Prolific Pair Production in Laser Beams

John Kirk

Max-Planck-Institut für Kernphysik
Heidelberg, Germany

Collaborators: Tony Bell (University of Oxford/CLF), Ioanna Arka (MPIK)

École Polytechnique, 22nd June 2009

Outline

Motivation

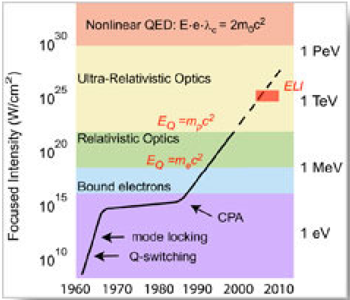
Physicists are planning lasers powerful enough to rip apart the fabric of space and time (Nature, 446 (2007))

Motivation

Physicists are planning lasers powerful enough to rip apart the fabric of space and time (Nature, 446 (2007))

- Within $\sim$ 1 year, pulses with 10^{23}–10^{24} $\mathrm{W\,cm^{-2}}$ available at $\lambda = 1\ \mu\mathrm{m}$
- Strength parameter

$$
\begin{aligned}
a &= \frac{\text{Larmor frequency}}{\text{wave frequency}} \\
&= eE\lambda/mc^2 \\
&= 855\sqrt{I_{24}\lambda^2_{\mu\mathrm{m}}}
\end{aligned}
$$

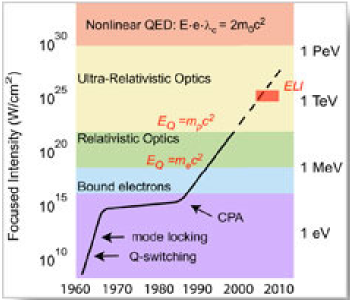


Motivation

Physicists are planning lasers powerful enough to rip apart the fabric of space and time (Nature, 446 (2007))

- Within $\sim$ 1 year, pulses with 10^{23}–10^{24} $\mathrm{W\,cm^{-2}}$ available at $\lambda = 1\ \mu\mathrm{m}$
- Strength parameter

$$a = \frac{\text{Larmor frequency}}{\text{wave frequency}} = eE\lambda/mc^2 = 855\sqrt{I_{24}\lambda^2_{\mu\mathrm{m}}}$$



Strong field QED:
in electron rest frame $E' \approx \gamma E \sim E_{\mathrm{crit}}\,(2 I_{24}\lambda_{\mu\mathrm{m}})$

Pair production using lasers I

'Standard' method, laser incident on solid surface:

- electrons accelerated to few MeV in burn-off layer
- enter high-Z foil and make gamma-rays by bremsstrahlung
- these produce pairs by Bethe-Heitler process in electrostatic field of nuclei

Pair production using lasers I

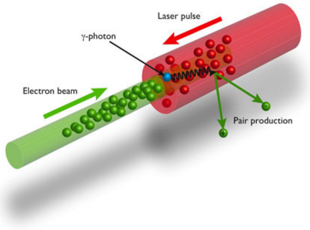
'Standard' method, laser incident on solid surface:

- electrons accelerated to few MeV in burn-off layer
- enter high-Z foil and make gamma-rays by bremsstrahlung
- these produce pairs by Bethe-Heitler process in electrostatic field of nuclei
- Laser used as accelerator, foil used as target
- Works at relatively low intensity ($\sim 10^{20}\ \mathrm{W\,cm^{-2}}$)
- Low efficiency ($< 10^{-5}$ of laser pulse goes into pairs)

Pair production using lasers II

SLAC experiment (Burke et al 1997):

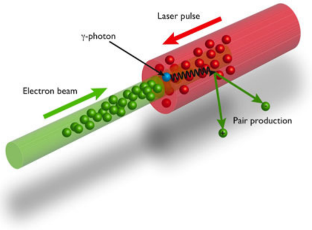
- $\sim$ 50 GeV electrons enter laser beam ($a \sim$ few) and scatter photons to $\sim$ GeV (NL Compton)
- these photons produce pairs by scattering on laser photons (NL Breit-Wheeler process)



Pair production using lasers II

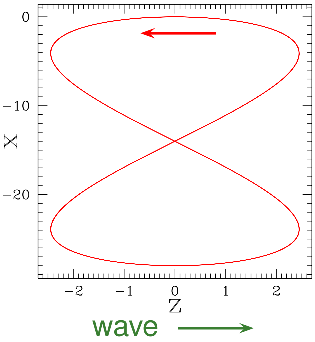
SLAC experiment (Burke et al 1997):

- $\sim$ 50 GeV electrons enter laser beam ($a \sim$ few) and scatter photons to $\sim$ GeV (NL Compton)
- these photons produce pairs by scattering on laser photons (NL Breit-Wheeler process)



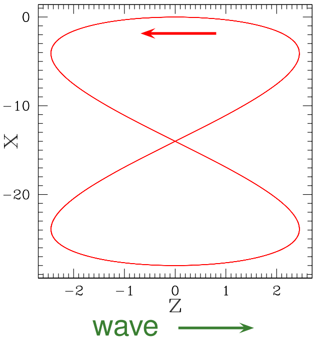
- SLAC accelerates, laser used as target
- relatively few pairs

Trajectory in a plane wave



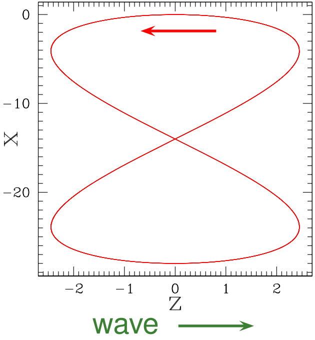
- Figure-of-eight in linearly polarized wave
- Periodic in a special frame (ZMF) with $\gamma \sim a$

Trajectory in a plane wave



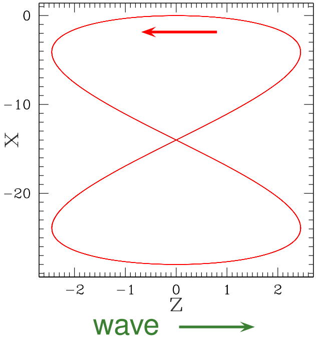
- Figure-of-eight in linearly polarized wave
- Periodic in a special frame (ZMF) with $\gamma \sim a$
- If picked up at rest in lab. frame, particle recoils
- ZMF reached by boost in direction of wave, with Lorentz factor $\approx a$

Trajectory in a plane wave



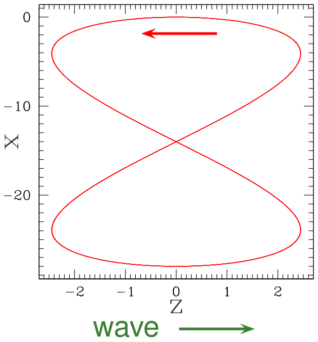
- Figure-of-eight in linearly polarized wave
- Periodic in a special frame (ZMF) with $\gamma \sim a$
- If picked up at rest in lab. frame, particle recoils
- ZMF reached by boost in direction of wave, with Lorentz factor $\approx a$
- Boost to ZMF red-shifts ν by factor $\sim a$
- In ZMF, fields weaker: $E' \sim E/a$, $B' \sim B/a$

- E-M wave in $\hat{\boldsymbol{z}}$ direction
- $\boldsymbol{E}$ along $\hat{\boldsymbol{x}}$
- $\boldsymbol{E} = -\hat{\boldsymbol{z}} \times \boldsymbol{B}$ Lorentz force vanishes for $\boldsymbol{v} \to c\hat{\boldsymbol{z}}$
- Interaction reduced – governed by perpendicular acceleration



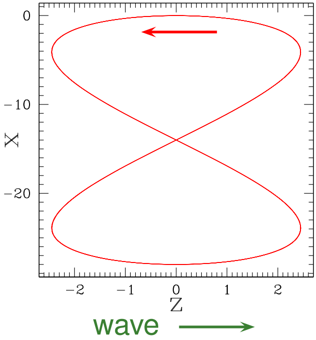
- E-M wave in $\hat{\boldsymbol{z}}$ direction
- $\boldsymbol{E}$ along $\hat{\boldsymbol{x}}$
- $\boldsymbol{E} = -\hat{\boldsymbol{z}} \times \boldsymbol{B}$ Lorentz force vanishes for $\boldsymbol{v} \to c\hat{\boldsymbol{z}}$
- Interaction reduced – governed by perpendicular acceleration
- More precisely, by

$$\begin{aligned}\eta &= (\hbar/m^2c^3)\sqrt{(\mathrm{d}p^\mu/\mathrm{d}\tau)(\mathrm{d}p_\mu/\mathrm{d}\tau)} \\ &= (e\hbar/m^3c^4)\,|F^{\mu\nu}p_\mu| \\ &= \underbrace{E/E_{\text{crit}}}_{\text{in pick-up frame}}\ |\cos\phi|\end{aligned}$$



- E-M wave in $\hat{\boldsymbol{z}}$ direction
- $\boldsymbol{E}$ along $\hat{\boldsymbol{x}}$
- $\boldsymbol{E} = -\hat{\boldsymbol{z}} \times \boldsymbol{B}$ Lorentz force vanishes for $\boldsymbol{v} \to c\hat{\boldsymbol{z}}$
- Interaction reduced – governed by perpendicular acceleration
- More precisely, by

$$\begin{aligned}\eta &= (\hbar/m^2c^3)\sqrt{(\mathrm{d}p^\mu/\mathrm{d}\tau)(\mathrm{d}p_\mu/\mathrm{d}\tau)} \\ &= (e\hbar/m^3c^4)\,|F^{\mu\nu}p_\mu| \\ &= \underbrace{E/E_{\mathrm{crit}}}_{\text{in pick-up frame}}\;|\cos\phi|\end{aligned}$$

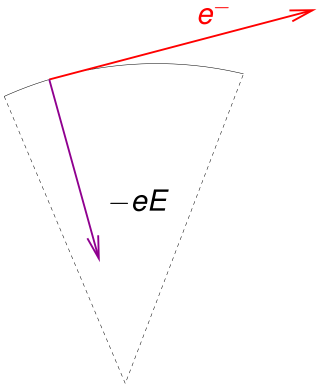


Laser beam plays the role of accelerator (to $\gamma \approx a$)

Counter-propagating beams

- Circular polarization:
  simple orbit at $B = 0$ node
  Bell & Kirk 2008:

$$
\begin{aligned}
eE/\gamma mc &= \omega_{\rm laser} \\
\eta &= \gamma E/E_{\rm crit} \\
&= 3.6\, I_{24} \lambda_{\mu\rm m}
\end{aligned}
$$



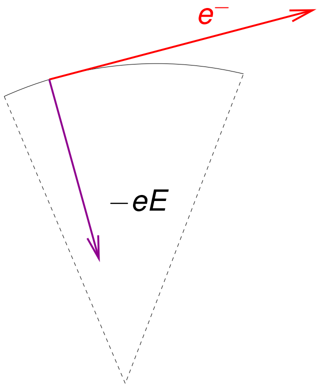
Counter-propagating beams

- Circular polarization: simple orbit at $B = 0$ node Bell & Kirk 2008:

$$\begin{aligned} eE/\gamma mc &= \omega_{\rm laser} \\ \eta &= \gamma E/E_{\rm crit} \\ &= 3.6\, I_{24} \lambda_{\mu\rm m} \end{aligned}$$

- Limited by radiation reaction when

$$\begin{aligned} \gamma &> \gamma_{\rm RR} = \sqrt{3E_{\rm crit}/2\alpha_{\rm f} E} \\ \Rightarrow I_{24} &> 0.13\, \lambda_{\mu\rm m}^{-4/3} \end{aligned}$$



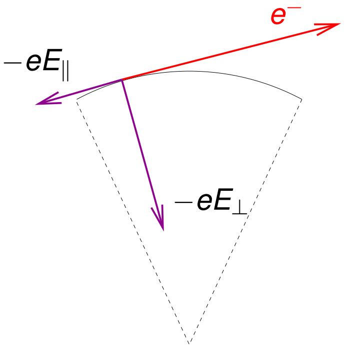
Counter-propagating beams

- Circular polarization:
  simple orbit at $B = 0$ node
  Bell & Kirk 2008:

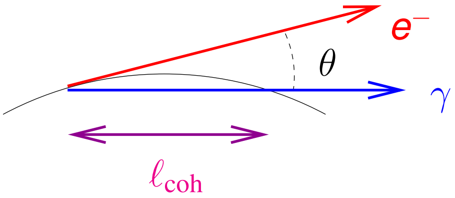
$$
\begin{aligned}
eE/\gamma mc &= \omega_{\mathrm{laser}} \\
\eta &= \gamma E/E_{\mathrm{crit}} \\
&= 3.6\, I_{24}\lambda_{\mu\mathrm{m}}
\end{aligned}
$$

- Limited by radiation reaction when

$$
\begin{aligned}
\gamma &> \gamma_{\mathrm{RR}} = \sqrt{3E_{\mathrm{crit}}/2\alpha_{\mathrm{f}}E} \\
\Rightarrow I_{24} &> 0.13\,\lambda_{\mu\mathrm{m}}^{-4/3}
\end{aligned}
$$



Coherence length

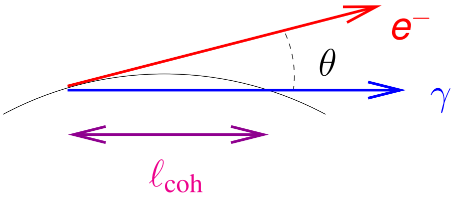


- $\sin\theta < 1/\gamma \qquad \Rightarrow \qquad \ell_{\rm coh} = mc^2/eE$
- Field quasi-static if

$$\begin{aligned} \ell_{\rm coh} &\ll \lambda \\ \Rightarrow \qquad a &\gg 1 \end{aligned}$$

- Identical requirement in QED

Coherence length



- $\sin\theta < 1/\gamma \quad \Rightarrow \quad \ell_{\text{coh}} = mc^2/eE$
- Field quasi-static if

$$\begin{aligned} \ell_{\text{coh}} &\ll \lambda \\ \Rightarrow \quad a &\gg 1 \end{aligned}$$

- Identical requirement in QED

$\Rightarrow$ *instantaneous*, *local* transition rates at each point on classical trajectory for $a \gg 1$

Weak field approximation

- In quasi-static limit transition rates depend on
  - η for electrons, and $\chi = e\hbar^2 \left| F^{\mu\nu} k_\nu \right| / 2m^3c^4$ for photons
  - field invariants $f = E^2 - B^2$ and $g = \boldsymbol{E} \cdot \boldsymbol{B}$ (both $\sim 10^{-6}\ I_{24}$)

Weak field approximation

- In quasi-static limit transition rates depend on
  - η for electrons, and $\chi = e\hbar^2 \left| F^{\mu\nu} k_\nu \right| / 2m^3 c^4$ for photons
  - field invariants $f = E^2 - B^2$ and $g = \boldsymbol{E} \cdot \boldsymbol{B}$ (both $\sim 10^{-6}\ I_{24}$)
- In γ-ray and pair production regime ($\eta \sim 1$, $\chi \sim 1$) rates depend only on η and χ

Weak field approximation

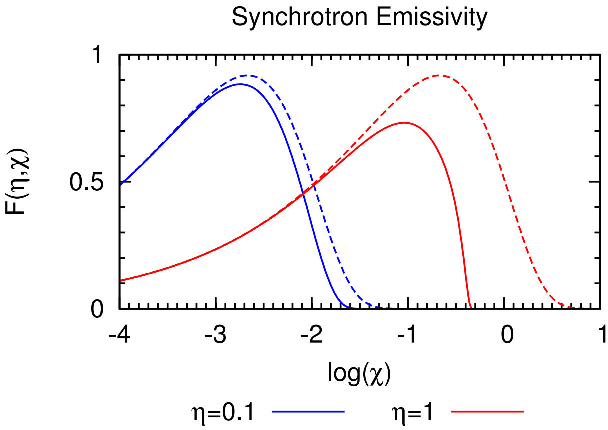
- In quasi-static limit transition rates depend on
  - η for electrons, and $\chi = e\hbar^2 \left| F^{\mu\nu} k_\nu \right| / 2m^3c^4$ for photons
  - field invariants $f = E^2 - B^2$ and $g = \boldsymbol{E} \cdot \boldsymbol{B}$ (both $\sim 10^{-6}\ I_{24}$)
- In γ-ray and pair production regime ($\eta \sim 1$, $\chi \sim 1$) rates depend only on η and χ
- Equivalent system:
  - static, homogeneous $\boldsymbol{B}$,
  - electron/photon with $\boldsymbol{p} \cdot \boldsymbol{B} = 0$,
  - in limit $\gamma \to \infty$, $B \to 0$, with η, χ held constant

Weak field approximation

- In quasi-static limit transition rates depend on
  - η for electrons, and $\chi = e\hbar^2 \left| F^{\mu\nu} k_\nu \right| / 2m^3 c^4$ for photons
  - field invariants $f = E^2 - B^2$ and $g = \boldsymbol{E} \cdot \boldsymbol{B}$ (both $\sim 10^{-6}\ I_{24}$)
- In γ-ray and pair production regime ($\eta \sim 1$, $\chi \sim 1$) rates depend only on η and χ
- Equivalent system:
  - static, homogeneous $\boldsymbol{B}$,
  - electron/photon with $\boldsymbol{p} \cdot \boldsymbol{B} = 0$,
  - in limit $\gamma \to \infty$, $B \to 0$, with η, χ held constant

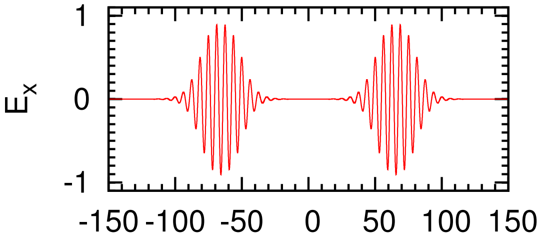
Magneto-bremsstrahlung and single-photon (magnetic) pair-production — computed in 1950's (Klepikov, Erber. . .)

Synchrotron radiation



NL Compton scattering: $e^{\pm} + n\,\gamma_{\text{laser}} \rightarrow e^{\pm} + \gamma$ for $n \gg 1$

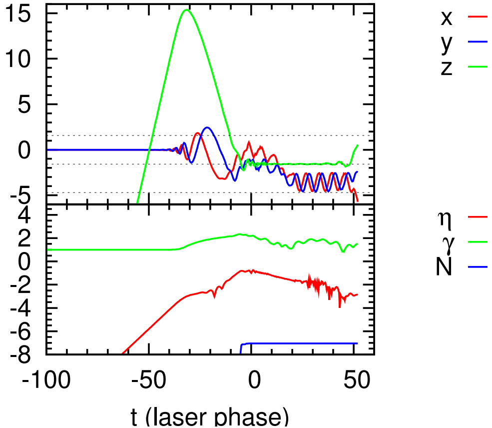
Shaped pulses



- Model pulses in cylinder of radius λ
- Integrate classical equations of motion (including radiation reaction)
- Evaluate intensity of synchrotron radiation
- Compute number of pairs produced per electron

Circularly polarized beams

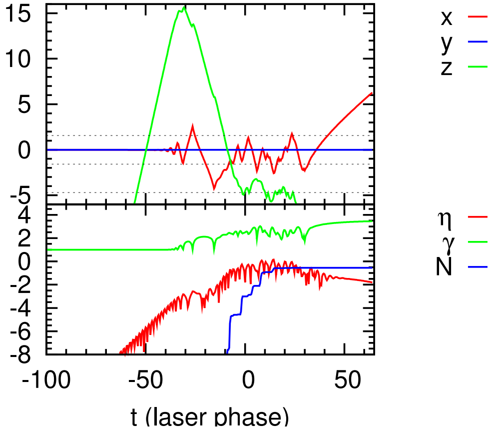
Beam intensity $6 \times 10^{23}\ \mathrm{W\,cm^{-2}}$



- $B = 0$ node unstable
- $E = 0$ node stable
- Pair production negligible

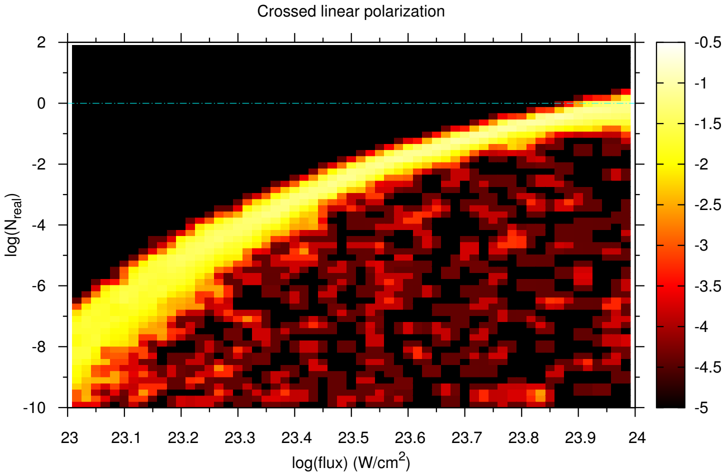
Aligned, linearly polarized beams

Beam intensity 6×10^{23} $\mathrm{W\,cm^{-2}}$



- Stable node less important
- Pair production significant

Crossed, linearly polarized beams



Summary/Outlook

- Present work
  - Classical trajectories adequate ($\eta < 1$)
  - Physical processes: synchrotron radiation, magnetic pair production ($a \gg 1$)
  - Counter-propagating beams in under-dense plasma likely to produce pair avalanche at beam intensity $10^{24}\ \mathrm{W\,cm^{-2}}$

Summary/Outlook

- Present work
  - Classical trajectories adequate ($\eta < 1$)
  - Physical processes: synchrotron radiation, magnetic pair production ($a \gg 1$)
  - Counter-propagating beams in under-dense plasma likely to produce pair avalanche at beam intensity $10^{24}\ \mathrm{W\,cm^{-2}}$
- Improvements
  - Discreteness of radiation reaction (“stragglers”) could be important (Shen & White 1971)
  - Monte-Carlo treatment of cascade needed
  - Reflected wave from laser-solid interaction? Hybrid P.I.C.+Monte-Carlo code needed