Report on the workshop

# Physics Opportunities at a Lepton Collider in the Fully Nonperturbative QED Regime

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The purpose of this workshop was to bring together members of a number of different scientific communities to further our understanding of the following issues:

1. Do we understand the basic physics processes in electron and positron interactions with electromagnetic fields in the regime at and far above the Schwinger critical field $eE \sim m_e^2 c^3/\hbar$?

2. What is the state of the art in the simulation of relativistic electrons and positrons in the presence of strong electromagnetic fields? These simulations are used to model accelerator beam-beam interactions, laser-plasma interactions, and extreme astrophysical environments. Are they adequate to the task?

3. Can we make quantitative predictions for the interactions of electron and positron beams in the extreme quantum limit of beamstrahlung? Can beamstrahlung emission lead to a design for a $\gamma\gamma$ collider with very high center-of-mass energy?

4. How can planned and future experiments on the interaction of high-energy electrons with a high-power laser improve our understanding of the questions above?

A resume of discussions and conclusions of the workshop follows. The complete schedule of talks can be found at: `https://conf.slac.stanford.edu/npqed-2019/agenda`.

**Theory of QED in the Strong-Field Limit**

We discussed perturbative and nonperturbative treatments of photon and $e^+e^-$ pair production in strong electromagnetic (EM) fields. For interaction of a relativistic electron with a background field, the characteristic quantum nonlinearity parameter is $\chi = eE\gamma/m^2$ in natural units. We reviewed calculations at $\chi \sim 1$ and $\chi \gg 1$.

A particular issue is the conjecture of Ritus and Narozhny that the usual QED perturbation theory breaks down for values of $\chi$ sufficiently large that $\alpha\chi^{2/3} > 1$ ($\chi > 1600$). This conjecture needs some qualification. Up to 3-loop order, all diagrams that are enhanced for $\alpha\chi^{2/3} \gg 1$ are subleading in $\alpha$. Recently, Fedotov and Mironov have identified an infinite series of diagrams that can be resummed to account for the effect of these diagrams. The result is a modification of the lowest order perturbation theory results at the 10% level. This gives optimism that the underlying QED can be understood through resummed perturbation theory.

**Local Constant Field Approximation (LCFA)**

Once the basic QED theory is formulated, it must then be incorporated into simulation codes that can follow the response of particles or plasma to the strong background EM fields and adjust the fields self-consistently. This is done in state-of-the-art 3-dimensional Particle-in-Cell (PIC) simulation codes used to simulate the dynamics of beams in accelerator structure and laser-plasma interactions and in the codes CAIN and Guinea-Pig used to simulate the beam-beam interaction at lepton colliders. At the workshop, we reviewed applications of these codes in all of those domains, in particular, applications to the astrophysics of jet formation from black holes and the acceleration of cosmic rays and applications to plasma wakefield acceleration.

At present, all of these codes make use of the Local Constant Field Approximation. That is, photon emission and $e^+e^-$ pair creation probabilities are computed with each cell of the simulation, using the formulae that would be appropriate if the local value of the field were constant throughout space. The created photons and pairs are then treated as incoherent with the other particles and fields in the simulation.

Two potentially important effects are missing in this description. First, photons and pairs from synchrotron radiation are created from the coherent action of the current of of the emitting electron over a fixed distance (the "formation length"). If the EM fields vary over distances shorter than the formation length, the radiation is suppressed. It is an important research project to understand how to include this formation length effect into the simulations.

Second, in a macroscopic laser field, $e^+e^-$ pairs are produced with quantum coherence. It seems important to ask whether this coherence affects some property of the pair plasma in a way that makes the coherence experimentally visible. This question seems not to have been asked before, and it is a potentially significant research direction.

**Beamstrahlung**

We reviewed the theory of synchrotron radiation in $e^+e^-$ bunch-bunch interactions ("beamstrahlung"), and its implementation in simulation codes. In the late 1980's, Blankenbecler and Drell, and Jacob and Wu, developed a detailed theoretical understanding of beamstrahlung that forms the basis of the current codes. However, this theory is developed from the limit of small disruption and extended (and coherent) collective fields from each bunch acting on particles in the other. Subject to the qualification just given, this theory correctly treats the extreme quantum limit $\chi$ or $\Upsilon \gg 1$. (In the accelerator community, the synchrotron radiation parameter $\Upsilon$ is often used in place of $\chi$.) Formation length effects, which might well be important in this limit, are neglected.

Blankenbecler and Drell emphasized that beamstrahlung with $\chi \gg 1$ can efficiently convert an electron bunch to high-energy photons, making it possible to create a $\gamma\gamma$ collider with high center of mass energy by colliding highly compressed electrons bunches. This possibility was discussed at the workshop in relation to possible experiments and to designs for eventual high-energy accelerators. However, these ideas should be validated by a more sophisticated treatment that takes into account realistic disruption and formation length effects. For the hardest photons, the formation length is much shorter than the disruption scale, but for lower-energy photons this ceases to be true. The effect on the photon spectrum and the fraction of photons at high fractional energy needs to assessed more carefully.

It should be noted that extremely short bunch lengths are required for this concept, and this issue also needs a dedicated accelerator physics demonstration.

**Experiments**

We reviewed planned experiments on electron-laser and laser-laser interactions at FACET-II, DESY, and ELI.

FACET-II has plans for a precision experiment on electron-laser interactions using the 10 GeV electron beam of FACET interacting with a 20 TW laser, reaching $\chi \sim 1$. The consensus at the workshop was that significant discrepancies would be seen between the photon and pair spectra in this experiment and the predictions of PIC codes. Thus, these experiments will play an additional important role in helping to refine PIC codes for applications in particle-astrophysics and future extreme-intensity experiments.

The workshop also discussed possible future experiments at SLAC, up to experiments with a 30 GeV electron beam and a PW laser, accessing $\chi \gtrsim 10$.

**Next steps**

We envision the next steps for this line of investigation, over the coming 2 years, as the following:

1. Continue theoretical investigation of coherence effects in particle-field interactions, developing a computationally practical quantum field theoretic understanding at ultra-high intensities of beamstrahlung and electron-laser interactions; and carry out experiments with $\chi \lesssim 1$ at FACET-II, DESY, and ELI and other high power laser systems.

2. Write a white paper with a more concrete $\gamma\gamma$ collider design at center of mass energy from 100 GeV to multi-TeV, including discussion of its physics case.

3. Improve our understanding of the $\chi \sim 100$ regime, sufficient to plan an experimental program on $e^+e^-$ pair creation in this extreme regime.

4. Further theoretical studies of the $\alpha\chi^{2/3} > 1$ regime.