High-energy photon emission and its back-reaction in laser-plasma interaction

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Context & Motivations

- PW and multi-PW laser facilities soon available in Europe :
  - Apollon 10PW (150 J / 15 fs), France
  - Vulcan 10P (300 J / 30 fs), UK
  - Extreme Light Infrastructure (ELI), Europe

- copious emission of high-energy photons (x-ray and γ domains)

- beyond 10^{22} W/cm^2, a non-negligible part of the incident laser power is radiated away

- back-reaction effect of photon emission on the electron dynamics has to be accounted for

- necessity to develop our simulation capabilities :
  - modified PIC codes
  - dedicated diagnostics
  - new theoretical modeling

Part I

General discussion

How to account for radiation friction in PIC codes?

Prior works (non-exhaustive)

Monte-Carlo modeling of radiation reaction in PIC codes

- Ridgers et al., Phys. Rev. Lett. **108**, 165006 (2012)

  - 10 PW laser striking a 1μm Al foil
  - synchroton radiation γ-ray photons (~ 25 MeV, conv. efficiency up to 35%)
  - electron-positron pair-creation (Breit-Wheeler process $\gamma_h + n\,\gamma_0 \rightarrow e^- + e^+$)
  - positron density ~ 10^{20} cm^{-3} with average energy 250 MeV

- Elkina et al., Phys. Rev. ST Accel. Beams **14**, 054401(2011)

  - radiation reaction & electron-positron-photon cascade
  - Poster during this workshop

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In the limit of classical electrodynamics (CED), radiation reaction follows from the incoherent emission of many photons but all with a small recoil (no jerk/straggling)

$$\chi_e = \frac{E'}{E_S} \ll 1$$

Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012)

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« Continuous » modeling : the radiation reaction force

- Schlegel et al., Phys. Plasmas **16**, 083103 (2009)

  - effect of radiation reaction on laser-driven hole-boring of thick targets
  - strong modification of the electron/ion dynamics
  - in particular for linearly polarized light

- Tamburini et al., New J, Phys. **12**, 123005 (2010)
  Chen et al., Plasma Phys. Control. Fusion **53**, 014004 (2011)
  Capdessus et al., Phys. Rev. E **86**, 036401 (2012)

  - effect of radiation friction on radiation pressure acceleration of thin foils
  - strong modification of the electron/ion dynamics for thin enough foils

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The RR force main effect is to reduce backward electron motion (toward the laser) thus reducing electron longitudinal heating

The Landau-Lifshitz Radiation Reaction Force

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- **The Lorentz-Abraham-Dirac (LAD) equation**

$$\frac{d}{d\tau}u^i = \frac{e}{m}F^{ik}\,u_k + \kappa\, g^i$$

look for g^i such that : (i) $u_i\, g^i = 0$
(ii) $g \to \ddot{v}$ for $v \ll c$

$$g^i = \frac{d^2u^i}{d\tau^2} + \frac{du_k}{d\tau}\frac{du^k}{d\tau}u^i$$

- formally allows for unphysical solutions
- inconsistencies are removed in the limit:

$$\alpha\,\chi_e \ll 1 \quad (\alpha = 1/137)$$

-friction force is small in the instantaneous rest-frame

- **The LL radiation reaction force**

$$g^i = \partial_l F^{ik}\,u_k\,u^l + F^{il}\,F_{lk}\,u^k + (F_{kl}\,u^l)\,(F^{km}\,u_m)\,u^i$$

- free of the LAD inconsistencies
- the RR force is **not** necessarily small in the laboratory-frame
- for ultra-relativistic particles, the 3rd term dominates:

$$\mathbf{f} = -\kappa\,\gamma^2\,\mathbf{f}_L^2\,(1 - \mathbf{v}^2\,\cos^2\theta)\,\mathbf{v}$$

Landau & Lifshitz, *The classical theory of fields* (§75,76)
Di Piazza et al., Rev. Mod. Phys. **84**, 1177 (2012), Talk on Friday 11am

The 1D3V PIC code SQUASH

Initialization

- (Macro-)particle positions and momenta are initialized
  - given density distribution: $n_s(t=0,\mathbf{x})$
  - given energy distribution (Maxwell, Maxwell-Juttner): $T_s(t=0,\mathbf{x})$
- Electromagnetic fields are initialized so that: $\nabla\cdot\mathbf{E}=\rho$ and $\nabla\cdot\mathbf{B}=0$.

PIC algorithm (time loop)

Field Interpolation

$$[\mathbf{E}(\mathbf{x}),\mathbf{B}(\mathbf{x})]\rightarrow[\mathbf{E^j},\mathbf{B^j}]$$

Particle Pusher (Boris-like)

$$\partial_t\,\mathbf{u}^j=\mathbf{F_L}^j+\mathbf{F_R}^j$$

$$\partial_t\,\mathbf{x}^j=\frac{\mathbf{u}^j}{\gamma^j}$$

$$P^j_{rad}\,,\,\omega^j_c$$

Charge & Current Projection*

$$[\mathbf{x^j},\mathbf{u^j}]\rightarrow[\rho(\mathbf{x}),\mathbf{J}(\mathbf{x})]$$

Maxwell Solver

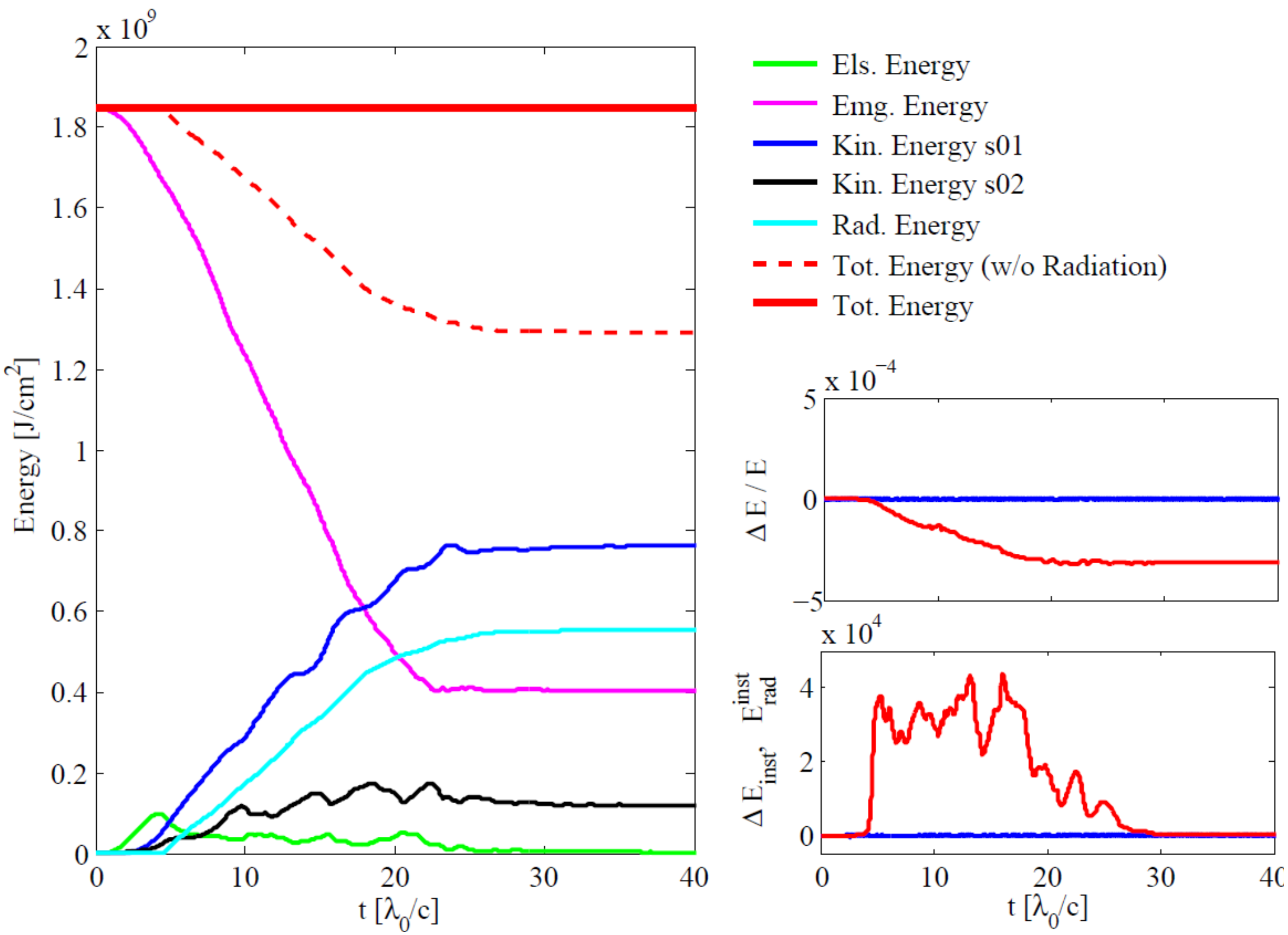
$$\partial_t\,\mathbf{E}=\nabla\times\mathbf{B}-\mathbf{J}$$

$$\partial_t\,\mathbf{B}=-\nabla\times\mathbf{E}$$

Grech et al., in preparation

(*) Ensuring charge conservation

The 1D3V PIC code SQUASH



Grech et al., in preparation

Part II

Application

Circularly-Polarized Laser Pulse Interaction with Semi-Infinite Targets

Simulation parameters

- Relativistic units: $c = 1,\ \omega_0\, t \to t,\ k_0\, x \to x,\ n_0/n_c \to n_0,\ E/E_c = a_0$

- Circularly polarized laser pulse ($\lambda_0 = 1\ \mu\mathrm{m}$):

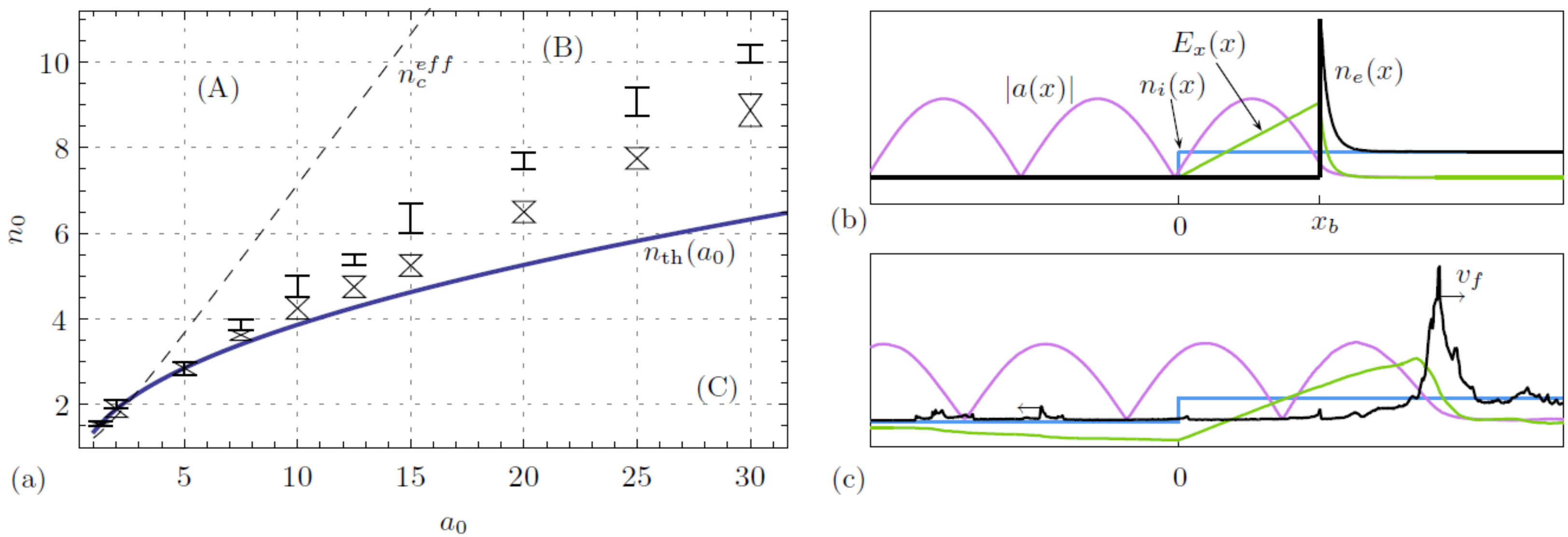
$$\mathbf{A}(t,x) = \frac{a_0}{\sqrt{2}}\,[\cos(t-x)\,\hat{\mathbf{y}} + \sin(t-x)\,\hat{\mathbf{z}}]$$

  - « infinitely » long pulse with sharp ramp-up
  - short pulse with sharp ramp-up/down
  - $a_0 = 25 - 200 \quad (I_L \sim 10^{21} - 5\times 10^{22}\ \mathrm{W/cm^2})$

- Overdense plasma: $n_0 = 1 - 30$
  - semi-infinite targets
  - constant density
  - immobile ions / deuterieum

- Numerical parameters:
  - $dt = \tau_0/1000,\ dx = \lambda_0/500$
  - up to 500 particles / mesh

Relativistic Self-Induced Transparency (RSIT)
(1) Immobile Ions ($m_i \to \infty$)



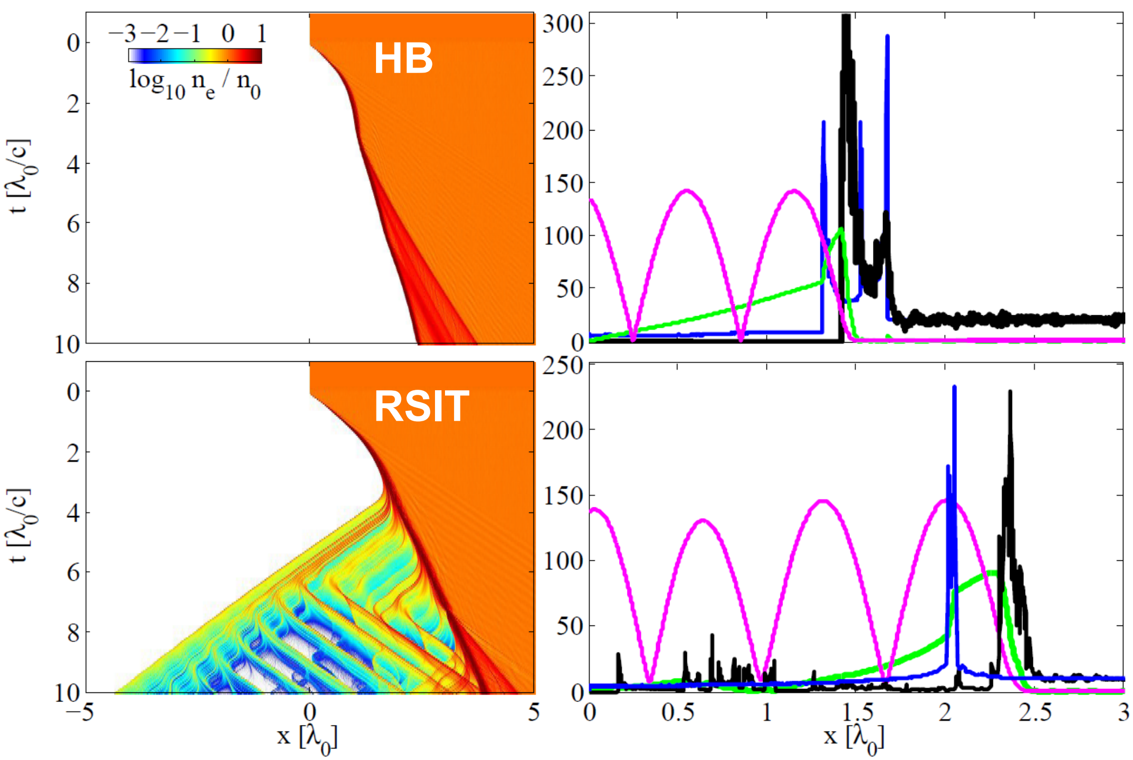
- the *opaque regime* of interaction is characterized by a stationary state
- RSIT is triggered by escaping electrons
- strong electrostatic fields $\sim \sqrt{2}a_0$ are created at the laser front
- for $a_0 \gg 1$, ion motion has to be accounted for !

⚠ RSIT here means that an *infinitely long* laser pulse will burn through the plasma

Siminos et al., arXiv 1209.3322, Poster at this workshop

Relativistic Self-Induced Transparency (RSIT)
(2) Moving Ions: RSIT vs. Hole-Boring (HB)

$$a_0 = 100\,, \quad n_0 = 10 - 20$$



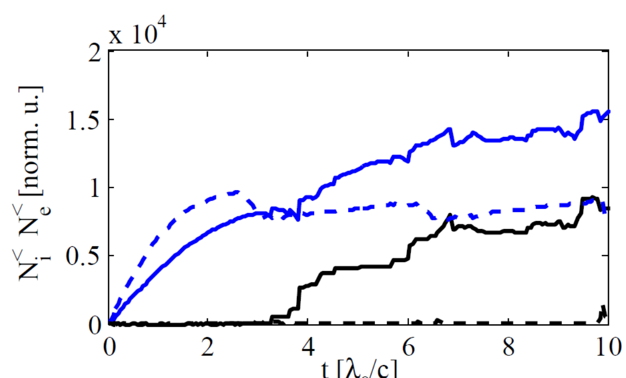
- in the **HB regime**, the laser pulse is reflected by the ion-electron front (so-called piston) which moves at constant velocity:

$$v_p = \frac{a_0/\sqrt{2\,m_i\,n_{i0}}}{1 + a_0/\sqrt{2\,m_i\,n_{i0}}}$$

- when the piston is formed, HB occurs and the target is opaque to the laser

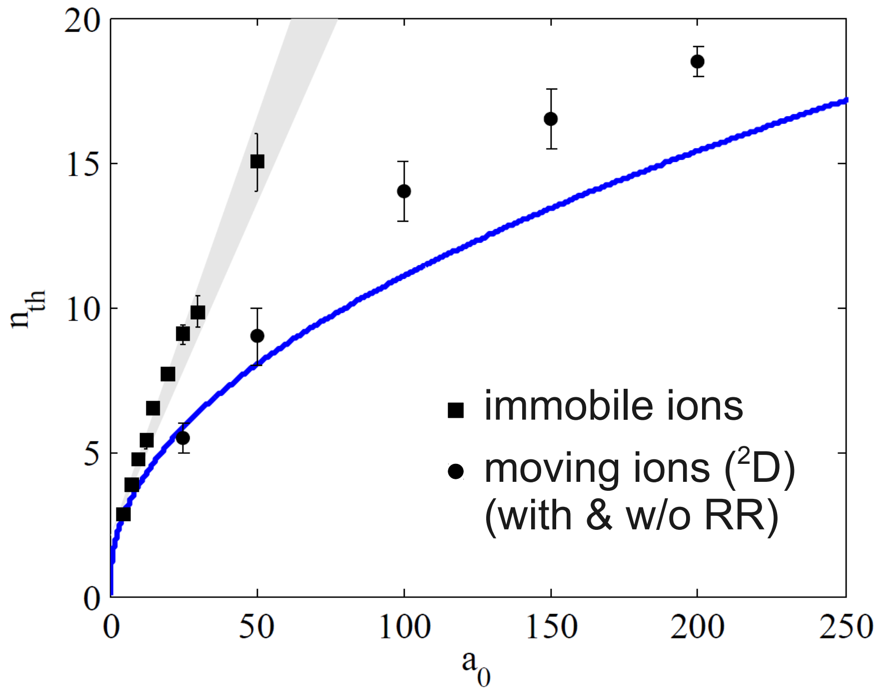
Schlegel et al., Phys. Plasmas **16**, 083103 (2009)

- **RSIT** is triggered by escaping electrons
- the number of both electrons and ions upstream of the « piston » increases
- eventually the piston is destroyed



RSIT / HB threshold

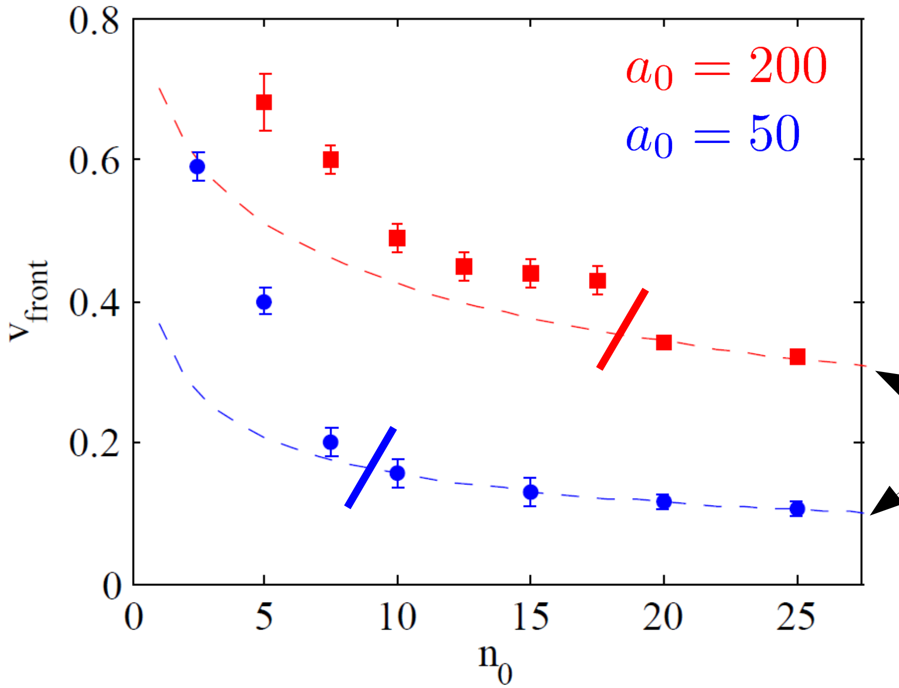
Effective critical density



- ion motion decreases the effective critical density
- the piston structure is « really robust »
- the radiation reaction force does not influence the threshold!

Effect of radiation reaction on the laser front propagation

Laser front propagation velocity



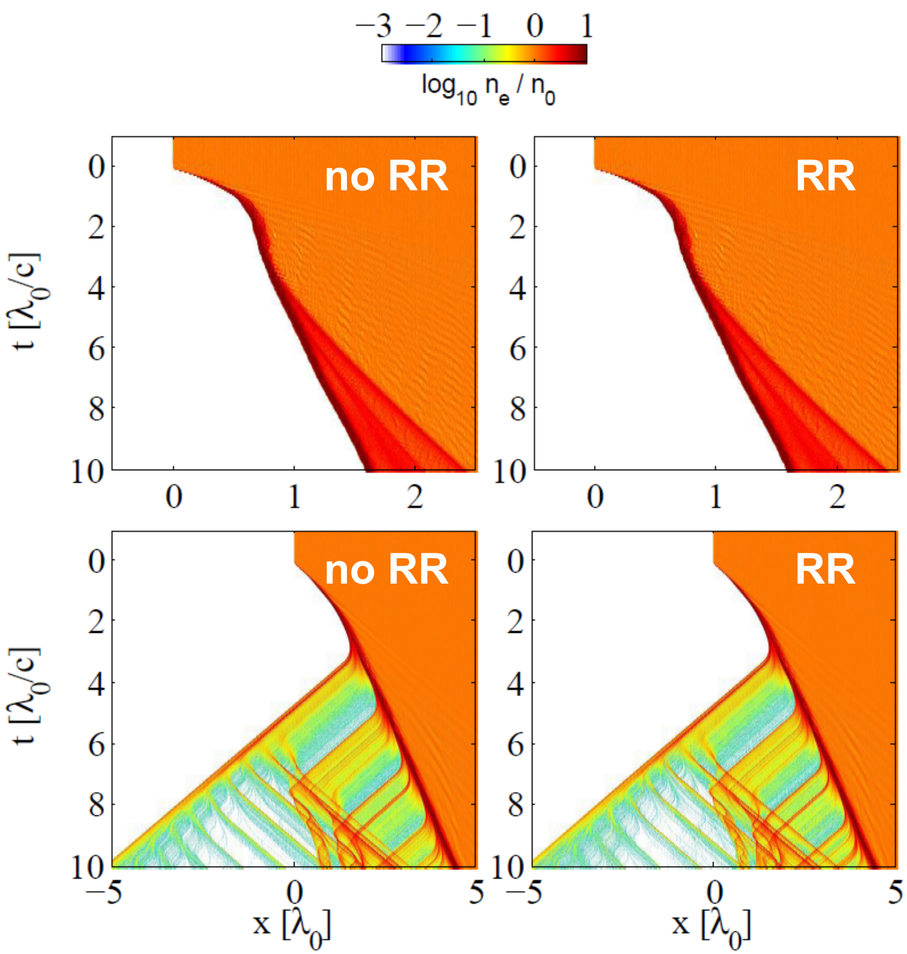
piston prediction

$$v_p = \frac{a_0/\sqrt{2\, m_i\, n_{i0}}}{1 + a_0/\sqrt{2\, m_i\, n_{i0}}}$$

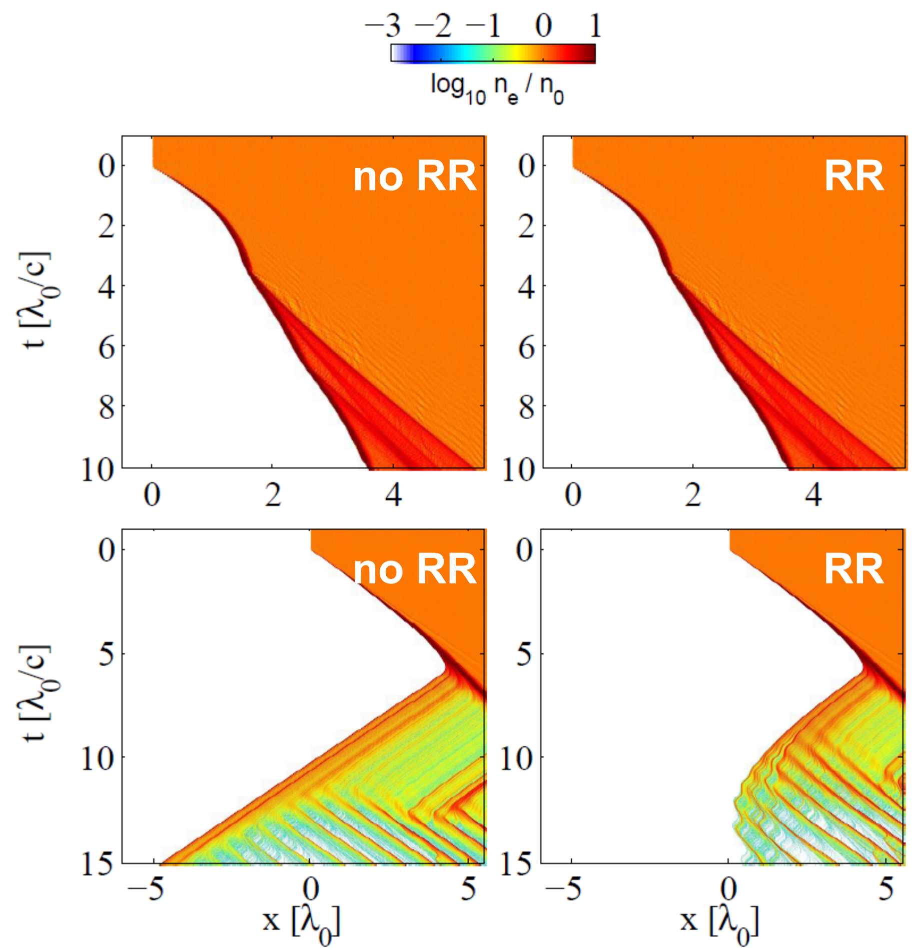
- in the HB regime, front velocity = piston velocity
- in the RSIT regime, front velocity >> piston velocity
- simulations accounting for RR give the same value for the piston velocity

Effect of radiation reaction on the plasma dynamics

$a_0 = 50 \quad (I_L \sim 3 \times 10^{21}\ \mathrm{W/cm^2})$



$a_0 = 200 \quad (I_L \sim 5 \times 10^{22}\ \mathrm{W/cm^2})$



- Radiation reaction (RR) does not influence LPI in the HB regime (evanescent field)
- For intensities $I_L \gtrsim 10^{22}\ \mathrm{W/cm^2}$ $(a_0 > 100)$, RR significantly modifies electron motion

High-energy photon emission
(1) conversion efficiency

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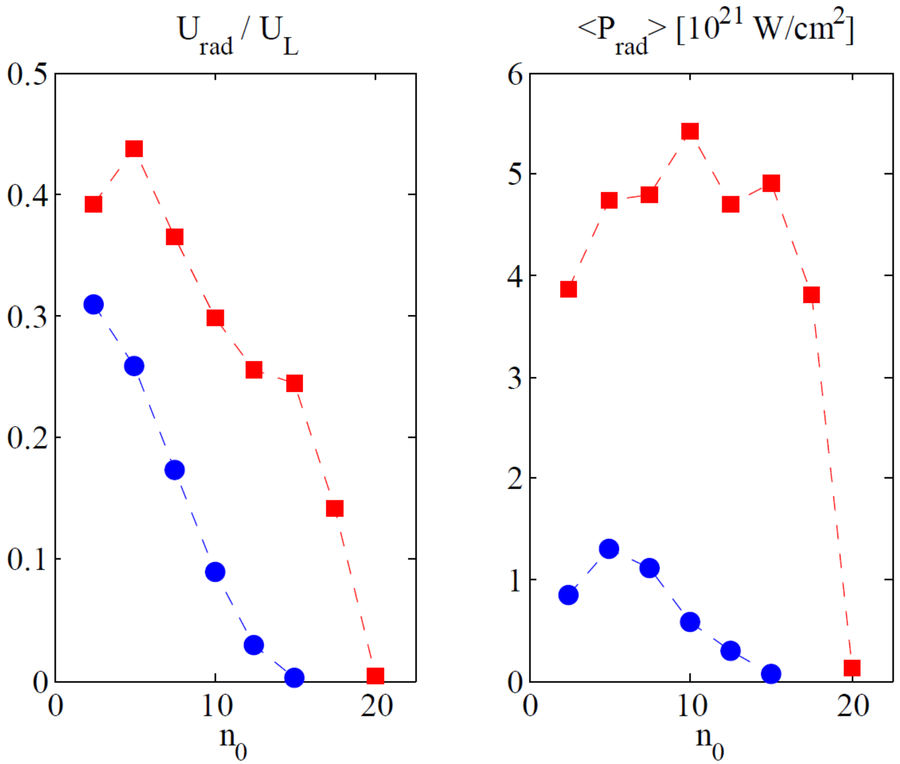
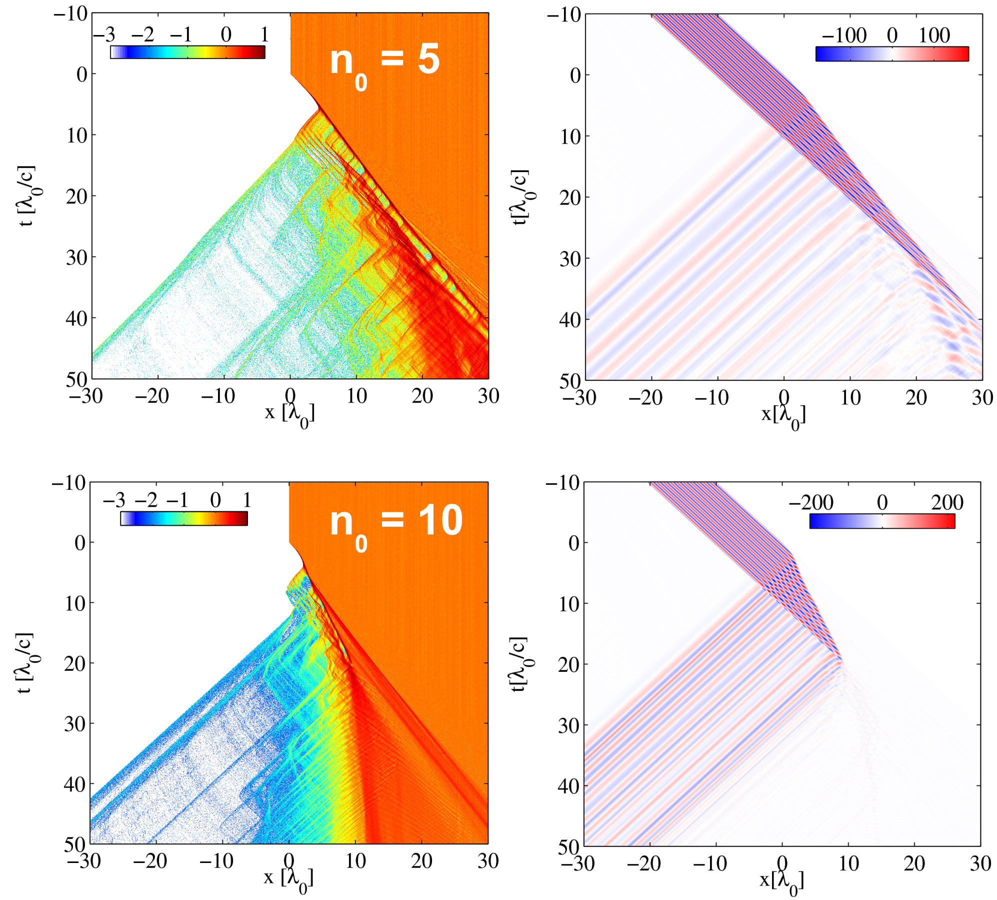
Conversion efficiency & Average radiated power





- The overall emission depends on:

  (i) the number of emitting electrons,

  (ii) the intensity at which the electrons radiate,

  (iii) how long they radiate.

High-energy photon emission (2) spectral properties

(WORK IN PROGRESS)

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Synchroton radiation diagnostics

- Incoherent radiation:

$$P^j_{\rm rad} = \alpha^j \, \Delta x \, \hat{P}^j_{rad} \Leftrightarrow 2\pi \, c/\omega_\gamma \ll n_e^{1/3}$$

$$\hat{P}^j_{\rm rad} = \alpha^j \left[\gamma^2 \left(\frac{d\mathbf{p}^j}{dt} \right)^2 - \left(\mathbf{p}^j \cdot \frac{d\mathbf{p}^j}{dt} \right)^2 \right]$$

- Only ultra-relativistic particles (γ >>1) radiate high-energy photons

$$\langle \gamma \rangle = \frac{\sum_j \gamma^j \, P^j_{rad}}{\sum^j P^j_{rad}} \gtrsim 100$$

- Synchroton-like radiation is emitted in the direction of the particle velocity ($1/\gamma$)

$$\frac{dI}{d\omega} \sim \gamma \, \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(x) \, dx$$

$$\omega_c = \gamma^2 \, \frac{\mathbf{p}^j \times d\mathbf{p}^j/dt}{\mathbf{p}^{j2}} \sim 10 \text{ MeV}$$

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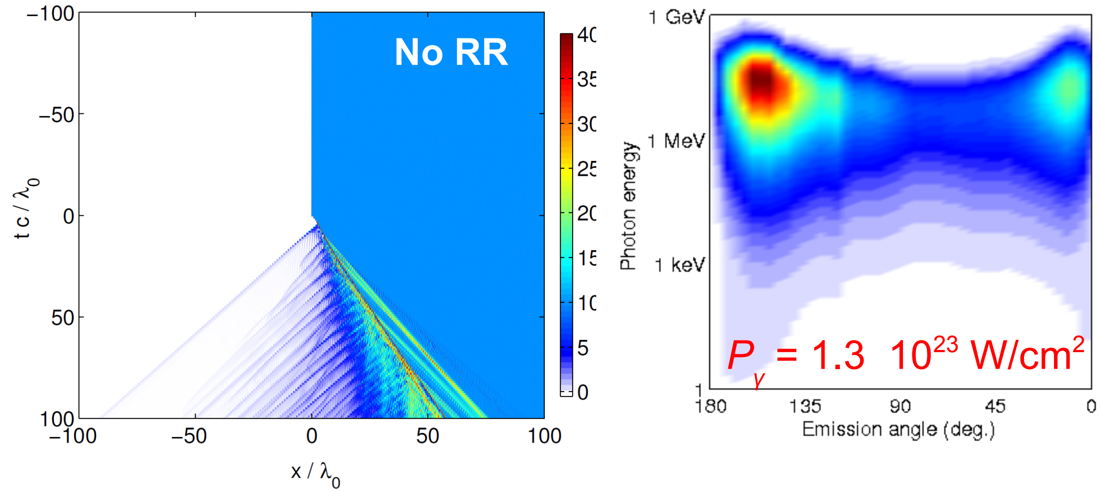
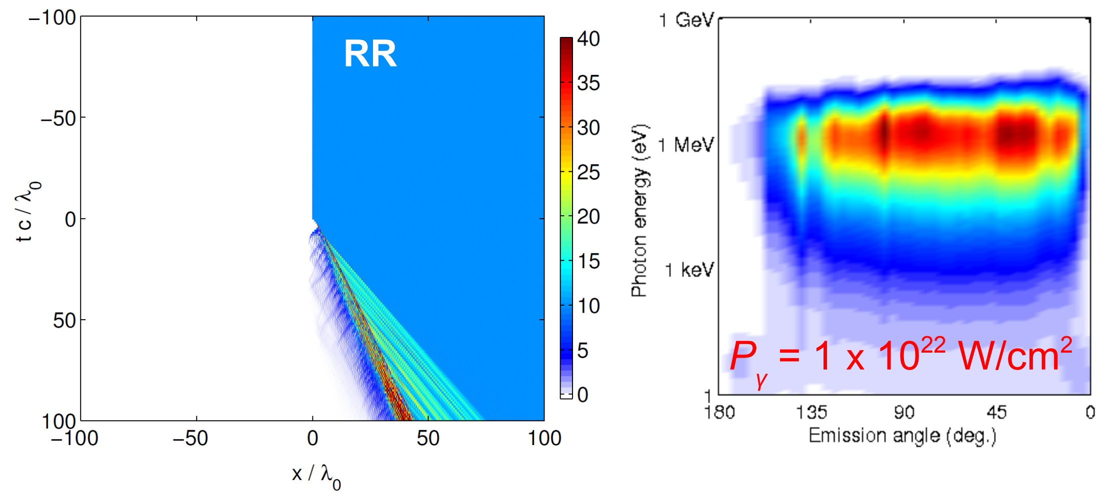
$$a_0 = 250 \; (I_L \sim 8 \times 10^{22} \; \mathrm{W/cm^2})$$





Part III

Conclusions & Perspectives

Conclusions & Perspectives

- RR has been introduced in the PIC code SQUASH
  - Landau-Lifshitz model
  - Boris pusher
  - energy conservation (error ~ 10^{-4})

- Transition between RSIT & HB (opaque regime)
  - RSIT triggerred by escaping electrons
  - strongly influence by ion motion
  - not influenced by RR

- RR develops in the RSIT regime
  - no modification of LPI in the opaque regime (evanescent field)
  - electron motion strongly modified (electron reflected after few wavelength)

- What about Quantum effects ?
  - $a_0 \sim 100 \rightarrow \xi_e \lesssim 0.1$ CED & friction force works fine
  - $a_0 \gtrsim 200 \rightarrow \xi_e \gtrsim 0.5$ QED effects should kick-in (MC)

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Thanks for your attention !

The synchroton radiation model

- From radiating macroparticles to radiating particles : **incoherent radiation**

$$P^j_{\rm rad} = \alpha^j \, \Delta x \, \hat{P}^j_{rad} \Leftrightarrow 2\pi \, c/\omega_\gamma \ll n_e^{1/3}$$

- Frequency & angle spectra of emitted radiations : basic approach

$$\frac{d^2 I}{d\omega \, d\Omega} = \omega^2 \left| \int_{-\infty}^{\infty} \mathbf{n} \times (\mathbf{n} \times \mathbf{v}) \, \exp\left[i \, \omega \, (t - \mathbf{n} \cdot \mathbf{r}(t)/c) \right] \right|^2$$

- fast oscillating term
- requires to know the particle trajectory at all times !

- We assume only ultra-relativistic particles ($\gamma >> 1$) radiate high-energy photons

- Synchroton-like radiation is emitted in the direction of the particle velocity ($1/\gamma$)

$$\hat{P}^j_{\rm rad} = \alpha^j \left[\gamma^2 \left(\frac{d\mathbf{p}^j}{dt} \right)^2 - \left(\mathbf{p}^j \cdot \frac{d\mathbf{p}^j}{dt} \right)^2 \right]$$

$$\frac{dI}{d\omega} \sim \gamma \, \frac{\omega}{\omega_c} \int_{\omega/\omega_c}^{\infty} K_{5/3}(x) \, dx \quad \text{where} \quad \omega_c = \gamma^2 \, \frac{\mathbf{p}^j \times d\mathbf{p}^j / dt}{\mathbf{p}^{j2}}$$

Parameters for the PIC simulations

- **Laser parameters :**

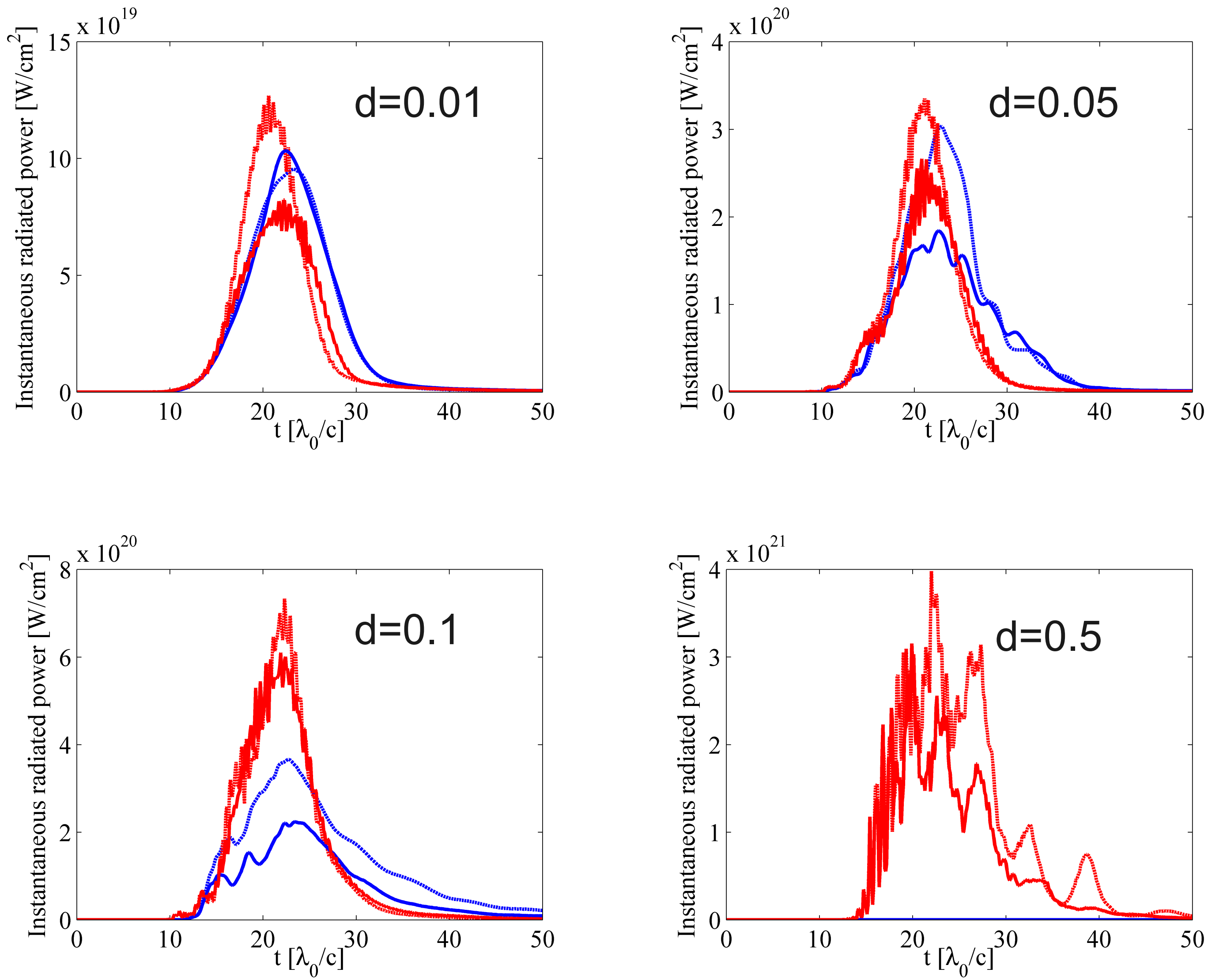
  - normally incident from $x<0$ onto the target at $x = 0$
  - both circular and linear polarization have been used
    the laser intensity is defined uniquely by $a_0 = 200$ (5×10^{22} W/cm^2)
  - a short (10 optical cycles FWHM) Gaussian pulse is considered
  - wavelength 1 micron

- **Plasma parameters :**

  - deuterium slab
  - electron density 100 n_C
  - thickness in the range 10^{-2} – 1 laser wavelength

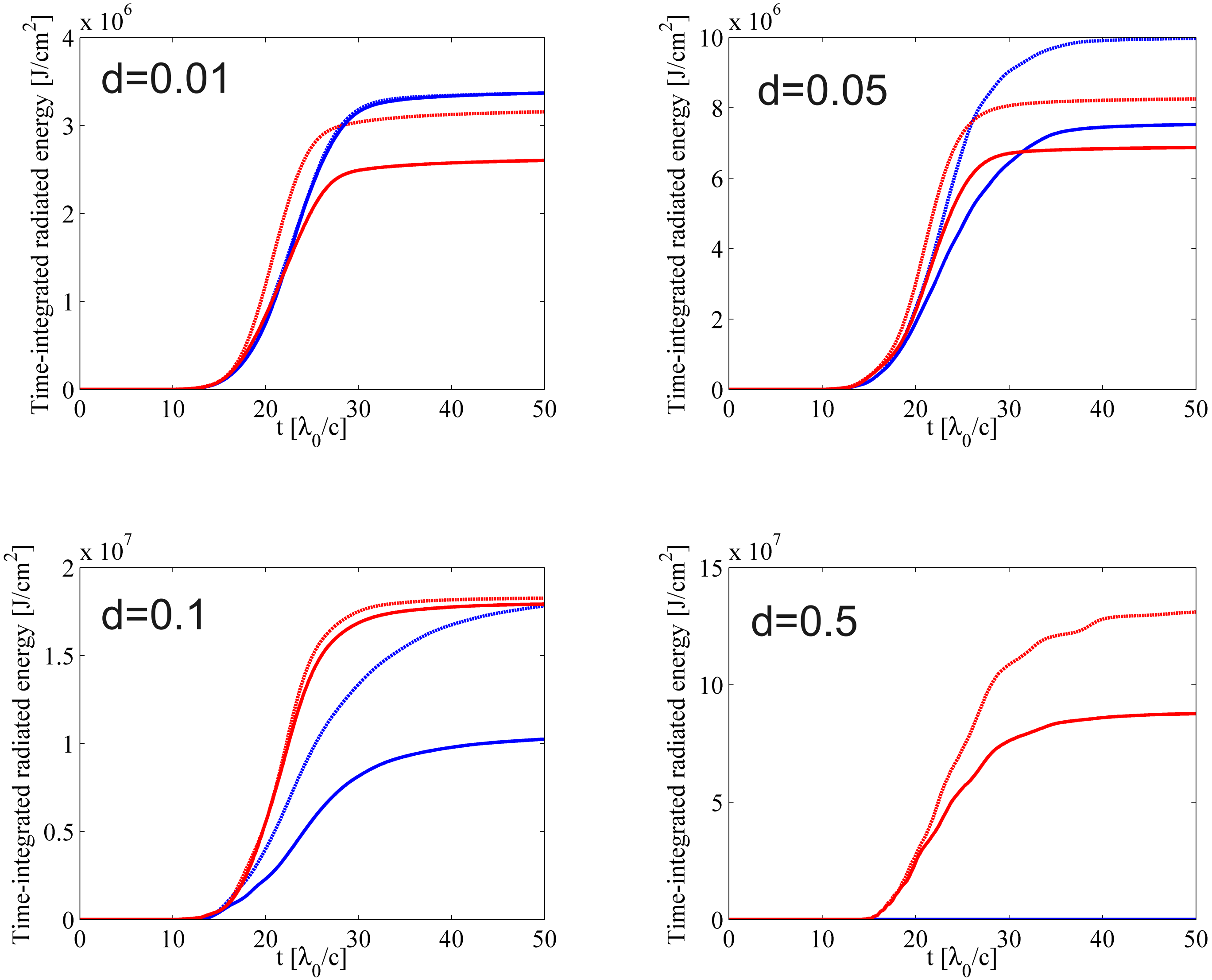
Instantaneous radiated power

Linear polarization
Circular Polarization
- - - w/o self-force
___ with self-force



NB : to be compared to the maximumlaser incident power : 5 x 10^{22} W/cm^2

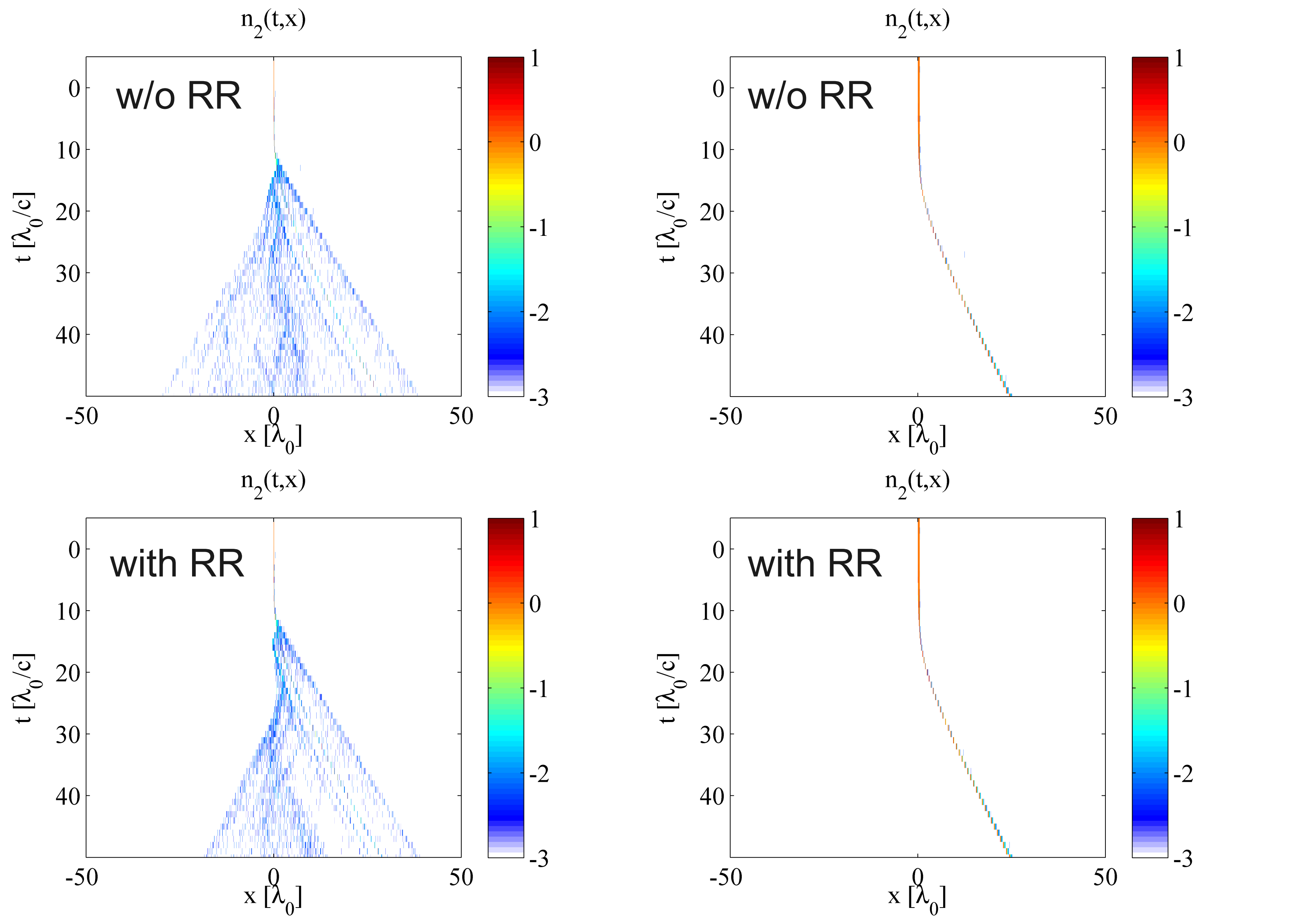
Time-integrated radiated energy



NB : to be compared to the total laser incident energy : 2 x 10^9 J/cm^2

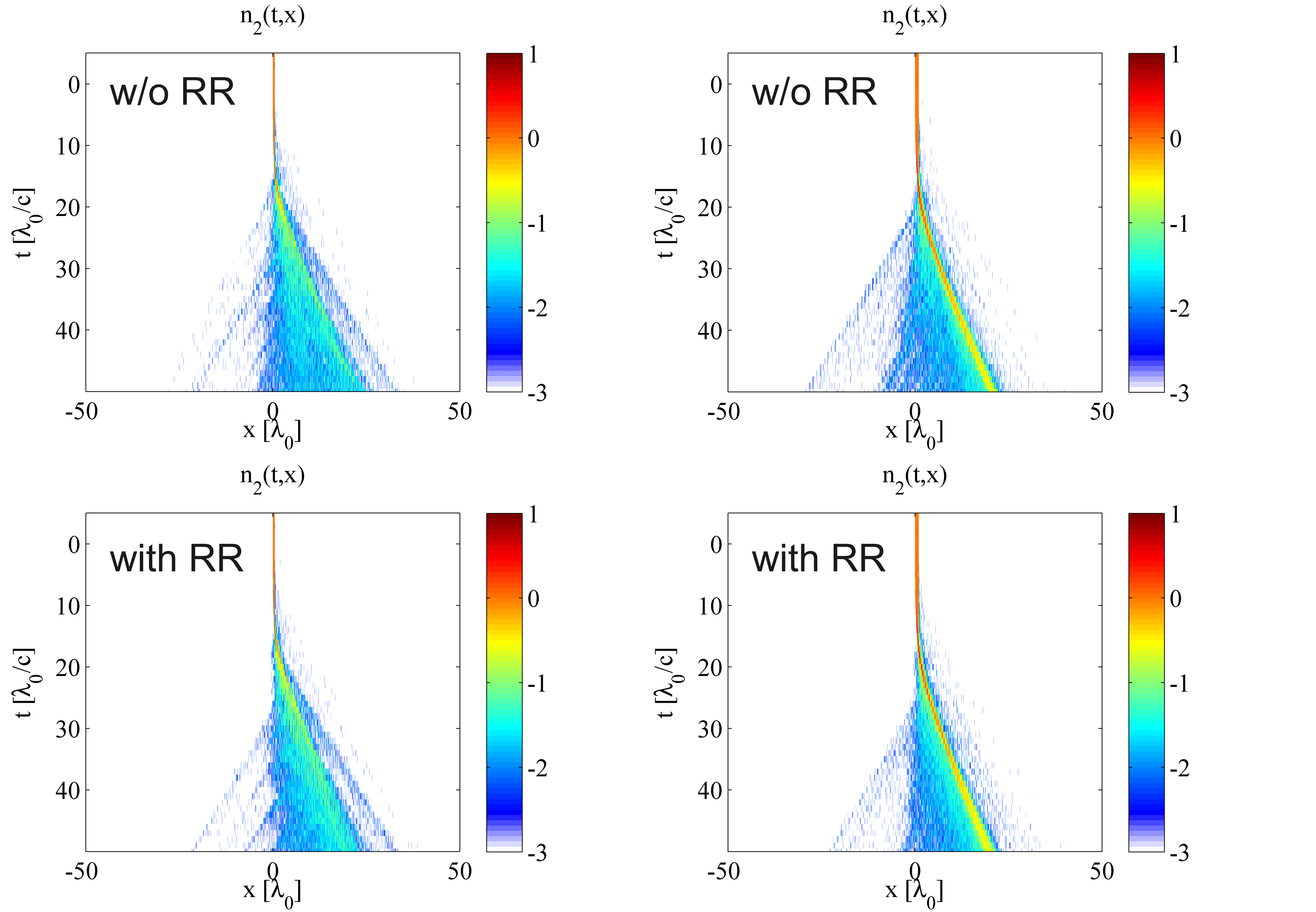
Global electron dynamics (circular polarization)

d = 0.10 | **d = 0.50**



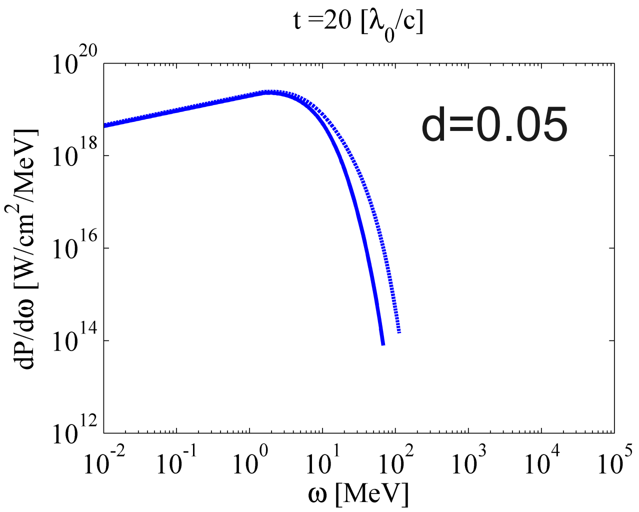
Global electron dynamics (linear polarization)

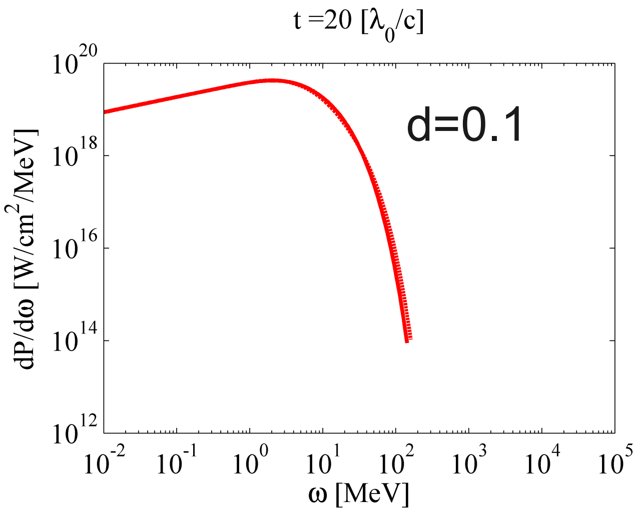
d = 0.50 | **d = 1.00**

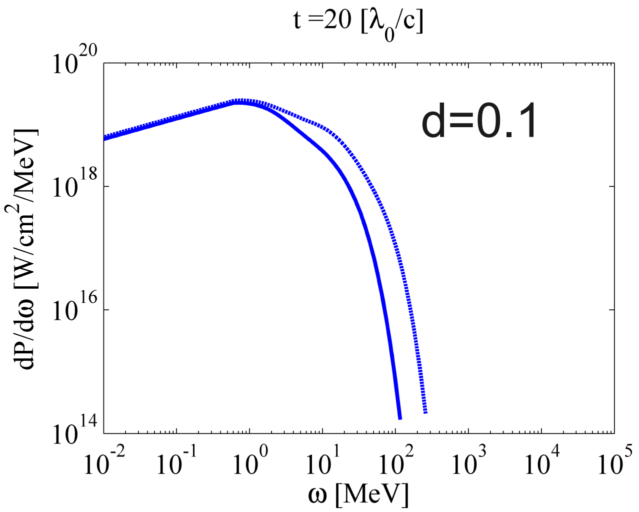


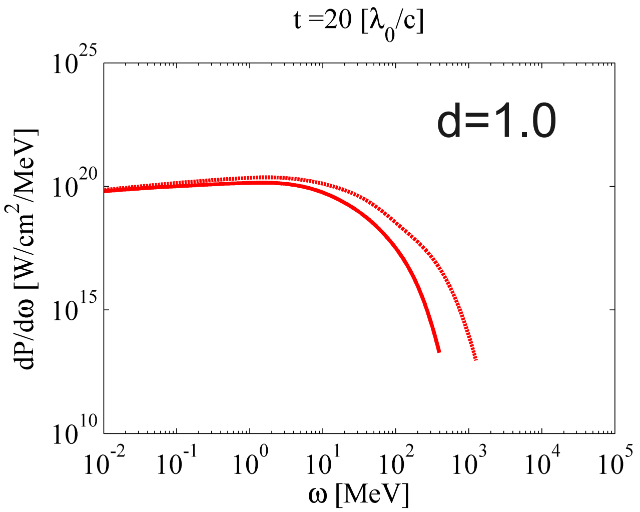
Characteristic energy spectra of radiated photons

CP | **LP**









Conclusion & Perspectives

- The radiation friction force has been introduced in two different PIC codes
  Both codes PICLS & SQUASH give similar results on its effect on the global electron-ion dynamics

- High-energy photon emission is computed assuming synchroton-like radiation giving access to:
  - time-resolved radiated power & energy
  - instantaneous emission spectra (energy & angle)

- More investigations should be undertaken :
  - to diagnose the high-energy photon emission (angular distribution)
  - phase-portraits : which particles dominate the radiation ?
  - to study in more details the effect of the self-force on the overall plasma dynamics which seems quite negligible in this study (short pulse / thin foil)