eli beamlines

Reaching high laser intensity by a radiating electron

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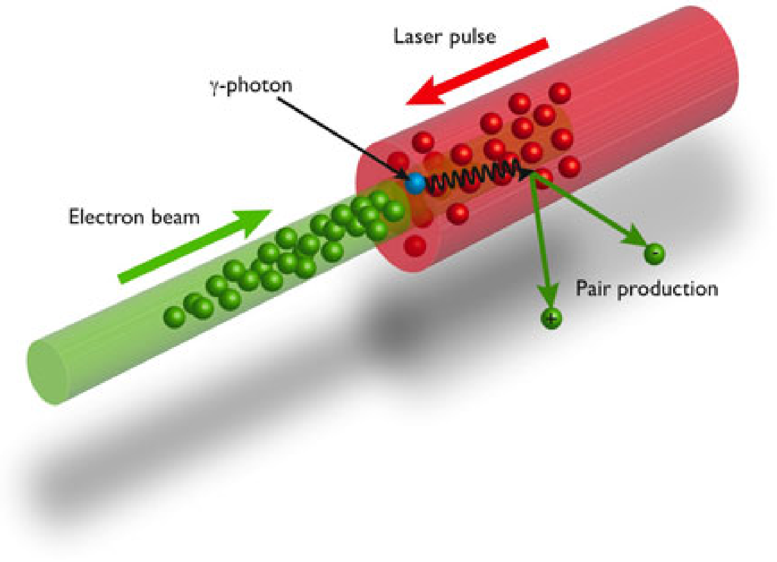
Motivation

Testing the non-linear QED vacuum properties in the laser-electron collision

- Today's record: ~ 8 GeV electron beam*, laser intensity** ~ 10^{22} W/cm^2.
- QED effects come into a play in a laser-electron collision.***
- For studying the QED vacuum properties we need a high energy electron experiencing a strong field.
- Radiation reaction
  - Reduces electron energy during the collision.
  - Can prevent the electron from reaching the strong field region.
- **What is the electron energy at the moment of experiencing the laser pulse amplitude?**



eli-laser.eu/science-applications/high-fields-physics/

*A.J.Gonsalves *et al*., Phys. Rev. Lett. **122**, 084801 (2019) **A.S. Pirozhkov *et al*. Opt. Express **25**, 20486 (2017) ***T.G. Blackburn, Rev. Mod. Plasma Phys. **4**, 5 (2020)

QED dominates for $\chi_e, \chi_\gamma > 1$

Quantum processes of the photon emission and the electron-positron pair creation*

- Two dimensionless and Lorentz invariant parameters characterizing interaction of electron (photon) with the electromagnetic field $F_{\mu\nu}$
  - χ_e – **Gamma-ray photon emission by an electron**

$$\chi_e = \frac{\sqrt{\left(F_{\mu\upsilon} p_\upsilon\right)^2}}{m_e c E_S}$$

  - χ_γ – **Pair creation by emitted photon**

$$\chi_\gamma = \frac{\sqrt{\left(F_{\mu\upsilon} \hbar k_\upsilon\right)^2}}{m_e c E_S}$$

Schwinger limit field $E_S = \frac{m_e^2 c^3}{e\hbar} \simeq 1.3 \times 10^{18}\ \mathrm{V/m}$

p_ν – electron four-momentum

$\hbar k_\nu$ – photon four-momentum

*V. I. Ritus, J. Exp. Theor. Phys. **30**, 1181 (1970)

Photon emission in the constant field

Photon emission probability in the quantum regime of radiation reaction ($\chi_e >> 1$)*

- Probability of single-photon emission per unit time for the Compton process in a constant field

$$W_\gamma \approx 3^{2/3} 28 \Gamma\left(2/3\right) \alpha m_e^2 c^4 \chi_e^{2/3} / 54 \hbar \mathcal{E}_e$$

- The electron emits one photon after the radiation time Δt

$$W_\gamma \Delta t = 1$$

- Average energy of the emitted photon

$$\mathcal{E}_\gamma \approx \left(16/63\right) \mathcal{E}_e$$

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Photon emission in the laser field

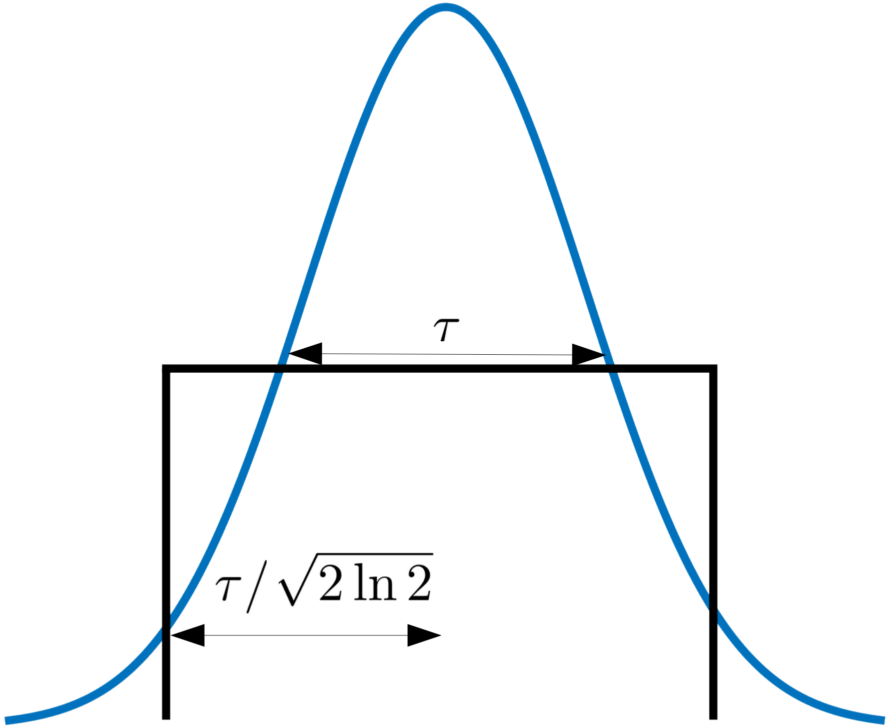
Radiation time accounting for a pulse envelope and field oscillations

- #photons ~ probability * radiation time

- Pulse envelope
  - We consider a flat-top laser pulse delivering the same energy as the gaussian one of FWHM duration τ

- Laser field oscillation
  - Photon emission probability is the highest twice per a laser period → factor ½ for radiation time

- Emitted energy ~ energy of one photon$^{\#\text{photons}}$



Threshold energy for electron reflection

Radiating electron can be prevented from reaching the laser pulse amplitude

- For $\gamma_e < \sqrt{1 + a_0^2/2}$
  - The electron can be prevented from experiencing the laser field amplitude due to the ponderomotive force even when RR is not considered.

- For $\gamma_e \gg \sqrt{1 + a_0^2/2}$
  - Radiating electron loses a significant fraction of its energy as it propagates towards the laser pulse.

- The electron reflection depends on the ponderomotive potential barrier and the actual energy of the radiating electron.

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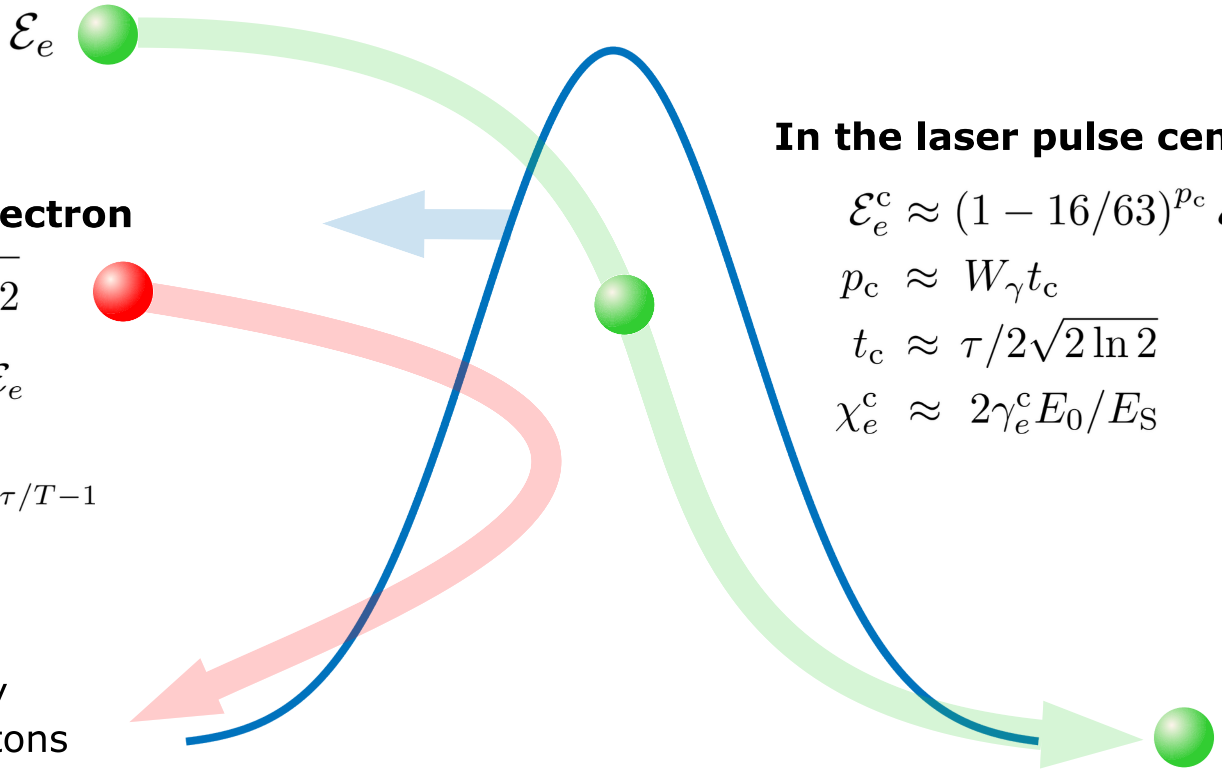
Energy of a radiating electron

Estimated values of electron energy



In the laser pulse center

$$\mathcal{E}_e^{\mathrm{c}} \approx (1-16/63)^{p_{\mathrm{c}}}\,\mathcal{E}_e$$
$$p_{\mathrm{c}} \approx W_\gamma t_{\mathrm{c}}$$
$$t_{\mathrm{c}} \approx \tau/2\sqrt{2\ln 2}$$
$$\chi_e^{\mathrm{c}} \approx 2\gamma_e^{\mathrm{c}} E_0/E_{\mathrm{S}}$$

Reflection of the electron

$$\mathcal{E}_e^{\mathrm{r}}/m_e c^2 \lesssim \sqrt{1+a_0^2/2}$$
$$\mathcal{E}_e^{\mathrm{r}} \approx (1-16/63)^{p_{\mathrm{r}}}\,\mathcal{E}_e$$
$$p_{\mathrm{r}} \approx W_\gamma t_{\mathrm{r}}$$
$$t_{\mathrm{r}} \approx t_{\mathrm{c}}/\sqrt{2}\left(\sqrt{2\ln 2}\right)^{\tau/T-1}$$

After the collision

$$\mathcal{E}_e^{\mathrm{f}} \approx (1-16/63)^{p_{\mathrm{f}}}\,\mathcal{E}_e$$
$$p_{\mathrm{f}} \approx W_\gamma t_{\mathrm{f}}$$
$$t_{\mathrm{f}} \approx \tau/\sqrt{2\ln 2}$$

$\mathcal{E}^{c,f,r}$ electron energy
$p_{c,f,r}$ number of photons
$t_{c,f,r}$ radiation time

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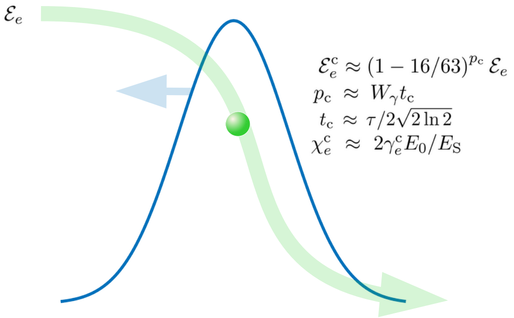
Electron energy in the pulse center

Comparison of the theory and 1D PIC simulations

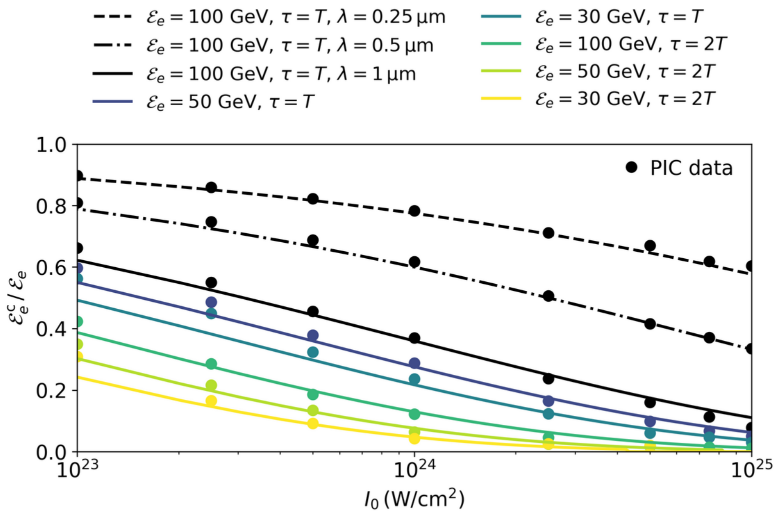
- How to reduce the emitted energy?

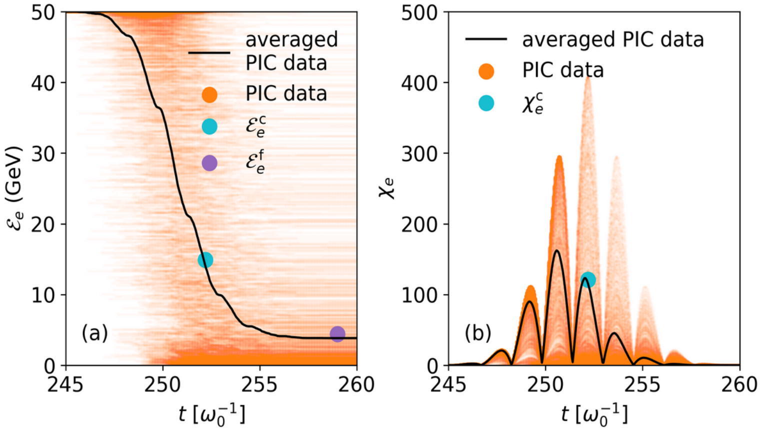
  - Increase the initial electron energy (emission probability ∝ $\gamma^{-1/3}$)

  - Shorten the laser pulse FWHM duration (emitted photon number ∝ t)



$$\mathcal{E}_e^{\mathrm{c}} \approx (1-16/63)^{p_{\mathrm{c}}}\,\mathcal{E}_e$$
$$p_{\mathrm{c}} \approx W_\gamma t_{\mathrm{c}}$$
$$t_{\mathrm{c}} \approx \tau/2\sqrt{2\ln 2}$$
$$\chi_e^{\mathrm{c}} \approx 2\gamma_e^{\mathrm{c}} E_0/E_{\mathrm{S}}$$





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Threshold intensity for electron reflection

Comparison of the theory and 1D PIC simulations

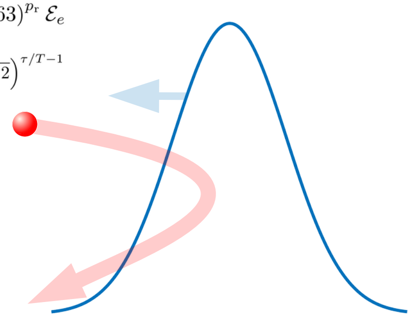
- Threshold intensity for electron reflection drops as its intial energy decreases and/or laser pulse duration increases.

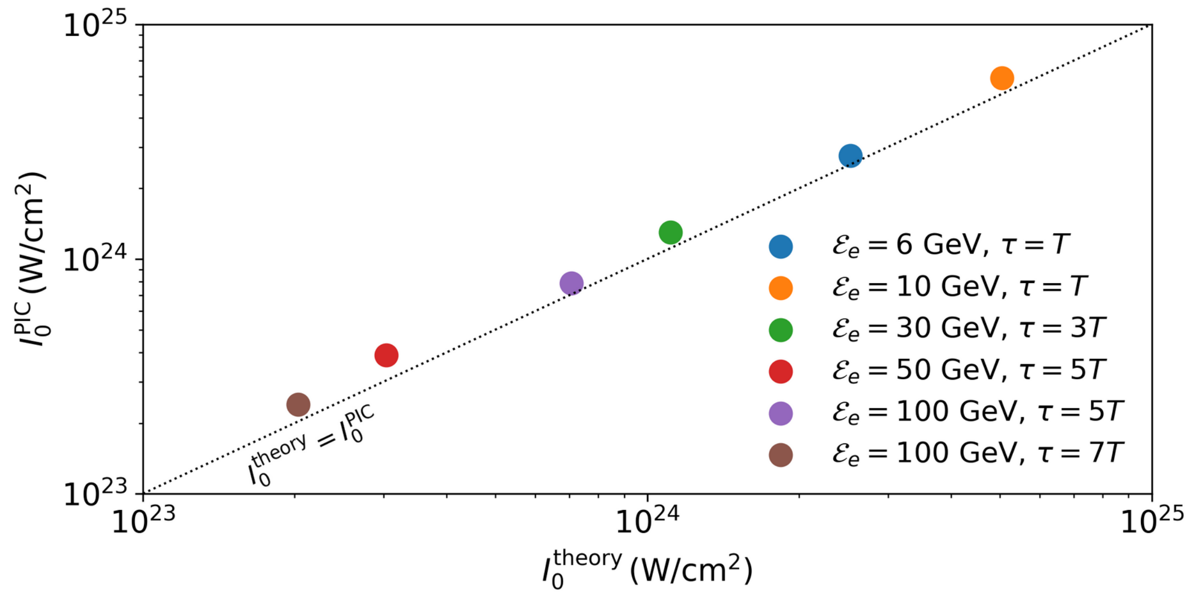
$$\mathcal{E}_e^{\rm r}/m_ec^2 \lesssim \sqrt{1+a_0^2/2}$$

$$\mathcal{E}_e^{\rm r} \approx (1-16/63)^{p_{\rm r}}\,\mathcal{E}_e$$

$$p_{\rm r} \approx W_\gamma t_{\rm r}$$

$$t_{\rm r} \approx t_{\rm c}/\sqrt{2}\left(\sqrt{2\ln 2}\right)^{\tau/T-1}$$





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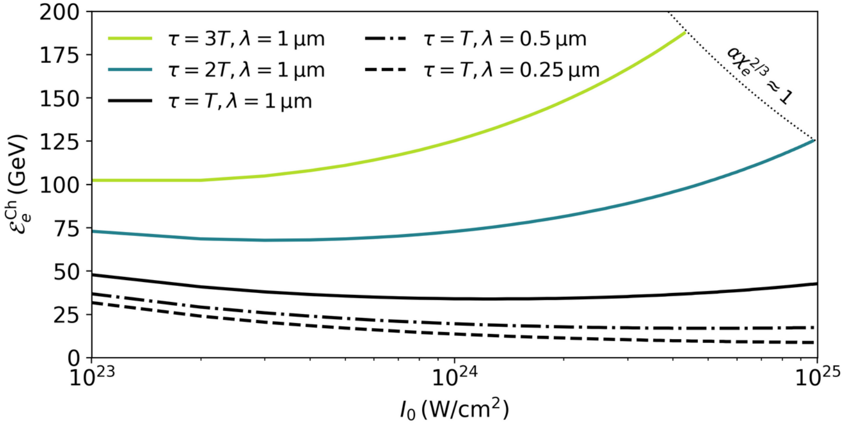
Cherenkov emission in a laser-electron collision

Cherenkov radiation from a high-energy electron traversing the electromagnetic field*

- The strong EM field of the laser pulse changes the vacuum index of refraction $n = 1 + \Delta n$.
- Then the colliding electron propagating with the super-luminal phase velocity can emit the Cherenkov photons in addition to Compton ones (synergic process).
- Conditions for Cherenkov emission
  - Electron energy $\gamma \geq 1/\sqrt{(2\Delta n)}$
  - Cherenkov radiation possible only for photons with $0 \leq \chi_\gamma \leq 15$, Δn has maximum for $\chi_\gamma \approx 5$
- Thus, the electron of the specific energy experiencing the amplitude of the laser field is required.

Required initial electron energy for Cherenkov radiation in the regime $\chi_\gamma << 1$



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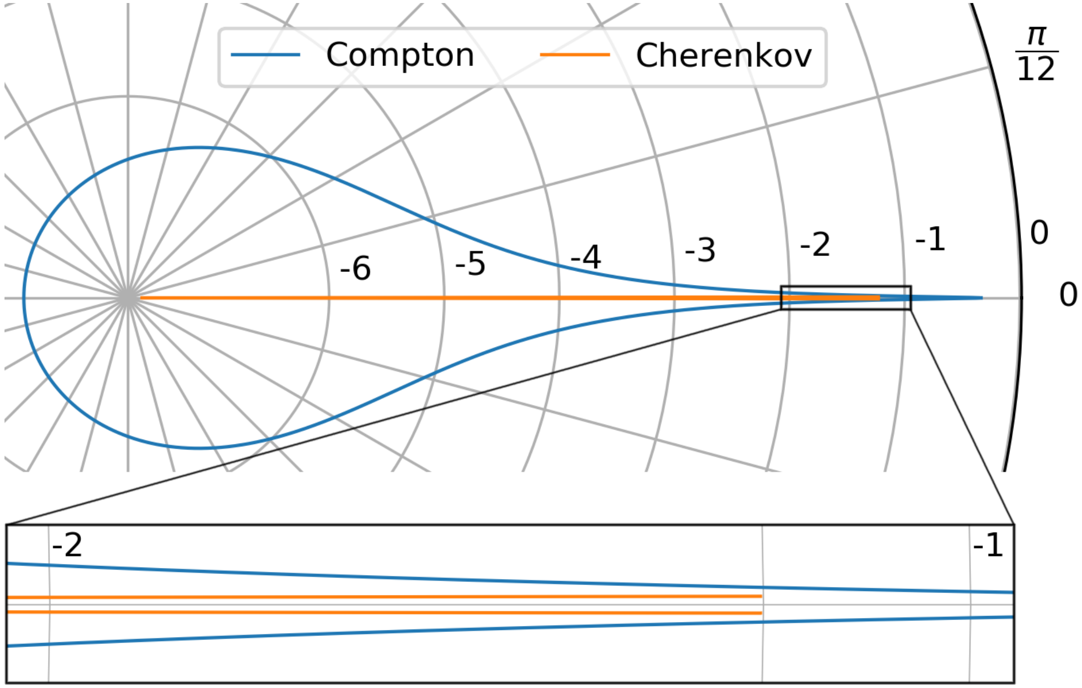
* Ritus, JETP. **30**, 1181 (1970),Dremin, JETP. **76**, 151 (2002),Macleod *et al*., PRL **122**, 161601 (2019),Bulanov *et al*., PRD **100**, 016012 (2019),Artemenko *et al*., NJP **22**, 093072 (2020)

Pairs created by Cherenkov photons

Cherenkov radiation for $\chi_\gamma \approx 1$: a threshold value for pair production

- The presence of the Cherenkov photons in the laser-electron collision can be indicated by the creation of Breit-Wheeler positrons.

- Example
  - $I_0 = 10^{25}$ W/cm^2, $\lambda = 1$ µm, $\tau = T$
  - 20 GeV electron beam
  - Cherenkov photons with $\chi_\gamma \approx 1$ emitted in the pulse center
  - Cherenkov process results in about 15% higher total positron number



The angular energy distribution log$_{10}$[E_γ(GeV)] of emitted Compton photons. Cherenkov photons withy $\chi_\gamma \approx 1$ are emitted within the cone $\theta_{\mathrm{Ch}} \approx 2\sqrt{4\alpha\left(E_0/E_{\mathrm{S}}\right)^2 + \left(m_e c^2/\mathcal{E}_e^{\mathrm{c}}\right)^2}$

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Conclusions

Collision of an electron with the counter-propagating electromagnetic wave ($\chi_e >> 1$)

- Analytical estimation
  - The average electron energy in the laser pulse center and after the interaction
  - Threshold energy for electron reflection

- Radiation reaction
  - Does not prevent reaching the multi-PW laser pulse amplitude by 10-100s GeV electron

- Observing Cherenkov radiation – flagship experiment for L4 laser at ELI Beamlines
  - The conditions on the initial electron energy provided – more photons/pairs produced

M. Jirka *et al*., Phys. Rev. A **103**, 053114 (2021)

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