Scientific Opportunities of Strong Field QED Experiments

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outline of this talk:

1. Proposals for strong field QED experiments
2. Intrinsic physics of strong field QED
3. Applications of strong field QED
An untapped frontier in the study of QED is that of very strong fields. The figure of merit is

$$\chi = eE/m_e^2$$

where $E$ is the electric field in an appropriate frame in electron-photon or photon-photon collisions. When $\chi > 1$, electron-positron pair creation proceeds freely. What happens then?
The most compelling previous experiment approaching this energy region was that SLAC experiment E-144 in electron beam - laser collisions, done the 1990’s. This experiment measured nonlinear Compton scattering and pair production, e.g.

\[ e + n\gamma \rightarrow e + \gamma \]

with fields in the initial electron frame at \( \chi \sim 0.3 \), finding good agreement with QED predictions.

Now there are many proposals to reach \( \chi > 1 \) where the nonlinearity becomes essential.
What are the proposed experiments?

SLAC: 13 GeV e- beam from FACET II + 20 TW laser

30 GeV e- beam from FACET/LCLS + few-PW laser

LBNL: e- beam from BELLA plasma accelerator + high-power laser

DESY: LUXE experiment: 17.5 GeV e- beam from XFEL + 30 - 300 TW laser

Pellegrini: LCLS II electrons + backscattered X-rays

ELI-NP: $\gamma \gamma$ collisions using two 10 PW lasers
Peak laser intensity $I_0 \text{ [W/cm}^2\text{]}$ – optical laser, laboratory frame

Classical intensity parameter $\alpha_0$

Peak quantum parameter

- CLIC (3 TeV)
- SLAC Double-Bunch FEL
- FACET-II 30 TW
- SLAC E-144
- NpQED Collider (125 GeV, 100 nm)
- SLAC 3 PW
- DESY 0.3 PW
- BELLA 1 PW (LWFA)
- ZEUS 3 PW (LWFA)
- Rochester 30 PW (LWFA)
- SEL 100 PW

Schwinger field

- Perturbative regime
- Relativistic threshold
- Nonperturbative laser field
- QED plasma (laser-laser)
- Nonperturbative radiation field

Sebastian Meuren
What are the fundamental physics issues at play in these system?

It is difficult to see that new laws of physics will appear in this regime. The experiments do not probe short distances, only distances $\hbar/m_c$ where the QED vacuum is well understood.

QED perturbation theory breaks down at high field (Ritus-Narozhny: at $\chi \sim \alpha^{-3/2}$), but this might be solved by resummation of e propagator diagrams (Fedotov-Mironov).
More interesting issues concern modeling and emergent behavior:

The pairs in the e+e- plasma created by Schwinger fields are produced coherently. What is the effect of this quantum coherence? Are there prominent plasma modes enhanced by this effect? Is there nonlinear pattern formation?

This is an unexplored regime, so we should expect surprises.

Fascinating nonlinear phenomena arise from coherent effects in high-harmonic X-ray generation and from spinodal decomposition in alloys and polymer solutions. Why not here?
At a more practical level:

All current modeling of e+e- plasmas is done using the Local Constant Field approximation. This assumes that the emission rates for e-, e+, γ are given by the formulae for uniform fields.

This ignores “formation length” effects: particles of low momentum $p$ cannot be produced if the background is not coherent over lengths of order $\hbar/p$. This is an issue in a wide range of applications. These experiments will allow us to develop a better description and better codes, matched to data.
What are the relevant applications?

Astrophysics:

e+e- plasmas are present in the most energetic astrophysical objects. Magnetars, a class of pulsars, have magnetic fields with $\chi \sim 1 - 100$. Active galactic nuclei can also host such strong magnetic fields in the vicinity of black holes. These strong fields and associated strong QED phenomena are probably responsible for Fast Radio Bursts, for the production of X-rays and gamma rays from astrophysical sources, and for the acceleration of cosmic rays in AGN jets. Our understanding of all of these systems depends on correct modeling with QED plasma codes.
Beamstrahlung at high-energy e+e- colliders has $\chi \sim 10$ at the highest energies in the CLIC design and much higher values of $\chi$ at higher energies. Beamstrahlung is a crucial constraint on beam parameters and luminosity. We must understand the underlying physics correctly.
Our group at SLAC has proposed e+e- collider parameters with very short bunches, of very high density to reach the extreme quantum limit of beamstrahlung. We rely on the formation length to inhibit production of low-energy $\gamma$s. Then the collider becomes a high energy $\gamma\gamma$ collider, as proposed in the 1980's by Blankenbecler and Drell. This is a very ambitious proposal; these experiments will provide a crucial test.
Thus, the motivation to explore the $\chi > 1$ regime is very strong.

In the rest of this session, we will hear proposals of how to explore this regime.