Laser-pulse-shape control of seeded QED cascades

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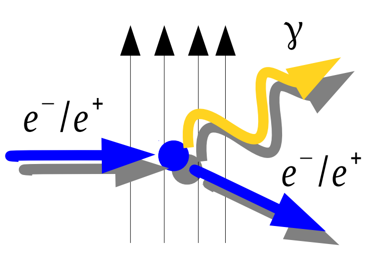
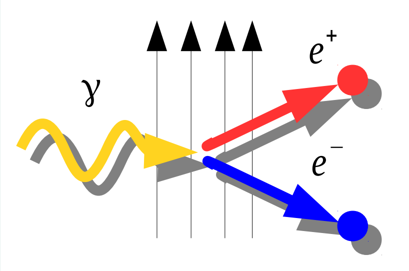
The basic QED processes in a strong background electromagnetic field

Photon emission by an e^-/e^+



Photon conversion into an e^-e^+ pair



Strong-field QED processes are controlled by the quantum parameter χ

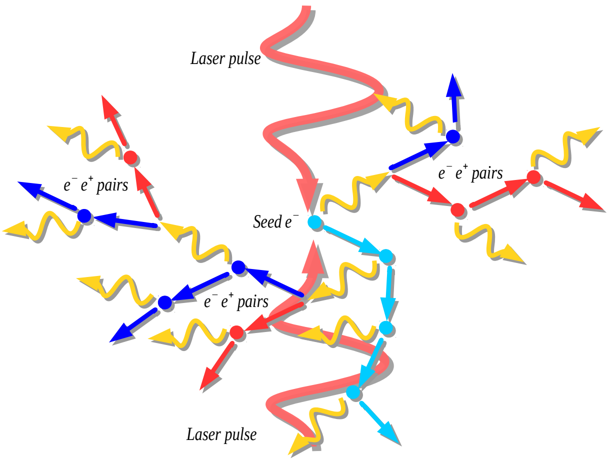
$\chi_{e/\gamma} = |F_{\mu\nu} p^{\nu}_{e/\gamma}|/E_{cr}mc$

For $\chi_e \ll 1$ the typical energy of the emitted photons is $\varepsilon_\gamma \approx \chi_e \varepsilon_e$, ε_e being the e^-/e^+ energy. Single photon emission recoil dominates when $\chi_e \gtrsim 1$.

$eE_{cr}\lambda_C = mc^2$; $E_{cr} \approx 1.3 \times 10^{16}$ V/cm

For $\chi_\gamma \ll 1$ the probability of photon conversion into an e^-e^+ pair is suppressed as $e^{-8/3\chi_\gamma}$. Photon conversion is important when $\chi_\gamma \gtrsim 1$.

Laser-driven seeded QED cascades



1) Seed e^- are violently accelerated by the laser fields and emit large amounts of γ which, in turn, convert into $e^- e^+$ pairs.

2) The generated $e^- e^+$ pairs are then accelerated by the laser fields and originate a new generation of particles.

3) QED cascades were predicted to develop in the collision of two laser pulses, each pulse with an intensity around 10^{24} W/cm^2 (Bell *et al.* PRL 2008, Fedotov *et al.* PRL 2010, Nerush *et al.* PRL 2011).

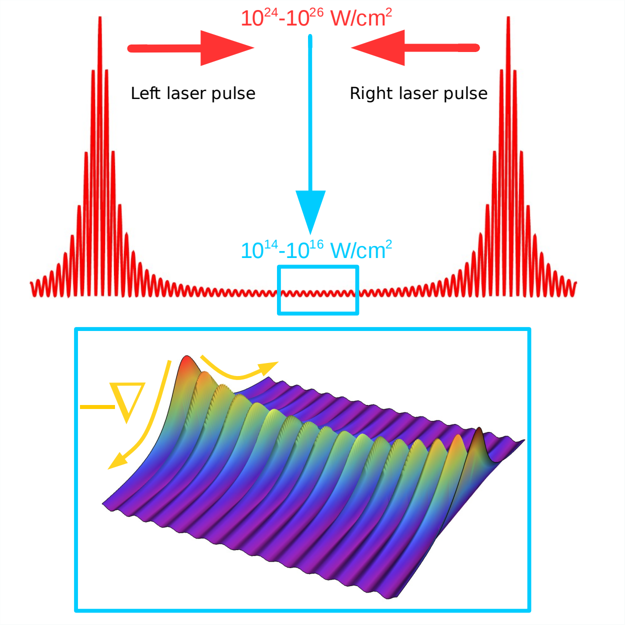
Introduction 3/3

Why are laser-driven QED cascades interesting?

- QED cascades open up the investigation of a new regime dominated by the interplay between strong-field QED and multiparticle processes. Raising number of publications! (Bell *et al.* PRL 2008, Fedotov *et al.* PRL 2010, Nerush *et al.* PRL 2011, Bulanov *et al.* PRA 2013, Gelfer *et al.* PRA 2015, Jirka *et al.* PRE 2016, Gonoskov *et al.* arXiv 2016, Zhu *et al.* NC 2016, Vranic *et al.* PPCF 2016, Grismayer *et al.* PRE 2017).
- QED cascades play a fundamental role in astrophysical environments such as the magnetosphere of pulsars, rendering an earth based implementation with intense lasers attractive (relativistic laboratory astrophysics viable with $\gtrsim 10$ PW lasers).
- QED cascades can limit the attainable intensity of extreme laser sources due to the depletion of the laser pulse energy (Fedotov *et al.* PRL 2010, Nerush *et al.* PRL 2011).

Our goal: how to control the onset of seeded QED cascades?

- Hitherto, the research has been focused on the intensity required to trigger QED cascades. The implications of the strong field gradients associated with tightly focused laser pulses have been neglected.
- We have shown (Tamburini *et al.*, Sci. Rep. **7**, 5694 (2017)) the essential role played by the laser field structure (e.g. waist radius and duration, relative orientation of the polarization axis) on the onset of seeded QED cascades.



Field gradients

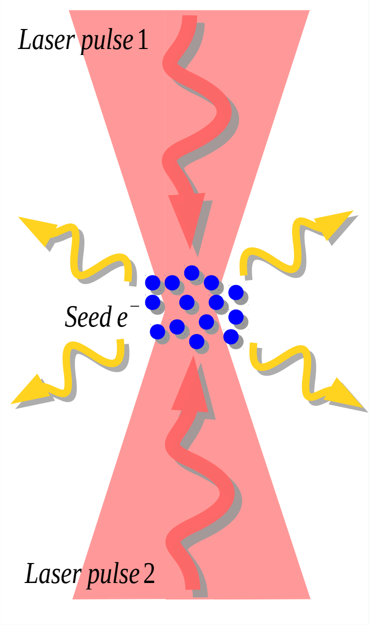
The presence of **field gradients** results into the expulsion of e^-e^+ from the regions where the field is stronger.

For instance, for a single laser pulse described by the vector potential $\mathbf{A}(\mathbf{r}, t)$, the secular e^-e^+ dynamics is known to be determined by the ponderomotive force:

$$\mathbf{f}_p = -mc^2\nabla(1 + \langle\mathbf{a}^2\rangle)^{1/2}$$

where $\mathbf{a} = e\mathbf{A}/mc^2$ is the normalized vector potential.

To attain the highest intensities $\Rightarrow$ tight focusing $\Rightarrow$ strong field gradients. Thus, the expulsion of e^-e^+ may play a **critical role** on the onset of QED cascades.

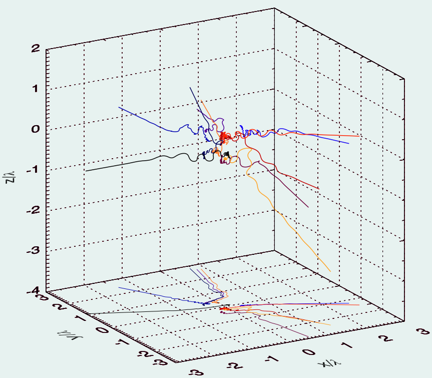


Parameters

- Two ultraintense linearly polarized ($LP_{\parallel}$ or $LP_{\perp}$) laser pulses collide head-on in a tenuous gas (such as the residual gas of a vacuum chamber).
- Their transverse spatial profile is Gaussian, with $\lambda = 0.8\,\mu$m wavelength, and sech^2 intensity envelope with 20 fs duration FWHM. Initially, the peaks of the two laser pulses are located at $z_0 = \pm 70\,\lambda$.
- A fully 3D description of the laser pulse fields with terms up to the fifth order in the diffraction angle $\epsilon = \lambda/\pi w_0$, w_0 being the waist radius, is employed.
- Initially, 10^3 seed electrons are located at rest within a λ^3 volume at the laser pulse focus with uniform random distribution. The electron density is $n = 2 \times 10^{15}\mathrm{cm}^{-3} \approx 10^{-6} n_c$, where the critical density is $n_c = m\omega^2/4\pi e \approx 1.7 \times 10^{21}\mathrm{cm}^{-3}$.
- Seed electrons originate from the ionization of different atomic species (e.g. H, O), and **go into the continuum at different values of the laser field at the focus**.

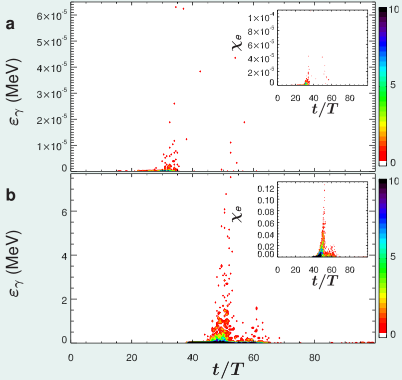
P=500 PW, $\mathbf{w_0 = 1\,\lambda}$, $I \approx 4.8 \times 10^{25}$ W/cm^2 per pulse.

Trajectories of ten seed electrons



The trajectories for $0 < t < 36.5\,T$ of ten seed electrons . At $t = 36.5\,T$ all seed electrons are outside the focal spot and the laser pulse peaks are still at $z = \pm 33.5\,\lambda$. The projection of the trajectories on the focal plane xy is also reported.

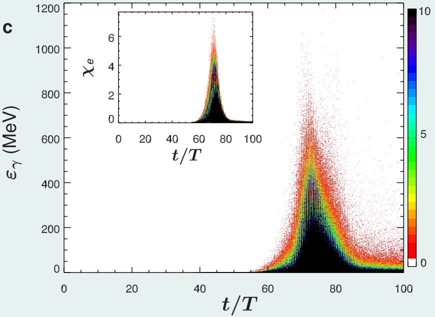
Emitted photon energies



The photon energy ε_γ and the χ_e parameter (inset) at each photon emission event as function of time. Initially, the peaks of the two laser pulses are located at $z_0 = \pm 70\,\lambda$. (a) Hydrogen (b) Hydrogen-like Oxygen. The colors correspond to the number of events (black means ≥ 10 events).

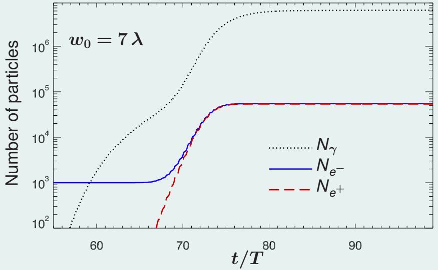
P=500 PW, $\mathbf{w_0 = 7\,\lambda}$, $I \approx 10^{24}\,\mathrm{W/cm^2}$ per pulse.

Emitted photon energies



The photon energy ε_γ and the χ_e parameter (inset) at each photon emission event. Initially, the peaks of the laser pulses are located at $z_0 = \pm 70\,\lambda$ and electrons originate from hydrogen. The colors correspond to the number of events (black means ≥ 10 events).

The number of particles



The evolution of the number of electrons N_{e-}, positrons N_{e+} and photons N_γ with energy $\varepsilon_\gamma > 2.5\,\mathrm{MeV}$. Although the laser pulse intensity decreases from $4.8 \times 10^{25}\,\mathrm{W/cm^2}$ to $10^{24}\,\mathrm{W/cm^2}$ here χ_e exceeds unity and copious emission of photons with hundreds MeV energy occurs.

M. Tamburini, A. Di Piazza, C. H. Keitel, Sci. Rep. **7**, 5694 (2017); arXiv:1511.03987 (2015).

Seeded QED cascade formation regimes 1/2

The onset of QED cascades as function of the laser pulse power P and waist radius w_0, both for $\mathrm{LP}_{\parallel}$ and $\mathrm{LP}_{\perp}$.

P (PW)	w_0 (λ)	$\mathrm{LP}_{\parallel}$ (H | O) H	$\mathrm{LP}_{\parallel}$ (H | O) O	$\mathrm{LP}_{\perp}$ (H | O) H	$\mathrm{LP}_{\perp}$ (H | O) O
200	1	N	N	N	N
	2	N	$C_{2.4}$	N	N
	3	N	$C_{1.4}$	N	N↔C
	4	G↔C	$C_{0.7}$	N	G↔C
	5	G	$C_{0.3}$	G	G
	$[6, 9]$	G	G	G	G
500	1	N	N	N	N
	2	N	$C_{6.0}$	N	N
	3	N↔C	$C_{3.7}$	N	N↔C
	4	$C_{1.6}$	$C_{2.4}$	N	$C_{2.1}$
	$[5, 8]$	$C_{[1.3,\,0.3]}$	$C_{[1.7,\,0.4]}$	$C_{[0.7,\,0.3]}$	$C_{[1.1,\,0.2]}$
	9	$C_{0.2}$	$C_{0.2}$	G↔C	G↔C
	$[10, 15]$	G	G	G	G

N = No e^-e^+ pairs, G = e^-e^+ gas, C = $e^-e^+\gamma$ cascade, A↔B = transition between regime A and B. The subscripts indicate the average cascade growth rate $\langle\Gamma\rangle$ in units of T^{-1}.

M. Tamburini, A. Di Piazza, C. H. Keitel, Sci. Rep. **7**, 5694 (2017); arXiv:1511.03987 (2015).

Seeded QED cascade formation regimes 2/2

The onset of QED cascades as function of the laser pulse intensity I and waist radius w_0, both for $\mathrm{LP}_{\parallel}$ and $\mathrm{LP}_{\perp}$.

I (W/cm^2)	w_0 (λ)	$\mathrm{LP}_{\parallel}$ (H | O)		$\mathrm{LP}_{\perp}$ (H | O)	
10^{24}	1	N	N	N	N
	2	N	G	N	N
	3	N↔G	G↔C	N	N↔G
	4	N↔G	C	N↔G	G
	5	G↔C	C	G	G
	≥ 6	C	C	C	C
10^{25} & 10^{26}	1	N	N	N	N
	2	N	C	N	N
	3	N↔C	C	N	N↔C
	4	C	C	N↔C	C
	≥ 5	C	C	C	C

N = No e^-e^+ pairs, G = e^-e^+ gas, C = $e^-e^+\gamma$ cascade, A↔B = transition between regime A and B.

Summary and conclusions

Our main findings on the onset of seeded QED cascades

- The laser field structure is of critical importance for the onset of e^-e^+ cascades. The laser intensity is not the only decisive parameter.
- We have highlighted the importance of the nature of the gas. Inner shell electrons of high-Z elements may go into the continuum only when the peaks of the laser pulses reach the focus. In this case the power required to initiate a QED cascade falls to 11 PW per pulse.
- The laser pulse structure is of critical importance also in more complex setups with, e.g., four colliding laser pulses.
- These findings open up the possibility of controlling the onset of seeded QED cascades. Seeded QED cascades can be:
  1) facilitated with $w_0 \gtrsim 4\lambda$ and high-Z gases at $I \lesssim 10^{24}\,\mathrm{W/cm^2}$
  $\Rightarrow$ relativistic laboratory astrophysics,
  2) prevented with $w_0 \lesssim 2\lambda$ and low-Z gases up to $I \approx 10^{26}\,\mathrm{W/cm^2}$
  $\Rightarrow$ attain the highest intensities and probe the QED vacuum.