Radiation Friction Effects on Ion Acceleration and Magnetic Field Generation in Superintense Laser-Plasma Interactions

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Outline

- Radiation friction (RF) basics
- RF modeling in laser-plasma interactions
- RF effect on radiation-pressure dominated ion acceleration
  - thin target (Light Sail regime)
  - thick target (Hole Boring regime)
- Magnetic field generation induced by RF losses

Introducing Radiation Friction

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Pedagogical example:
electron in a magnetic field $\mathbf{B}_0$

$\mathbf{f}_L = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c)$ Lorentz force

$$m_e \frac{d\mathbf{v}}{dt} = \mathbf{f}_L = -\frac{e}{c}\mathbf{v} \times \mathbf{B}_0$$

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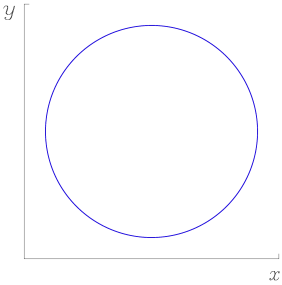
Solution: uniform circular motion

$|\mathbf{v}| = v =$ cost.



$K = \frac{1}{2} m_e v^2 =$ constant $\qquad \omega_c = \dfrac{eB_0}{m_e c} \qquad r = \dfrac{v}{\omega_c}$

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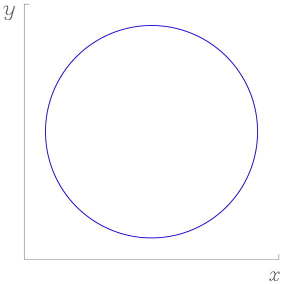
BUT the electron radiates:

$$P_{\text{rad}} = \frac{2e^2}{3c^3}\left|\frac{d\mathbf{v}}{dt}\right|^2 = \frac{2e^2}{3c^3}\omega_c^2 v^2$$



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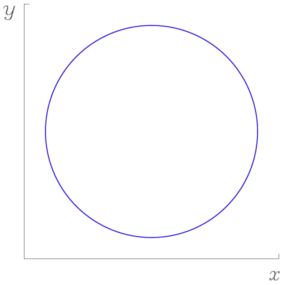
Energy loss due to radiation:

$$\frac{dK}{dt} = -P_{\text{rad}} \longrightarrow v(t) = v(0)\mathrm{e}^{-t/\tau}$$

$$\tau = \frac{3m_e c^3}{2e^2\omega_c^2} = \frac{3c}{2r_c\omega_c^2}$$



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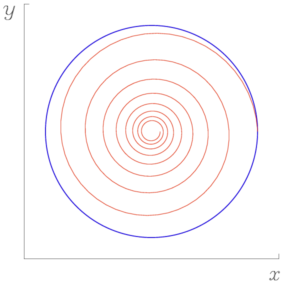
If $r(t) \simeq v(t)/\omega_c$, electron "falls" along a spiral



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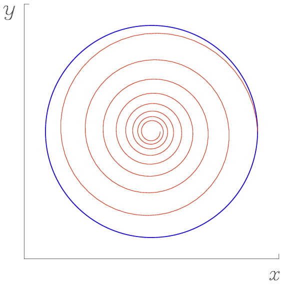
The Lorentz force does not describe the electron motion consistently: need to include an extra force



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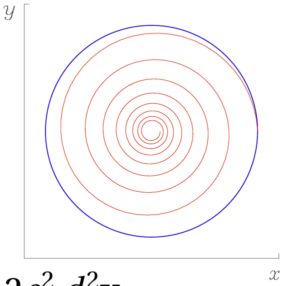
$$m_e \frac{d\mathbf{v}}{dt} = \mathbf{f}_L + \mathbf{f}_{\text{rad}}$$



Work done by extra force = energy loss

$$\int_0^t \mathbf{f}_{\text{rad}} \cdot \mathbf{v}\, dt = -\int_0^t P_{\text{rad}}\, dt \longrightarrow \mathbf{f}_{\text{rad}} = -\frac{2e^2}{3c^3}\frac{d^2\mathbf{v}}{dt^2}$$

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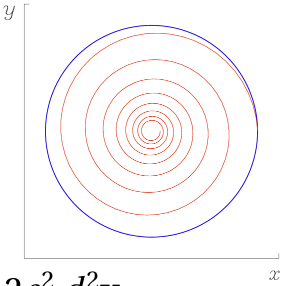

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Physical interpretation: the electron is affected by the self-generated radiation field (radiation *reaction* or *self-force*)

Landau-Lifshitz approach

$\mathbf{f}_{\text{rad}} = -\frac{2e^2}{3c^3}\frac{d^2\mathbf{v}}{dt^2}$ is unsatisfying:

- unphysical runaway solutions $\dot{\mathbf{v}}(t) = \dot{\mathbf{v}}(0)\mathrm{e}^{t/\tau}$
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LL iterative approach brings $\mathbf{f}_{\text{rad}} = \mathbf{f}_{\text{rad}}(\mathbf{E},\mathbf{B})$:

$$\mathbf{f}_{\text{rad}} \simeq -\frac{2e^2}{3c^3}\left(-\frac{e}{m_e}\frac{d}{dt}\mathbf{f}_L\right) = \frac{2e^3}{3m_ec^3}\left(\dot{\mathbf{E}} - \frac{e}{m_ec}\mathbf{E}\times\mathbf{B}\right)$$

in the "instantaneous" frame where $\mathbf{v} = 0$

L.L.Landau, E.M.Lifshitz, *The Classical Theory of Fields* (Elsevier, 1975), 2nd Ed., par.76

Relativistic Landau-Lifshitz RF force

$$f^{\mu}_{\text{rad}} = -\frac{2r_c^2}{3}\left[F^{\mu\nu}F_{\alpha\nu}u^{\alpha} - F^{\alpha\nu}u_{\nu}F_{\alpha\beta}u^{\beta}u^{\mu} + \frac{m_e c}{e}\partial_{\alpha}F^{\mu\nu}u^{\alpha}u_{\nu}\right]$$

Spatial component in the laboratory frame:

$$\begin{aligned}\mathbf{f}_{\text{rad}} &= -\frac{2r_c^2}{3}\left\{\gamma^2\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2-\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c}\right.\\ &\left.-\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)\times\mathbf{B}+\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)\mathbf{E}\right]+\gamma\frac{m_e c}{e}\left(\dot{\mathbf{E}}+\frac{\mathbf{v}}{c}\times\dot{\mathbf{B}}\right)\right\}\end{aligned}$$

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$$E < E_s = \frac{m_e c^2}{\lambda_c} = \frac{m_e^2 c^3}{e\hbar} < \frac{m_e c^2}{r_c} \qquad \frac{c}{\omega} > \lambda_c = \frac{\hbar}{m_e c}$$

$E_s = 1.3 \times 10^{16}$ V cm^{-1} (Schwinger field)
$\lambda_c = 4 \times 10^{-11}$ cm (Compton wavelength)

Why worry about Radiation Friction?

The relevant fields seem out of reach, but ...

- Depending on the interaction geometry the field amplitudes and frequencies are much higher in the rest frame of the electron

  Example: collision of an electron with $\gamma \gg 1$ and a plane wave

  $$F = \frac{2}{3}\left(\frac{e^2}{m_e c^2}\right)|\mathbf{E}\times\mathbf{B}| = \frac{8\pi}{3} r_c^2 I \longrightarrow F' = \frac{8\pi}{3} r_c^2 (4\gamma^2 I) \gg F$$

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[J.Koga, T.Esirkepov, S.V. Bulanov, PoP **12**, 093106 (2005)]

RDR in a laser field: (radiation loss)≃(initial energy)
Electron counterpropagating to laser field ⇒ $\mathbf{f}_{\text{rad}}$ is maximized ⇒
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$$P_{\text{rad}}\frac{2\pi}{\omega} \simeq \mathscr{E}_{\text{osc}} = m_e c^2 \left[\left(1+\frac{\mathbf{p}^2}{m_e c^2}\right)^{1/2} - 1\right]$$

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($\beta_0 = v_0/c$, $\gamma_0 = (1-\beta_0^2)^{-1/2}$ initial β- and γ-factor)

$R = 1$ for $\gamma_0 = 300$ (150 MeV) and $a = 336$ (2.4×10^{23} W cm^{-2})

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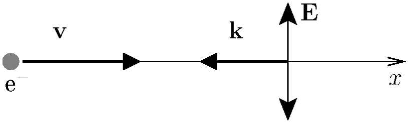
Thomson Scattering with RF included

TS of a 35 fs pulse by 150 MeV electrons



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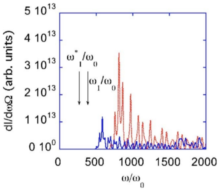

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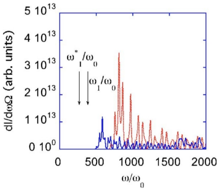

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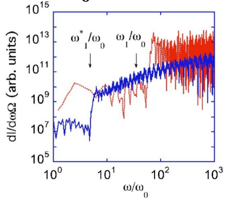

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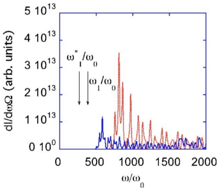
Total power and low-frequency cut-off are strongly affected by RF already when $R \ll 1$

$a_0 = 30$



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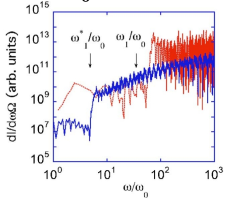

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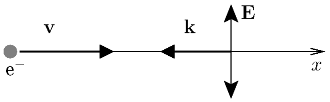
Angular RF signatures in Thomson Scattering

Key point: the RF decreases v_x
(velocity component anti-parallel to $\mathbf{k}$)



Change in v_x affects
the angular distribution
of the scattered radiation

"Backward" TS observed with RF
$I = 5 \times 10^{22}$ W cm^{-2}, 27 fs pulse
40 MeV electrons, $R \simeq 0.05$

[A.Di Piazza, K.Z.Hatsagortsyan, C.H.Keitel, PRL **102**, 254802 (2009)]

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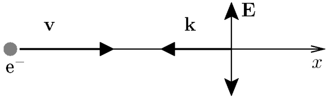

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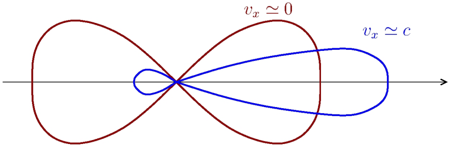

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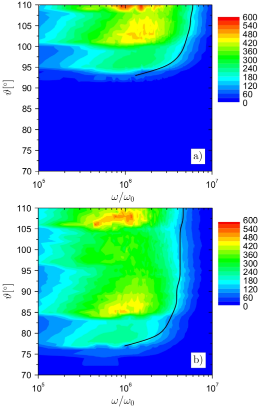

[A.Di Piazza, K.Z.Hatsagortsyan, C.H.Keitel, PRL **102**, 254802 (2009)]

Radiation Reaction modeling - I

"Reduced" Landau-Lifshitz equation for electrons
[M. Tamburini, F. Pegoraro, A. Di Piazza, C. H. Keitel, A. Macchi, New J. Phys. **10**, 123005 (2010)]

$$\begin{aligned}
\frac{d\mathbf{p}}{dt} &= -e\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)+\mathbf{F}_{\text{rad}} \\
\mathbf{F}_{\text{rad}} &= -\left(\frac{2r_c^2}{3}\right)\times\left\{\gamma^2\left[\left(\mathbf{E}+\frac{\mathbf{v}}{c}\times\mathbf{B}\right)^2-\left(\frac{\mathbf{v}}{c}\cdot\mathbf{E}\right)^2\right]\frac{\mathbf{v}}{c}\right. \\
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Radiation Reaction modeling - II

Kinetic equation for electrons and some properties

$$\partial_t f + \nabla_{\mathbf{r}} \cdot (\mathbf{v} f) + \nabla_{\mathbf{p}} \cdot (\mathbf{F} f) = 0, \qquad f = f(\mathbf{r}, \mathbf{p}, t)$$

$$\mathbf{F} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c) + \mathbf{F}_{\text{rad}}, \qquad \nabla_{\mathbf{p}} \cdot (\mathbf{F}_{\text{rad}} f) = 0 \neq \mathbf{F}_{\text{rad}} \cdot \nabla_{\mathbf{p}} f$$

$$\frac{d}{dt} \int f \ln f \, d^3\mathbf{p} d^3\mathbf{q} = \int f \, d^3\mathbf{p} d^3\mathbf{q} \nabla_{\mathbf{p}} \cdot (\mathbf{F}_{\text{rad}}) < 0$$

- Entropy decrease and phase space contraction because of RF cooling effect

[M. Tamburini et al, NIMA **653** (2011) 181]

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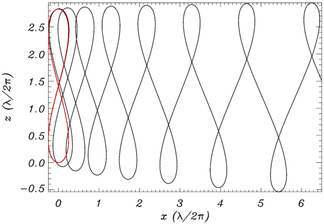

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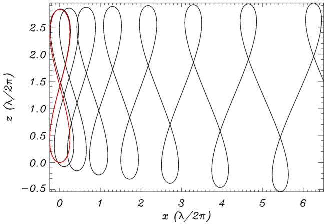

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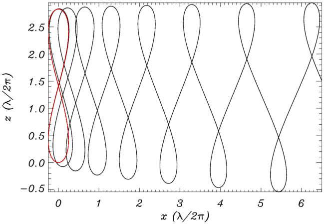

Radiation Reaction modeling - IV

Assume main contribution to RF losses is at wavelengths $\lambda_{\mathrm{RF}} \ll (3/4\pi n_e)^{1/3}$

→ radiation is incoherent and escapes from the plasma; it appears as energy dissipation

In simulations:

- RF-relevant wavelengths are not resolved (smaller than spatial grid resolution); "coherent" wavelengths are double-counted in the RF force but their contribution is small
- radiative losses may be estimated only by comparing results with and without RF included

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Radiation energetics with RF included

1D PIC simulations of laser-plasma interaction with radiation emission calculated as a diagnostic [Capdessus et al., PRE **86**, 036401 (2012)]

$n_e = 10n_c$, $d = 100\lambda$, $\tau_L = 16T$

1e21–1e22–8e22–3e23 W cm^{-2}

With RF (left): energy balance is consistent

Without RF (right): radiative loss $\simeq$ input laser energy for the highest intensity!

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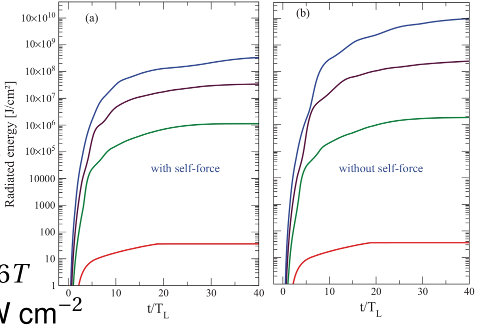

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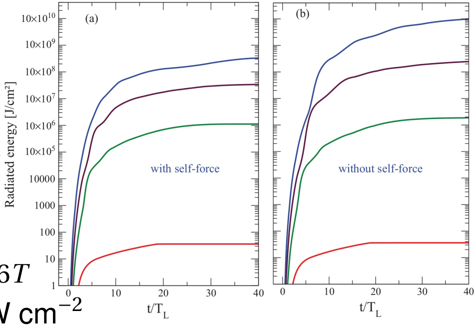

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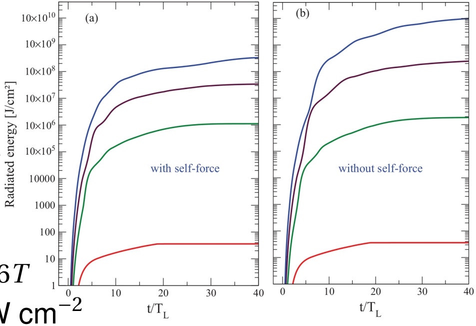

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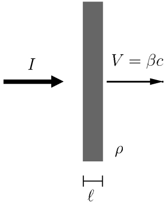
- Motivations:
  Radiation Pressure Dominant Acceleration (RPDA) of thin solid foils by ultra-relativistic laser pulses ($I\lambda^2 > 10^{23}$ W cm$^{-2}\mu$m^2) is a possible route to "unlimited" acceleration towards the GeV/nucleon limit



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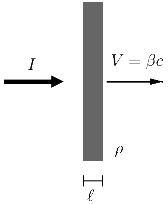

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Radiation Friction/Reaction misunderstanding

Quoting an anonymous referee for Tamburini et al, "*Radiation-pressure-dominant acceleration: Polarization and radiation reaction effects* ..."

- "*The standard PIC algorithm does include the RR when it appears as N^2 effect. For example, the RPDA of plasma is the result of radiation reaction acting on the plasma as a whole [...] The RPDA itself is an example of the RR effect acting on the plasma as a whole. [...] at higher resolution the RR effects become better approximated by the standard PIC algorithm*"

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- Laser pulse: $(9T) \times (10\lambda)^2$ (FWHM) $[T = \lambda/c]$
  Circular (CP) or Linear (LP) polarization
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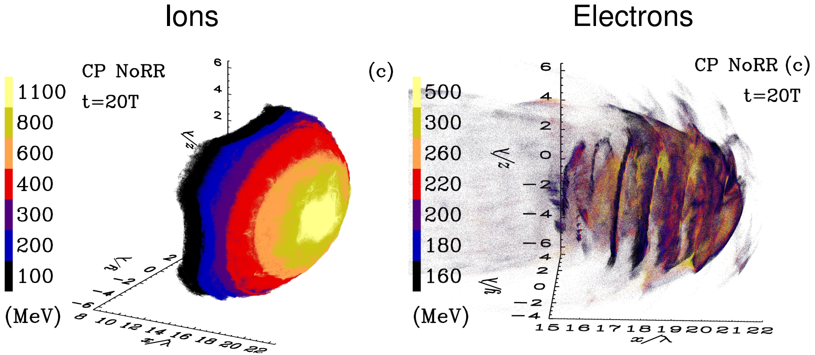
Space-energy distribution: CP, no RF



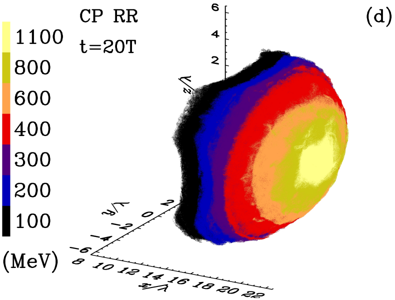
Symmetric, collimated distribution of ions

Cut-off energy of ~ 1.6 GeV at $t = 20T$

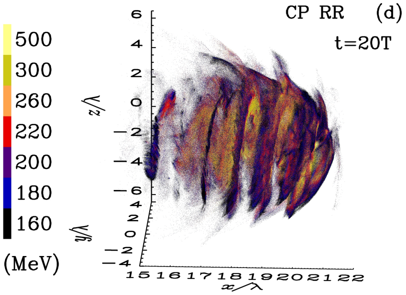
[Tamburini et al, PRE **85** (2012) 016407]

Space-energy distribution: CP, with RF

Ions



Electrons



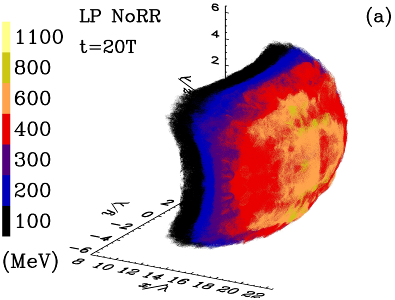
Ion distribution unchanged by RF

Cooling of electrons in pulse tail due to radiative losses

[Tamburini et al, PRE **85** (2012) 016407]

Space-energy distribution: LP, no RF

Ions



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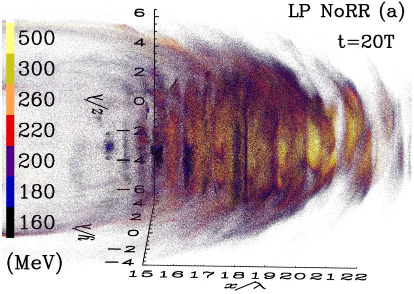
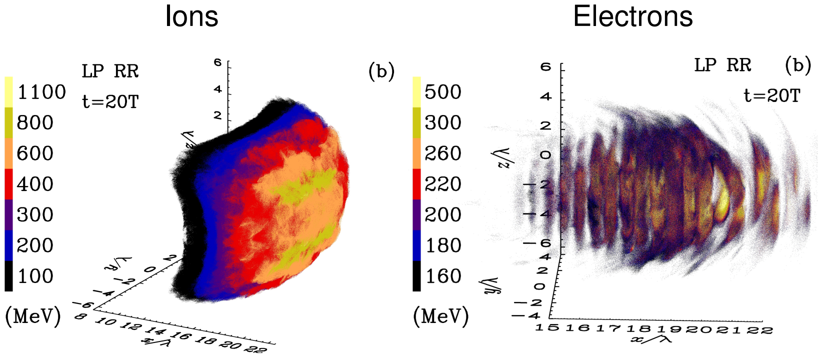


Asymmetric distribution with highest energy ions off-axis

Cut-off energy of ~ 0.9 GeV much lower than for CP

[Tamburini et al, PRE **85** (2012) 016407]

Space-energy distribution: LP, with RF



Strong cooling of electrons by radiative losses

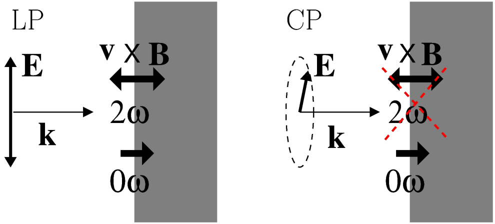
Cut-off energy is *increased* up to ~ 1.1 GeV by RF

[Tamburini et al, PRE **85** (2012) 016407]

Polarization effect on RF losses

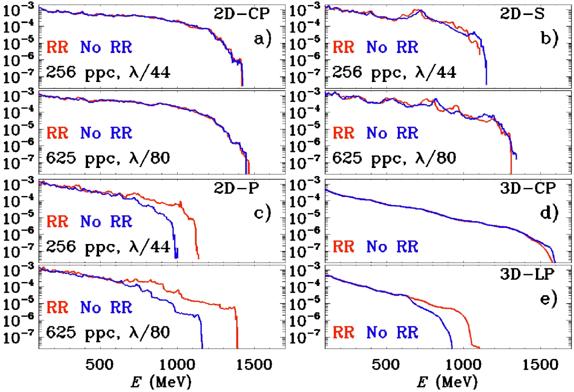
For CP, electrons move coherently with the foil at $v_x \sim c$ and reflection is small $(R \sim (1-v_x/c)/(1+v_x/c))$; they almost co-propagate with the laser pulse $\Rightarrow \mathbf{f}_{\text{rad}} = 0$

For LP, the $\mathbf{J} \times \mathbf{B}$ *oscillating* term causes $v_x \sim -c$ periodically $\Rightarrow$ "colliding" geometry maximizes $\mathbf{f}_{\text{rad}}$



Effects of reduced dimensionality and resolution

Comparison of 3D ion spectra with 2D results (both S and P for LP) for both the same and higher resolution



Effects of 2D vs 3D and of limited resolution are evident, but kept below physical effects

The “optimal” CP case is the most robust (but energy is *lower* in 2D vs 3D !)

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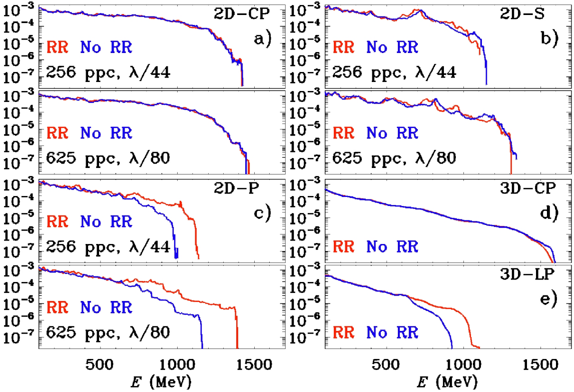

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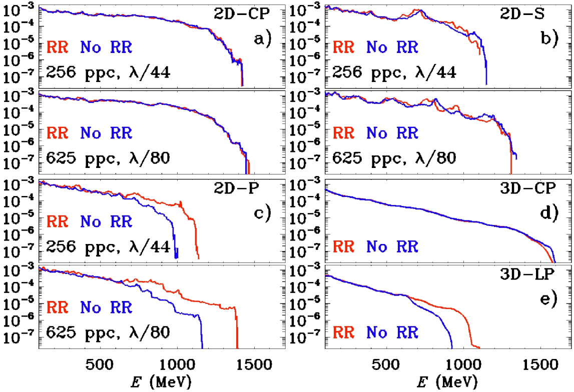

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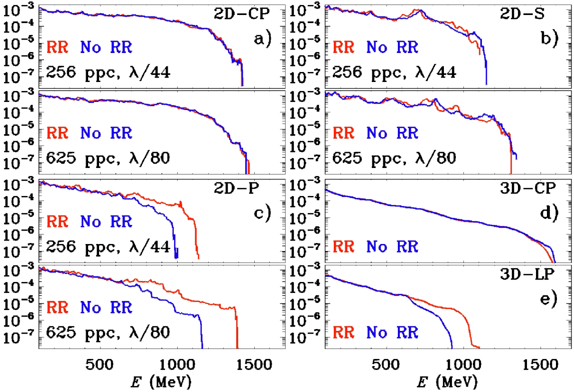

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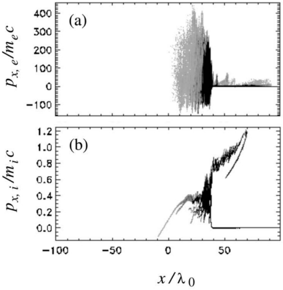
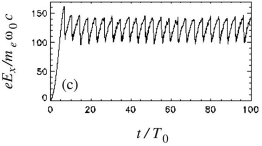
RF losses in thick targets

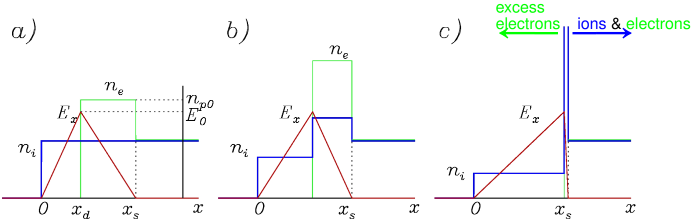
- RF losses are small for thin targets pushed by CP pulses
- But thick targets show major RF losses also for CP!
  [Naumova et al, PRL **102** (2009) 25002; Schlegel et al, PoP **16** (2009) 83103; Nerush & Kostyukov, PPCF **57** (2015) 35007]
- "piston oscillations" produce bunches of returning electrons → collective "collisions" with the laser pulse → high RF losses



Figures from Schlegel et al.
$I = 4 \times 10^{22}$ W cm^{-2}
$a_0 = 100$
$n_e = (10-20)\,n_c$
up to $\sim 40\%$ energy dissipated by RF



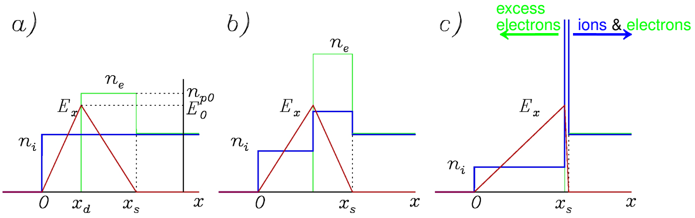
Model for returning electrons in thick targets



- Light pressure generates an excess of electrons in the skin layer and of ions in the depletion layer
- At the end of the acceleration stage, equilibrium between electrostatic tension and ponderomotive force (i.e. local light pressure) is lost

$\longrightarrow$ the excess electrons return quickly towards the laser

Estimating the number of returning electrons



- $eE_0 n_{p0}\ell_s/2 \simeq 2I/c$ (pressure balance) $(\ell_s = x_s - x_d)$
- $E_0 = 4\pi e n_0 d$ (Poisson-Gauss equation)
- $n_{p0}\ell_s = n_0(d+\ell_s)$ (charge conservation)

→ $N_x = (n_{p0} - n_0)\ell_s \simeq n_{p0}\ell_s \simeq a_0/r_c\lambda$
returning electrons per unit surface $(r_c = e^2/m_e c^2)$

Estimating radiation from returning electrons

- Radiation power for an electron in the laser field

$$P_r = \frac{2e^4 E_L^2}{3m_e^2 c^3}\gamma^2\left(1-\frac{v_x}{c}\right)^2 \simeq \frac{8e^4 E_L^2\gamma^2}{3m_e^2 c^3} = \frac{8e^2\omega^2 a_0^2}{3c}$$

- Fraction of laser energy re-emitted as radiation from N_x electrons with $v_x \simeq -1$

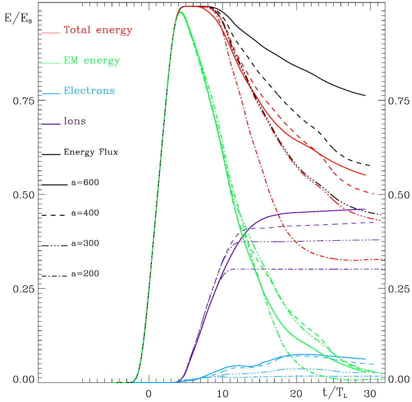
$$\eta \equiv \frac{U_r}{U_L} \simeq \frac{P_r(\tau_L/2)N_x}{E_L^2 c\tau_L/4} \simeq \frac{16}{3}\frac{r_c}{\lambda}\gamma^2 a_0$$

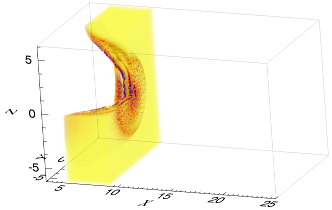
(assuming radiation is emitted for a $\simeq \tau_L/2$ time)

- If $\gamma = (1+a_0^2/2)^{1/2} \simeq a_0/\sqrt{2}$ ($|p_x| \ll |p_\perp|$)

$$\eta \simeq \frac{8r_c}{3c\tau_L}a_0^3$$

Radiation losses in 3D thick target simulations





$n_e = 90 n_c = 1.6 \times 10^{23}$ cm^{-3}

$a_0 = (200 - 600)$

$I = (0.9 - 7.8) \times 10^{23}$ W cm^{-2}

$\eta \simeq 22\%$ for $a_0 = 600$

Scaling $\eta \propto a_0^3$ fairly consistent with the model

Angular momentum absorption

- A CP laser pulse carries "spin" angular momentum (AM) that may be absorbed by the target

$$L_z = \int_0^\infty \ell_z(r) 2\pi r \mathrm{d}r = -\int_0^\infty \frac{r}{2c\omega} \partial_r I(r) 2\pi r \mathrm{d}r$$

- Reflection from a perfect mirror conserves number of photons and does *not* change sign of "spin"

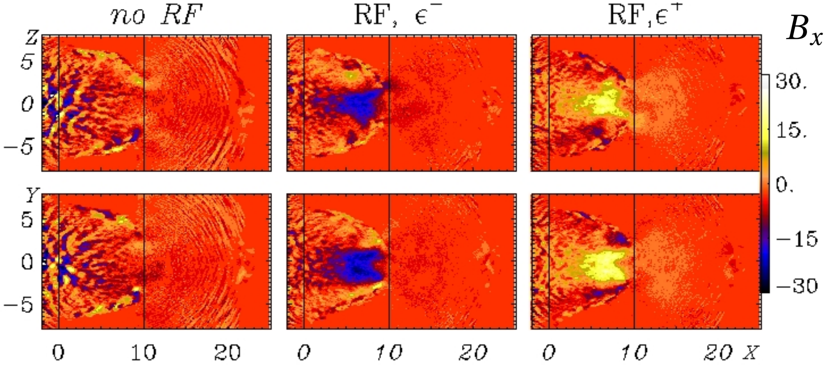
→ No AM absorption if "dissipation" is absent ($A = 0$)

- First 3D simulations of RPA showed very small AM absorption (AMA)

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

- Can RF provide efficient dissipation for AMA?
- Does RF-induced AMA leads to generation of an axial magnetic field ("Inverse Faraday Effect")?

Axial magnetic fields induced by RF



Sign of the B_x field depends on laser pulse helicity

Field amplitude $B_{\max} \simeq 4 \times 10^9$ G for $a_0 = 600$

(units: $B_0 = 2\pi m_e c/(e\lambda) = 1.34 \times 10^8$ G)

B-field saturation and AM transfer to ions

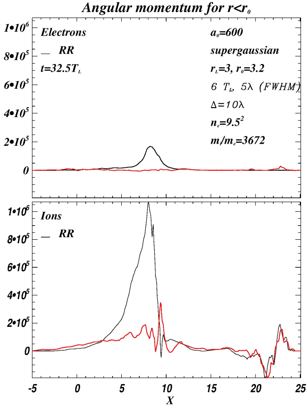
Induced electric field $E_\phi = -(r/2c)\partial_t B_x$ leads to saturation of B_x growth and exerts a torque on ions

$$\frac{dL_e}{dt} = M_{\rm abs} - M_E \, , \qquad \frac{dL_i}{dt} = +M_E$$

For rapid saturation $M_{\rm abs} = P_{\rm abs}/\omega \simeq M_E$
and $L_i \simeq U_{\rm abs}/\omega \gg L_e$
Magnetic field at saturation
(ℓ: thickness, r_L, r_0: pulse length & radius)

$$B_{xs} \simeq 4\eta \frac{r_L}{\ell} \left(\frac{c}{r_0\omega}\right)^2 \frac{n_c}{n_e} a_0^2 B_0$$

consistent with $\eta \simeq 0.2$ and $n_e \simeq 0.1 n_0$
(due to axial density depletion)



Conclusions

- The Landau-Lifshitz "reduced" model is a "good compromise" which allows 3D Particle-In-Cell simulations with Radiation Friction included
- Effects on Light Pressure acceleration strongly depend on laser pulse polarization and target thickness
- Dissipation due to radiation friction leads to absorption of angular momentum from a circularly polarized pulse and generation of multi-Gigagauss axial magnetic fields

  [T. V. Liseykina, S. V. Propruzhenko, A. Macchi, "*Inverse Faraday Effect driven by Radiation Friction*", in preparation]