Universität Rostock
Traditio et Innovatio

Quantum Theory & Many–Particle Systems

Radiation-dominated plasma dynamics in the interaction of super-intense circularly polarized laser pulses with thick plasma targets

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Goal, Set-up, Model & Means

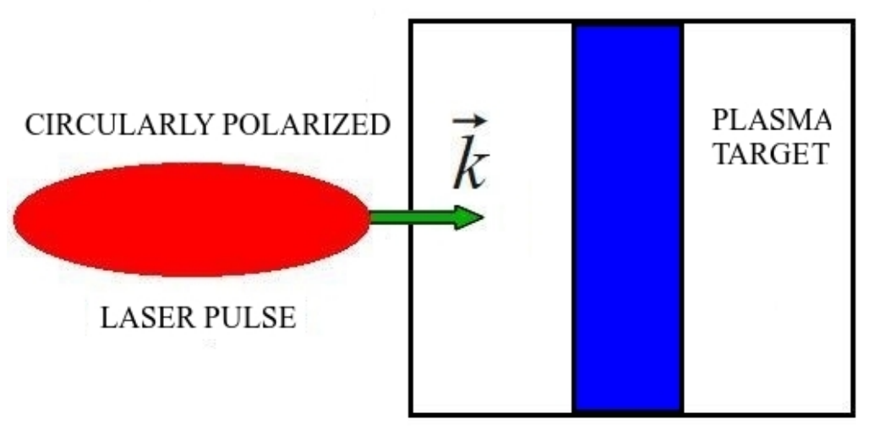
Objectives:

- How strong a magnetic field generated in a laser lab can be?
- Where should we expect the transition between the classical and quantum dynamics in strong-field laser-plasma interactions?

Laser pulse parameters: extremely intense, $I\lambda^2 > 10^{23}$ W/cm$^2\mu$m^2, and circularly polarized

Targets: thickness: much greater than the evanescence length of the laser field; electron density: such to remain above the treshold for relativistic transparency $\Rightarrow$ to keep a steady "hole-boring" regime

Set-up:



Model:

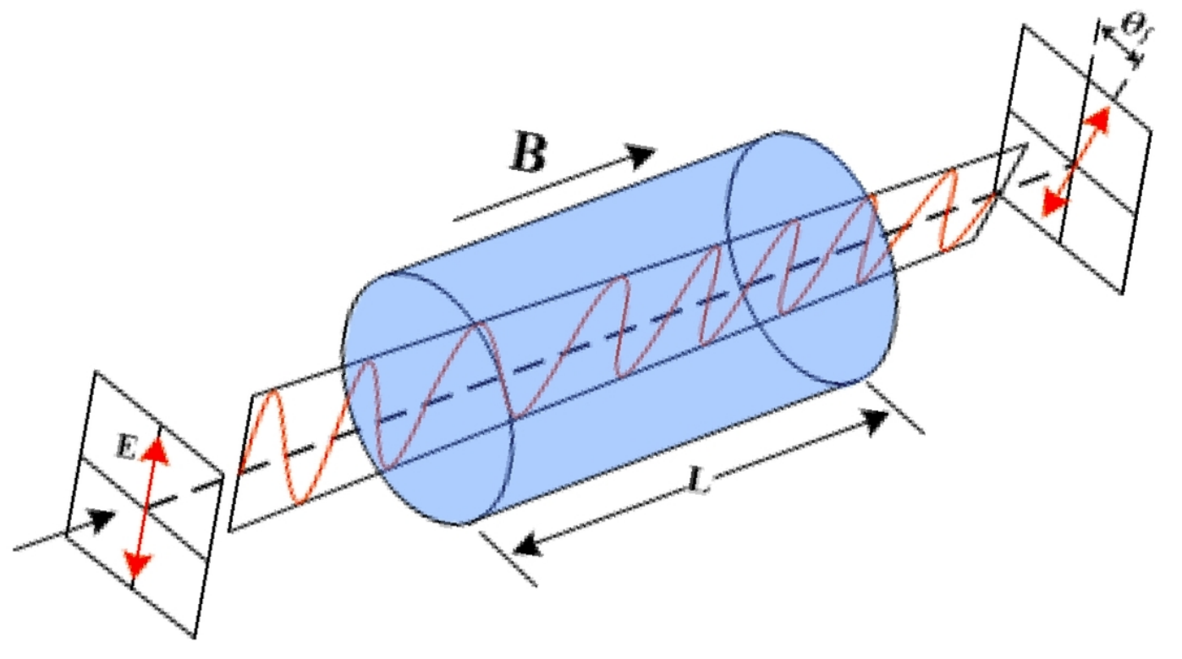
- 3D (**essential!**)
- Kinetic equation for plasma distribution function
- Maxwell equations for the electromagnetic fields
- Radiation friction included

Means:

- Relativistic Particle-In-Cell simulations

Why circular polarization?

Faraday Effect (M. Faraday, 1845)



Left- and right circularly polarized waves propagate with slightly different phase velocities $\longrightarrow$ rotation of the polarization plane of the linear polarized light: $\theta \propto B$.

Inverse Faraday Effect (L. Pitaevskij, 1960)

Circularly polarized light induces a magnetization along the wave vector $\vec{k}$ in the transparent medium.
Left- and right-handed polarization waves induce magnetization of opposite signs

- optically transparent plasmas $\longrightarrow$ absorption of the angular momentum $\longrightarrow$ generation of an axial magnetic field [M.G. Haines, PRL 87 (2001), 135005]
- opaque plasmas???

Logic

Need to deposit angular momentum into plasma	==>	circular polarization
Want to achieve extremely strong agnetic fields	==>	extremely strong CP laser pulses
In intense laser field collisional absorption plays no role collective effects do not lead to absorption of angular momentum	==>	radiation is the only mechanism of absorption
Should provide a situation when radiation is strong	==>	back reaction of radiation on electrons's dynamics must ne taken into account

Hole-boring regime

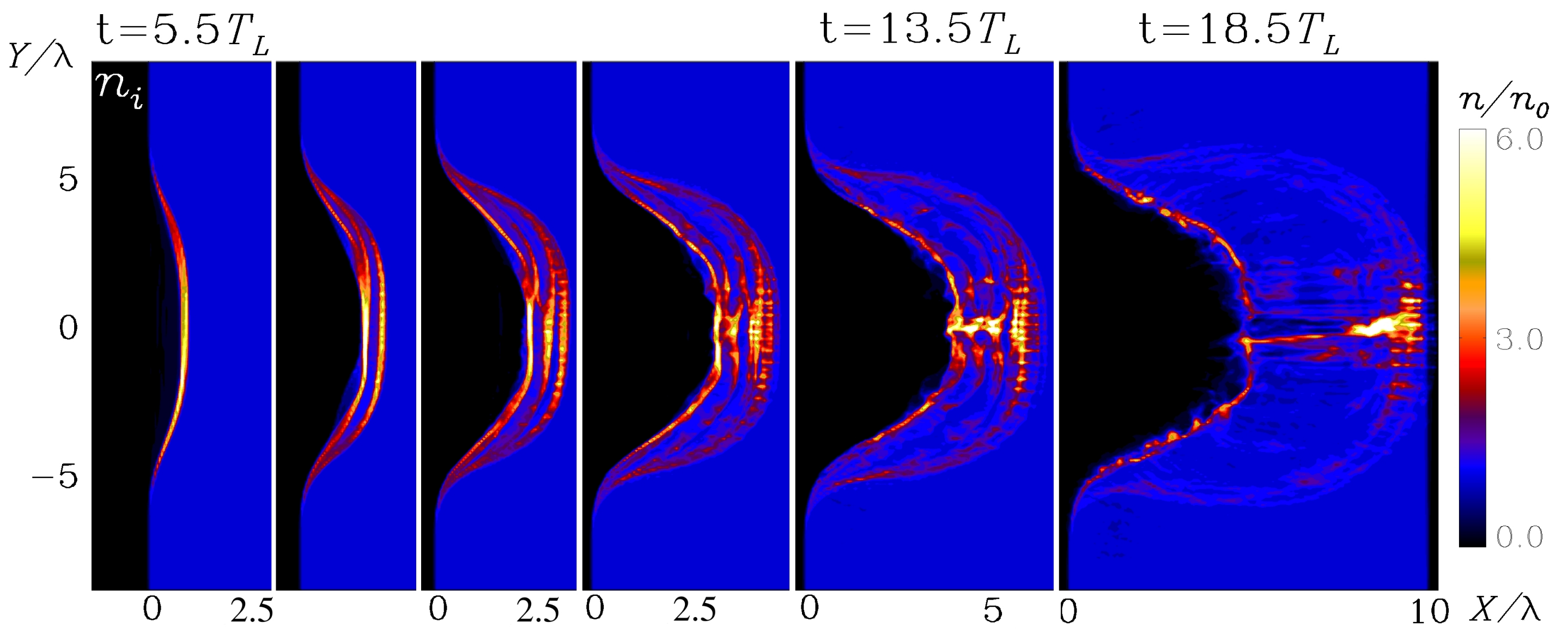


FIG.1. *Time evolution of the ion number density* for $I_L = 10^{24} W/cm^2$, and $n_0 = 1.6 \times 10^{23} cm^{-3}$.

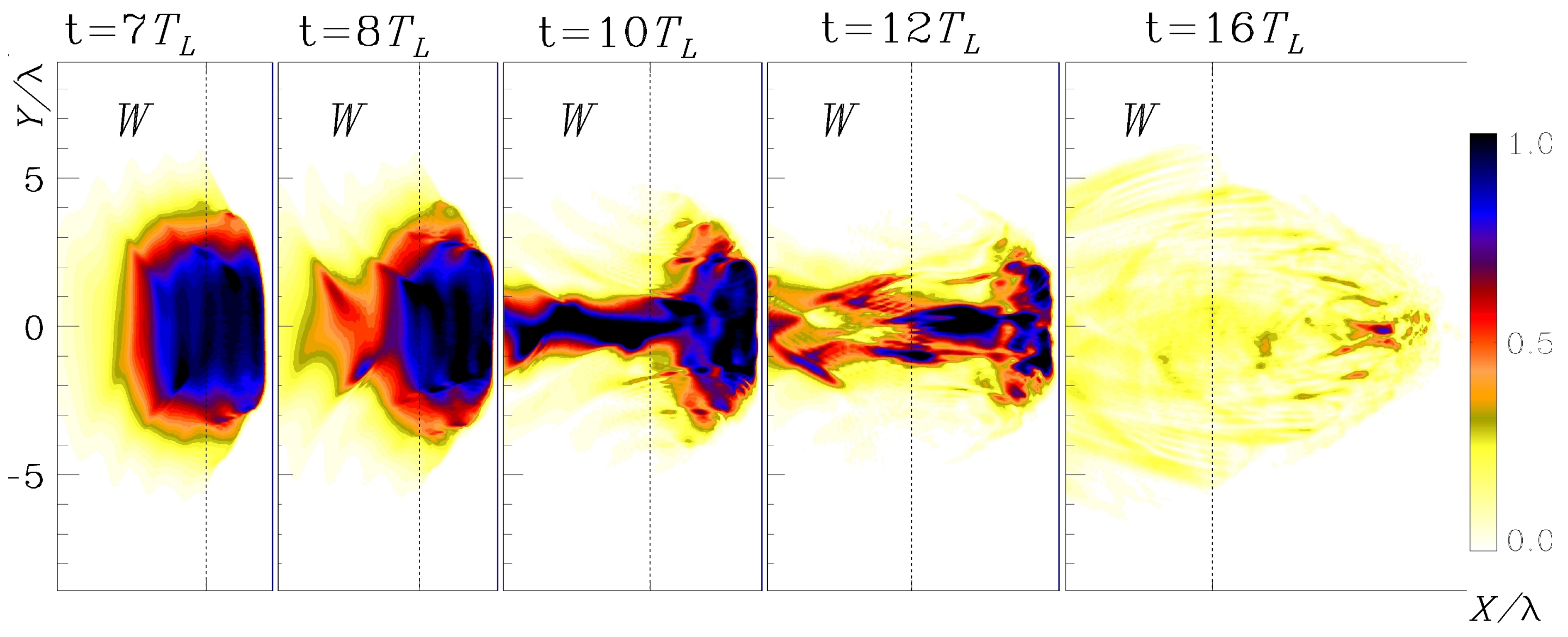


FIG.2. *Time evolution of the laser pulser energy density* for $I_L = 10^{24} W/cm^2$, and $n_0 = 1.6 \times 10^{23} cm^{-3}$.

Radiation Reaction modeling

- "Reduced" Landau-Lifshitz equation for electrons

$$\frac{d\mathbf{p}}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B}\right) + \mathbf{F_{rad}}$$

$$\mathbf{F}_{\rm rad} = -\left(\frac{2r_c^2}{3}\right)\left\{\gamma^2\left[\left(\mathbf{E}+\frac{v}{c}\times\mathbf{B}\right)^2 - \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c} - \left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B} + \left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right]\right\}$$

more details in M. Tamburini et al., New J. Phys. 10, 123005 (2010)

- Spin force and smaller terms in $\mathbf{F_{rad}}$ are neglected
- Dominant term $\sim \gamma^2\mathbf{v}$ acts as nonlinear **friction**

- Assume main contribution to Radiation Friction (RF) losses is at wavelengths $\lambda_{rf} \ll (3/4\pi n_e)^{1/3}$
$\Rightarrow$ • radiation is incoherent and escapes from the plasma • it appears as energy dissipation

- RF-relevant wavelenghth are not resolved on the numerical grid
- "coherent" wavelengh are double-counted in the RF force, but their contribution is small

Axial Magnetic field with- and without- RF included

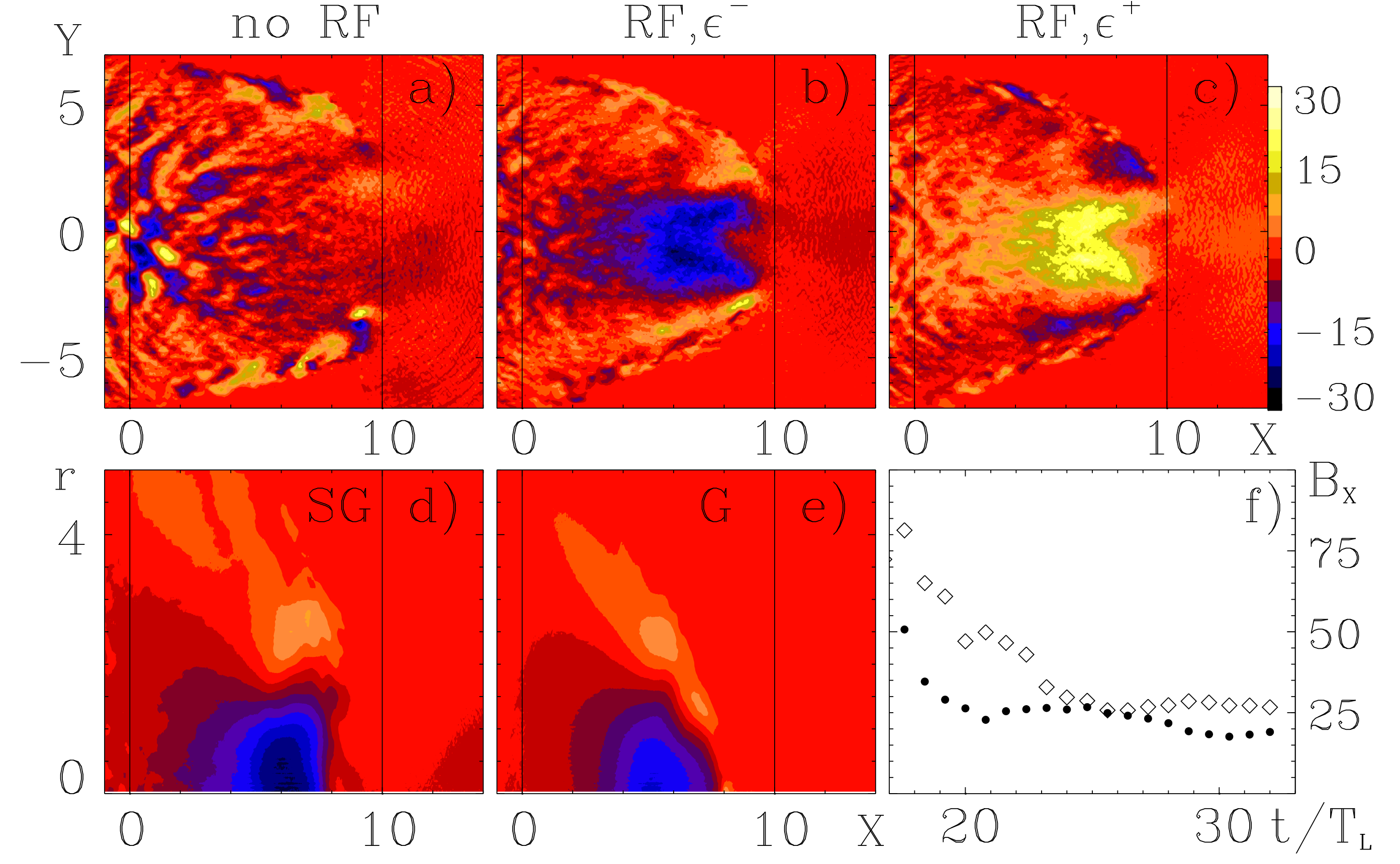
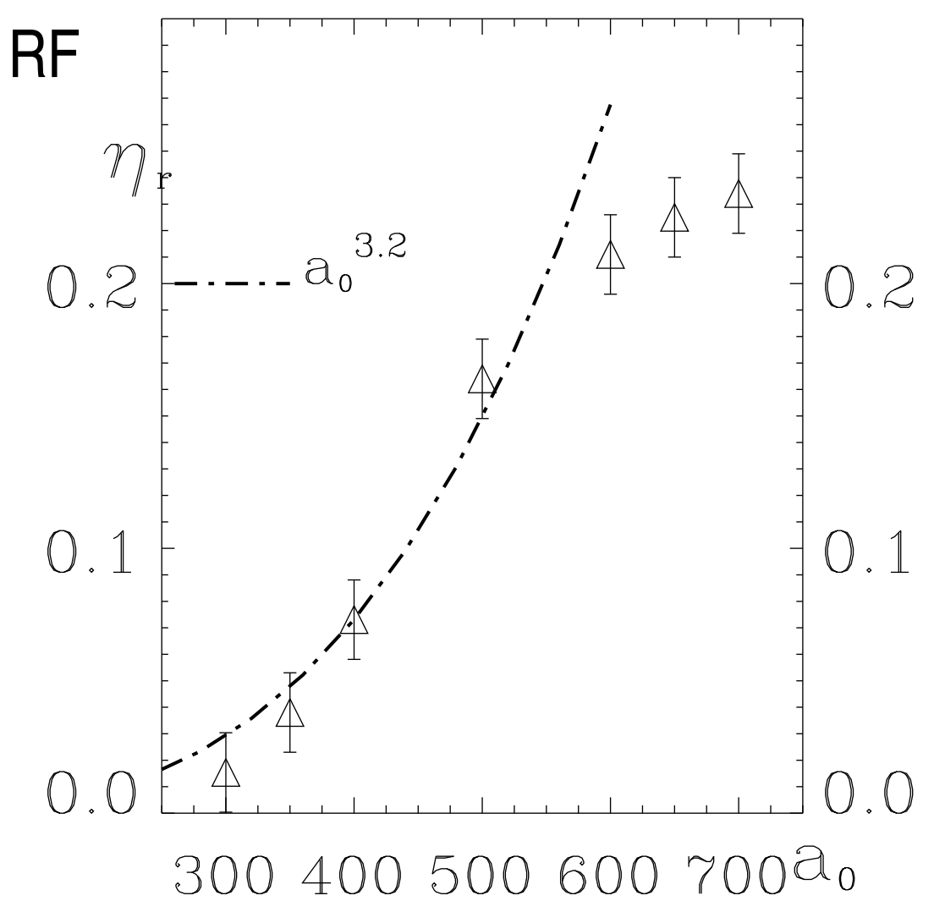


FIG.3. *Axial magnetic field B_x normalized to $B_0 = 1.34 \times 10^8$G a super-Gaussian pulse without RF a) and with RF included and for opposite helicities (b-c). The field is shown in the xy plane $t = 33\lambda/c$ after the beginning of the interaction. d) and e): B_x averaged over the azimuthal direction comparison for Gaussian (G) and super-Gaussian (SG) pulse profiles. f): the temporal evolution of the maximum value of B_x on the x axis for the G (filled dots) and SG (empty diamonds) pulses.*

- no significant axial field is apparent in the simulation without RF
- Axial magnetic field of amplitude $B_{\rm max} \simeq 4$GG & extending over several μm is generated
- Sign of the axial magnetic field depends on the polarization
- Field is slowly varying over more than 10 λ/c, no sign of rapid decay



Macroscopic model [1] delivers $B_{\rm max} \simeq C\eta a_0 B_0$
with η– absorption coefficient:
$\eta = U_r/U_L = \mathcal{A}c\tau R^2 a_0^2 B_0^2 / \int P_r n_e d^3 r dt$

Radiation in the field of CP wave

$$\vec{E}(t,x) = (E_d, \quad E_0\cos\varphi, E_0\sin\varphi), \qquad \vec{B}(t,x) = (0, -E_0\sin\varphi, E_0\cos\varphi)$$

Model [1]

$P(\vec{v}) = 2e^2\omega^2 v_0^2\gamma^4/3c^3\,(1 - v_x/c)^2$
$P_r \sim a_0^4$ and $U_r \sim a_0^5$
$\eta = \xi a_0^3$ with $\xi = 4\pi r_e/3\lambda \simeq 1.5 \cdot 10^{-8}$
$a_{cr} = \xi^{-1/3} \simeq 300$ for $\eta = 1$
$I_{cr} \simeq 5 \times 10^{23} W/cm^2$

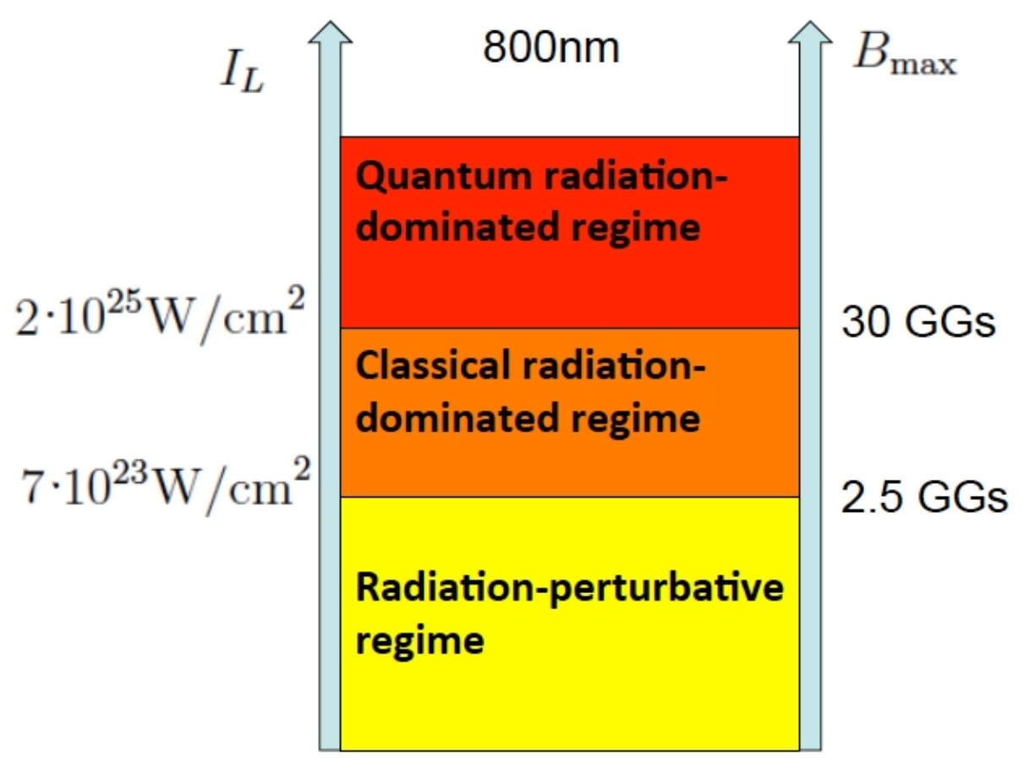
- Simulations: Correct scaling with intensity but too small absolute values of η

Zeldovich model [2]

$\vec{F}_r = -P(\vec{v})\vec{v}/c^2$
$eE_d - eE_0\,(v_0/c)\sin\theta - P(\gamma, v_x)v_x/c^2 = 0$
$eE_0\,(1 - v_x/c)\sin\theta + P(\gamma, v_x)v_0/c^2 = 0$
$\gamma m\omega v_0 = eE_0\cos\theta$
$\gamma^2\left(1 + \xi^2\gamma^6\right) = a_0^2$ and $\eta = \xi\gamma^4(a_0)/a_0$

- More consistent with simulations: for $a_0 \gg a_{cr}$, $\quad \eta \simeq 0.5$

Transition from classical to quantum regime [3]



Emitted photon energy $\sim$ electron kinetic energy $\longrightarrow$ quantum effects are dominant
$\hbar\omega_q \simeq \gamma^3\hbar\omega \simeq \gamma mc^2$
for $\lambda = 0.8\mu$m $\longrightarrow \gamma > \gamma_q \simeq 600$

- Effect of radiation reacton force is not accounted $\longrightarrow$ $a_0 < a_q = 600$ and $I < 2 \times 10^{24}$W/cm^2
- With $\gamma^2\left(1 + \xi^2\gamma^6\right) = a_0^2 \longrightarrow$ $a_0 < a_q \equiv a(\gamma_q) = 2000$ and $I < 2 \times 10^{25}$W/cm^2

1. T. Liseykina, S. Popruzhenko, A. Macchi, New J.Physics 18, 072001 (2016)
2. Y.B. Zeldovich, Usp.Fiz.Nau 115, 161 (1975)
3. S. Popruzhenko, A. Macchi, T. Liseykina, in preparation

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