Dynamics of Radiation Pressure Acceleration

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Outline

- Ion acceleration by Radiation Pressure Acceleration

(using Circularly Polarized pulses):

the thick (“Hole Boring”) and thin target (“Light Sail”) regimes

- thick targets: acceleration with few-cycle pulses and preplasma effects

- thin targets: the “Light Sail” (accelerating mirror) model revisited

Why Circular Polarization?

Using CP and normal incidence (*an experimentalist's nightmare*...) fast electron generation by the $\mathbf{j}\times\mathbf{B}$ force is strongly suppressed, maximizing radiation pressure and obtaining a "smooth" acceleration of the bulk target

A.Macchi et al, Phys.Rev.Lett. **94** (2005) 165003

Studies of thick (semi-infinite) targets ("Hole Boring"):

T.V.Liseikina & A.Macchi, Appl.Phys.Lett. **94** (2007) 165003;
N.Naumova et al, Phys.Rev.Lett. **102** (2009) 025002;
A.P.L.Robinson et al, Plasma Phys.Contr.Fus. **51** (2009) 024004.

Studies of ultrathin (sub-wavelength) targets ("Light sail"):

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, Phys.Rev.Lett. **100**, (2008) 135003 ;
B.Qiao et al, Phys.Rev.Lett. **102** (2009) 145002;
V.K.Tripathi et al, Plasma Phys.Contr.Fus. **51** (2009) 024014.

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

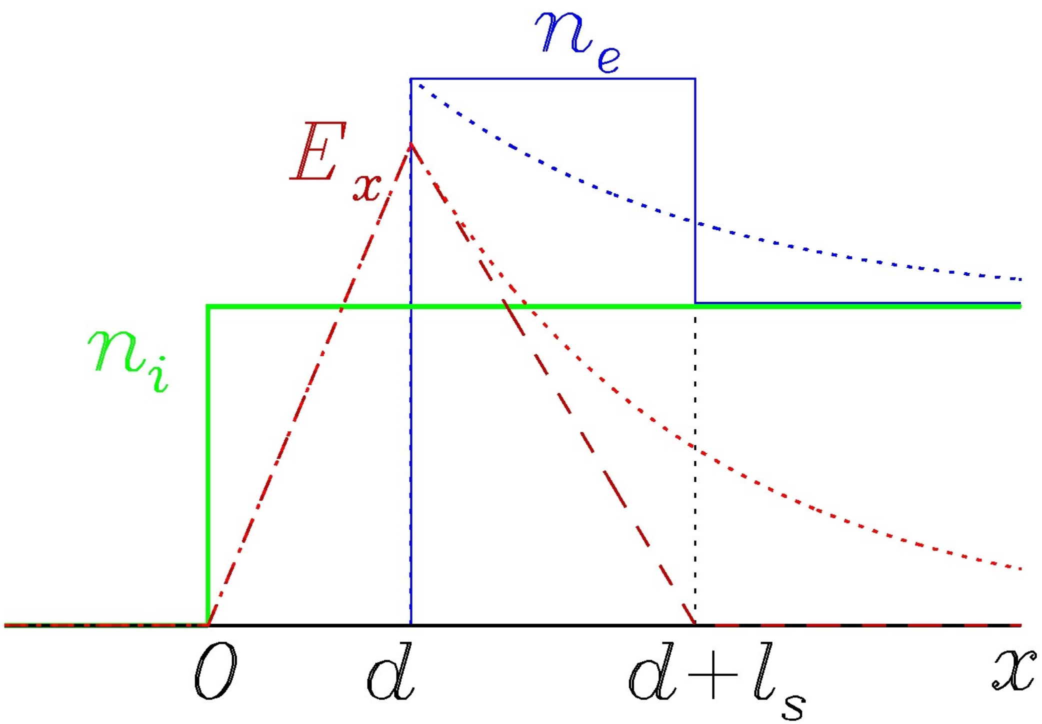
T.V.Liseikina et al, Plasma Phys.Contr.Fus. **50** (2008) 124033;
S.G.Rykovanov et al., New J. Phys. **10**, (2008) 113005;
L.Ji et al, Phys.Rev.Lett. **101** (2008) 164802;
Y.Yin et al, Phys.Plasmas **15** (2008) 093106;
A.R.Holkundkara and N.K.Gupta, Phys.Plasmas **15** (2008) 123104;
M.Chen et al, Phys.Plasmas **15** (2008) 113103;
X.Zhang et al, PRST-AB **12** (2009) 021301;
A.A.Gonoskov et al, Phys.Rev.Lett. **102** (2009) 145002;
X.Q.Yan et al, arXiv:0903.4584;
M.Chen et al, arXiv: 0903.3567.

Experimental investigations are highly desired!!!

Laser penetration discriminates thick vs. thin targets

In the early stage the laser pulse penetrates into the target creating an electron depletion ($0<x<d$) and an electron compression ($d<x<d+l_s$) layer

A balance between the electrostatic field E_x and the ponderomotive force (=local radiation pressure) is established.



Laser penetration discriminates thick vs. thin targets

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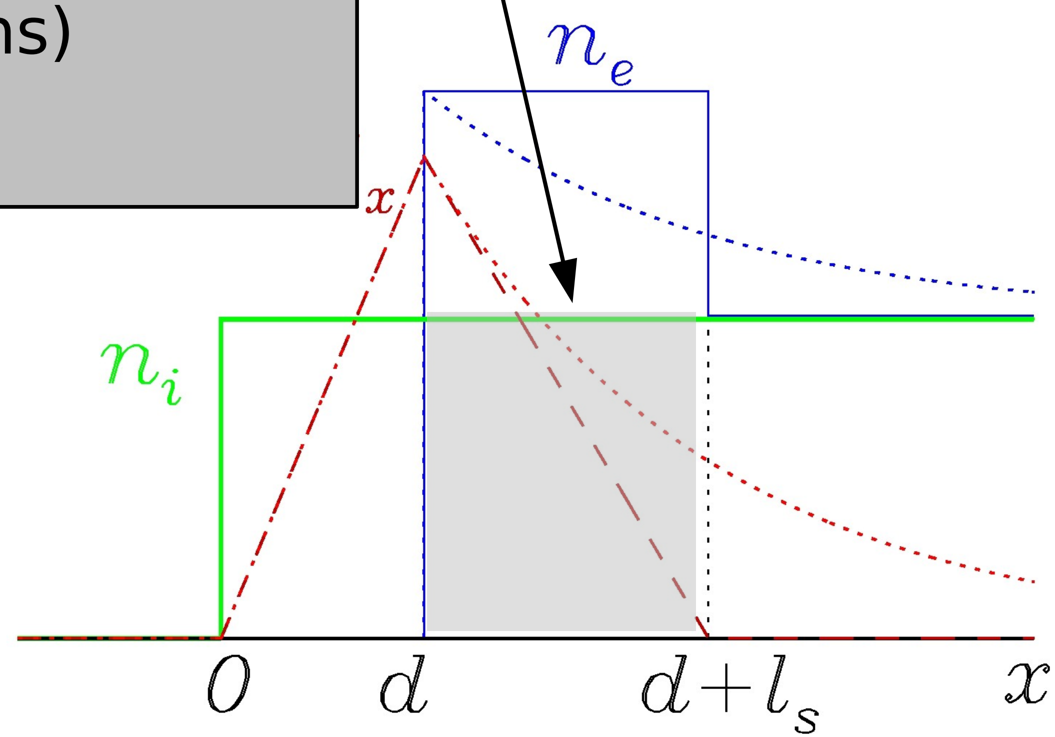
Ions in this layer
$d<x<d+l_s$
are accelerated
"by RPA" (actually by
the electric field
balancing the
radiation pressure
on electrons)



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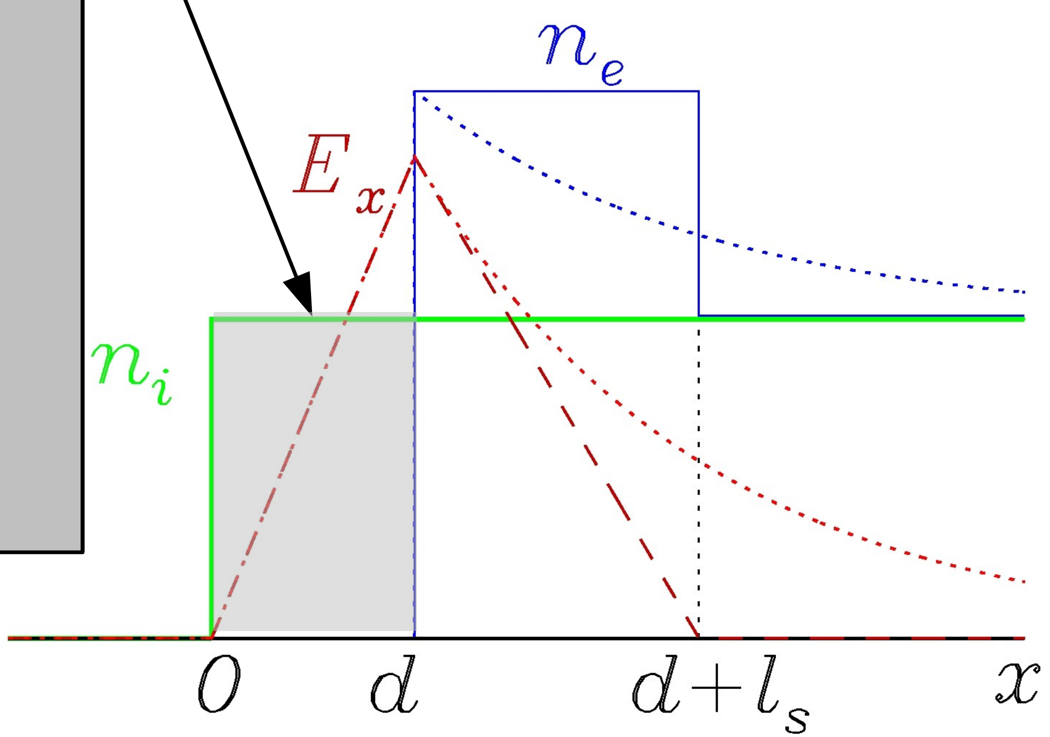
Ions in the “front” layer of electron depletion

$0<x<d$

are accelerated by their own space-charge field (Coulomb explosion) and do not reach “RPA” ions



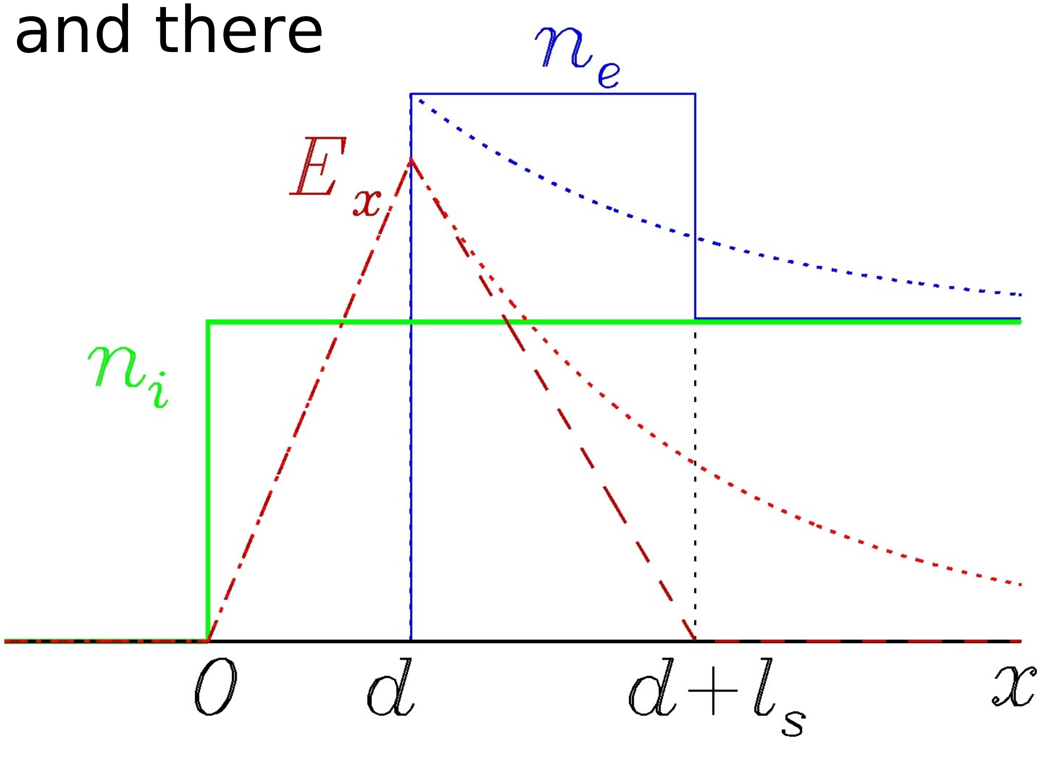
“Hole boring” and thick vs. thin targets

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.



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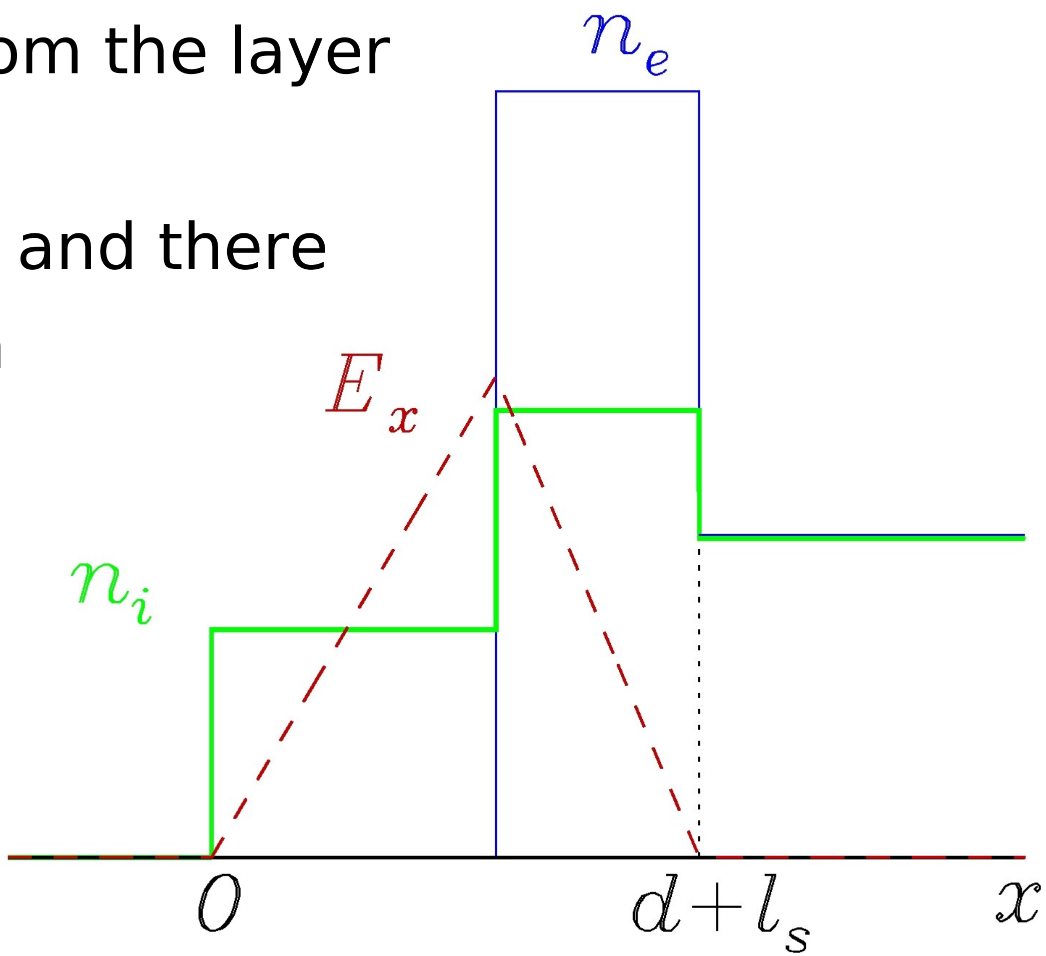

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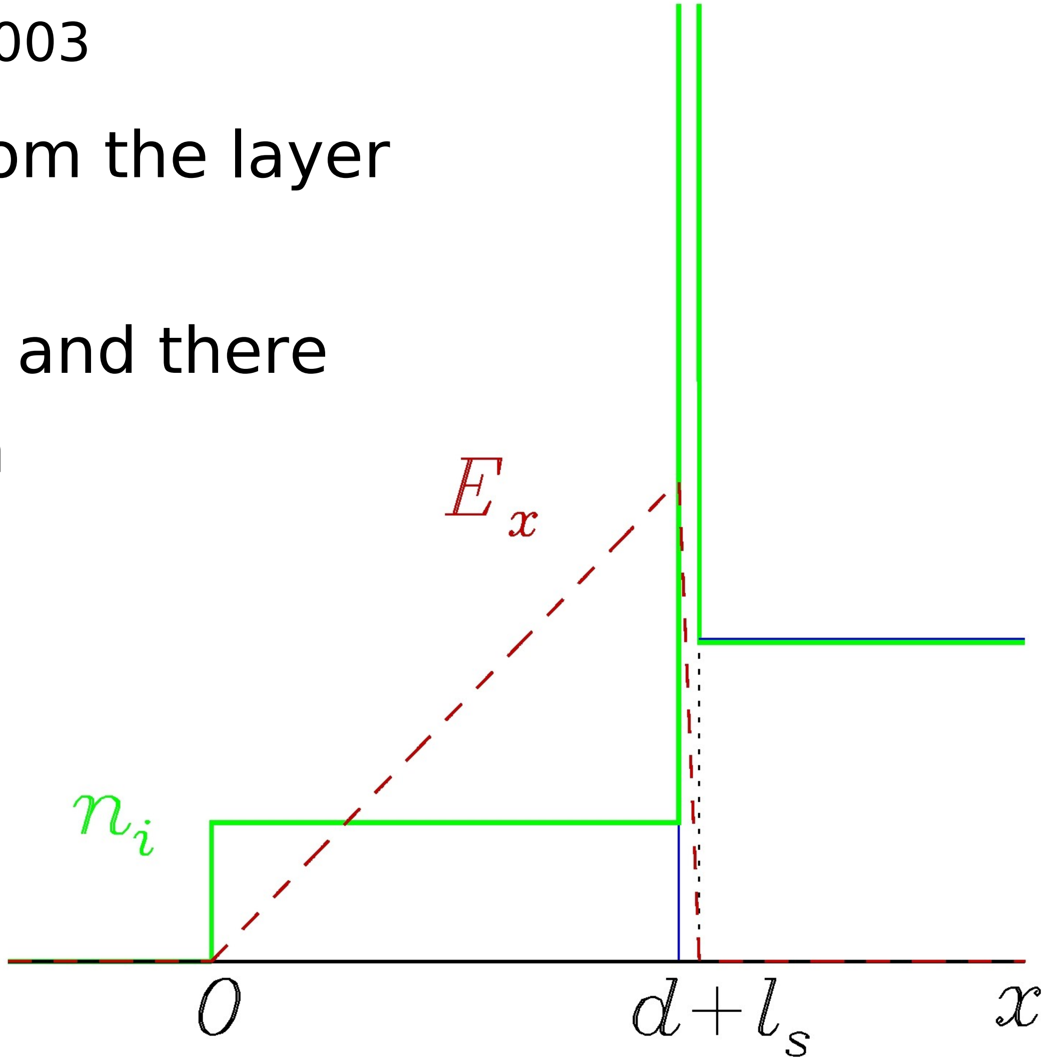

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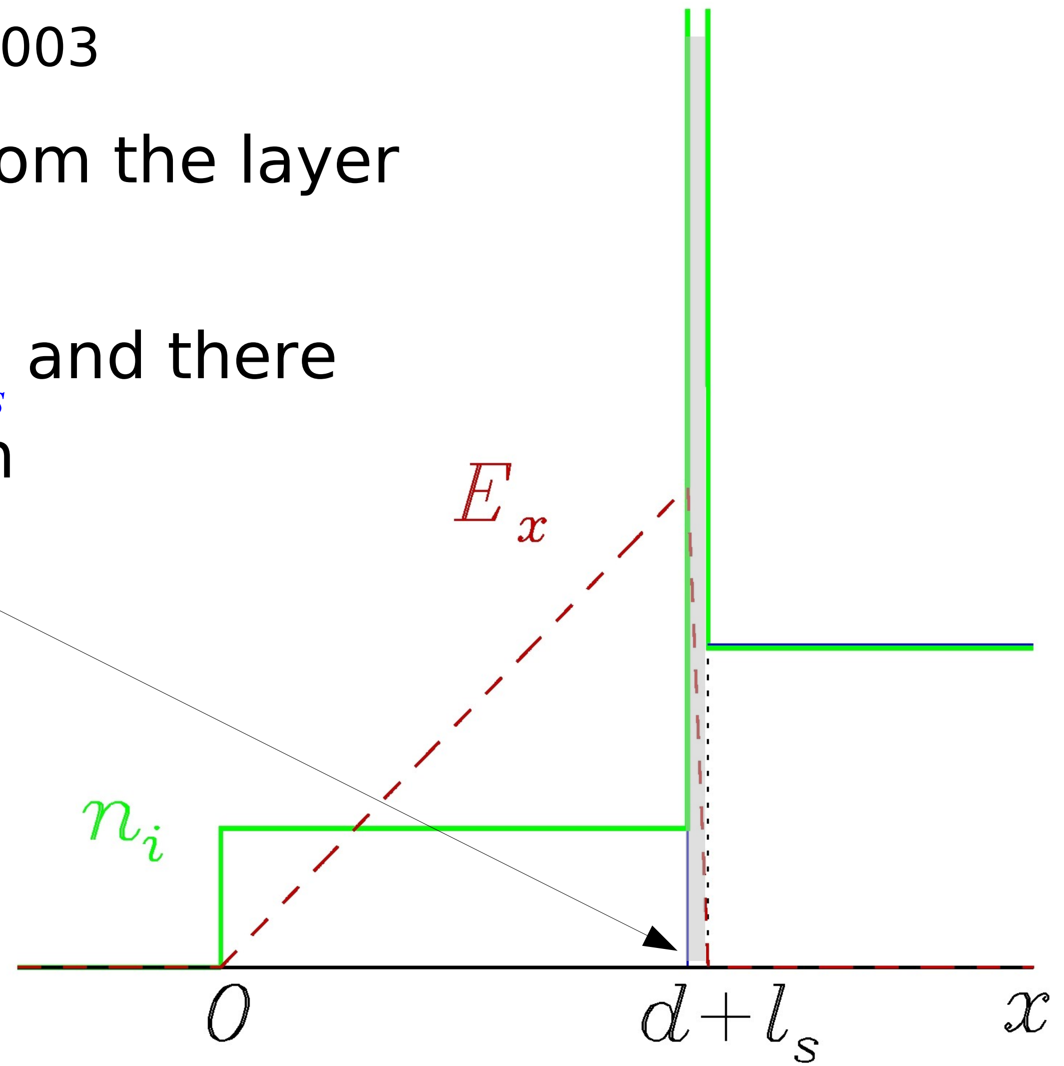
A "thin" target should end here, i.e have a thickness $\ell \approx d+l_s$ in order to allow "repeated" acceleration of the "fast" ion layer



Scaling laws in the hole boring regime

"Piston parameter"

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

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

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

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

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

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

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

Hole Boring: Pro et Contra

- Ion energy scales with intensity, not with pulse energy

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

BUT

- with respect to “Light Sail” (requiring ultrathin targets) the scheme seems more robust and less prone to, e.g., prepulse effects

- HB works in “preplasma”: lower densities boost ion energy
  [Liseikina, Borghesi, Macchi, Tuveri, PPCF **50** (2008) 124033]

- if a moderately overdense gas or liquid jet can be used as a target, higher energies may be obtained in combination with high repetition rate
  - gas jet with CO2 laser? (work in progress with Bologna...)
  - liquid hydrogen jet with Ti:Sa laser?

Hole Boring Acceleration with Few-Cycle Pulses

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

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

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

Case study:

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

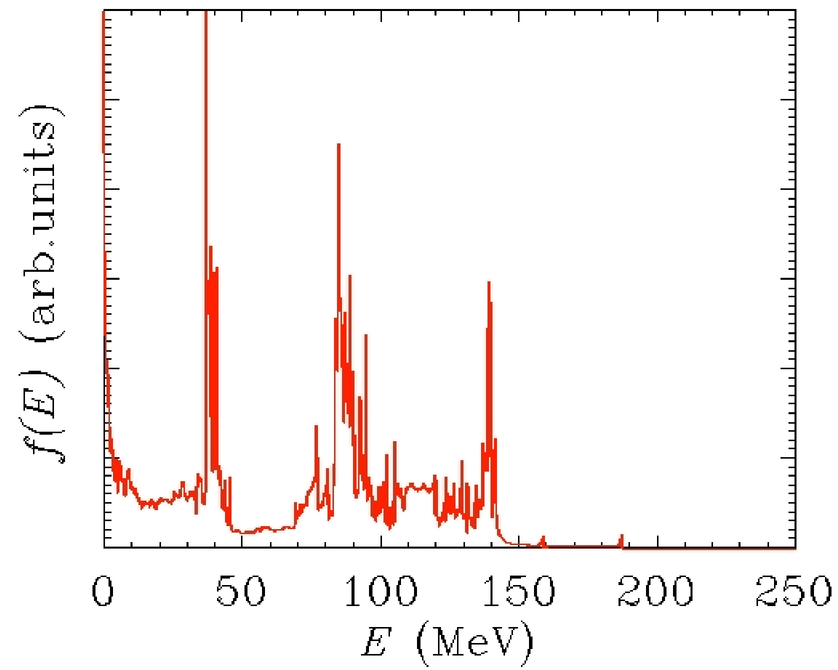
CP laser pulse with $\lambda = 0.8 \mu$m and 2 cycles duration (FWHM)
Peak intensity $I = 4.9 \times 10^{22}$ W/cm^{-2} ($a_0 = 106$)

(suggestion by M.Zepf, Queen's University Belfast)

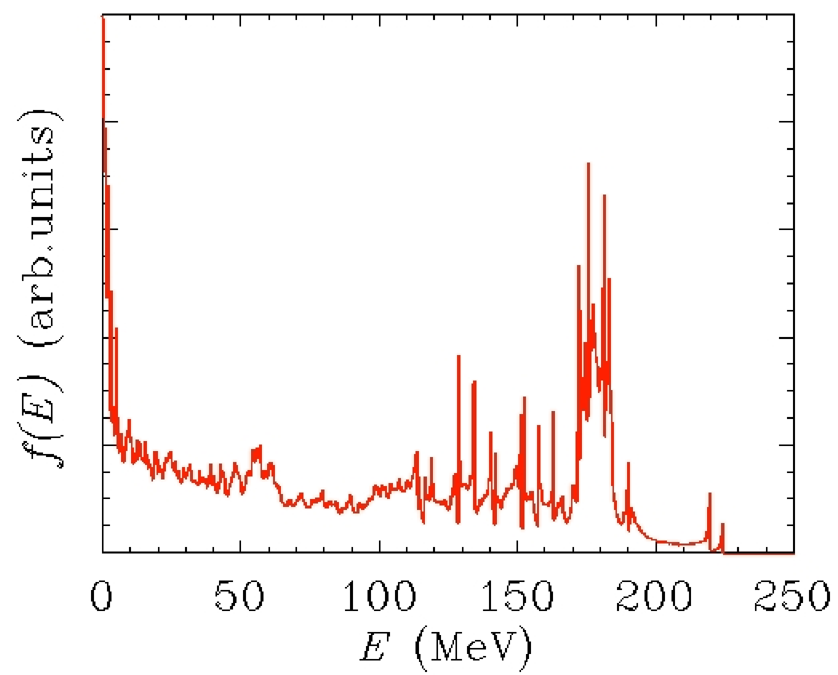
The ion spectrum is improved by a density gradient

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

(bunch production time is less than laser cycle)



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



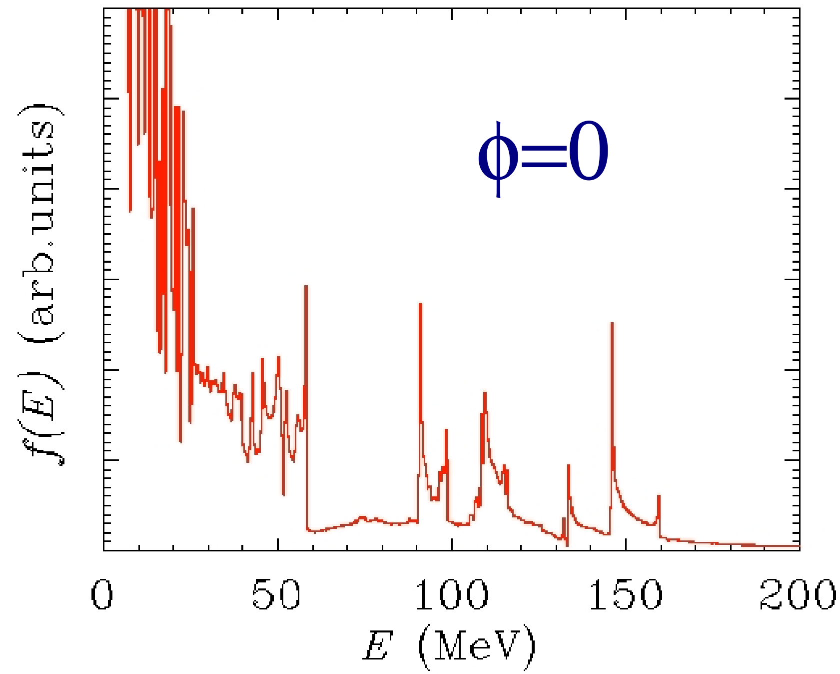
Circular Polarization stabilizes CE phase effects

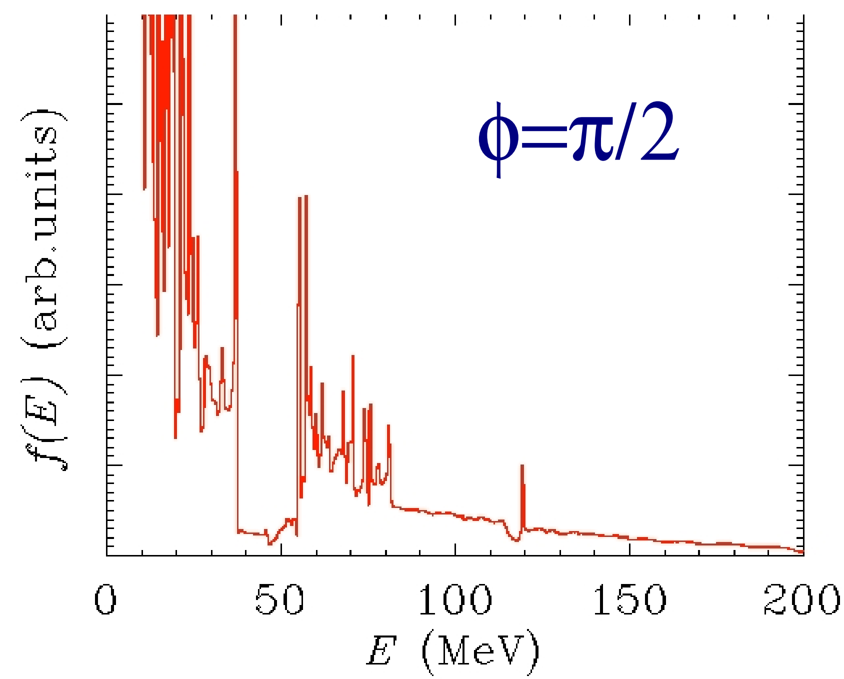
Laser-matter interaction with few-cycle pulses is sensitive to the Carrier-Envelope phase ϕ:

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

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

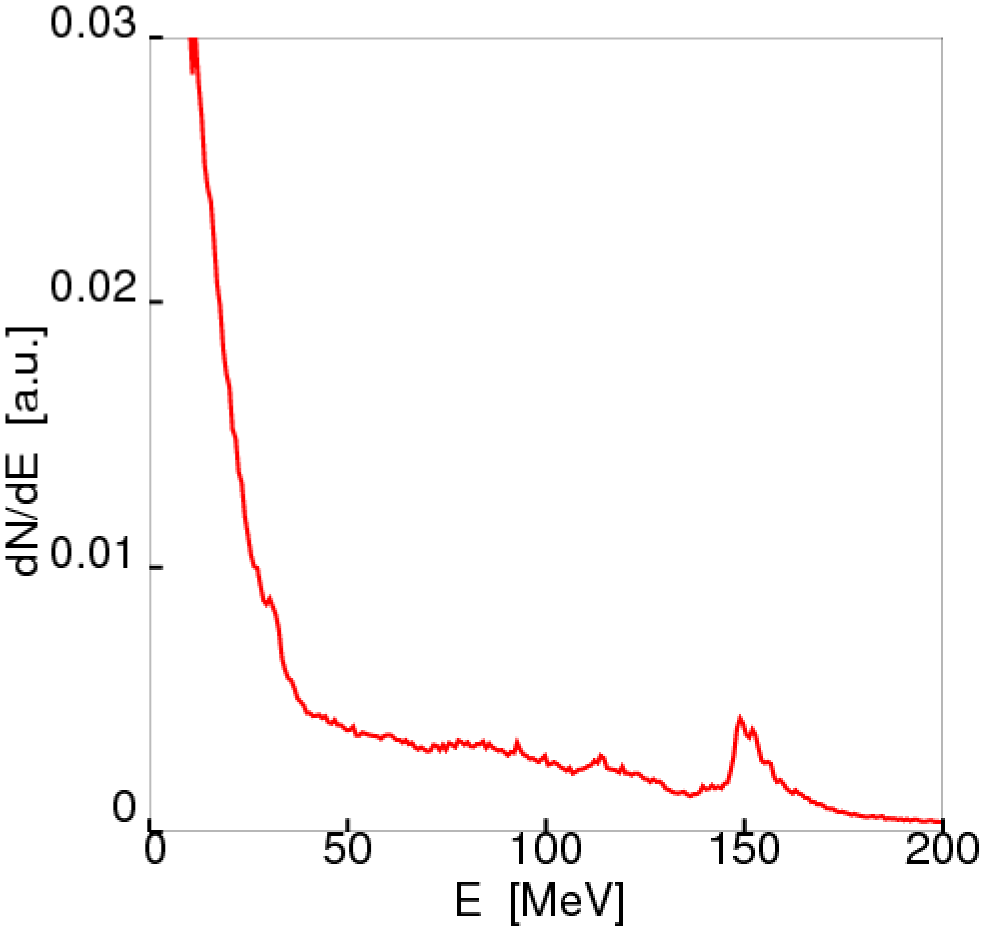
For circular polarization, there is almost no dependence on ϕ because $|E(t)|^2$ is constant in this case

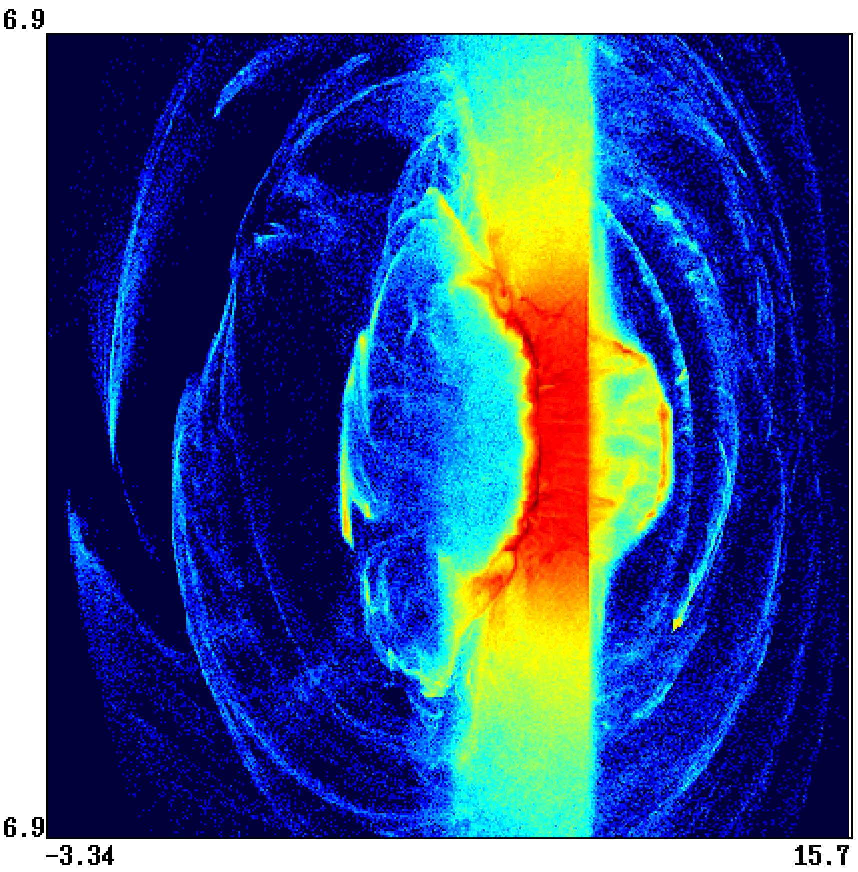




2D simulations with the AlaDyn code

(C.Benedetti et al.)

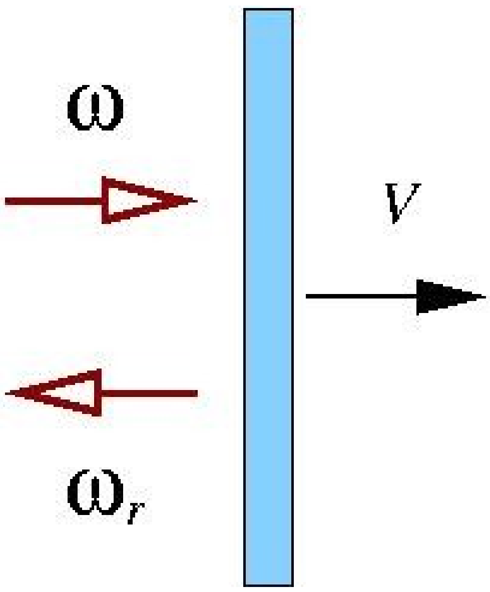




1D modeling is predictive for ions near the laser axis

The "Light Sail" or (Accelerating Mirror) model

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



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

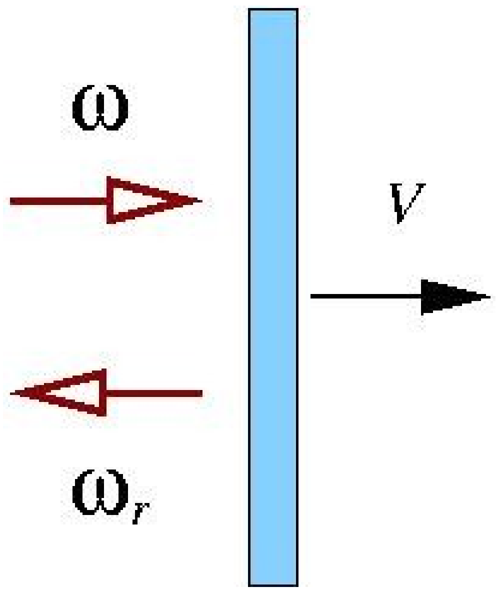
$$\beta(t) = \frac{(1+\mathcal{E})^2 - 1}{(1+\mathcal{E})^2 + 1}, \qquad \mathcal{E} = \frac{2F(t)}{\rho\ell c^2} = 2\pi \frac{Z}{A}\frac{m_e}{m_p}\frac{a_0^2\tau}{\zeta}$$

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

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

The "Light Sail" or (Accelerating Mirror) model

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



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

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

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

100% efficiency in the relativistic limit

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

Comparison of LS model with 1D PIC simulations

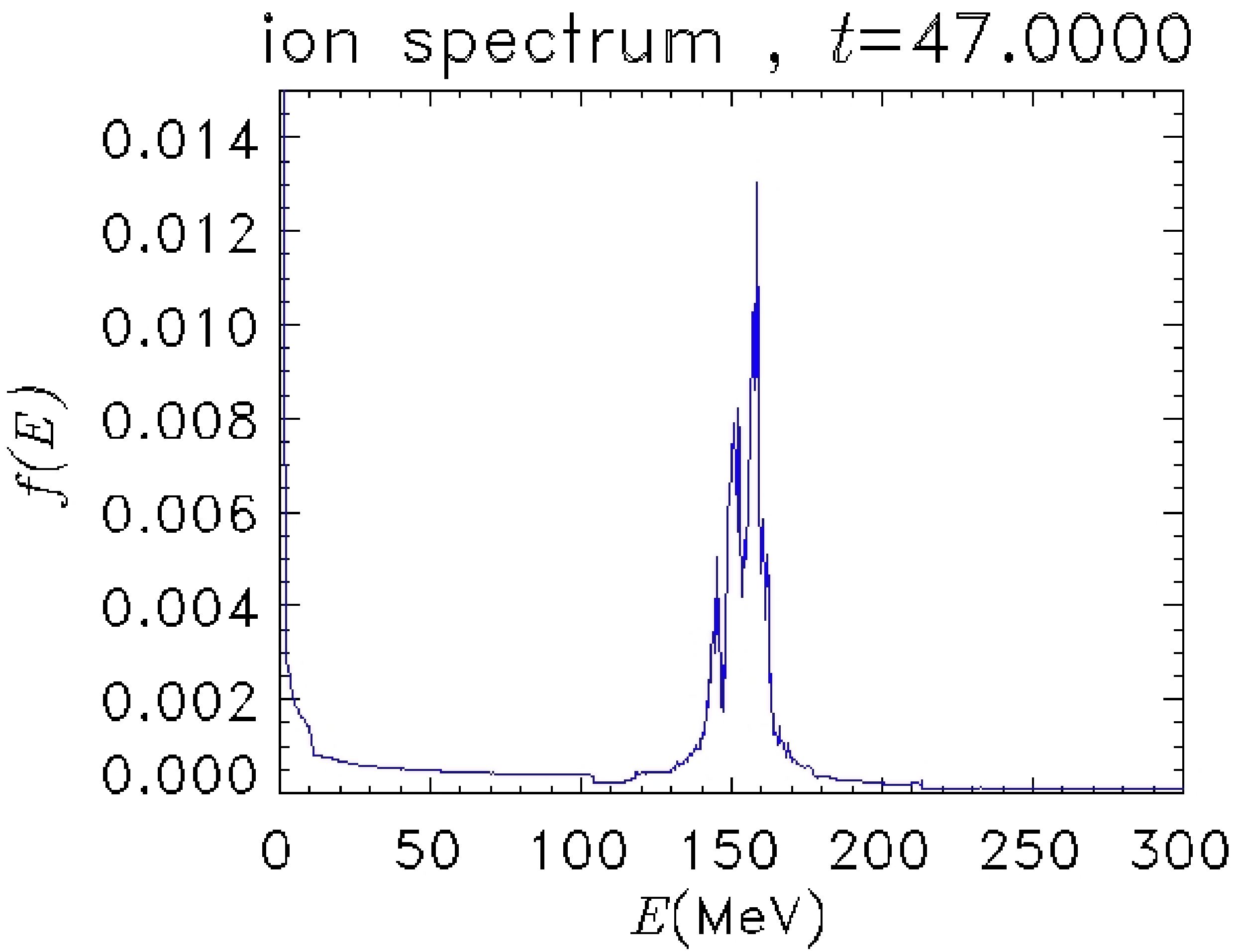
Laser pulse: a_0=**5-50**, τ=8 cycles ("flat-top" envelope)

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

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

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

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



A.Macchi, S.Veghini, F.Pegoraro, arXiv:0905.2068

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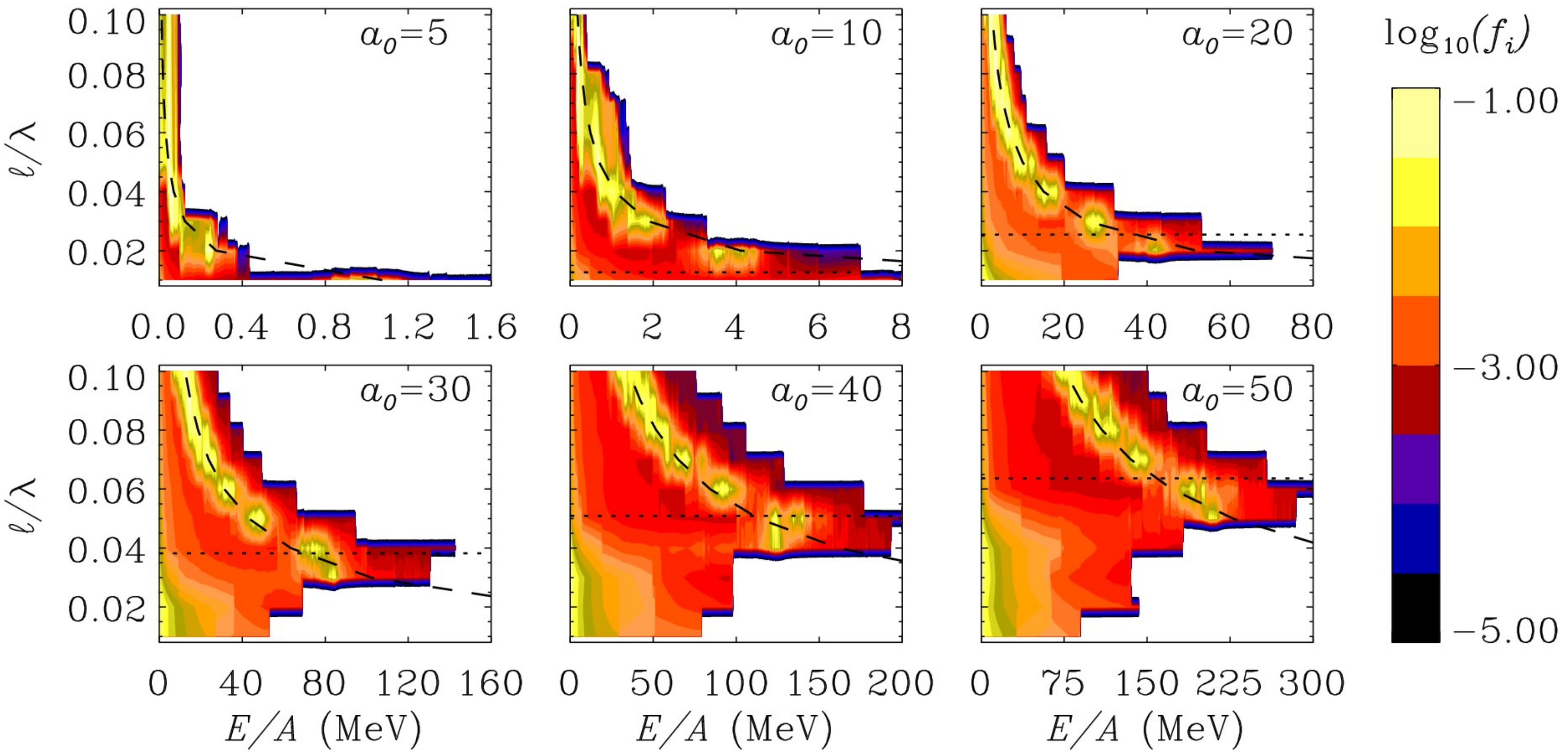
Energy spectra vs. a_0 and ℓ:



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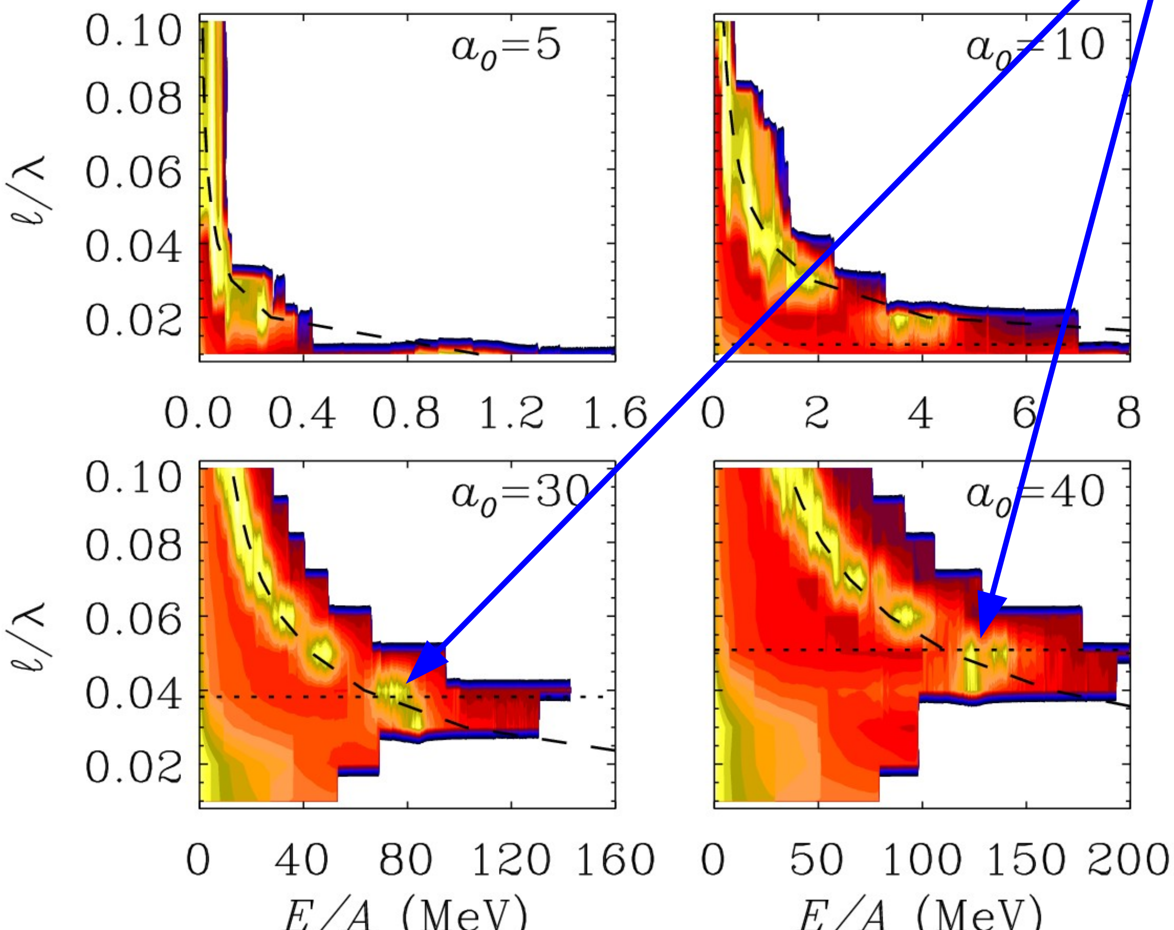
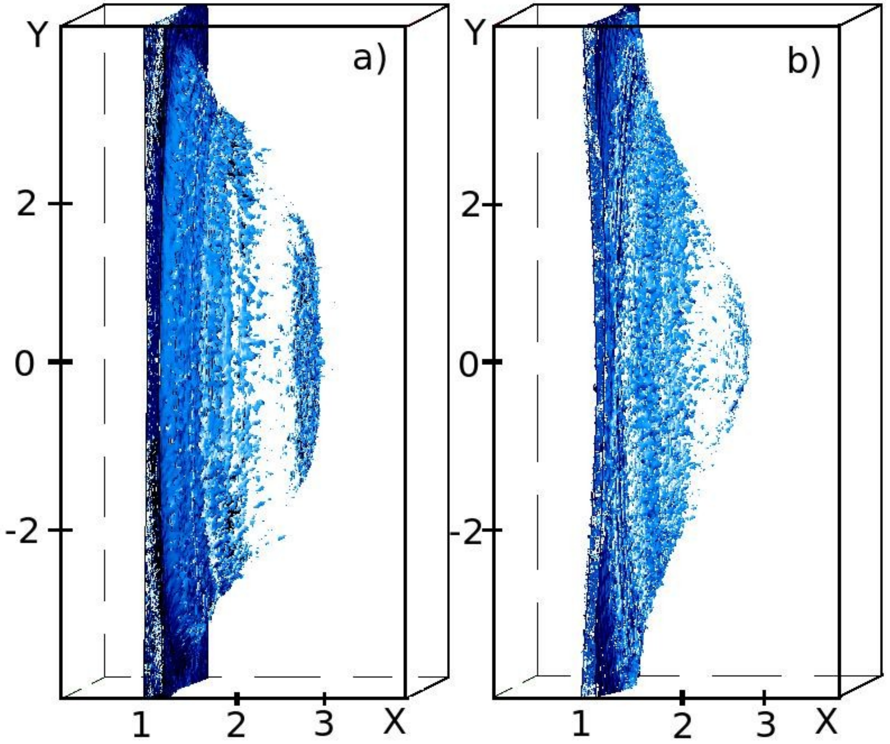


A **narrow spectral peak** is observed for $a_0 < \zeta$. The max energy is at $a_0 = \zeta$ (dotted line)

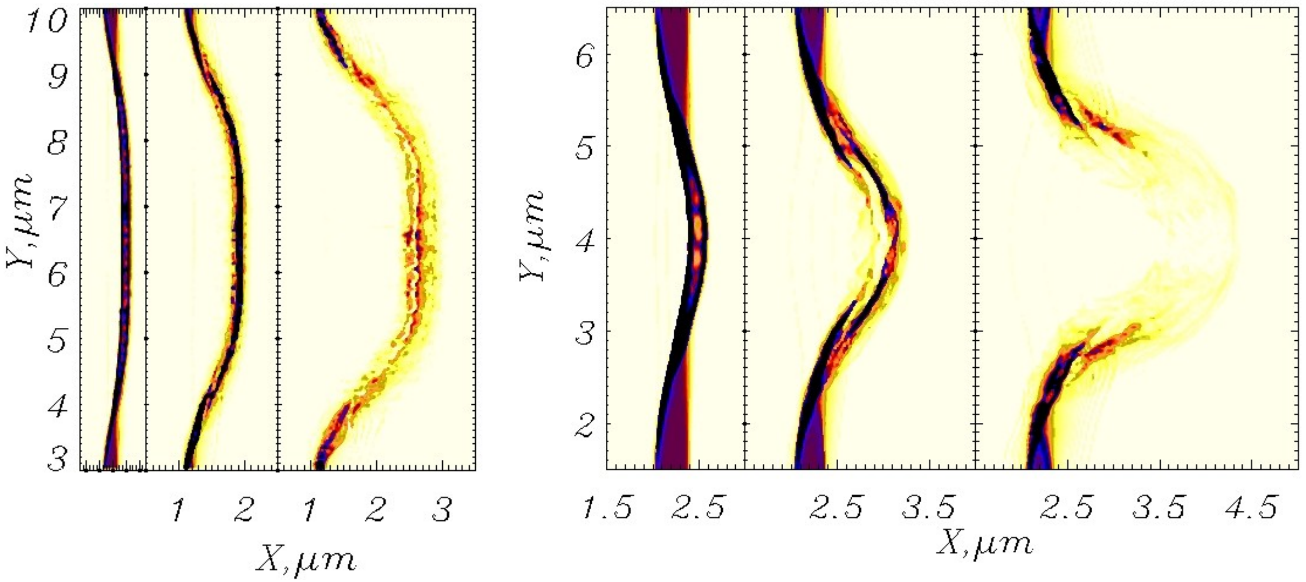
The energy of the peak is in good agreement with the LS formula (dashed black line)

A.Macchi, S.Veghini, F.Pegoraro, arXiv:0905.2068

3D simulations “support” 1D modeling



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



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

However, some questions remain...

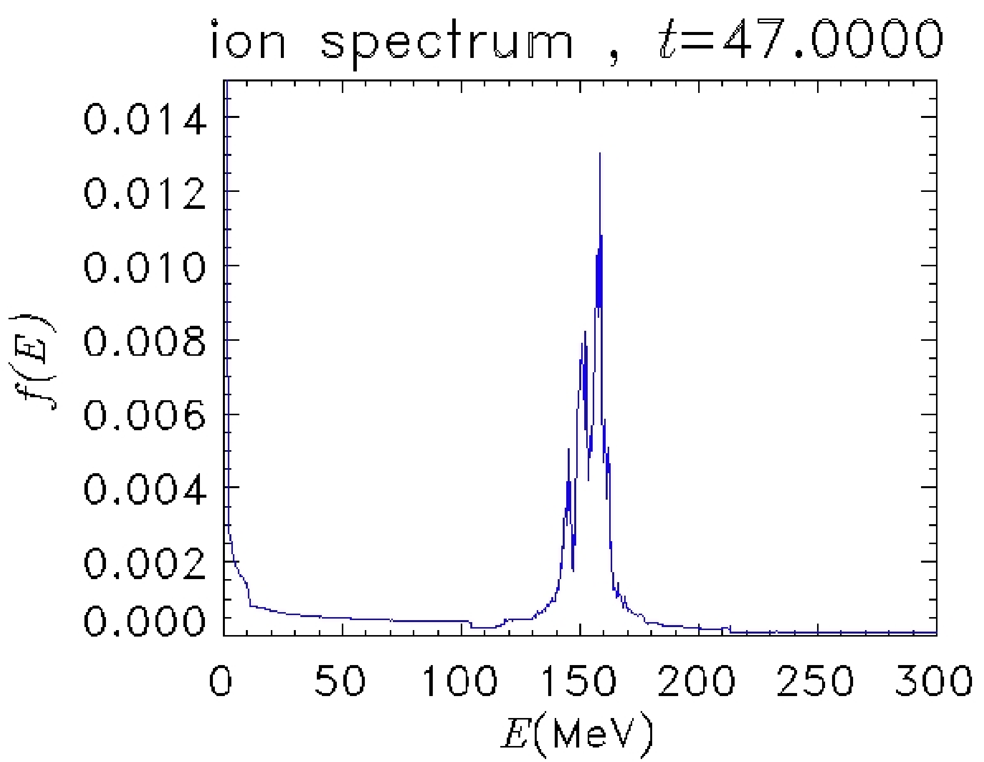
- What determines the "optimal thickness" condition $a_0 < \zeta$?

- Does the foil remain neutral after the acceleration?

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

$\rightarrow$ Only part of the foil is accelerated?

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

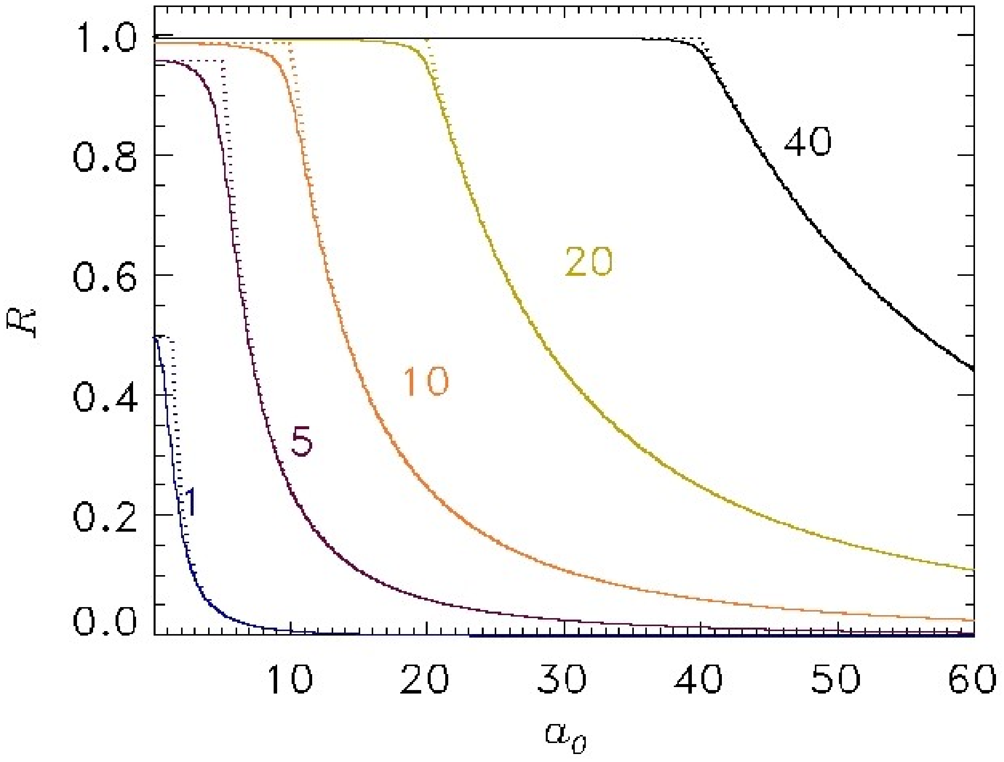


Nonlinear reflectivity accounts for optimal thickness

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

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

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



approximated (but rather precise) formula:

$R\approx\zeta^2/(\zeta^2+1)$ 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 $I\sim a_0^2$)

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

Balance of radiation and electrostatic pressures

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

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

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

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

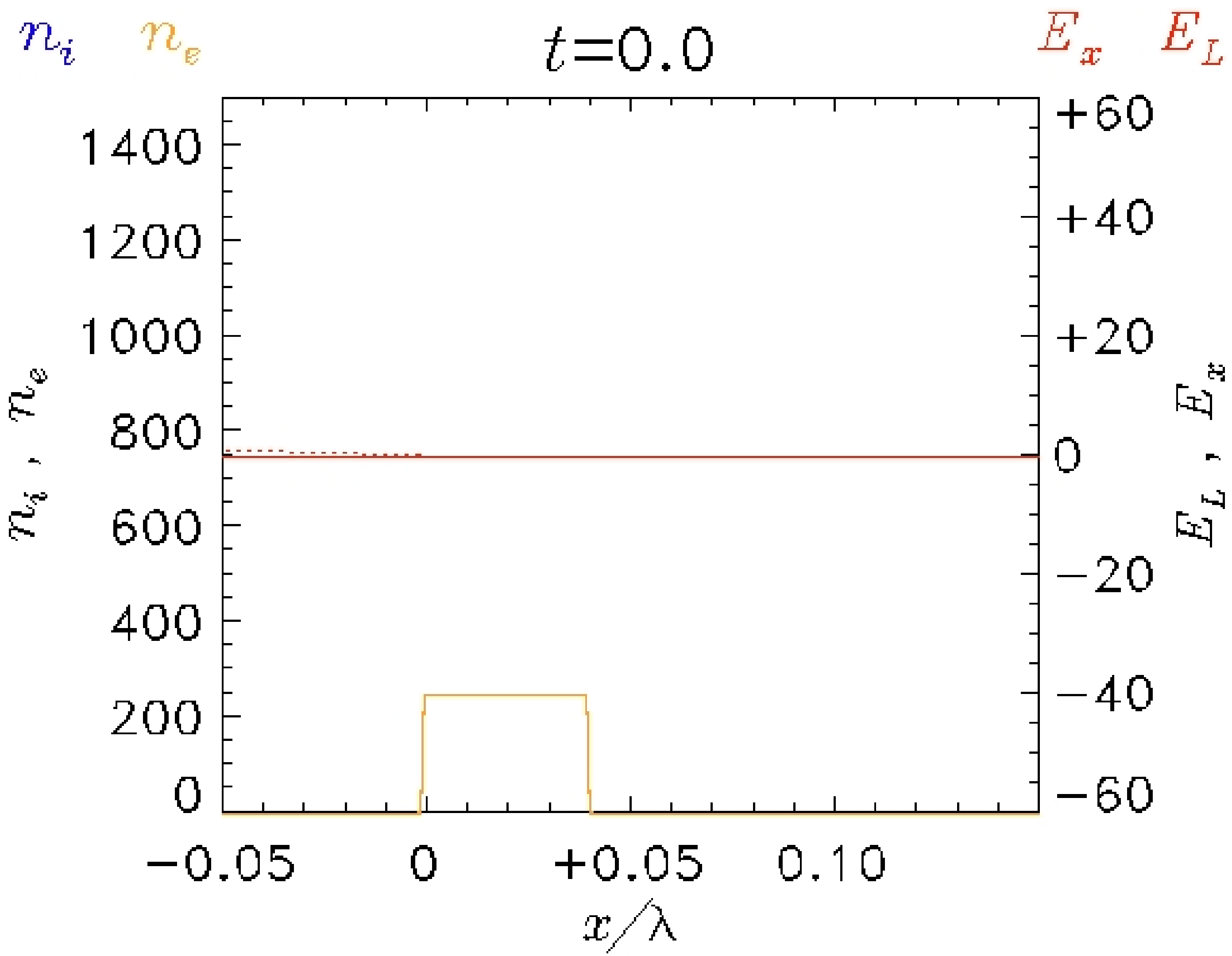
For $a_0 \rightarrow \zeta$ all the electrons must pile up near the rear surface in order to establish the equilibrium between P_{rad} and P_{es} .

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

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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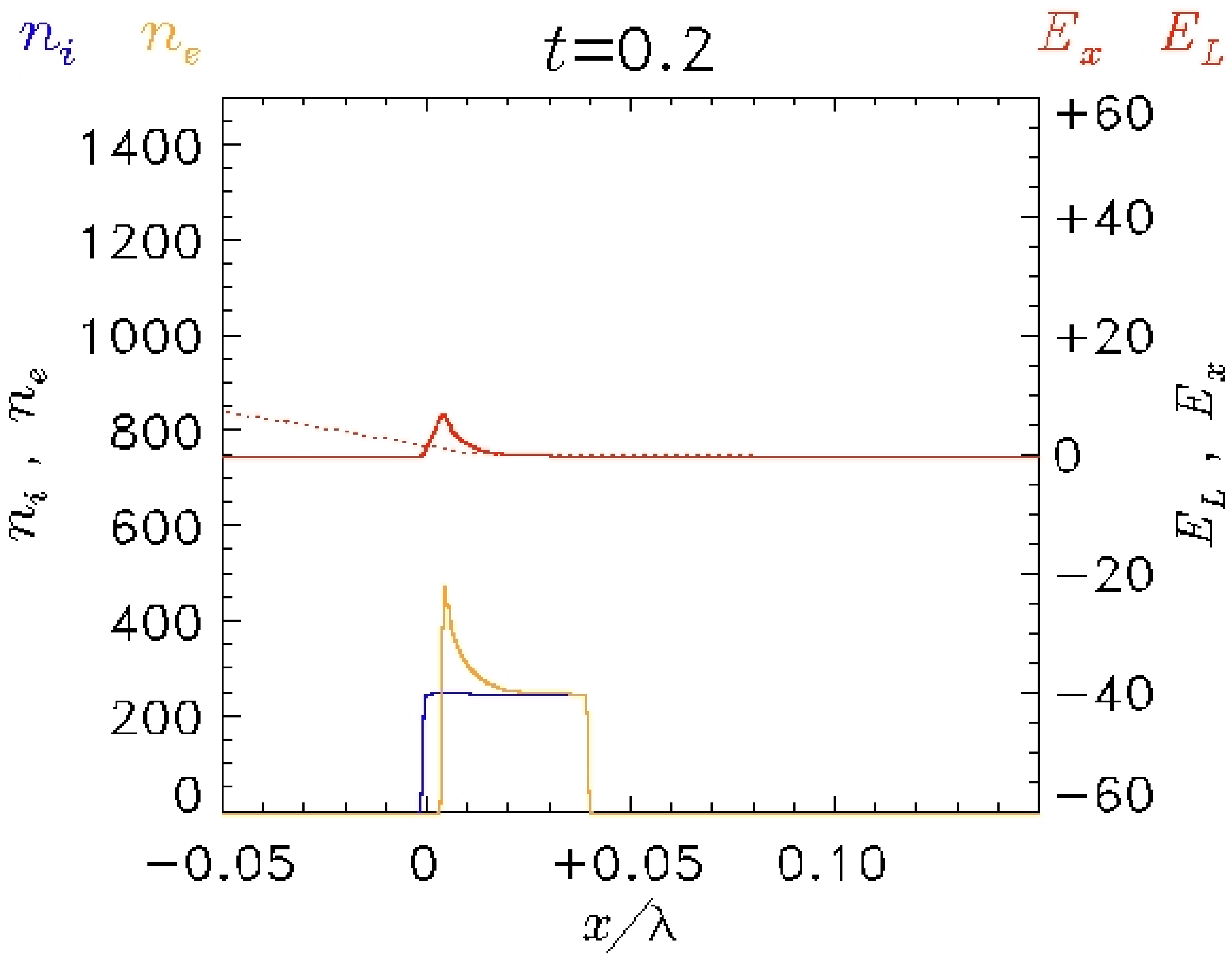

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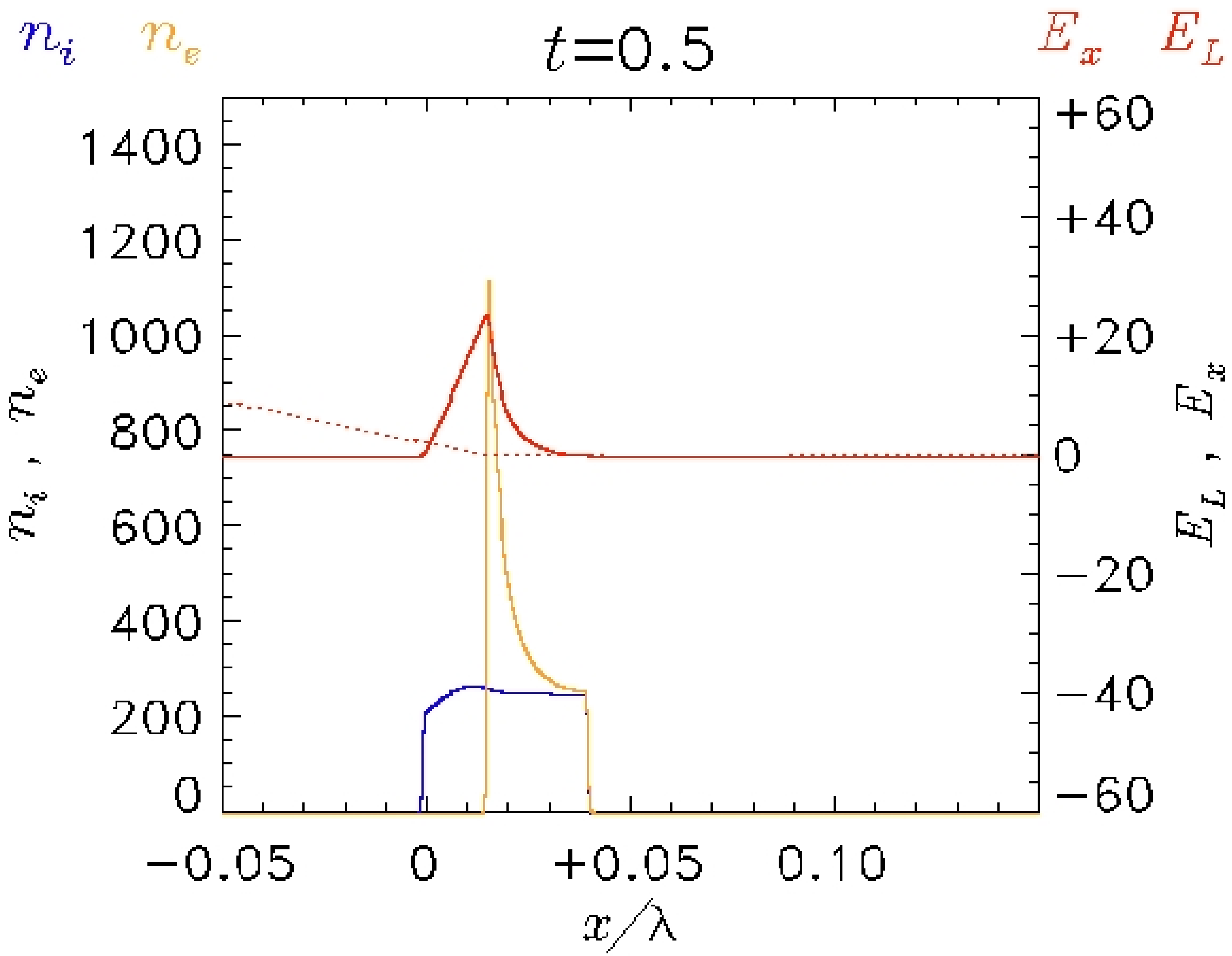

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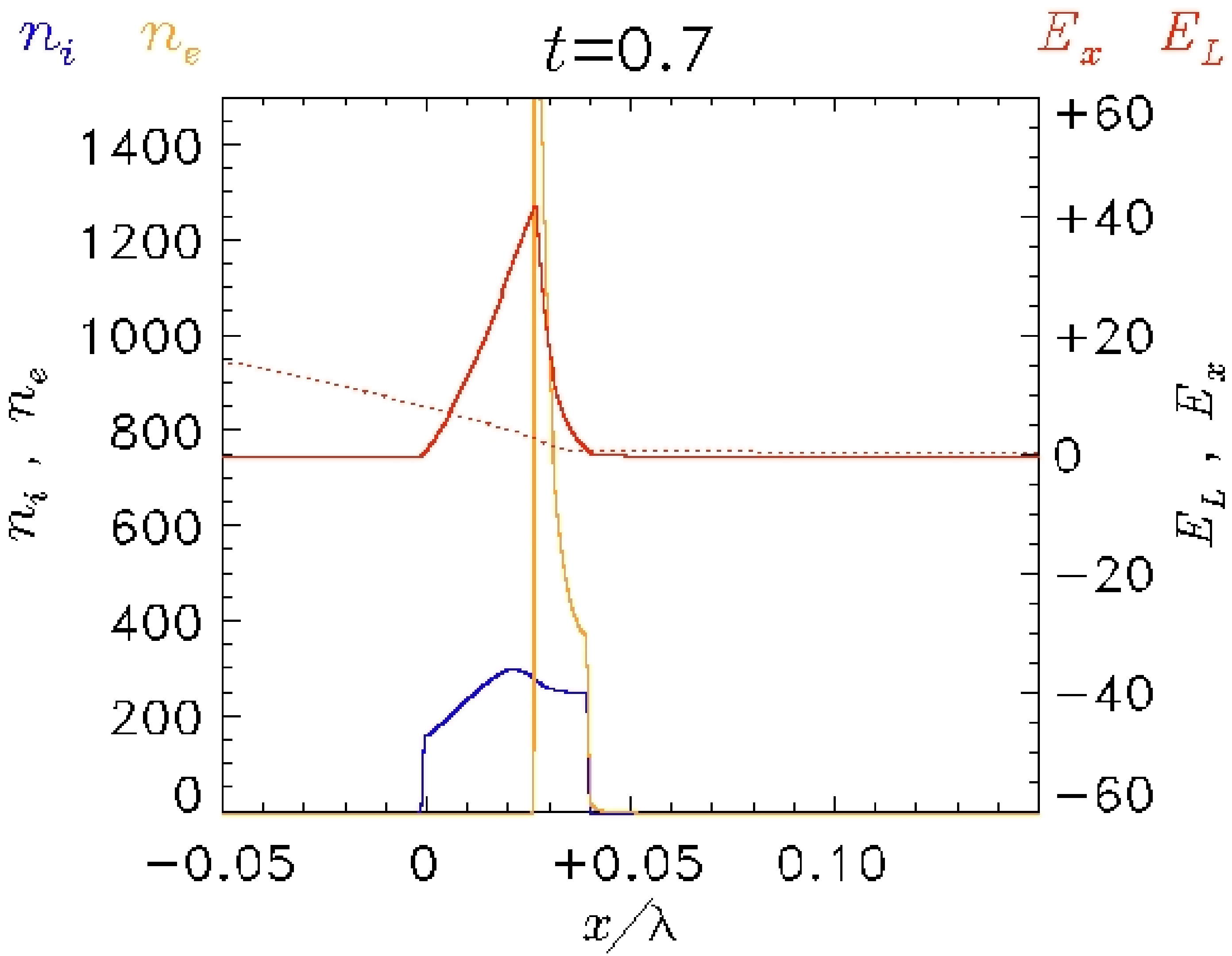

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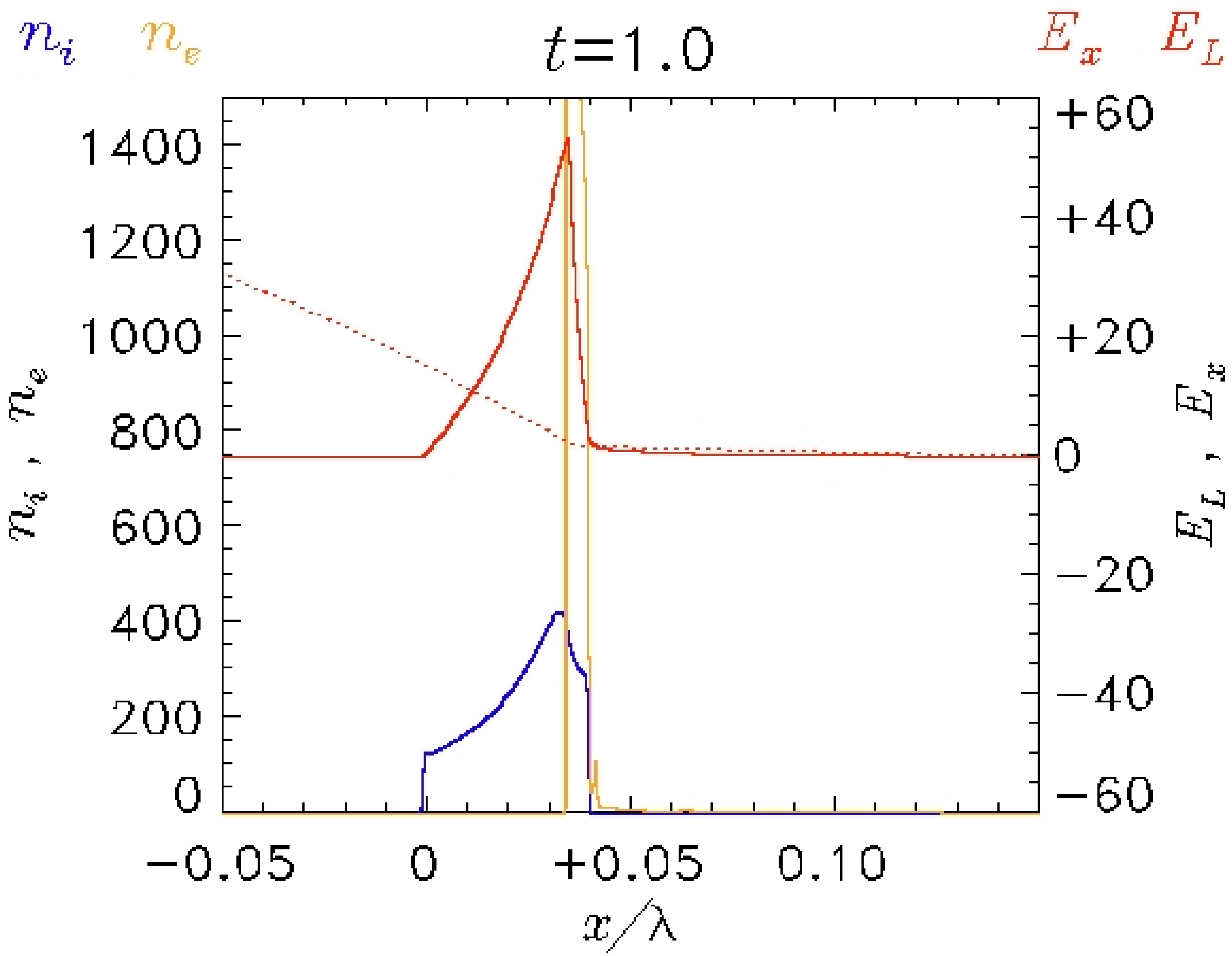

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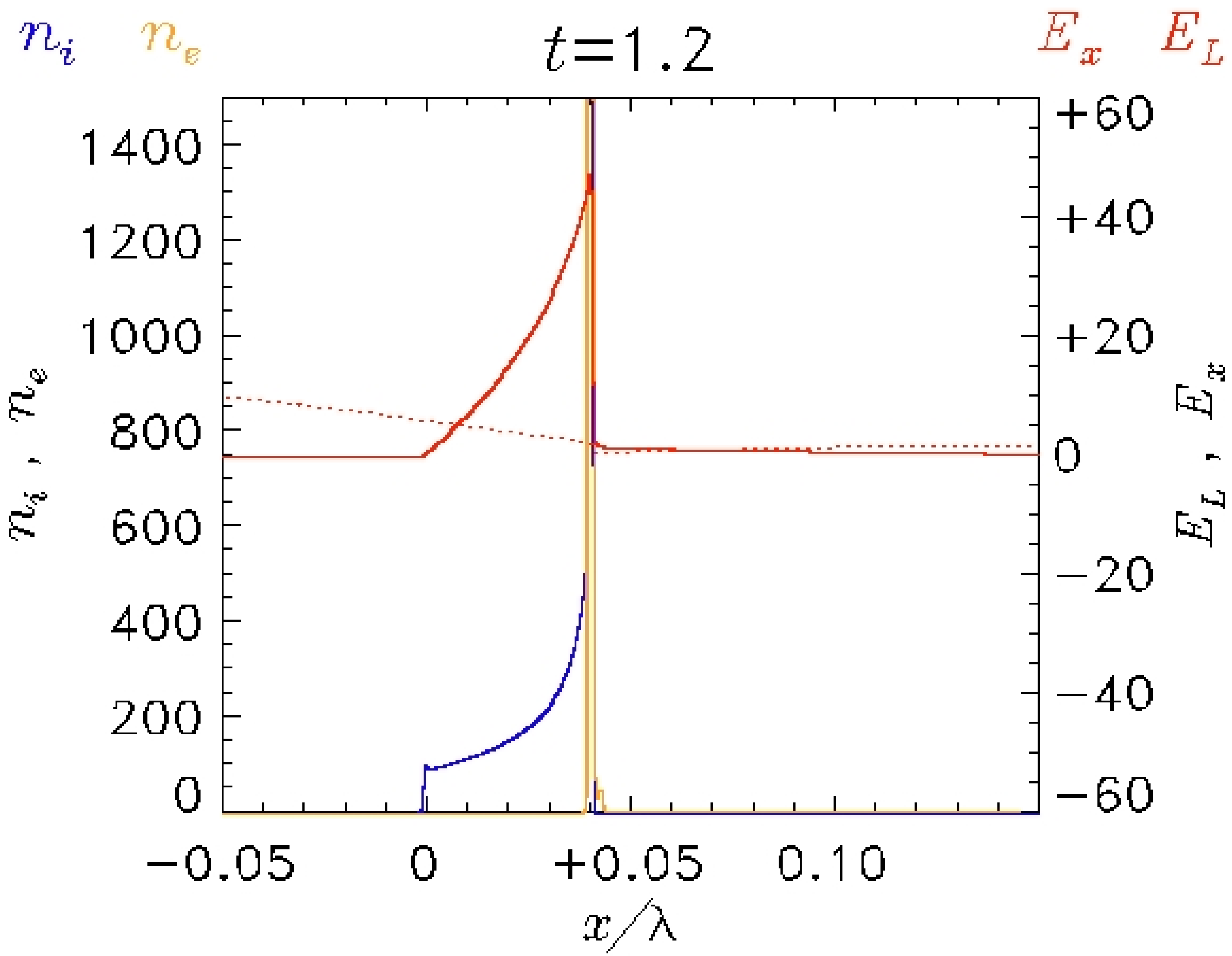

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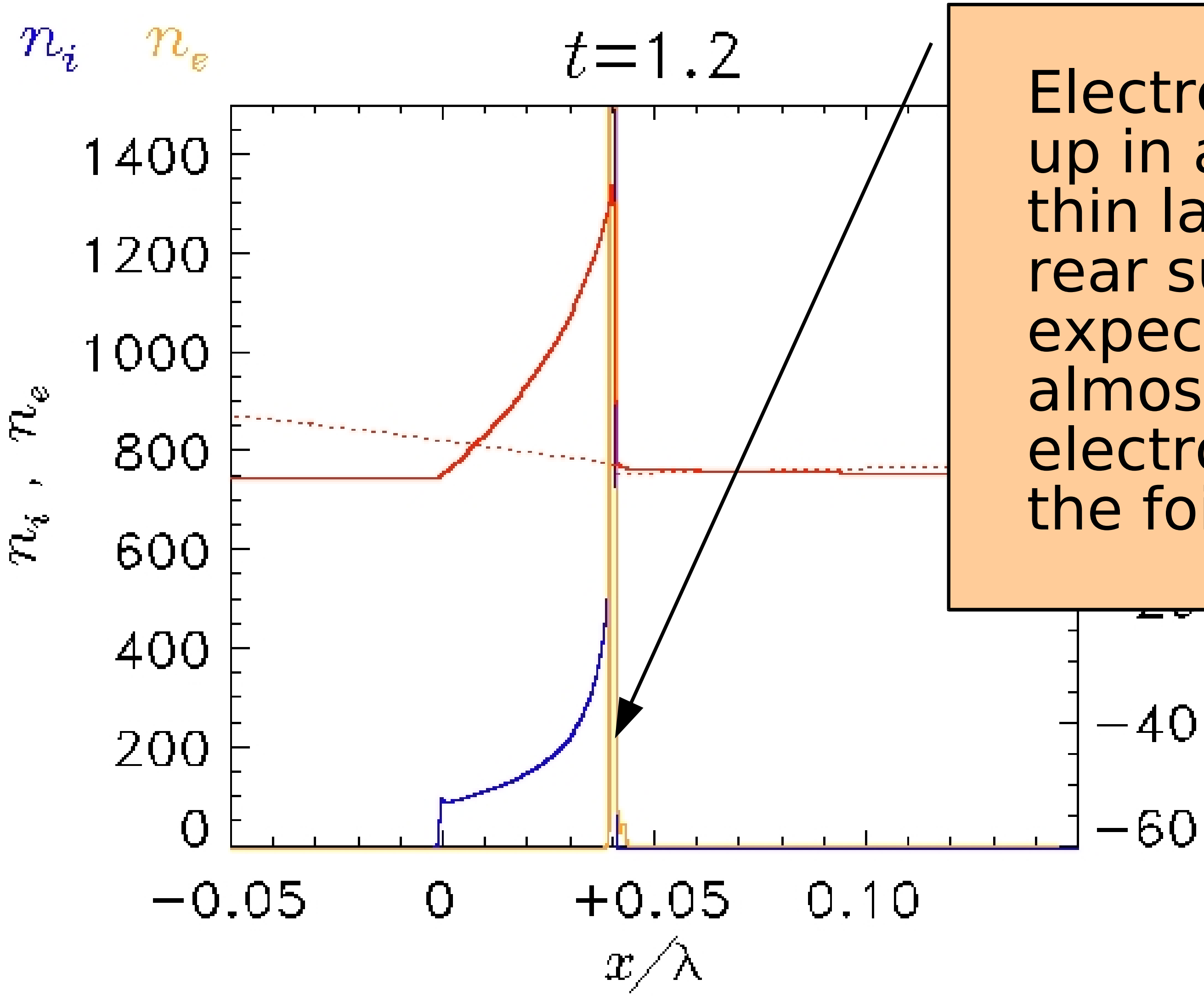

Electrons pile up in a very thin layer at the rear surface as expected; almost no electrons leave the foil

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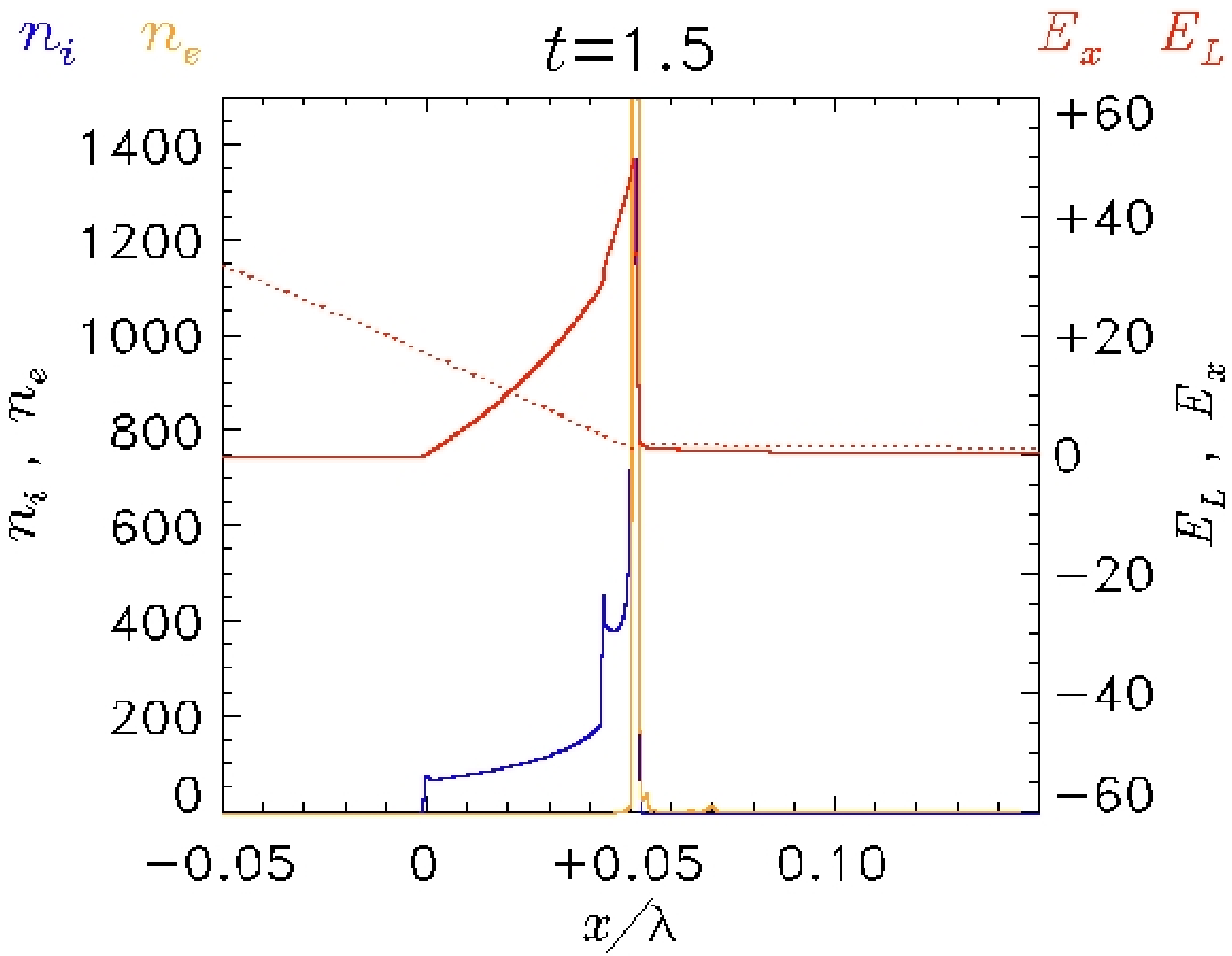

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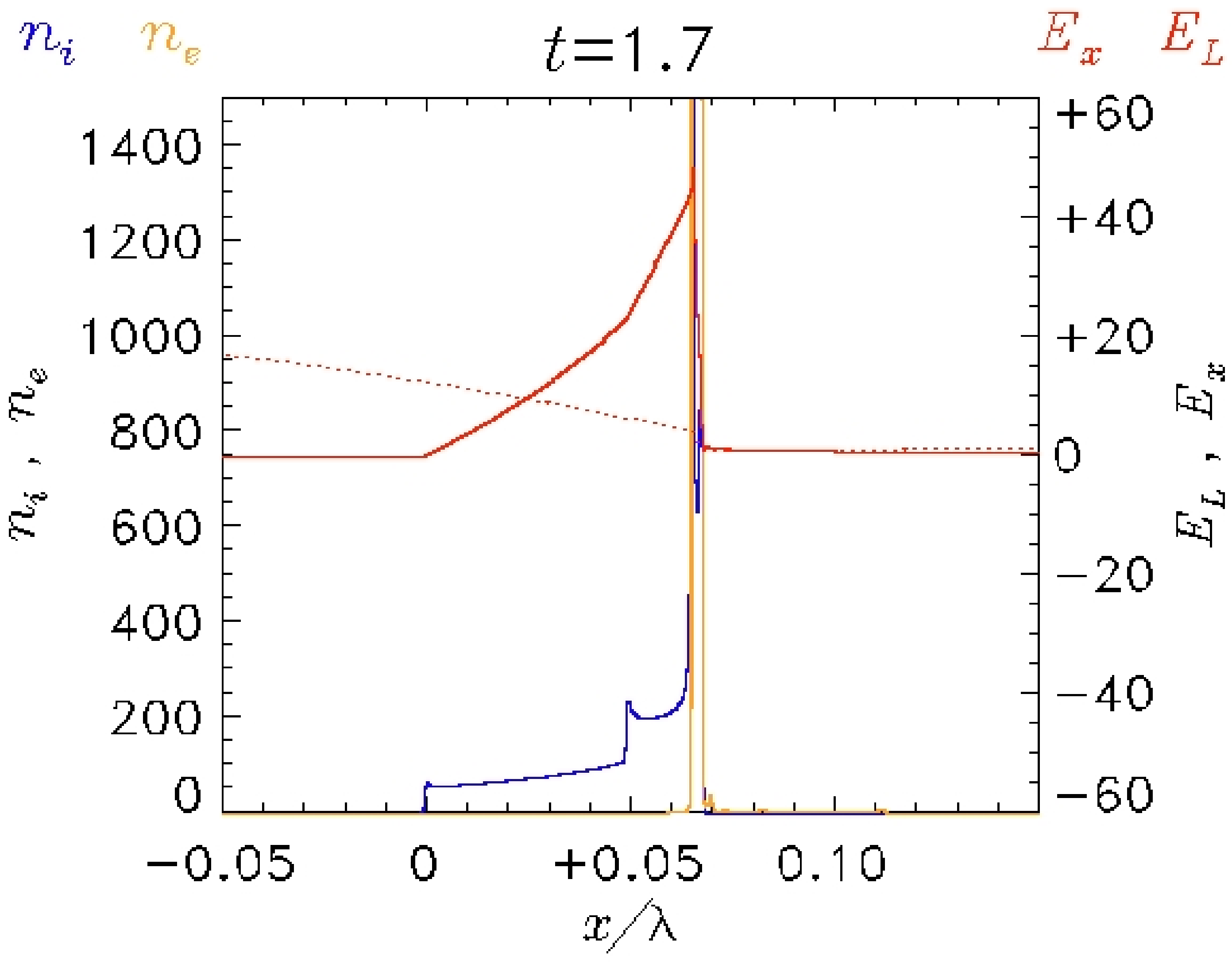

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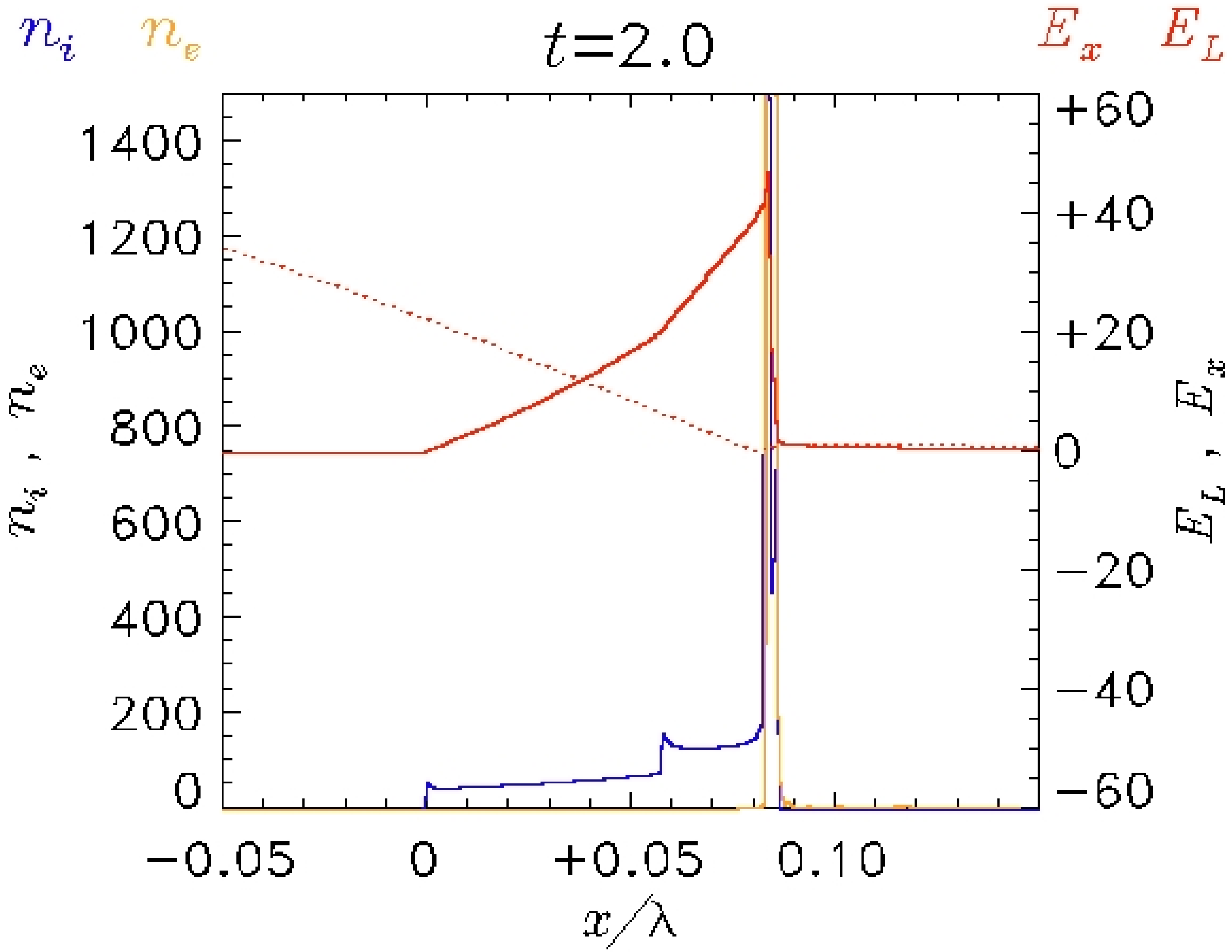
Thin foil target: n_e=250n_c , ℓ=0.04λ , ζ=31.4,



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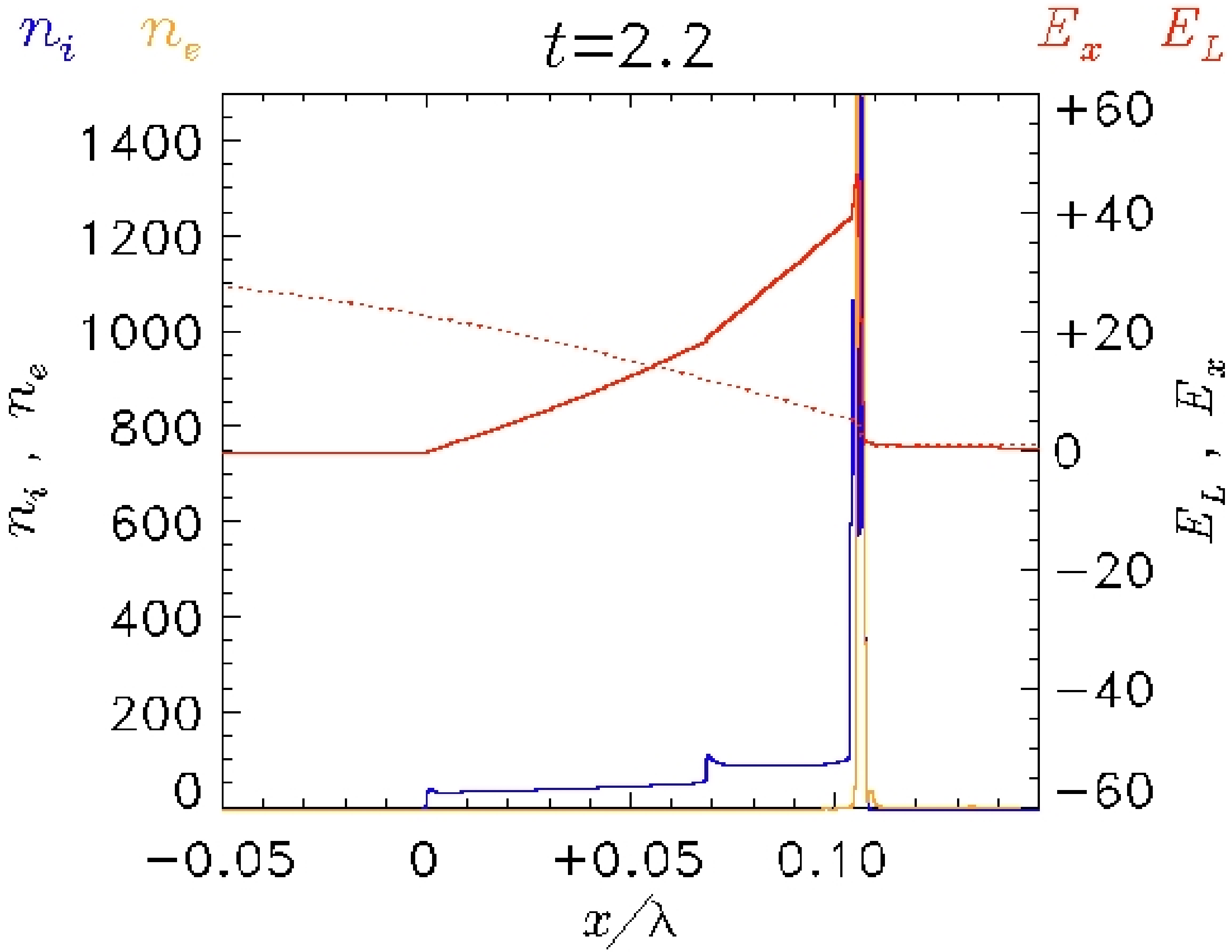

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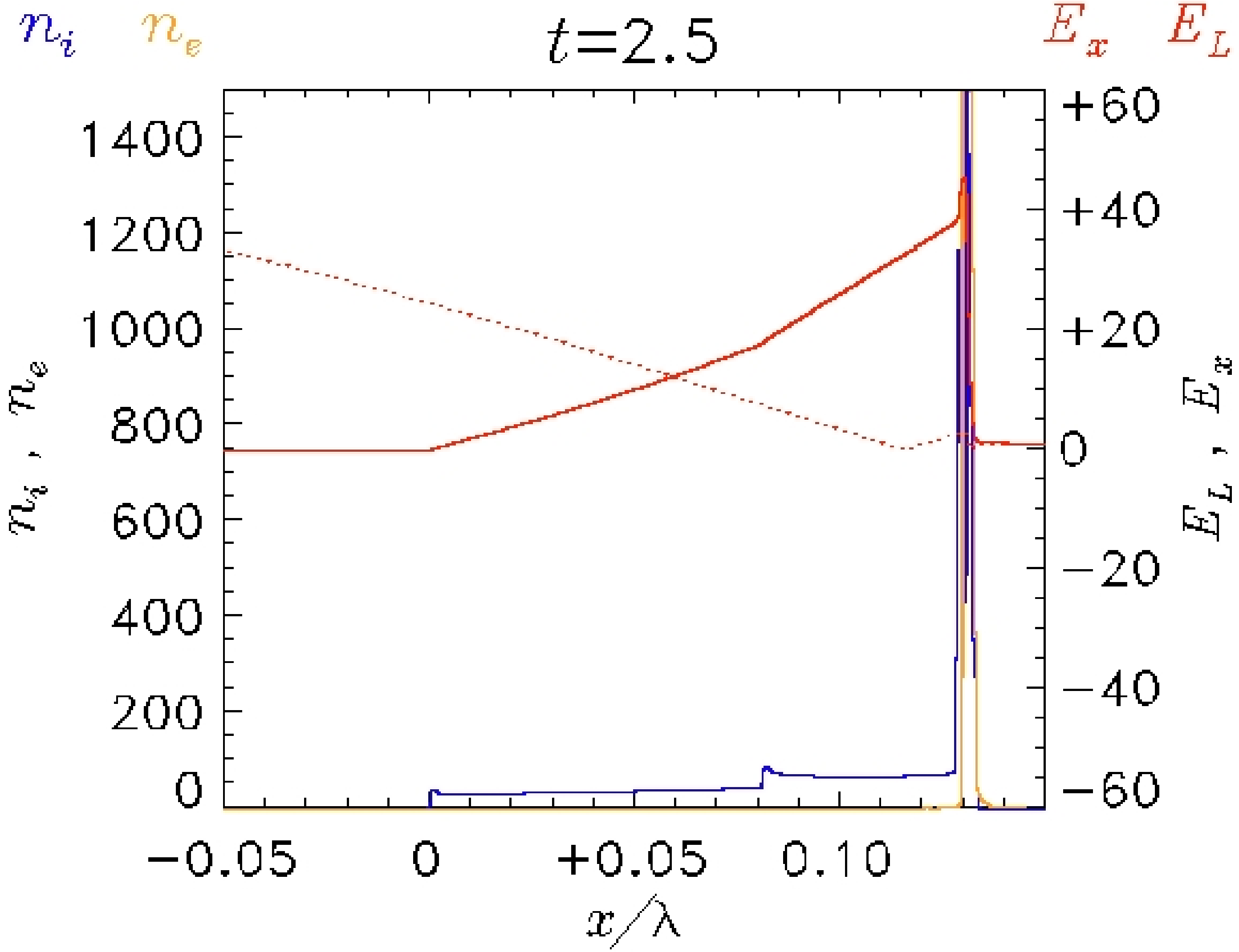

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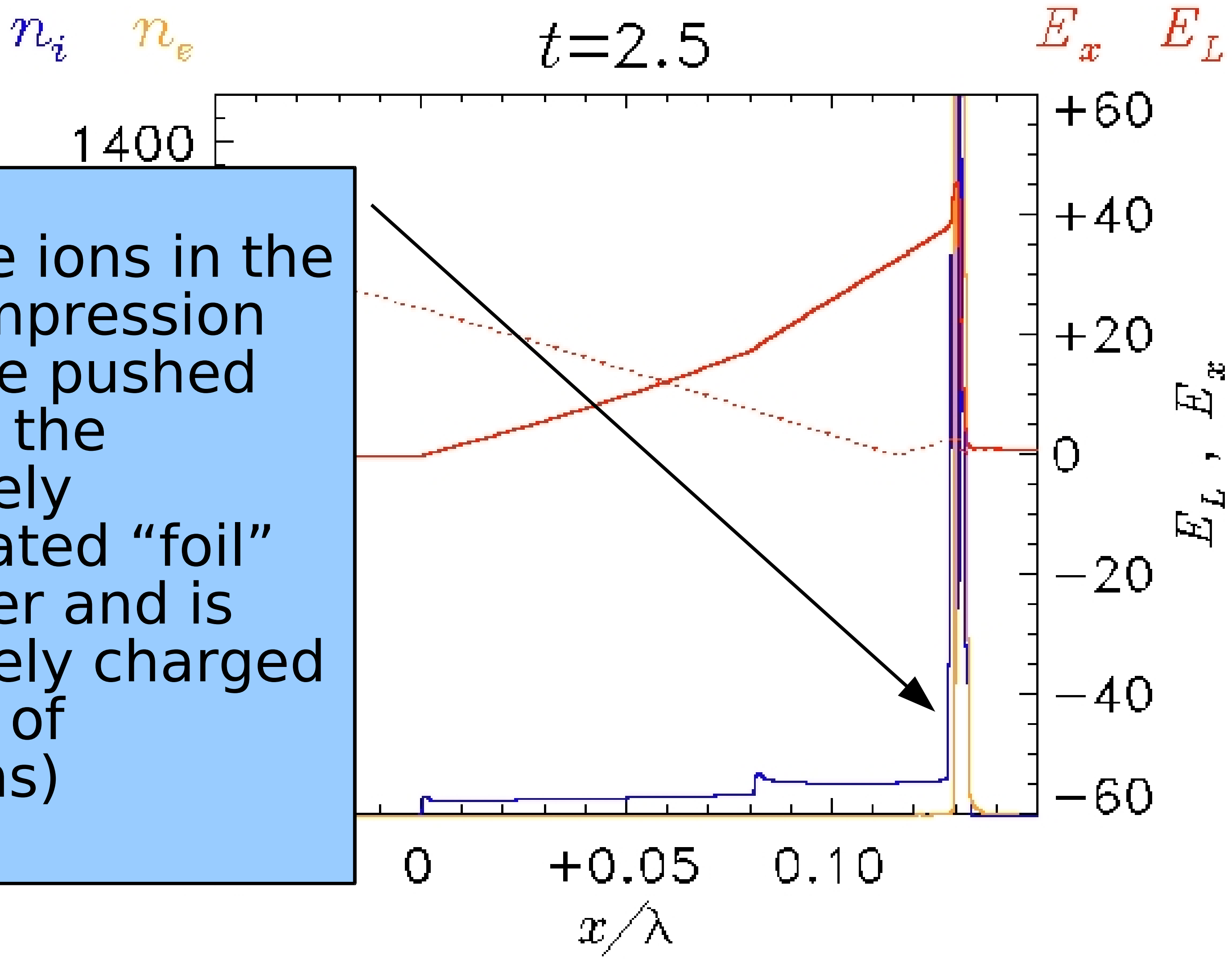

Only the ions in the thin compression layer are pushed by RPA; the effectively accelerated "foil" is thinner and is negatively charged (excess of electrons)

“Excess” electrons leave the foil after the pulse

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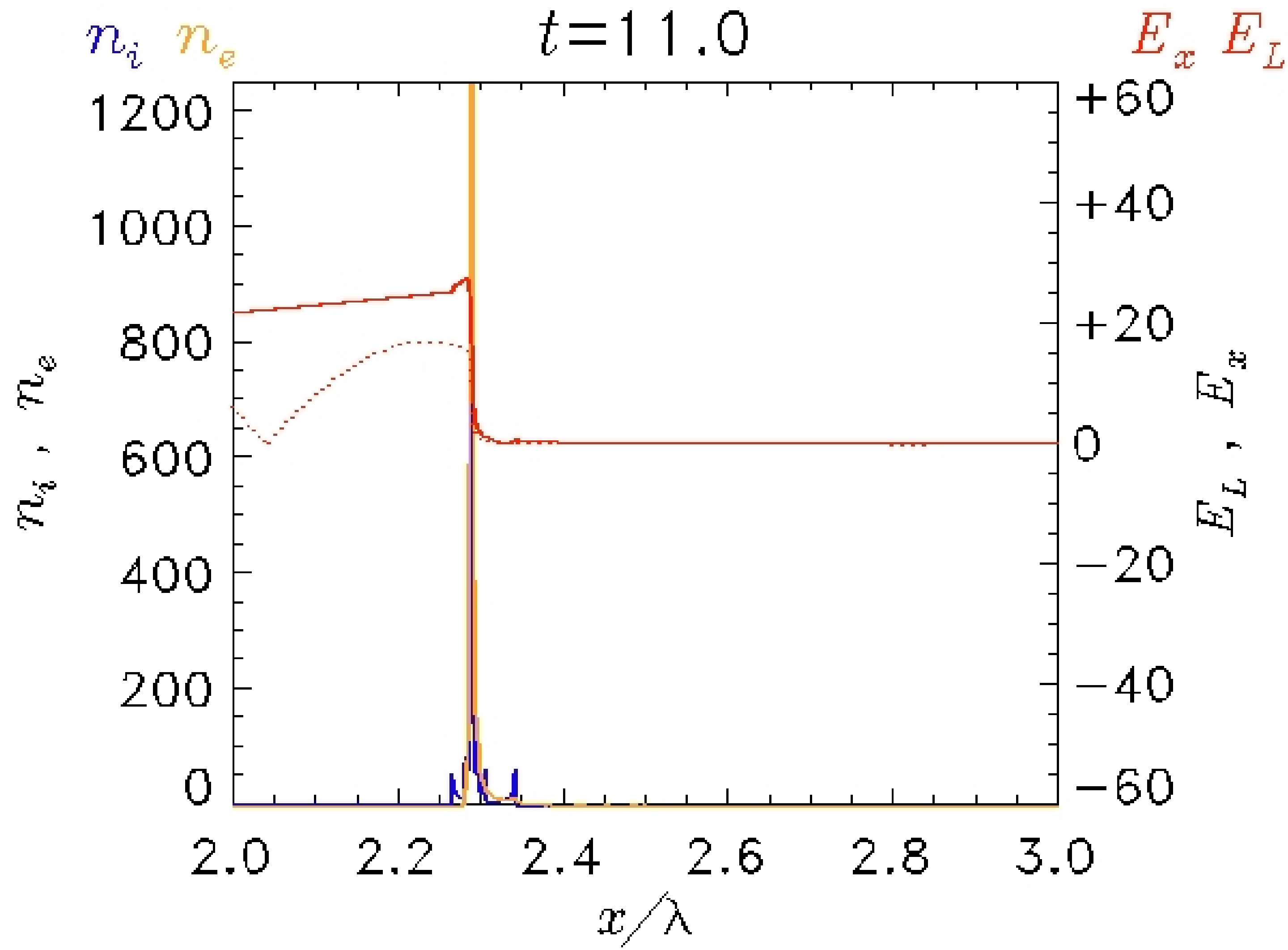

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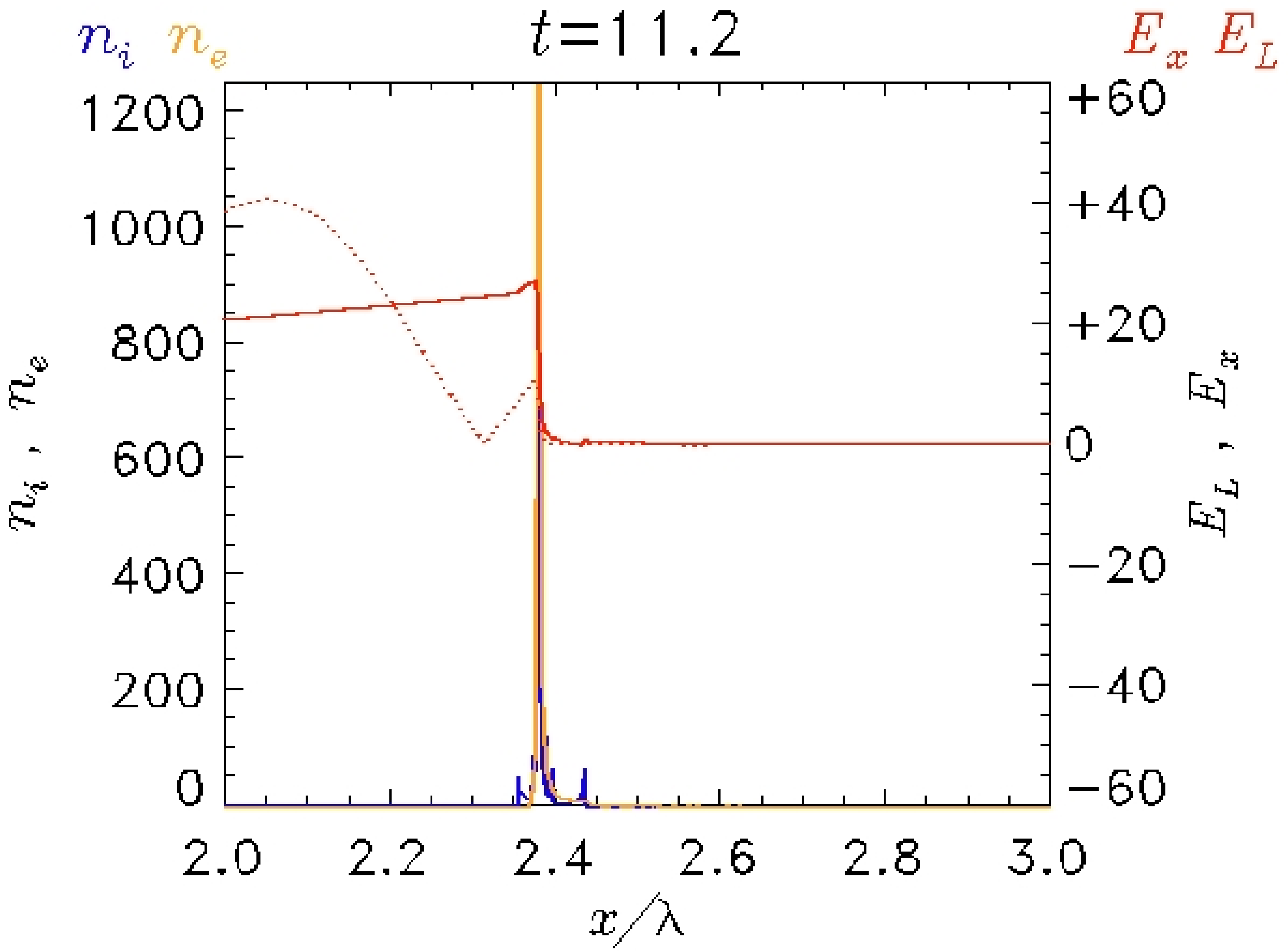

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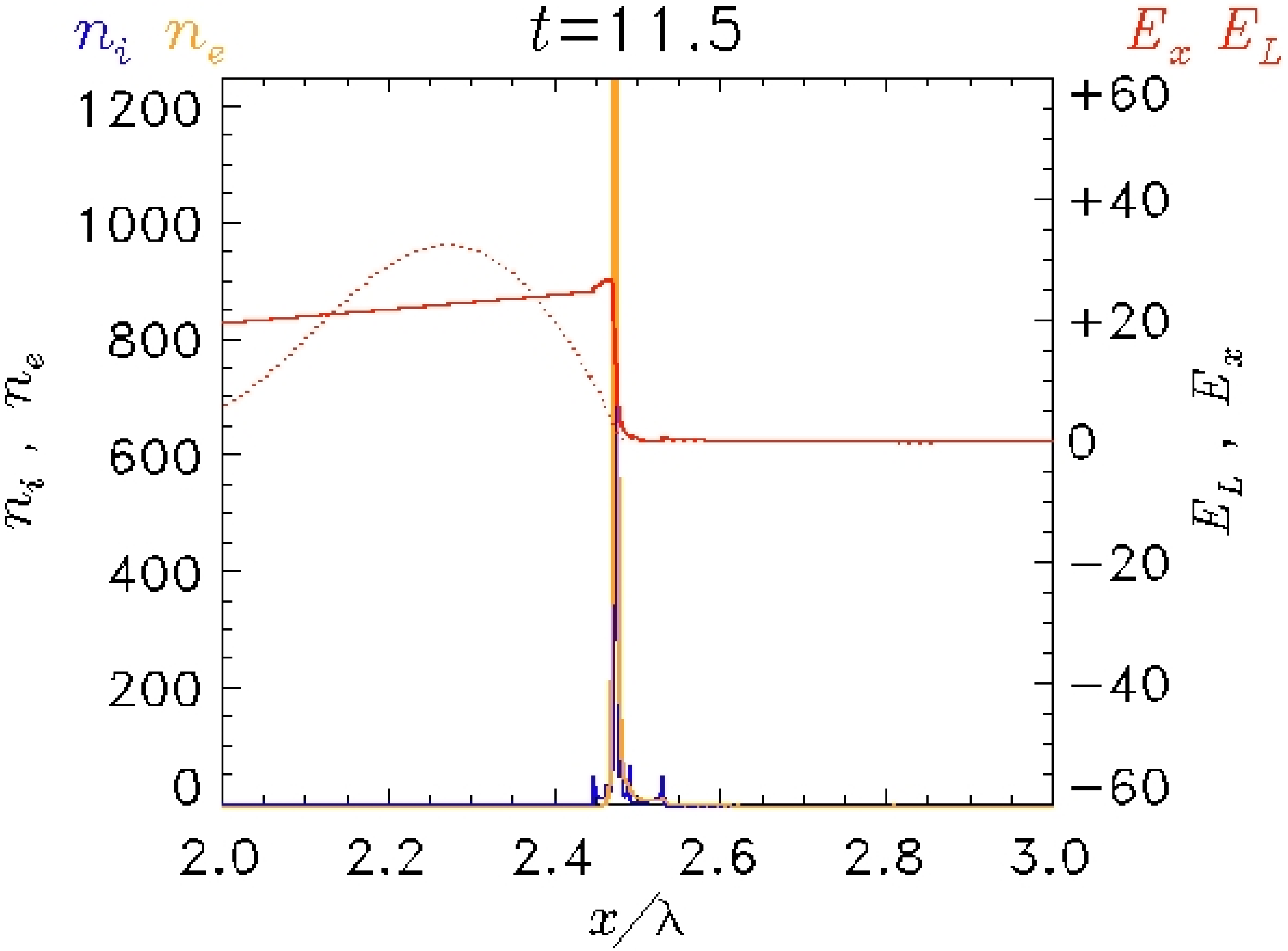

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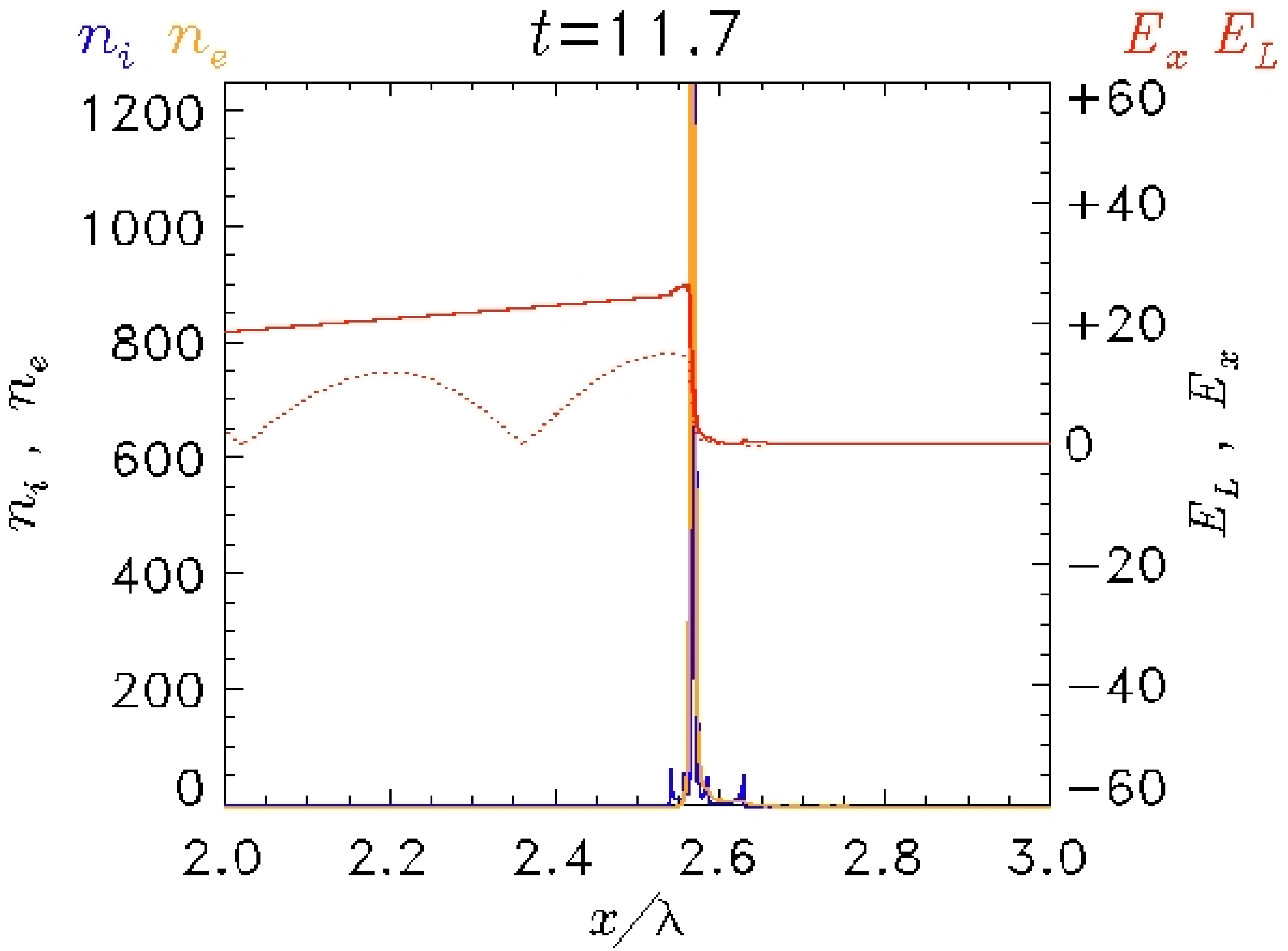

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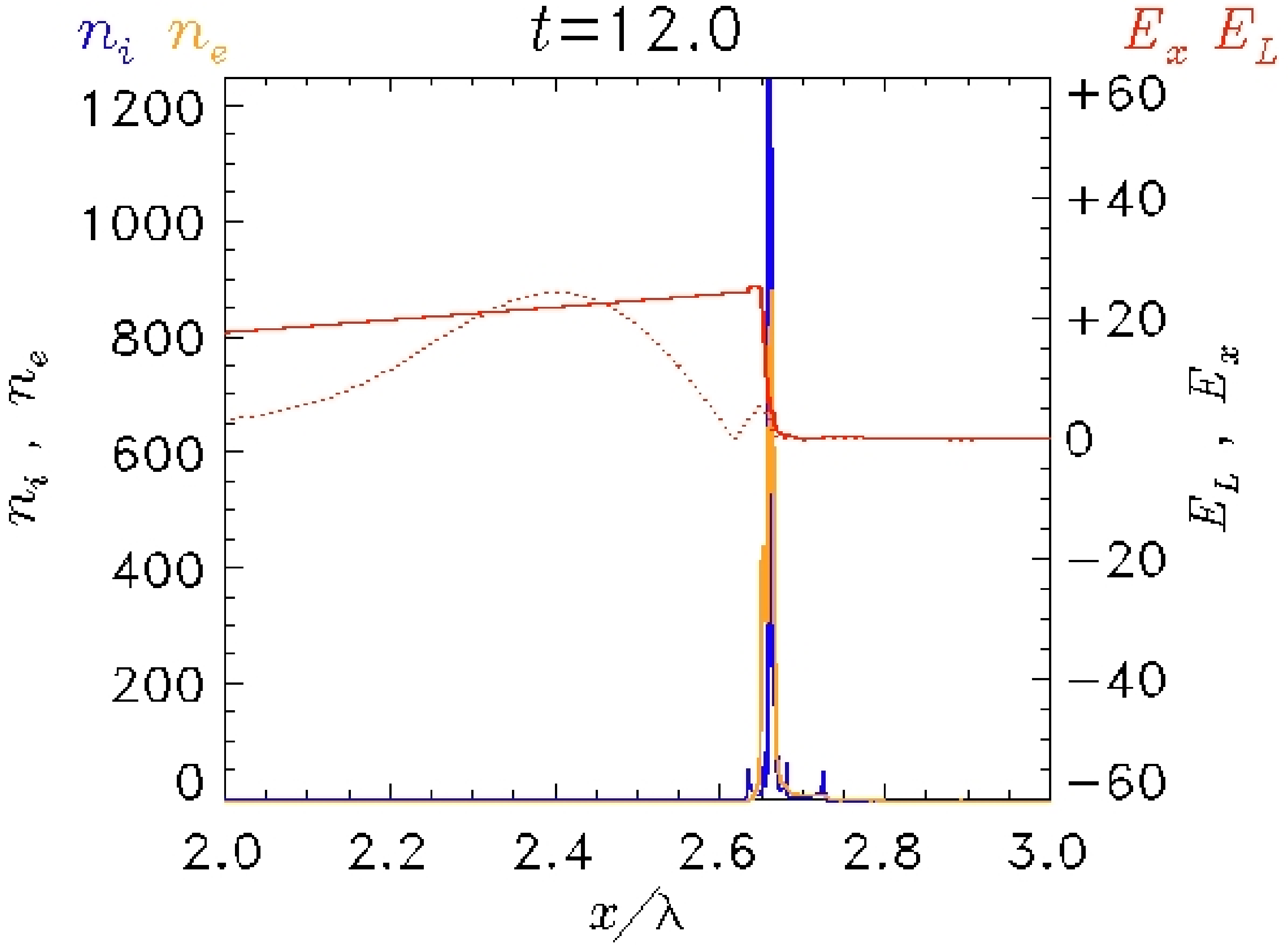

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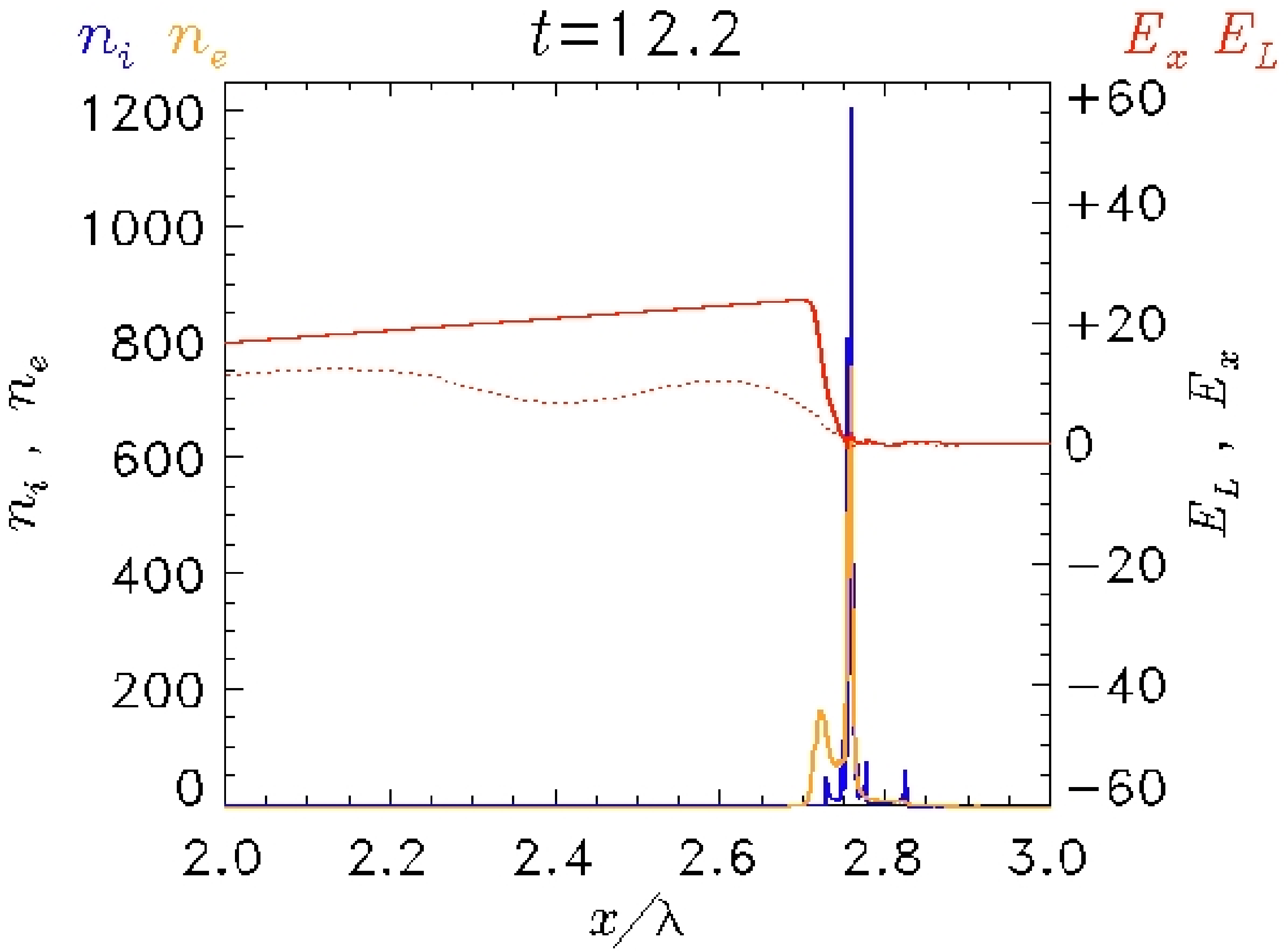

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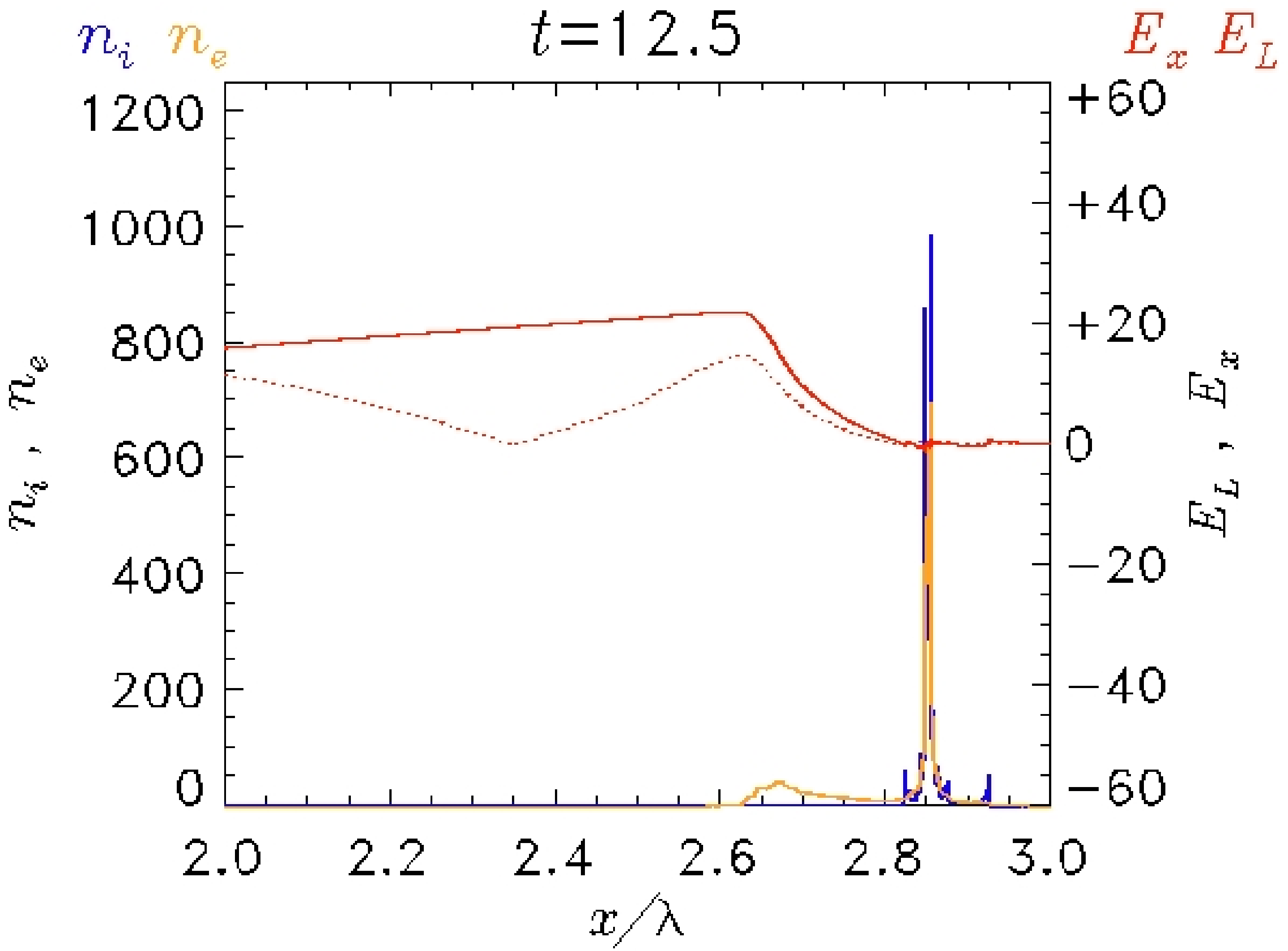

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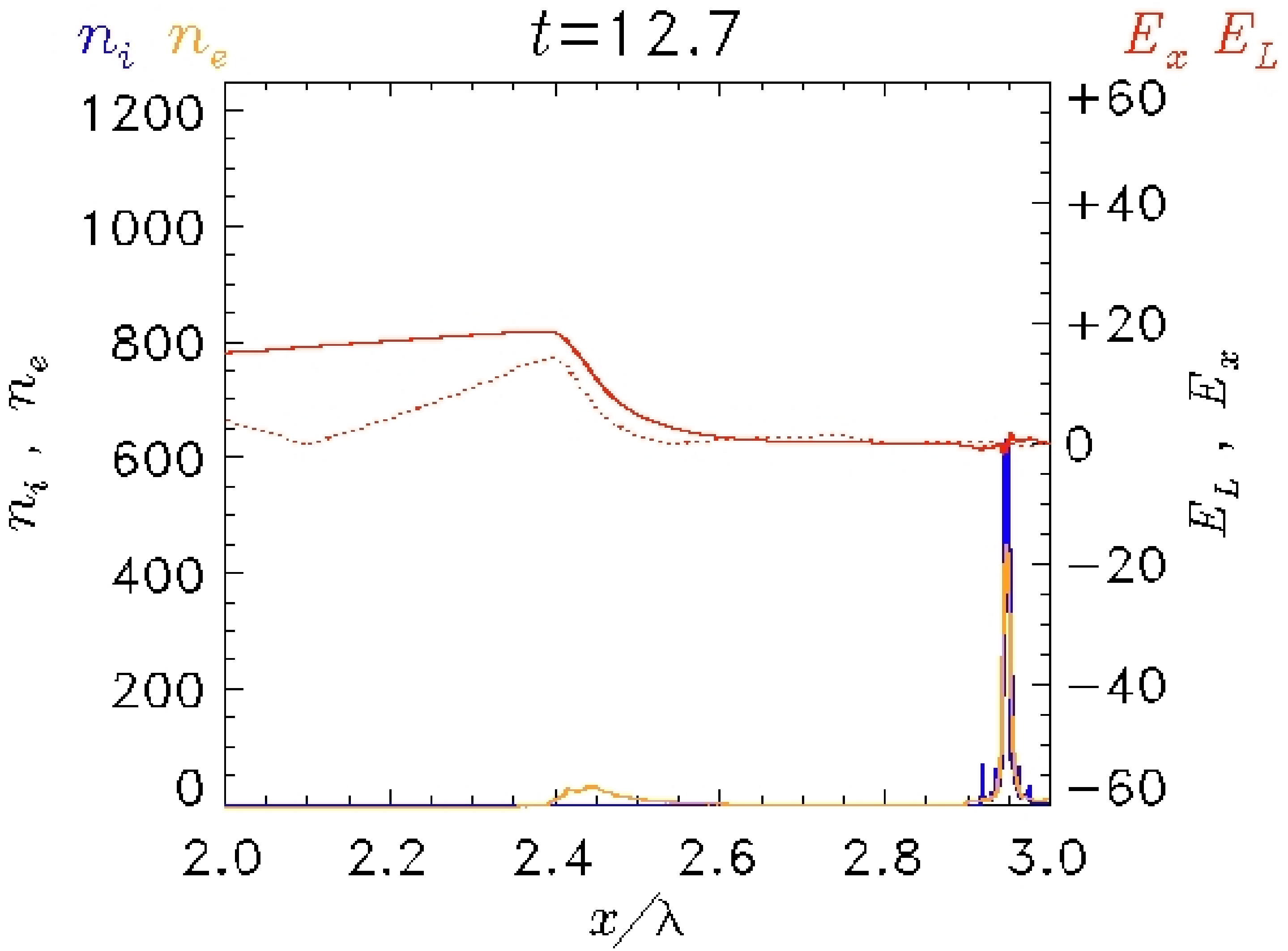

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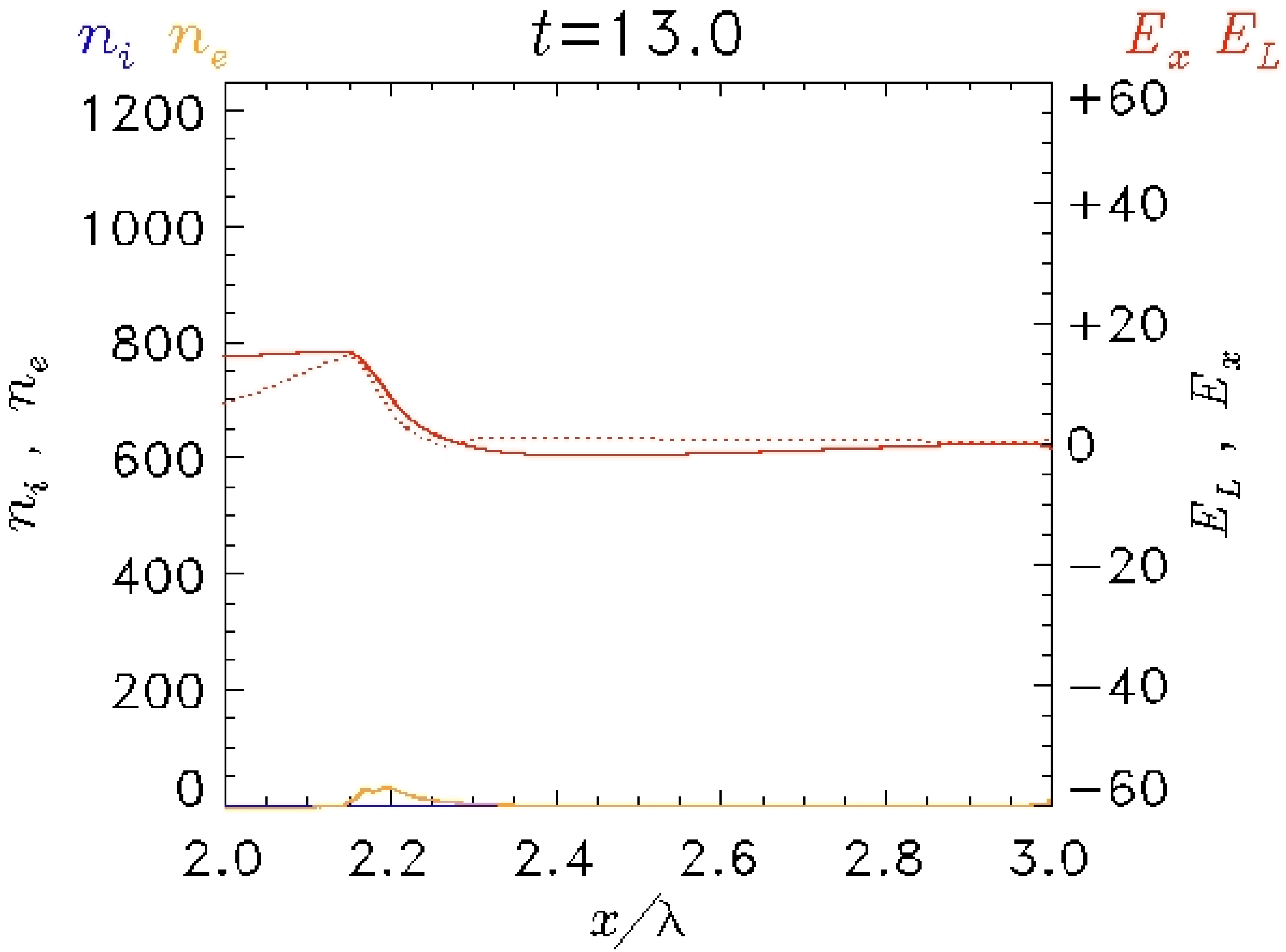

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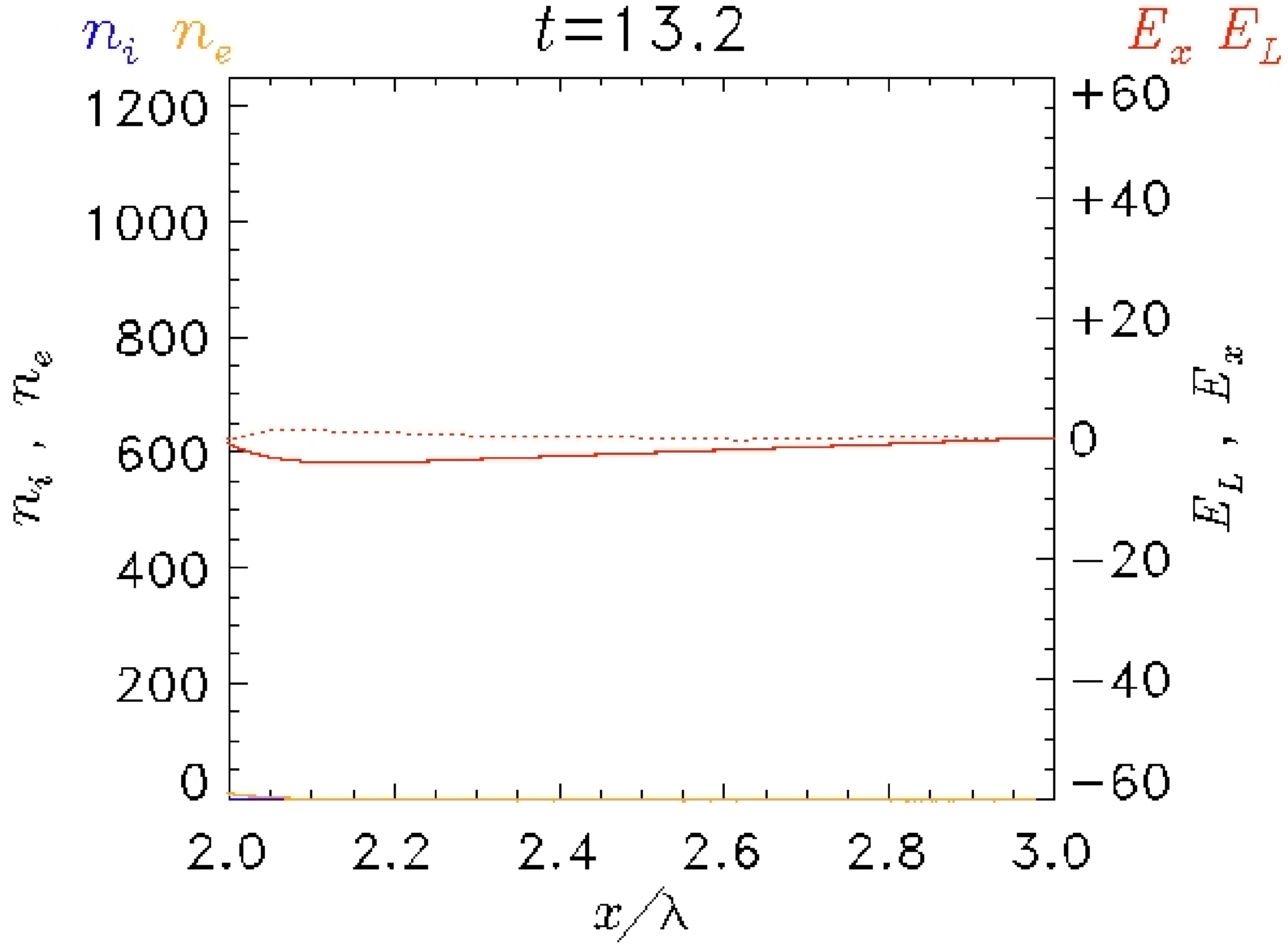

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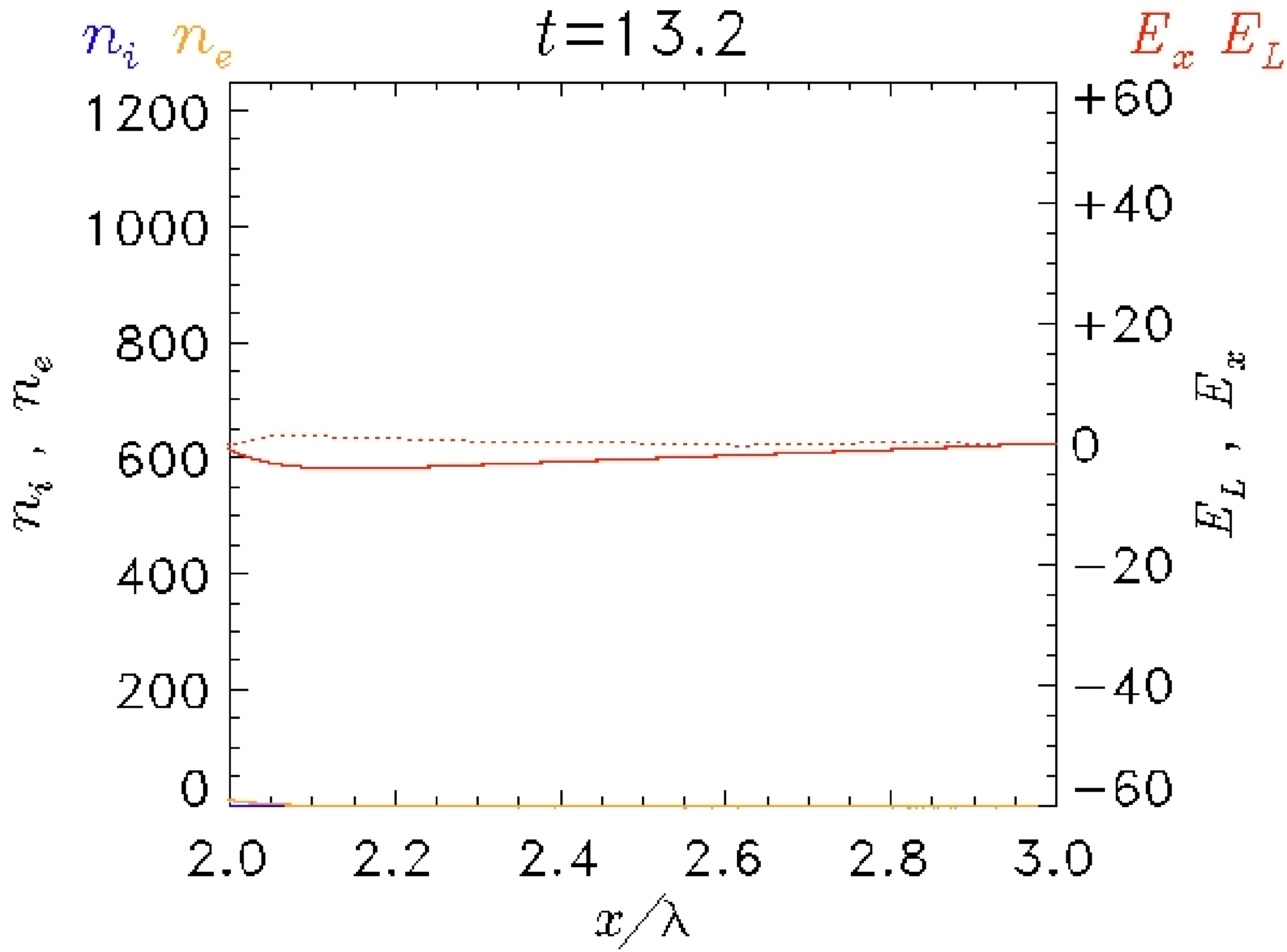


“Light Sail” RPA is not “front side” acceleration

The effective acceleration of only a thin rear layer implies that the scheme may work in double-layer targets (either manufactured or “natural”- hydrogen impurities on the surface) and might be used for the acceleration of protons

This may explain why the “transition to RPA dominance” was observed in numerical experiments for double layer targets

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

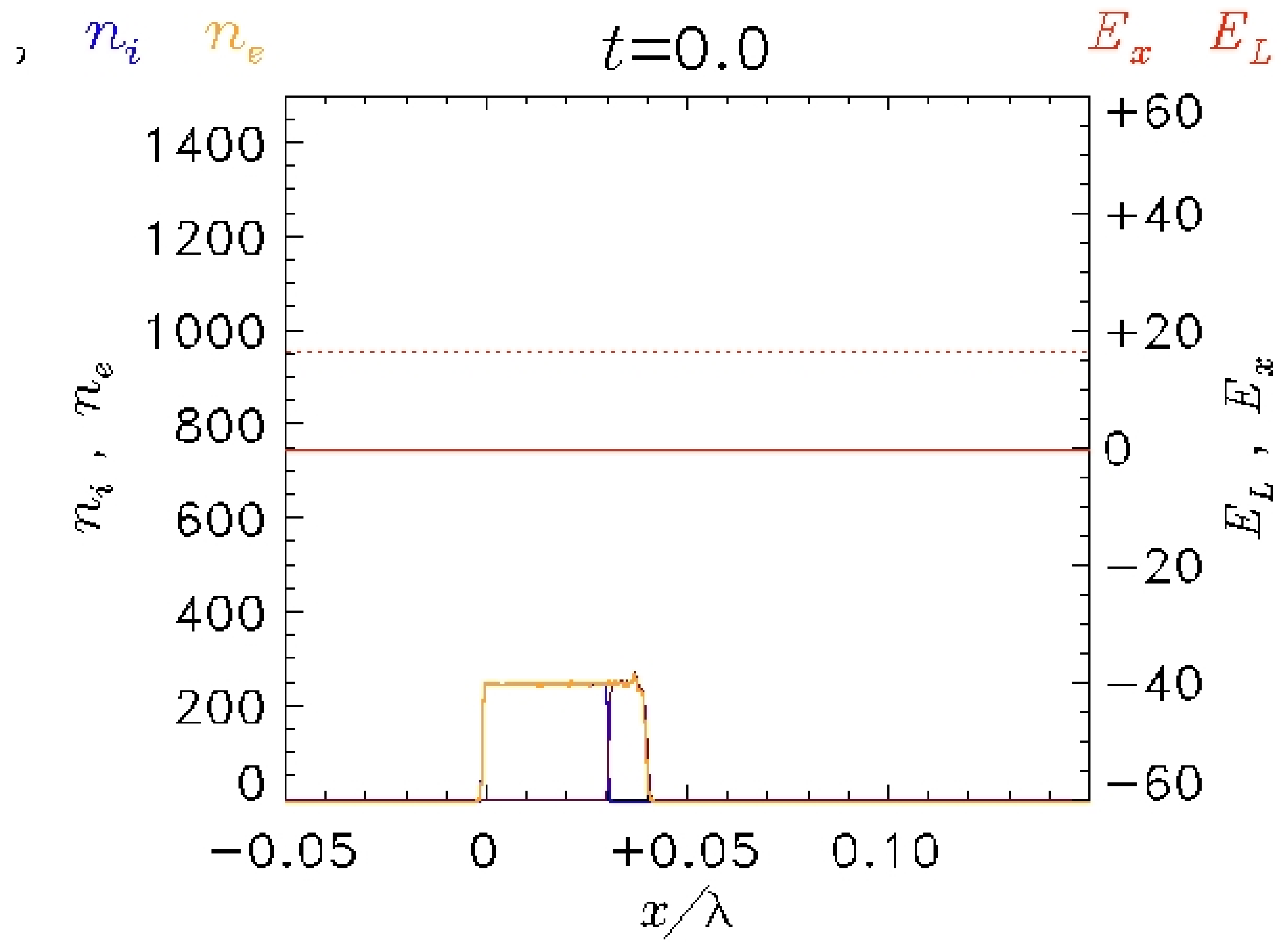
Such simulations were performed for linear polarization, showing a “transition to RPA dominance” at $I > 10^{23}\ \mathrm{W/cm^{-2}}$ (“Laser-Piston”) which has not a simple explanation (strongly relativistic effects probably need to be considered)

[T.Esirkepov et al., PRL **92**, 175003 (2004)]

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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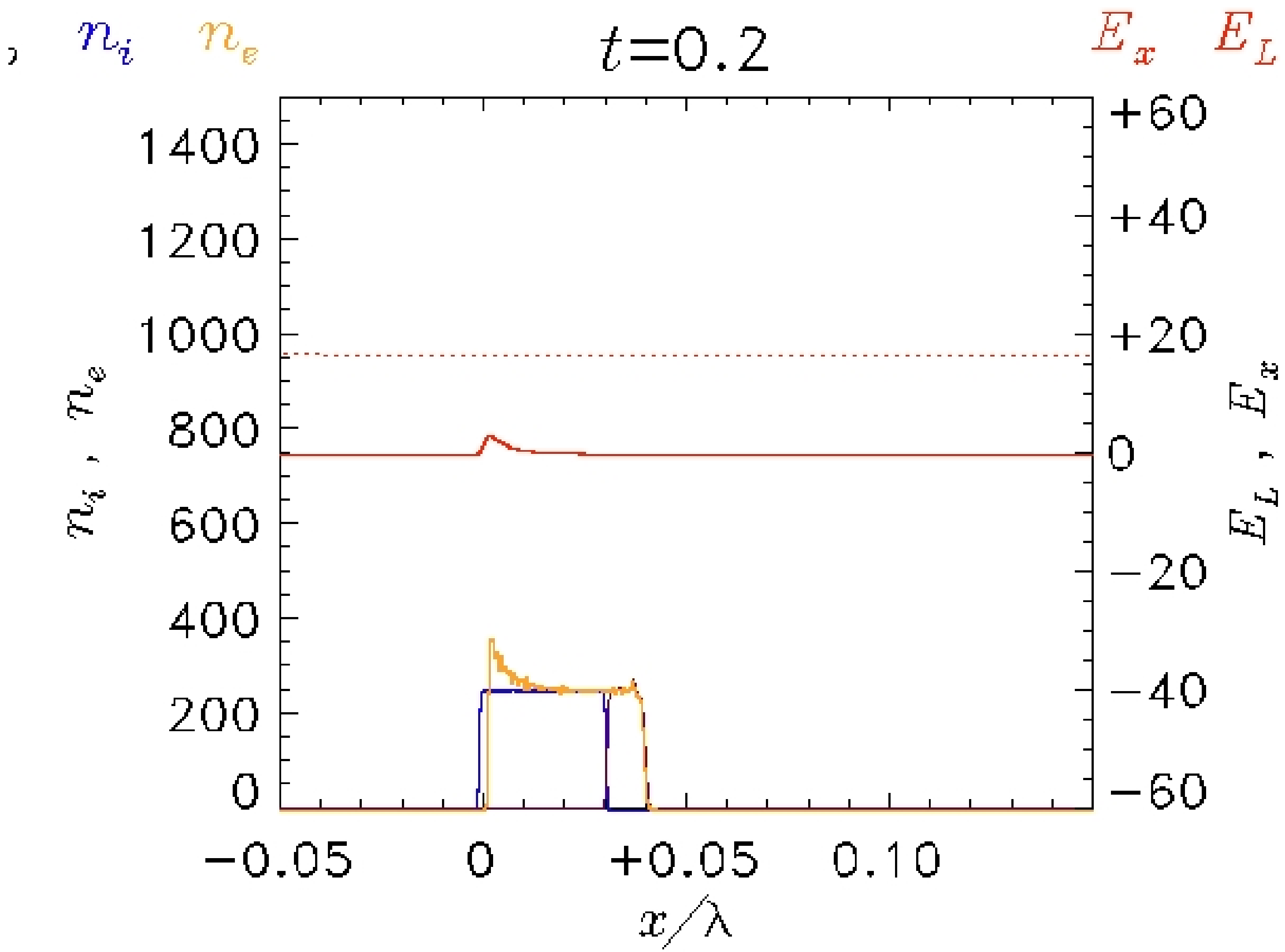

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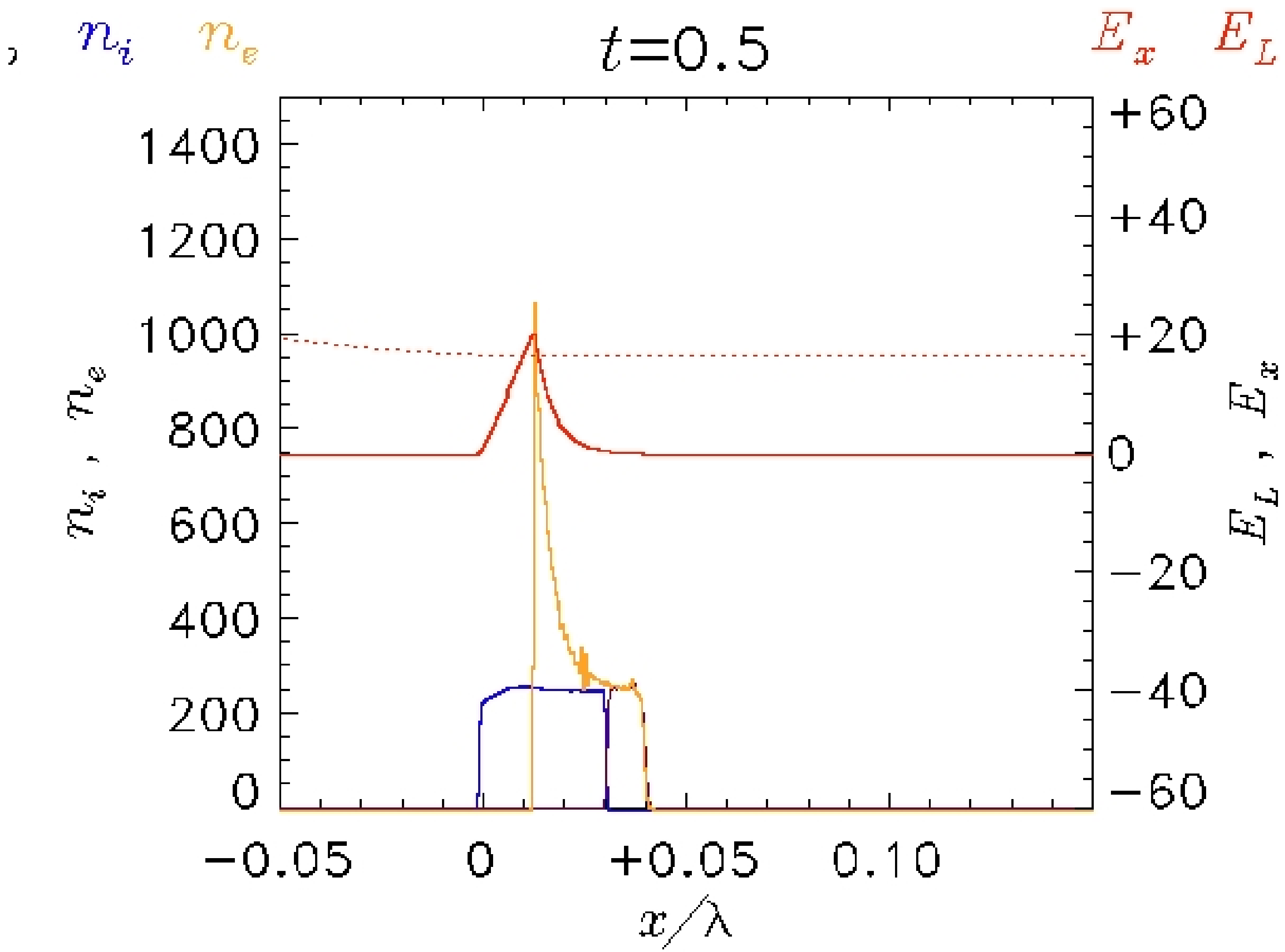

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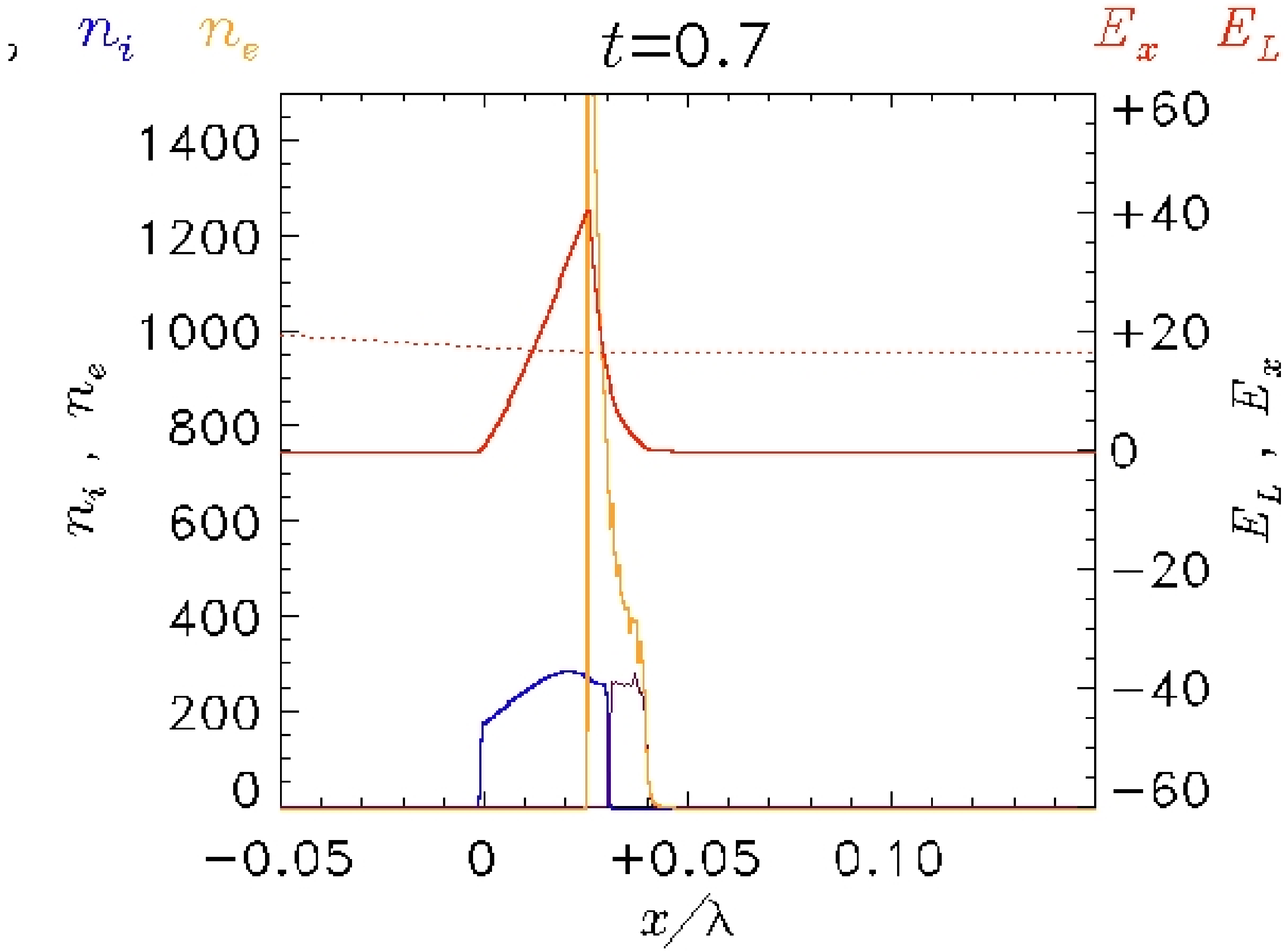

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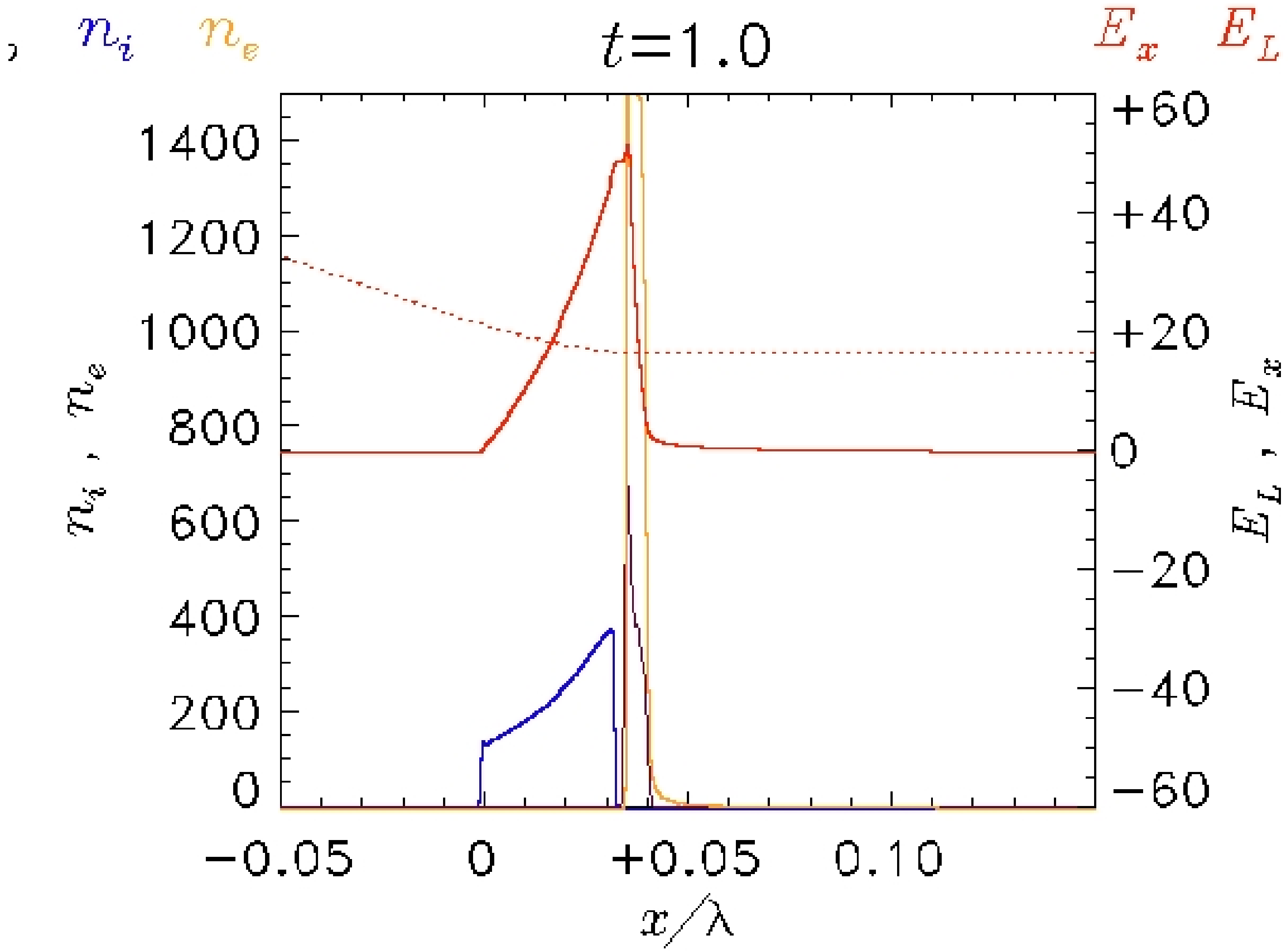

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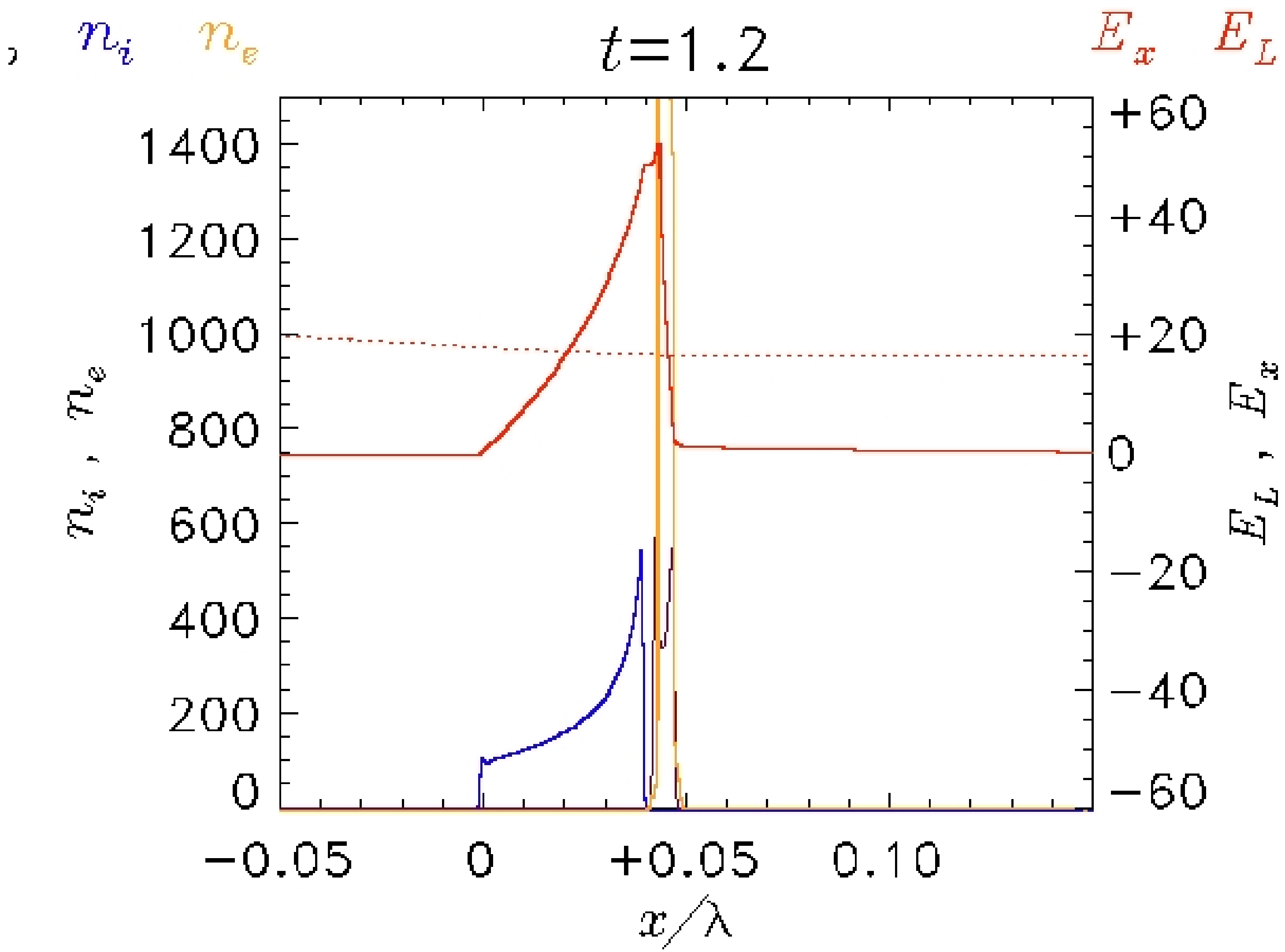

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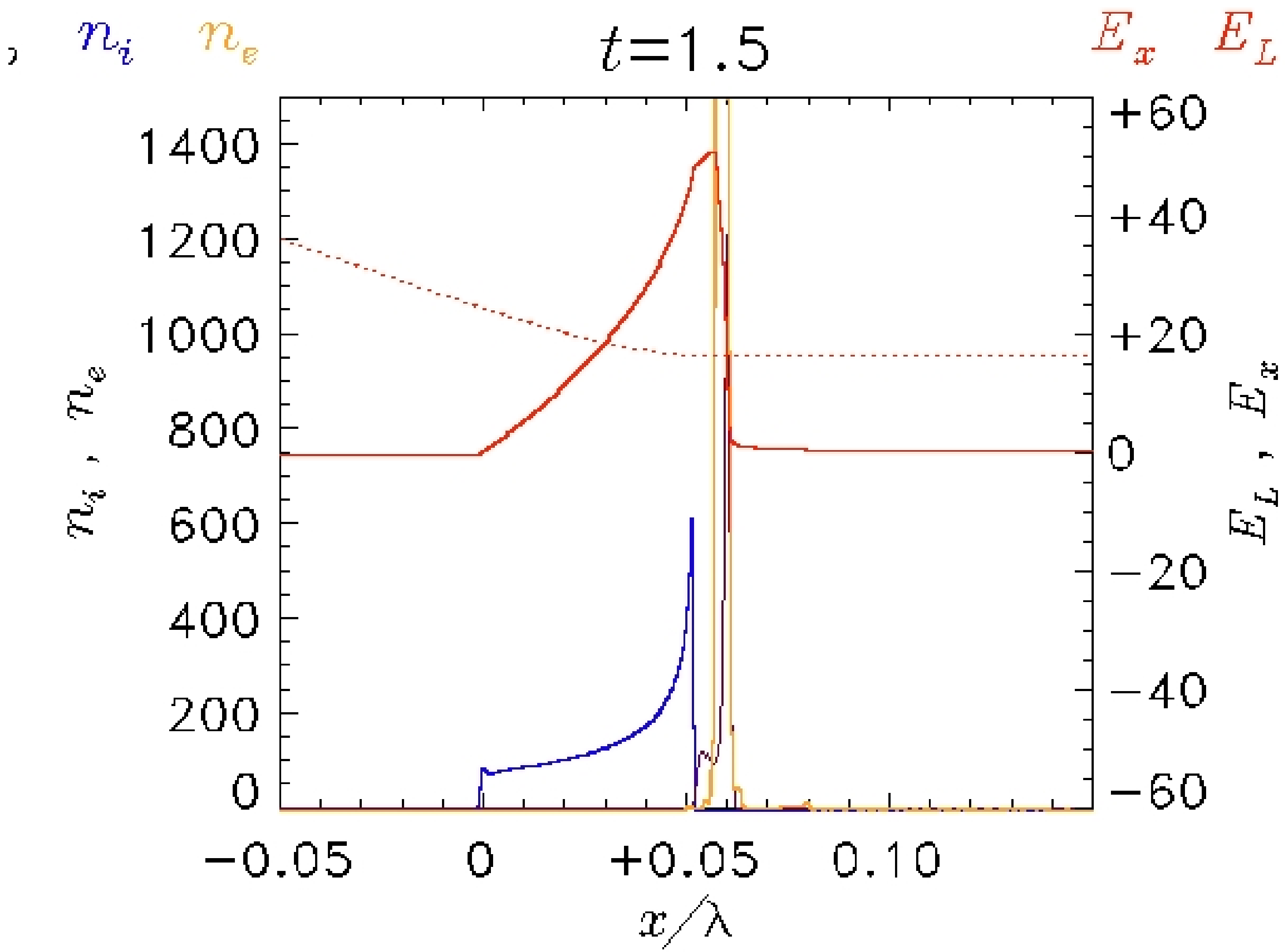

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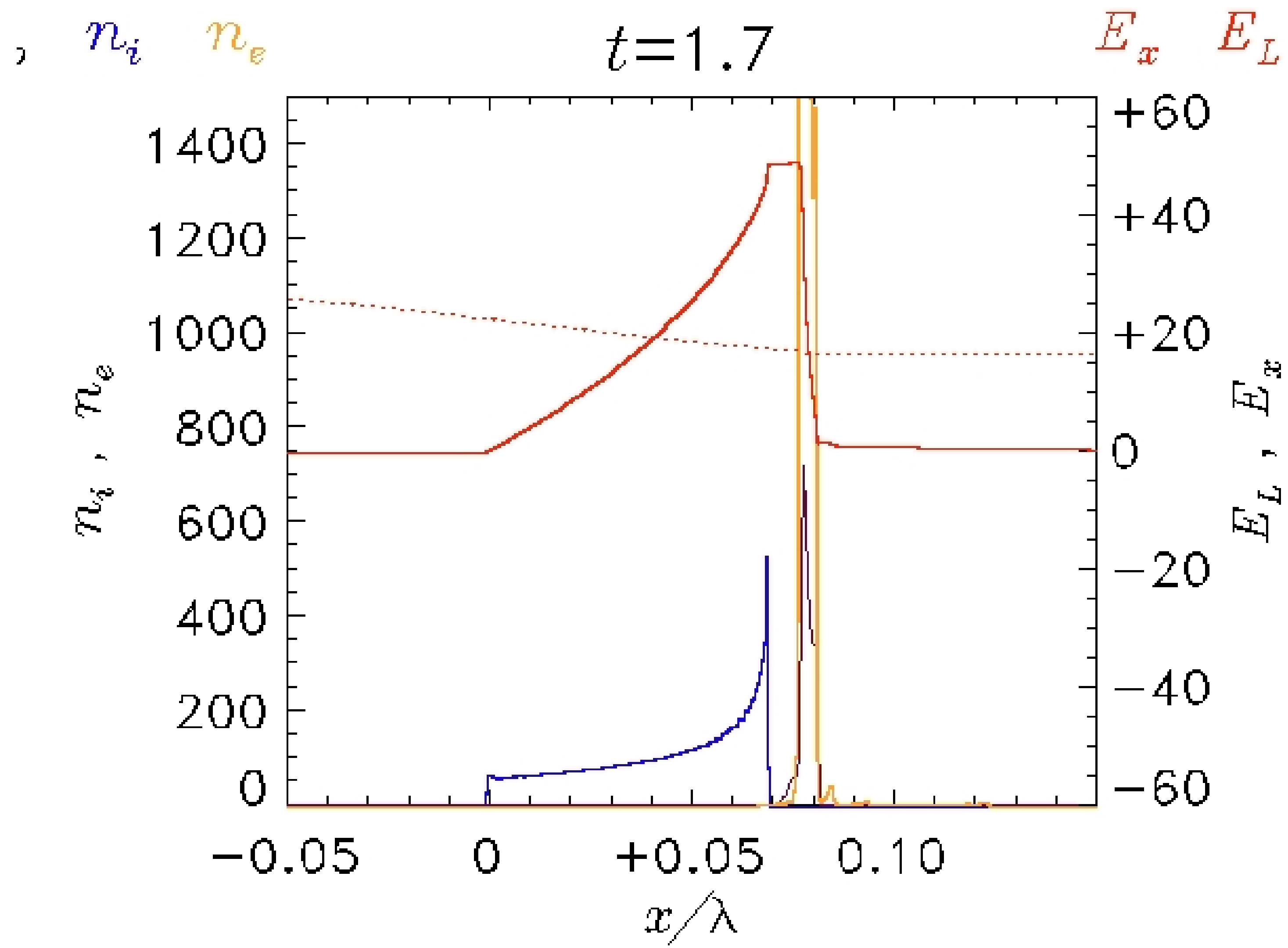

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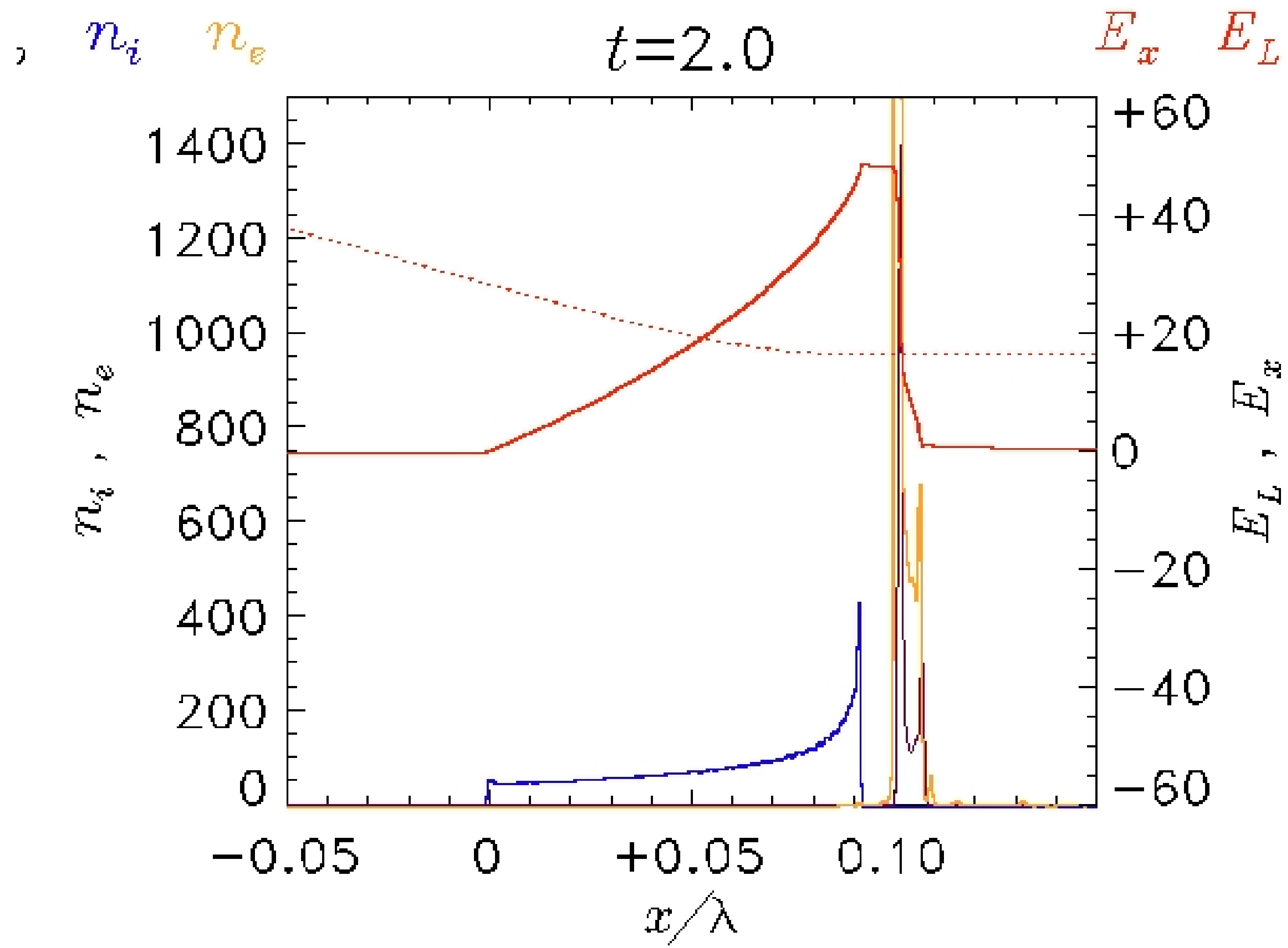

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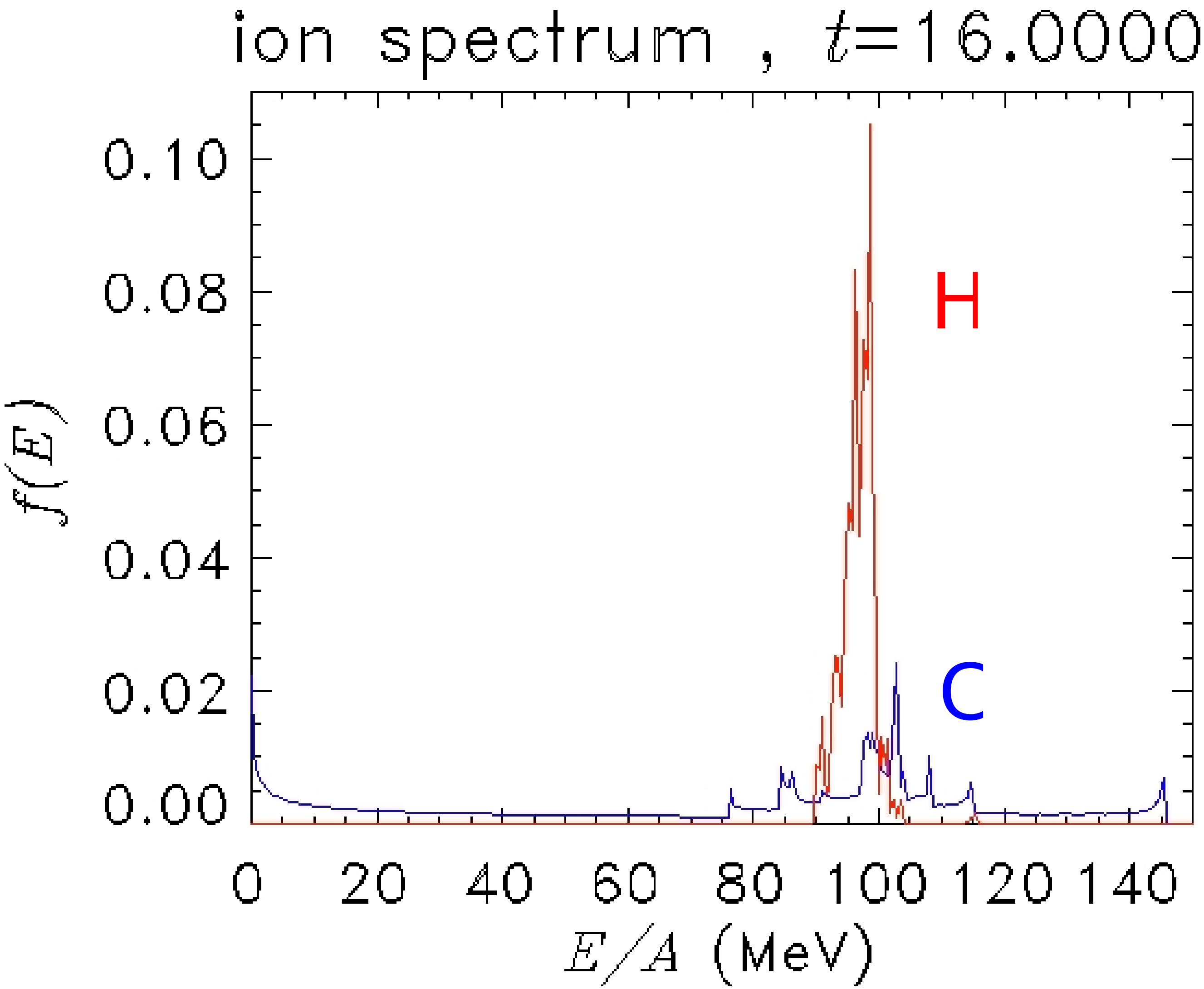

The effective mass of the foil

We are left with one question:

Why the foil velocity is given by the LS formula where the whole mass (≡thickness) of the foil must be used BUT only a thinner, lower mass "foil" is accelerated?

Energy stored in the electrostatic field E_x :

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

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

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

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

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

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Stored electrostatic energy ≡ inertial mass

total mass=
accelerated ions mass + "electrostatic mass" =
initial mass of the foil

the effective conversion into ion energy $< 2\beta/(1+\beta)$

A.Macchi, S.Veghini, F.Pegoraro, arXiv:0905.2068

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Conclusions

- Hole boring RPA:

  - more “robust”
  - less favorable scaling
  - preplasma control may improve the energy spectrum
  - interesting for next-future few-cycle interactions and if suitable “flowing”, moderate-density targets can be used

- Light Sail RPA:

  - (much) more challenging (ultra-high contrast pulse needed, flat-top profiles important...)
  - very attractive for energy and efficiency
  - revisited LS model accounts for most of the numerical observations
  - in principle suitable for double-layer targets and proton acceleration

This talk may be downloaded from
www.df.unipi.it/~macchi/talks.html