Radiation Pressure Acceleration: Microscopic Dynamics and (Non-)Optimal Conditions

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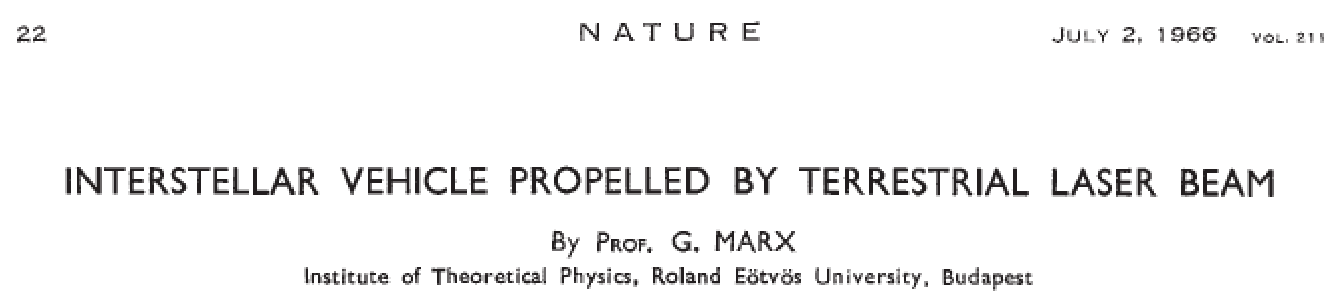
Outline

- RPA of ultrathin foils: “the perfect mirror” or “light sail” model
- Beyond the perfect mirror: a “pedagogical” model for reflectivity and charge depletion effects
- Comparison with 1D simulations
- RPA in preformed plasmas
- RPA with elliptically polarized pulses
- 3D simulations: pulse breakthrough and angular momentum absorption

Radiation Pressure Acceleration: transfering the momentum of light to matter

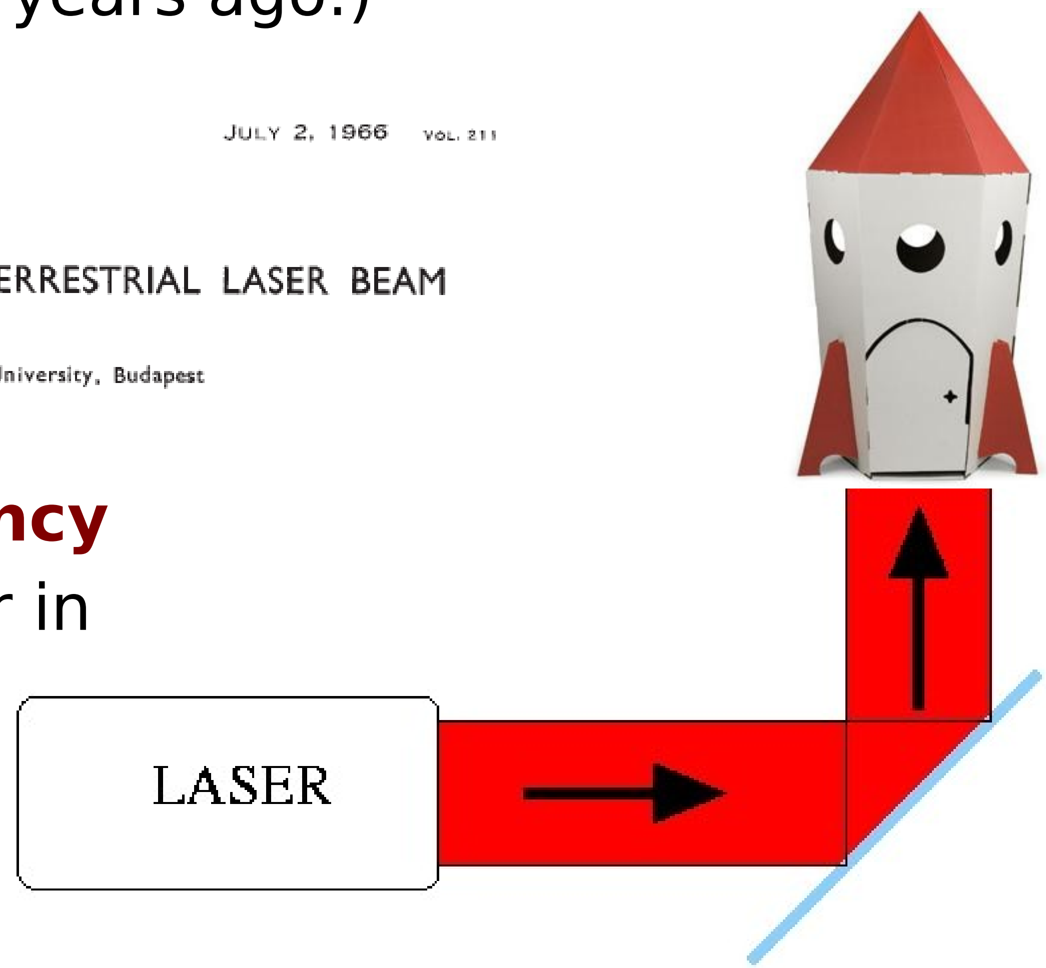
The **acceleration of a massive mirror** by light pressure is particularly efficient when the velocity becomes close to the speed of light (this suggested the “visionary” application of a **laser-propelled rocket** 42 years ago:)


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

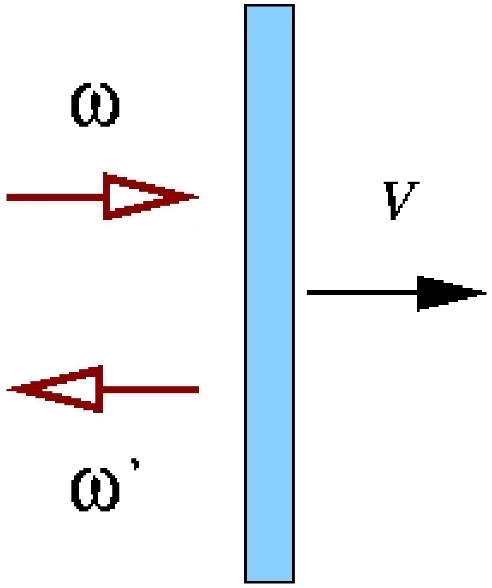
A **breakthrough in efficiency** is thus expected as we enter in the **relativistic regime**



Efficiency of RPA for a perfect mirror

Steady acceleration of a rigid mirror
reaches 100% efficiency as

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



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

Simple argument:

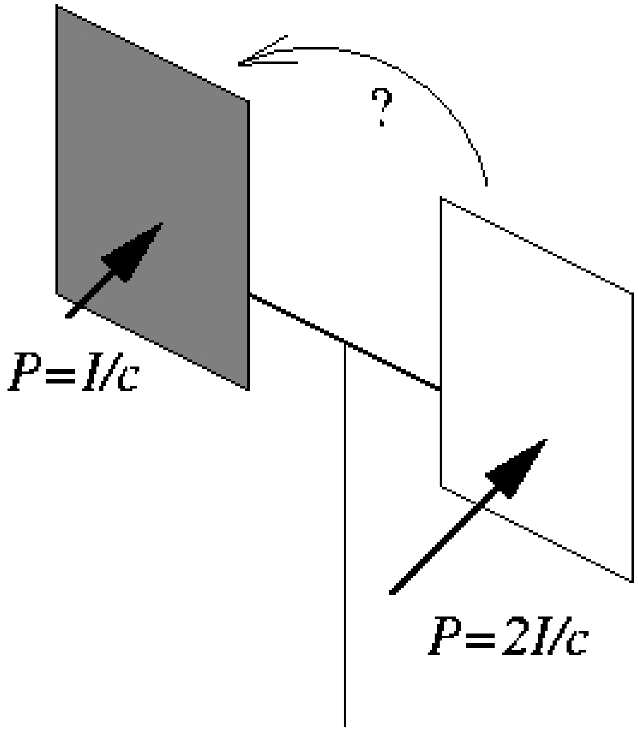
conservation of
"number of photons"
plus
Doppler shift
of reflected light

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

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

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

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:

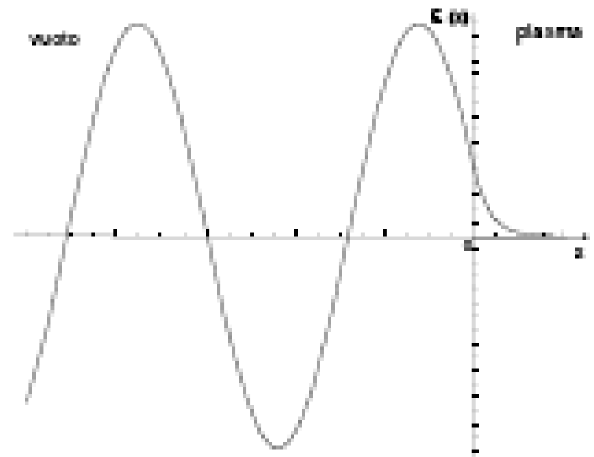
the heating of the **black** (absorbing) surface increases the thermal pressure of the background gas (imperfect vacuum!)

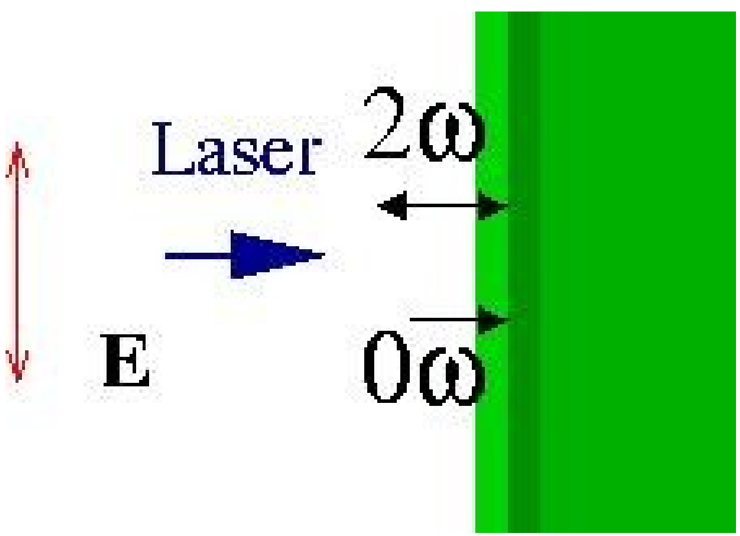
In the high-intensity irradiation of a solid-density (plasma) target, “heating” is due to energy absorption into electrons

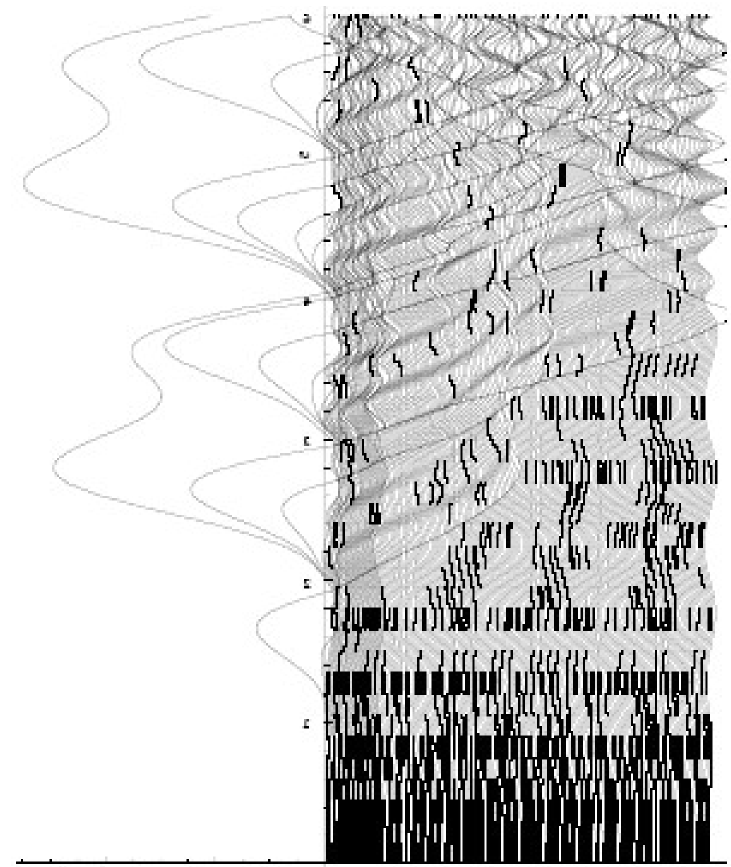
How do we suppress undesired target heating?

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





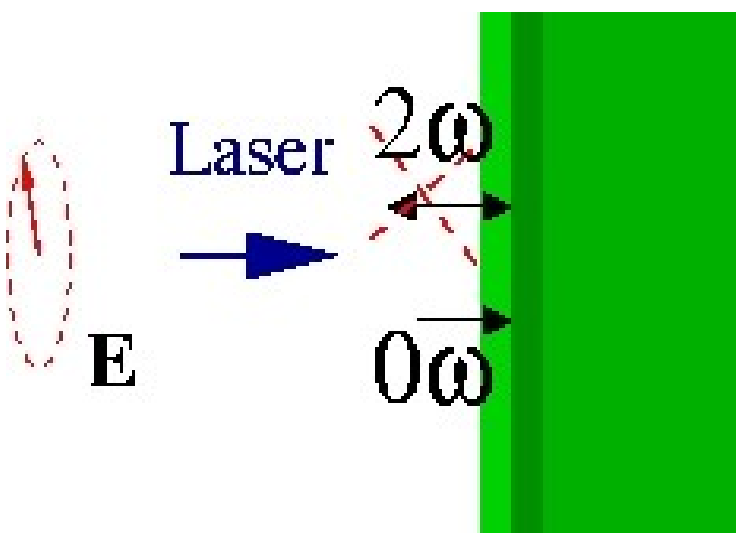


S. Tuveri, tesi di Laurea, 2006

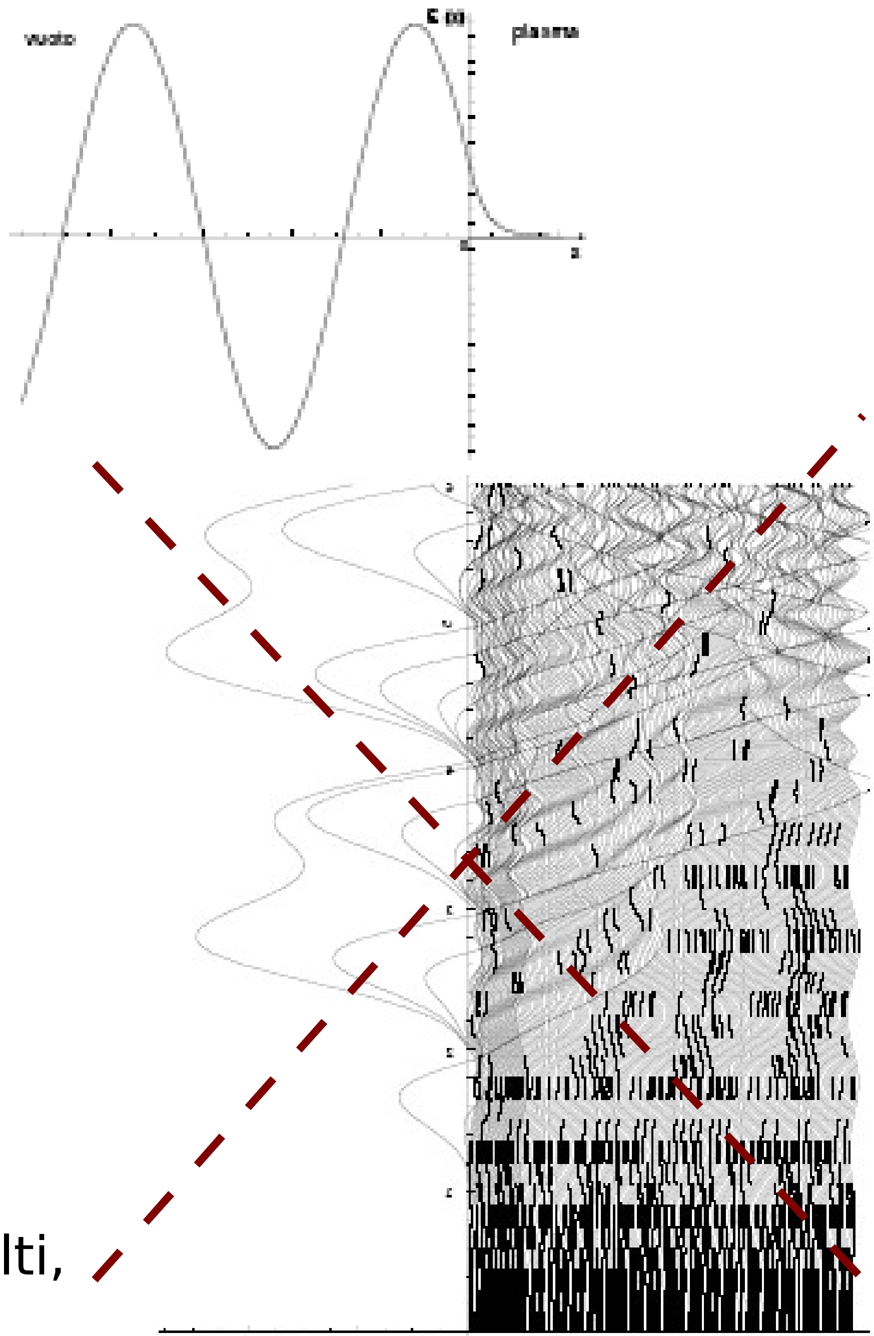
How to “switch off” fast electrons

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

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

The accelerating (perfect) mirror or "Light Sail" model applied to laser interaction with thin foils predicts some 10^{10} ions to be accelerated to GeV/A energies with 1PW, 1ps pulses (~10^{21} W/cm^2 intensity)

[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]

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

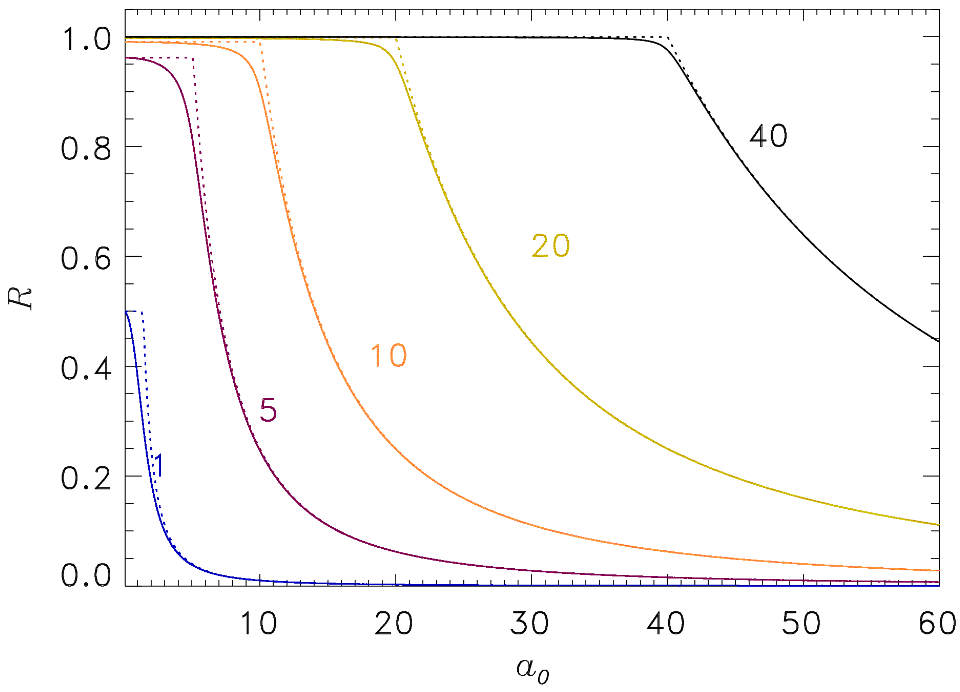
However, apart from "technical" difficulties (e.g. ultrahigh contrast and normal incidence required) a thin foil targets is ***not*** either a "perfect mirror" (and reflectivity may drop down due to relativistic induced transparency) or a "rigid body" (the ponderomotive force separates electrons from ions creating a space charge field)

A "pedagogical" model for thin foil acceleration

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

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

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



a_0: laser amplitude

$\zeta=\pi n_0 L/n_c\lambda$ "optical thickness"

approximated (but rather precise) formula:

$R\approx\zeta^2/(\zeta^2+1)$ for $a_0<\zeta$

$R\approx\zeta^2/a_0^2$ for $a_0>\zeta$

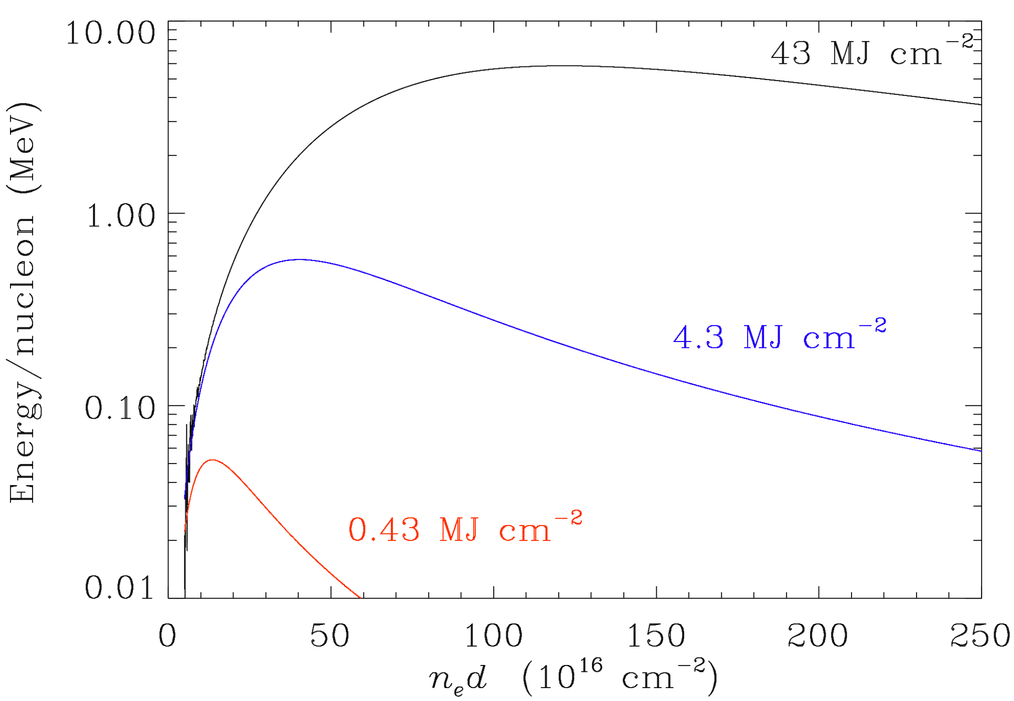
P_{rad} does not depend on a_0 for $a_0>\zeta$! (since $I\sim a_0^2$)

Model predicts "optimal" thickness for acceleration

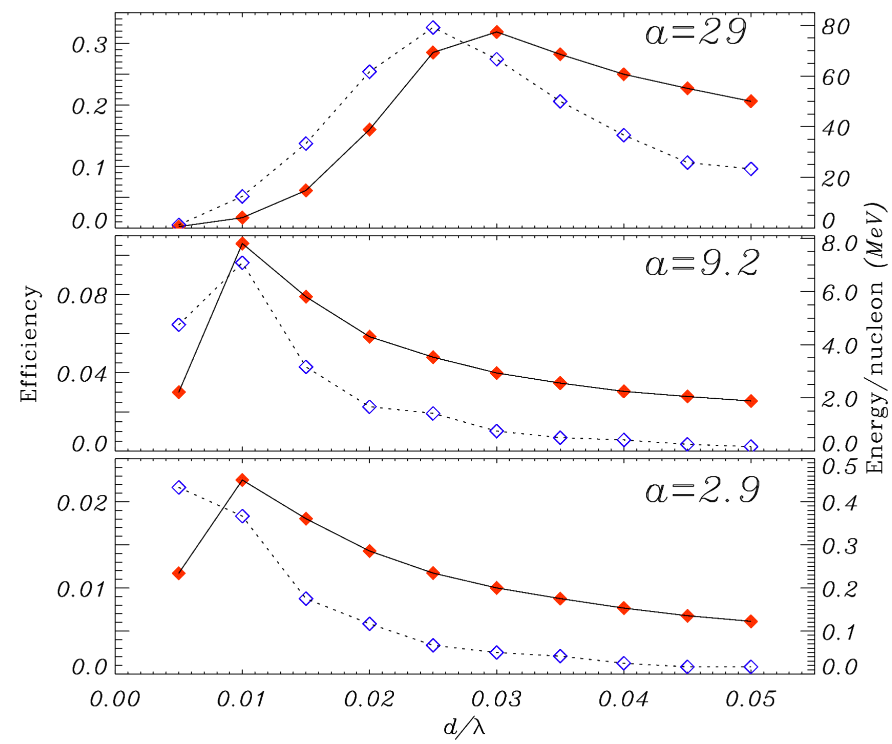
Equations of motion for laser-driven mirror with reflectivity R:

$$\frac{d(\gamma\beta)}{dt} = \frac{2I(t - X/c)}{\rho d c^2}\frac{1-\beta}{1+\beta}R\left(\omega\frac{1-\beta}{1+\beta}\right), \qquad \frac{dX}{dt} = \beta c$$

Computed energy/nucleon as a function of the pulse fluence



Qualitative agreement with PIC data, but *lower* energies in the model



“Hole boring” and thick vs. thin targets

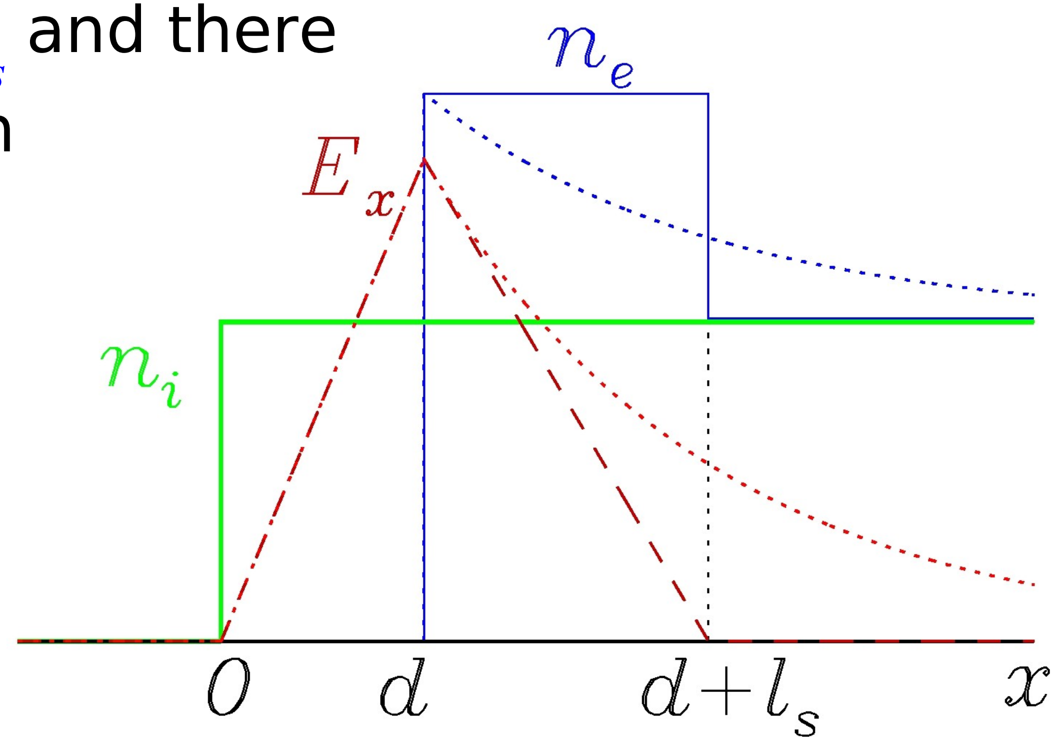
A simple modeling for RPA of semi-infinite targets (“hole boring” regime) accounts for the dynamics observed in PIC data and gives scalings for ion energy and acceleration time

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

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

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

A “thin” target should have a thickness $L \approx d+l_s$ in order to allow “repeated” acceleration of the “fast” ion layer



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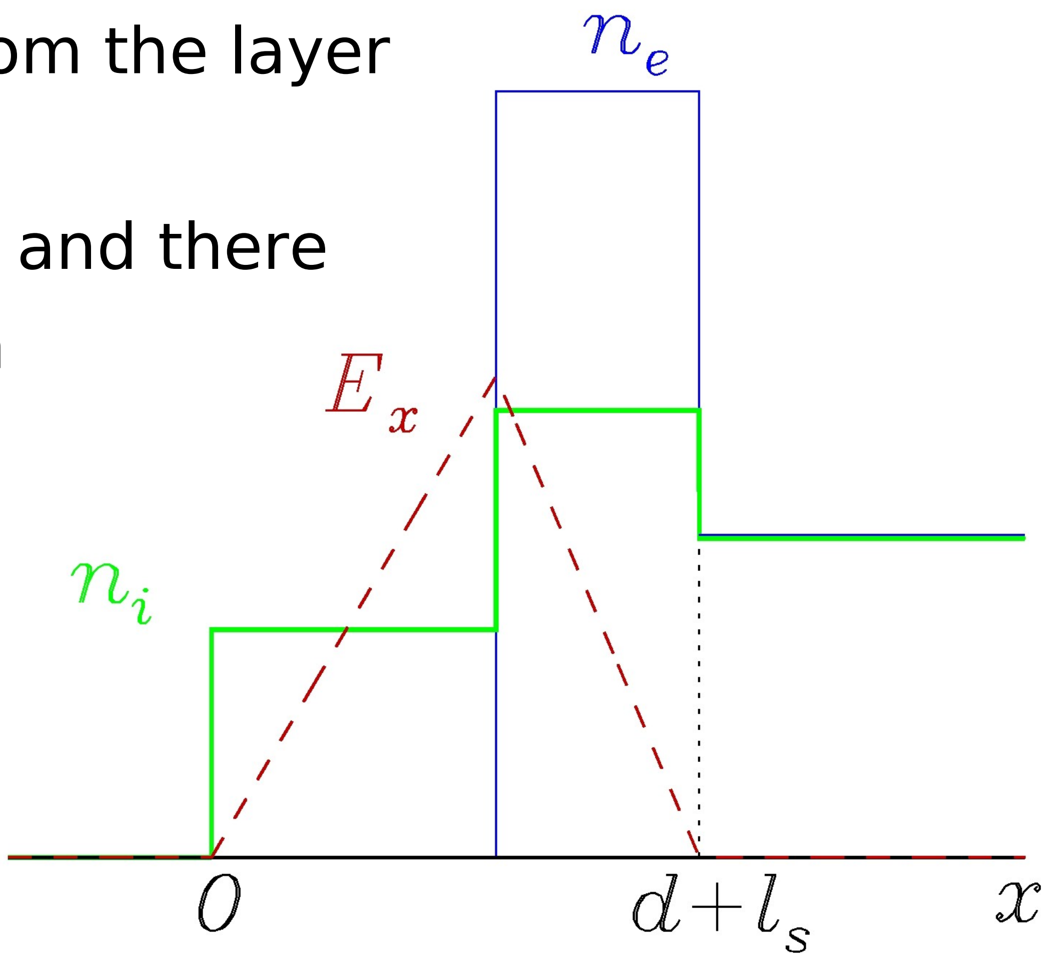

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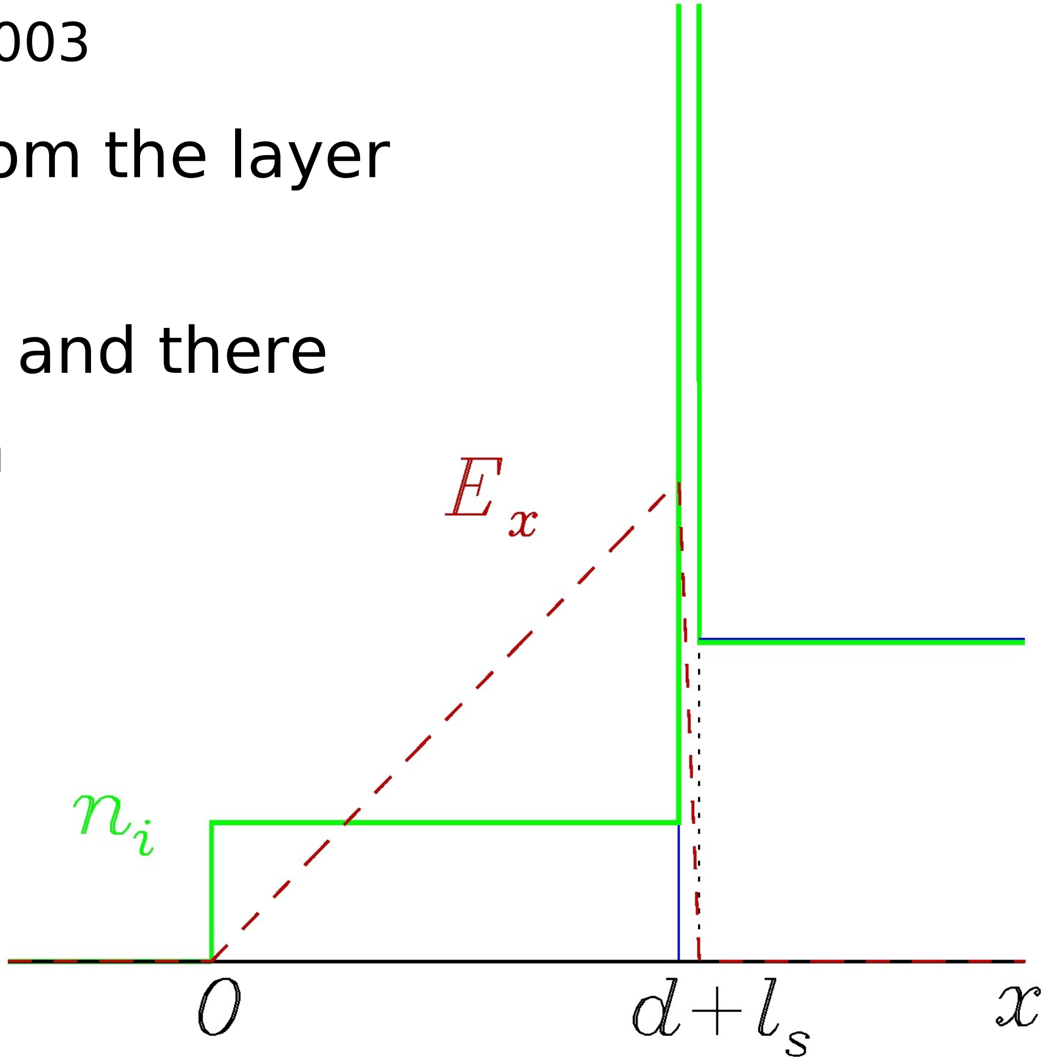


Radiation vs. electrostatic pressure in a thin foil

Question: *can we remove all or part of the electrons from the foil*? (-> transition to Coulomb explosion regime)

The radiation pressure should exceed the maximum electrostatic pressure that can be generated, but in a foil the ***opposite*** condition holds
(for circular polarization and quasi-equilibrium conditions!)

$$P_{\mathrm{rad}} = (2I/c)R < P_{\mathrm{es}} = 2\pi (e n_0 L)^2 \quad \text{for } a_0 < \zeta$$

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

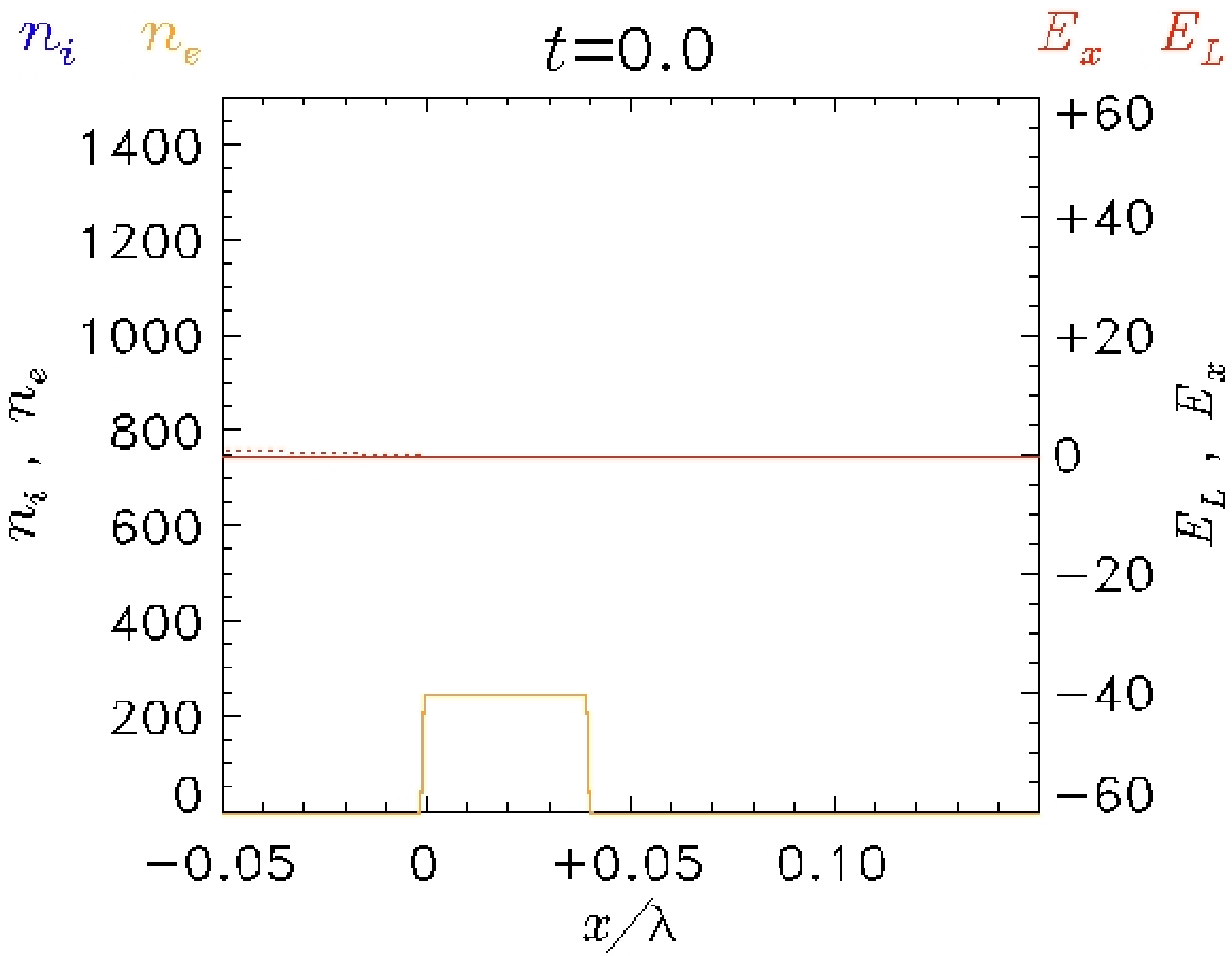
The threshold condition $a_0 = \zeta$ is equivalent to that of the "opacity to transparency" transition!

We thus expect (most of) the electrons to pile up near the rear surface of the foil, but without leaving it!

1D PIC simulations confirm model suggestions

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

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



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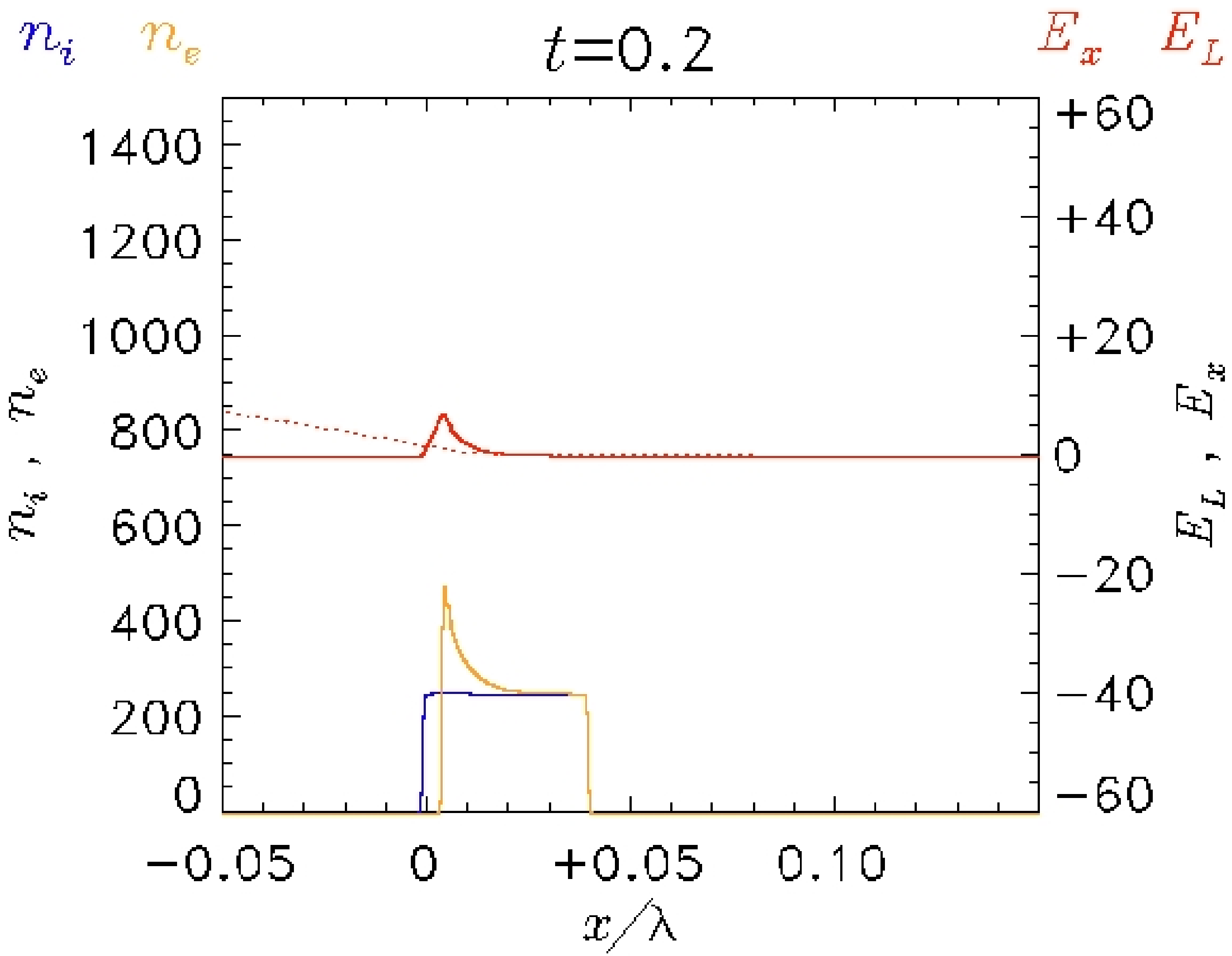

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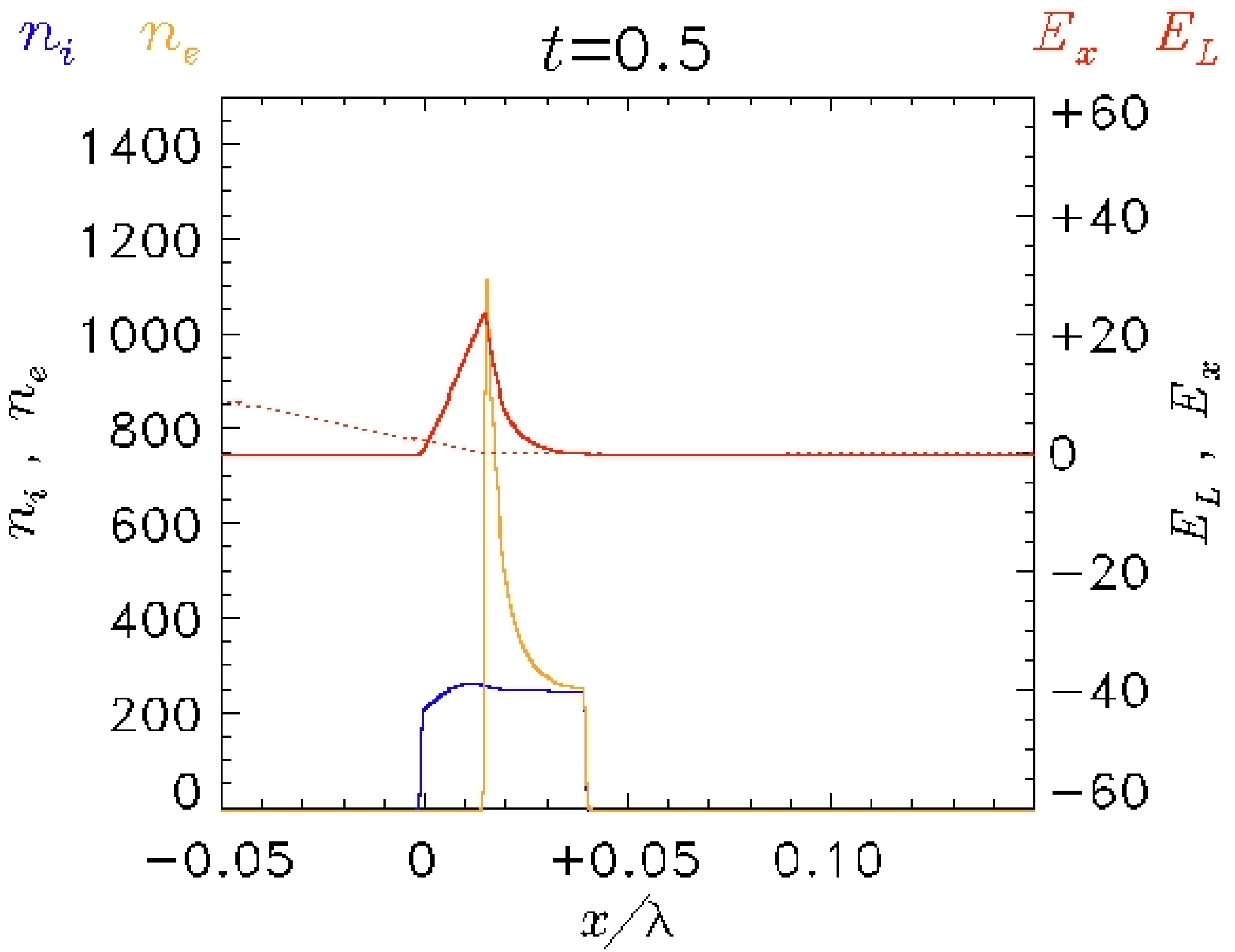

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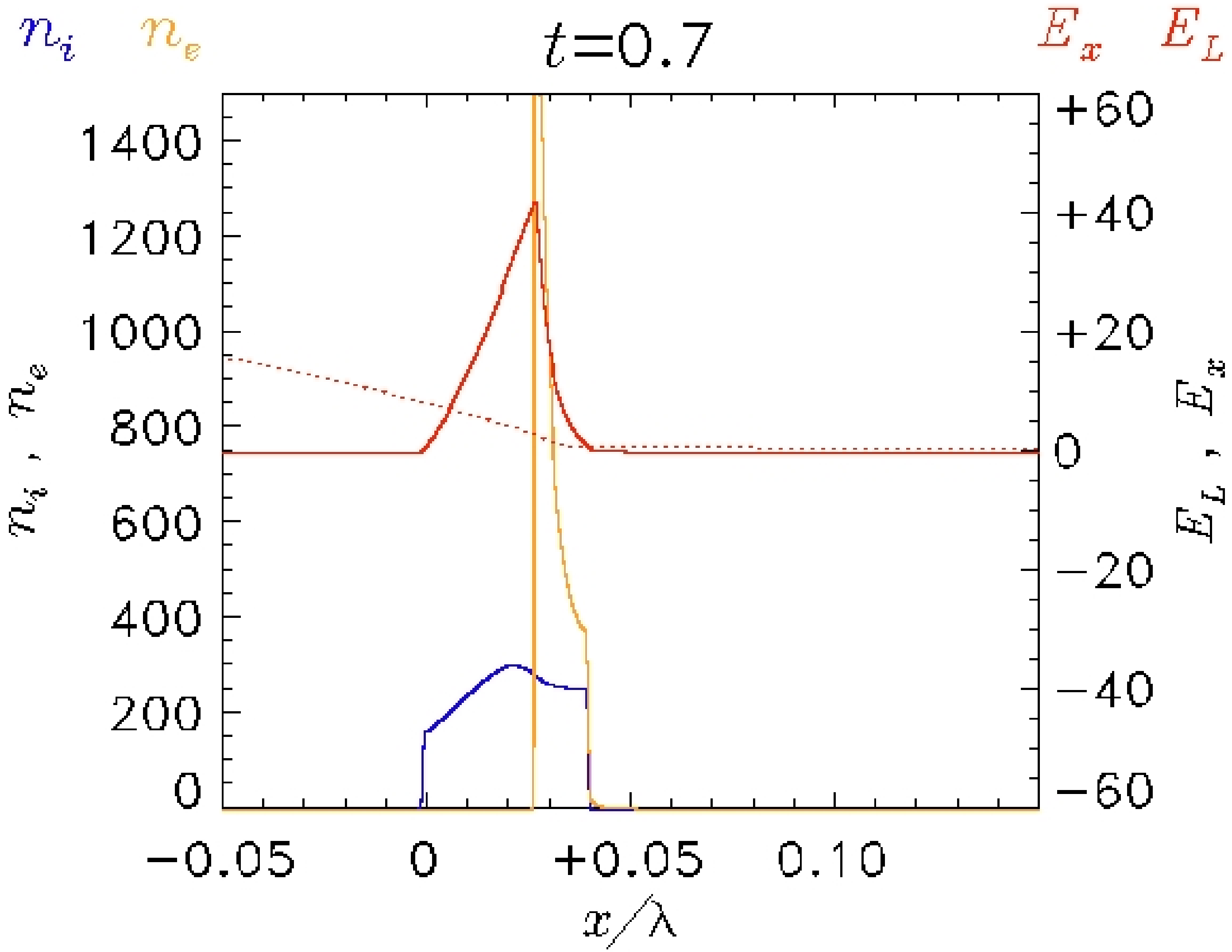

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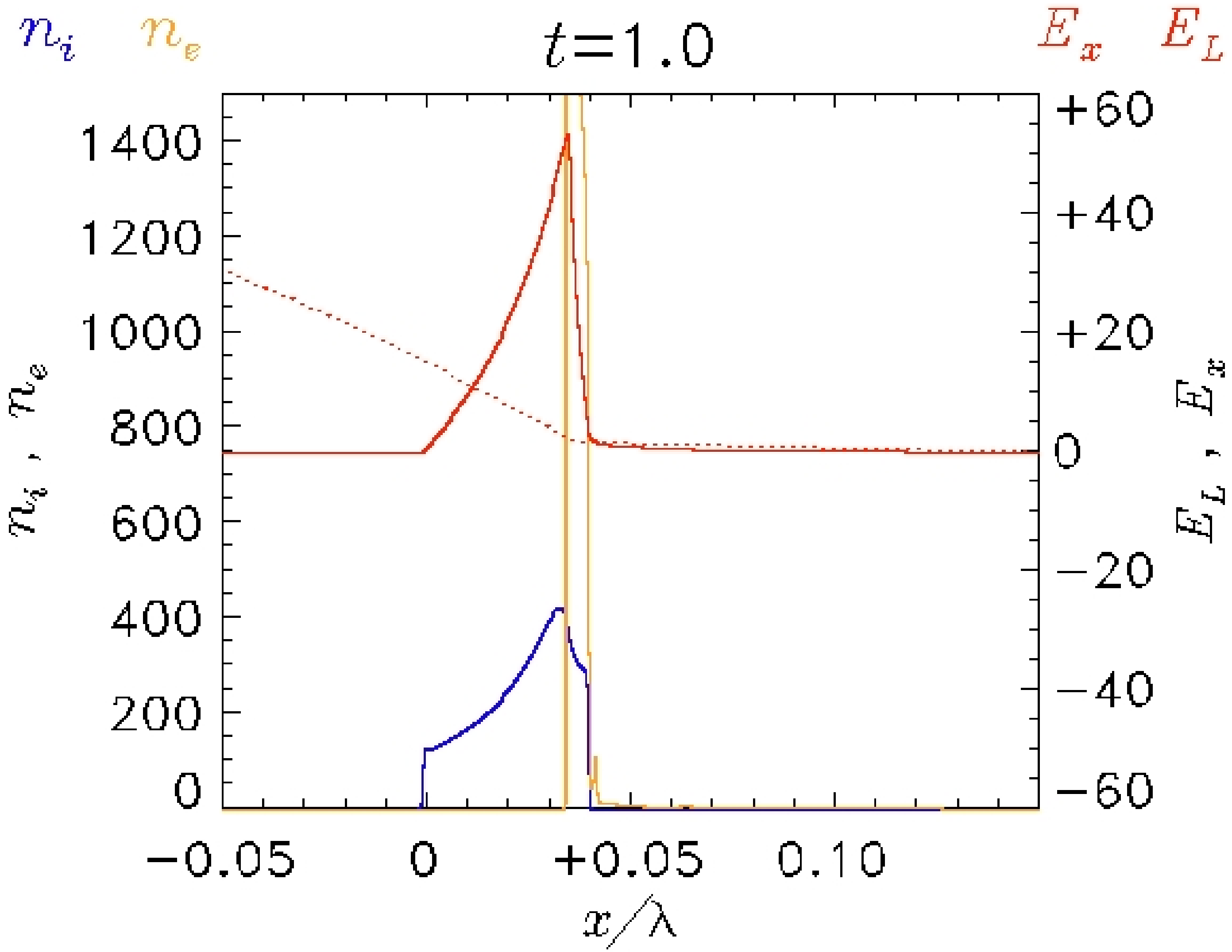

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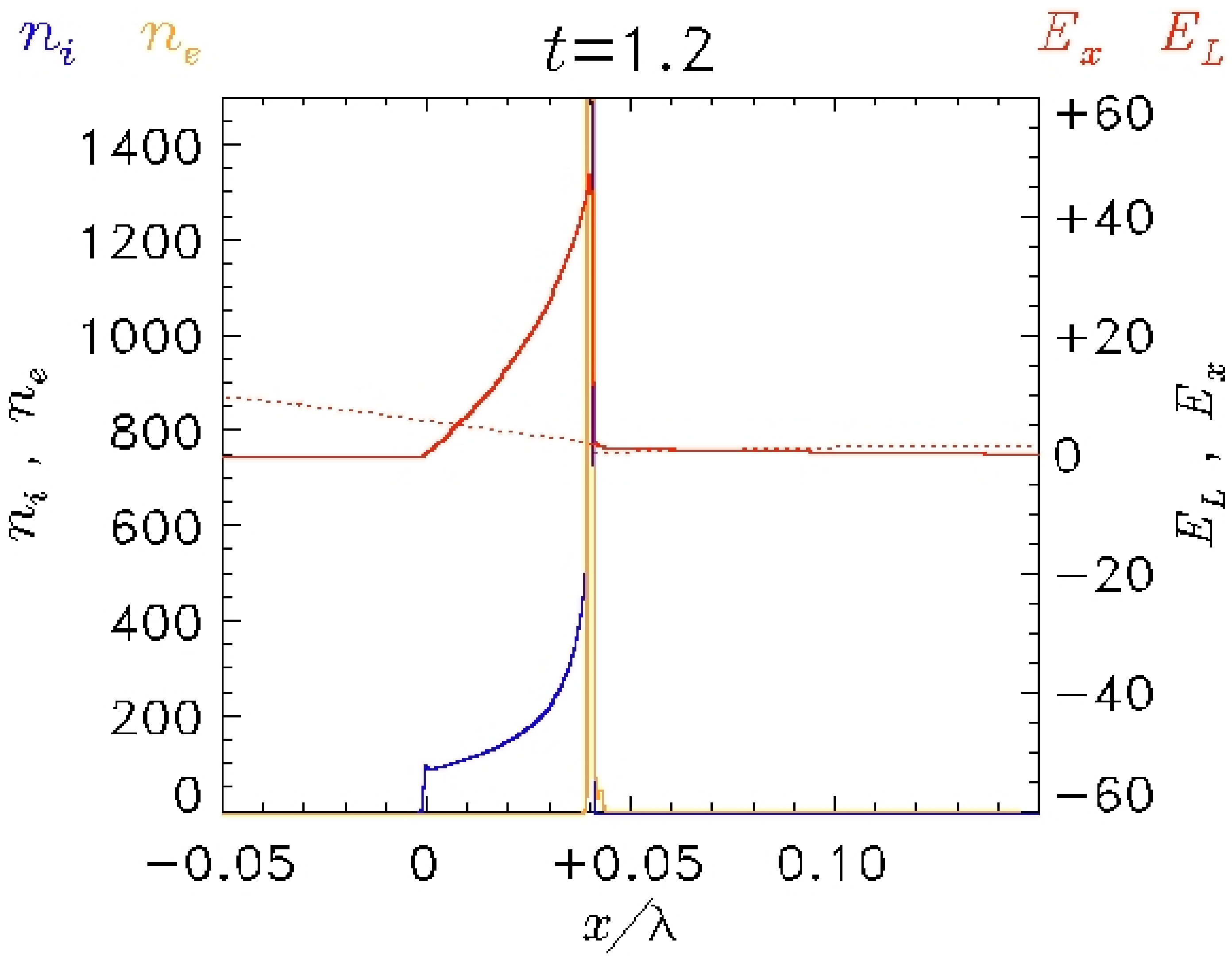

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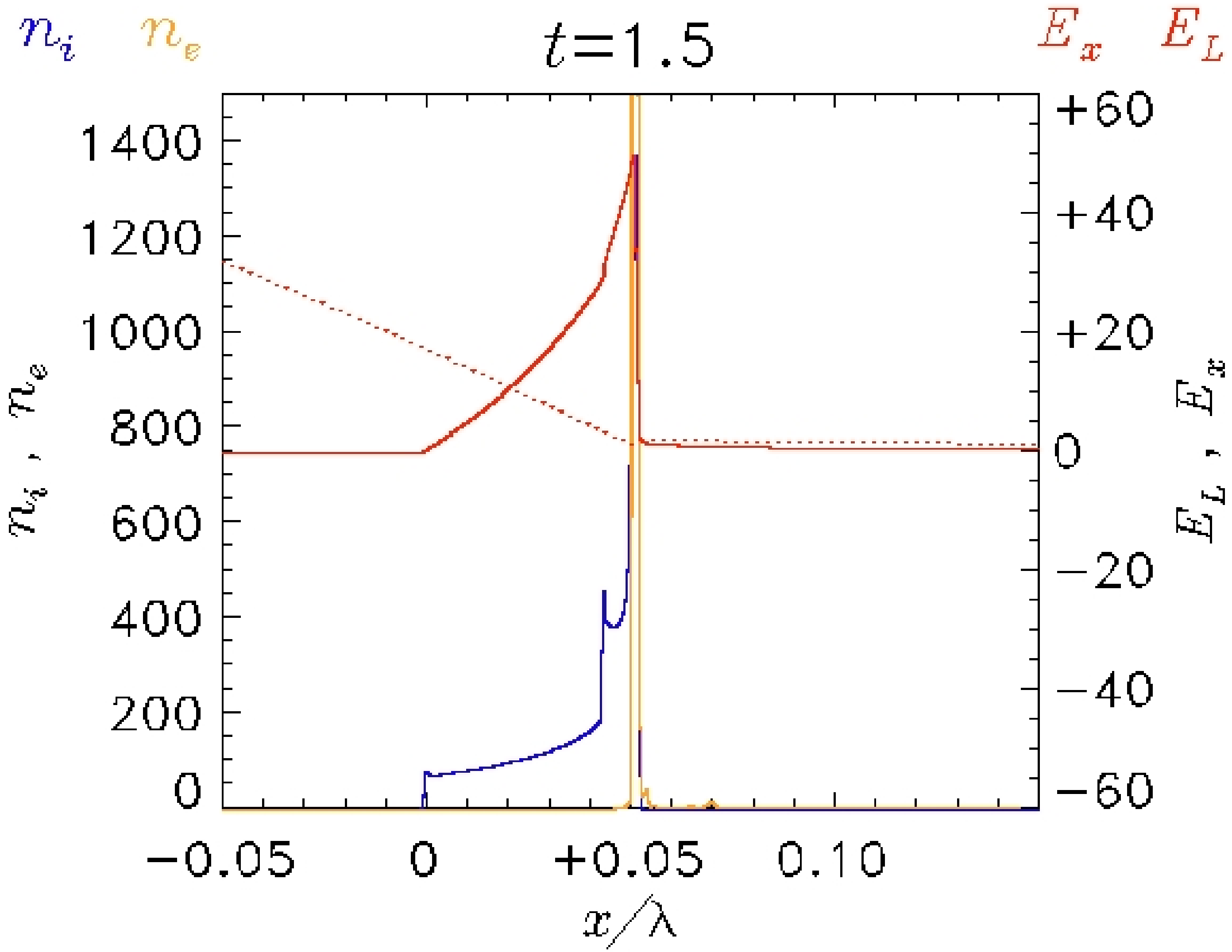

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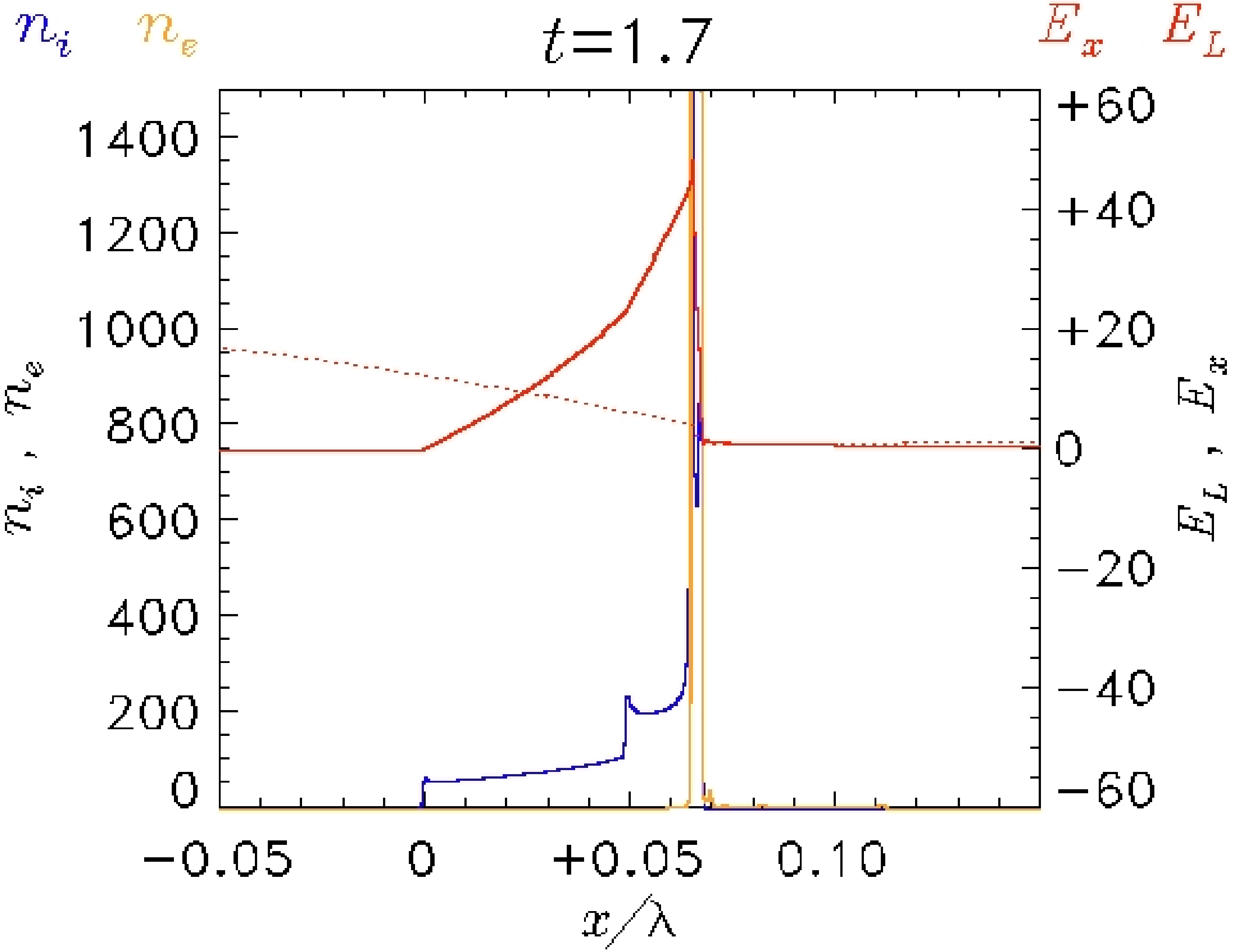

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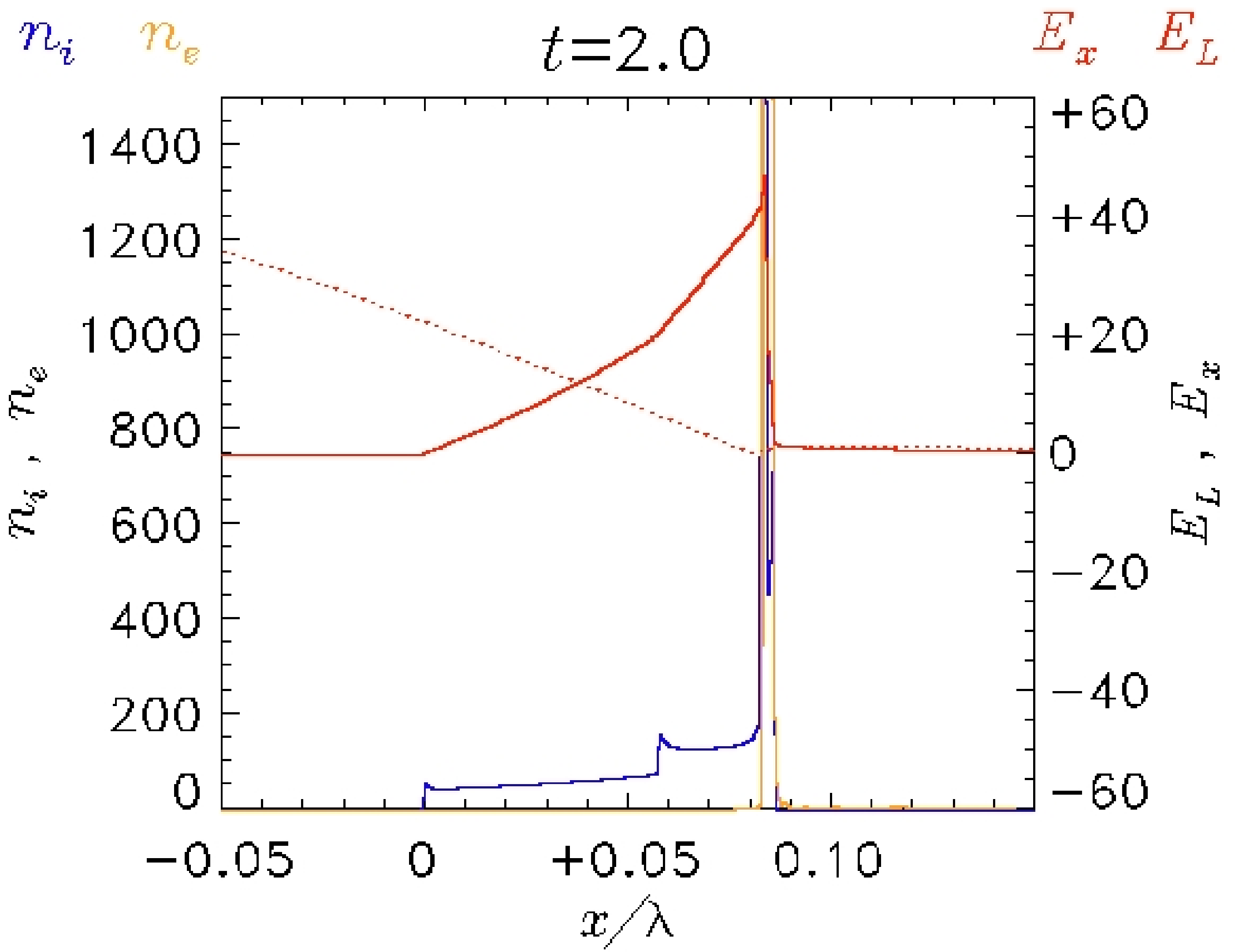

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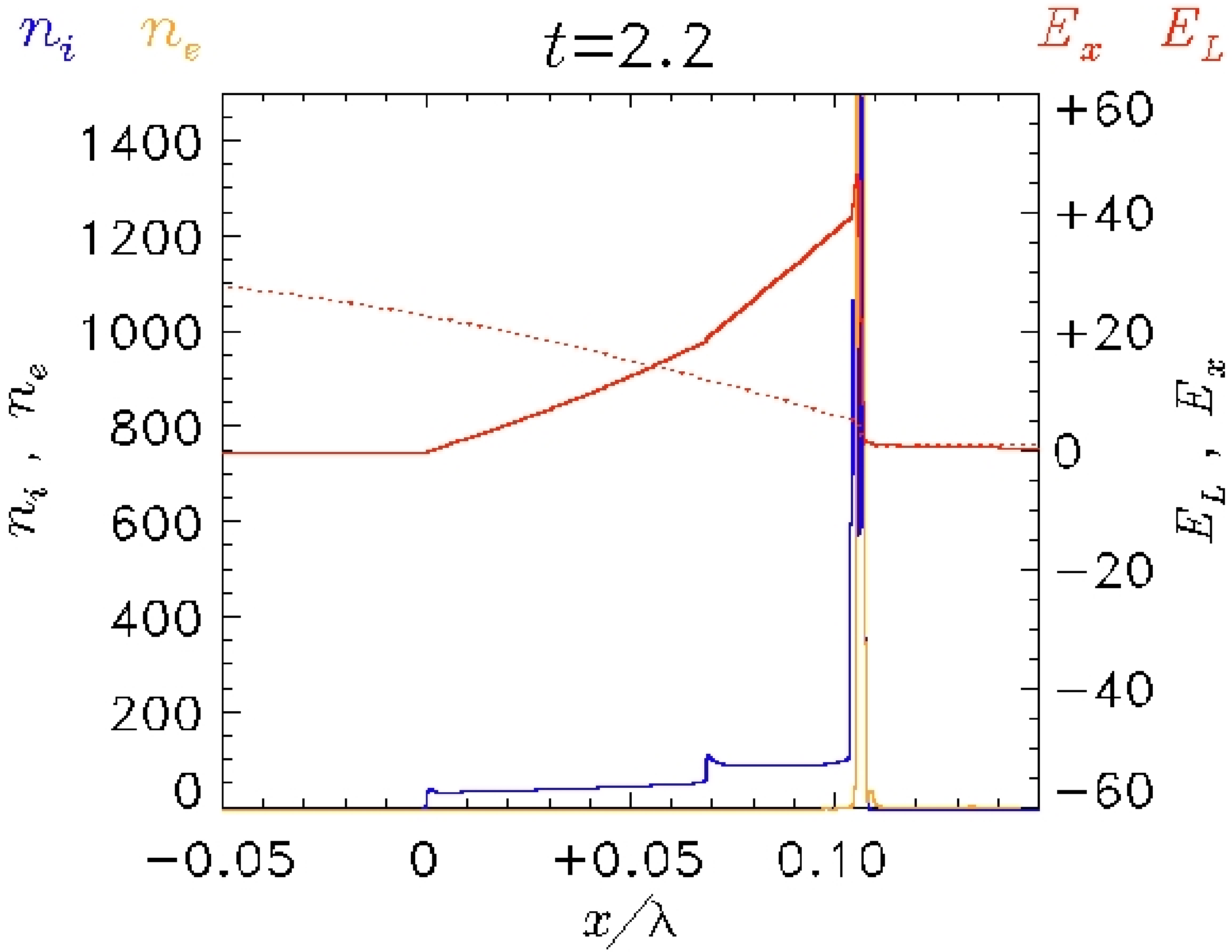

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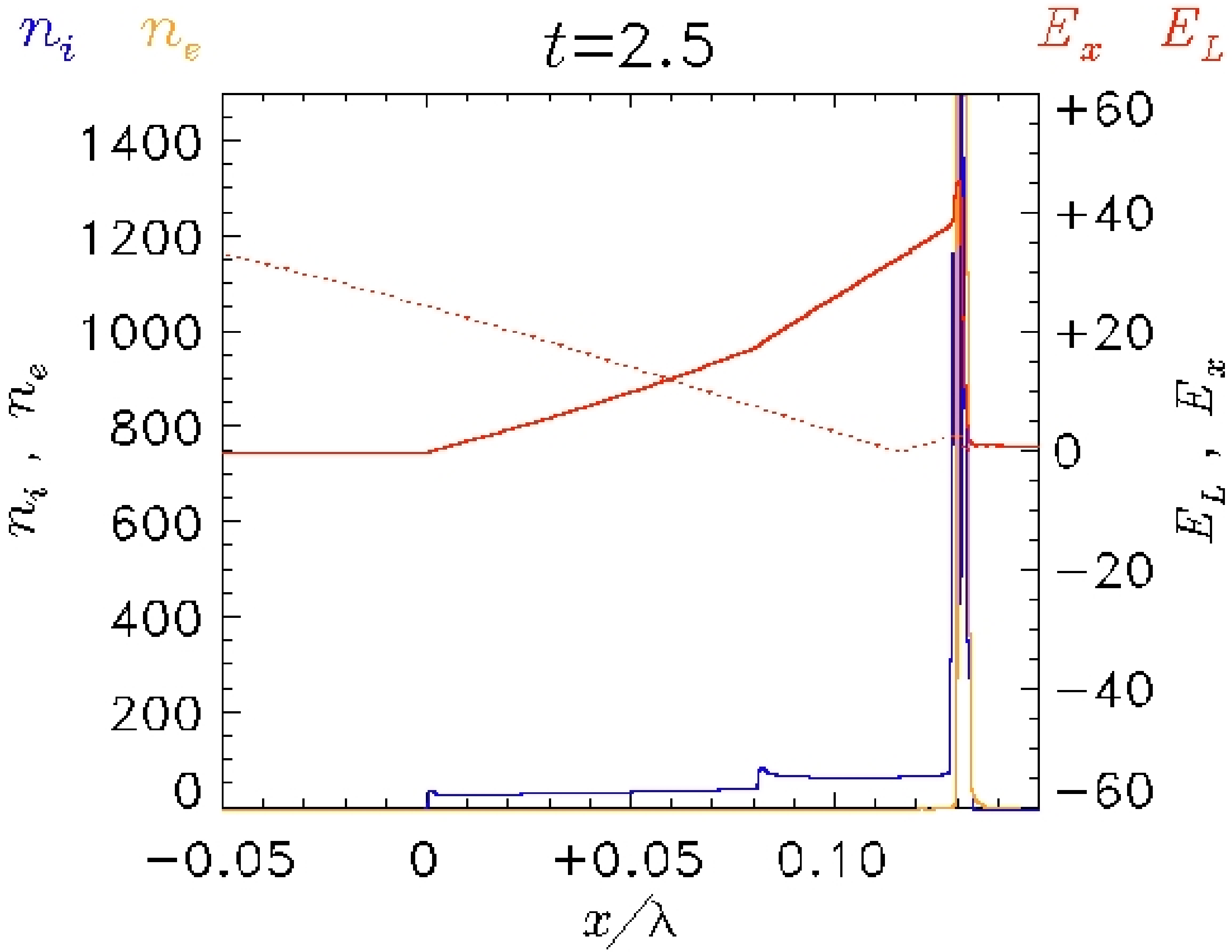

Ion energy spectrum

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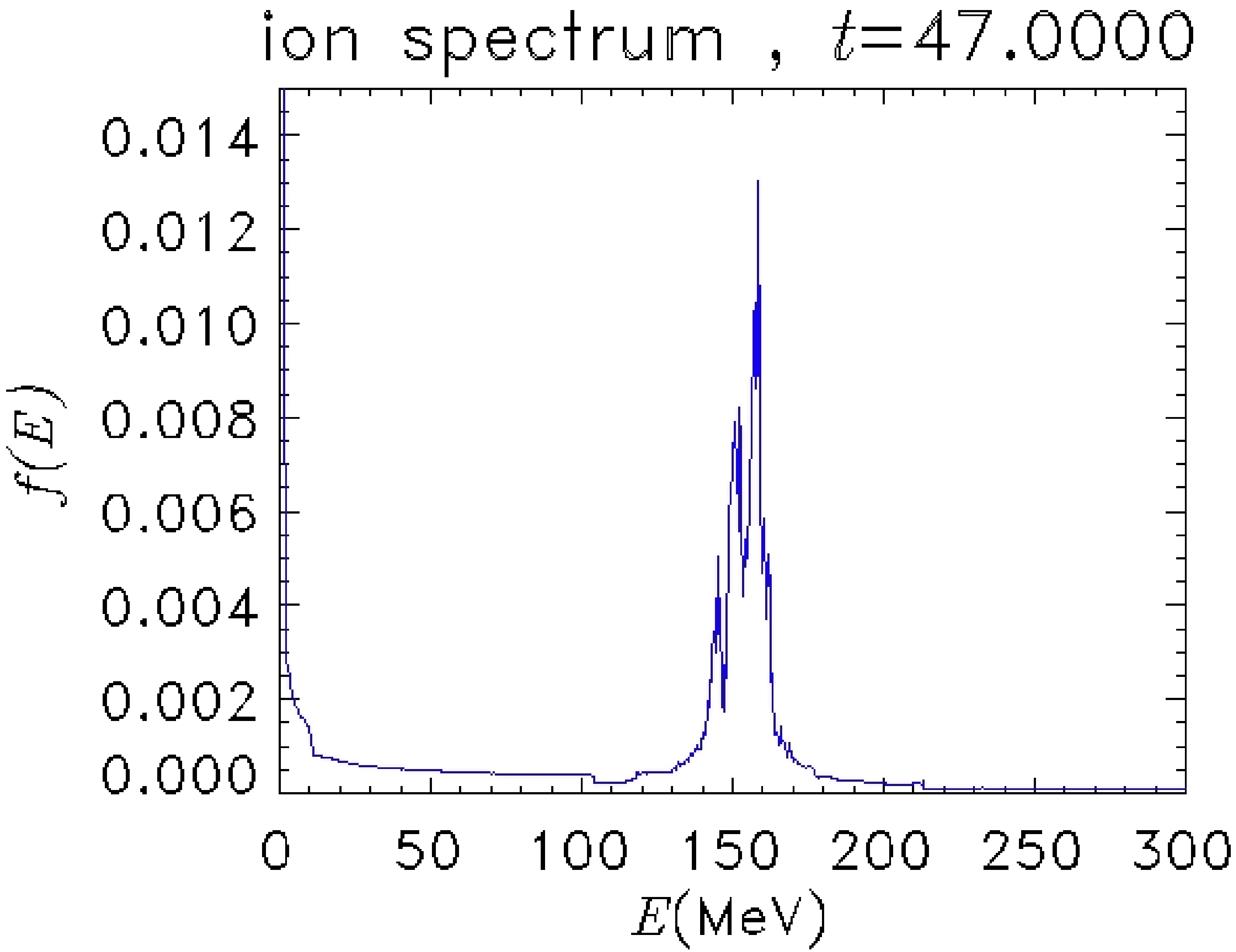

A few considerations following the model

- Only a portion of the foil of thickness l_s is accelerated; the accelerated mirror formulas may be used with a lower mass $M_r \approx M(l_s/L) \approx 1/8$ for the simulation shown
→ better agreement of the model with PIC data!

- the foil remains negatively charged during the acceleration stage; excess electrons detach at the end of the laser pulse (see next PIC movie)

- It is possible to use a double layer target, e.g. for proton acceleration)

- the dynamics involves bery short spatial scales (e.g. the density spike) and low densities (e.g. the ion “shelf” at the front side); very high resolution is needed in PIC codes to resolve such features accurately!

“Excess” electrons leave the foil after the pulse

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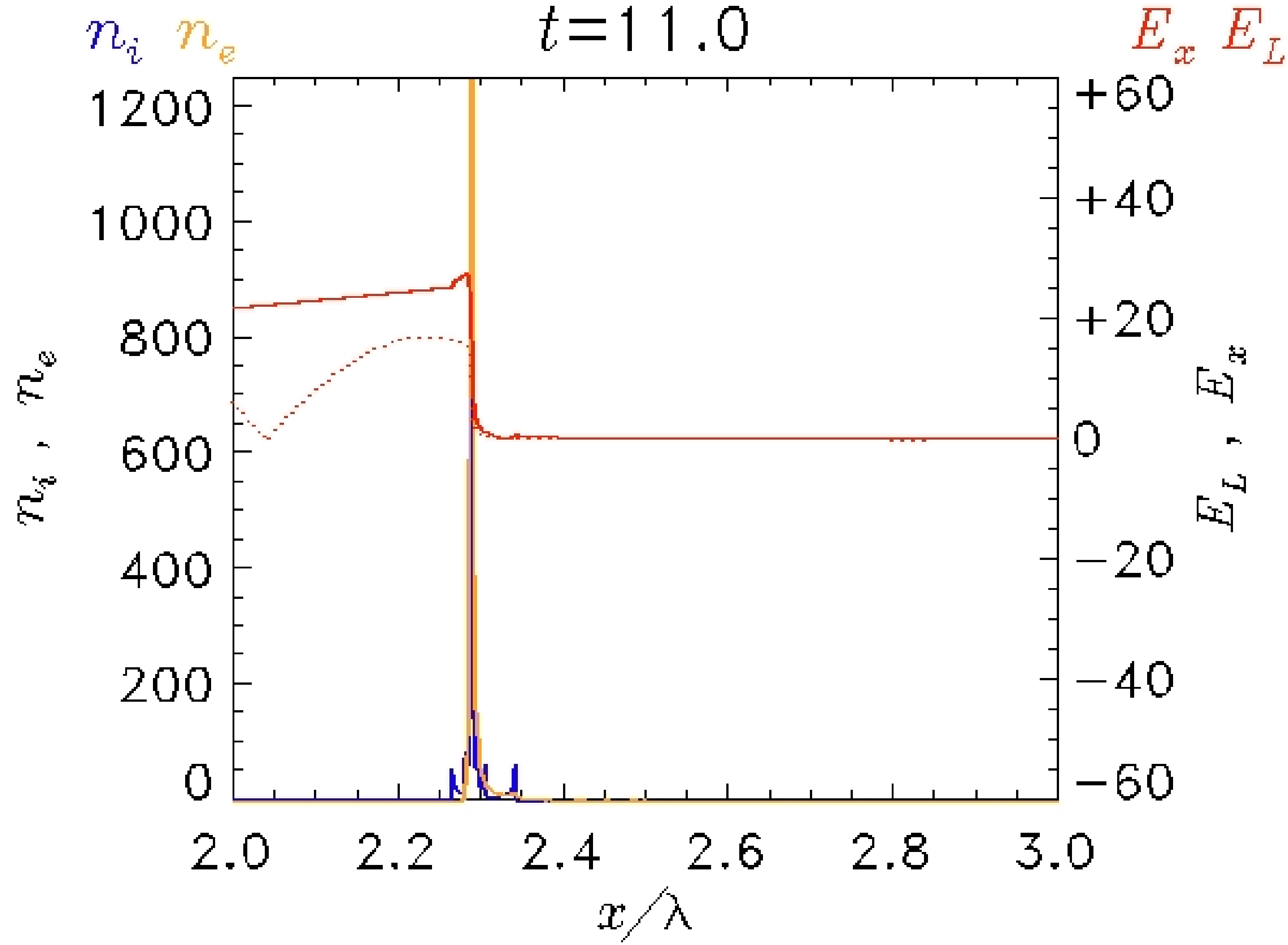

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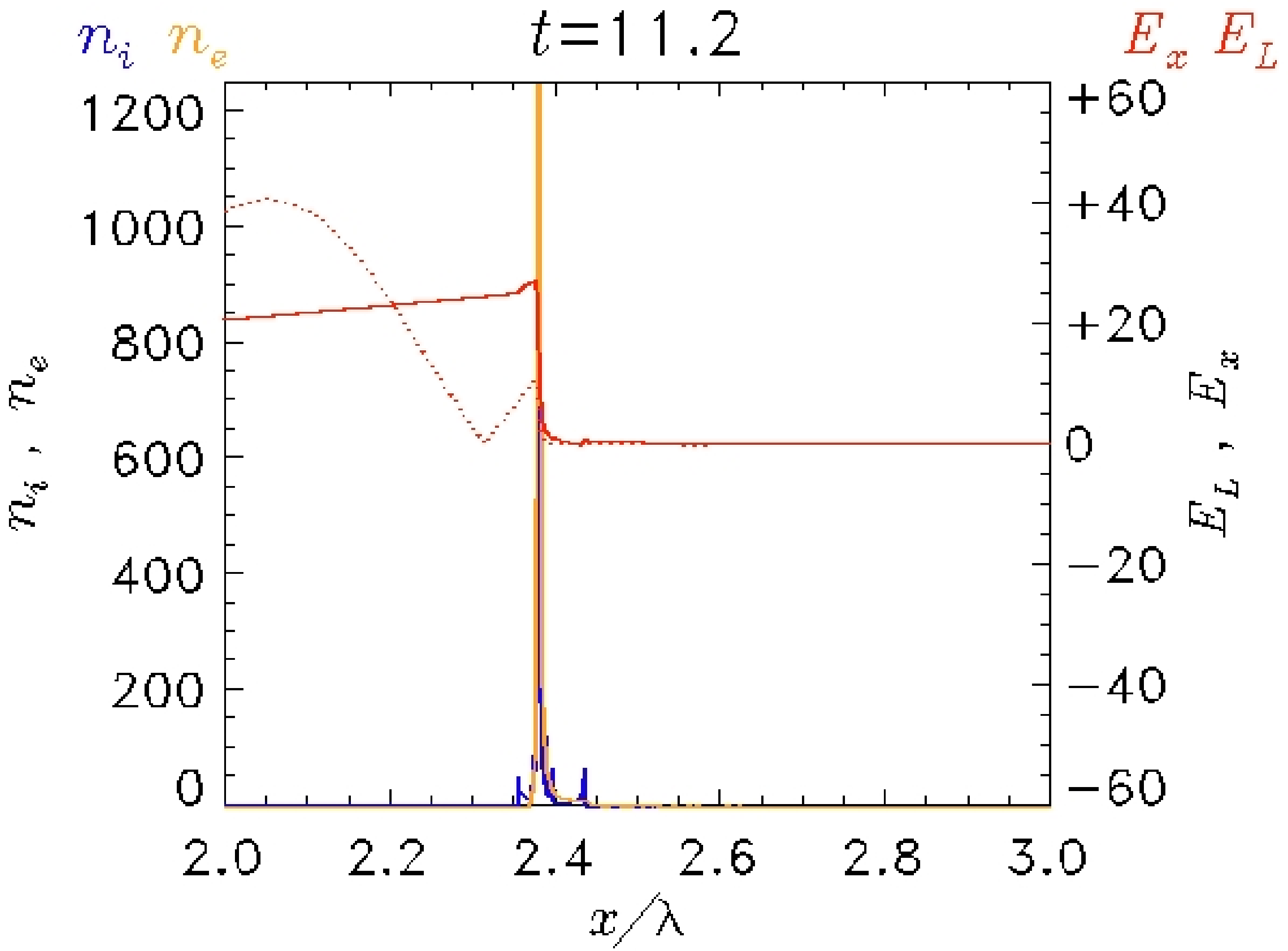

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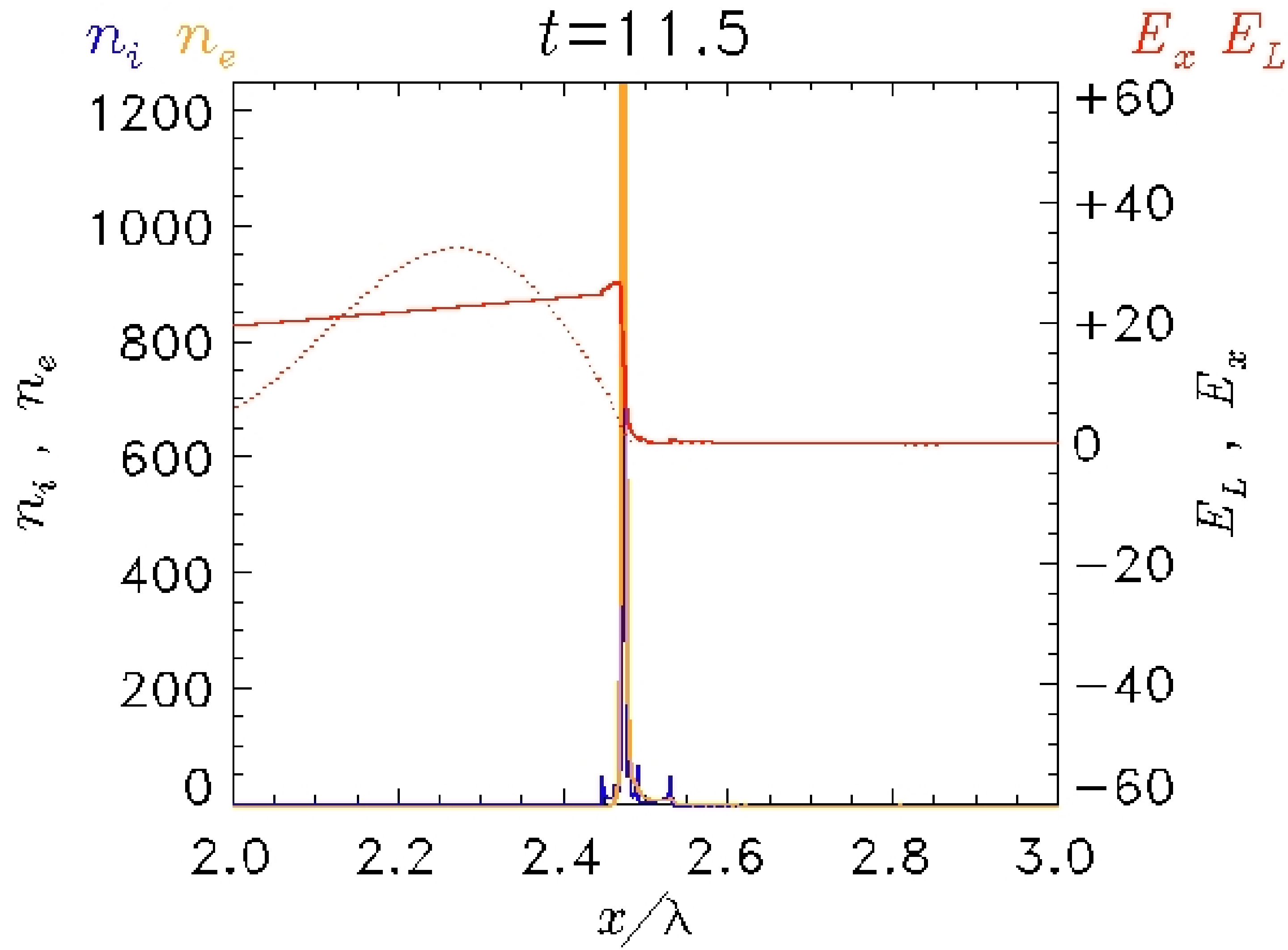

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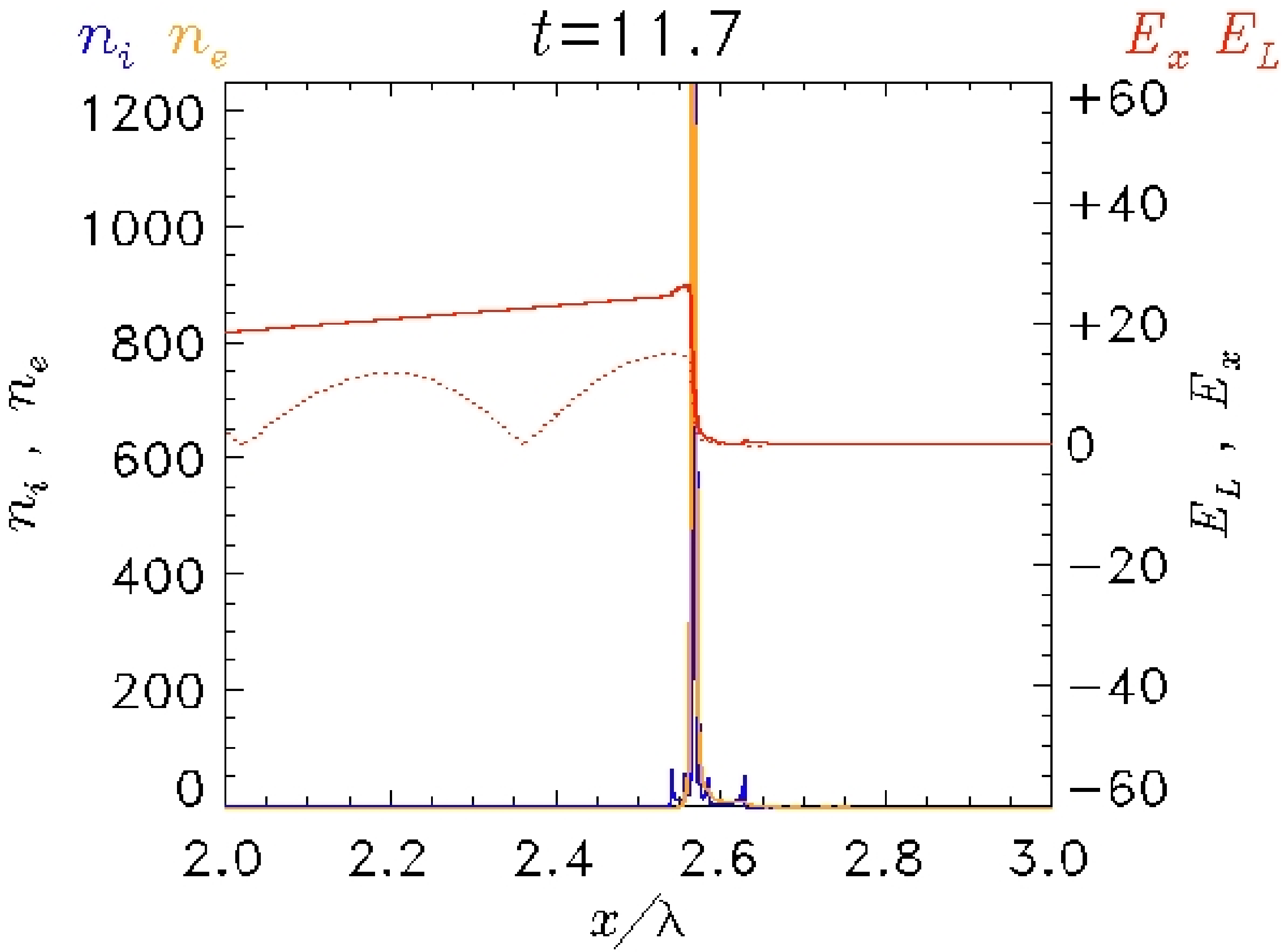

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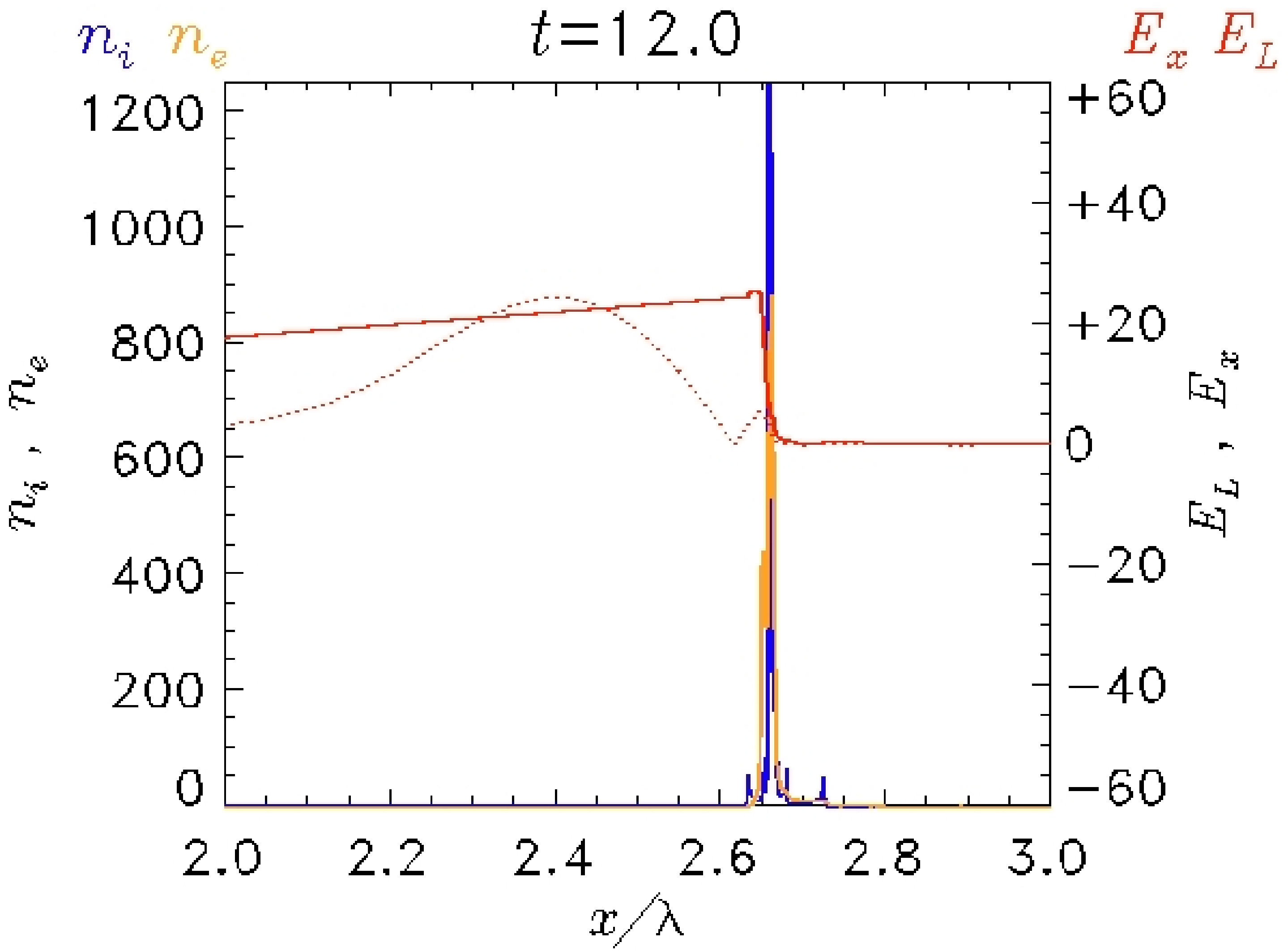

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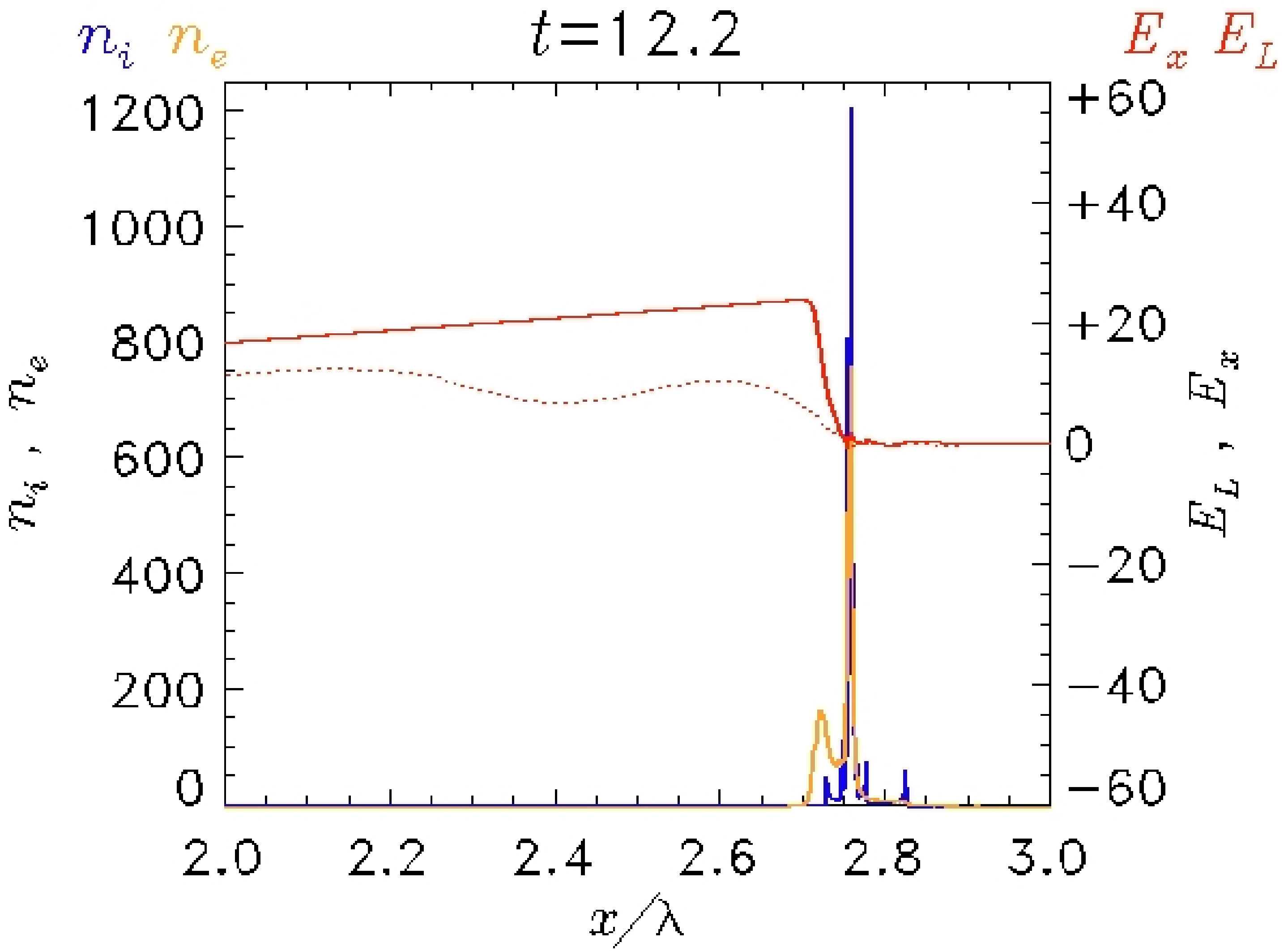

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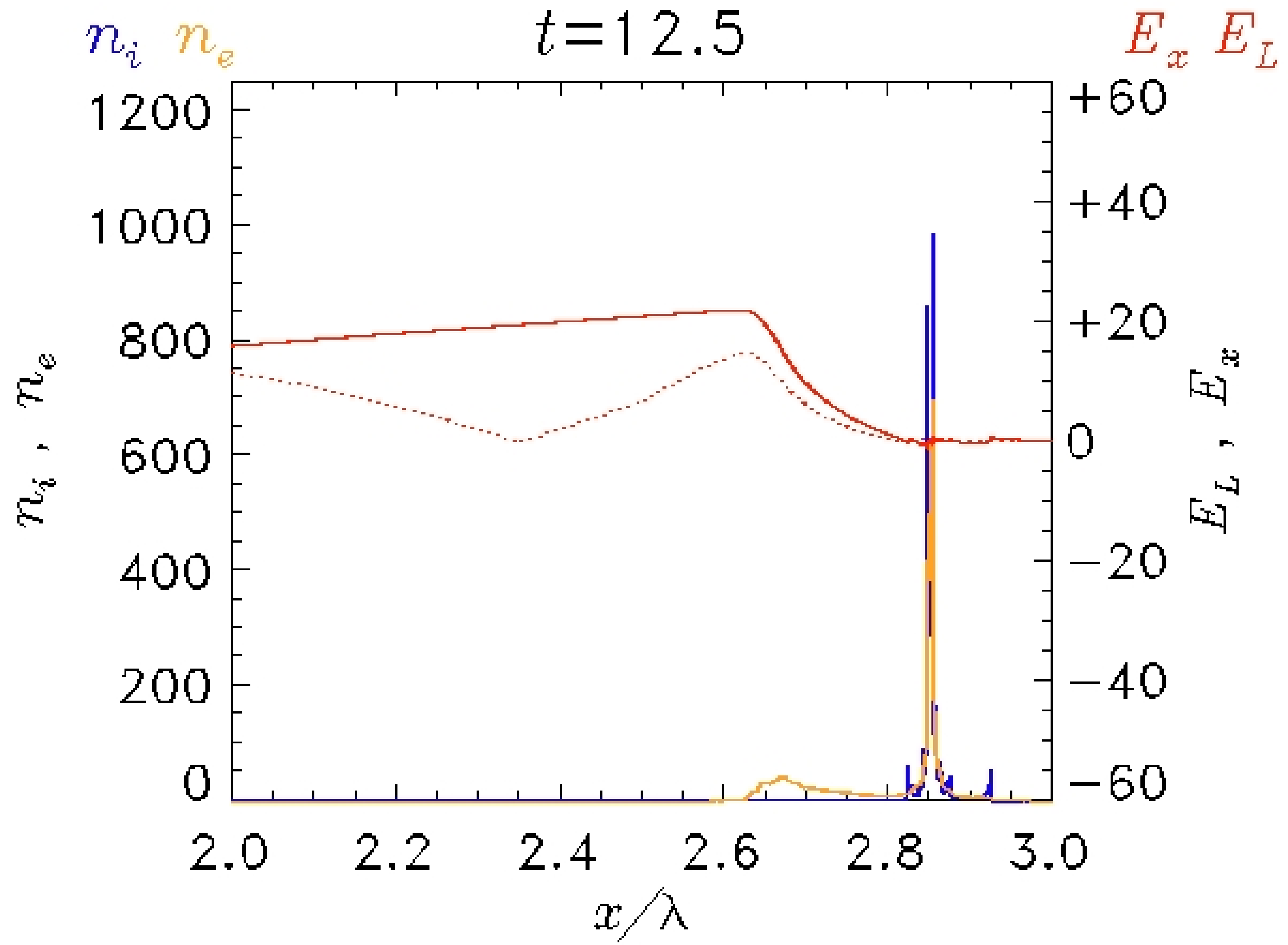

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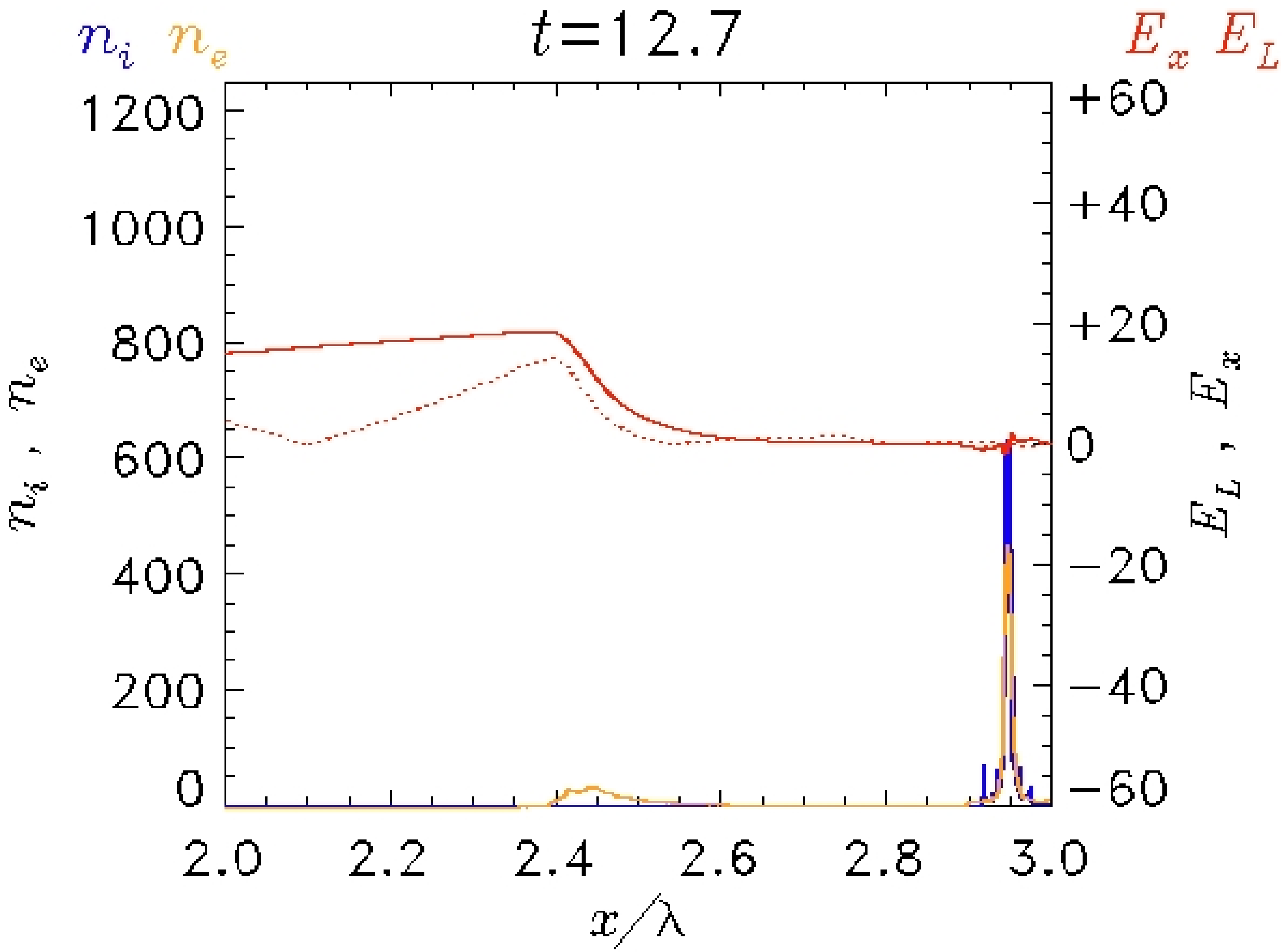

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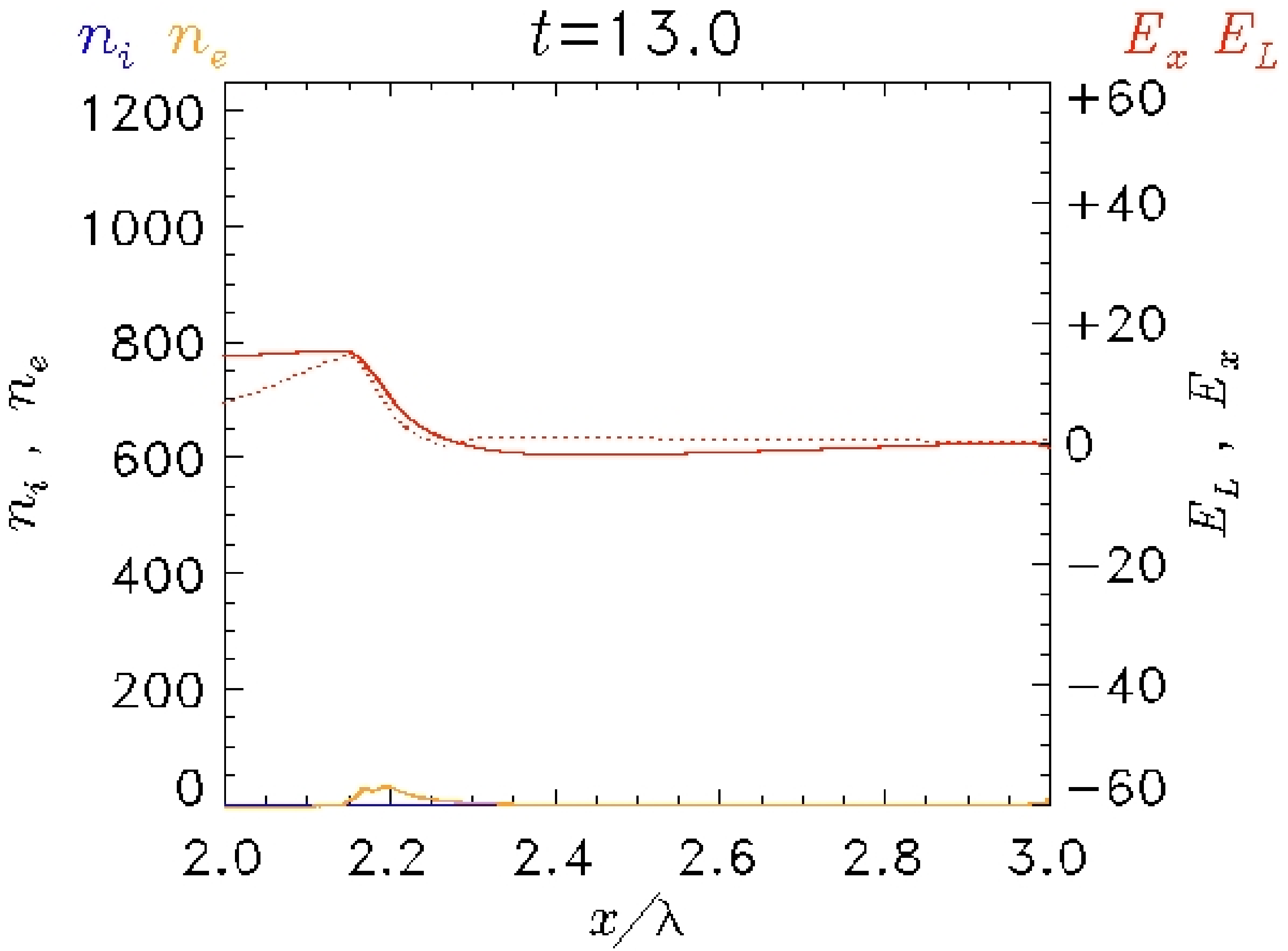

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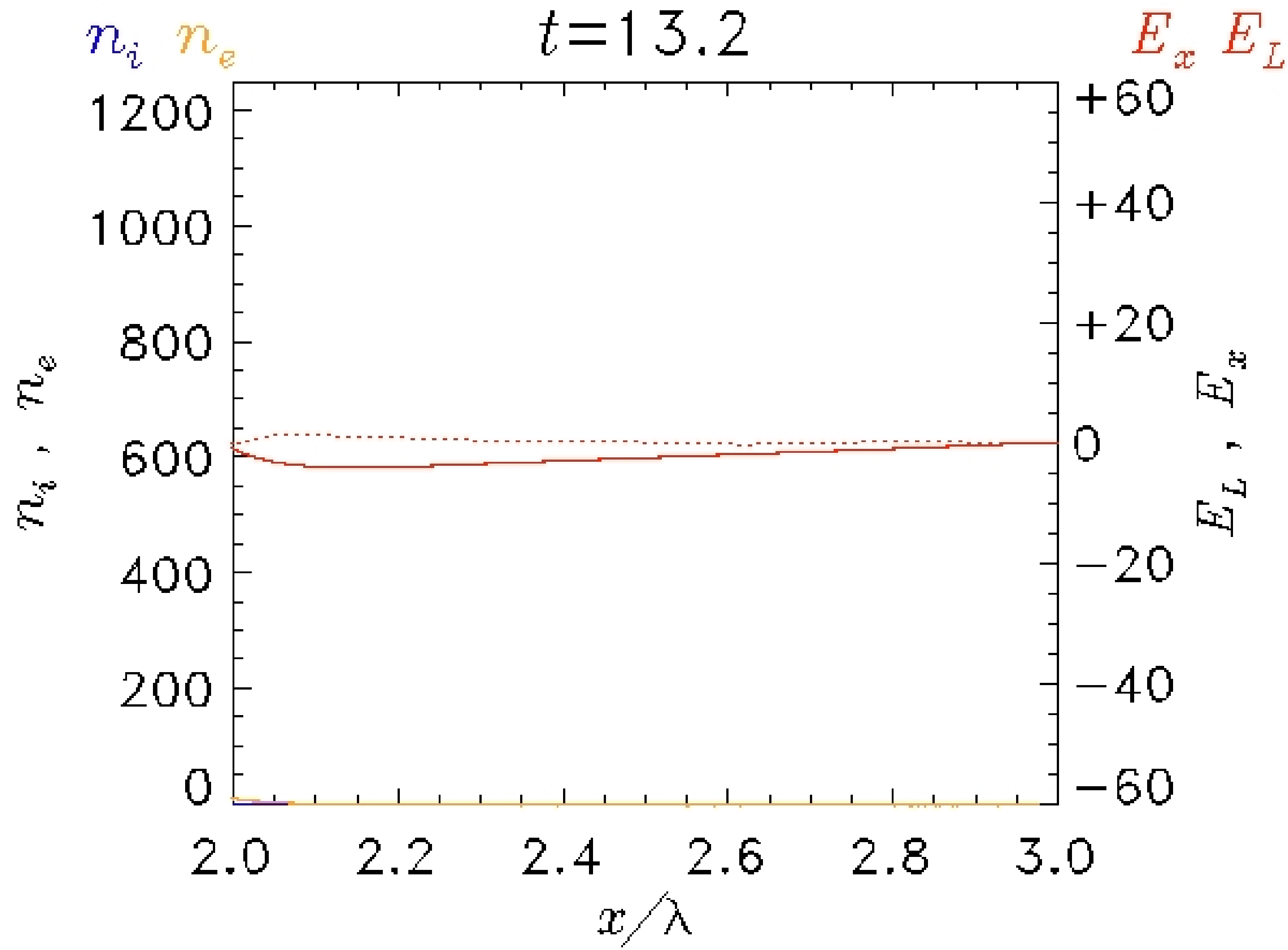

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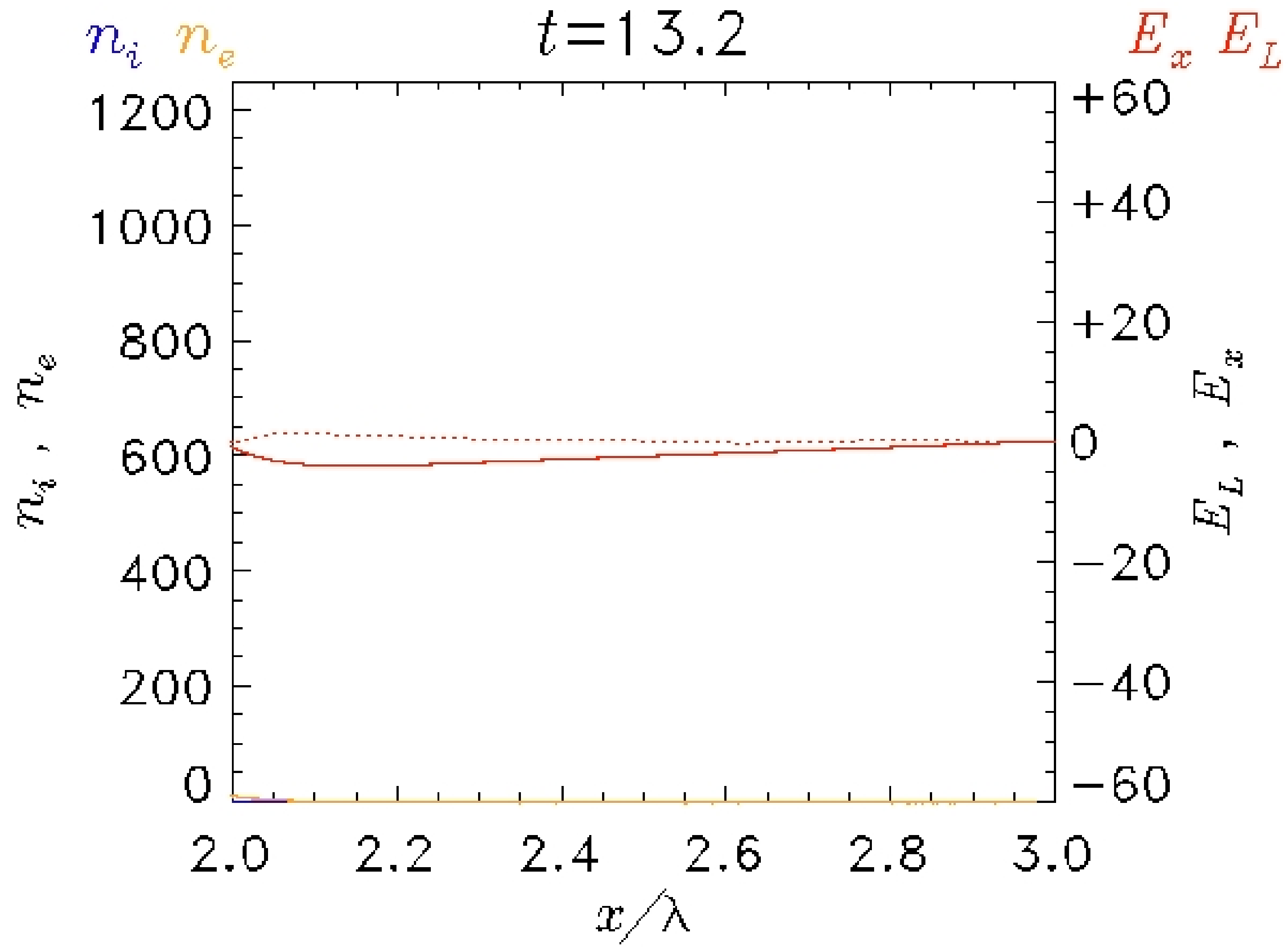
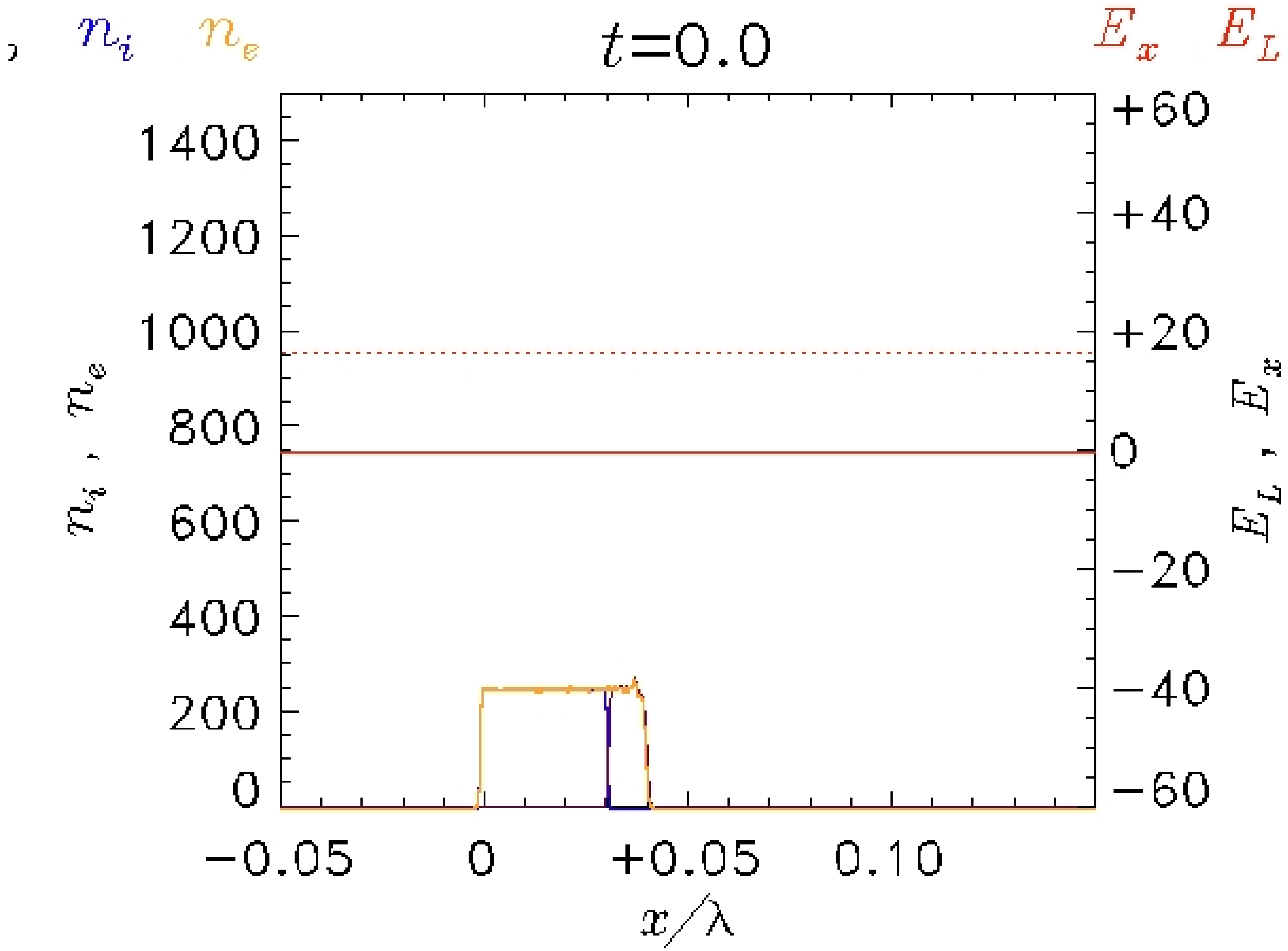


Simulation of double layer target

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

Thin foil target: n_e=250n_c, L=0.04λ, ζ=31.4, C and H layers



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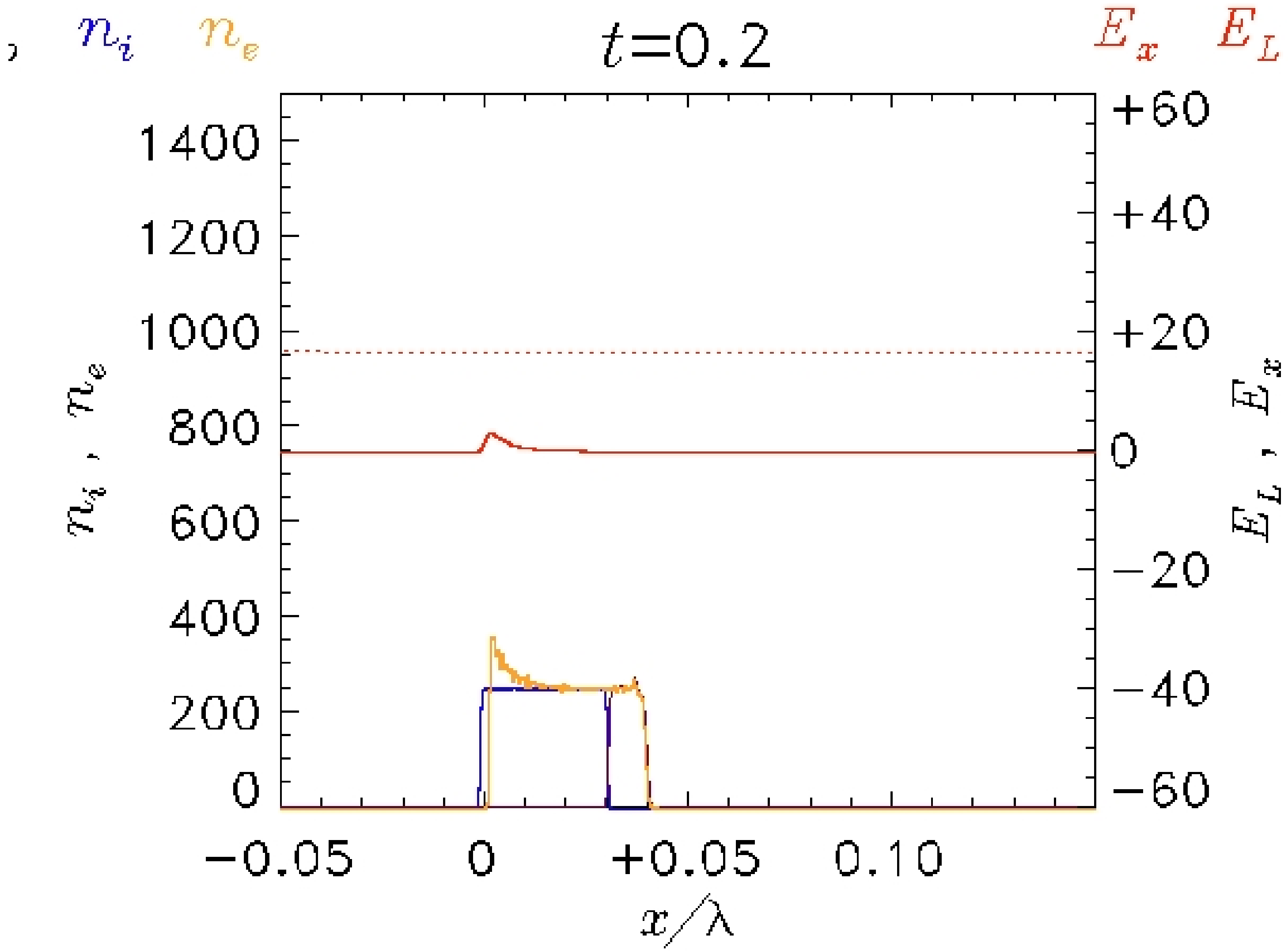
Thin foil target: n_e=250n_c , L=0.04λ , ζ=31.4, C and H layers



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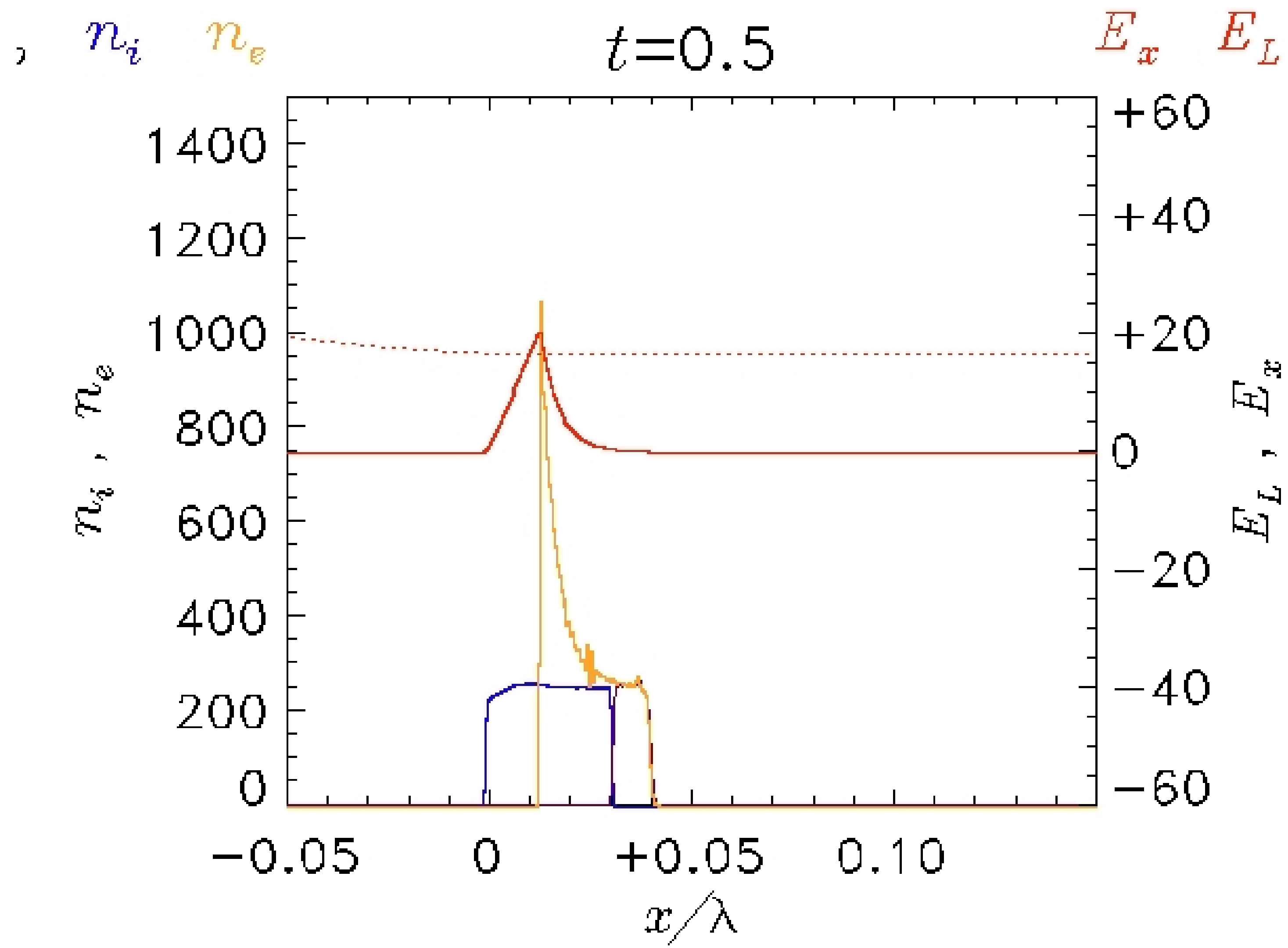

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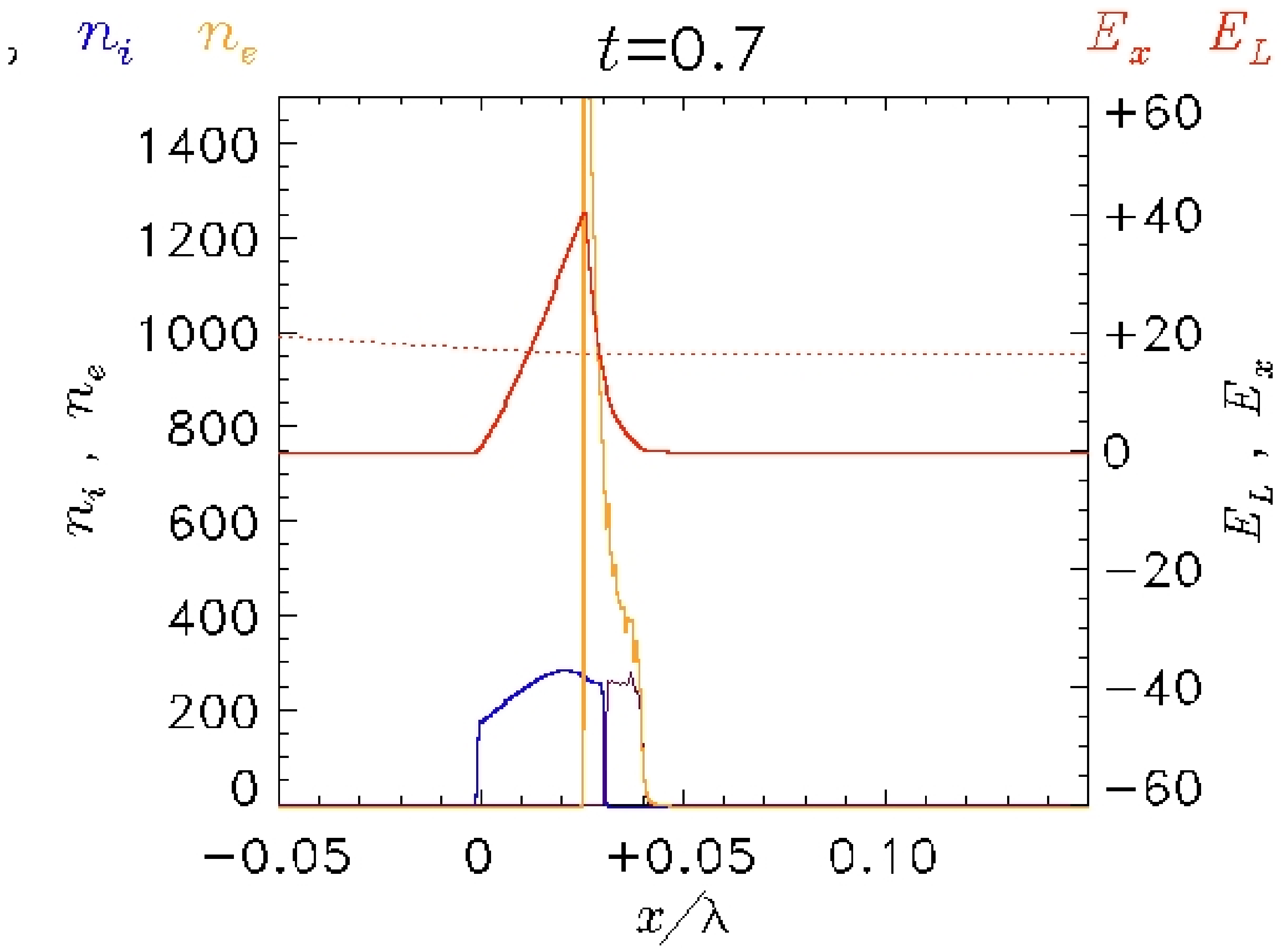

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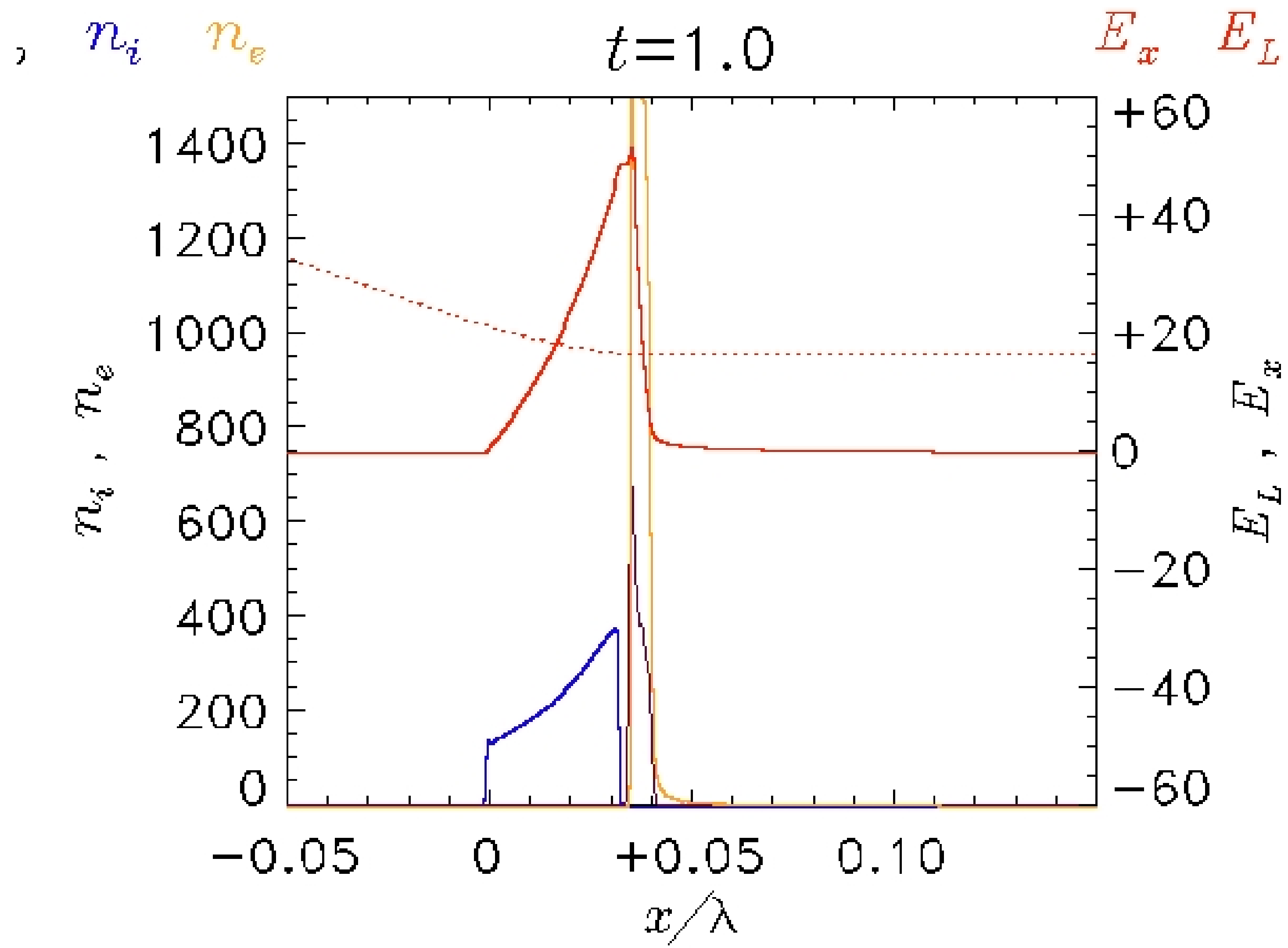

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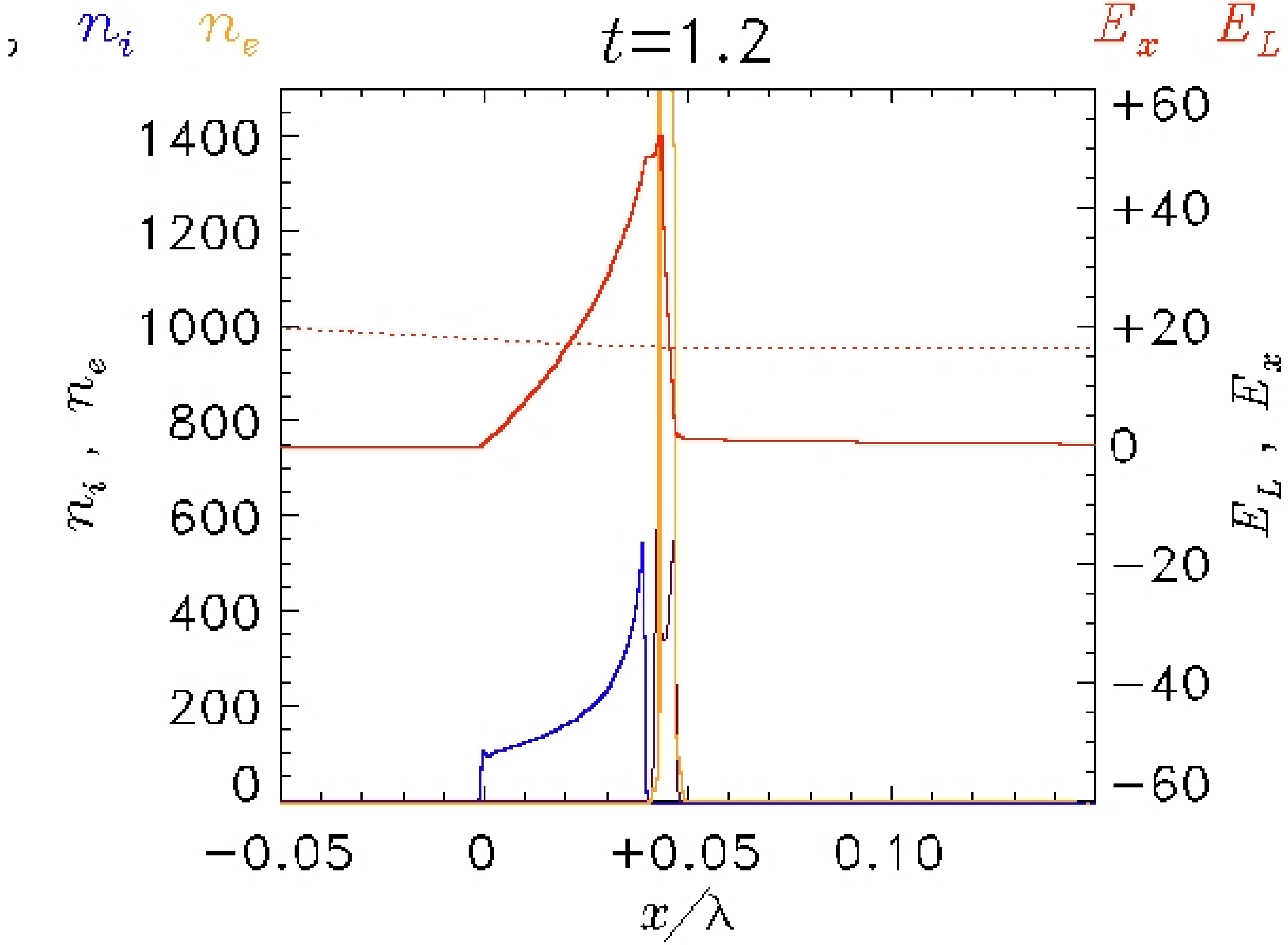

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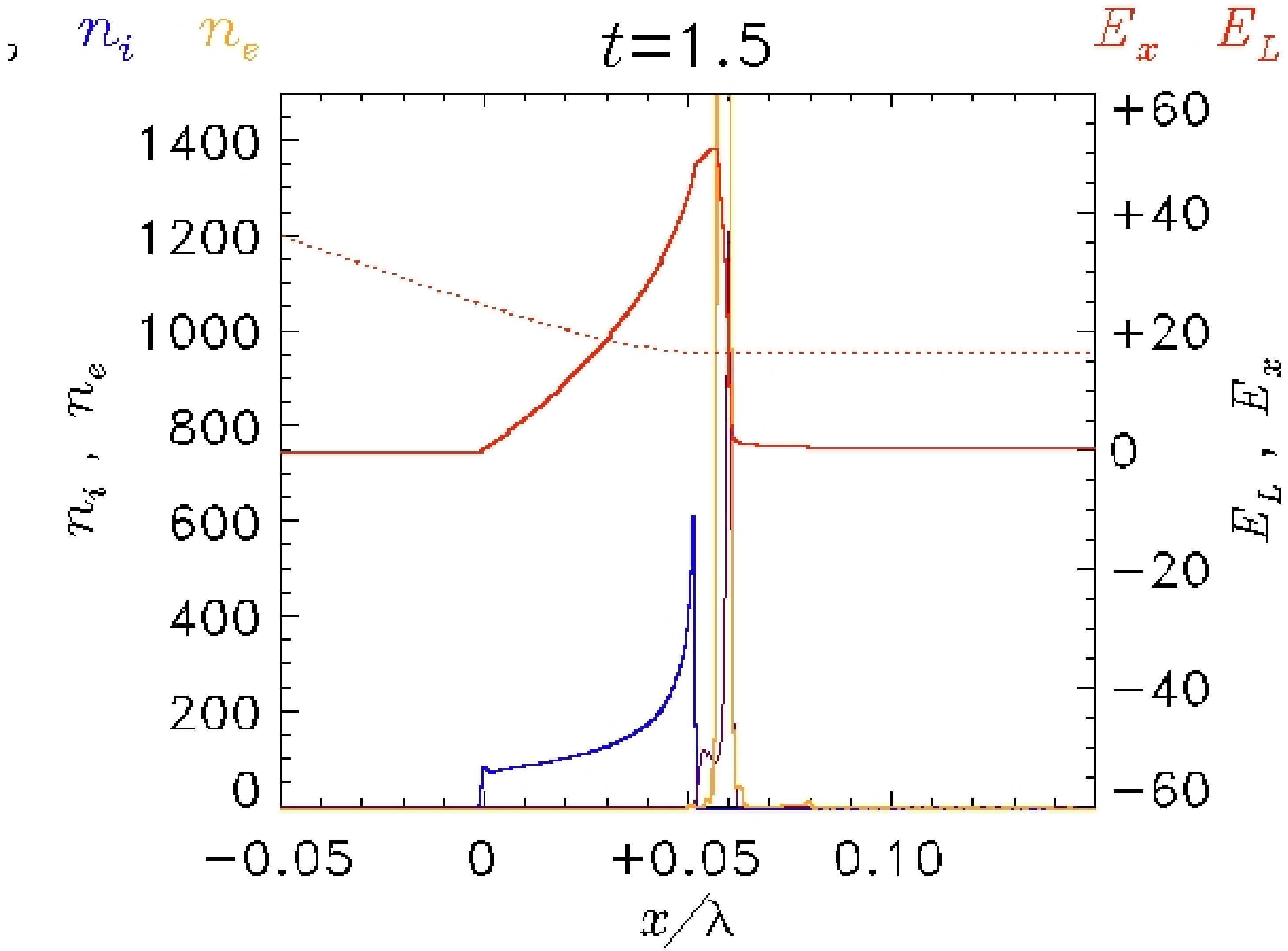

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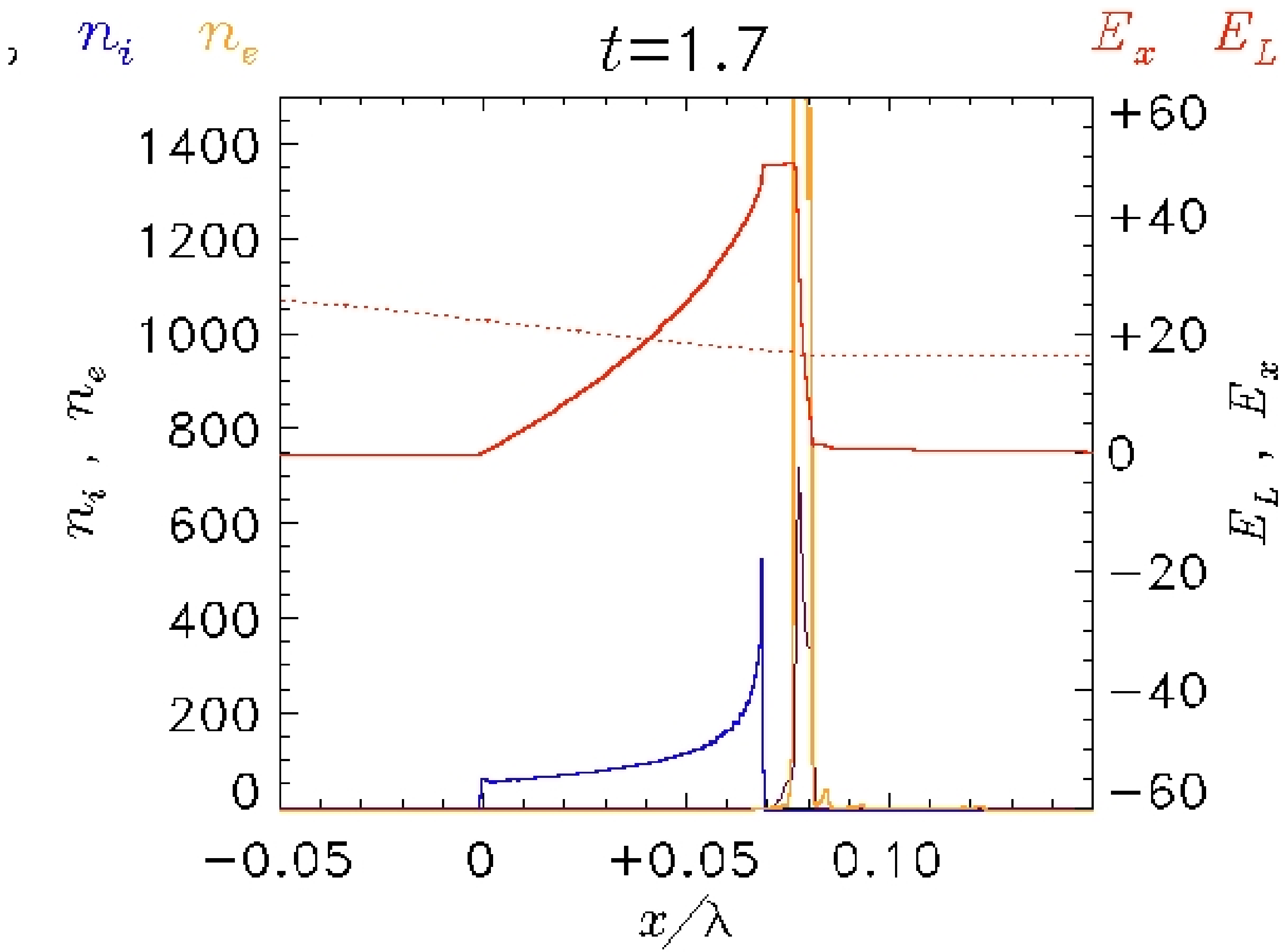

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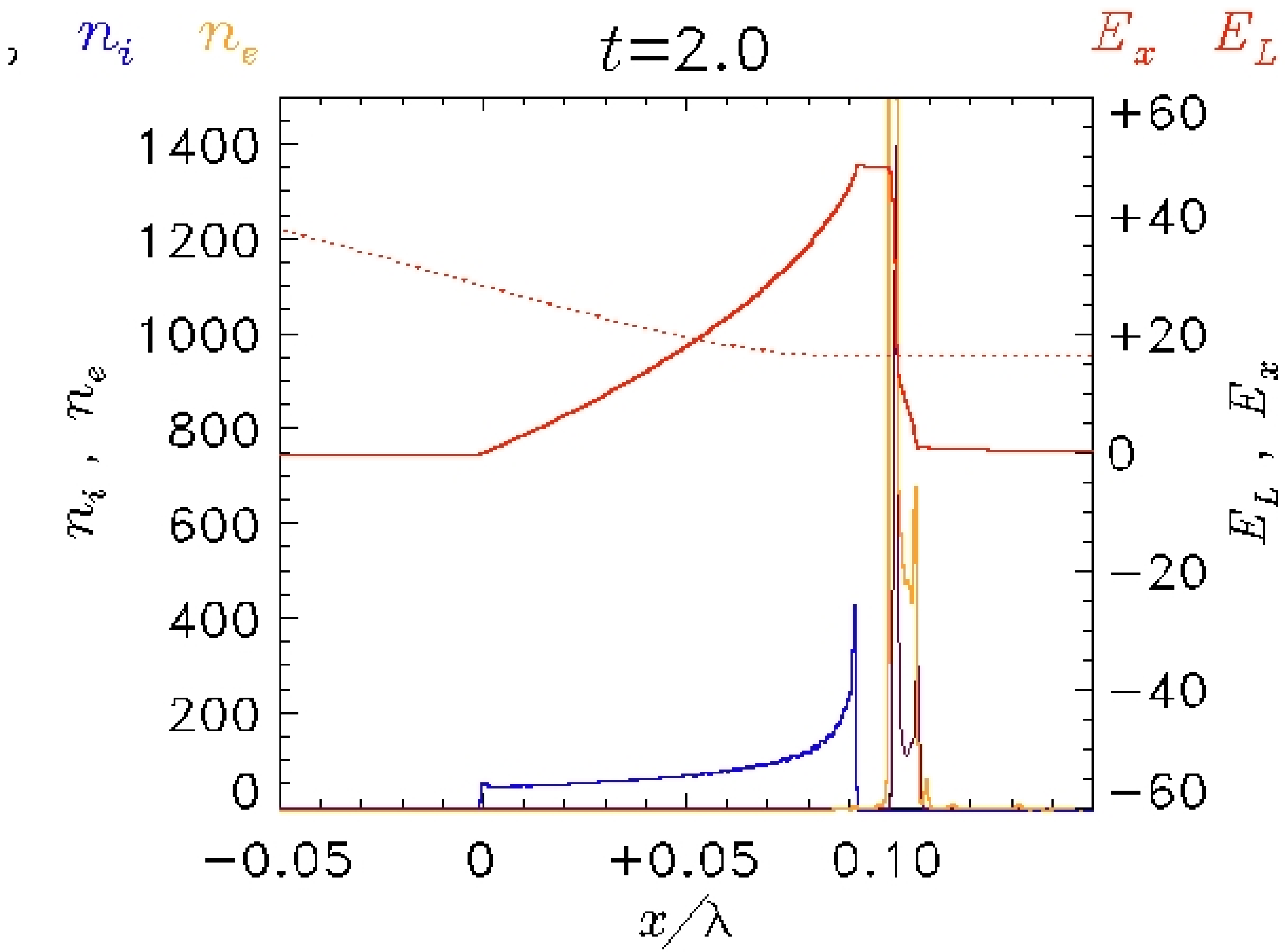

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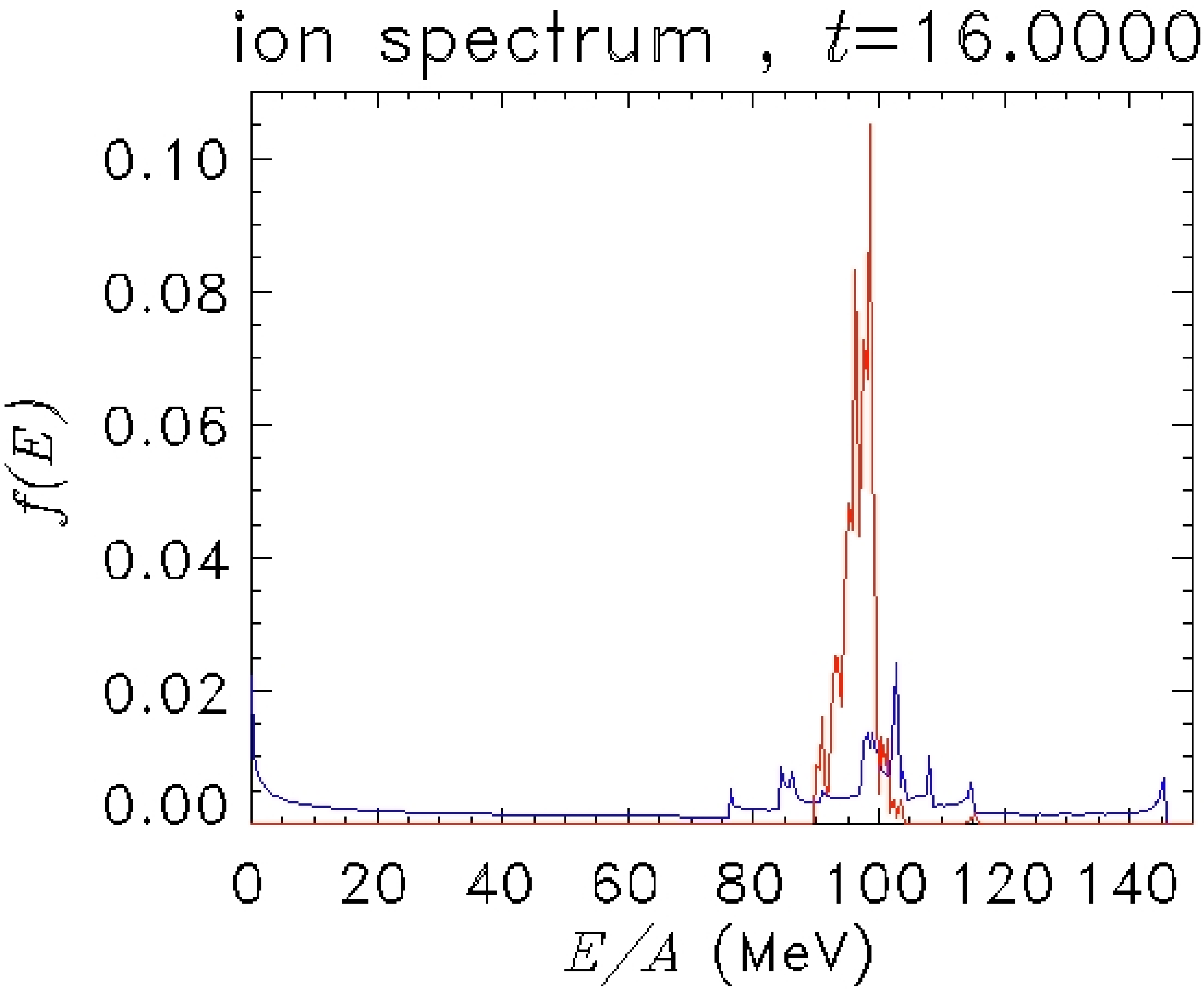


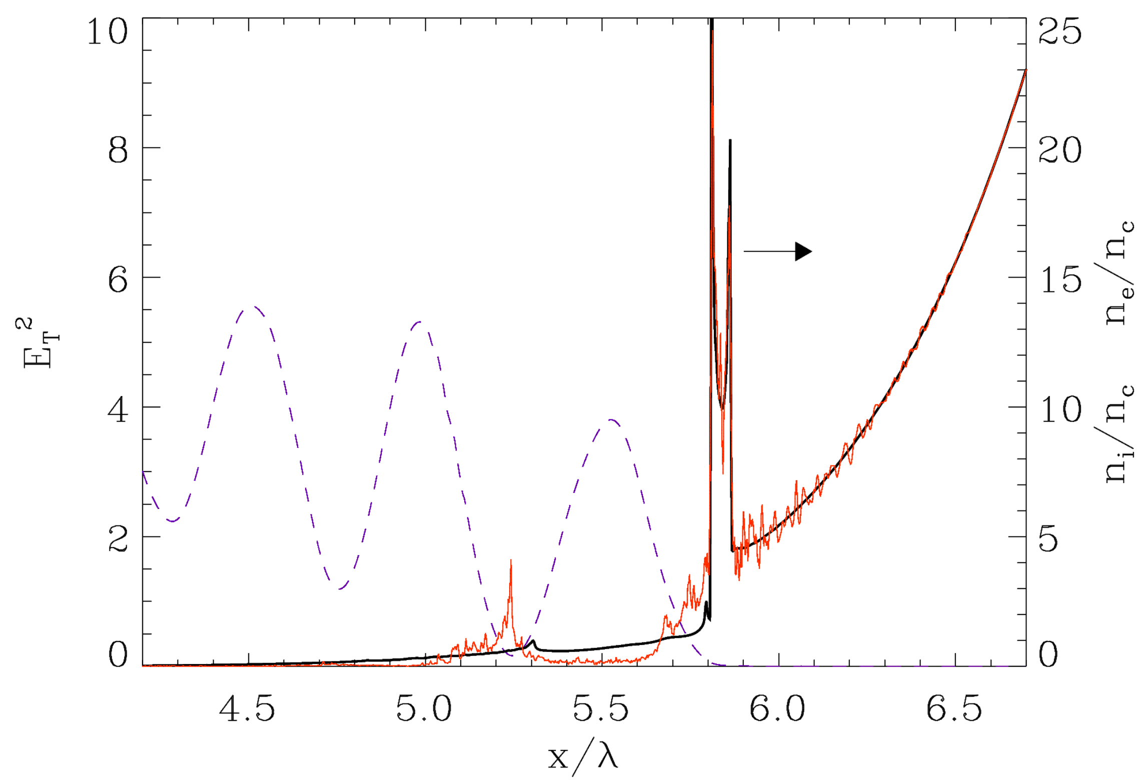
Non-ideal effects I: RPA in a preplasma

Models and simulations have investigated RPA either in ultrathin targets (“light sail”) or in thick targets with steplike density profiles (“hole boring”).

Preplasma formation occurs in most of the experiments. Does this prevent RPA of ions?

1D PIC simulations in a short-scalelength ($L_n \sim \lambda$) preplasma show a similar dynamics to that of “thick”targets with a steplike profile (formation of a short-duration ion bunch)

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



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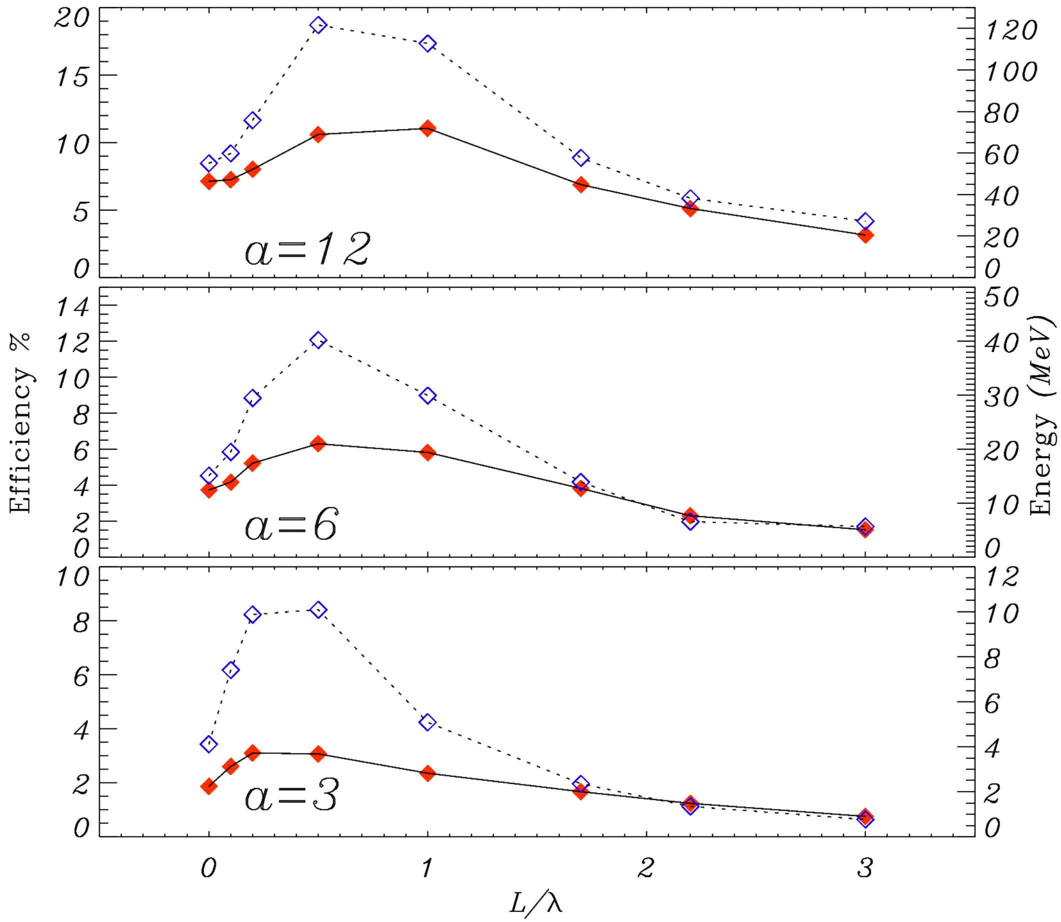
Models and simulations have investigated RPA either in ultrathin targets ("light sail") or in thick targets with steplike density profiles ("hole boring").

Preplasma formation occurs in most of the experiments. Does this prevent RPA of ions?

The ion energy scales with n_c/n_e and thus higher energy ions ma be obtained for a give intensity with respect "solid" targets, especi if prepulse control car implemented.

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



Non-ideal effects II: ellipticity effects

Longitudinal force $F_x = (\mathbf{v} \times \mathbf{B})_x$ and electrostatic field E_x generated by an elliptically polarized pulse incident on a step-like density profile (quasi-linear approximation):

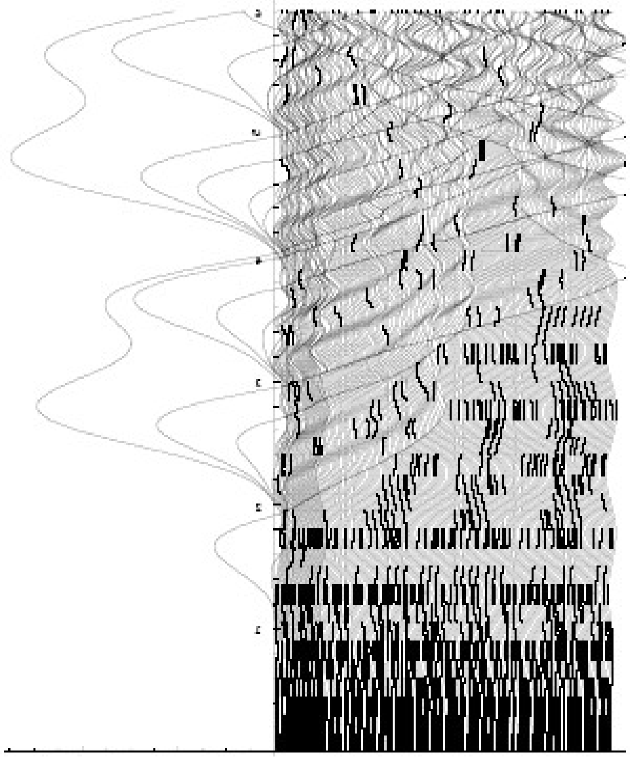
$$F_x = F_0 \mathrm{e}^{-2x/d_p} \left(1 + \frac{1-\epsilon^2}{1+\epsilon^2} \cos 2\omega t \right), \qquad F_0 = \frac{e^2 A^2(0)}{2 d_p m_e c^2}$$

$$E_x = \frac{F_0}{e} \mathrm{e}^{-2x/d_p} \left(1 + \frac{1-\epsilon^2}{1+\epsilon^2} \frac{\cos 2\omega t}{1 - 4\omega^2/\omega_p^2} \right)$$

For “above thresold” ellipticity values

$$\epsilon > \epsilon_T = (\omega_p^2 / 2\omega^2 - 1)^{-1/2}$$

electrons are dragged into the vacuum side driving “vacuum heating” absorption



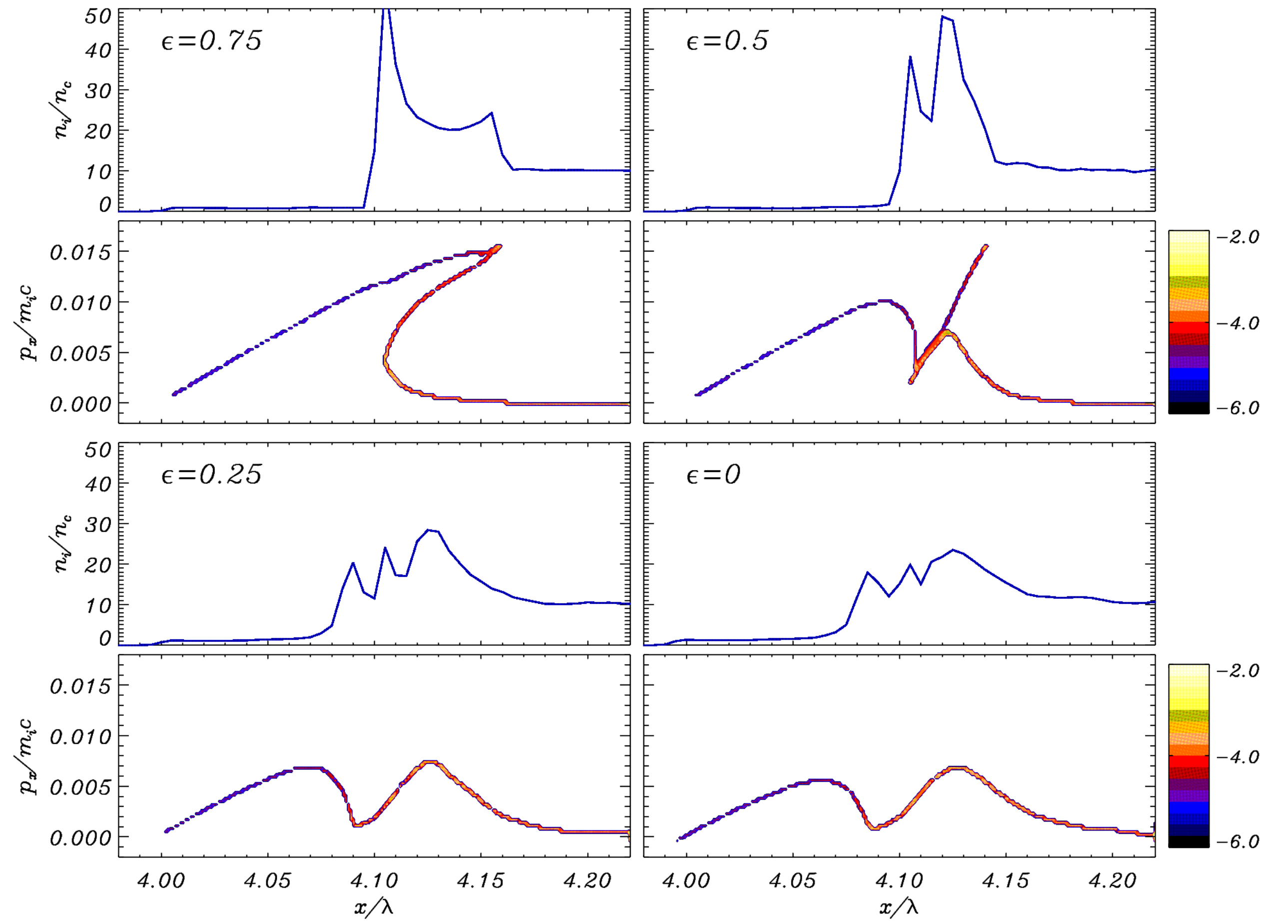
A.Macchi et al, C.R.Physique (2009), in press

Non-ideal effects II: ellipticity effects

Simulations for different ellitpicity $\varepsilon=0.75, 0.5, 0.25, 0$ (Lin.Pol.) .

Laser pulse: $a_0=30$, $\tau=8$ cycles, thick target: $n_e=10n_c$

The number of ion "bunches" increases with ε because ions now cross the evanescence point at different times corresponding to positive maxima of E_x



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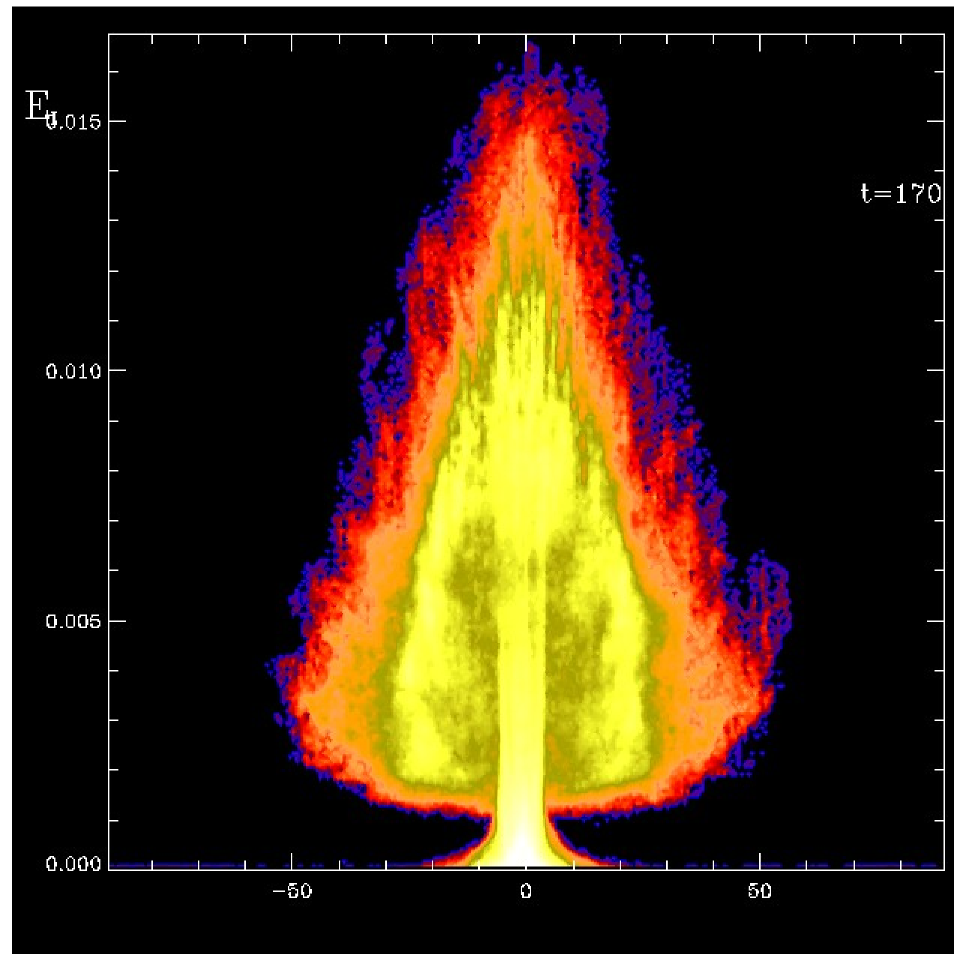
Need for 3D simulations of CP-RPA

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

[Quotation from the referee report of T.Liseikina and A. Macchi, in *Images in Plasma science* IEEE Trans. Plasma Sc. **36**, 1136-1137 (2008)]

The “Xmas tree” is a contour plot of ion energy vs. emission angle from 2D simulations, showing a high and energy-dependent collimation



Need for 3D simulations of CP-RPA

"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 a fundamental reason: a Circularly Polarized beam carries angular momentum from "photon spin" that must be conserved in the interaction!

We thus performed a set of 3D simulations for thin and thick targets and for "feasible" computational parameters

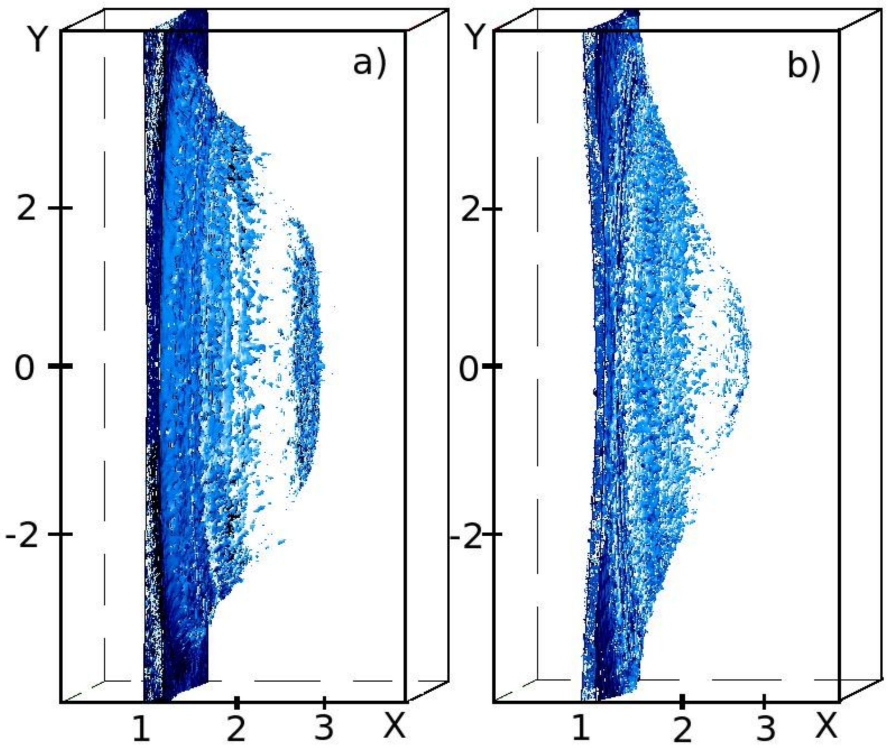
typical simulation set-up:

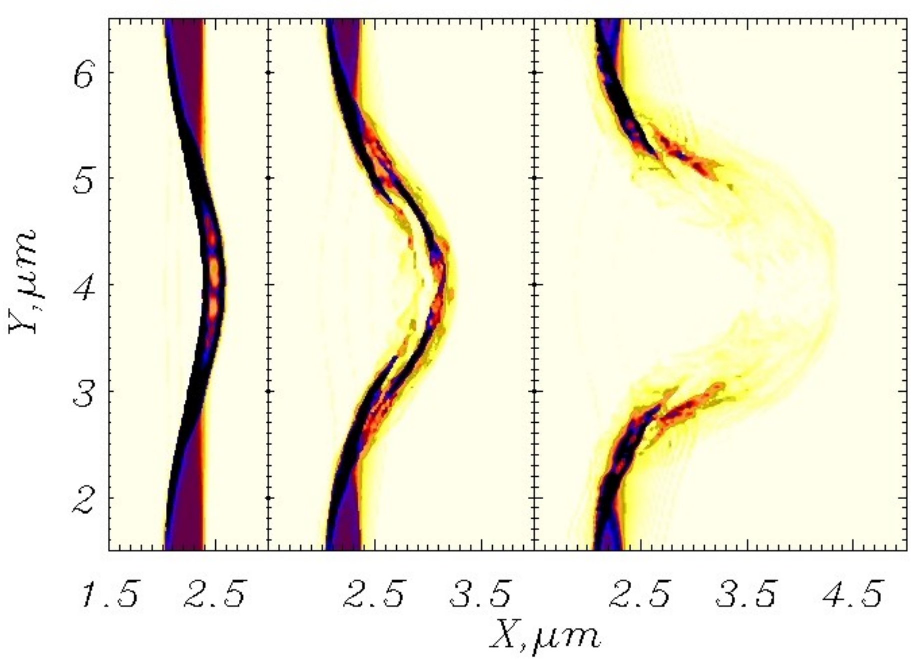
plasma slab: $L=0.4\lambda$, $n_e=16n_c$

laser pulse: $a_0=5$, $\tau=10$ cycles, 2λ spot radius

320 X 1050 X 1050 grid, cell size $\lambda/80$, 27 particles per cell (1.5 billions in total)

Supergaussian pulses prevent pulse burnthrough



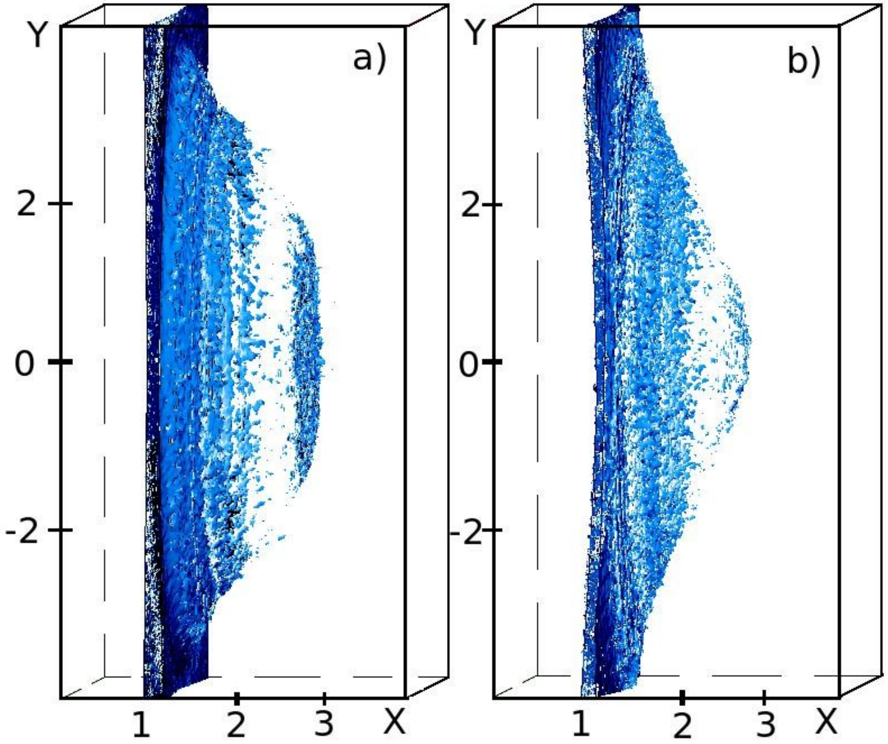


a) Supergaussian radial profile
$\sim\exp(-r^4/w^4)$

b) Gaussian profile
$\sim\exp(-r^2/w^2)$

Early “burnthough” occurs with the Gaussian pulse due to lateral expansion of the target

Supergaussian pulses prevent pulse burnthrough



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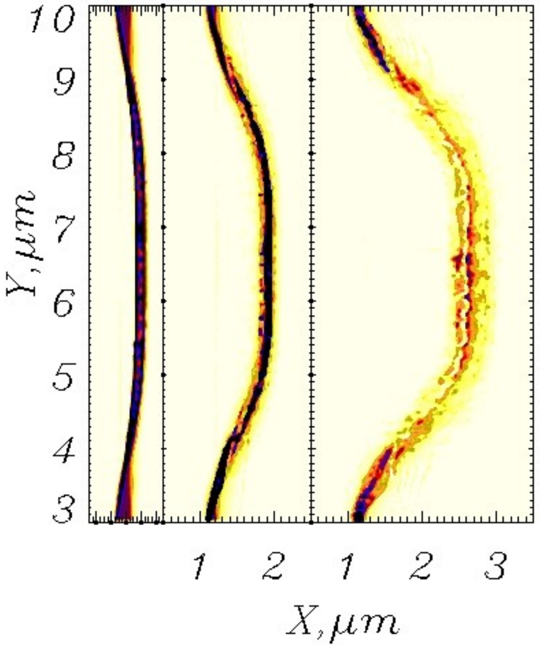
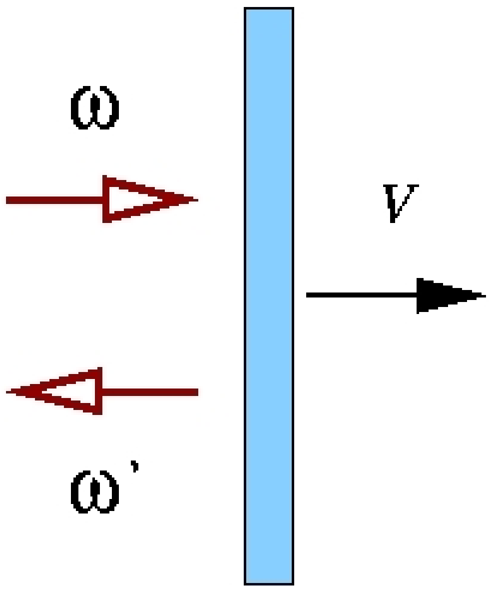


The superGaussian pulse leads to a 1D-like motion preventing burnthough

Angular momentum absorption in CP-RPA?

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



(The "spin" of the light is not reversed as the momentum – classical proof is straighforward but more lengthy than "quantum" picture!)

Evaluating the angular momentum absorption (AMA) by the plasma in PIC simulations can be a "test" of the mirror model, because only "irreversible" processes violating the "conservation of photon number" may contribute to AMA

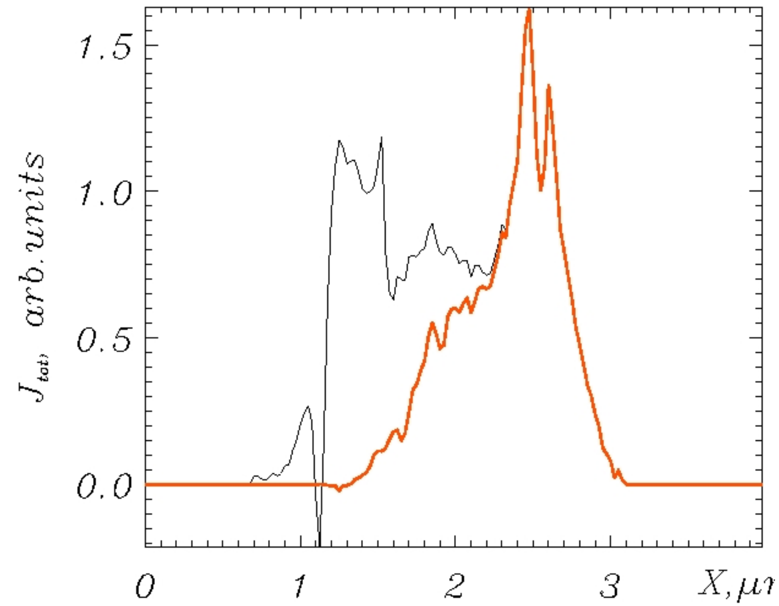
Analysis of angular momentum absorption...

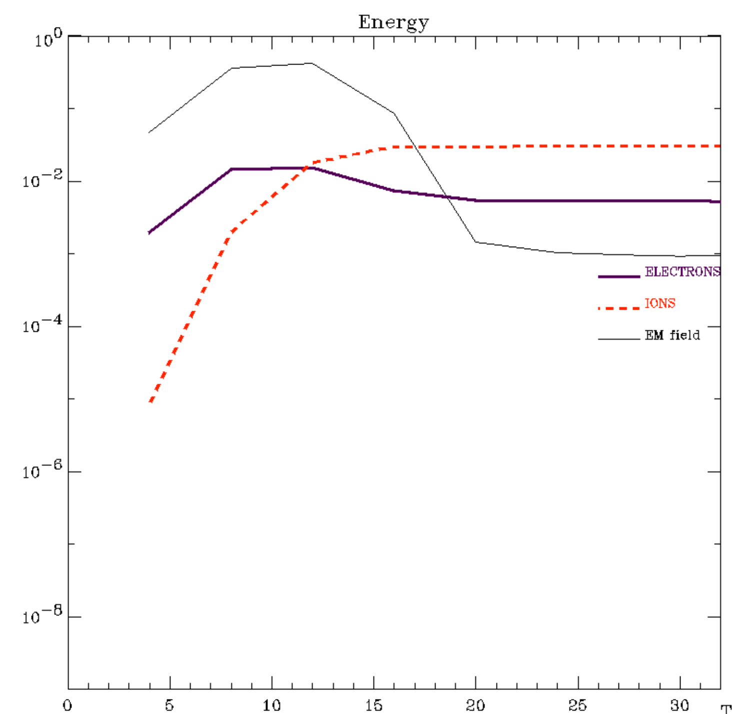
.. in 3D PIC simulations is not easy (large data set, noise, limited set of runs and output...)

The clearest signature is a net poloidal ion current $J_{i\phi}$ after the interaction

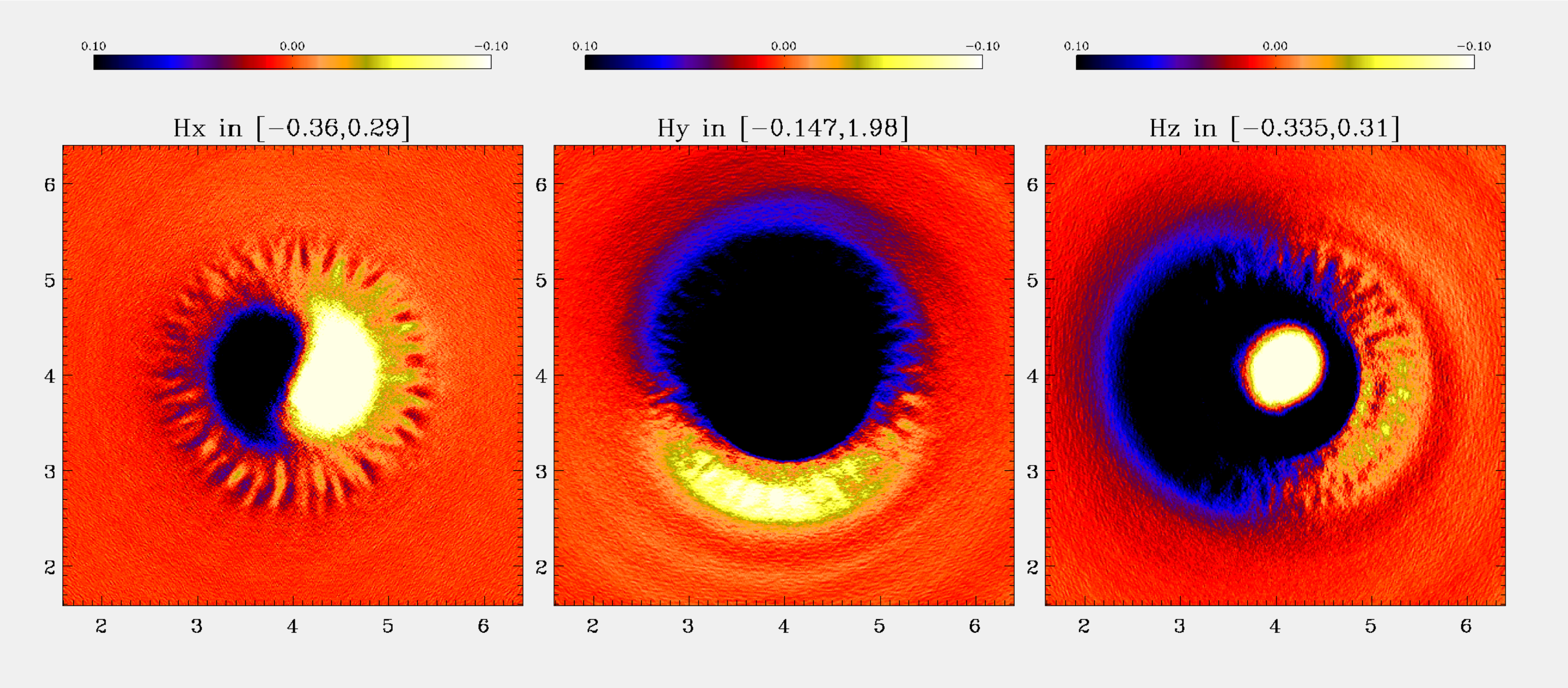
AMA degree varies across different simulations, but the trend is that of few per cent AMA both in electrons and ions, which is a sizeable fraction of energy absorption (say, ~50%)

AMA seems to be mediated by electrons which later transfer angular momentum to ions





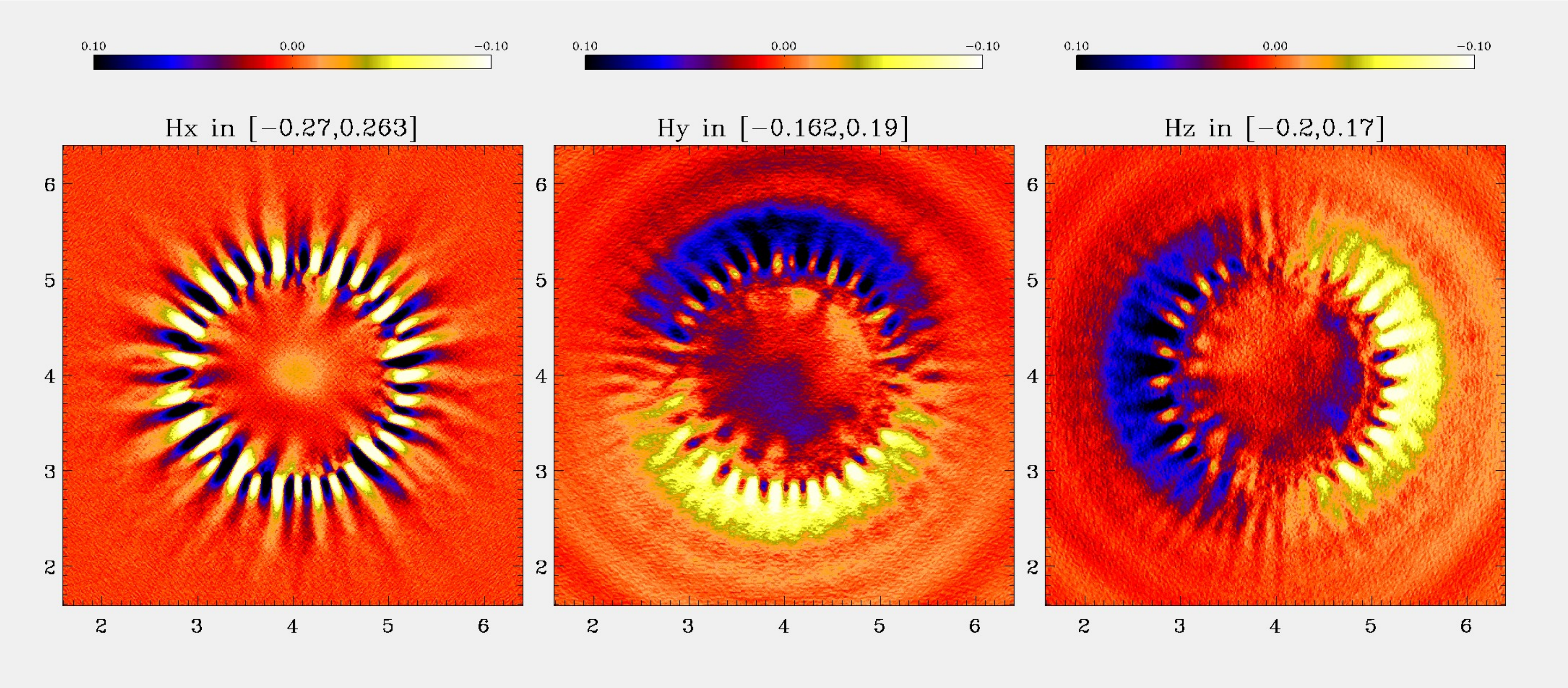
Magnetic field structures



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

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

Magnetic field structures



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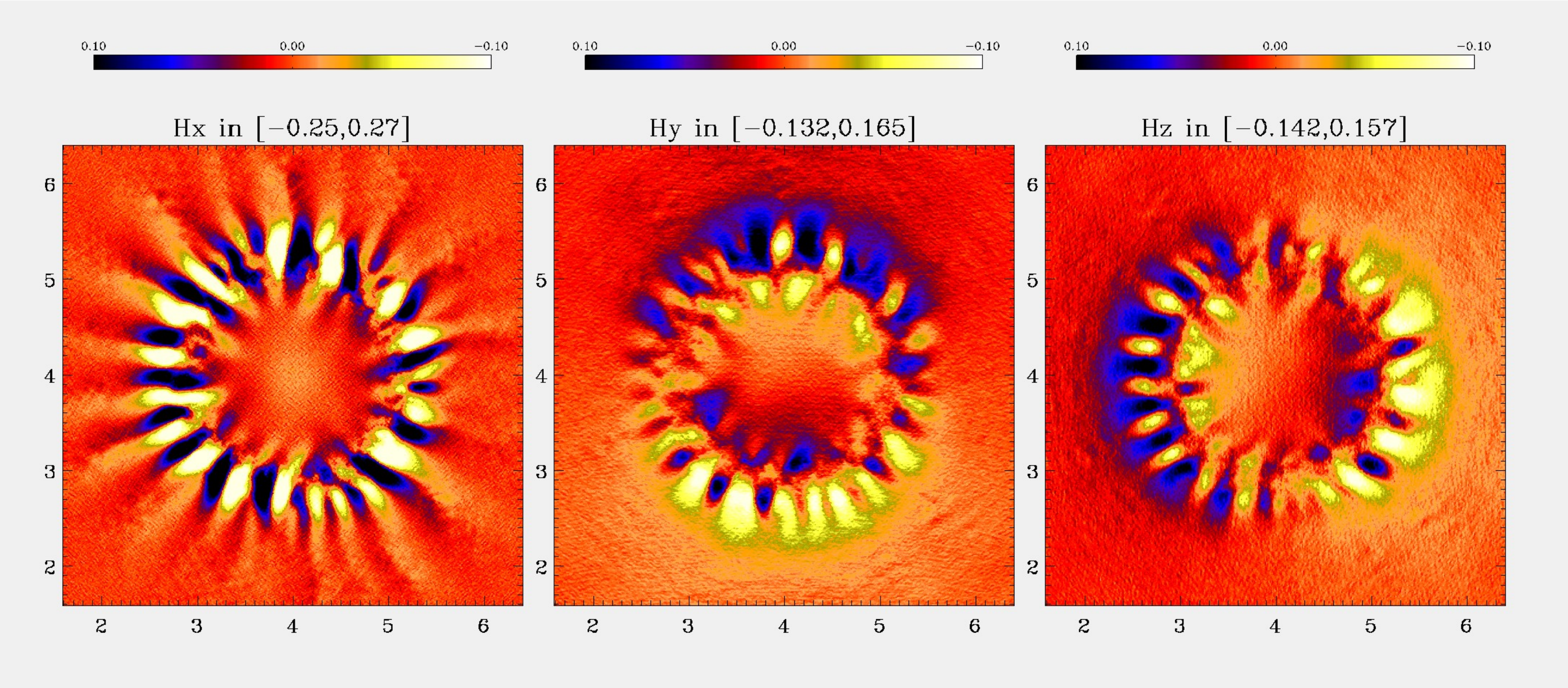

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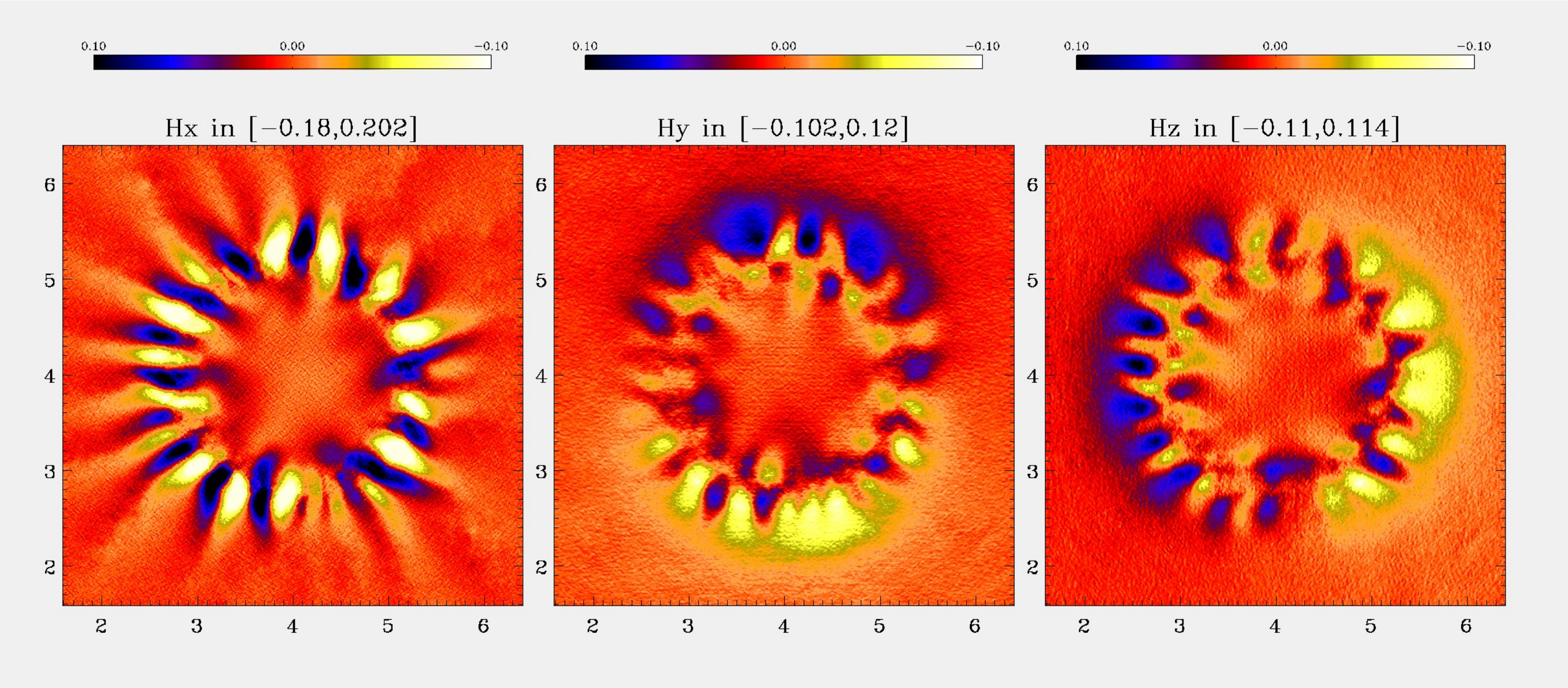

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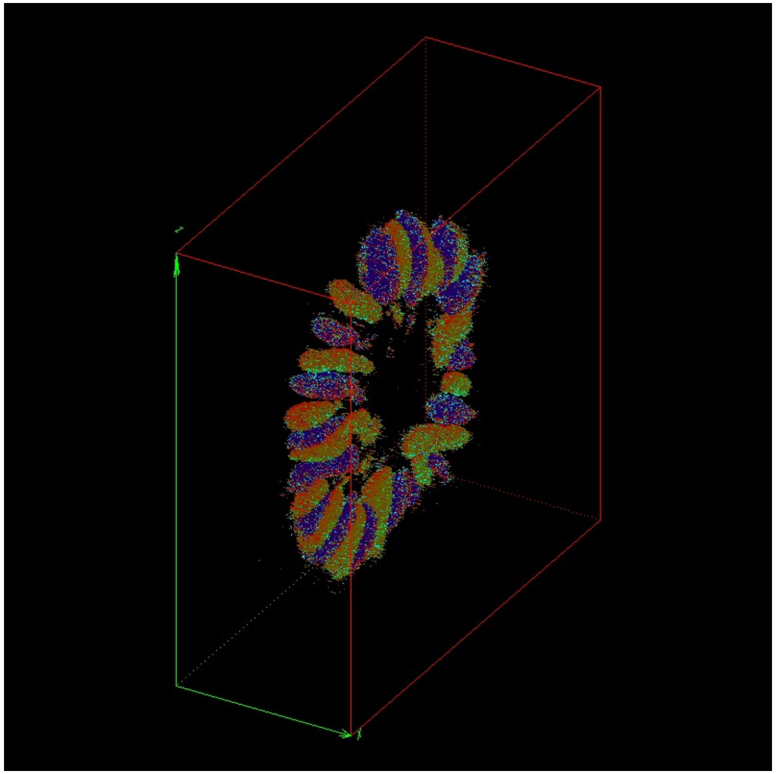
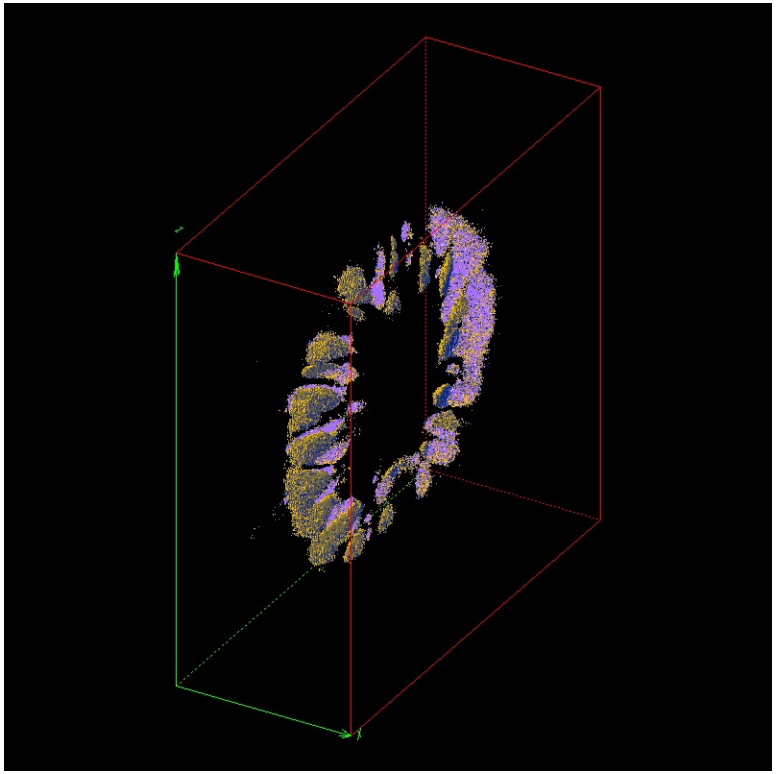


$B_x(x,y,z)$



$B_z(x,y,z)$

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

Where does angular momentum absorption come from?

- The observed magnetic field structures suggest that the absorbed angular momentum is stored into a "corona of vortices" at the edge of the laser spot, i.e. where the EM angular momentum density has its maximum:

$$\ell_x = \ell_x(r) = -\frac{r}{2c\omega}\frac{\partial I(r)}{\partial r}$$

- At the edge, "irreversible" energy absorption into electrons occurs because of longitudinal components of $\mathbf{E}$

f

- We are presently seeking a theoretical model for the generation of vortices and the coupling between electrons and ions providing an exchange of angular momentum
  (most important attempts by S. Propuzhenko)

Conclusions

- A simple and possibly "pedagogical" model of RPA by Circularly Polarized pulses (CP-RPA) of a thin plasma foil including self-induced transparency and charge separation effects has been developed and accounts for some typical features observed in PIC simulations

- The model may help to identify the "optimal" conditions for RPA in the thin foil or "light sail" regime (e.g. the foil thickness)

- Simulations shows that CP-RPA is also effective in short-scale preformed plasma profiles, which might be "engineered" to achieve higher ion energies for a given intensity

- 3D simulations support 1D modeling (self-consistently with the need of pulses with "flat-top" radial profiles, e.g. Supergaussian

- The issue of angular momentum absorption has been addressed and stimulates further theoretical work

This talk may be downloaded from

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