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Radiation Pressure Acceleration in the "Light Sail" regime

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OUTLOOK

1. Light Sail Revisited

- The basic LS concept
- LS improved: Self-Induced Transparency effects
- The “dark mass” puzzle
- Electron and ion dynamics and self-organization

2. Radiation Reaction effects

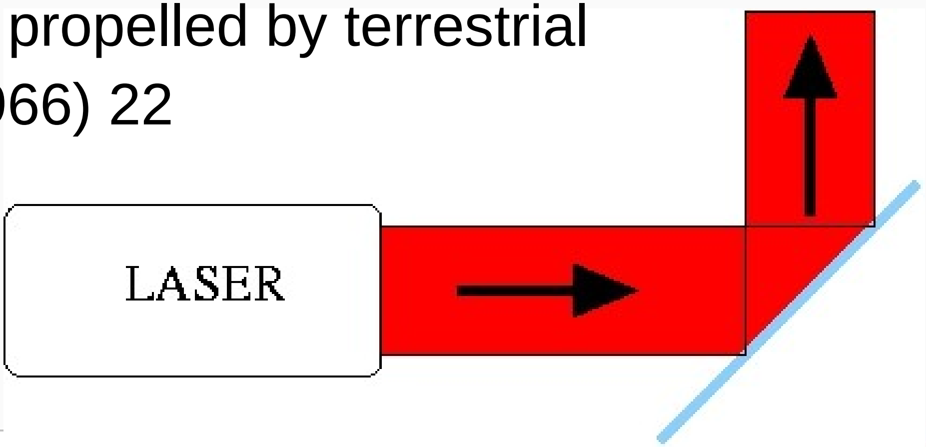
- RR inclusion in PIC via Landau-Lifshitz equation

THE “LIGHT SAIL” CONCEPT

Originally proposed as a way to
accelerate a massive mirror
by the Radiation Pressure of an Earth-based laser

R.L.Forward, “Roundtrip interstellar travel using laser-pushed lightsails”,
J. Spacecraft and Rockets **21** (1964) 187

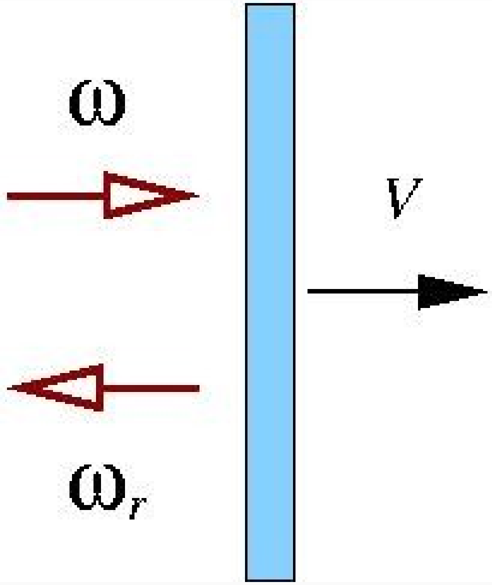
G.Marx, “Interstellar vehicle propelled by terrestrial laser beam”, Nature **211** (1966) 22



ACCELERATING MIRROR MODEL

perfectly reflecting, rigid mirror of mass $M=\rho\ell S$ boosted by a plane light wave

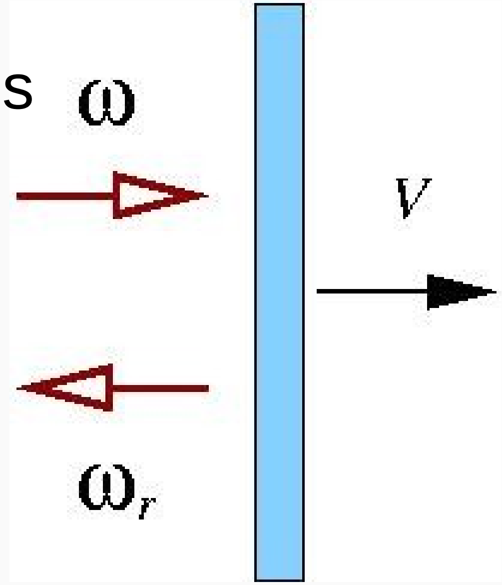
Mirror velocity as a function of the light pulse intensity I and duration τ and of the surface density $n_e\ell$ of of the target:



$$\beta(t) = \frac{(1+\mathcal{E})^2-1}{(1+\mathcal{E})^2+1}, \qquad \mathcal{E} = \frac{2F(t)}{\rho\ell c^2} = 2\pi\frac{Z}{A}\frac{m_e}{m_p}\frac{a_0^2\tau}{\zeta}$$

$$F(t) = \int_0^t I(t')dt' \propto a_o^2\tau, \qquad \zeta = \pi\frac{n_e}{n_c}\frac{\ell}{\lambda}$$

MECHANICAL EFFICIENCY



The efficiency η of the acceleration process can be obtained by a simple argument of conservation of "number of photons" plus the Doppler shift of the reflected light:

$$N = \frac{IS\tau}{\hbar\omega}, \qquad \omega_r = \omega\frac{1-\beta}{1+\beta}$$

$$\eta = \frac{\mathcal{E}_{\rm abs}}{\mathcal{E}_{\rm laser}} = \frac{N\hbar(\omega-\omega_r)}{IS\tau} = \frac{2\beta}{1+\beta}$$

$$\beta \to 1 \Rightarrow \eta \to 1$$

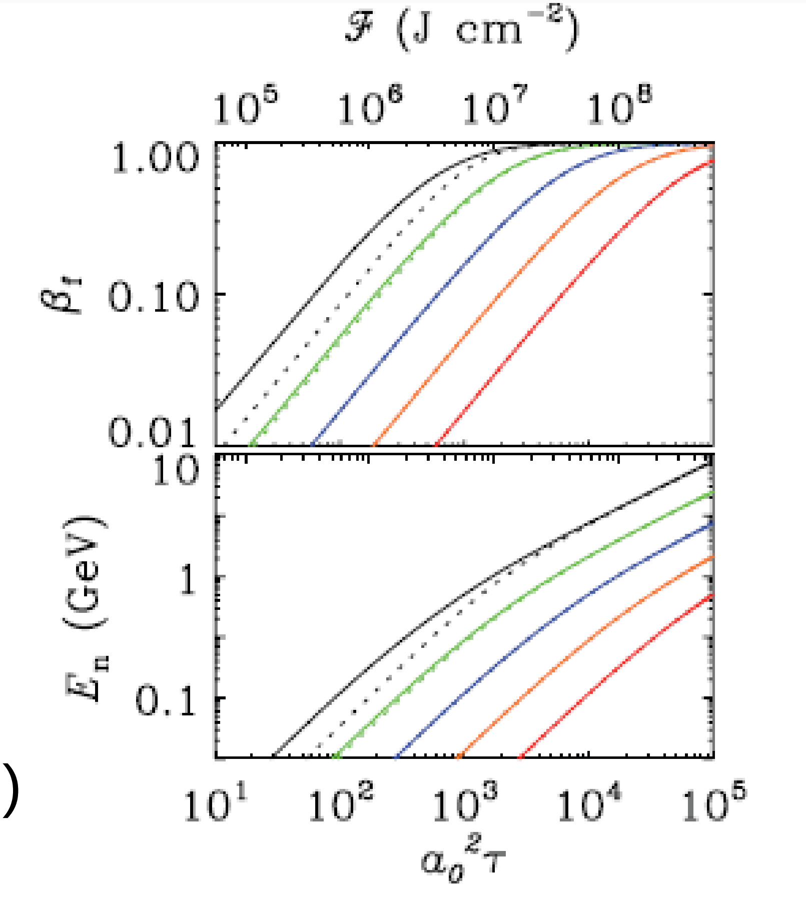
100% efficiency in the relativistic limit!

SCALING TO LASER-SOLID INTERACTIONS

Velocity and energy/nucleon for LS-RPA of a ultrathin solid target

vs. laser pulse fluence $\mathcal{F}$
for (dimensionless) surface target densities

$\zeta = 1, 3.16, 10, 31.6, 100$



Experimental requirements:
- nm foil targets (e.g. DLC)
- ultrahigh contrast (plasma mirrors)
- circular polarization

a_0 :dimensionless amplitude,

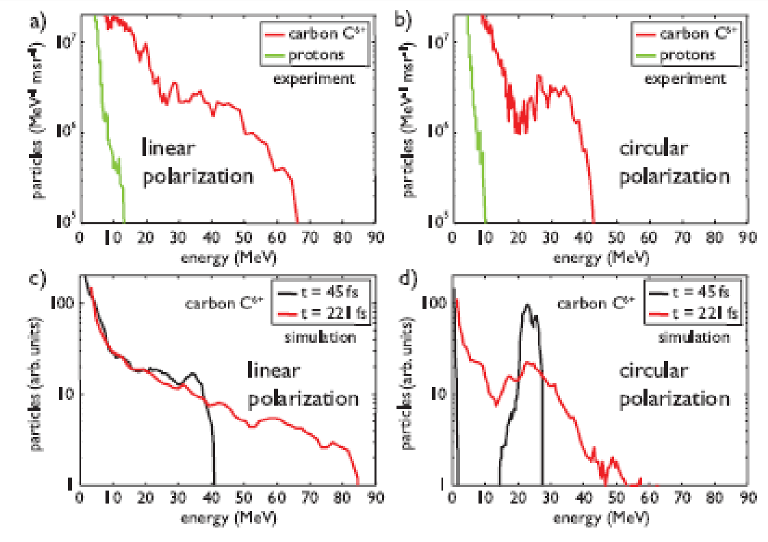
τ : duration in cycles

WHY CIRCULAR POLARIZATION?

Using CP and normal incidence fast electron generation is strongly suppressed, maximizing radiation pressure and preventing foil expansion of the foil target

Early study in “thick” targets:
Macchi et al, PRL **94** (2005) 165003

Proposal of CP-RPA of
ultrathin foils for efficient
and monoenergetic acceleration:
Zhang et al, PoP **14** (2007) 073101
Robinson et al, NJP **10** (2008) 013201;
Klimo et al, PRST-AB **11** (2008) 031301.



First experimental study reported:

Henig et al, PRL **103** (2009) 245003

THEORETICAL INTEREST IN CP-RPA...

Thick (semi-infinite) targets
("Hole Boring"):
Liseikina & Macchi, APL **94** (2007) 165003;
Naumova et al, PRL **102** (2009) 025002;
Schlegel et al, PoP **16** (2009) 083103;
Robinson et al, PPCF **51** (2009) 024004 & 095006;
Macchi & Benedetti, NIM A (2010), in press

Ultrathin (sub-wavelength) targets
("Light sail"):
Yan et al, PRL **100**, (2008) 135003 ;
Qiao et al, PRL **102** (2009) 145002;
Tripathi et al, PPCF **51** (2009) 024014;
Eliasson et al. NJP **11** (2009) 073006;
Yan et al, PRL **103** (2009) 135001;
Macchi et al, PRL **103** (2009) 085003;
Macchi et al, NJP **12** (2010) 045013.

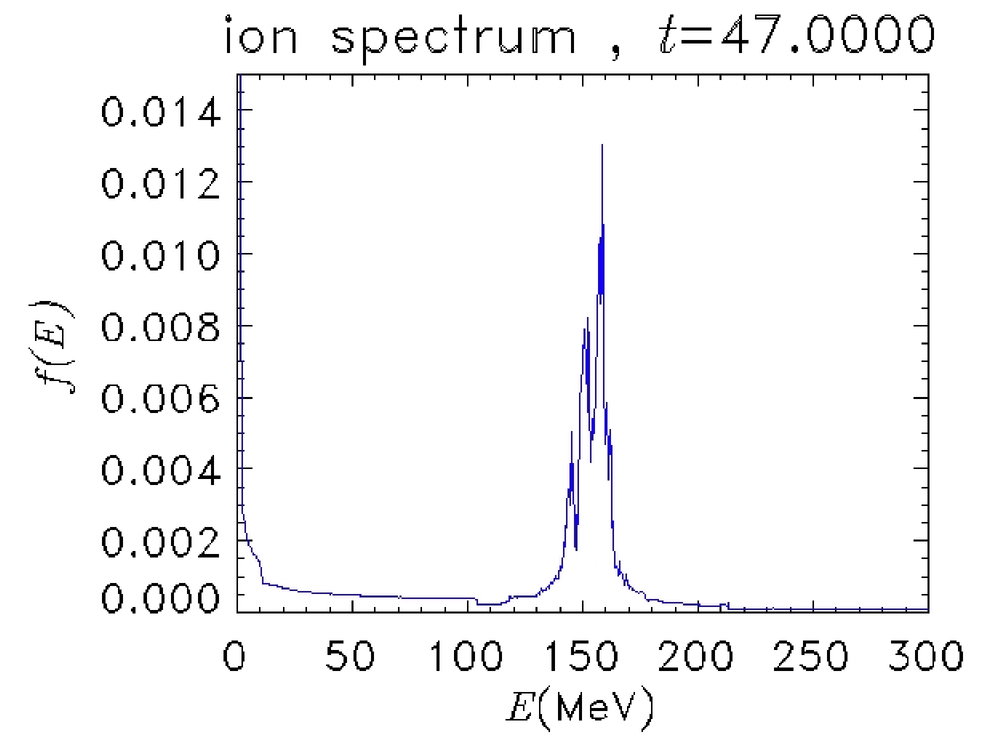
Variations on the theme
(side effects, structured targets, ...):
Liseikina et al, PPCF **50** (2008) 124033;
Rykovanov et al., NJP **10**, (2008) 113005;
Ji et al, PRL **101** (2008) 164802;
Yin et al, PoP **15** (2008) 093106;
Holkundkara and Gupta, PoP **15** (2008) 123104;
Chen et al, PoP **15** (2008) 113103;
Zhang et al, PRST-AB **12** (2009) 021301;
Gonoskov et al, PRL **102** (2009) 145002;
Chen et al, PRL **103** (2009) 024801
Grech et al, NJP **11** (2009) 093035

LS MODEL VS 1D PIC SIMULATIONS - I

Laser pulse: a_0=**5-50**, τ=8 cycles (“flat-top” envelope)

Thin foil target: $n_e=250n_c$, ℓ=**0.01-0.1**λ (ζ=**7.8-78.5**)

A narrow spectral peak is observed for $a_0<\zeta$.



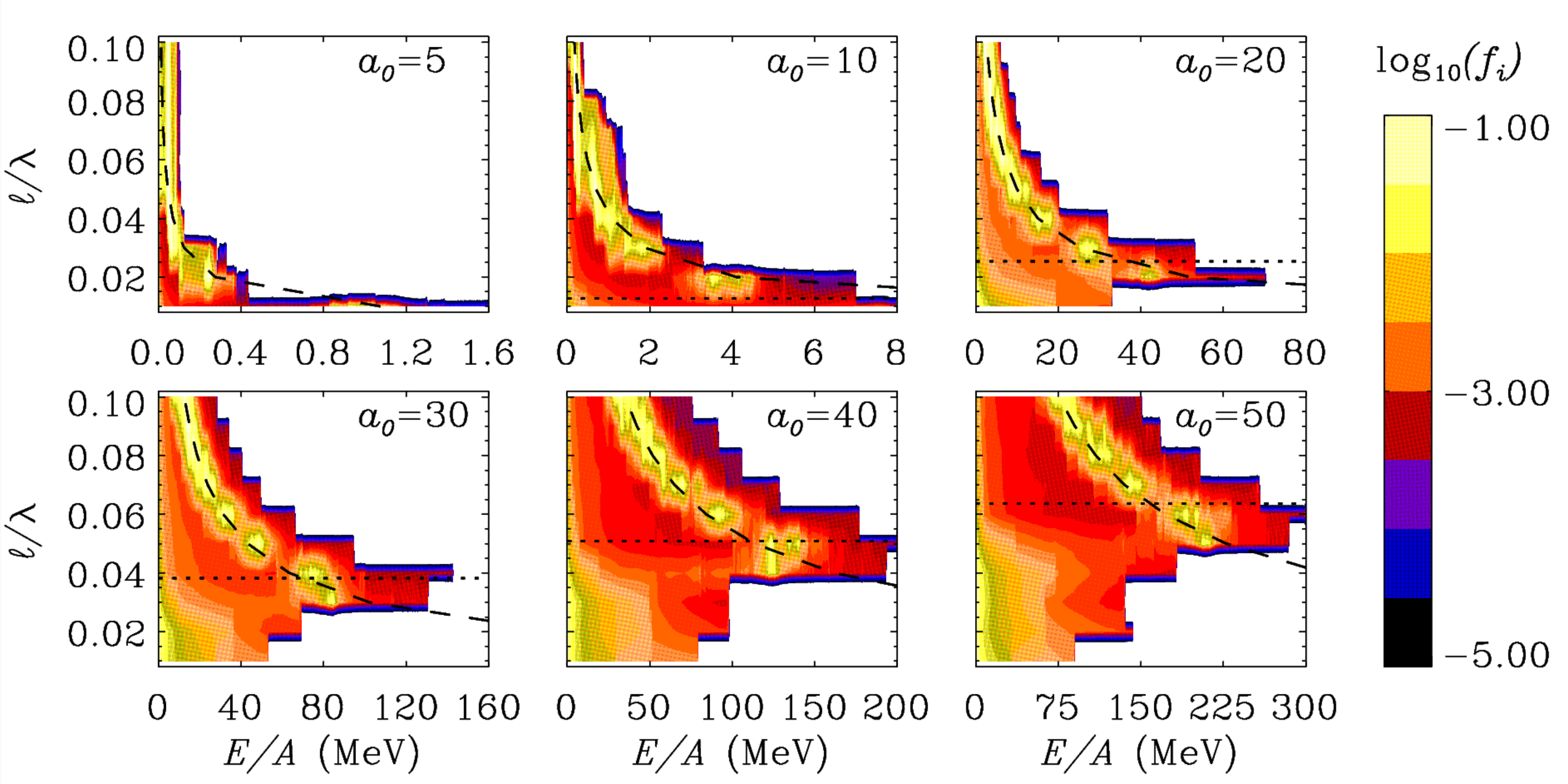
The energy of the peak is in good agreement with the LS formula

For $a_0>\zeta$, the dynamics is dominated by a Coulomb explosion of the foil

LS MODEL VS 1D PIC SIMULATIONS - II

Energy spectra vs. a_0 and ℓ:

(Dashed line: LS model prediction, dotted line: $a_0=\zeta$)

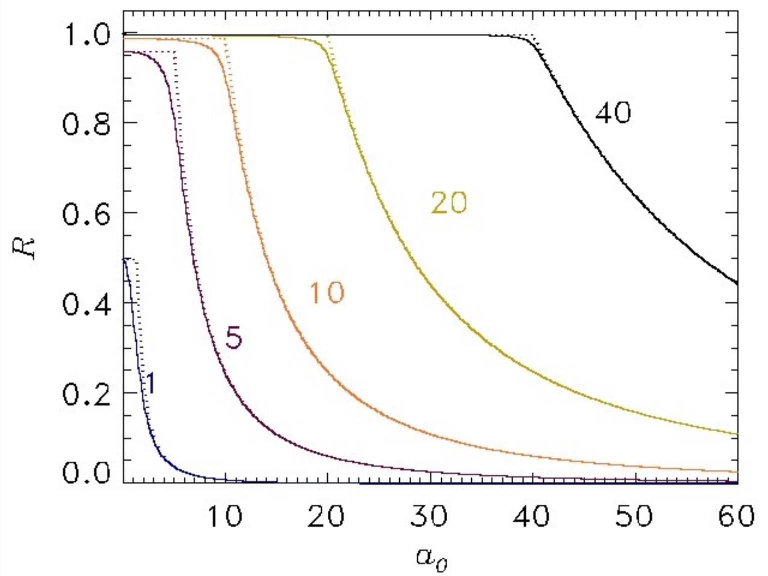


TRANSPARENCY AND “OPTIMAL” THICKNESS

Ultrathin slab model: $n_e(x)=n_0\ell\delta(x)$, foil thickness $\ell<<\lambda$

Total radiation pressure in rest frame $P_{\mathrm{rad}}=(2I/c)R$

Nonlinear reflectivity $R=R(\zeta,a_0)$ includes Self-Induced Transparency



$$R\approx\zeta^2/(\zeta^2+1) \quad (a_0<\zeta)$$

$$R\approx\zeta^2/a_0^2 \quad (a_0>\zeta)$$

P_{rad} does not depend on a_0 for $a_0>\zeta$! (since $I\sim a_0^2$)

The maximum boost of the foil is at $a_0\approx\zeta$

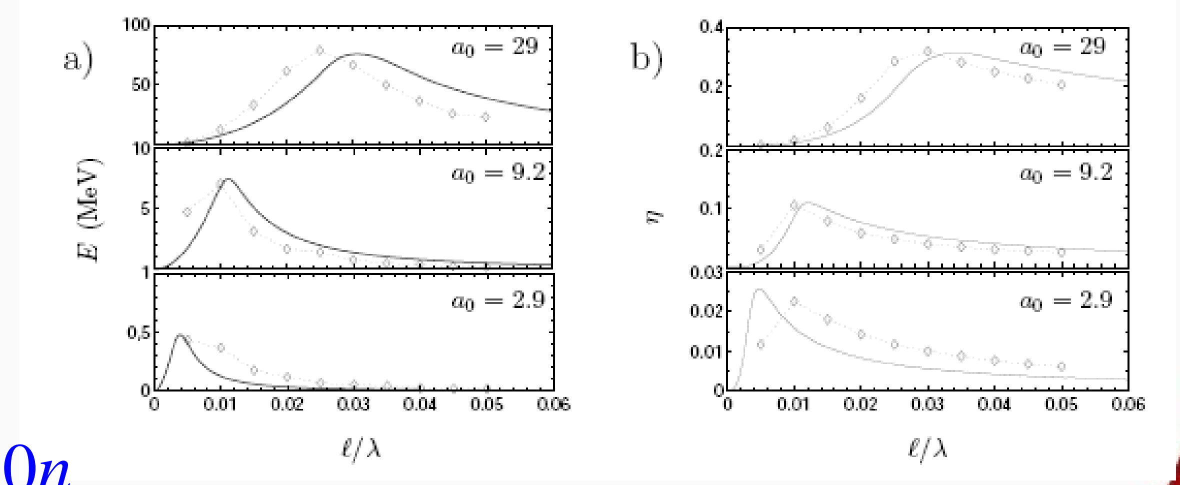
LS MODEL WITH SIT INCLUDED

Modified foil velocity formula for $R<1,\ a_0<\zeta$

$$\beta(t)=\frac{(1+\mathcal{E}-\zeta^{-2})^2+(1+\mathcal{E}-\zeta^{-2})\sqrt{(1+\mathcal{E}-\zeta^{-2})^2+4\zeta^{-2}}+2\zeta^{-2}-2}{(1+\mathcal{E}-\zeta^{-2})^2+(1+\mathcal{E}-\zeta^{-2})\sqrt{(1+\mathcal{E}-\zeta^{-2})^2+4\zeta^{-2}}+2\zeta^{-2}+2}$$

$$\mathcal{E}=\frac{2F(t)}{\rho\ell c^2}=2\pi\frac{Z}{A}\frac{m_e}{m_p}\frac{a_0^2\tau}{\zeta}$$

Ion energy and conversion efficiency vs. intensity and thickness
(solid: theory, points: PIC sims.)



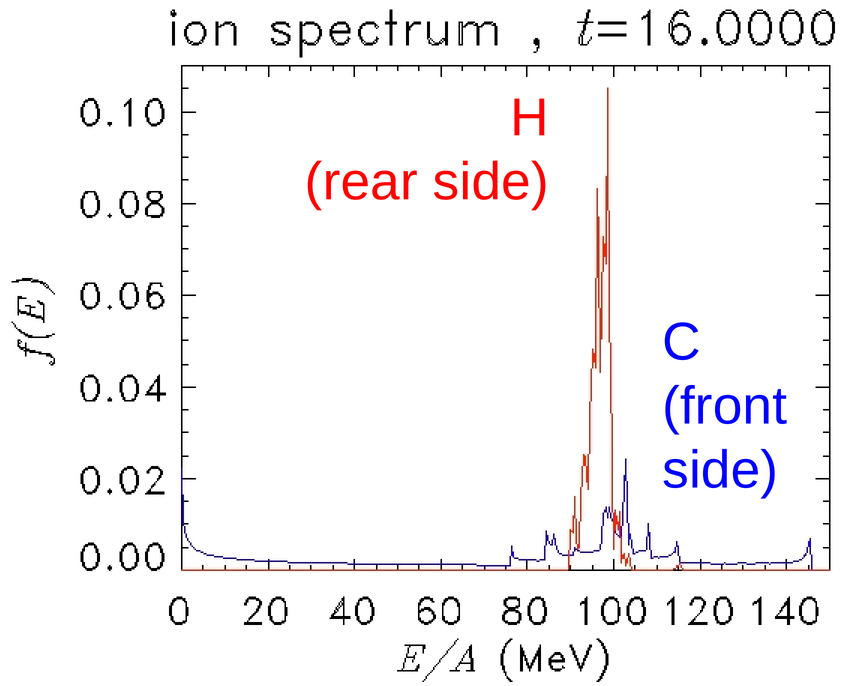
9 cycles pulse, $n_e=250n_c$

A PUZZLING ISSUE: “DARK” MASS

The RPA peak contains only ~30% of all the ions (and ~64% of their energy)

Only the rear side of the foil is accelerated (thus LS RPA may work for double-layer targets!)

→ *Why there is very good Agreement of the energy with the LS formula when inserting there the whole mass of the target (and not ~30% of it)?*



RADIATION VS ELECTROSTATIC PRESSURE

Radiation pressure drives electron depletion and generates back-holding electrostatic pressure

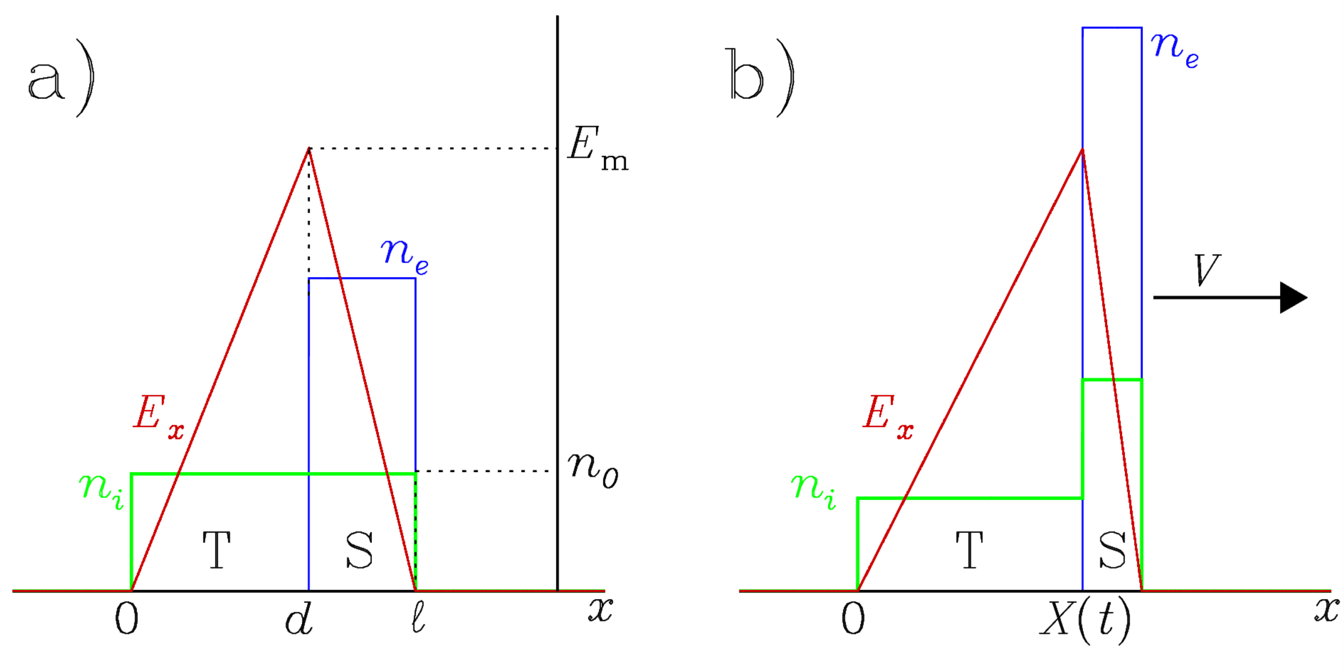
$$P_{\rm rad}=(2I/c)R \leq P_{\rm es}=2\pi(en_0\ell)^2 \text{ for } a_0\leq\zeta$$

If $a_0<\zeta$ and $\zeta>>1$, $R\approx1$ and no electrons are pushed away

For $a_0\rightarrow\zeta$ all electrons must pile up near the rear surface in order that $P_{\rm rad} \simeq P_{\rm es}$.

→ the electron pile-up layer is much thinner than the foil
→ only a fraction of the foil is accelerated

TWO ION POPULATIONS: TAIL & SAIL



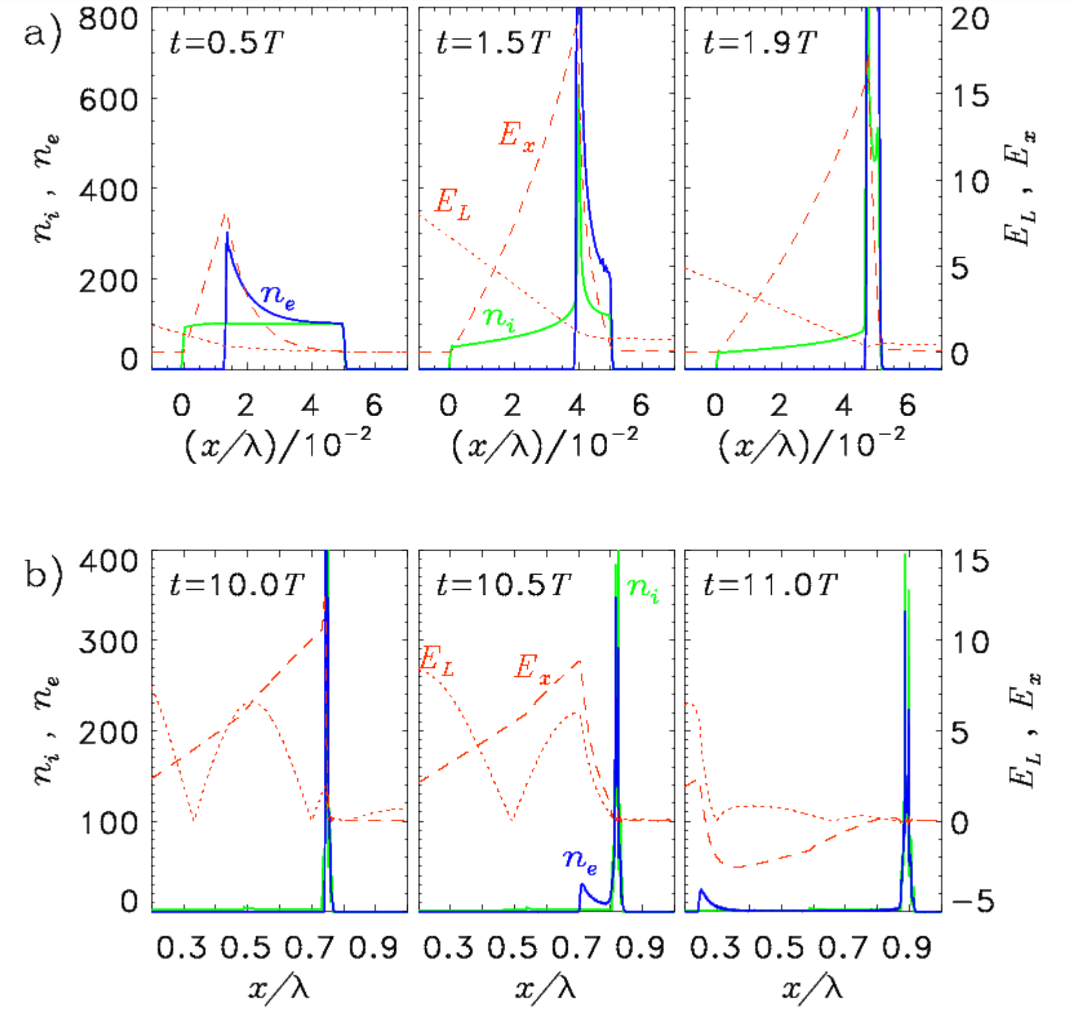
Sail (S): ions are bunched accelerated by $E_x = f_p / e$ and move coherently as a “foil” : monoenergetic component

Tail (T): ions are accelerated by their own space-charge field and “Coulomb explode”: broad spectrum component

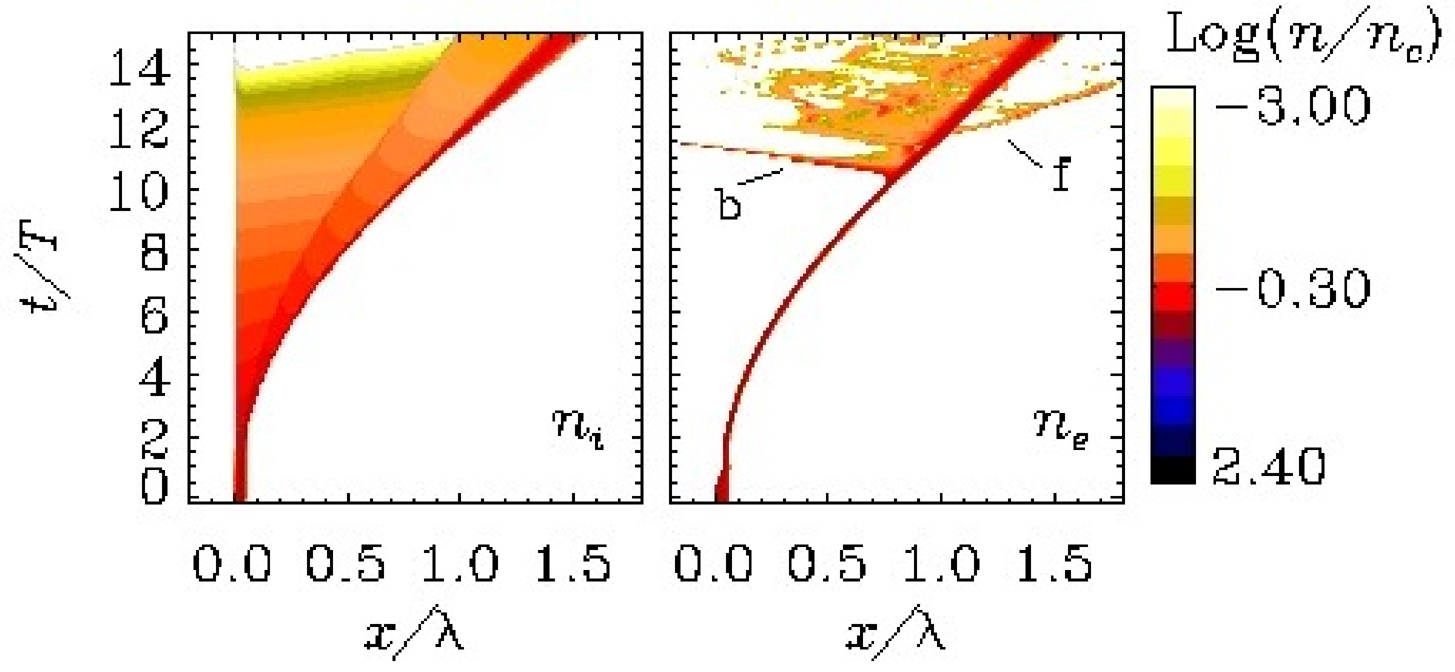
SAIL CHARGING/DISCHARGING

PIC simulations show ions in the compression layer to form a “Sail” thinner than the original foil and negatively charged (excess of electrons)

The excess electrons “detach” from the Sail near the end of the laser pulse, moving backwards and leaving a neutral plasma bunch



COLLAPSE OF ELECTRON EQUILIBRIUM



Near the end of the acceleration stage the pressure balance for electrons breaks down: formation of bunches in forward & backward directions and heating

Ion spectrum broadens in the post-acceleration stage

MISSING INERTIA IS LOWER PRESSURE

Equilibrium of radiation and electrostatic pressure on *electrons*:

$$P_{\text{rad}} \doteq \int (-e) n_e E_x dx = \int n_e f_p dx$$

Electrostatic pressure on *ions*:

$$P_{\text{es}} = \int Z e n_i E_x dx < P_{\text{rad}} \qquad (Z n_i < n_e)$$

Calculation on equlibrium profiles yields:

$$P_{\text{es}} = \frac{M_{\text{Sail}}}{M_{\text{Foil}}} P_{\text{rad}}$$

Equation of motion:

$$P_{\text{es}} = \frac{d}{dt}(M_{\text{Sail}}\mathbf{V}) \Longleftrightarrow P_{\text{rad}} = \frac{d}{dt}(M_{\text{Foil}}\mathbf{V})$$

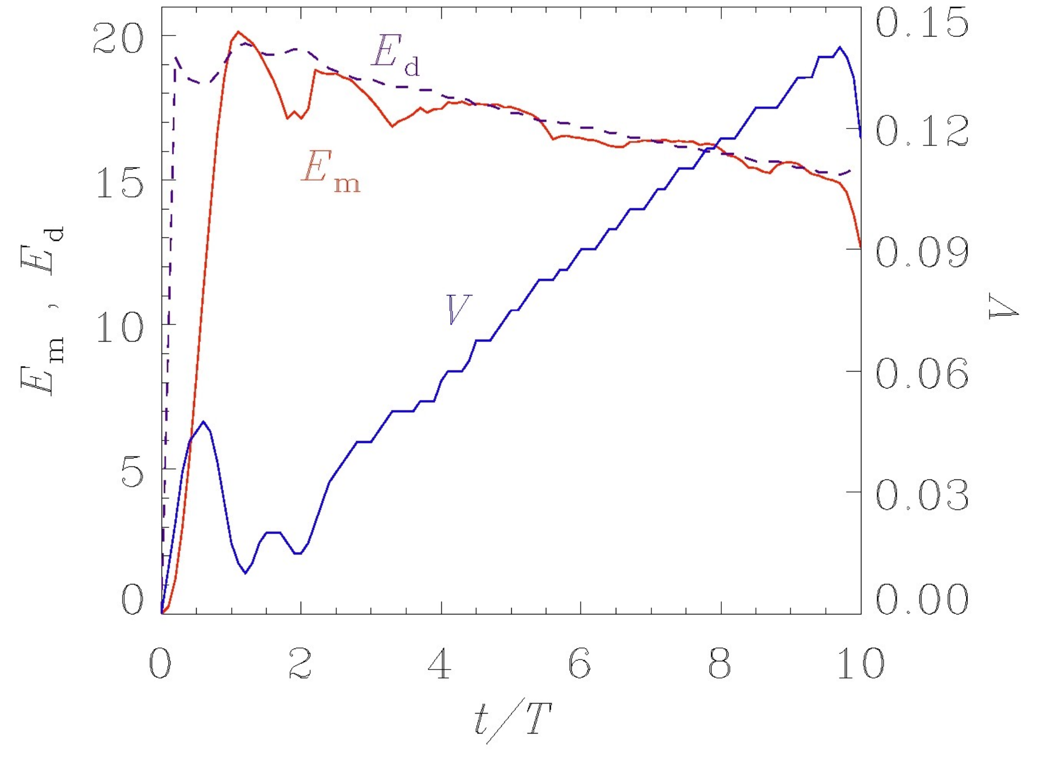
→The Sail moves as if it had the total mass of the foil

DYNAMIC PRESSURE BALANCE

P_{rad} decreases with velocity in the Lab frame

$(P_{rad})^L = (1-\beta)/(1+\beta) P_{rad}$

To keep pressure equilibrium there is a mass flow (ion current) from M_{tail} to M_{sail}



ENERGY BALANCE

Efficiency depends only on β (the Sail velocity)
BUT the kinetic energy of the Sail is less than the total!

Energy stored in the electrostatic field E_x :

$$U_{\text{es}} = U_{\text{es}}(t) = \int_0^{X(t)} \frac{E_x^2(x,t)}{8\pi} dx$$

$$\frac{dU_{\text{es}}}{dt} = \frac{1}{8\pi} E_x^2[X(t),t] \frac{dX}{dt} = \frac{1}{8\pi} E_0^2 \beta c$$

"Conversion efficiency" into electrostatic energy η_{es} :

$$\eta_{\text{es}} = \frac{1}{I} \frac{dU_{\text{es}}}{dt} = 2\beta \left(\frac{d}{\ell}\right)^2 \left(\frac{\zeta}{a_0}\right)^2$$

For $a_0 = \zeta$, the depletion width $d \approx \ell$ thus $\eta_{es} \approx 2\beta$:

most of the stored energy is converted into electrostatic energy and eventually goes to Tail ions

TWO-DIMENSIONAL SIMULATIONS

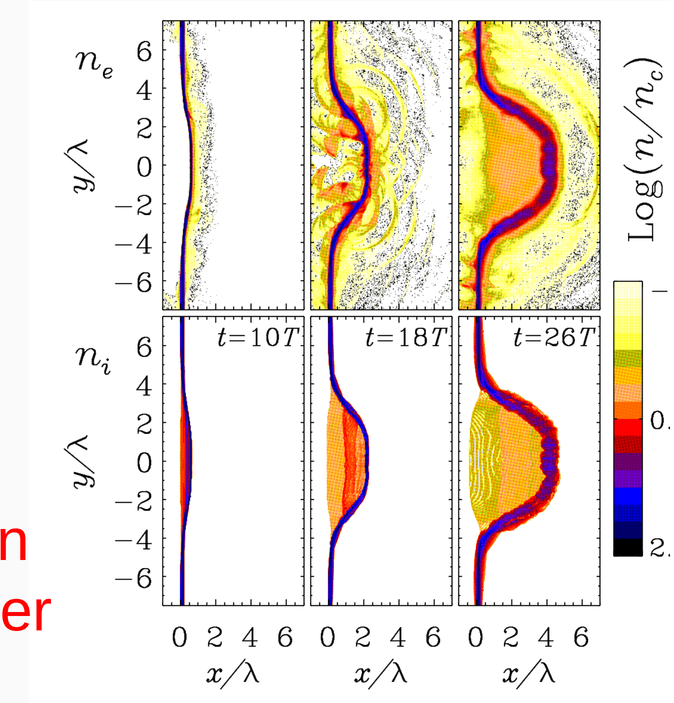
2D sims for

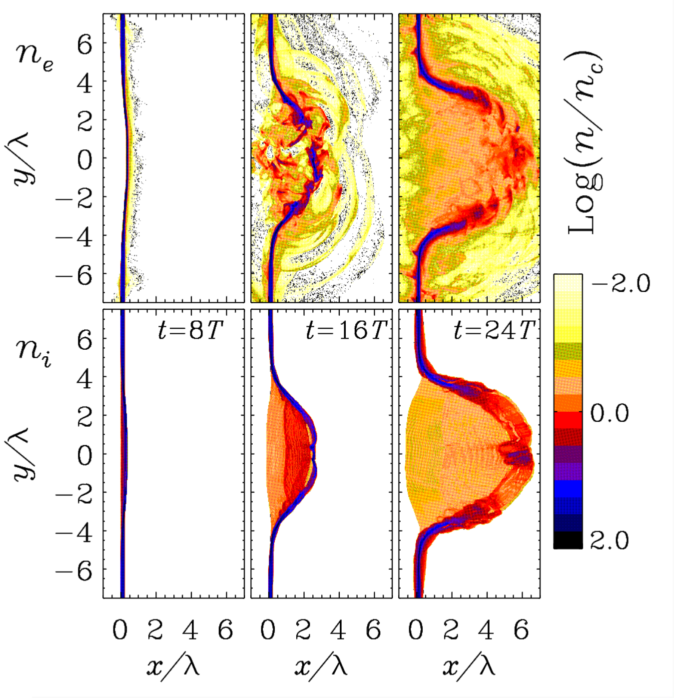
ζ=31.4 and

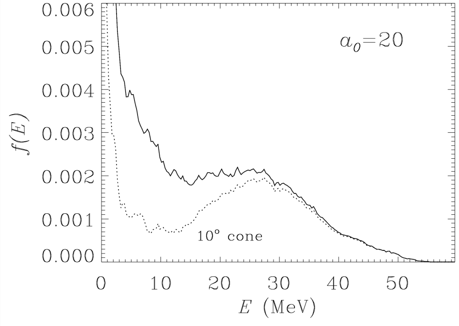
a_0 =20 (left)

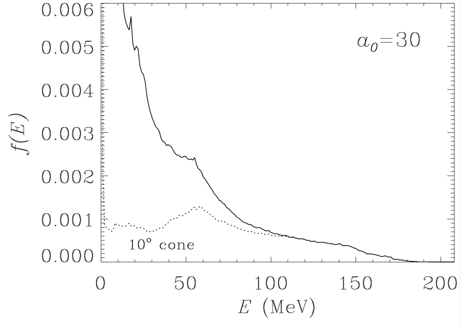
a_0 =30 (right)

stronger electron heating and lower “penetration” threshold with respect to 1D: ion spectrum is broad







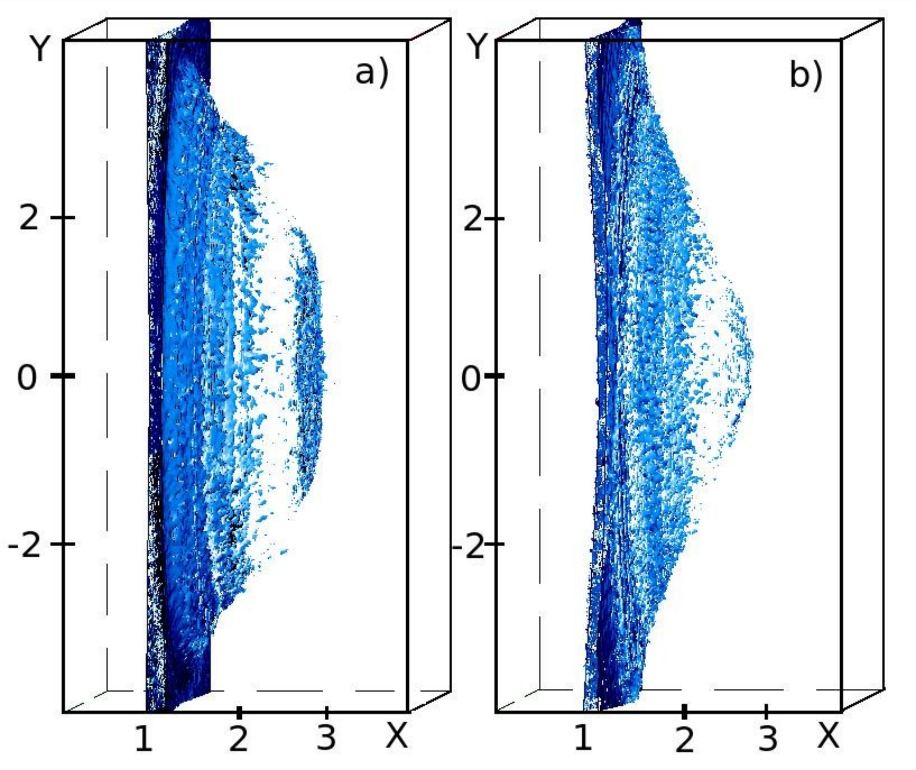


THREE-DIMENSIONAL SIMULATIONS

3D sims for $\zeta=15$, $a_0=5$, τ=18 cycles

left: Supergaussian spot profile

right: Gaussian



Supergaussian “flat-top” profiles keep a “quasi-1D” geometry and prevent early breakthrough of laser pulse due to lateral expansion

RADIATION REACTION EFFECTS

Motivation: RR is important for ultra-relativistic particles in EM fields and is thus expected to play a strong role in next generation experiments at ultra-high intensities.

The typical intensity for relevant RR effects is estimated to be ~10^{23} W/cm^{2} . This corresponds, e.g., to the foreseen regime of) RPA dominance (even for Linear Polarization)
[Esirkepov et al, PRL **92** (2004) 175003]

Two RPA simulation studies (for CP at lower intensity) suggest a “beneficial” effect of “electron cooling” by RR
[Schlegel et al, PoP **16** (2009) 083103;
Chen et al, arXiv:0909.5144]

RADIATION REACTION FORCES

$$mc\frac{du^\mu}{d\tau} = f_L^\mu + f_{RR\,1}^\mu + f_{RR\,2}^\mu + f_S^\mu$$

EoM of classical particle with spin in EM field

$$f_L^\mu = eF^{\mu\nu}u_\nu$$

$$f_{RR\,1}^\mu = e\tau_0\left(\partial_\alpha F^{\mu\nu}u_\nu u^\alpha\right)$$

$$f_{RR\,2}^\mu = \frac{e^2}{mc}\tau_0\left(F^{\mu\nu}F_{\nu\alpha}u^\alpha + (F^{\nu\beta}u_\beta F_{\nu\alpha}u^\alpha)u^\mu\right)$$

$$f_S^\mu = -\frac{1}{2c}S^{\gamma\delta}\partial^\mu F_{\gamma\delta} + \frac{1}{2c}\left(S^{\gamma\delta}\partial_\alpha F_{\gamma\delta}u^\alpha\right)u^\mu$$

$$u^\alpha = \left(\gamma, \gamma\frac{\mathbf{v}}{c}\right) \qquad \partial^\mu \equiv \left(\frac{\partial}{\partial t}, -c\nabla\right)$$

RADIATION REACTION MODELING

EoM with Landau-Lifshitz force in non-covariant notation

$$
\begin{aligned}
\frac{d\mathbf{p}}{dt} = & -\Big(\mathbf{E} + \mathbf{v}\times\mathbf{B}\Big) \\
& \boxed{- \ \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\gamma\Big[\Big(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\Big)\mathbf{E} + \mathbf{v}\times\Big(\frac{\partial}{\partial t} + \mathbf{v}\cdot\nabla\Big)\mathbf{B}\Big]} \\
& \boxed{+ \ \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\Big[\Big(\mathbf{E} + \mathbf{v}\times\mathbf{B}\Big)\times\mathbf{B} + \Big(\mathbf{v}\cdot\mathbf{E}\Big)\mathbf{E}\Big]} \\
& - \ \left(\frac{4}{3}\pi\frac{r_e}{\lambda}\right)\gamma^2\Big[\Big(\mathbf{E} + \mathbf{v}\times\mathbf{B}\Big)^2 - \Big(\mathbf{v}\cdot\mathbf{E}\Big)^2\Big]\mathbf{v}
\end{aligned}
$$

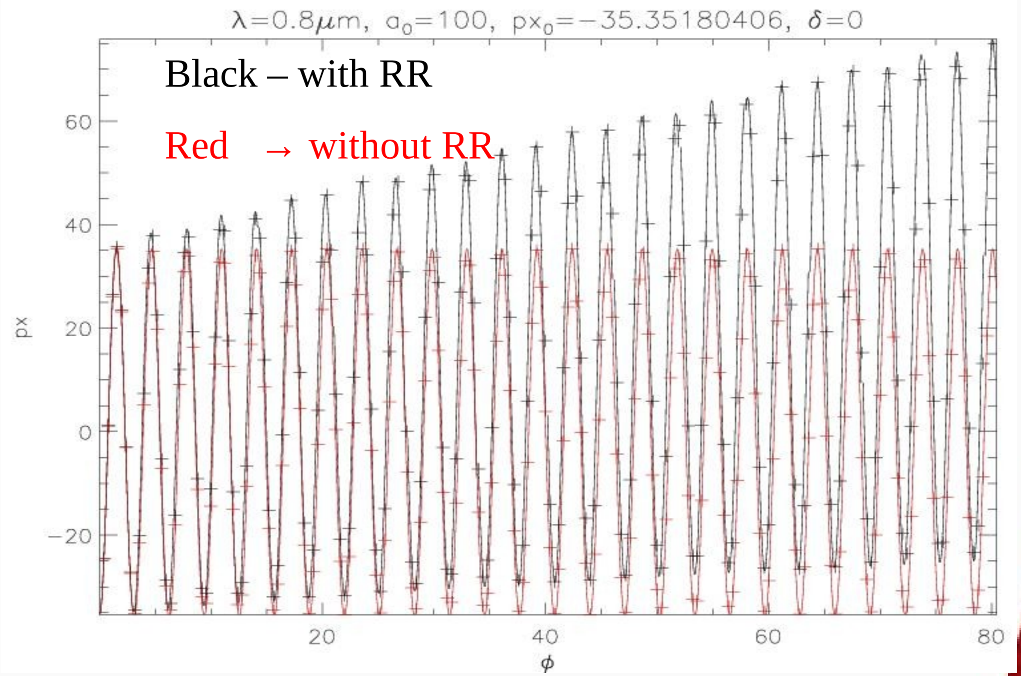
The last “friction” term is the dominant one
(first two terms are smaller than spin contribution)

BENCHMARK WITH EXACT SOLUTIONS

Exact solution of the Landau-Lifshitz equation in a plane wave
A.Di Piazza, Lett.Math.Phys. **83** (2008) 305

Test of particle pusher algorithm with “reduced” LL included:

- excellent agreement for intensities up to 10^{24} W/cm^2
- straightforward to include in a “standard” PIC code (based on Boris pusher)
- only ~10% increase in CPU time



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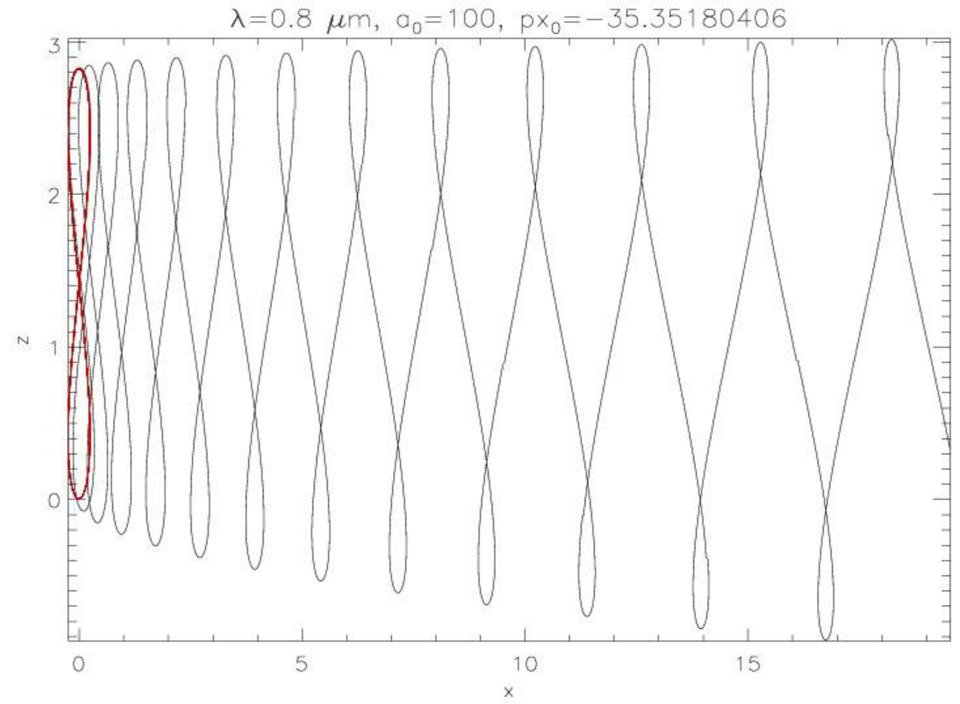
Black – with RR

Red → without RR



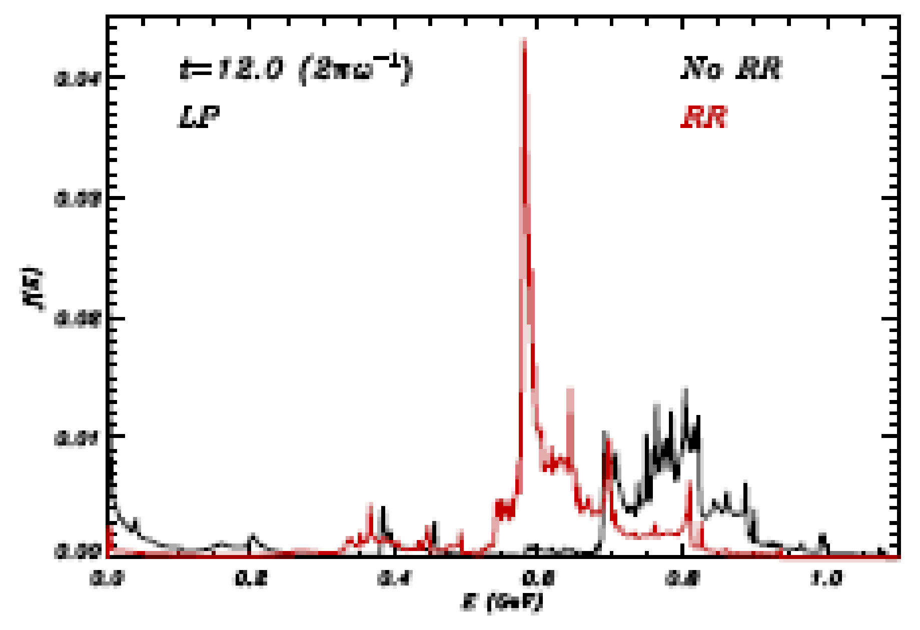
RR EFFECTS ON ION SPECTRA – I (LP)

RP-dominated regime: 10^{24} W/cm^2 , 11 cycles pulse

1 um foil, $100n_c$, linear polarization

Lower energy,
narrower spectrum
with RR included

~20% energy
“dissipated” by RR



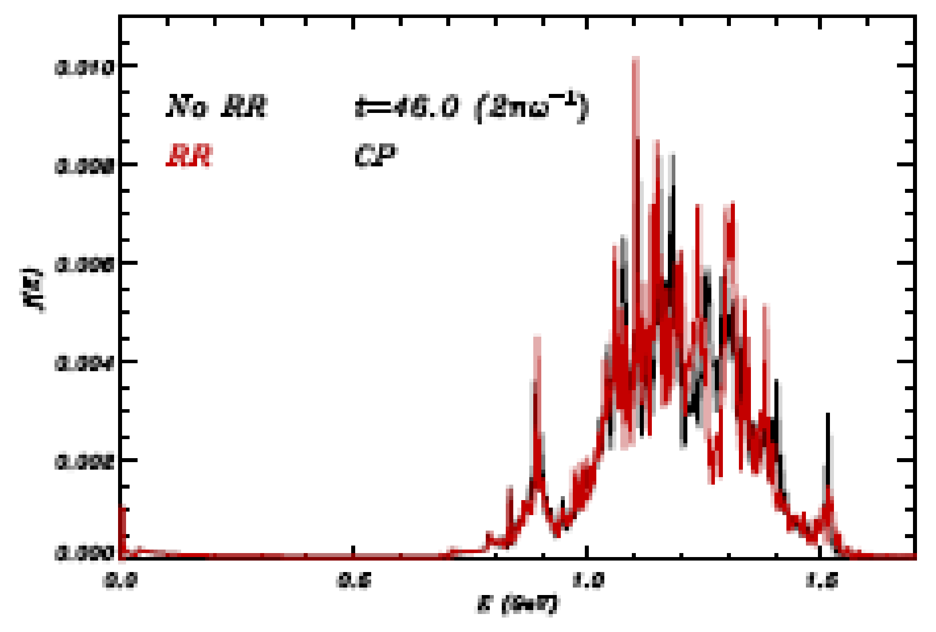
RR EFFECTS ON ION SPECTRA – II (CP)

RP-dominated regime: 10^{24} W/cm^2 , 11 cycles pulse

1 um foil, $100n_c$, circular polarization

Negligible RR effects on ion spectrum!

Higher energy than in LP case



CONCLUSIONS

- The simple Light Sail model correctly predicts the ion energy and conversion efficiency observed in simulations
- Not all the ions are accelerated as a monoenergetic bunch
- Dynamics and self-organization underlying LS has been unfolded
- Keeping a monoenergetic spectrum is difficult
- Radiation Reaction effects at ultrahigh intensities are important only for Linear Polarization

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