Launching QED cascades in high-intensity laser pulses

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- Nonlinear QED in strong EM fields: radiation reaction, electron-positron pair creation and cascades.

- Exploring the same physics at near-term laser intensities: high-energy electrons and photons as cascade seeds.

- Prospects for experimental observation.
Nonlinear QED

 Fundamental processes

- Simplest two: photon emission and pair creation.
- Each first order in the fine-structure constant $\alpha$.
- Expect that first order processes are more probable than second order, which are more probable than third order, etc.
However, in strong electromagnetic fields, the probability for “only one” process is exponentially suppressed.
Nonlinear QED

Cascades...

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- A single high-energy electron emits many photons (radiation reaction).
- A single photon creates an electron and positron that radiate additional photons.
Nonlinear QED
Cascades...

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Nonlinear QED

... in strong electromagnetic fields

- Energetic particles in strong magnetic fields feature in astrophysical environments.
- Magnetars are speculated to have magnetic fields $10 \times$ the critical field of QED.
- Vacuum birefringence, photon splitting and electromagnetic cascades.
Nonlinear QED

... in strong electromagnetic fields

- State-of-the-art QED calculations are limited to second-order, i.e. multiplicity = 2, and to field configurations with high symmetry.

- Estimated multiplicity in the polar cap of a pulsar magnetosphere = $10^5$.

- Also, back-reaction of cascade development can cause depletion of the strong EM field.

Nonlinear QED

... in future laser experiments

- Next-generation laser facilities producing intensities $10^{23}$ W/cm$^2$ (ELI, Apollon etc).


- Coupling between classical plasma dynamics and nonlinear QED in fields with complex structure.

Colliding beams

Motivation

- Explore the same physics at lower laser intensity.
- Probabilities for QED processes depend on parameter $\chi = \gamma E/E_{\text{crit}}$, i.e. rest frame electric field.
- Probe laser pulses exceeding $10^{21}$ W/cm$^2$ with energetic electrons or photons ($\gamma$ or $\omega/m > 1000$), e.g. Gemini, CoReLS, Apollon, ELI etc.
$R_c = \text{radiation reaction parameter, ratio of the RR and Lorentz forces (or the fractional energy loss per laser period)}$

$R_c = \alpha a_0 \chi_0$

$\approx 0.13 \left( \frac{E_0}{500 \text{ MeV}} \right) \left( \frac{I_0}{10^{22} \text{ W cm}^{-2}} \right) \left( \frac{\lambda}{\mu \text{m}} \right)$
Colliding beams
Parameter space

- $R_c =$ radiation reaction parameter, ratio of the RR and Lorentz forces (or the fractional energy loss per laser period)

\[
R_c = \alpha a_0 \chi_0 \\
\approx 0.13 \left( \frac{E_0}{500 \text{ MeV}} \right) \left( \frac{l_0}{10^{22} \text{ Wcm}^{-2}} \right) \left( \frac{\lambda}{\mu\text{m}} \right)
\]

- Recently $@ a_0 = 10, \chi = 0.1$: evidence of radiation reaction
Colliding beams
All-optical experiments

- Collision between wakefield-accelerated electron beam and intense laser pulse.
- Decelerated electrons and gamma rays pass through hole in f/2 optic.
- Measure electron and gamma spectra on a shot-to-shot basis and look for coincidences.

Gemini laser facility, CLF Rutherford Appleton Laboratory, UK

Cole et al, PRX 8, 011020 (2018)
Colliding beams

All-optical experiments

- Beams with lower energy associated with largest gamma ray signal.
- Low probability to get this signal purely from background fluctuations.
- Augment with the critical energy of the gamma spectrum, inferred from Geant simulations of the CsI scintillator response.

Cole et al, PRX 8, 011020 (2018)
Colliding beams

All-optical experiments

- 4 shots with CsI signal significantly above background.
- Hardest gamma rays associated with lowest energy in electron beam: indicative of a radiation reaction process.

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Colliding beams
All-optical experiments

- 4 shots with CsI signal significantly above background.
- Hardest gamma rays associated with lowest energy in electron beam: indicative of a radiation reaction process.
- Data inconsistent with neglect of RR. Classical RR overpredicts critical energies. Quantum RR slightly better.

Cole et al, PRX 8, 011020 (2018)
Colliding beams
All-optical experiments

- Explore the full parameter space and tune the relative importance of RR, quantum effects etc.
- Advantages: natural synchronization of the two beams; matched size of high-charge electron bunch and target laser pulse.
- “Soon” @ $a_0 > 30$, $\chi > 0.1$: RR + nonlinear Breit-Wheeler pair creation.
Photon-seeded cascades

Threshold

- Onset of nonlinear pair creation is approximately $\chi_\gamma > 0.1$.
- With optical lasers operating near the current intensity limit, necessary photon energy is in the GeV range:

$$\chi_\gamma = \frac{a_0 \omega_0 \omega (1 + \cos \theta)}{m^2}$$

$$\approx 0.8 \left( \frac{\omega}{1 \text{ GeV}} \right) \sqrt{\frac{l_0}{10^{22} \text{ W/cm}^2}}$$
Photon-seeded cascades

From bremsstrahlung

- Use bremsstrahlung of multi-GeV electron beam in a high-Z target.
Photon-seeded cascades
From bremsstrahlung

- Use bremsstrahlung of multi-GeV electron beam in a high-Z target.

- Broad spectrum up to the initial energy of the electron $E_0$ ($f = \omega / E_0$ and $\ell = L / L_{\text{rad}}$):

  \[
  \frac{dN_\gamma}{df} = \frac{(1 - f)^{4\ell/3} - e^{-7\ell/9}}{f \left[ \frac{7}{9} + \frac{4}{3} \ln(1 - f) \right]}
  \]

- Divergence $\theta$ scales as $\ell^{1/2} / E_0$

TGB and Marklund, PPCF 60, 054009 (2018)
Photon-seeded cascades
From bremsstrahlung

- Ideal target thickness is $0.7L_{\text{rad}}$: thick enough to make lots of photons, but not so thick as to deplete the high-energy tail by Bethe-Heitler pair creation.
- Positron yield can be in the 1000s...
- But unless divergence of the photons is reduced, the overlap between the beams is too small.

TGB and Marklund, PPCF 60, 054009 (2018)
Electron-seeded cascades

Motivation

- Consider making pairs using a high-energy electron beam, rather than a photon beam.
- To make pairs, need a laser pulse with $a_0 > 30$.
- But that laser pulse is also good at making high-energy photons, as in non-linear Compton scattering, the harmonic order scales as $a_0^3$. 
Electron-seeded cascades

Motivation

- A laser-electron beam collision creates photons where they are needed.
- The highest-energy photons are created in the rising edge of the pulse; pairs at the centre.
- Source and converter separated by microns, photon divergence scales like $a_0/\gamma$. 
Electron-seeded cascades
Theory and simulation

- Interaction can be modelled directly from QED [e.g. Ilderton, PRL 106, 020404 (2011)], but only at second order, i.e. electron emits only one photon.

- Integrated, full-scale QED-PIC simulations for wakefield acceleration plus photon and pair creation [Lobet et al, PRAB 20, 043401 (2017)].
Electron-seeded cascades
How accurate are QED-PIC codes?

- Compare PIC photon spectra with exact QED results.
- Power spectrum, total energy, laser absorption accurate to % level for $a_0 > 5$.

Electron-seeded cascades
Scaling laws

\[ \frac{dN_{\gamma}}{d\omega} \propto \frac{\exp\left( -\frac{2\omega}{3\chi_c(E_0 - \omega)} \right)}{\sqrt{\chi_c(E_0 - \omega) + 4\omega}} \]

\[ \omega_c \approx E_0 \frac{\sqrt{\frac{2\chi_cm^2}{a_0E_0\omega_0}}}{1 + \sqrt{\frac{2\chi_cm^2}{a_0E_0\omega_0}}} \]

\[ E_+ \approx \frac{\omega_c}{2} \left[ 1 + \frac{1.6\alpha a_0^2\omega_0\omega_c}{m^2} g\left( \frac{a_0\omega_0\omega_c}{m^2} \right) \right]^{-1} \]

\[ \frac{N_{\pm}}{N_e} \approx 3.8P_{\pm}\chi_c \frac{(E_0 - \omega_c)^2}{E_0} \frac{dN_{\gamma}}{d\omega} \bigg|_{\omega = \omega_c} \]

- Positron yield from synchrotron spectrum × pair creation probability.
- For pair creation, we need a photon \( \chi \) about 1, so we will end up with a positron \( \chi \) of about 0.5.

TGB, Ilderton, Murphy and Marklund, PRA 96, 022128 (2017)
Electron-seeded cascades

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Threshold

- To observe pair creation (say 1000 positrons for $10^9$ electrons @ 30 fs)

$$\left( \frac{l_0}{10^{21} \text{ W/cm}^2} \right) \left( \frac{E_0}{2 \text{ GeV}} \right) \approx 1$$

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$$\left( \frac{l_0}{10^{21} \text{ W/cm}^2} \right) \left( \frac{E_0}{2 \text{ GeV}} \right) \gtrsim 1$$

- Use measurements of the gamma ray yield and critical energy to identify shots where a positron signal is expected.

TGB, Ilderton, Murphy and Marklund, PRA 96, 022128 (2017)
Cascades (multiple QED events per incident particle) will be launched by high-energy photons or electrons in laser pulses at and above the current intensity limit.

Dynamics in this regime is dominated by nonperturbative QED, for which no complete theoretical description exists.

Coincidence measurements of electron, positron and photon spectra isolate successful collisions from shot-to-shot fluctuations.