Radiation Reaction and Laser Polarization Effects on Ultraintense Laser Acceleration of Thin Foils

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Coworkers

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Motivations

- Radiation Pressure Dominant Acceleration (RPDA) of thin ($\ell \lesssim 1$ μm) solid foils by ultra-relativistic laser pulses ($a_0 > (m_p/m_e)/2\pi$, $I\lambda^2 > 10^{23}$ W cm$^{-2}\mu$m^2) has been suggested as a route to "unlimited" acceleration towards the GeV/nucleon limit (relativistic ions)

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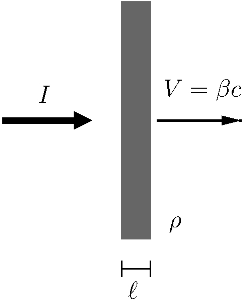
Physics background 1: Light Sail model

$E_{\text{ion}}(t) \simeq \left(2It/\rho\ell c^2\right)^{1/3} \quad (t \to \infty)$

$E_{\text{max}} \simeq m_p c^2 \mathscr{F}/2$

$\mathscr{F} = 2(\rho\ell)^{-1} \int_0^\infty I(t')dt'$



Favorable scaling with laser pulse fluence $\mathscr{F}$
100% efficiency in the relativistic limit
"Perfect" monoenergeticity for "rigid", coherent motion of the foil
Limits: "slow" energy gain, foil transparency

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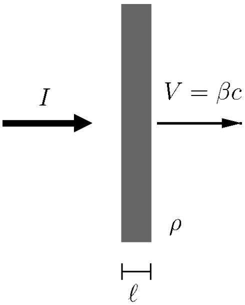

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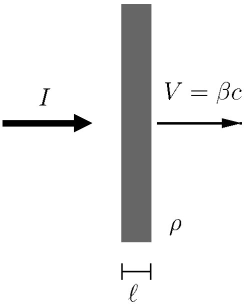

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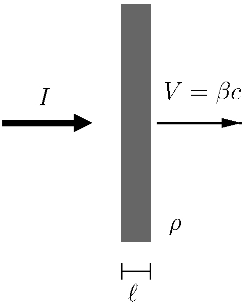

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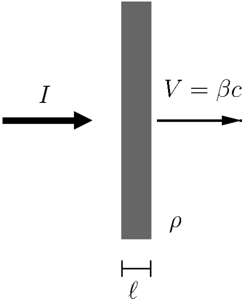

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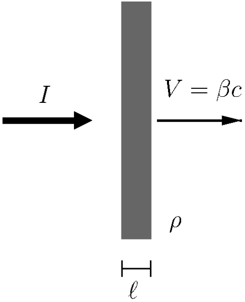

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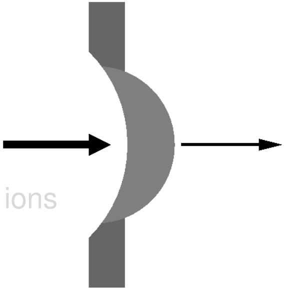
Transverse expansion of the target reduces surface density $\rho\ell$
$\Rightarrow$ “unlimited” acceleration possible
at the expense of the number of accelerated ions
[Bulanov 10]



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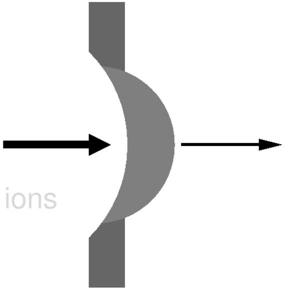

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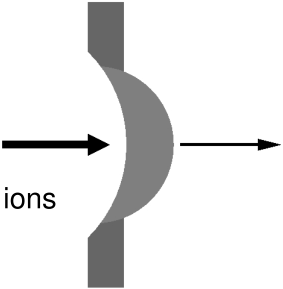

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- Early numerical demonstration of RPDA [Esirkepov 04] by 3D simulations suggests polarization is inessential
- Unlimited acceleration first demonstrated by 2D simulation and circular polarization (CP) [Bulanov 10]
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- Radiation Friction (or Radiation Reaction - RR) effects are expected to play an important role in ultrarelativistic laser-plasma dynamics

$\Rightarrow$ address role of RR on RPDA

- Effect of RR on ion acceleration (both in thin and thick targets) investigated by several authors [Schlegel 09, Chen 11, Capdessus 12]
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- "Feasible" 3D Particle-In-Cell simulations are at the limit of present-day computational resources: hard to check numerical convergence
- RPDA simulations further challenging because of high density and long times to reach asymptotic regime
- when including RR the high-energy, low-density tail of the electron distribution needs to be resolved properly

⇒ check effects of limited resolution with simulations in lower dimensionality (2D)

⇒ upgrade the code for more efficiency, use larger supercomputers . . . and do what you can

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Radiation Reaction modeling - I

"Reduced" Landau-Lifshitz equation for electrons

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

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

- Spin force and smaller terms in $\mathbf{F}_{\text{rad}}$ are neglected
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Kinetic equation for electrons and some properties

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

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- Simple, modular and computationally cheap algorithm for inclusion in standard PIC codes has been developed [Tamburini et al. NJP **10**, 123005 (2010)]
- Numerical benchmark of single particle motion with exact solution in a plane wave [Di Piazza 08]
- High-frequency radiation is assumed consistently to be incoherent and to escape from the plasma; it appears as energy dissipation
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Radiation Reaction misunderstanding

Quoting an anonymous referee:

- "*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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Set-up of 3D simulations

- Laser pulse: $(9T) \times (10\lambda)^2$ (FWHM) $[T = \lambda/c]$ $\sin^2 \times$Gaussian shape, $a_0 = 280\ (198)$ for LP (CP), $\lambda = 0.8\ \mu$m
- Plasma: $\ell = 1\lambda$, $n_0 = 64n_c$, $Z = A = 1$

  Note: $a_0 \simeq \zeta = \pi(n_e/n_c)(\ell/\lambda)$
- Numerical: $1320 \times 896 \times 896$ grid, $\Delta x = \Delta y = \Delta z = \lambda/44$, $\Delta t = T/80 = \lambda/80c$, 216 particles per cell (for both e and p), 1.526×10^{10} in total

Runs performed on 1024 processors (1.7 GBytes each) of IBM-SP6 at CINECA (Italy)

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- Laser pulse: $(9T) \times (10\lambda)^2$ (FWHM) [$T = \lambda/c$]
  $\sin^2 \times$Gaussian shape, $a_0 = 280$ (198) for LP (CP),
  $\lambda = 0.8$ μm
- Plasma: $\ell = 1\lambda$, $n_0 = 64n_c$, $Z = A = 1$
  Note: $a_0 \simeq \zeta = \pi(n_e/n_c)(\ell/\lambda)$
- Numerical: $1320 \times 896 \times 896$ grid, $\Delta x = \Delta y = \Delta z = \lambda/44$,
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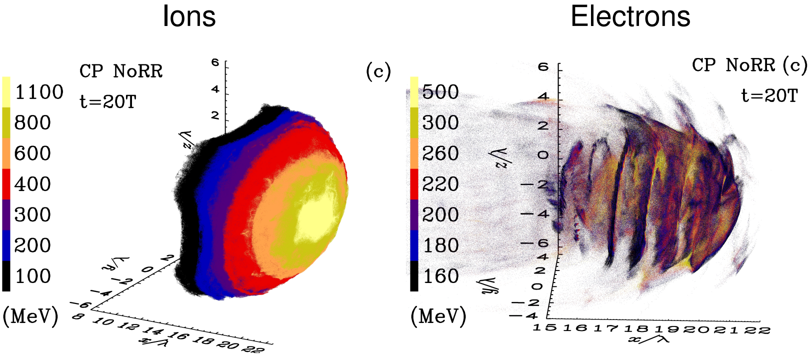
Space-energy distribution: CP, no RR

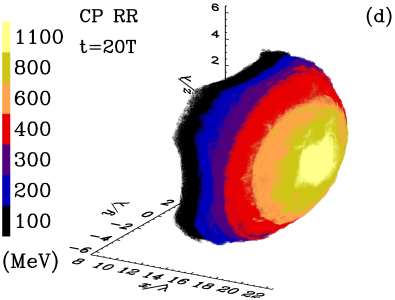


Symmetric, collimated distribution of ions

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

Space-energy distribution: CP, with RR

Ions



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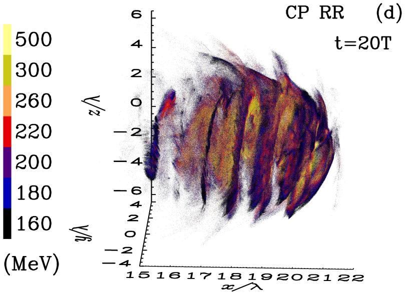

Ion distribution unchanged by RR

Cooling of electrons in pulse tail due to radiative losses

Space-energy distribution: LP, no RR

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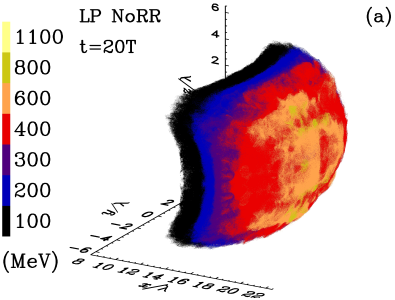

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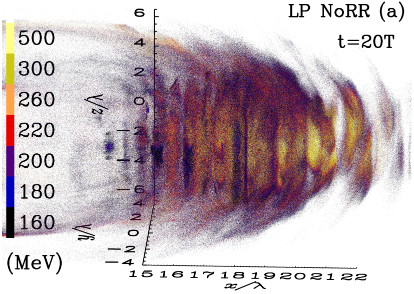
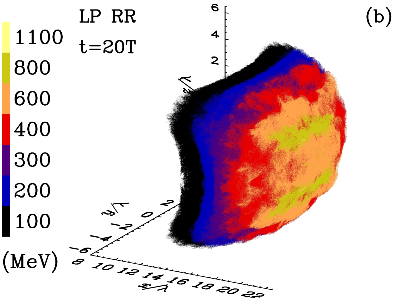


Asymmetric distribution with highest energy ions off-axis

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

Space-energy distribution: LP, with RR

Ions



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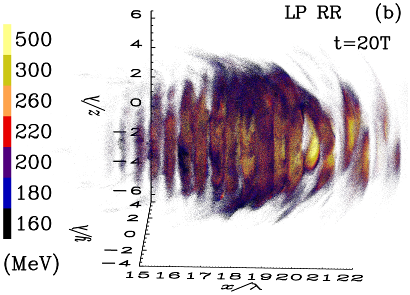
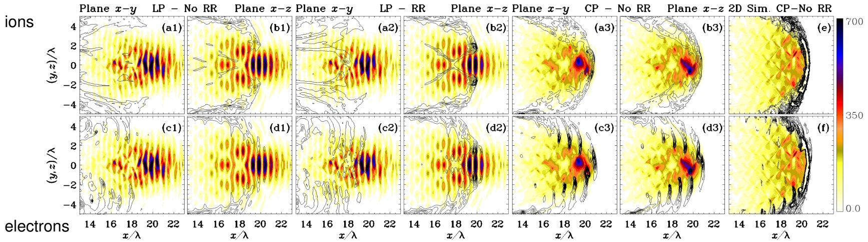


Strong cooling of electrons by radiative losses

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

Pulse self-wrapping by the foil

Sections of 3D fields [a1)-d3)] vs 2D simulations [e)-f)]



Focusing of the pulse down to $\sim \lambda^3$ volume for CP [see series -3)]

"Wrapping" and focusing effects are weaker in 2D vs 3D [see e)-f)]

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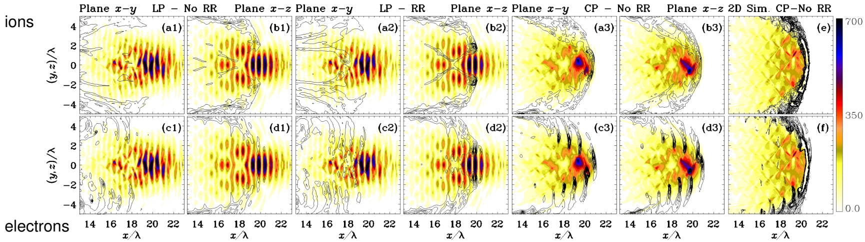

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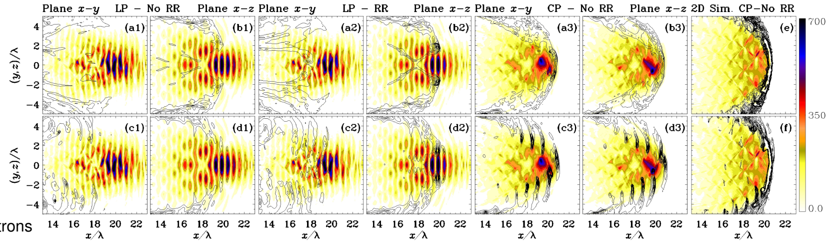

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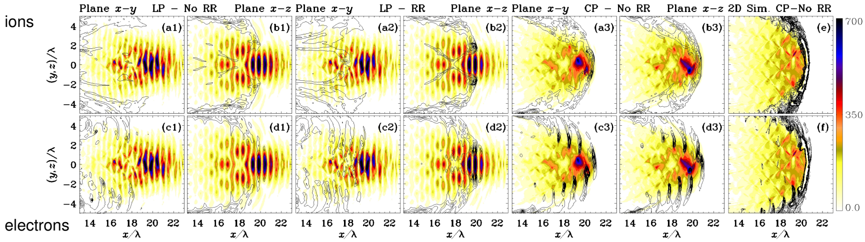

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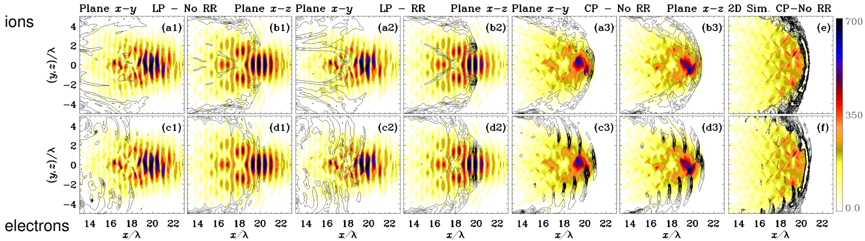

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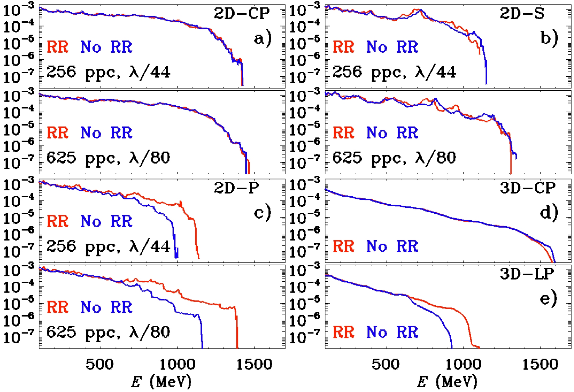
Effects of reduced dimensionality and resolution

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



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

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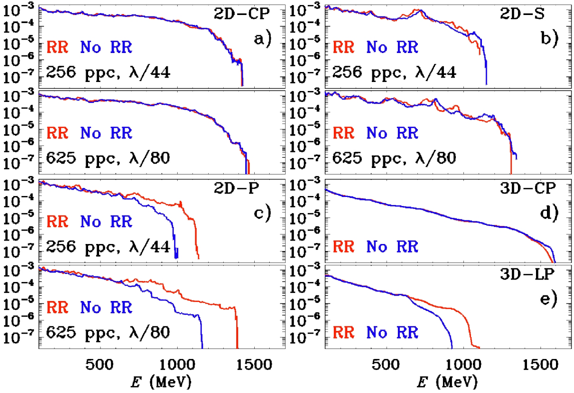

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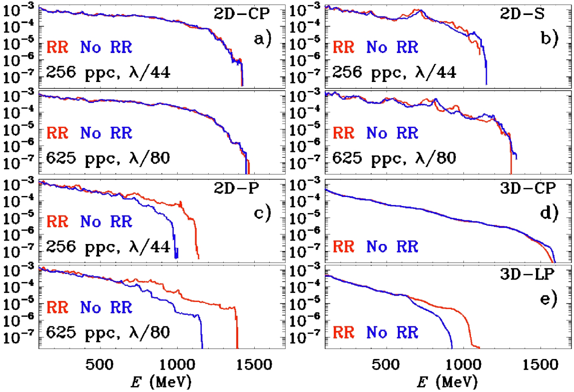

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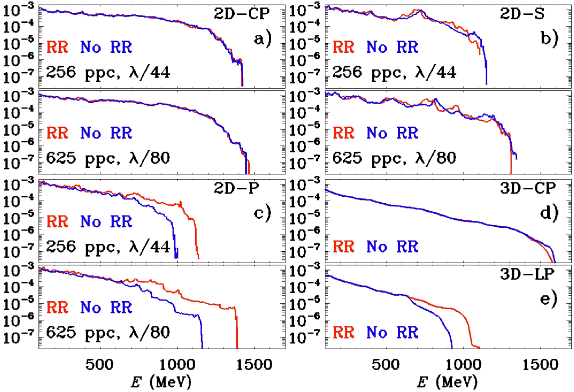

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$\Rightarrow$ electrons move with $v_x \simeq 1$ in a "quasi" propagating wave with $E \simeq B \Rightarrow \mathbf{F}_{\text{rad}} = 0$: weak RR effects

- For Linear Polarization, the $\mathbf{J} \times \mathbf{B}$ *oscillating* term causes $v_x \sim -c$ periodically ("colliding" geometry) maximizing $\mathbf{F}_{\text{rad}}$: strong RR effects
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References for this work

- M. Tamburini, T. V. Liseykina, F. Pegoraro, A. Macchi, “Radiation Pressure Dominant Acceleration: Polarization and Radiation Reaction Effects and Energy Increase in Three Dimensional Simulations” , Phys. Rev. E **85**, 016407 (2012)
- M. Tamburini, F. Pegoraro, A. Di Piazza, C. H. Keitel, T. V. Liseykina, A. Macchi, “Radiation Reaction Effects on Electron Nonlinear Dynamics and Ion Acceleration in Laser-Solid Interaction”, Nucl. Inst. Meth. Phys. Res. A **653**, 181 (2011)
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[Di Piazza 09] A. Di Piazza et al, PRL **102**, 254802 (2009)

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[Qiao 12] B.Qiao et al, PRL **108**, 115002 (2012)

[Schlegel 09] T.Schlegel et al, PoP **16**, 083103 (2009)

What's next?

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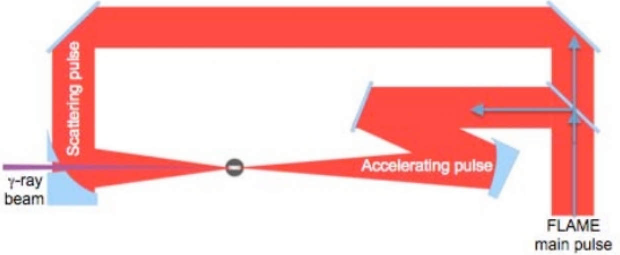

Possible test bed for experiments on detecting RR signatures
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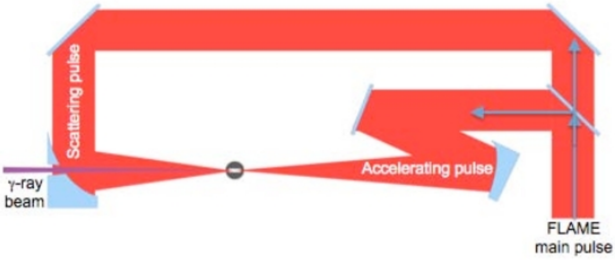

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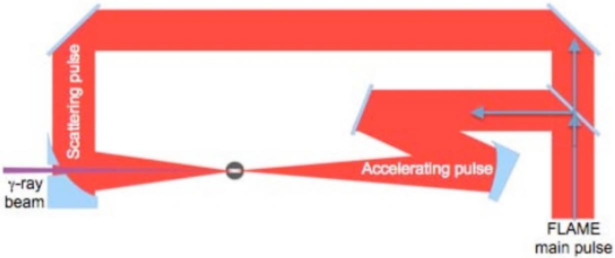

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Acknowledgments

- Thanks to A. Di Piazza and C. H. Keitel for early collaboration on the Radiation Friction modeling
- Work sponsored by the FIRB-MIUR (Italy) project SULDIS (“Superintense Ultrashort Laser-Driven Ion Sources”)
- Use of supercomputing facilities at CINECA (Italy) sponsored by the ISCRA project TOFUSEX (“TOwards FUll-Scale simulations of laser-plasma EXperiments”) award N.HP10A25JKT-2010