QED at Critical Field Strength

(SLAC Experiment 144)

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Summary

We seek a Supplemental Grant of $90k in FY92 in support of SLAC experiment 144. In this experiment we will explore e^+e^- pair creation in fields of strength $\sim 10^{16}$ V/cm, *i.e.*, the QED critical field $m^2c^3/e\hbar$. We would be sensitive to anomalous structures in the pair-mass spectrum with a resolution of 10 keV. Such structures may well exist if the positron peaks seen in heavy-ion collisions at Darmstadt are indeed a strong-field QED effect. Our experimental has a pure-QED initial state, light-by-light scattering of a laser beam against a high-energy γ-beam, with systematic control of the intensity and energy of the beam particles.

The Princeton group is to construct a pair spectrometer instrumented with CCD's, as well as diagnostics of the γ-beam. To complete the spectrometer by the end of FY93 we need to build a CCD test station to select the CCD type by the end of FY92. The present request for funding is to construct the test station, whose components will largely be reused in the final spectrometer. Projections for funding needs in FY93 are also given.

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1 Introduction

Our experimental program has its origins with O. Klein (Z. Phys. **53** (1929) 157) who noted that the reflection coefficient is infinite when Dirac electrons hit a steep barrier (Klein's paradox). F. Sauter (Z. Phys. **69** (1931) 742) deduced that the paradox arises only in electric fields exceeding the critical strength:

$$E_{\rm crit} = \frac{m^2c^3}{e\hbar} = 1.32 \times 10^{16} \text{ Volts/cm}.$$

At the critical field, the voltage drop across a Compton wavelength is the electron rest energy:

$$eE_{\rm crit} \cdot \frac{\hbar}{mc} = mc^2.$$

Heisenberg and Euler (Z. Phys. **98** (1936) 718) realized that at the critical field the vacuum 'sparks' into e^+e^- pairs.

However, QED critical fields are rare in nature. The magnetic field at the surface of a neutron star approaches the critical field $B_{\rm crit} = 4.4 \times 10^{13}$ Gauss; perhaps aspects of pulsar radiation depend on these ultrastrong fields.

The maximum electric field experienced by an atomic electron near a nucleus of charge Z is

$$E \approx \frac{Ze}{\lambda_C^2} = Z\alpha E_{\rm crit}.$$

Hence QED critical fields have played little role in atomic physics.

During heavy-ion collisions where $Z_{\rm total} = 2Z > 1/\alpha$, the critical field can be exceeded and e^+e^- production is expected. The line spectrum seen in positron production in heavy-ion collisions (Darmstadt; Phys. Rev. Lett. **51** (1983) 2261, **56** (1986) 444; Phys. Lett. **B218** (1989) 12, **B245** (1990) 153) is not understood, and is one of the few observed phenomena in elementary particle physics that doesn't fit into the current Standard Model.

We plan to take advantage of the technology of high-energy physics to produce critical field in e-laser interactions. The electric field due to a laser as seen in the rest frame of a high-energy electron is

$$E^\star = \gamma(1+\beta)E_{\rm lab} \approx 2\gamma E_{\rm lab}$$

The critical field can be achieved with a laser beam of intensity

$$I = \frac{E_{\rm lab}^2}{377\Omega} = \frac{E_{\rm crit}^2}{4\gamma^2 \cdot 377}.$$

Thus for 46-GeV electrons ($\gamma = 9 \times 10^4$) we can achieve $E_{\rm crit}$ with a focused laser intensity of 1.43×10^{19} Watts/cm^2. Such intensities are now attainable in table-top teraWatt (T^3) lasers (Maine *et al.*, IEEE **QE-24** (1988) 398) in which a Joule of energy is compressed into one picosecond and focused into a few square microns.

This led to the formation of a collaboration between Princeton U., U. Rochester, and SLAC to study critical fields by installing a teraWatt laser in the SLAC final-focus test beam (FFTB). Our proposal was approved as experiment 144 on Dec. 20, 1991, subject to a demonstration that the laser can be focused to intensity 2×10^{19} Watts/cm^2. The demonstration is now underway at U. Rochester and should be complete by June 1992.

The physics program of E-144 has four components including two basic-physics measurements, and two topics in accelerator physics:

1. Nonlinear Compton Scattering: $e + n\omega \rightarrow e' + \gamma'$

   — Semiclassical theory $\Rightarrow$ data will diagnose laser intensity.

   — Provides γ beam for light-by-light scattering.

2. Beamstrahlung

   — As number of interacting laser photons rises, the e-laser interaction mimics beamstrahlung in future e^+e^- colliders.

   — $e + n\omega \rightarrow e'e^+e^-$ is analog of important pair-production backgrounds in future colliders.

3. The Multiphoton Breit-Wheeler Reaction: $\gamma + n\omega \rightarrow e^+e^-$

   — Use backscattered γ-beam from topics 1 and 2.

   — Might show anomalous structure in e^+e^- invariant mass when $E > E_{\text{crit}}$.

4. Copious e^+e^- Production

   — e^+e^- pairs from e-laser collisions could be best low-emittance source of positrons.

   — No Coulomb scattering in laser 'target.'

   — An intense laser beam 'cools' the positrons via multiple nonlinear Compton scattering (which can be thought of as a kind of synchrotron radiation).

   — When $E > E_{\text{crit}}$ the laser beam is effectively more than a radiation length thick.

   — Production is optimal for ~ 150 GeV electrons.

The experiments will require only modest running time, once the high-quality electron and laser beams are operating in synchronization. When $E \approx E_{\text{crit}}$ all cross sections of interest are 10^{-26}-10^{-27} cm^2. With 1 laser pulse per second, and 10^{10} e's per bunch, we will typically have 0.1-10 events second.

The QED processes we study are the dominant ones in e-laser collisions. Of course, detector backgrounds from synchrotron radiation and electromagnetic showers must be suppressed by masking and collimation.

Responsibilities for components of the experiment are shared among the collaboration as follows:

- e-beam .... SLAC

  e-beam diagnostics (including beamstrahlung positron spectrometer)

  RF timing

  Laser and spectrometer buildings

- Pair Spectrometer .... Princeton

  γ-beam diagnostics

- Laser systems .... Rochester
  Laser-beam transport and diagnostics

The anticipated schedule for the experiment is

- Spring-Fall '92: build FFTB, modify beam dump, construct laser building.
- Winter '92-93–Spring '93: Commission FFTB, begin accelerator physics program, build laser beam transport.
- Summer '93: build extension to FFTB for pair spectrometer, first e-laser collisions (with detectors inside radiation area).
- Fall '93: Initial running of E-144 with γ's from nonlinear Compton scattering into pair spectrometer.

2 The Pair Spectrometer

The principal detector for the nonlinear Compton scattering and Breit-Wheeler pair production experiments is a pair spectrometer, to be constructed at Princeton U. To detect Compton backscattered photons the spectrometer will be preceded by a convertor.

The pair spectrometer is to be instrumented with CCD arrays, which give space points along the electron and positron tracks with accuracy 5-6 μm and minimal multiple scattering. The excellent pattern recongnition capability of pixel devices will permit several interactions to be reconstructed each beam crossing. While the CCD readout is too slow for most high-energy-physics experiments, it is well matched to the 1 Hz rate set for us by the laser.

The characteristic production angle of the photons, electrons, and positrons is $1/\gamma \approx 10^{-5}$. To resolve this, the spectrometer will be located 100 m downstream of the interaction region, and outside the beam tunnel. The spectrometer magnet will impart a kick of 200 MeV/c, and hence a typical angle of 10 mrad to a 20-GeV/c electron/positron. The CCD's will be located about 1 m from the magnet, and so should be located about 1 cm transverse to the beam line. A sketch of the spectrometer layout is given in Fig. 1. Four planes of detectors in each arm of the spectrometer will provide excellent resolution ($\approx$ 10 keV/c^2 in pair mass) and track pattern recognition.

The CCD instrumentation is based on work by the SLAC SLD collaboration (Damerell *et al.*, Nuc. Instr. and Meth. **A275** (1989) 484, **A288** (1990) 236). Their FASTbus readout system is the only one suitable for multiple CCD's read out more often than once per second. However, the CCD's used at the SLD are smaller than optimal for our experiment, and larger ones have become available in the last two years. A promising candidate is the EEV model CCD05-20 with area 17×27 mm^2, but there are several others of interest.

Thus the first step in constructing the pair spectrometer is choosing the CCD. Because CCD's are designed for detection of optical photons rather than minimum-ionizing particles, candidate CCD's must be evaluated by us with a charged-particle source to determine their suitability. To deliver the completed spectrometer by the end of FY93, the CCD test setup must be constructed in FY92. The present Supplemental Proposal addresses the construction of the test station.

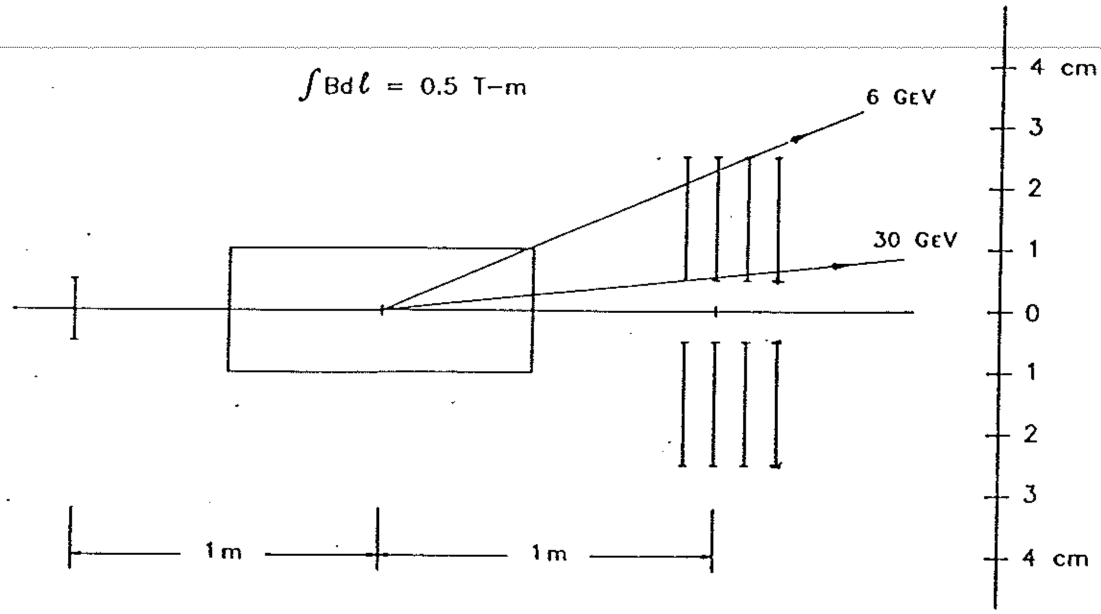

Figure 1: Layout of the pair spectrometer. The CCD (and tungsten convertor) upstream of the spectrometer is used only for the nonlinear Comptom scattering experiment. To obtain good noise performance, the CCD's must be cooled to −100°C, and to minimize multiple scattering the CCD's must be mounted inside the beam vacuum pipe.

The overall schedule for construction of the pair spectrometer is:

- Spring-summer '92: Assemble CCD test stand based on SLD FASTbus electronics. Redesign and fabricate 2 FASTbus boards (VSC and VCT).
- Fall '92: Evaluate and choose CCD for the spectrometer. Redesign and fabricate the VDA FASTbus board.
- Winter '93: Design CCD chip carrier, mechanical supports, cooling, and vacuum system.
- Spring-summer '93: Assemble spectrometer.
- Fall '93: Commission spectrometer at SLAC.

Tables 1 and 2 indicate the projected apparatus budgets for FY92 and FY93 to construct the pair spectrometer.

As has been mentioned only in passing, Princeton U. also has responsibility to provide a diagnostic of the intensity and transverse profile of the backscattered photon beam. This diagnostic should be available to the SLAC Main Control Center. We propose to place two CCD's in the γ-beam for this: one downstream of the pair spectrometer, and a second on a movable stage at the light-by-light scattering point. Because the γ-beam CCD's may encounter large numbers of hits the SLD readout system is not suitable, and we propose to use a commerical frame grabber. The budget for the beam diagnostics is included in Table 2.

35 CAP EQUIP
25 OPERATING

Table 1: Apparatus budget for the CCD spectrometer, FY92.

1. FASTbus/Qbus interface, diagnostic modules	\$15k
2. Sample CCD's	\$10k
3. Build 2 FASTbus CCD-driver modules (VSc and VCT)	\$10k
4. CCD test boards	\$10k
5. Power supplies, small test equipment	\$5k
6. PC-based CCD readout	\$10k
7. **Total 1992**	**\$60k**

Table 2: Apparatus budget for the CCD spectrometer, FY93.

1. Modify FASTbus CCD-readout module (VDA)	\$10k
2. FASTbus → video display system	\$10k
3. Online computer	\$20k
4. 12 CCD's @ \$5k each	\$60k
5. Custom CCD carrier boards	\$20k
6. Spectrometer vacuum chamber, feedthroughs	\$15k
7. Vacuum chamber for Compton-γ convertor	\$10k
8. Vacuum chamber for γ-laser IP diagnostic	\$10k
9. In-vacuum motion control system	\$10k
10. Cooling system (−100°C)	\$10k
11. 2 digital CCD cameras for γ-beam diagnostics	\$20k
12. Digital oscilloscope, test equipment	\$15k
13. **Total 1993**	**\$190k**

3 Request for Supplemental Funds in FY92

- Travel (incl. indirect costs) $10k
- New post-doc (3 mos., incl indirect costs)) $20k
- Small equipment/supplies (< $500, incl. indirect costs) $25k
- Large equipment (> $500) $35k
- **Total Supplement** **$90k**
- Personnel support from existing grant:

  —Summer salary

  —1 pre-generals student (4 mos.)

  —Post-doc (3 mos.)

  —Electrical engineer (2 mos.)

  —Electrical technician (2 mos.)

4 Anticipated Funding Funding Request for FY93

This request will become part of the renewal proposal for our main high-energy physics DoE Grant.

- Travel $30k
- Small equipment/supplies (< $500) $65k
- Large equipment (> $500) $125k
- **Total** **$220k**
- Personnel:

  —Summer salary

  —1 post-generals student

  —1 pre-generals student

  —2 post-docs

  —Electrical engineer (2 mos.)

  —Electrical technician (4 mos.)

  —Mechanical engineer (2 mos.)

  —Mechanical technician (6 mos.)