From Intense Fields to Radiation Dominated Regime

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γ-resist kick-off meeting,
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Outline of the talk

- A "soft" introduction to Radiation Friction
- Landau-Lifshitz approach
- Radiation Friction effects in Laser-Plasma interactions
- The Radiation Dominated Regime
- Radiation Friction signatures in Thomson Scattering

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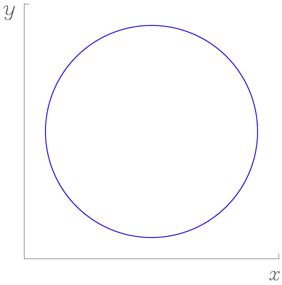
$$m_e \frac{d\mathbf{v}}{dt} = \mathbf{f}_L = -\frac{e}{c}\mathbf{v} \times \mathbf{B}_0$$

Solution: uniform circular motion

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

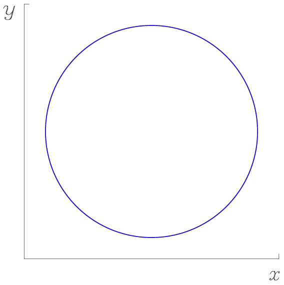
$$K = \frac{1}{2} m_e \upsilon^2 = \text{cost.} \qquad \omega_c = \frac{eB_0}{m_e c} \qquad r = \frac{\upsilon}{\omega_c}$$



Introducing Radiation Friction

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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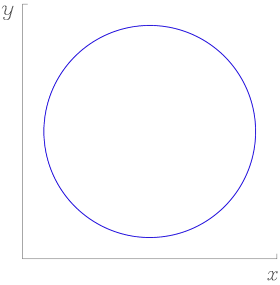
Energy loss due to radiation:

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

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



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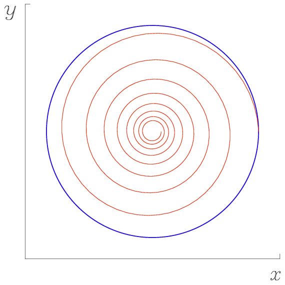

If $r(t) \simeq v(t)/\omega_c$, electron "falls" along a spiral

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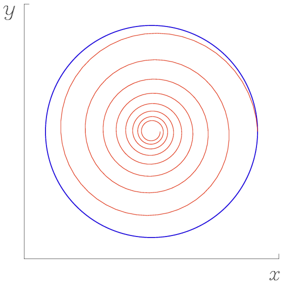
The Lorentz force does not describe the electron motion consistently: need to include an extra force



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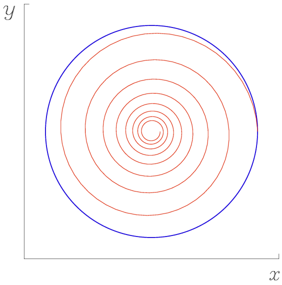
The Lorentz force does not describe the electron motion consistently: need to include an extra force

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



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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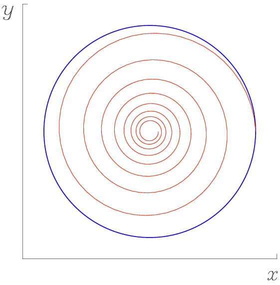

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Physical interpretation: the electron is affected by the self-generated radiation field (radiation *reaction* or *self-force*)

Landau-Lifshitz approach

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

- unphysical runaway solutions $\dot{\mathbf{v}}(t) = \dot{\mathbf{v}}(0)\mathrm{e}^{t/\tau}$
- need of “extra” initial condition $\dot{\mathbf{v}}(0)$

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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

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Iterative approach valid if $|\mathbf{f}_{\text{rad}}| \ll |e\mathbf{E}|$ in the instantaneous frame

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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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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:

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

Dominant term ($\sim -\gamma^2\mathbf{v}$) acts as nonlinear friction

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Inclusion of RR in plasma modeling and simulation

Kinetic equation for electrons

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

$$\mathbf{F} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}/c) + \mathbf{f}_{\text{rad}}$$

- Eq.(*) is solved by the Particle-In-Cell approach
- Including RF accounts for loss of incoherent radiation of wavelength $\lambda \ll {n_e}^{-1/3}$: system becomes dissipative

[see e.g. Tamburini, Pegoraro, Di Piazza, Keitel, Macchi, New J. Phys. **12**, 123005 (2010)]

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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!

$\Longrightarrow$ RF inclusion is necessary at intensities $> 10^{22}$ W cm^{-2}

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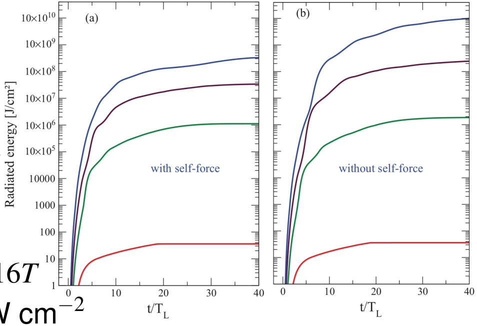

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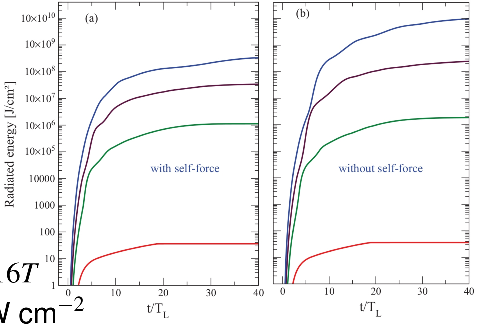

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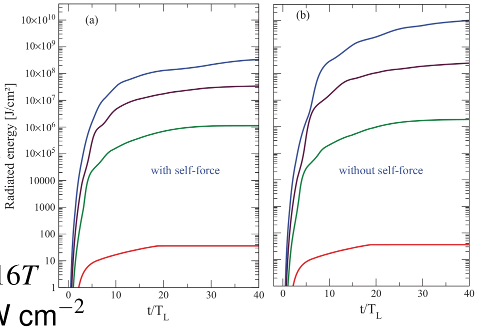

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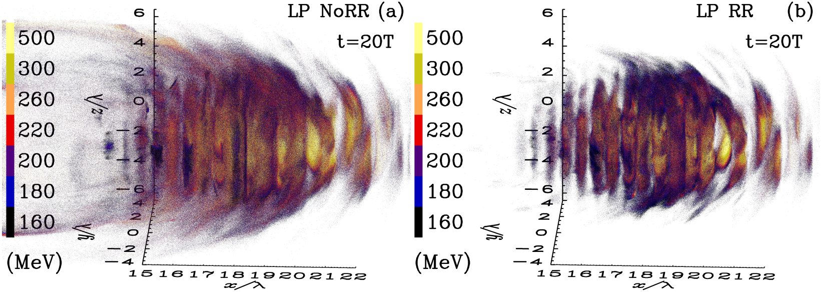
3D PIC simulations with RF included



Thin foil acceleration ($d = 1\lambda$, $n_e = 64 n_c$, $I = 1.7 \times 10^{23}$ W cm^{-2})

Space-Energy electron distribution without (left) & with (right) RF

[Tamburini, Liseykina, Pegoraro, Macchi, PRE **85**, 016407 (2012)]

Radiation Dominated Regime

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

RDR in a laser field: (radiation loss)$\simeq$(initial energy)
Electron counterpropagating to laser field $\Rightarrow$ $\mathbf{f}_{\text{rad}}$ is maximized
$\Rightarrow$ Thomson scattering geometry "enhances" RF effects

$$P_{\text{rad}}\frac{2\pi}{\omega} \simeq \mathscr{E}_{\text{osc}} = m_e c^2 \left[\left(1+\frac{\mathbf{p}^2}{m_e c^2}\right)^{1/2} - 1\right]$$

$$R \equiv \frac{2 r_c \omega}{3c}\gamma_0(1+\beta_0)a^2 \simeq 1 \qquad a = \frac{eE}{m_e \omega c}$$

($\beta_0 = v_0/c$, $\gamma_0 = (1-\beta_0^2)^{-1/2}$ 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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RDR in a laser field: (radiation loss)≃(initial energy)
Electron counterpropagating to laser field ⇒ $\mathbf{f}_{\text{rad}}$ is maximized
⇒ Thomson scattering geometry "enhances" RF effects

$$P_{\text{rad}}\frac{2\pi}{\omega} \simeq \mathscr{E}_{\text{osc}} = m_e c^2\left[\left(1+\frac{\mathbf{p}^2}{m_e c^2}\right)^{1/2} - 1\right]$$

$$R \equiv \frac{2r_c\omega}{3c}\gamma_0(1+\beta_0)a^2 \simeq 1 \qquad a = \frac{eE}{m_e\omega c}$$

($\beta_0 = v_0/c$, $\gamma_0 = (1-\beta_0^2)^{-1/2}$ 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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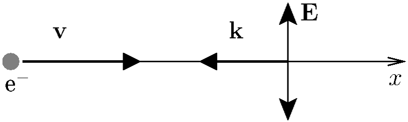
Thomson Scattering with RF included

TS of a 35 fs pulse by 150 MeV electrons



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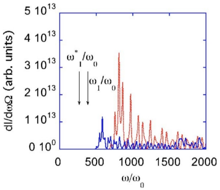
$a_0 = 30$



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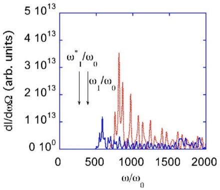

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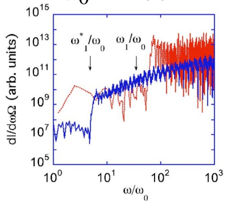

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Total power and low-frequency cut-off are strongly affected by RF already when $R \ll 1$

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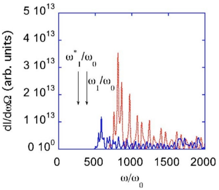

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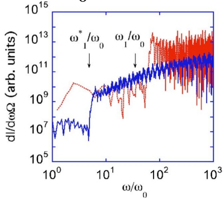

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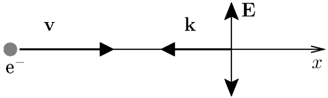
Angular RF signatures in Thomson Scattering

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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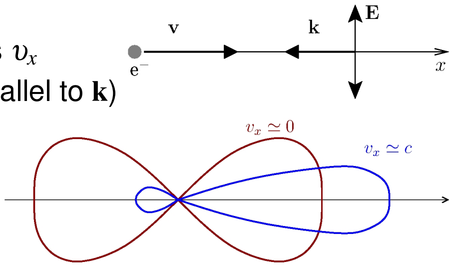

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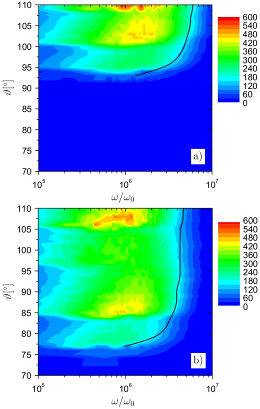

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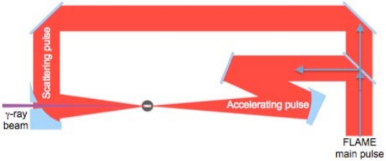
"All-Optical" TS as a test bed for RF?



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  - large number of electrons for strong signal
  - short electron bunch duration
  - easier synchronization with laser pulse
- FLAME parameters are possibly still under threshold for detectable RF effects, but AO-TS characterization may be considered as a "feasibility study"

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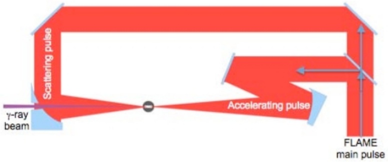

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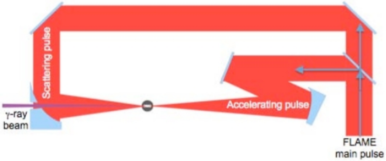

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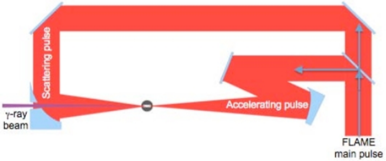

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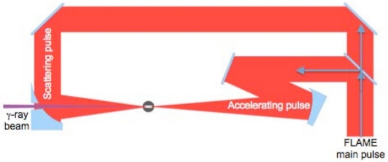

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