Towards experimental investigations of QED in the strong field regime and beyond

Miles Radford - Miles.Radford@liverpool.ac.uk
Dr Lewis Reid
Harry Jones
Jonathan Christie
Alex Morris
Dr Laura Corner

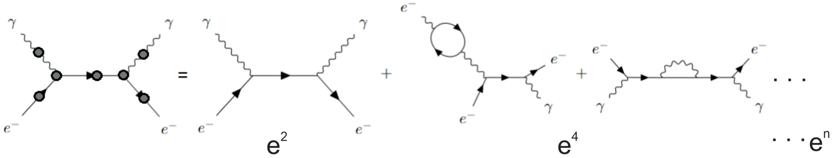
29/09/22

UNIVERSITY OF LIVERPOOL

Introduction

- QED is an extremely successful theory, but largely untested in the non-perturbative regime.
- By colliding intense laser pulses with electron beams one can investigate this area for the first time.
- I will first introduce the theory of strong field QED in the context of laser/electron beam interactions.
- I will then talk in more detail about potential SFQED experiments at Daresbury Laboratory.
- I will present simulations I have carried out and discuss the implications of these for future experiments.

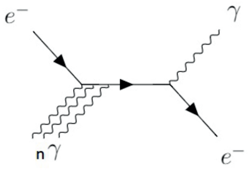
Compton Scattering



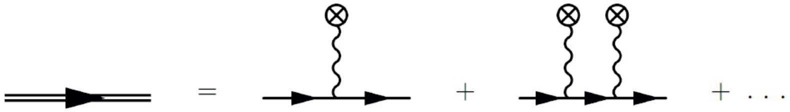
- The diagram on the left indicates the full all order Compton scattering process (Incalculable!).
- On the right hand side is an infinitely long series of diagrams that contribute to the probability of the process.
- The power series is an expansion in the coupling constant (e).
- When the coupling is small, we can ignore terms/diagrams of higher orders in e.
- So in perturbative QED we only need to claculate up to a few orders in e to get an accurate prediction.

SFQED in intense laser pulses

$$a_0 = \frac{eE_L\lambda}{\hbar\omega_L}$$



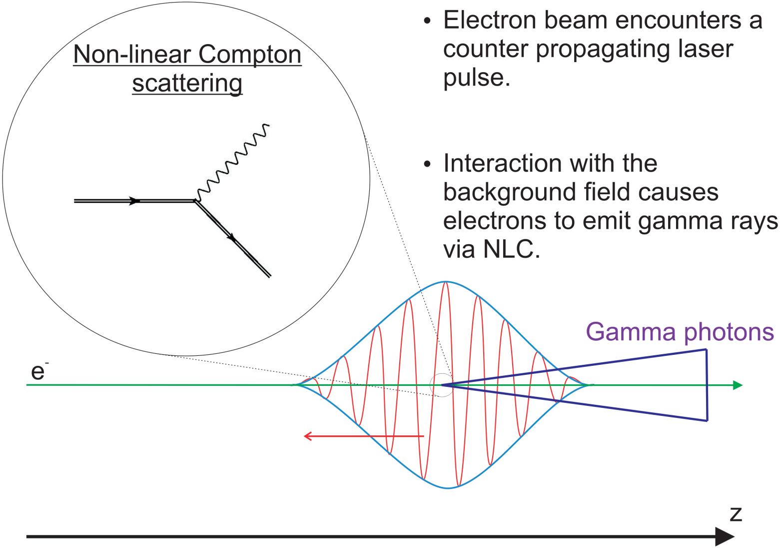
- In intense laser pulses one cannot assume single photon absorption is the most probable process as would be done in perturbative QED.
- Instead the laser is treated non-perturbatively as a classical background field.
- The laser field is parameterised by the normalized intensity a_0.
- In SFQED this paremeter replaces the electric charge to become the effective coupling, governing the strength of interactions between charges and the background electric field.



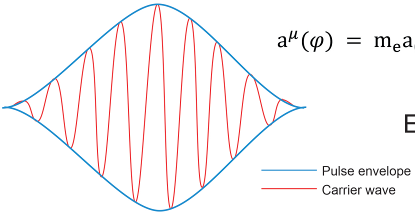
- The electron/laser interaction is used to modify the electron propagator.

NLC in intense laser pulses

- Electron beam encounters a counter propagating laser pulse.
- Interaction with the background field causes electrons to emit gamma rays via NLC.



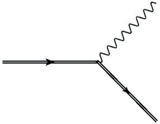
Calculating NLC rate in a laser pulse



$$a^{\mu}(\varphi) = m_e a_0 \mathcal{F}\left(\frac{\varphi}{\Phi}\right)\left(\varepsilon^{\mu}\cos(\varphi) + \bar{\varepsilon}^{\mu}\cos(\varphi)\right)$$

↑ Envelope ↑ Carrier

<u>How can we calculate the probability of NLC in this specific laser pulse?</u>



- S matrix element for NLC:

$$\mathcal{S}_{\text{NLC}} = \text{-ie} \int d^4x \, \bar{\Psi}_{p'}(x) \gamma^{\mu} \epsilon^{*}_{\ell} \Psi_p(x) e^{i\ell' \cdot x}$$

- Using the Volkov solution, for an electron in a classical plane wave background:

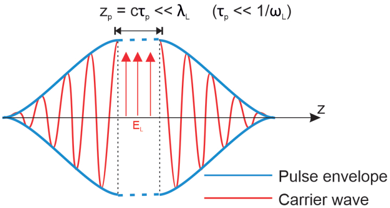
$$\Psi_p(x) = \left(1 + \frac{\gamma^{\mu} k_{\mu} \gamma^{\nu} a_{\nu}(\varphi)}{2k \cdot p}\right) u_p e^{-i\mathcal{S}_p(x)}$$

- The classical action for an electron in a plane wave background contains an integral for which only special case solutions are known, beyond these solutions we require an approximation to simplify the action.

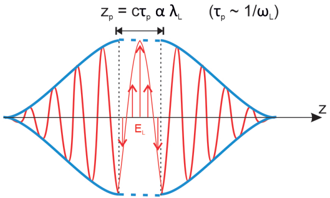
$$\mathcal{S}_p(x) = p \cdot x + \int_{-\infty}^{\varphi} dt \, \frac{2p \cdot a(t) - a^2(t)}{2k \cdot p}$$

LCFA and LMA - Strong field approximations to full QED

Locally constant field approximation - (a_0 >>1)



Locally monochromatic approximation - (a_0 ~ 1)



- Electric field is assumed to be constant over photon creation timescale.

$$\tau_p \sim m_e c / e E_L$$

- This is only valid if the photon creation length is much shorter than the laser wavelength.

- Electric field is assumed to be locally monochromatic over photon creation timescale.
- This is valid even if the photon creation length is similar to the laser wavelength.
- The slow variation of the envelope is included via a local expansion.

Probabilities calculated in LCFA and LMA

Locally constant field approximation

$$\mathbb{P} \approx -\frac{\alpha}{b} \int d\varphi \int_0^1 ds\, \mathrm{Ai}_1(z) + \left(\frac{2}{z} + \chi_\gamma \sqrt{z}\right) \mathrm{Ai}_2(z)$$

- Probability of photon emission in LCFA is expressed in terms of Airy functions. **No harmonics!**

Locally monochromatic approximation

$$\mathbb{P} \approx \sum_{n,m=-\infty}^{\infty} \int d\varphi_1 \int d\varphi_2\, \mathcal{M}_n^*(\varphi_1)\, \mathcal{M}_m(\varphi_2)$$

- Probability of photon emission in the LMA is expressed in terms of Bessel harmonics due to the interference between the pulse envelope and the carrier wave. **Harmonics!**

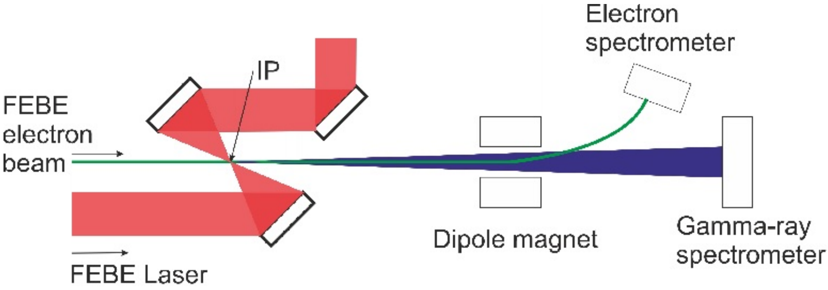
Story so far

- We can't calculate full QED results in the non-perturbative regime.
- Using SFQED we can obtain predictions but we need to apply approximations to our laser pulse.
- Two main approximations are the LCFA and LMA.

Can we investigate these models experimentally?

- The LMA predicts harmonics in the photon emission due to interference between the envelope and the carrier wave, can we observe this?
- Ptarmigan is a Monte-Carlo code that implements both models, can be used to simulate potential experiments at DL. (https://github.com/tgblackburn/ptarmigan)

Experimental layout - SFQED at FEBE



- 250MeV FEBE electron beam interacts with high power laser.
- Laser intensities from $a_0 = 0.5, 10$ can be probed capturing the transition from perturbative to non-perturbative QED.
- NLC photon and electron spectra can be analysed to compare classical, perturbative and non-perturbative QED models.

Simulation parameters

Laser intensity (a0)	1 - 10
Laser beam size w0 (um)	3
Electron beam energy (MeV)	250
Electron beam size (um)	0 - 1
Electron beam charge (pC)	20

- Electron beam parameters are based on the stretch/R&D parameters for FEBE. (Update on FEBE design - E Snedden - 16-06-21)
- Scanning through a0 range 1 to 10.
- Laser beam given a spot size of 3 microns, could be reviewed.
- Electron beam size to be scanned from 0 microns to 1 micron, to investigate the effect of the transverse laser intensity profile.
- Outputs are histograms of emitted photons, both in the LCFA and LMA.

250MeV FEBE electron beam - zero size - LMA

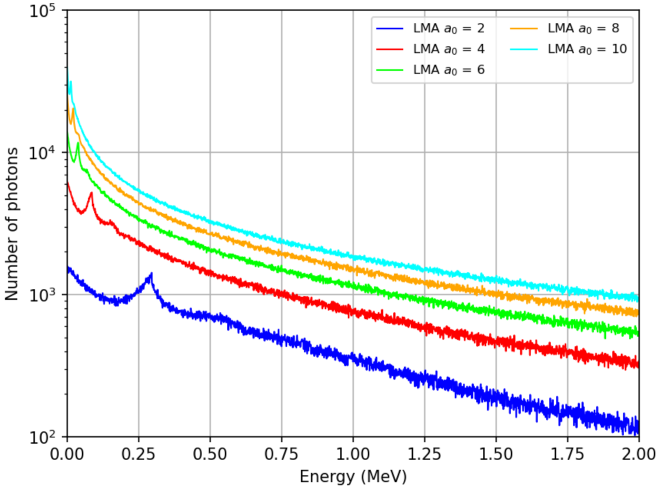
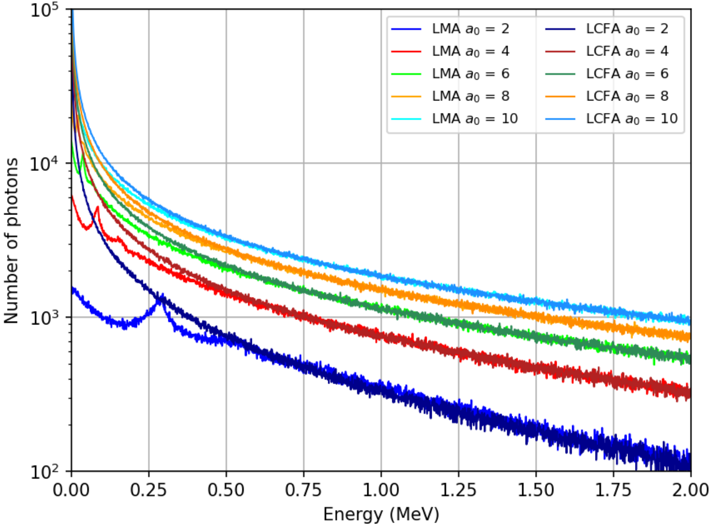


Figure: Zero electron beam size, so all electrons experience peak laser intensity.

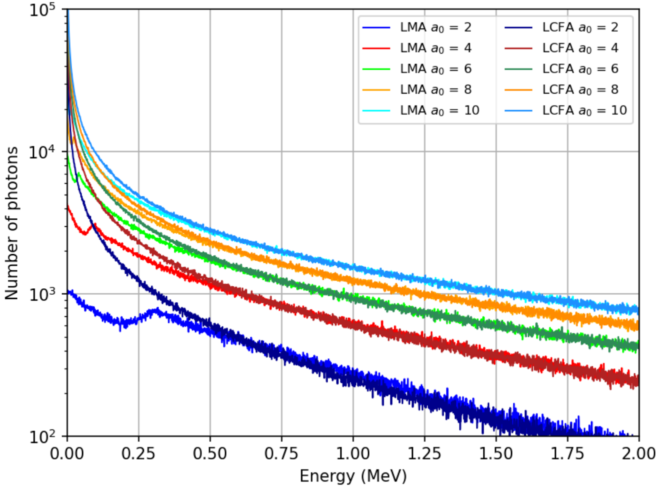
Comparing photon emission in the LCFA and LMA



Story so far

- In an experiment, possible at FEBE harmonics predicted by the LMA could be visible.
- The LCFA visibly diverges from the LMA increasingly with decreasing laser intensity as expected.
- We need to account for the transverse variation in laser intensity and how that effects photon emission.

250MeV - 1 micron electron beam, 3 micron laser spot



concluding remarks

Outcomes:

- The LMA predicts harmonics in the photon emission spectrum due to NLC.
- The LCFA does not recover the harmonic structure.
- An experiment using the FEBE electron beam and a new TW laser may be able to detect these harmonics, providing a robust test of QED in the strong field regime.

Future work:

- Further work will include simulations below a0=1, comparing leading order QED calculations to LMA and LCFA simulations.
- Analyze electron spectrum for further signatures of non-perturbative QED effects.
- Investigate gamma ray spectrometer requirements.
- Use further Monte-Carlo simulations to investigate the effect of jitter.

Laser intensity vs Peak power