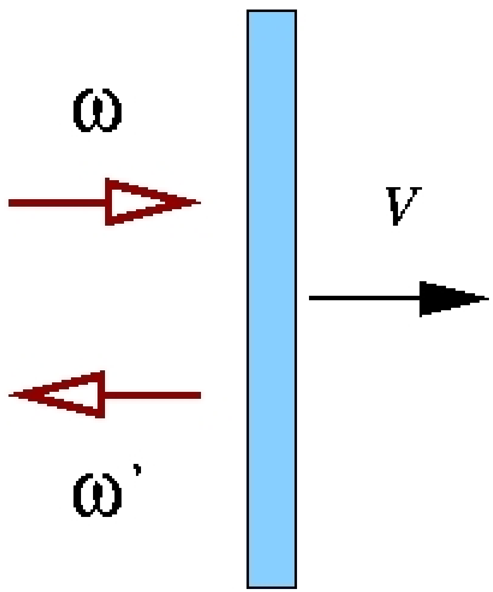
Angular momentum absorption in CP-RPA?

Quoting an (over)critical referee:

“Circular polarization is primarily 3D; it is a problem that 2D simulations might be not sufficient to reflect the nature of the interaction“

This may be true in principle for some reason
e.g. a CP beam carries angular momentum
from “photon spin”
that must be conserved in the interaction!

If the target were a “perfect mirror” the conservation of the “number of photons” implies there is NO absorption of angular momentum because each photon has the same spin $\hbar$ whatever the frequency!



This can be a “test” of the mirror model...

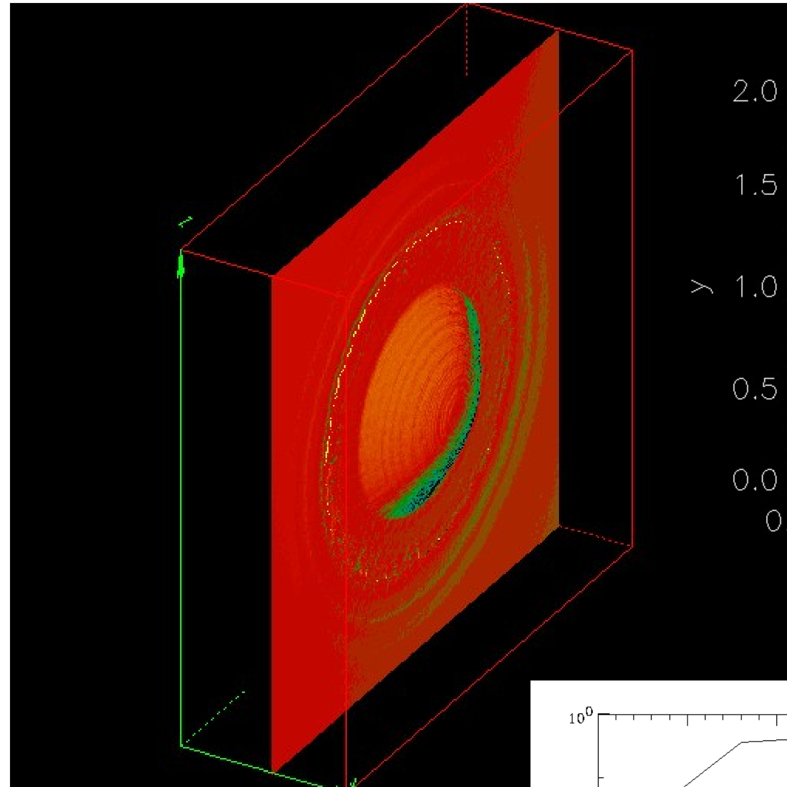
3D simulations of CP-RPA

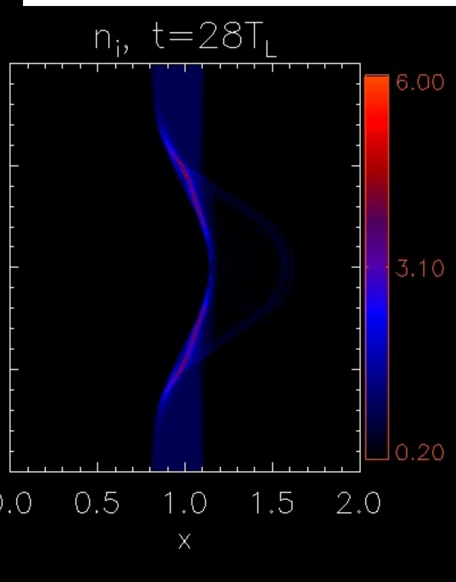
3D PIC simulations performed on 100 CPUs at the CINECA facility (Bologna, Italy)

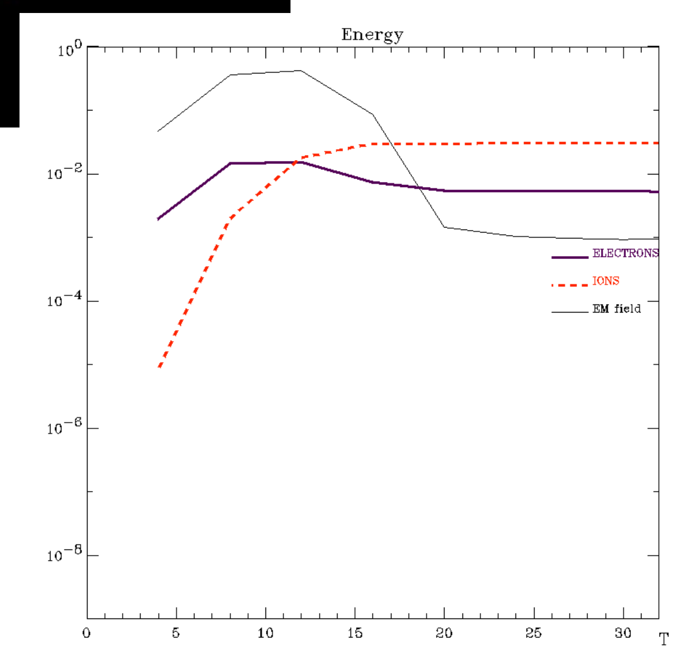
$d=1.0\lambda$, $n_{max}=5n_c$

$a_0 = 3.0$

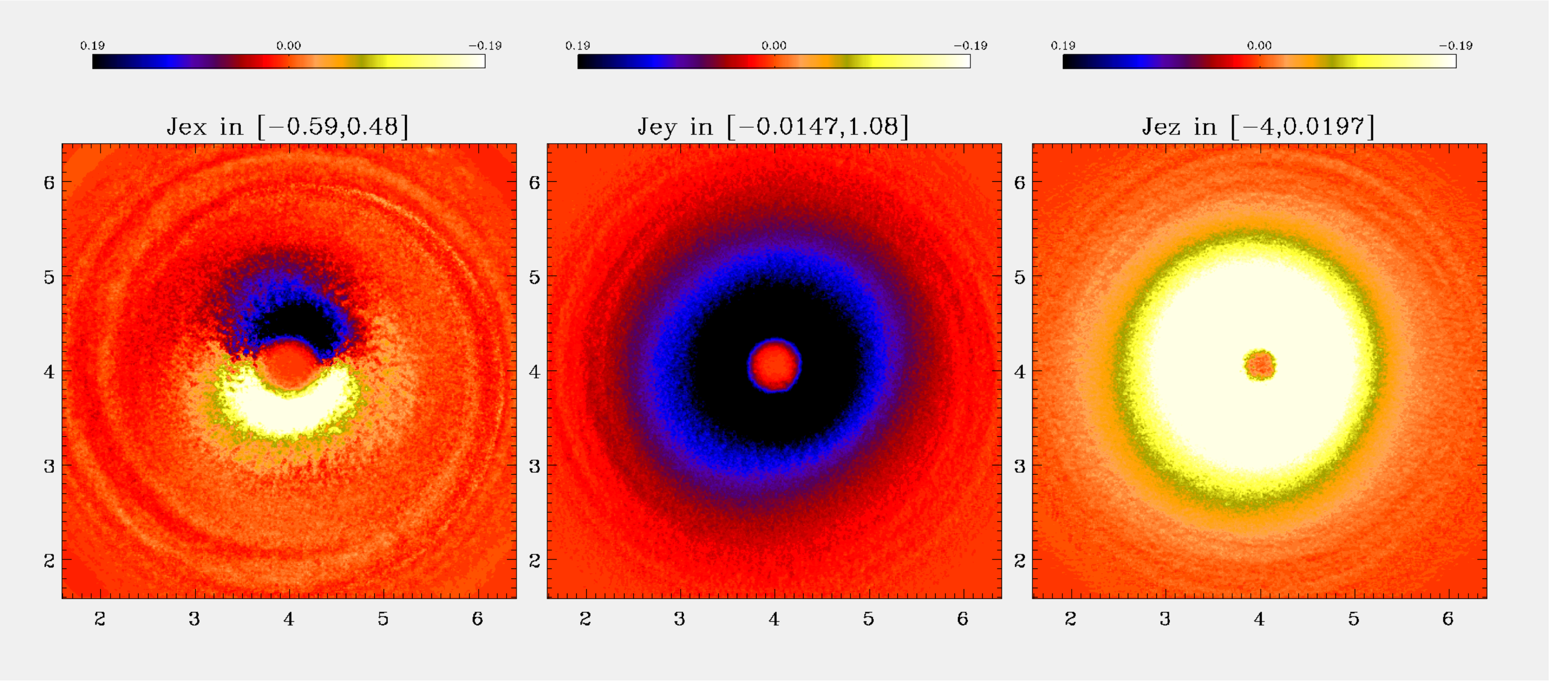
simulations are restricted to “easy” parameters due to limited resources, but basically confirm 1D and 2D results.







Induced electron currents in the transverse plane



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complicated (3D) structure (“corona of vortices”?)

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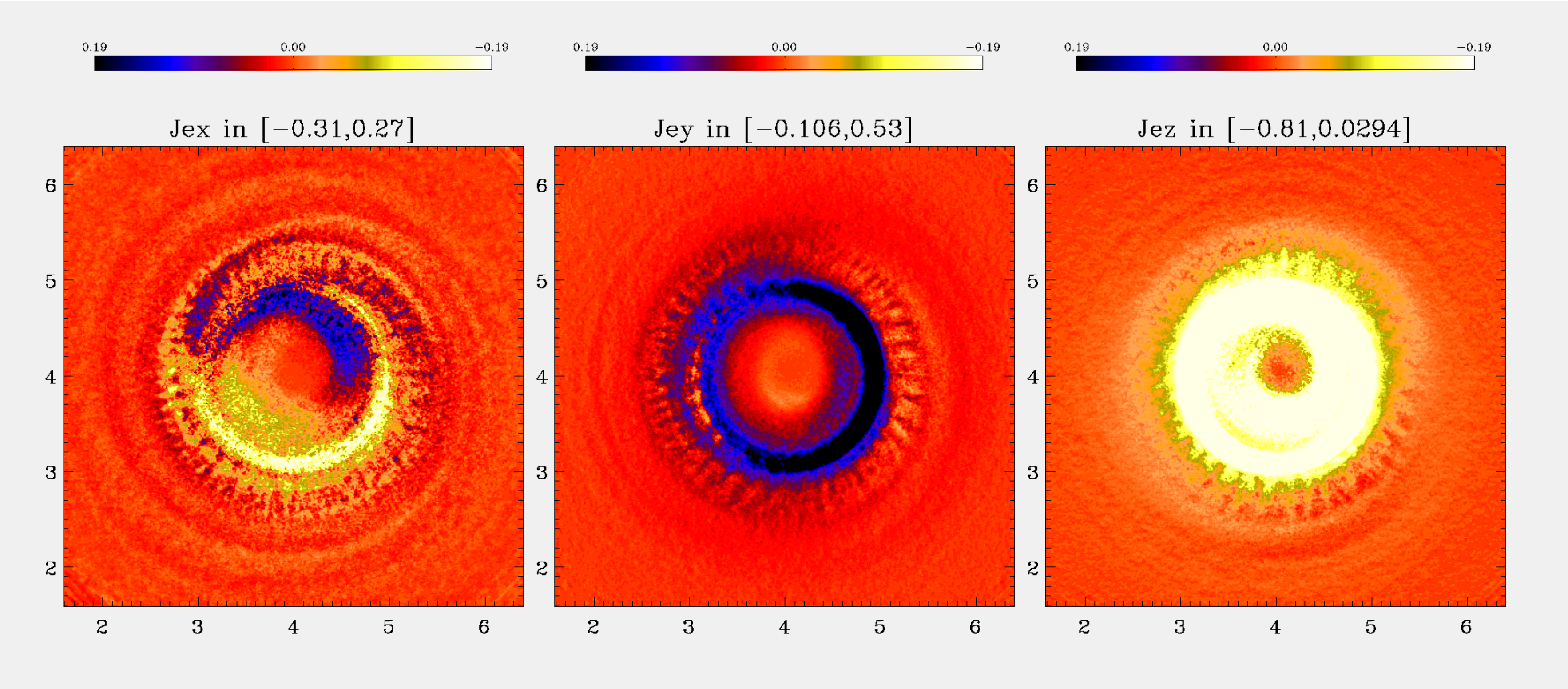

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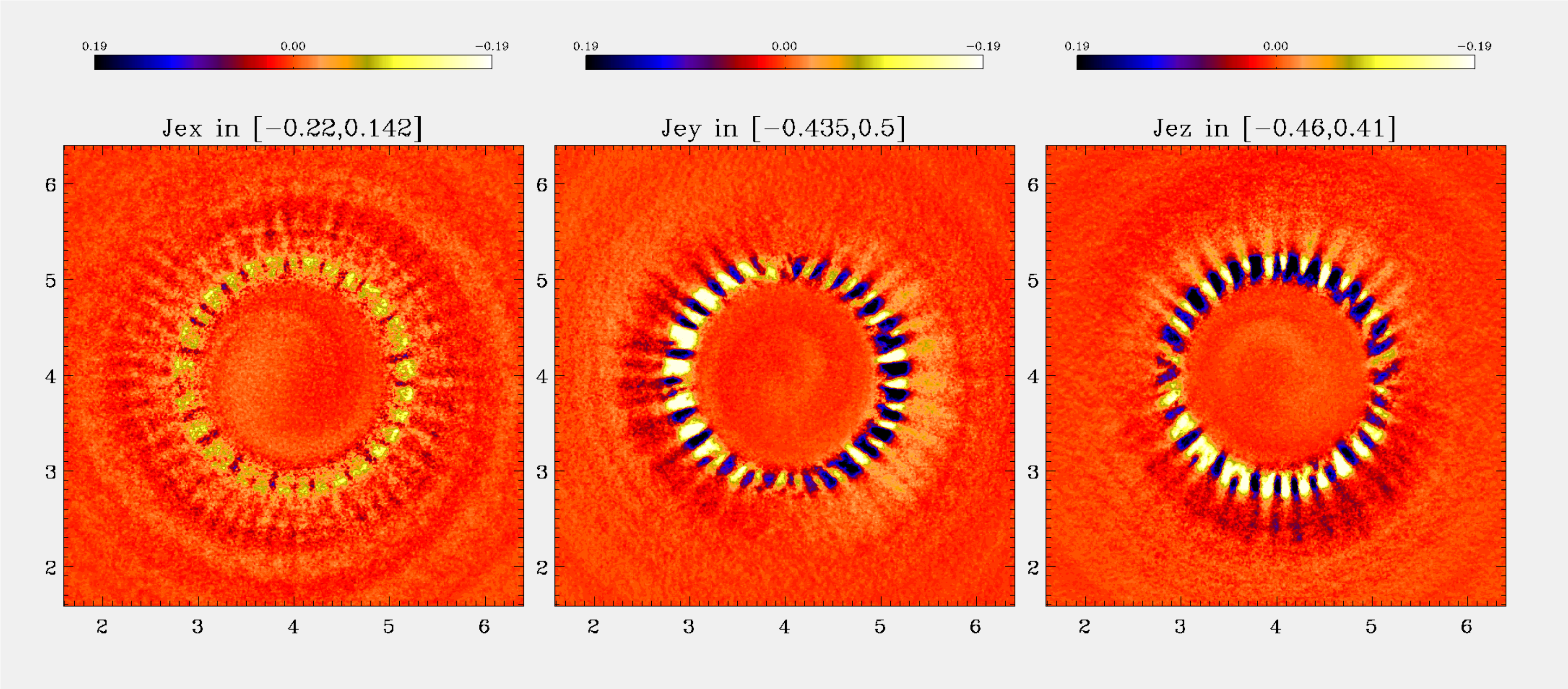

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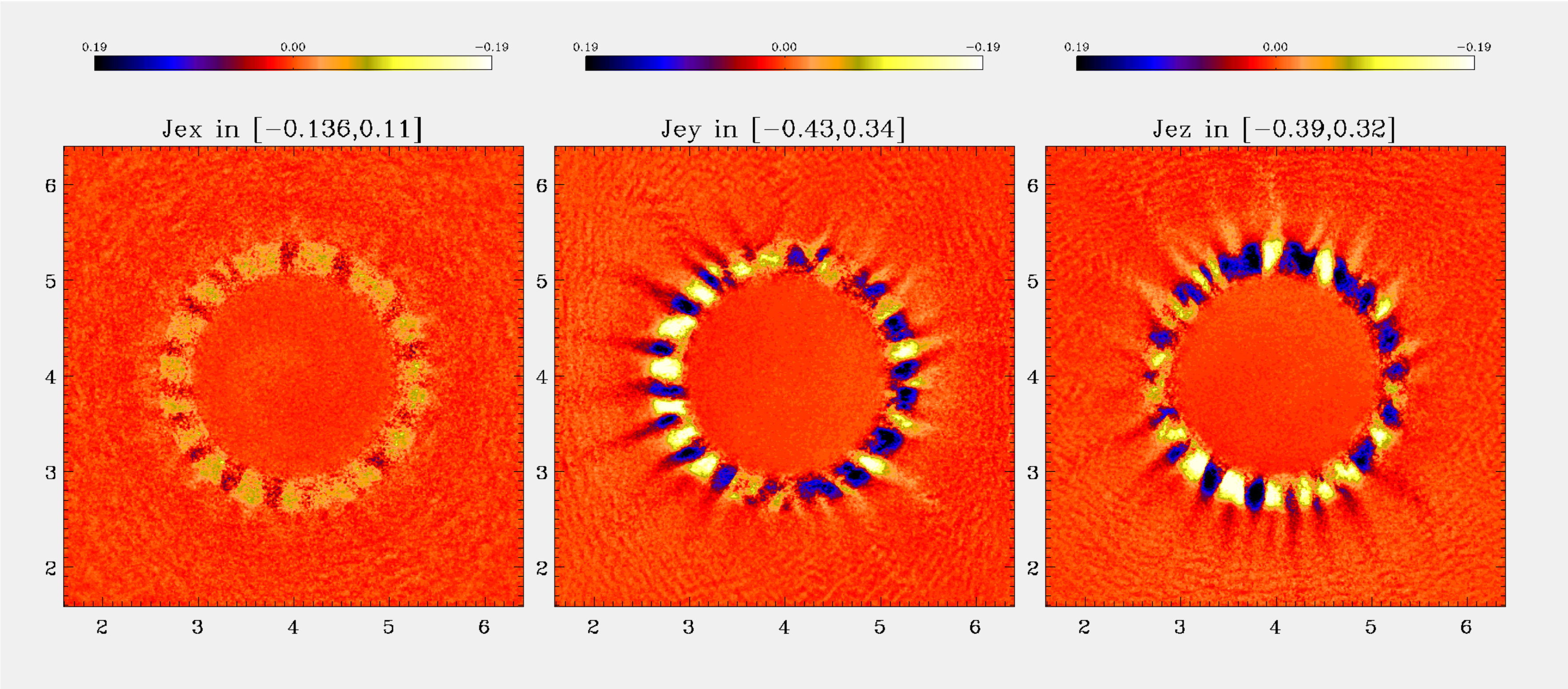

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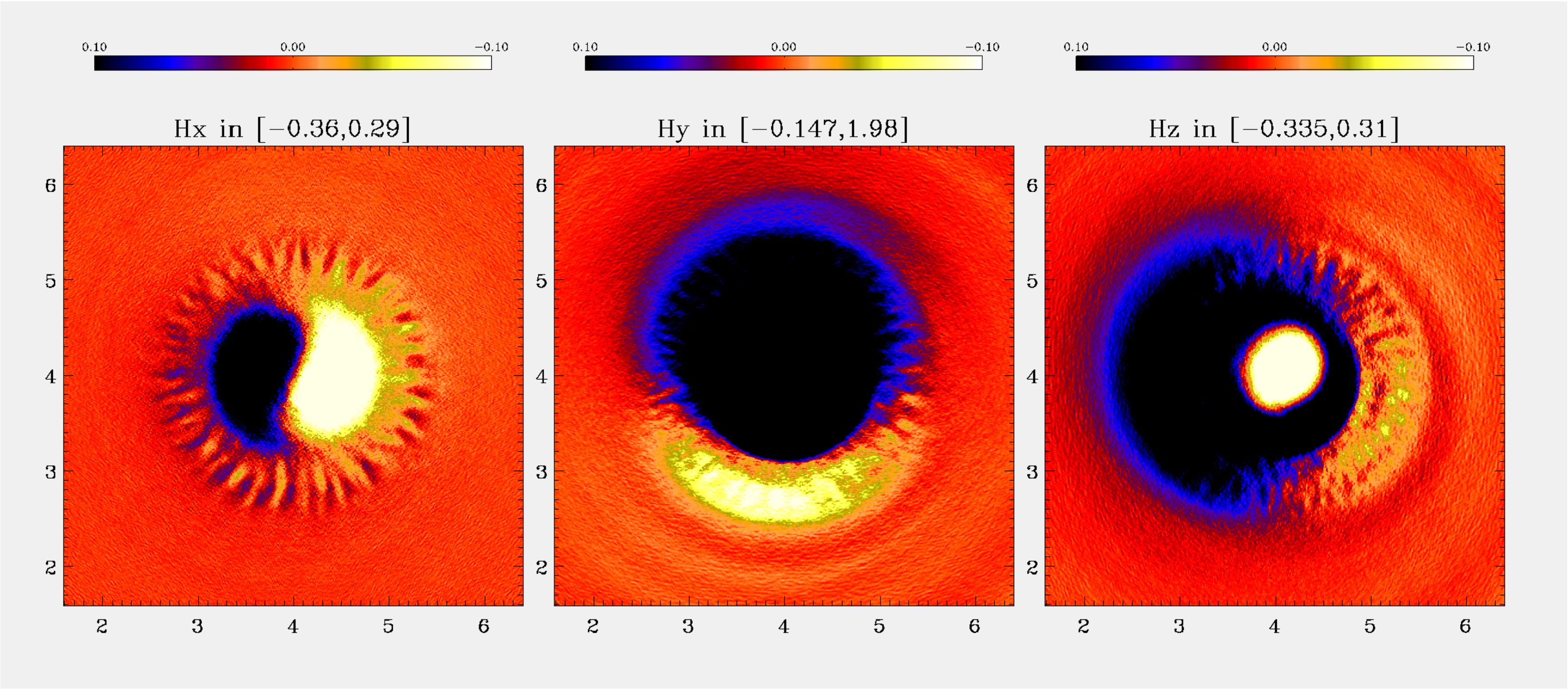
Magnetic field structures



$B_x(y,z)$ $B_y(y,z)$ $B_z(y,z)$

- 3D small-scale structures at the beam edge
- almost no "Inverse Faraday Effect" (i.e. generation of B_x in the centre)

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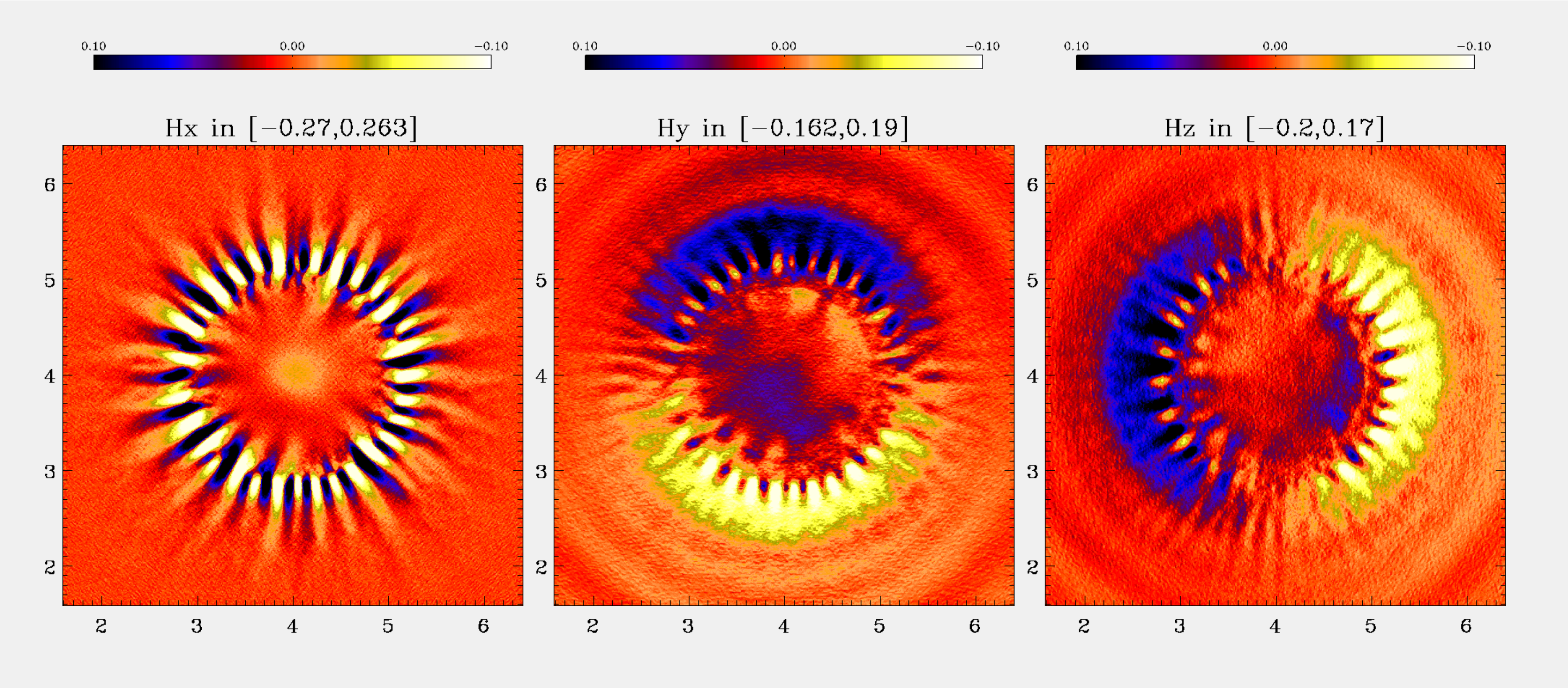

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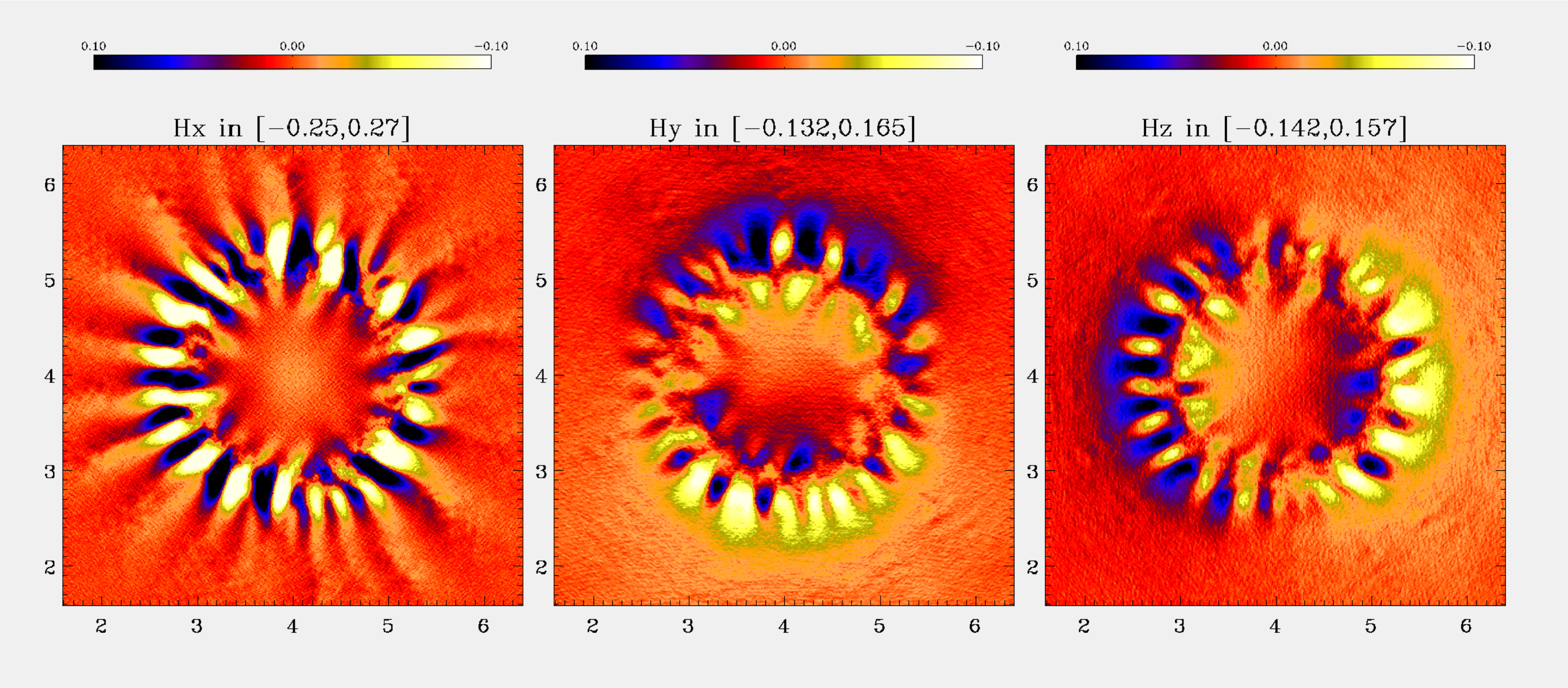

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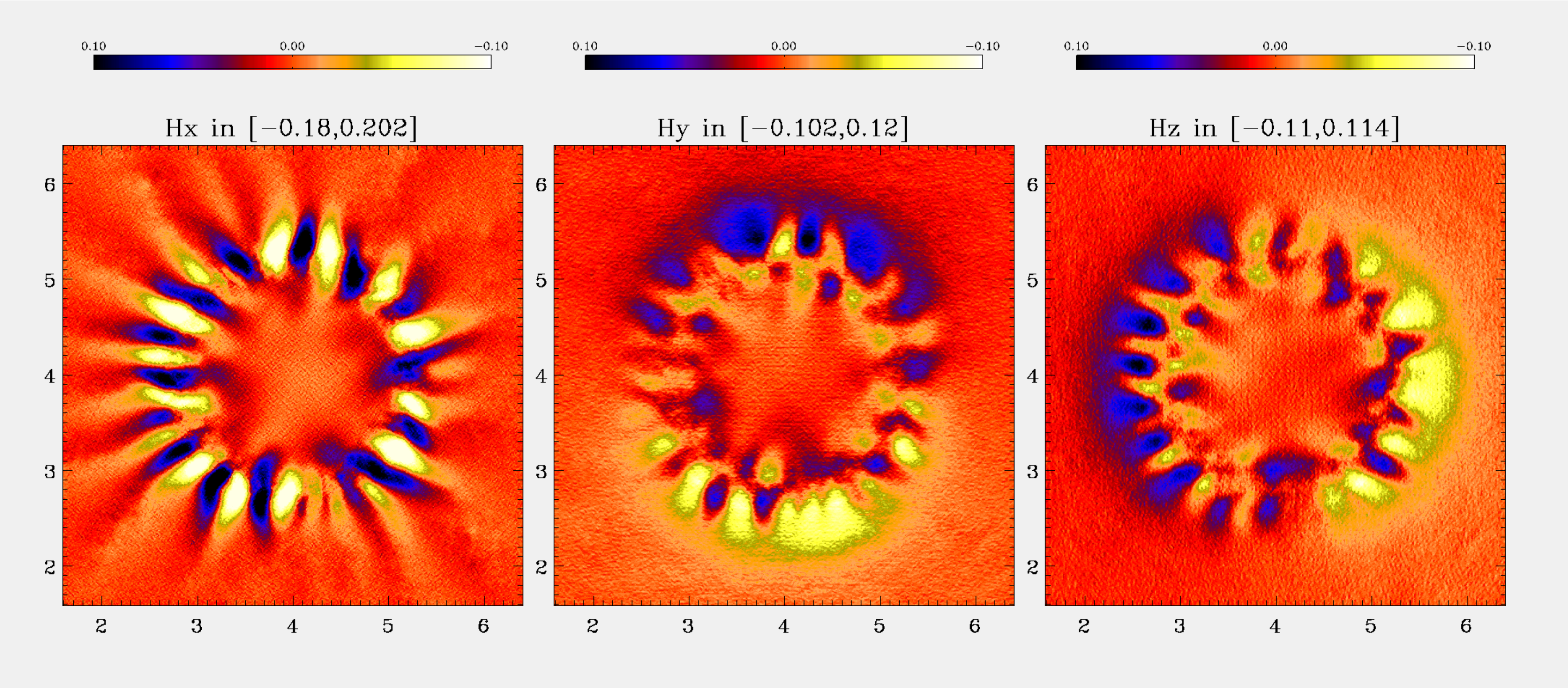

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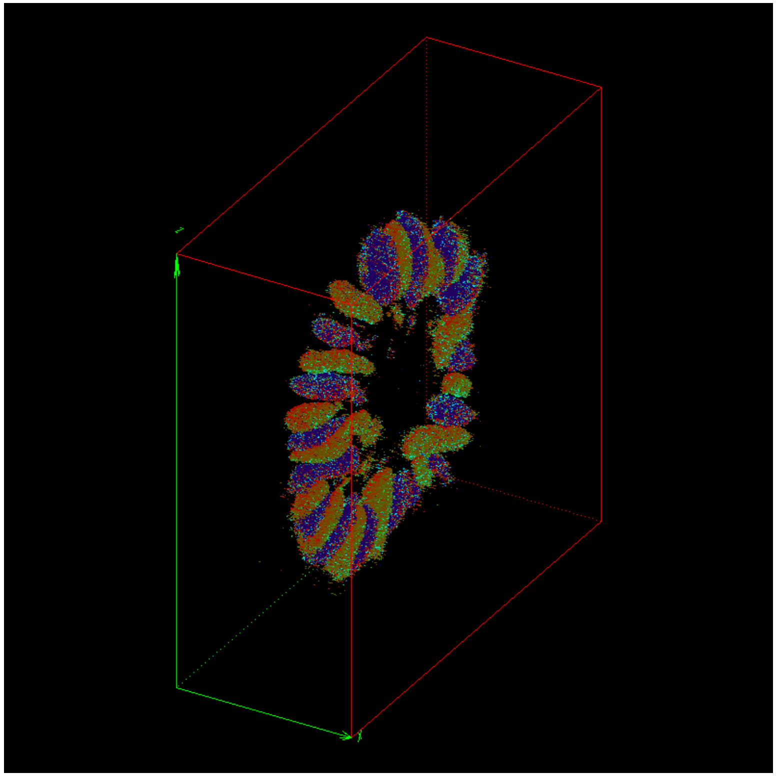

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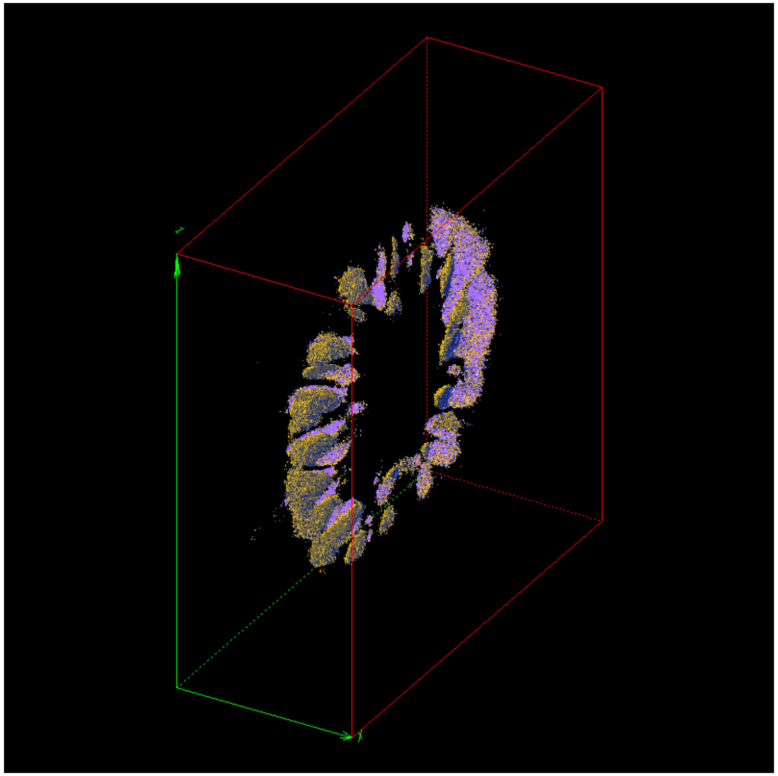

$B_z(x,y,z)$

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Conclusions

- Theory and simulation suggest that RPA with CP is a possible route to high-energy, quasi-monoenergetic, solid-density ion “beams” (or “matter pulses”?) that warrants to be experimentally investigated

- Ideal experimental conditions should combine ultrathin targets with sufficiently “long” pulses (challenging task, due to prepulse effects...)

- Preliminary 1D studies suggest that “preplasma control” may help to give evidence of RPA (higher ion energy due to low density)

- In >1D transverse (in)stability of thin foil target is an issue

- First 3D simulations confirm 1D and 2D results and show no Inverse Faraday effect but a complex magnetic field structure

This talk may be downloaded from

www.df.unipi.it/~macchi/talks.html