QED at Critical Field Strength
(SLAC Experiment 144)

V. Balasubramanian (grad. student), C. Bula, C. Lu,
K.T. McDonald, and E. Prebys

Princeton U.

May 3, 1993
The QED Critical Field Strength

• O. Klein (Z. Phys. 53, 157 (1929)) noted that the reflection coefficient is infinite when Dirac electrons hit a steep barrier (Klein’s paradox).

• F. Sauter (Z. Phys. 69, 742 (1931)) deduced that the paradox arises only in electric fields exceeding the critical strength:

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

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

\[ eE_{\text{crit}} \cdot \frac{\hbar}{mc} = mc^2. \]

• At the critical field the vacuum ‘sparks’ into \( e^+ e^- \) pairs (Heisenberg and Euler, Z. Phys. 98, 718 (1936)).
Where to Find Critical Fields

- The magnetic field at the surface of a neutron star approaches the critical field \( B_{\text{crit}} = 4.4 \times 10^{13} \) Gauss.

- During heavy-ion collisions where \( Z_{\text{total}} = 2Z > 1/\alpha \), the critical field can be exceeded and \( e^+e^- \) production is expected.

  The line spectrum observed in positron production in heavy-ion collisions (Darmstadt) is not understood.

- Pomeranchuk (1939): The earth’s magnetic field appears to be critical strength as seen by a cosmic-ray electron with \( 10^{19} \) eV.

- The electric field of a bunch at a future linear collider approaches the critical field in the frame of the oncoming bunch.
Critical Fields in e-Laser Collisions

- The electric field due to a laser as seen in the rest frame of a high-energy electron is

\[ E^* = \gamma (1 + \beta) E_{\text{lab}} \approx 2\gamma E_{\text{lab}} \]

- The critical field is achieved with a laser beam of intensity

\[ I = \frac{E_{\text{lab}}^2}{377 \Omega} = \frac{E_{\text{crit}}^2}{4\gamma^2 \cdot 377}. \]

Thus for 46-GeV electrons (\( \gamma = 9 \times 10^4 \)) we can achieve \( E_{\text{crit}} \) with a focused laser intensity of \( 1.43 \times 10^{19} \text{ Watts/cm}^2 \) (\( \Rightarrow \approx 10^{27} \text{ photons/cm}^3 \), \( E_{\text{lab}} = 7 \times 10^{10} \text{ Volts/cm} \)).

- Such intensities are now attainable in table-top teraWatt (T\(^3\)) lasers in which a Joule of energy is compressed into one picosecond and focused into a few square microns.
Proposal for a

STUDY OF QED AT CRITICAL FIELD STRENGTH
IN INTENSE LASER–HIGH ENERGY ELECTRON COLLISIONS
AT THE STANFORD LINEAR ACCELERATOR

October 20, 1991

C. Bula, C. Lu, K. T. McDonald and E. Prebys
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544

C. Bamber\(^{(1)}\), T. Blalock\(^{(1)}\), S. Boerge\(^{(1)}\), A. G. Melissinos\(^{(1)}\), D. Meyerhofer\(^{(2)}\) and T. Kotseroglou\(^{(1)}\)
Department of Physics\(^{(1)}\), Department of Mechanical Engineering\(^{(2)}\),
University of Rochester, Rochester, NY 14627

Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

W.M. Bugg, R. S. Kroeger and A.W. Weidemann
Department of Physics and Astronomy
University of Tennessee, Knoxville, TN 37996

(Approved as SLAC Experiment 144 on December 20, 1991)
1. Beamstrahlung

- $E \approx 10^{11} \text{ V/cm}$ in bunches at future $e^+e^-$ colliders.
- $e + n\omega_{\text{laser}}$ laser interactions with large $n$ mimic beamstrahlung.
- $e + n\omega \rightarrow e'e^+e^-$ is analog of important pair-production backgrounds in future colliders.

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

- Semiclassical theory $\Rightarrow$ data will diagnose laser intensity.
- Provides $\gamma$ beam for light-by-light scattering.

3. The Multiphoton Breit-Wheeler Reaction:

$$\gamma + n\omega \rightarrow e^+e^-$$

- 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.'
- Positrons largely preserve the geometric emittance of the electron beam ⇒ 'cooling' of invariant emittance.
- Can produce 1 positron per electron if $\Upsilon > 1$
- Production with visible laser is optimal for $\sim 500$ GeV electrons.

[Or use a 50-nm FEL with 50-GeV electrons.]

5. $e$-laser technology of E-144 is precursor of $e\gamma$ and $\gamma\gamma$ colliders.
Figure 4.4: Trajectories of electrons and positrons through the FFTB dump magnets.
Strong-Field QED Experiments

1. Nonlinear Compton Scattering
   \[ e + n \text{ with laser} \rightarrow e' + \gamma \]

   50 GeV \( e^- \) \( \rightarrow \) Laser \( \rightarrow \) Pair Spectrometer

   \( e^- \)

   \( e^+ \)

   \( e^- \)

   \( e^- \)

   Convector

2. Pair Creation by Light
   \[ \gamma + n \text{ with laser} \rightarrow e^+ e^- \]

   50 GeV \( e^- \) \( \rightarrow \) Laser \( \rightarrow \) User \( \rightarrow \) Laser \( \rightarrow \) Pair Spectrometer

   \( e^- \)

   \( e^+ \)

   \( e^- \)

   \( e^- \)

   10 keV resolution on \( M_{e^+ e^-} \) at 1.8 MeV/c^2
Laser Demonstration – June 1992

(D. Meyerhofer, U. Rochester)

• Laser system performs at diffraction limit.

• Pulse energy .................................................. 2 J

• Focal-spot area .................................................. $26 \, \mu m^2$

• Pulse FWHM .................................................. 1.4 ps

• Peak intensity ................................................. $6 \times 10^{18} \, \text{Watts/cm}^2$

• $\gamma = 2\gamma E/E_{\text{crit}}$ ........................................... 0.7

Satisfied requirements of the EPAC for full approval of E-144, which was granted in Sept. 1992.
Final Focus Test Beam

Prototype final focus for a future linear collider.
CCD Pair Spectrometer

1 CCD for diag. and converter

\[ BdI = 0.5 \text{ T-m} \]

8 CCDs

6 GeV e-

30 GeV e-

e+

1m 1m
Pair Spectrometer with CCD’s

| Large Area CCD Image Sensor | CCD05-20 Series
|-----------------------------|----------------------
| Slow Scan Scientific Version | Scientific Image Sensor |

**FEATURES**

- 770 (H) x 1152 (V) pixel format
- 17.3 x 26 mm active area
- Extremely low pixel readout noise
- Visible light and X-ray sensitive
- Two readout registers
- Uniform response over whole image area
- Two low noise amplifiers for slow scan systems and two large signal amplifiers for high speed applications
- Symmetrical anti-static gate protection
- Long life expectancy
- Low voltage operation
- Radiation tolerant

- Pixel size $22.5 \times 22.5 \, \mu m \Rightarrow \sigma_x = 5-6 \, \mu m$.

- $17 \times 26 \, mm^2$ active area per CCD.

- 4 CCD’s in each arm of pair spectrometer.

- Mass resolution $\approx 10 \, keV$ at $M_{e^+e^-} = 1.8 \, MeV$.

- 1 CCD + converter can be put in beam:
  - Diagnose beam position.
  - Convert $\gamma$’s in Compton experiment.

- Readout based on commerical frame grabbers.
Pb-Si calorimeter assembled from spare Si detectors for SLD luminosity monitor.  

Readout using RABBIT electronics from FNAL E-706.
Monitor for Time Structure of the Electron Beam

Cross-correlation of optical synchrotron radiation with the psec laser pulse (D. Meyerhofer)

Summer 1993: Monitor optical synchrotron radiation.
Responsibilities

- e-beam ....................................................... SLAC
e-beam diagnostics

RF timing

Laser & spectrometer buildings

- Laser systems ................................. Rochester
  Laser-beam transport and diagnostics (with SLAC)

- Silicon calorimeters \((e^+, e^-, \gamma)\) .................... Tennessee
  Calorimeter readout (with Princeton)

- CCD Pair Spectrometer .............................. Princeton
E-144 History

Oct. 1991: Strong-field QED experiment proposed to SLAC.

Dec. 1991: Conditional approval of E-144 by SLAC EPAC.

June 1992: Memorandum of Understanding between Princeton, Rochester and SLAC.

June 1992: Demonstration of laser focused to $10^{19}$ Watts/cm$^2$ at U. Rochester.


Apil 1993: SLAC beam test of silicon calorimeters.
May 1993: Laser shipped to SLAC from U. Rochester.

June 1993: FFTB commissioning begins.


Fall 1993: Double laser frequency.

Winter/Spring 1994: Beamstrahlung experiments with silicon calorimeters.

Summer 1994: Install CCD spectrometer.

Summer/Fall 1994: Nonlinear Compton experiments

Fall 1994: Install γ-laser interaction region.

Winter/Spring 1995: Pair-production experiments.
E-144 Princeton Equipment Budget

FY92 (Supplement) ........................................ $35k
FY93 ................................................................. $125k
FY94 (proposed) .................................................. $105k

1. Two 486-PC computers ......................... $10k
2. 10 custom CCD carrier boards ............... $20k
3. 10 CCD readout boards (Dipix) ........... $30k
4. Oil-free vacuum pump ......................... $10k
5. Workstation (DEC α-VAX) ................ $15k
6. Digital oscilloscope .......................... $15k
7. Power supplies ........................................ $5k