Radiation reaction effects on ultraintense laser-driven ion acceleration

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Outline

I/ The context

II/ Theoretical basis
- 2.1 Motion equations
- 2.2 Synchrotron radiation in a plasma

III/ Ion acceleration
- 3.1 Purely relativistic self-induced transparency regime
- 3.2 Hole boring regime

IV/ Conclusions

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Physical issues : exploration of new regimes

- **Intense synchrotron radiation sources**,
  Laser intensity requiered : I> 10^{23} W/cm^2

Di Piazza et al. PR.L **102**, 254802 (2009)
Thomas *et al,* PRX, **2**, 041004 (2012)

The **radiation reaction** (RR) can play an **important rôle** on the plasma dynamics for laser intensities **beyond 10^{22} W/cm²**.

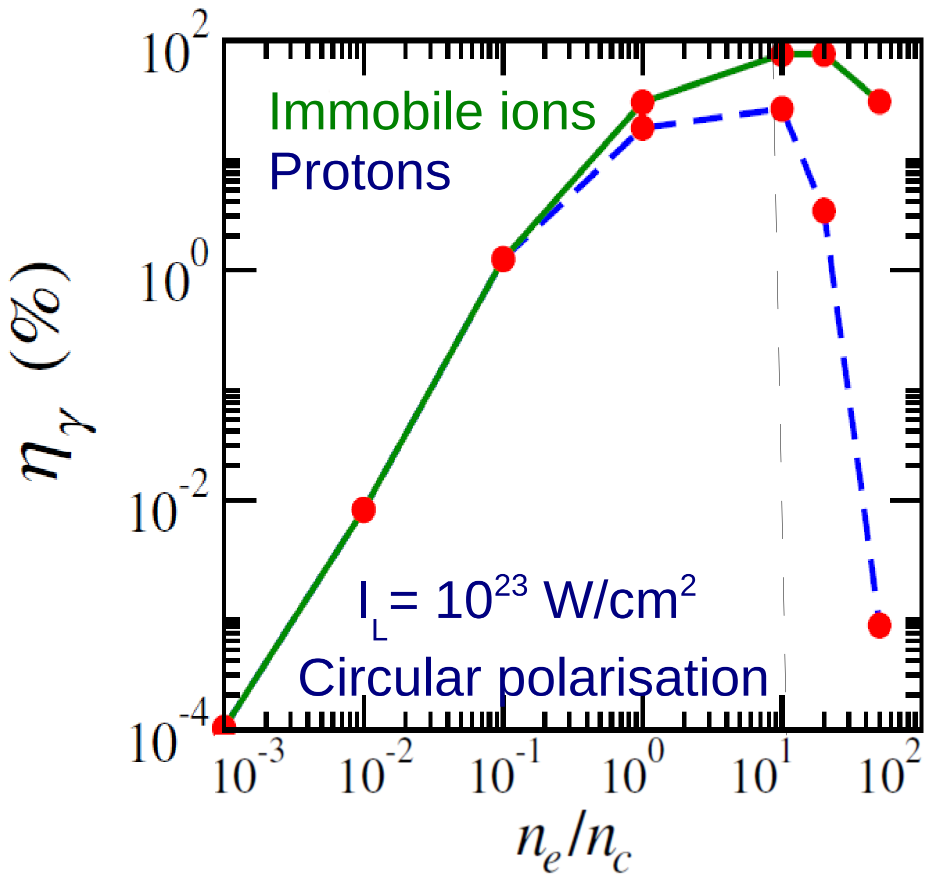
- **Ion acceleration**
  mono-energetics beams,
  small spreading ~ µm
  Laser intensity requiered I> 10^{22} W/cm^2

Esirkepov et al. PRL **92**, 17 (2004)
H. Daido et al., Rep. Prog. Phys., **75**, 056401 (2012)
A, Macchi et al. Rev. Mod. Phys., **85**, 751 (2013)

→ European **ELI** facility which be able to provide laser intensity peaks beyond 10^{24} W/cm² in near future.
Necessity to account for RR.

Purpose of the talk : Role of the radiation reaction (RR) on ion acceleration at ultra-high laser intensities

Interaction regimes where the RR could be important ?



R. Capdessus *et al*, PRL, **110**, 215003 (2013)

The radiated energy is important for $n_e = 10\, n_c$, implying $a_L \gg n_e/n_c$.

Study of the RR effects in **the relativistic self-induced transparency regime.**

We restrain our study to classical regimes where quantum effetcs are negligibles on ion acceleration.

II/ Theoretical basis

The Sokolov equations

$$\frac{d\mathbf{p}_e}{dt} = \mathbf{F}_{Le} \underbrace{- ec\,\boldsymbol{\delta\beta}_e \times \mathbf{B} - \gamma_e^2 \left(\boldsymbol{\delta\beta}_e . \mathbf{F}_{Le}\right) \boldsymbol{\beta}_e}_{\mathbf{F}_{\text{rad}}}$$

$\mathbf{F}_{Le} = -e\left(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}\right)$ Lorentz force

$\mathbf{F}_{\text{rad}}$ Radiation reaction force

$$\frac{d\mathbf{x}_e}{dt} = c\left(\boldsymbol{\beta}_e + \boldsymbol{\delta\beta}_e\right)$$

$$\boxed{\boldsymbol{\delta\beta}_e} = \frac{\tau_r}{m_e c} \frac{\mathbf{F}_{Le} - (\mathbf{F}_{Le} . \beta_e)\boldsymbol{\beta}_e}{1 + \frac{\tau_r}{m_e c^2}(\mathbf{v}_e . \mathbf{F}_{Le})}$$

- Conserves the 4-vector energy-momentum such as $p^2=m^2c^2$ [1].
- Simpler write of the radiation reaction force than the Landau-Lifshitz model.
- Easy implementation in PIC code.
- It has been implemented in the code PICLS [2].

[1] : I. Sokolov, JET P., 2009, Vol. ***109****, No. 2*
[2] : R. Capdessus et al. PRE, ***86****, 036401 (2012)*

Synchrotron radiation

Radiated power by one electron

$$\frac{d^2 P_r}{d\omega d\boldsymbol{\Omega}} = \gamma_e^2 \frac{\tau_r}{m_e} \mathbf{F}_{Le}^2 \left(1 - \cos^2 \psi \beta_e^2\right) \boldsymbol{\delta} \left(\boldsymbol{\Omega} - \frac{\mathbf{p}_e}{\|\mathbf{p}_e\|} \right) S \left(\frac{\omega}{\omega_{cr}} \right)$$

Electron plasma, radiated intensity per volum unit

$$\mathcal{W}_\gamma = \int_{\mathbb{R}^3} \int_0^{4\pi} \int_{\mathbb{R}+} f_e \frac{d^2 P_r}{d\omega d\boldsymbol{\Omega}} d\omega d\boldsymbol{\Omega} d\mathbf{p}_e$$

$$\omega_{cr} = \frac{3}{2} \gamma_e^3 \frac{\|\mathbf{p}_e \times \mathbf{F}_{Le}\|}{p_e^2}$$

Critical frequency

Assuming a Maxwell-Juttner distribution, it yields

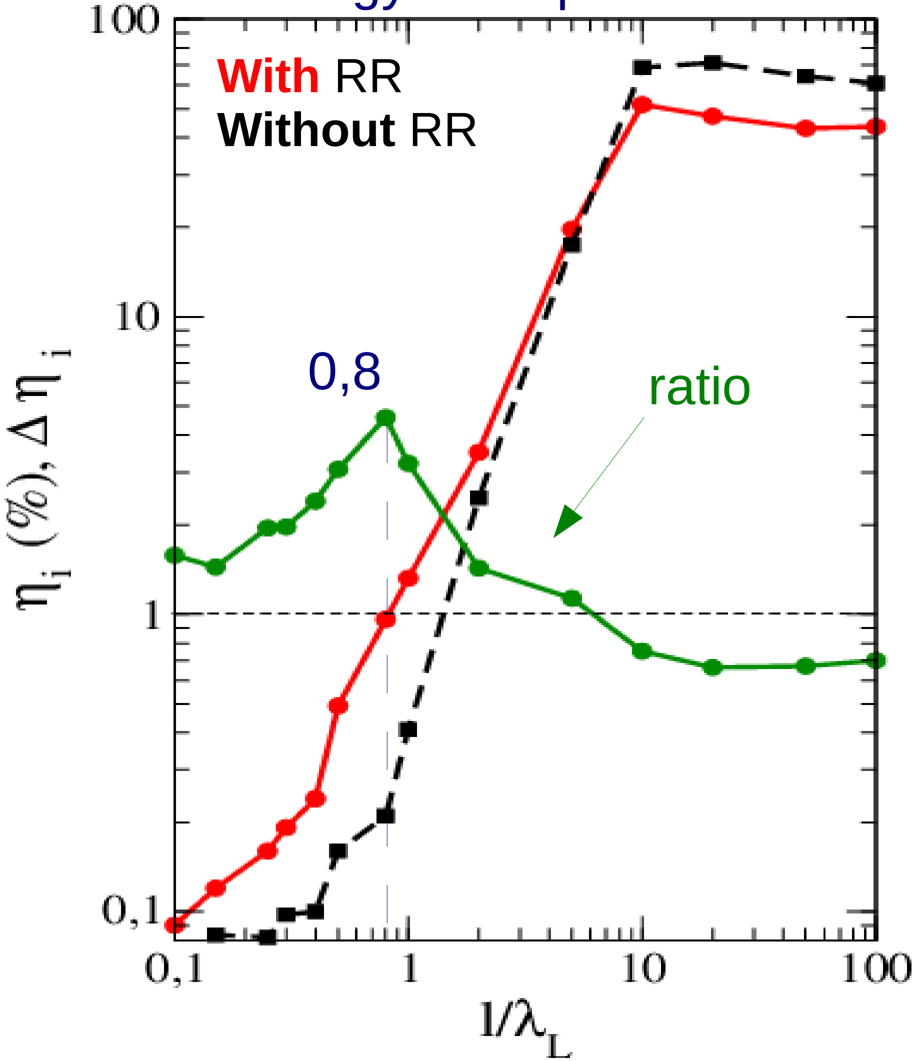
$$\mathcal{W}_\gamma \simeq 6 n_e \left(g + \alpha^2\right) a_L^4 \tau_r \omega_L m_e c^2 \omega_L$$

Temporal profile of the laser pulse (g)

Ratio of the electrostatic field to the laser field (α) → Collective effects

Results

Energy absorption to ions



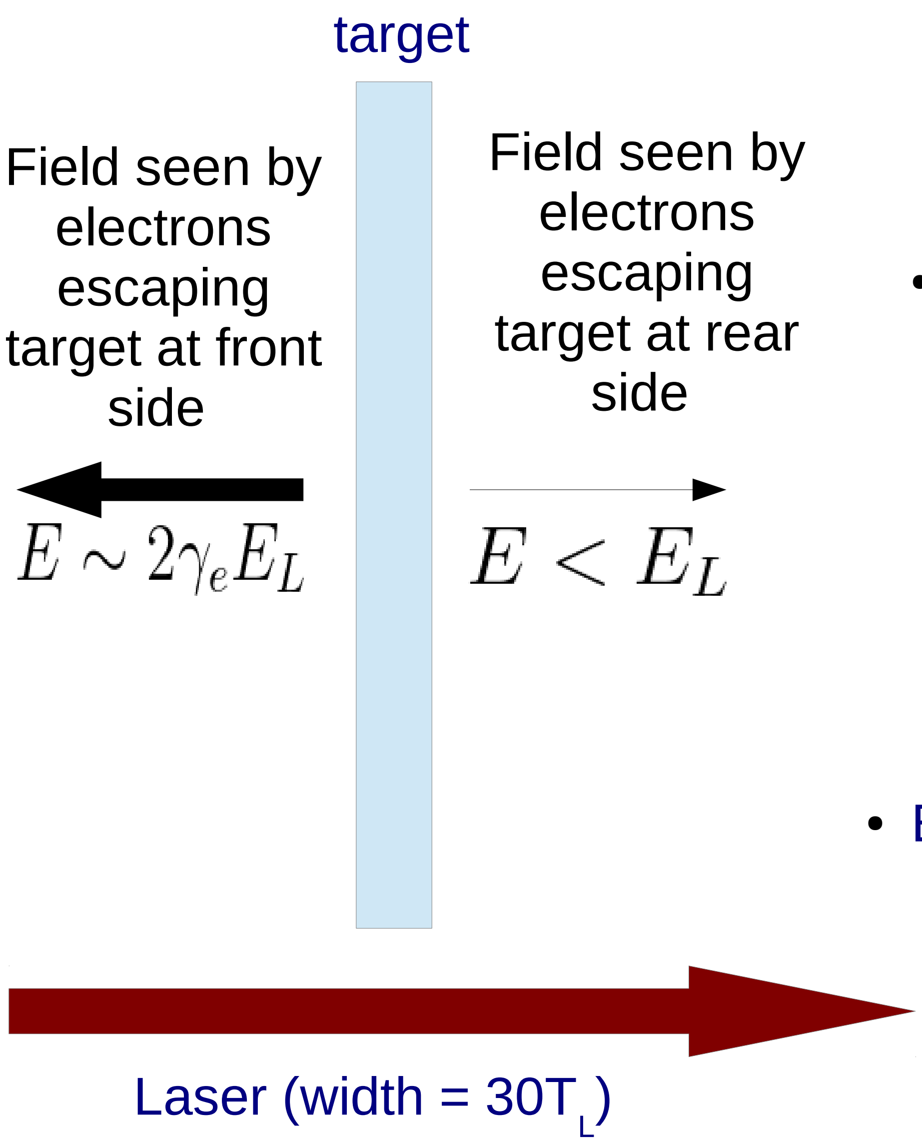
(target thickness)

I= 1.1*10[23] W/cm[2]
Circular polarisation
FWHM= 13 T_L

n_{e0}= 10n_c
Deuteron plasma

- The radiation impacts strongly the energy absorption to ions.
    - For thin target, radiation reaction enhances ion acceleration.
  - For thick target higher than 10 λ_L, the radiation reaction decreases the hole boring velocity.

3.1. Purely relativistic self-transparency induced regime



(1): $0 < t < 10\ T_L$

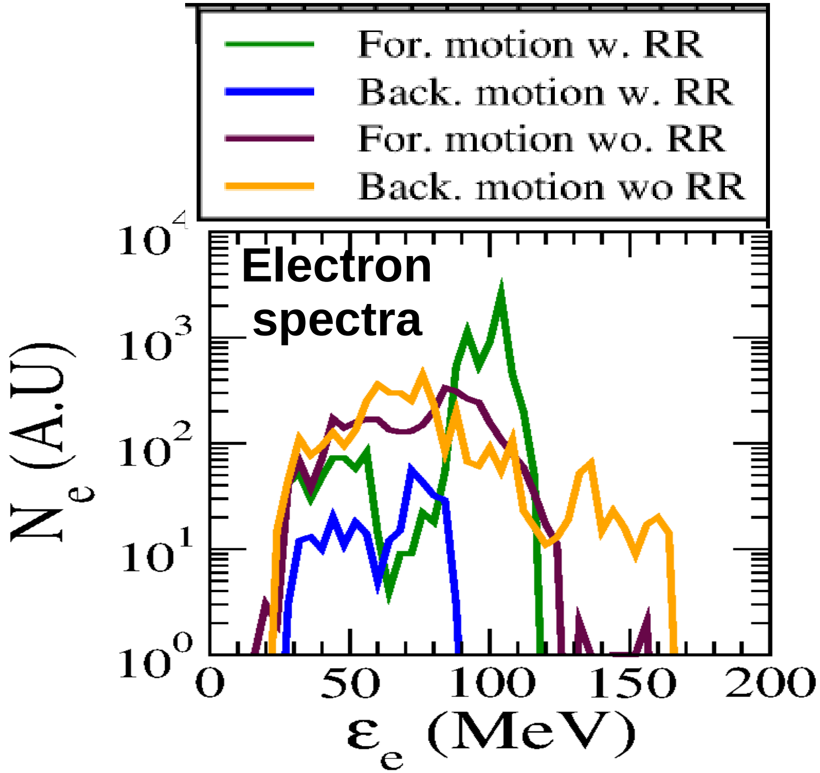
- **Modification of the target expansion.** Radiation reaction involves a non-symetric longitudinal expansion.
- Electrons getting a strong negative momentum are more cooled down than electrons propagating with the laser (relativistic Doppler effect).
- Electrons escaping at the front of the target are trapped by the electrostatic field which implies $E_x > 0$ for $10\ T_L < t < 30\ T_L$.

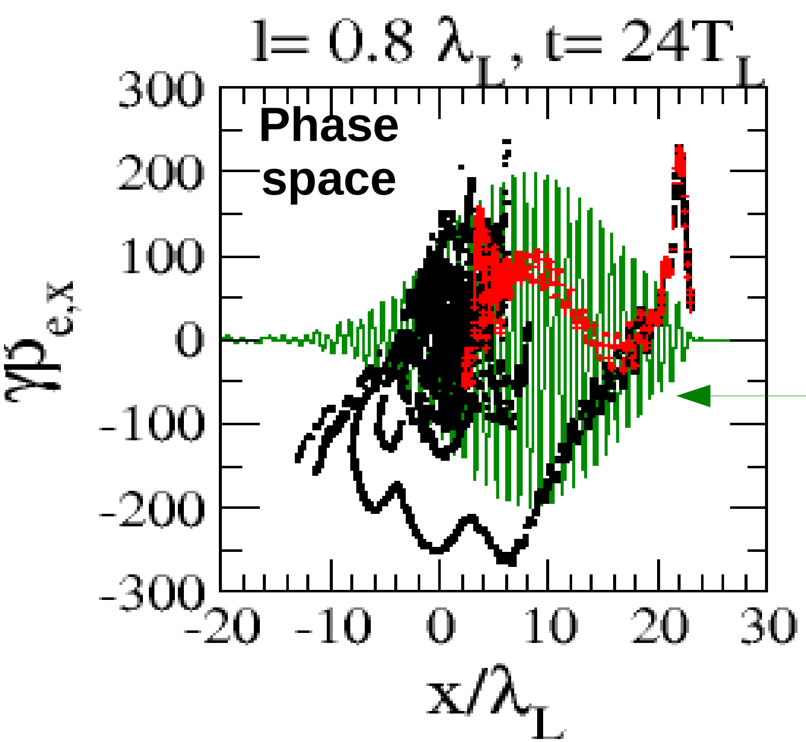
3.1 Purely relativistic self-transparency induced regime

(2): $10\ T_L < t < 30\ T_L$

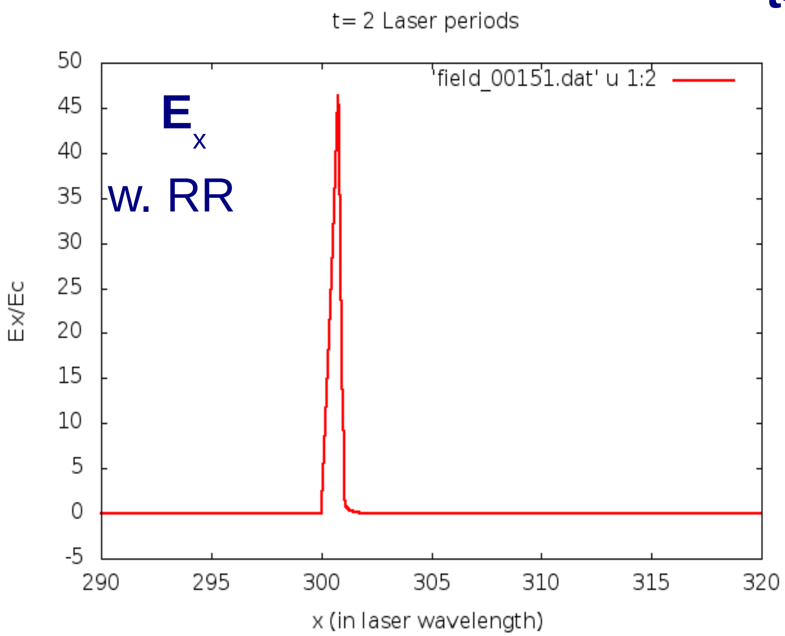
- Electrons escaping at the front of the target are trapped by the electrostatic field which implies $E_x > 0$

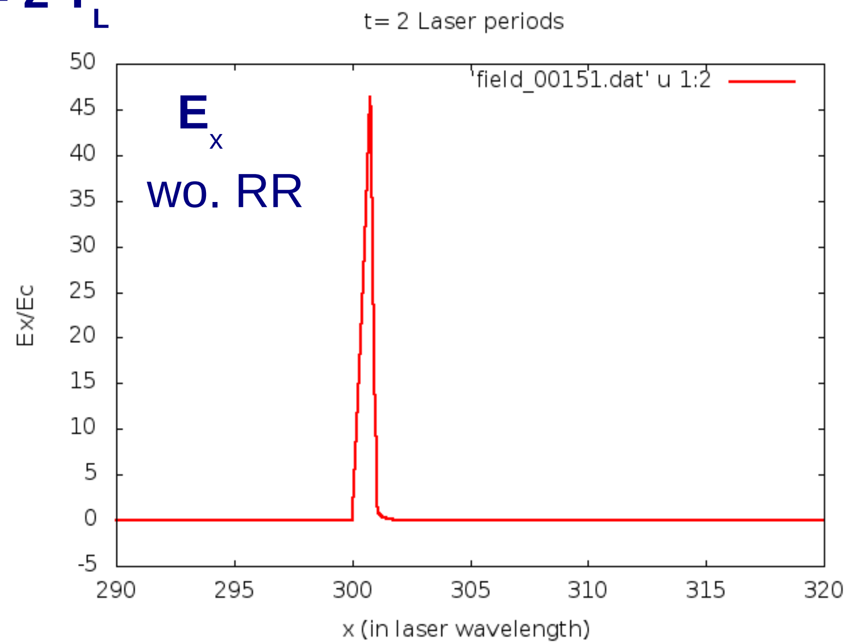
- It involves an electron phase space enhancing the electrostatic field at the rear of the target.





t= 2 T_L


t= 2 Laser periods
'field_00151.dat' u 1:2
E x
w. RR
Ex/Ec
x (in laser wavelength)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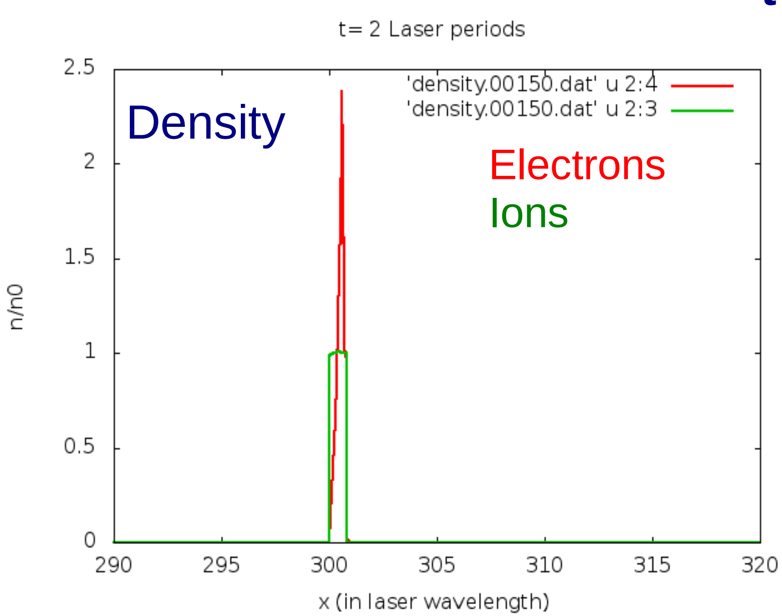
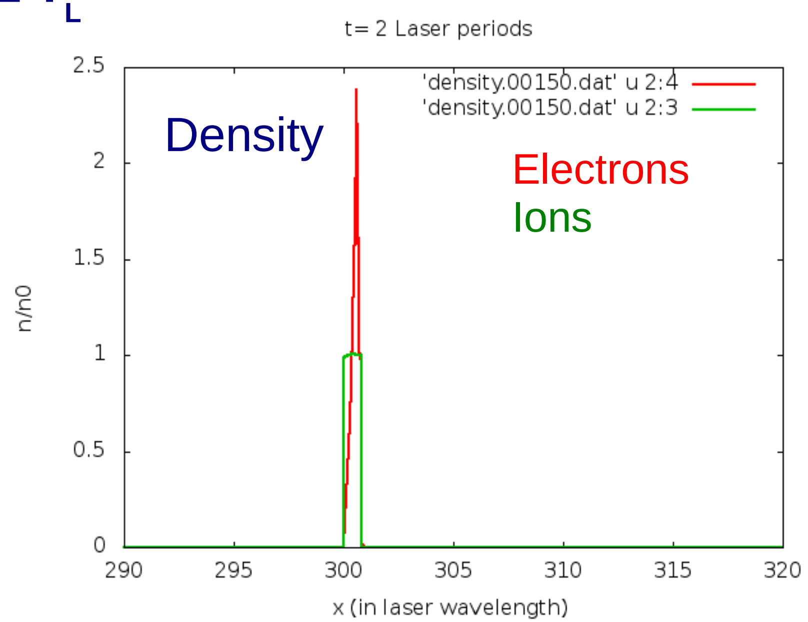
E x
wo. RR
Ex/Ec
x (in laser wavelength)

t= 2 T_L


t= 2 Laser periods
'density.00150.dat' u 2:4
'density.00150.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)


t= 2 Laser periods
'density.00150.dat' u 2:4
'density.00150.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

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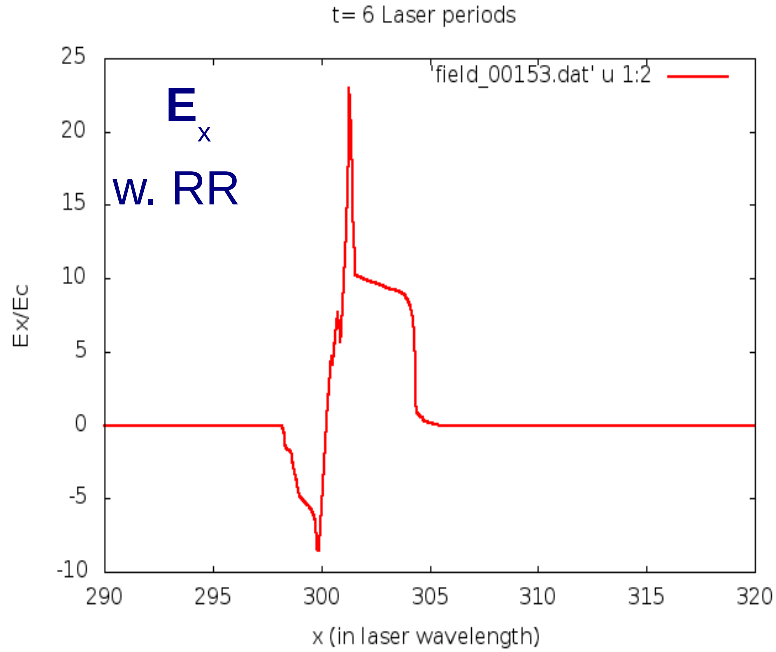
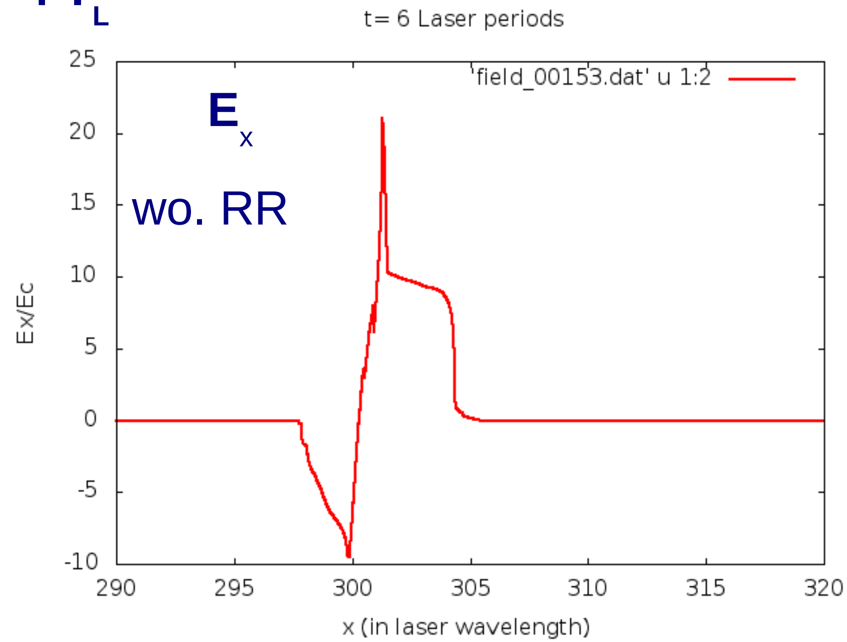
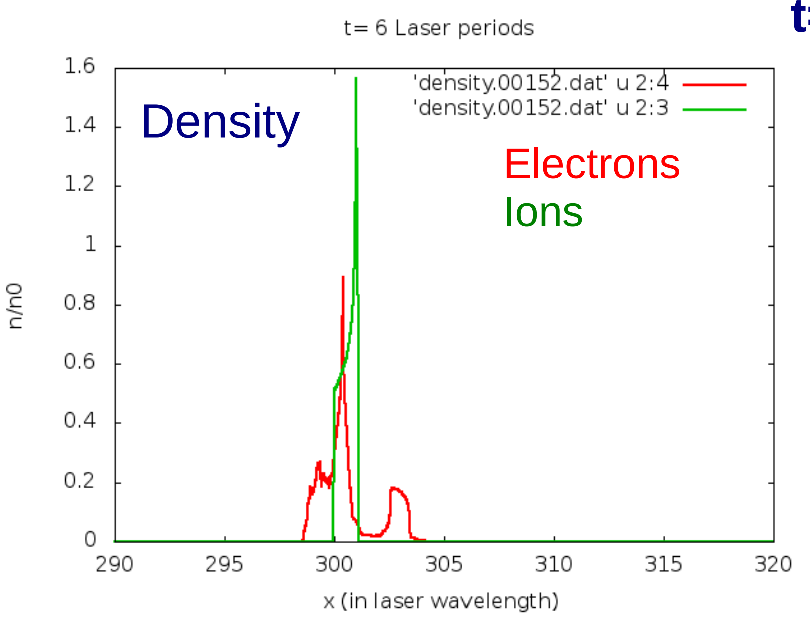
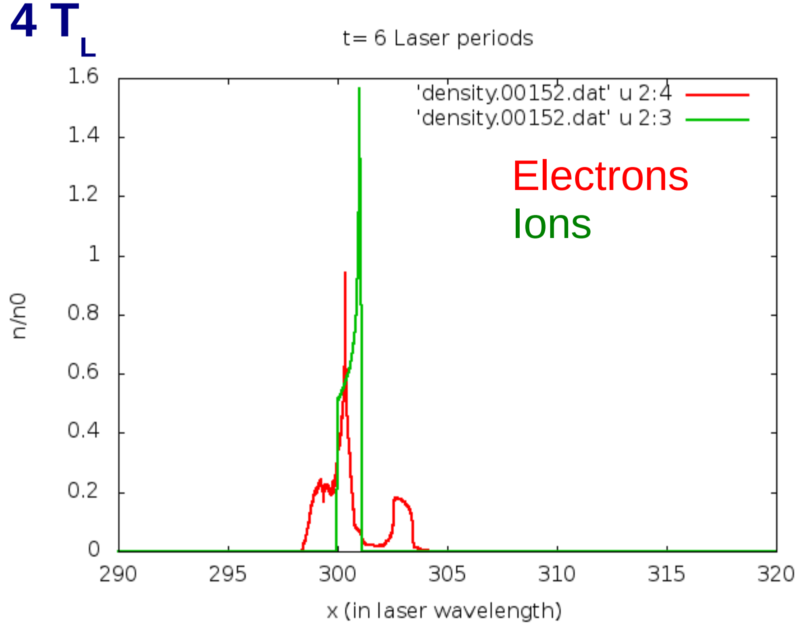
$t = 4\ T_L$



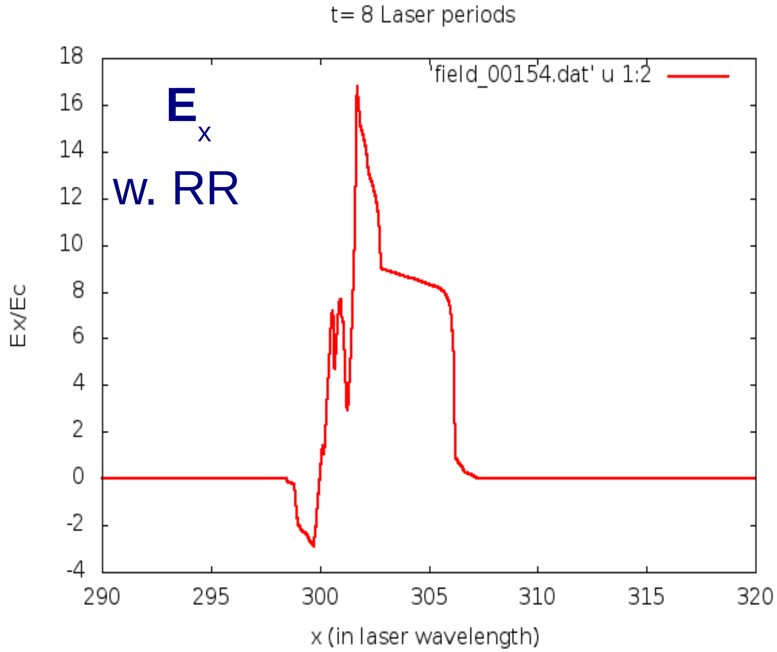


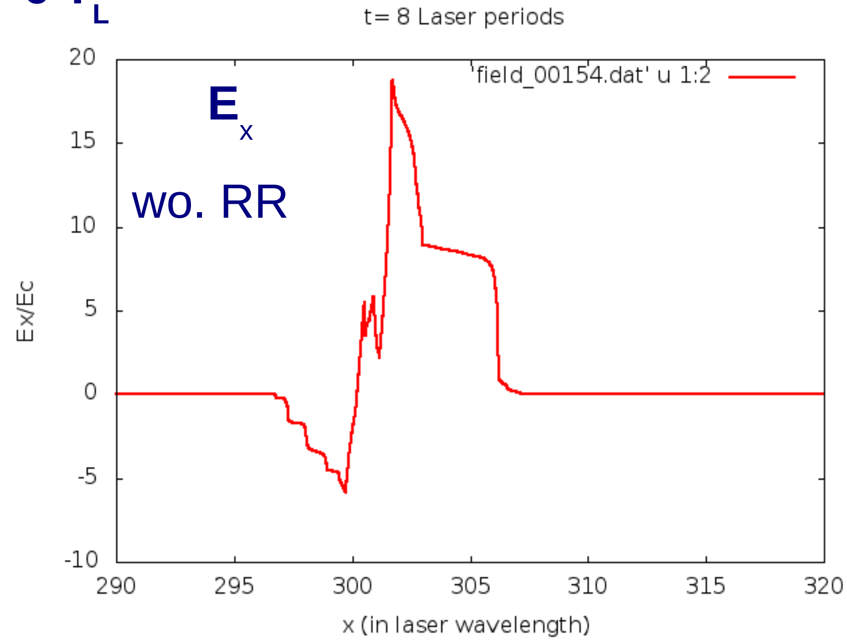
$t = 4\ T_L$





t= 6 T_L


t= 8 Laser periods
'field_00154.dat' u 1:2
E_x
w. RR
Ex/Ec
x (in laser wavelength)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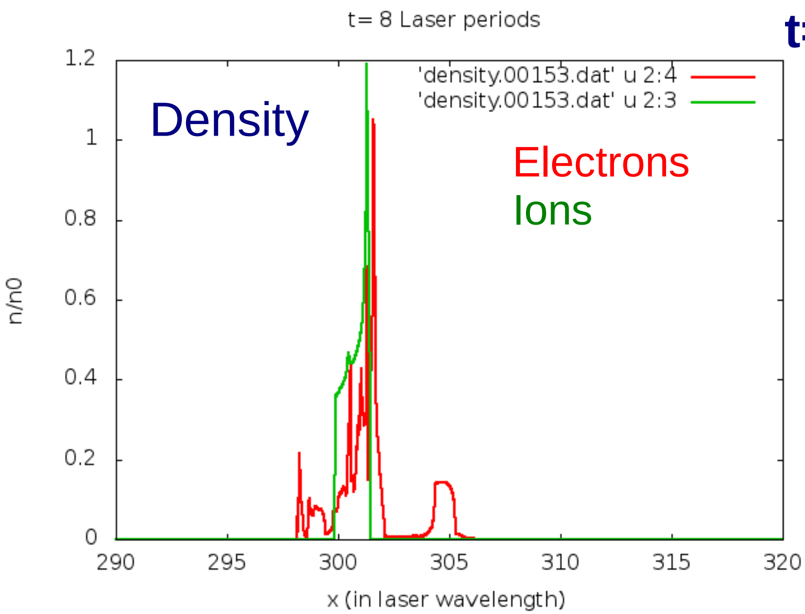
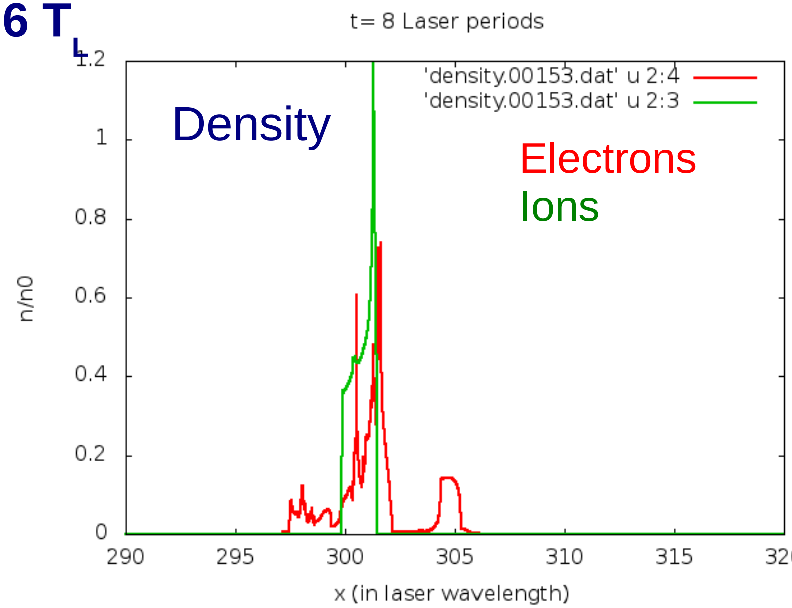
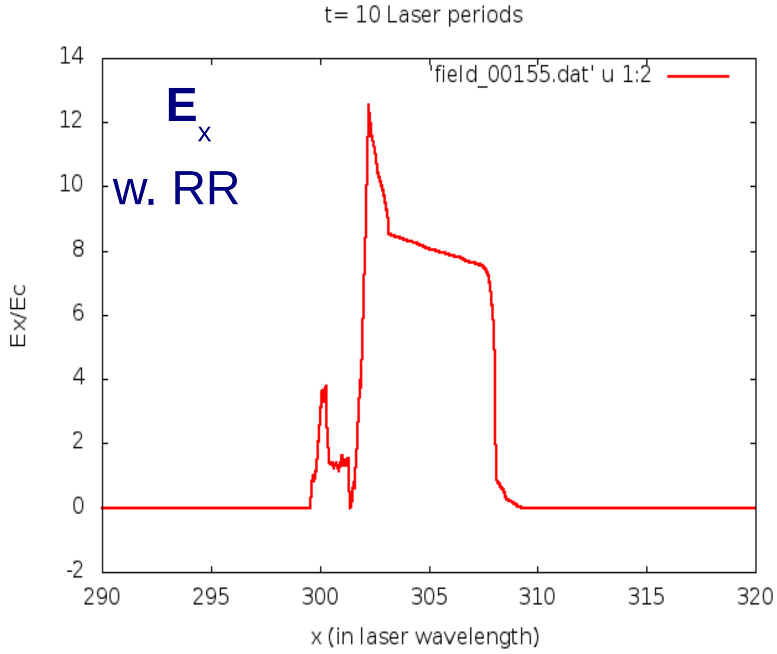
'field_00154.dat' u 1:2
E_x
wo. RR
Ex/Ec
x (in laser wavelength)

t= 6 T_L


t= 8 Laser periods
'density.00153.dat' u 2:4
'density.00153.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)


t= 8 Laser periods
'density.00153.dat' u 2:4
'density.00153.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

t= 8 T_L


t= 10 Laser periods
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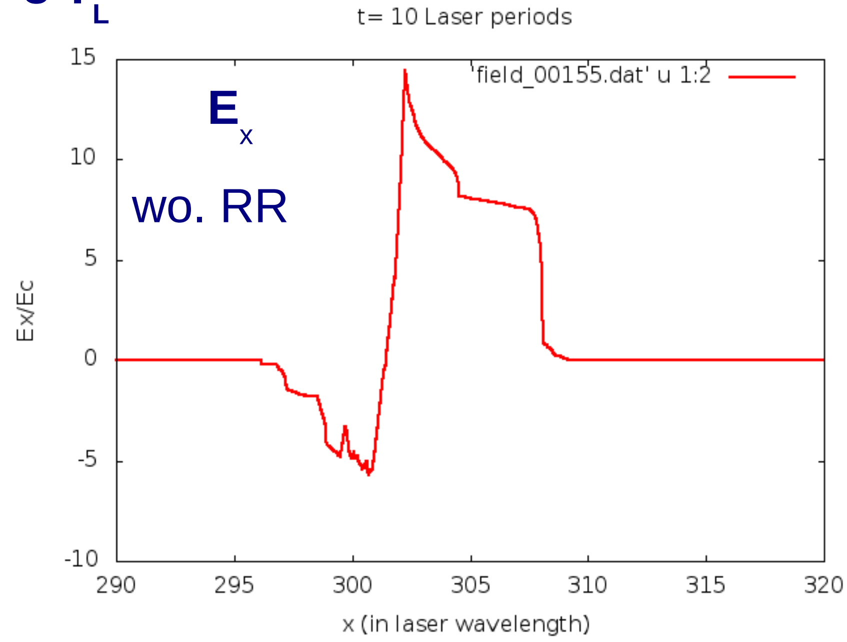
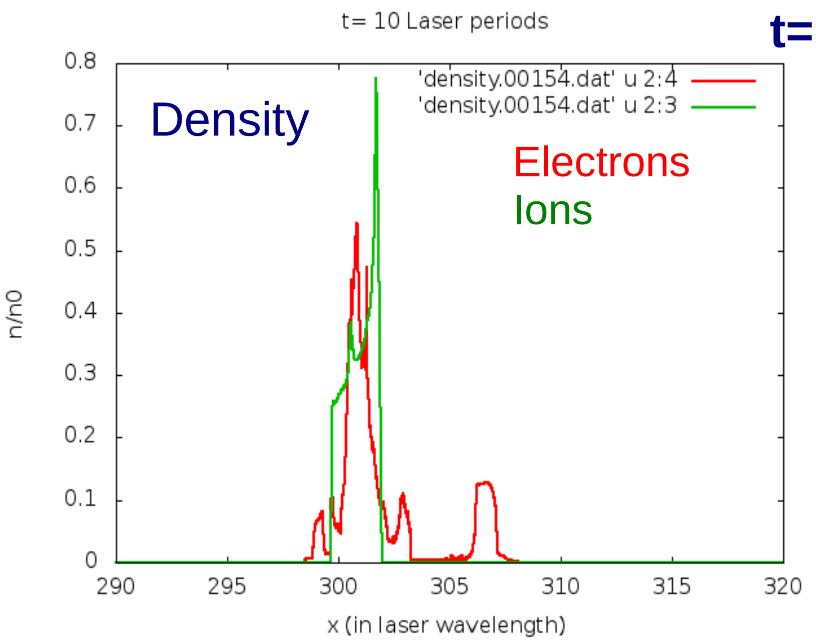
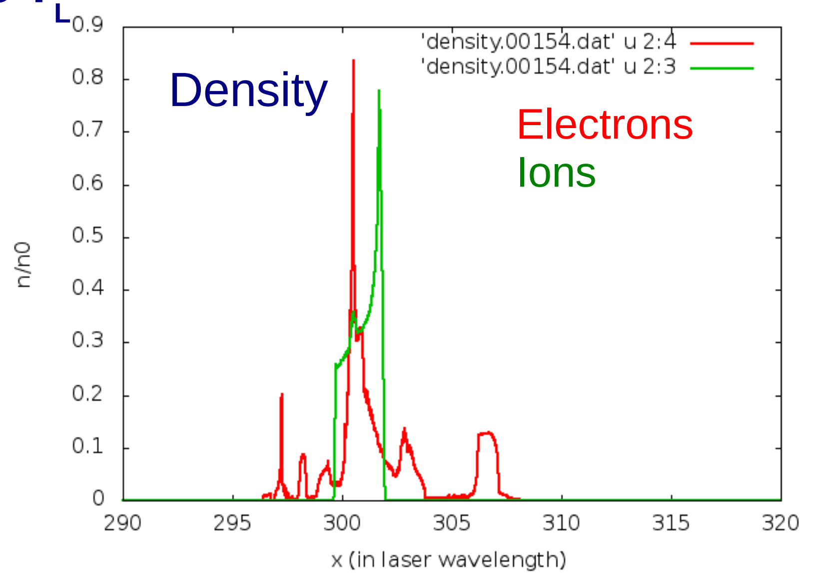
E_x
w. RR
Ex/Ec
x (in laser wavelength)

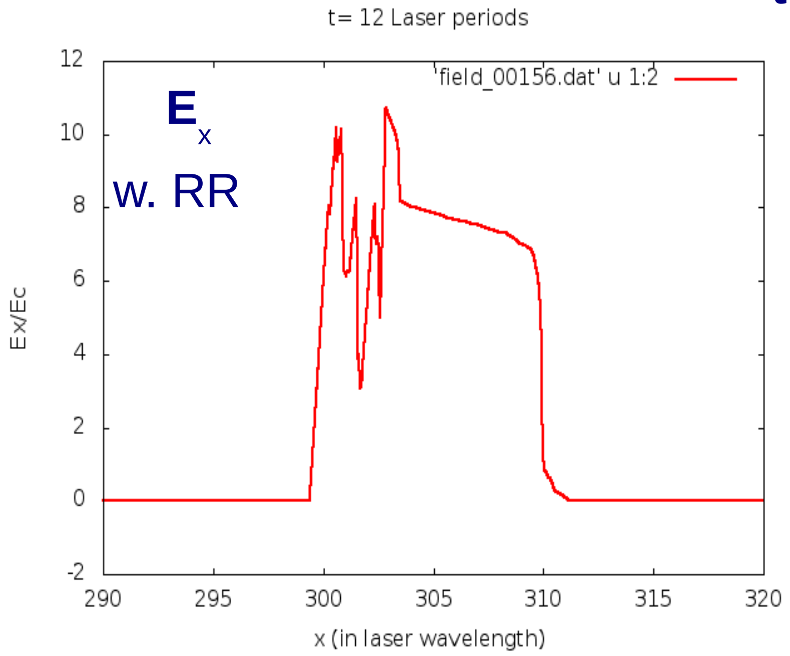

t= 10 Laser periods
'field_00155.dat' u 1:2
E_x
wo. RR
Ex/Ec
x (in laser wavelength)

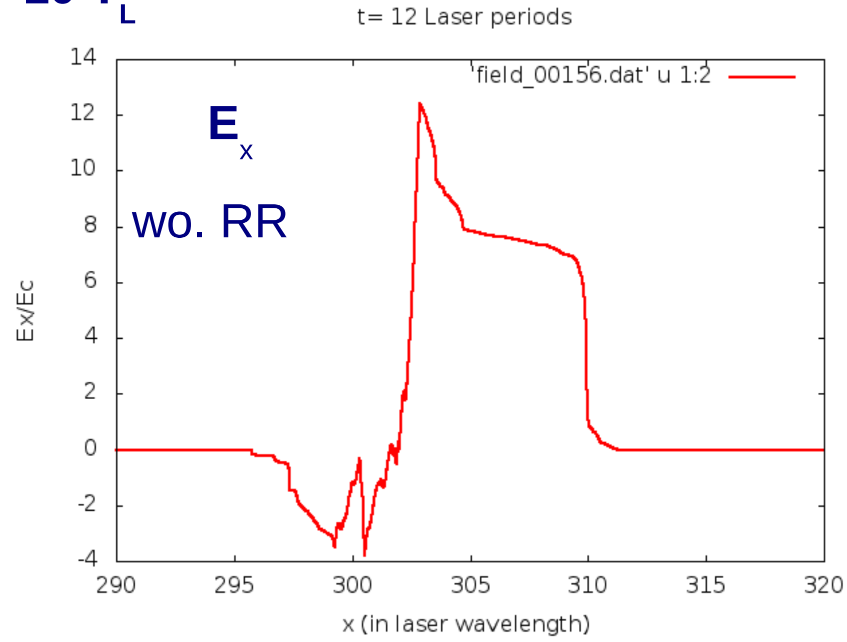
t= 8 T_L


t= 10 Laser periods
'density.00154.dat' u 2:4
'density.00154.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

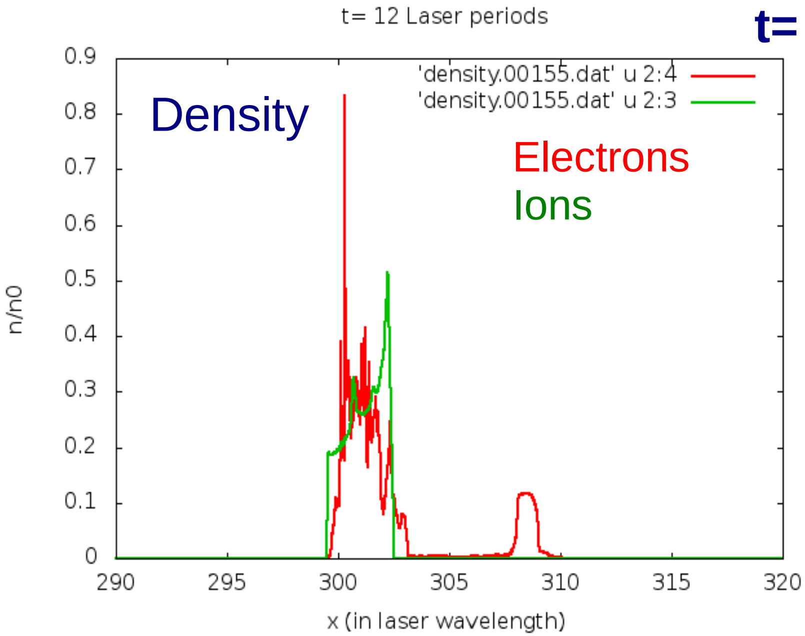

t= 10 Laser periods
'density.00154.dat' u 2:4
'density.00154.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

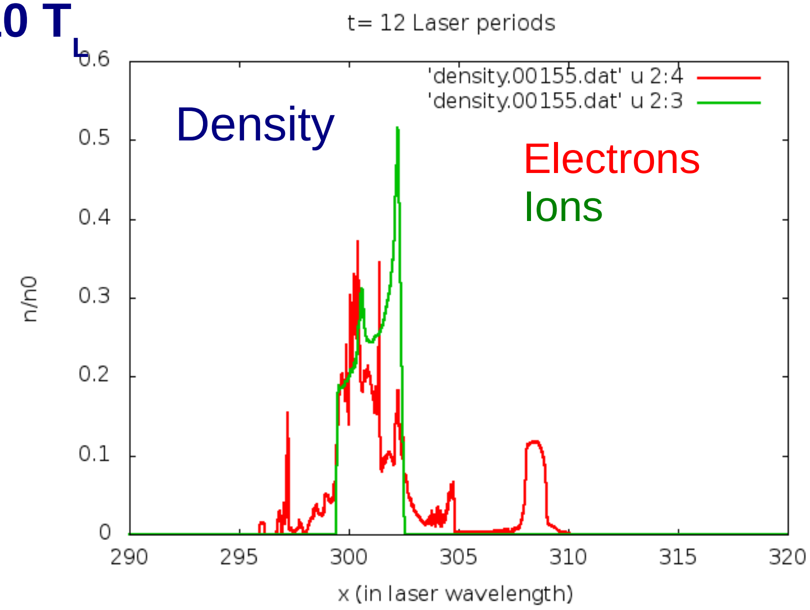
t= 10 T_L


t= 12 Laser periods
'field_00156.dat' u 1:2
E_x
w. RR
Ex/Ec
x (in laser wavelength)

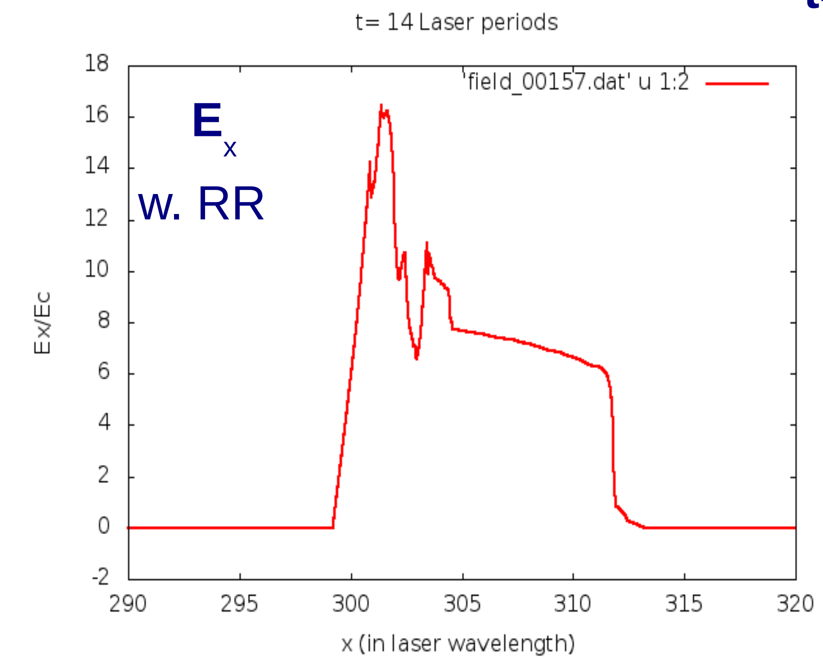

t= 12 Laser periods
'field_00156.dat' u 1:2
E_x
wo. RR
Ex/Ec
x (in laser wavelength)

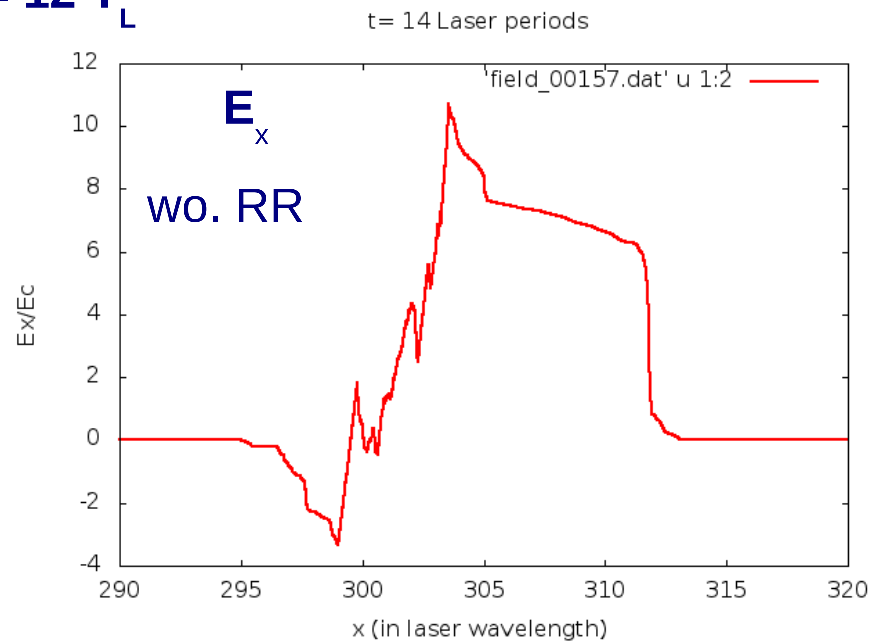
t= 10 T_L


t= 12 Laser periods
'density.00155.dat' u 2:4
'density.00155.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

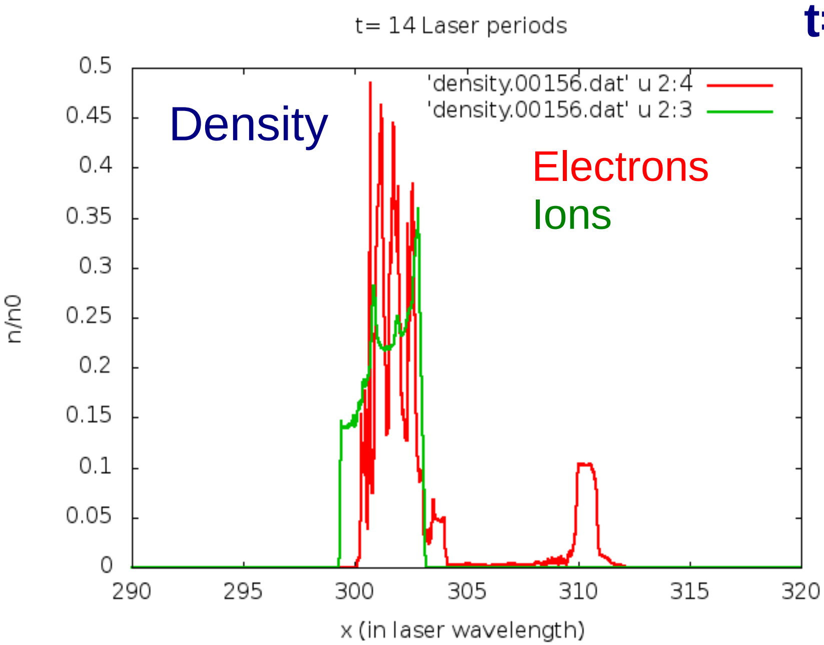

t= 12 Laser periods
'density.00155.dat' u 2:4
'density.00155.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

$t = 12\ T_L$


t= 14 Laser periods
'field_00157.dat' u 1:2
Ex
w. RR
Ex/Ec
x (in laser wavelength)


t= 14 Laser periods
'field_00157.dat' u 1:2
Ex
wo. RR
Ex/Ec
x (in laser wavelength)

$t = 12\ T_L$


t= 14 Laser periods
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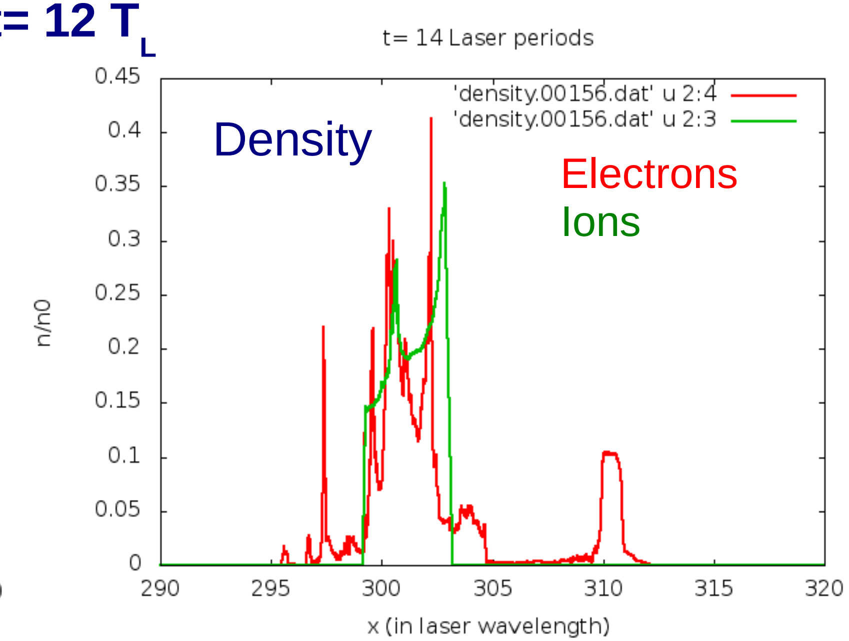
'density.00156.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)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'density.00156.dat' u 2:4
'density.00156.dat' u 2:3
Density
Electrons
Ions
n/n0
x (in laser wavelength)

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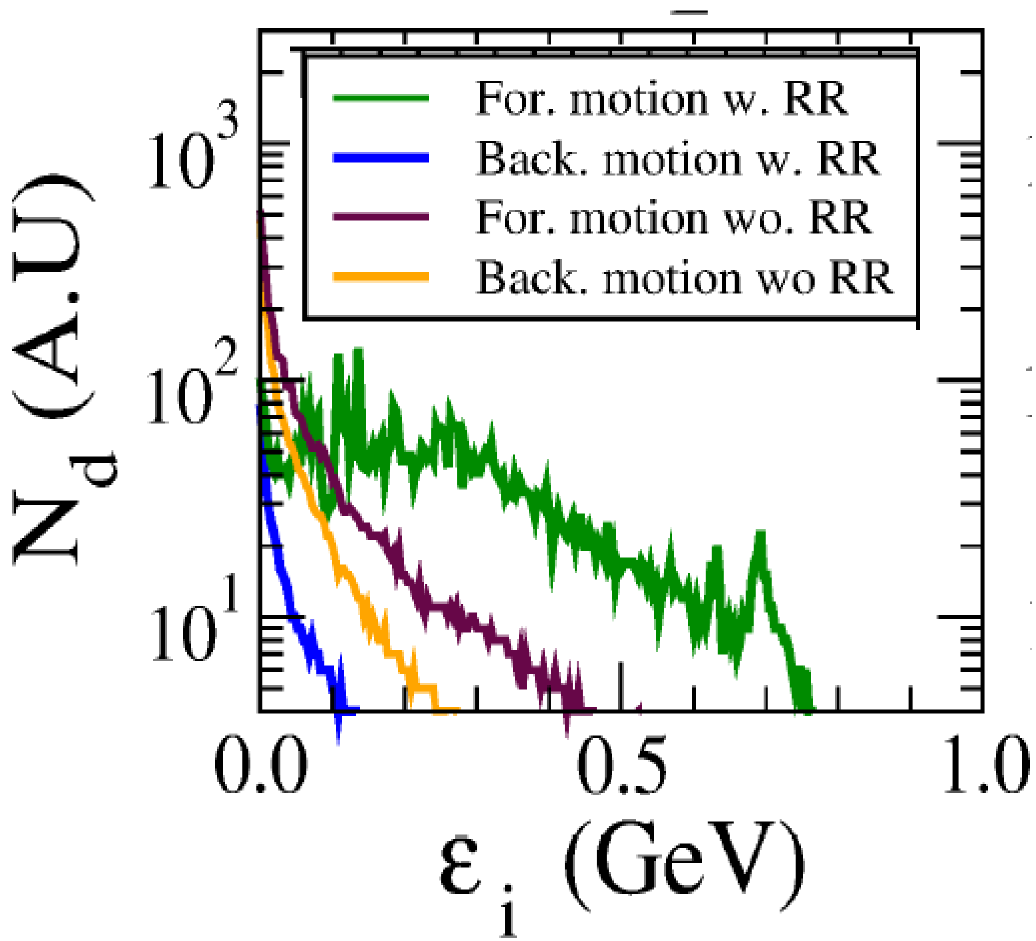
3.1 Purely relativistic self-transparency induced regime

l= 0,8 λ_L

Ion energy spectra



(3): t > 30 T_L (width of the laser)

- The radiation reaction **changes the target expansion**, which increases the acceleration time of ions.
  - This leads to generation of an energetic ion peak ~ 0,7 GeV
- This peak generation is enhanced with a proton plasma.
- **Radiation reaction improves the forward ion acceleration efficiency.**

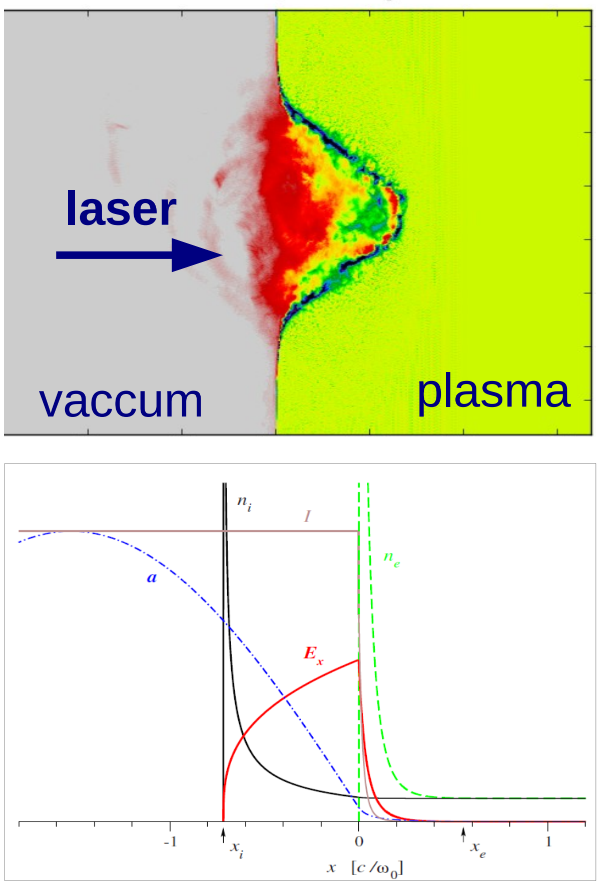
3.2 Hole boring regime

Previous works theoretical and numerical work have been done in this area :

- The laser energy is assumed to be coupled with 100% efficiency into the punching ions. 1D model.
See, T. Schlegel *et al*, PoP **16**, 083103 (2009)
See A. Robinson *et al*, PPCF **51**, 024004 (2009)

- Accounting for of the electron heating :
See Ping et al., PRL **109**, 145006 (2012)
See Levy *et al.*, POP **20**, 103101 (2013)

In our study, we have taken into account the radiation within the conservation laws.



T. Schlegel *et al*, PoP (2009)

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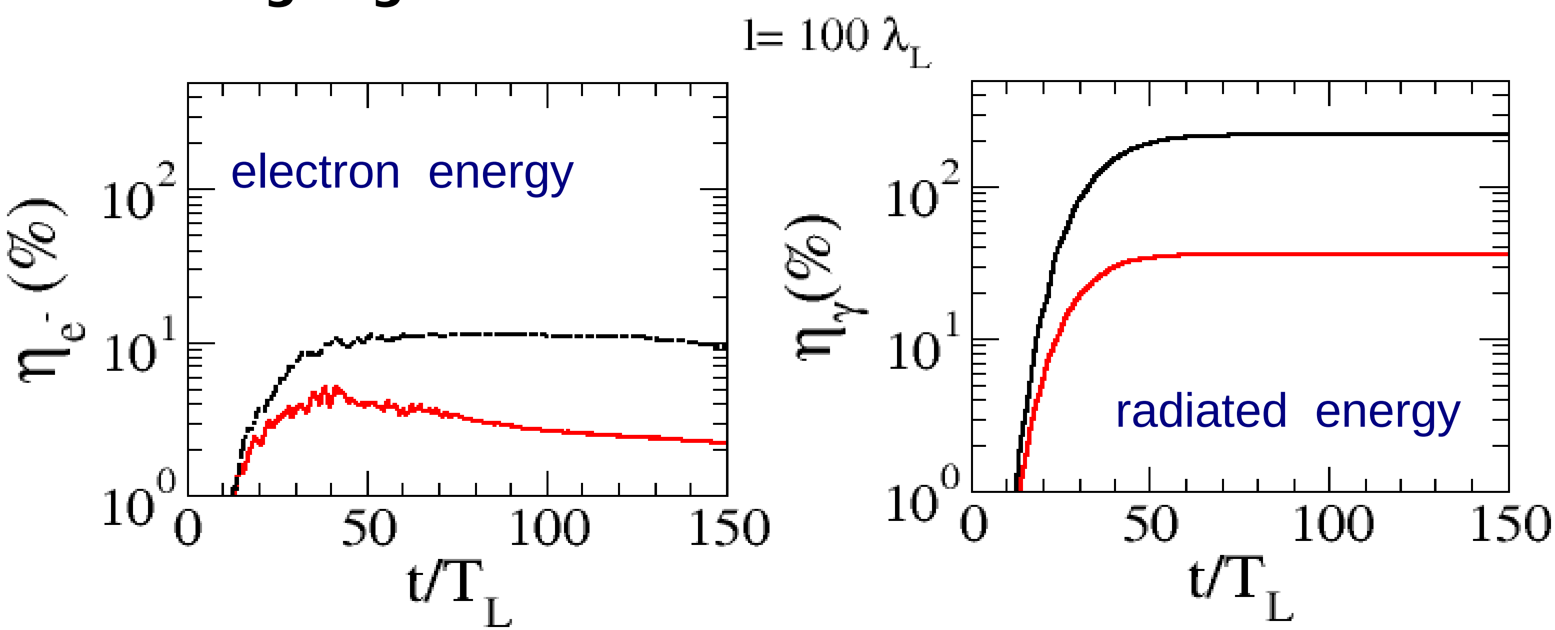
3.2 Hole boring regime



With RR
Without RR

$$B = \left(\frac{n_c}{n_e}\frac{m_e}{m_e + Zm_i}\right)^{1/2} a_L$$

Conservation of the **energy flux** yields :

$$(1-\mathcal{R})(1-\beta_p) = \langle \mathcal{E}_\gamma \rangle + 2\frac{\beta_p^3}{B^2}\gamma_p^2$$

$$\langle \mathcal{E}_\gamma \rangle \equiv \frac{\int_0^\infty W_\gamma dt}{\mathcal{E}_L}\lambda_L$$

Reflection coefficient

Piston velocity

Intense radiation contribution

Ion contribution

3.2 Hole boring regime

Conservation of the **momentum flux** yields :

$$(1+\mathcal{R})(1-\beta_p) = \langle \mathcal{P}_\gamma \rangle + 2\frac{\beta_p^2}{B^2}\gamma_p^2$$

$$B = \left(\frac{n_c}{n_e}\frac{m_e}{m_e + Zm_i}\right)^{1/2} a_L$$

Radiation pressure of intense synchrotron

However, The characteristic of the emitted radiation is much shorter than distance between electrons.

$$l_{cr} \sim \frac{2\pi c}{\omega_{cr}} \propto \frac{1}{\gamma_e^3} \ll d \sim n_e^{-1/3}$$

→ The plasma is transparent to the intense synchrottron radiation.

The pressure $\langle P_\gamma \rangle$ has therefore no effects on plasma dynamics.

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3.2 Hole boring regime

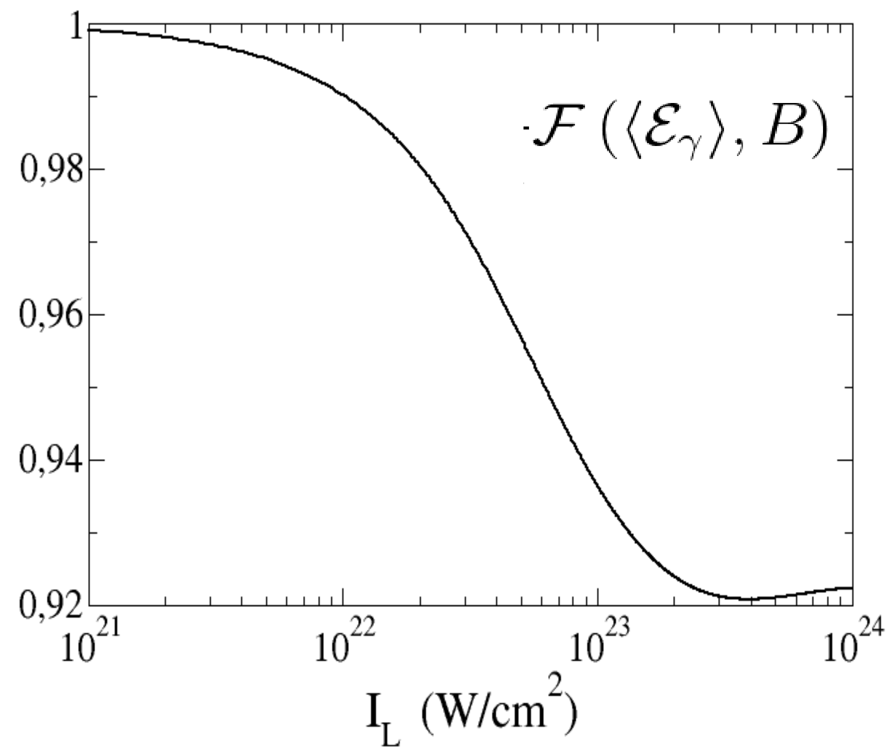
Neglegting the radiation pressure of intense radiation, we can deduce the expression of the reflection coefficient :

$$\mathcal{R} = \frac{1-\beta_p}{1+\beta_p} - \frac{\langle E_\gamma \rangle}{2\left(1-\beta_p\right)}$$

The laser energy is no longer 100 % converted into the piston drive.

The piston velocity writes :

$$\beta_p = \frac{B}{B+1}\mathcal{F}\left(\langle \mathcal{E}_\gamma \rangle, B\right)$$



When $\langle \mathcal{E}_\gamma \rangle$ is negligible, one gets $\beta_p = \frac{B}{B+1}$ in agreement with previous publications.

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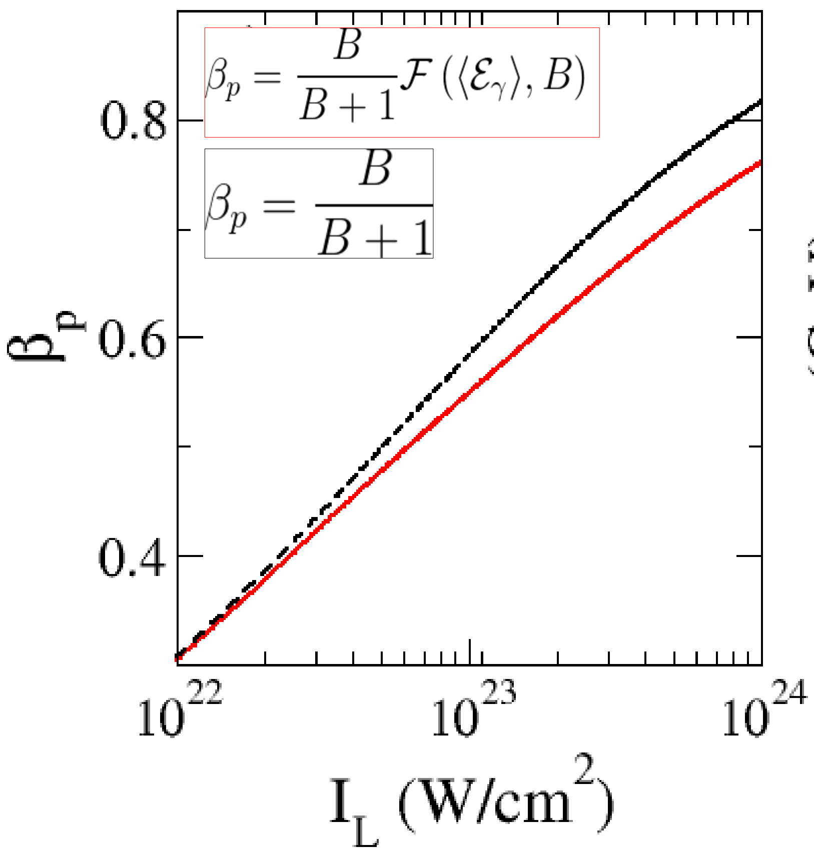
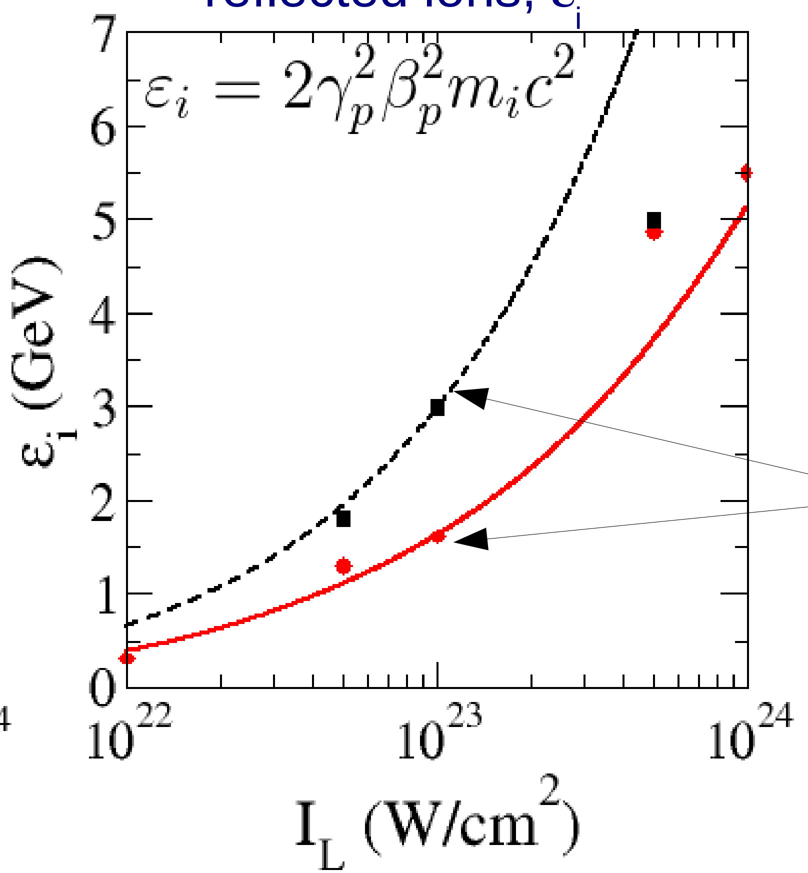
3.2 Hole boring regime

Piston velocity



l= 100λ_L

Energy of reflected ions, ε_i



With RR
Without RR

Simulation datas

The radiation reaction reduces the efficiency of ion acceleration at ultra-high laser intensities without modify the behavior over the laser intensity.

Summary

• The effects of RR on the energy spectrum of accelerated ions in ultraintense laser-plasma interactions is shown to depend strongly on the target thickness and thus the underlying ion accelerationmechanism.

• In the **purely relativistic self induced transparency regime** (thin target), the RR changes the **target expansion**. The **maximum ion energy is enhanced** and a spectral **peak produced** in the case of relativistically transparent targets

• An analytical model needs to be developed to better understand the influence of the RR on the target expansion.

• In the **hole boring regime** (thick target), more than 30% of the laser energy is converted into intense synchrotron radiation, which **reduces the piston velocity and thus the ion energy by a factor of 2**. ($I_L=10^{23}$W/cm^2).

• The reflection coefficient depends not only on the piston velocity, but also on the radiated energy during the interaction.

Thanks for your attention