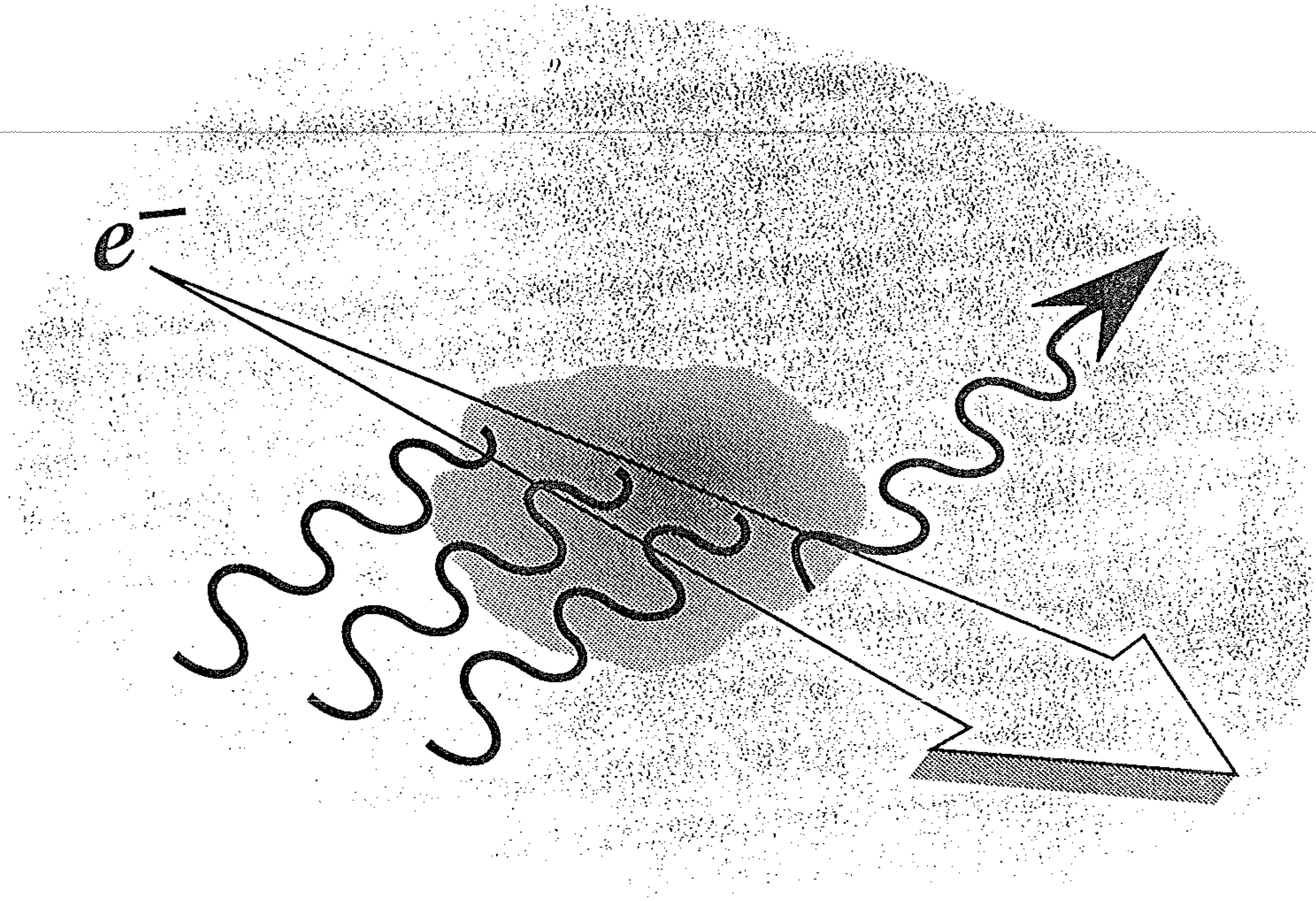

SLAC Experiment 144
QED at Critical Field Strength

A Progress Report

C. Bula, K.T. McDonald and E.J. Prebys

Princeton U.

May 31, 1995

E-144 Home Page on World Wide Web

http://www.slac.stanford.edu/exp/e144/e144.html

E144

cranked beyond the limit

Proposal for a

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

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Proposed October 20, 1991

Conditional approval as Experiment 144 on December 20, 1991

Full approval on September 30, 1992

Motivation and Goals

- The Higgs mechanism implies that elementary particles have important interactions with strong background fields.
- Only with electromagnetism can intense, controllable, macroscopic fields be created in the laboratory.
- Explore the validity of QED for electromagnetic field strengths in excess of the 'critical field strength' $m^2c^3/e\hbar = 1.6 \times 10^{16}$ V/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)).
- Explore QED in the realm where multiphoton interactions dominate, *i.e.*, when $eE/m\omega c \geq 1$.

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

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

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

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

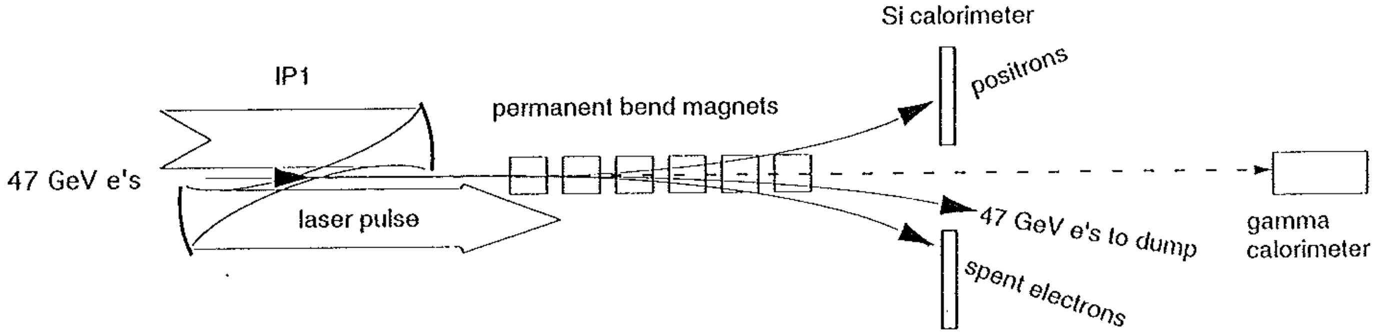
  Thus for 46-GeV electrons ($\gamma = 9 \times 10^4$) we can achieve $E_{\rm crit}$ with a focused laser intensity of 1.4×10^{19} Watts/cm^2 ($\Rightarrow E_{\rm lab} = 7 \times 10^{10}$ Volts/cm).

- 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.

- At these intensities the photon density is $\sim 10^{27}/\mathrm{cm}^3$, and the radiation length of this 'photon solid' is $\sim \lambda/\alpha \approx 100\ \mu$m.

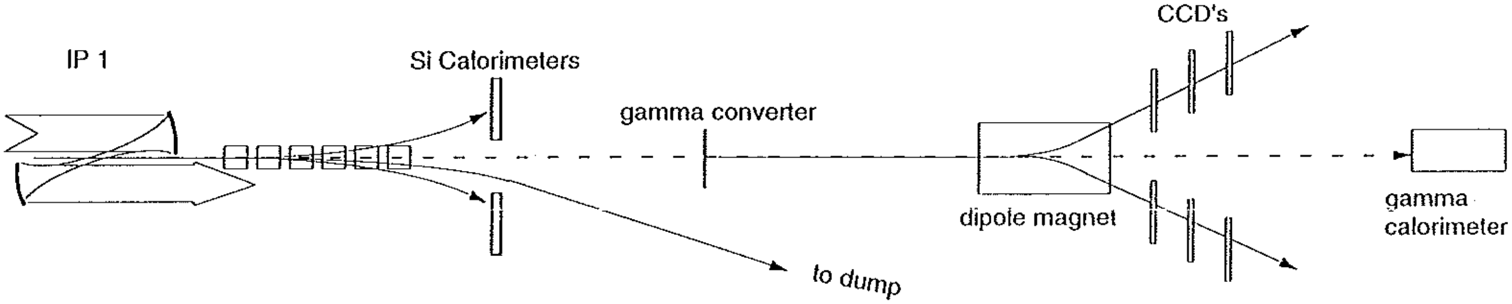
E-144 Physics Program

1. Compton Polarimetry
    - Both the E-144 laser and electron beams are polarized.
    - Compton polarimetry provides a basic check of the E-144 apparatus, as well as a confirmation of the SLC beam polarization.
2. Beamstrahlung
    - $E \approx 10^{11}$ V/cm for the E-144 laser, and for electron 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.



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

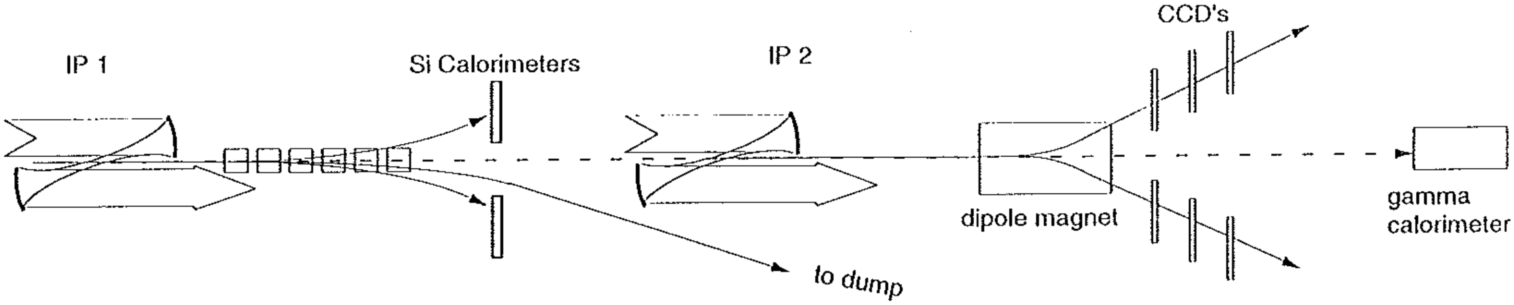
- Semiclassical theory $\Rightarrow$ data will diagnose laser intensity.
- Provides γ beam for light-by-light scattering.



4. The Multiphoton Breit-Wheeler Reaction:

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

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



5. 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 $\Rightarrow$ 'cooling' of invariant emittance.
- Can produce 1 positron per electron if $E^\star > E$crit.
- Production with visible laser is optimal for $\sim$ 500 GeV electrons.

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

6. Accelerator-physics spinoffs:

- Nonlinear-optics diagnostic of electron-bunch length
- e-laser technology of E-144 is precursor of e-γ and γ-γ colliders.

Experimental Ingredients

- Low-emittance electron beam
- Terawatt laser
- Synchronization of e and laser beams to 1 psec in time, and a few μm in space
- Silicon calorimeters for 'coarse-grain' detection of e^-, e^+ and γ's
- CCD pair spectrometer for 'fine-grained' measurements.
- Data-acquisition system based on PC's interconnected via a local ethernet.

TeraWatt Laser Via Chirped-Pulse Amplification

1 Joule in 1 ps $\Rightarrow 10^{12}$ Watt.

Diffraction limited spot area $\approx \lambda^2 (f/D)^2 \approx 10\ \mu\text{m}^2$,

$\Rightarrow I \approx 10^{19}\ \text{W/cm}^2$.

Repetition rate of 0.5 Hz using slab amplifier.

High power pulses can damage optics!

$\Rightarrow$ stretch pulse, then amplify and compress.

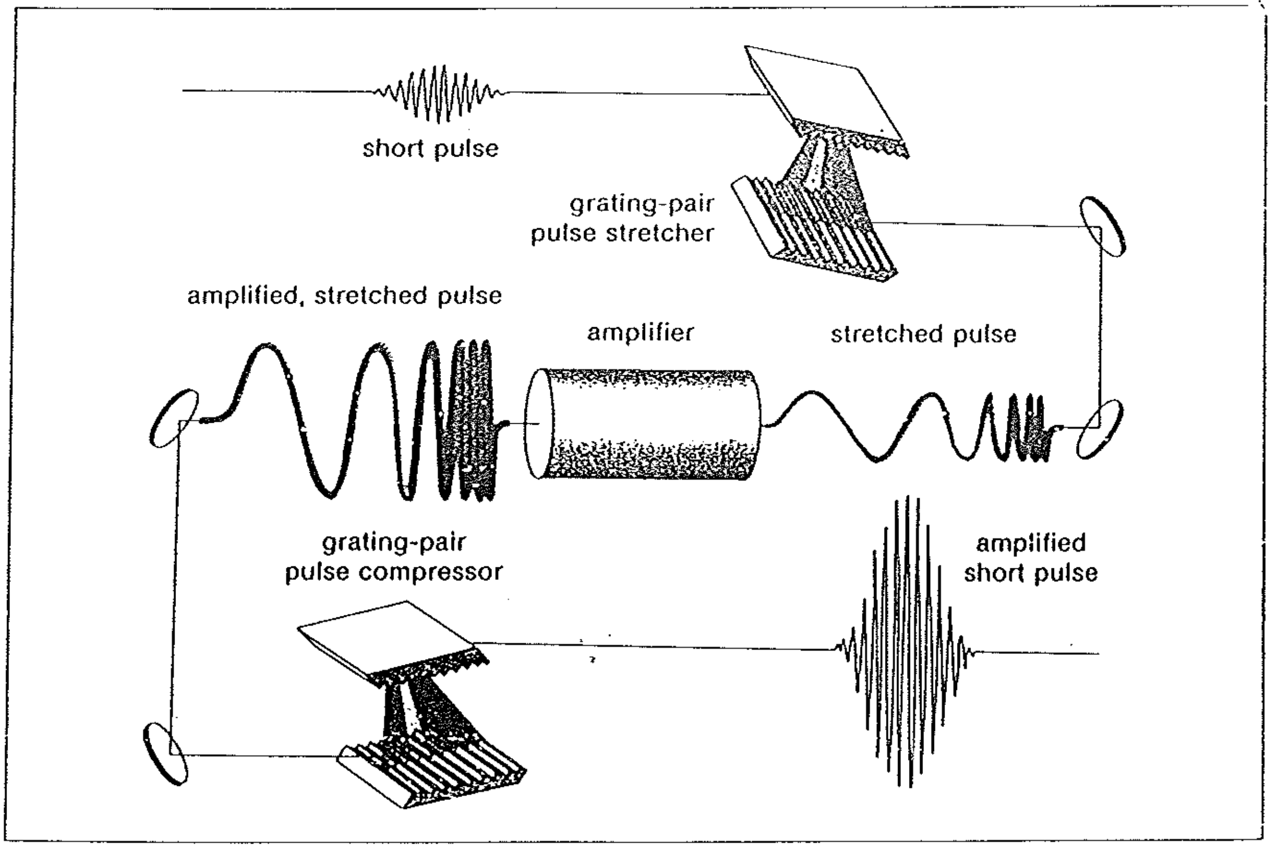
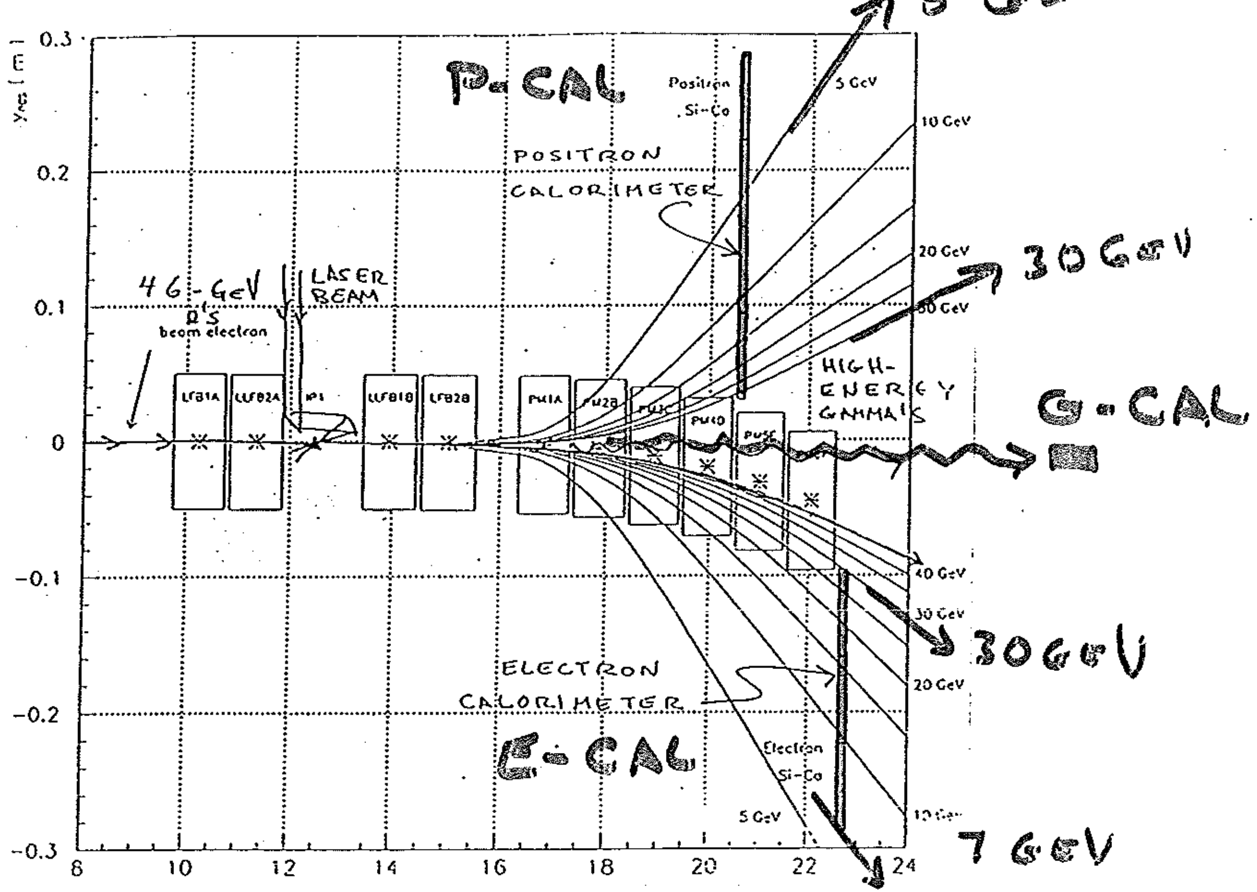


FIGURE 1. In chirped pulse amplification a short optical pulse is stretched and compressed by two compensating grating pairs.

Silicon Calorimeters

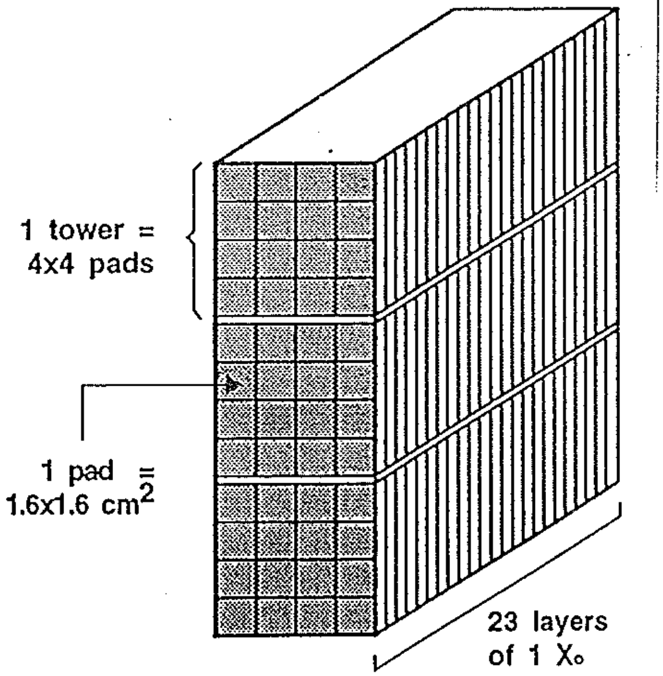


Silicon-tungsten calorimeters: pads 1.6 × 1.6 cm^2.

E-cal: 48 towers

P-cal: 64 towers

3 longitudinal segments



Readout using RABBIT electronics from FNAL E-706.

CCD Pair Spectrometer

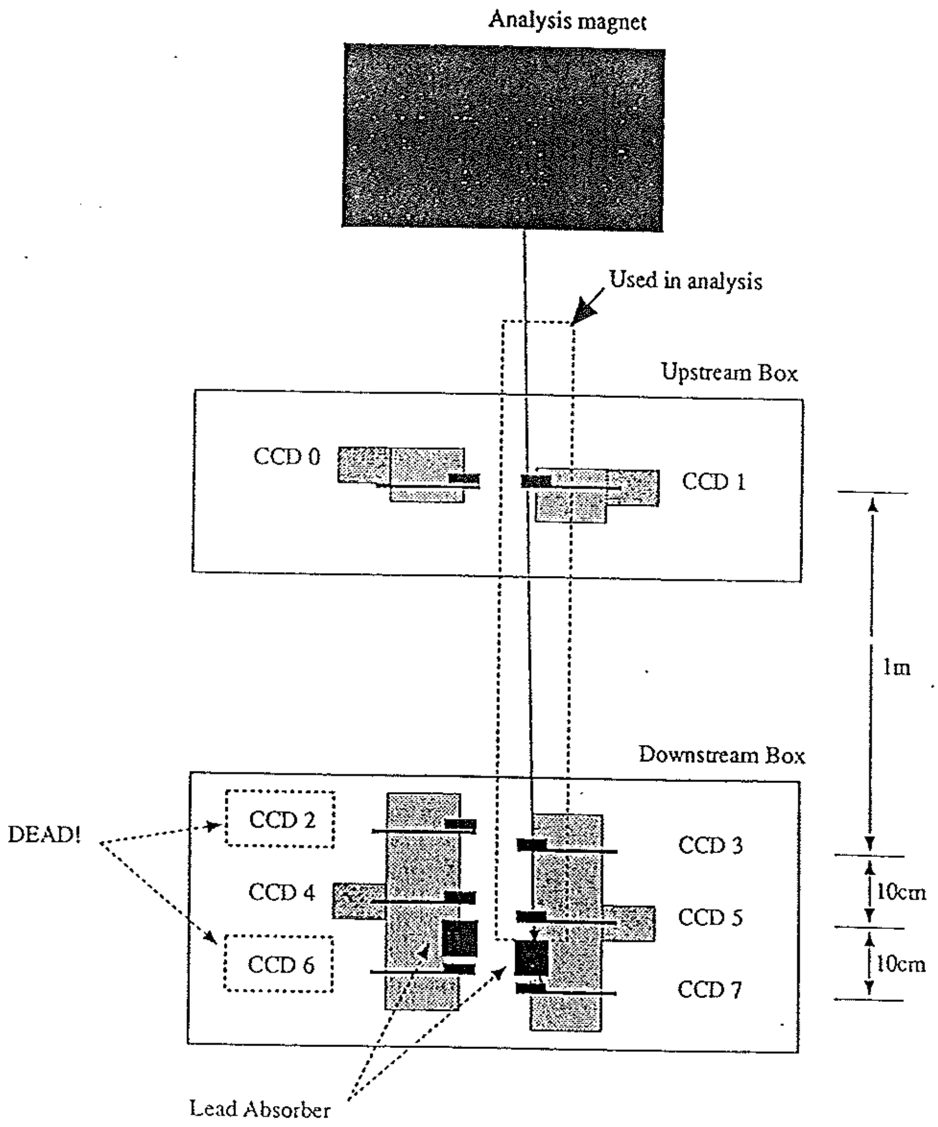
5D36 magnet followed by two arms of 4 CCD's each.

770×1150 pixels per CCD; pixel size = 22.5 μm.

$\Rightarrow$ Mass resolution $\approx$ 15 keV at $M_{e^+e^-} = 2$ MeV/c^2.

Readout via PC-based frame grabbers.

Top View:



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.

Sept. 1992: Full approval of E-144.

Oct. 1992: U. Tennessee joins E-144 collaboration.

Apr. 1993: SLAC beam test of silicon calorimeters.

May 1993: Laser shipped to SLAC from U. Rochester.

Aug. 1993: First run of FFTB; tests of e- and γ-calorimeters.

Apr. 1994: First data taking by E-144 at the FFTB:
e-beam polarization measurement;
evidence for quadratic effects in Compton scattering

Sept. 1994: Further studies of nonlinear Compton scattering: evidence for 2, 3 and 4-photon effects.

Mar. 1995: 5-day run to study nonlinear Compton scattering, and search for positron production.
First use of CCD pair spectrometer.

Accomplishments During the April/May 1994 Run

8 shifts dedicated to E-144 during 5 blocks of FFTB running.

Simultaneous operation of all components of the teraWatt laser system.

Operation of a data-acquisition system based on 9 PC's with ethernet interconnection.

Synchronization of the laser and electron beam established to ~ 3 ps, as diagnosed by the Compton scattering signal.

Measurement of the electron-beam polarization.

Testing of a prototype forward CCD spectrometer.

Observation of (nonlinear) double Compton scattering of electrons by the laser.

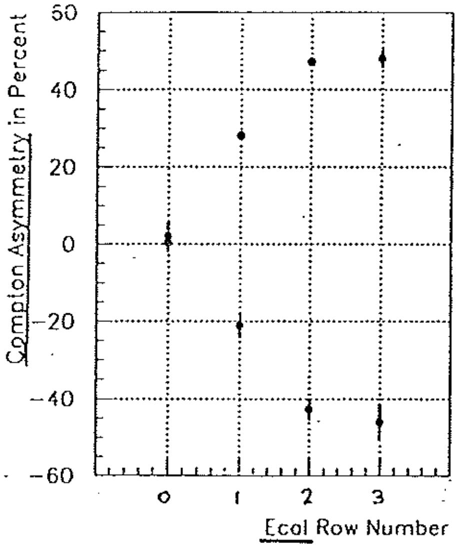
Measurement of e-Beam Polarization

Laser pulse energy ~ 3 mJ.

Asymmetry zero at 25.4 GeV is in top row of E-cal.

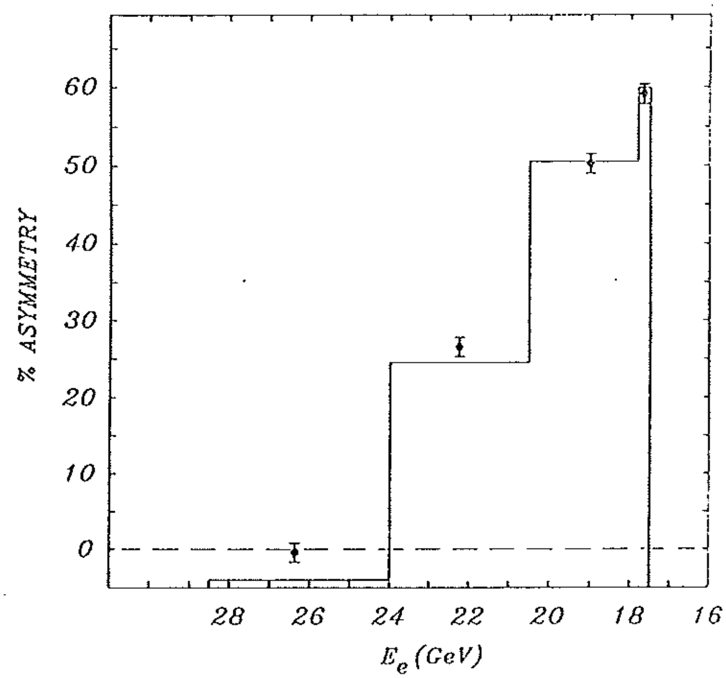
Fit to measured polarization asymmetry in 4 energy bins yields $$P_e P_{\text{laser}} = 0.81 \pm 0.01.$$

Laser polarization $< 0.96 \Rightarrow P_e = 0.81^{+0.04}_{-0.01}$.



Run 4053
'normal'
laser polarization

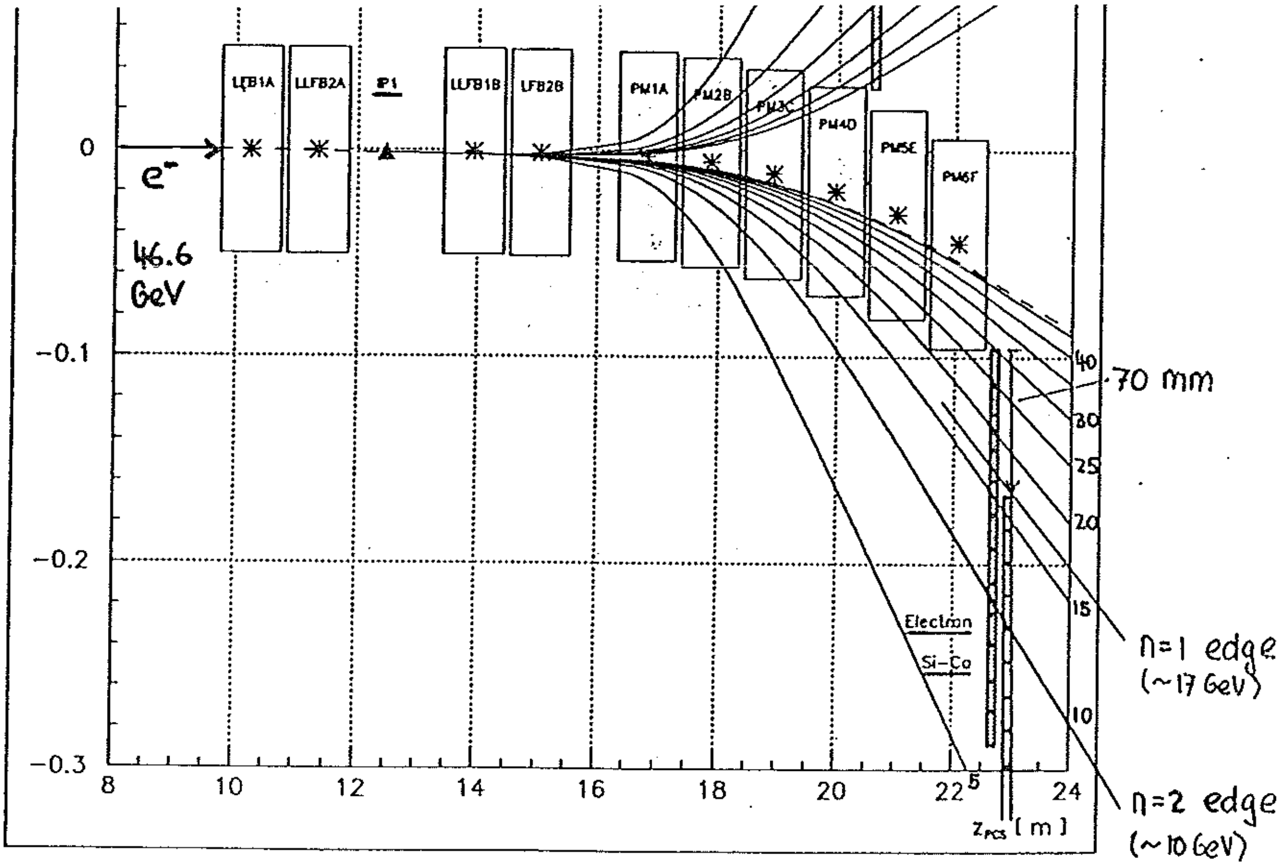
Run 4056
'opposite'
laser polarization

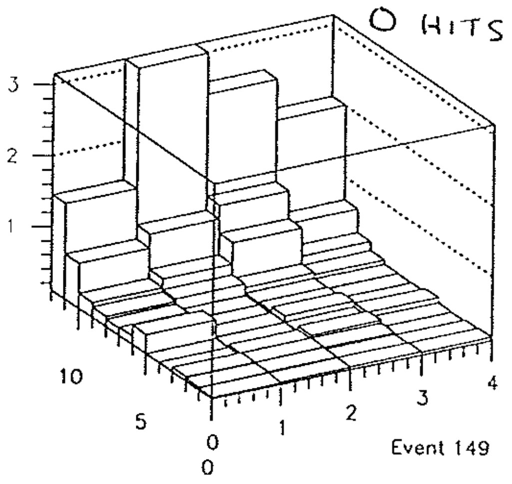


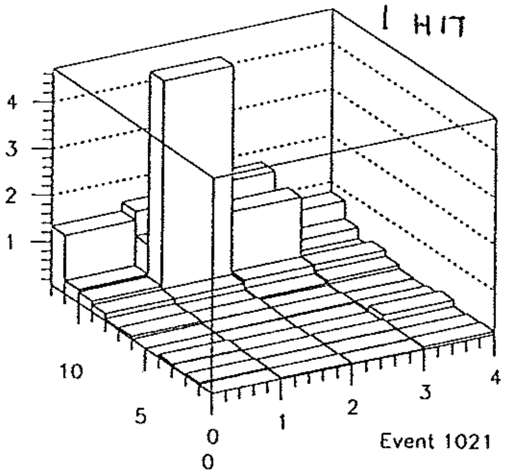
First Evidence for Nonlinear Compton Scattering

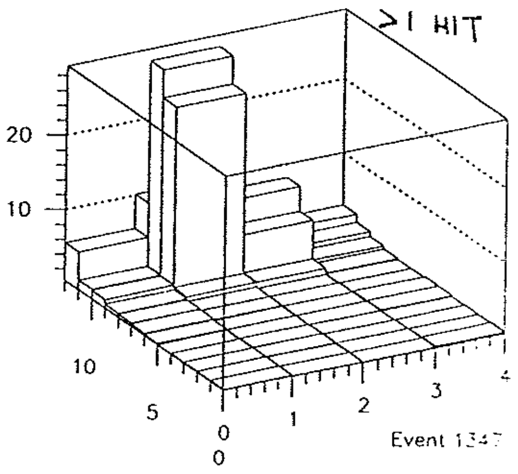
Laser pulse energy varied from 10 to 50 mJ (May '94).

E-cal lowered beyond linear Compton edge.

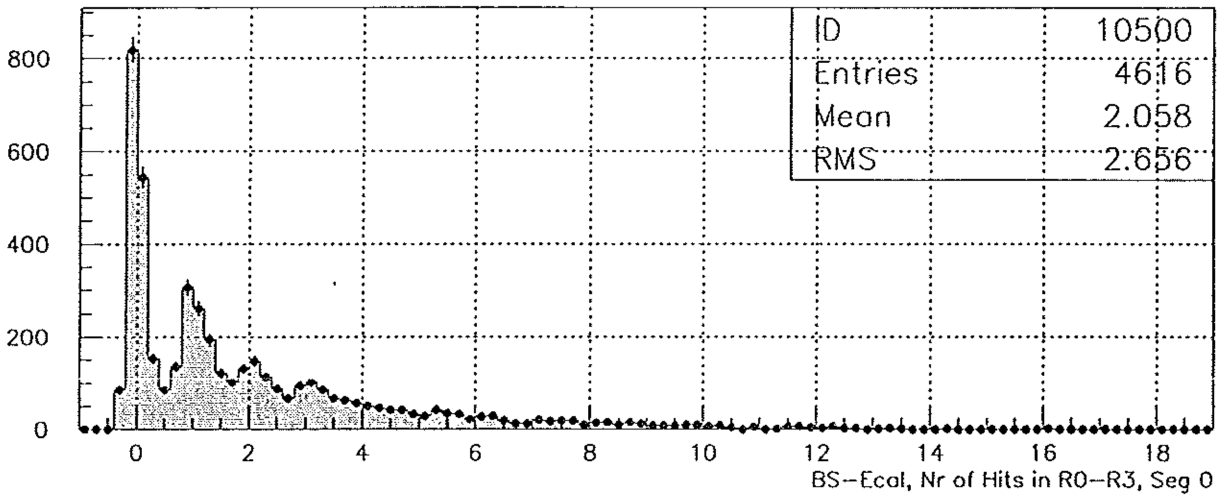




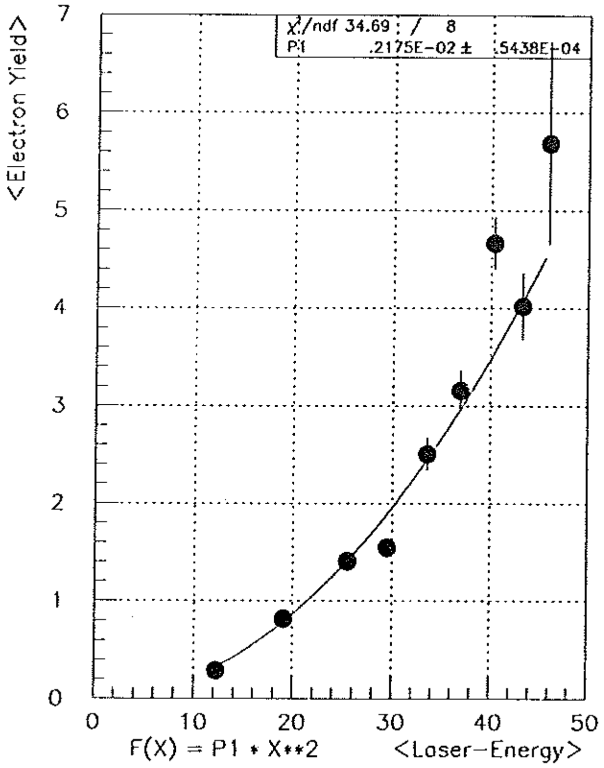




Analysis of first longitudinal segment resolves 1, 2 and 3 electron peaks.



Number of hits varies quadratically with laser pulse energy.



⇒ nonlinear scattering.

Double Compton Scattering *vs.* Nonlinear Compton Scattering

Nonlinear Compton scattering: $e + 2\gamma_{\rm laser} \to e' + \gamma$.

Double Compton scattering: $e + \gamma_{\rm laser} \to e' + \gamma_1$,

$$e' + \gamma_{\rm laser} \to e'' + \gamma_2.$$

Both processes are quadratic in laser intensity.

Kinematics of the final-state electrons are identical.

Spectra of final-state electrons are similar.

Rates are similar in conditions of E-144.

Best distinguished via the final-state photon:

nonlinear Compton scattering ⇒ one, higher-energy γ;

double Compton scattering ⇒ two, normal-energy γ's.

⇒ need CCD spectrometer to resolve the two processes.

September '94 Run

Improved doubling efficiency ⇒ up to 1 J at $\lambda = 530$ nm.

Shot-by-shot spot-area measurment for latter part of run. Observed $20 < A < 100\ \mu\mathrm{m}^2$.

Shot-by shot pulse length measurement not available.

Streak camera ⇒ $1.5 < \Delta t < 3$ ps.

$\Rightarrow 3 \times 10^{17} < I_{\max} < 10^{18}\ \mathrm{W/cm}^2$.

March '95 Run

Wire scanner in IP1 box ⇒ easier setup of *e*-laser collisions.

laser oscillator rebuilt ⇒ improved timing stability.

CW autorcorrelator to monitor oscillator pulse length.

New slab amplifier.

Single-shot autocorrelator for 1060 nm.

$I_{\mathrm{max}} \sim 10^{18}$ W/cm^2.

Extensive x-y-z-t scans of *e*-laser overlap.

Installed CCD pair spectrometer.

'Hi-lo' *e*-beam used to reduce backgrounds in CCD's.

Future Run Plans

December 1995:

- Improve laser intensity to design spec of 7×10^{18} W/cm^2.
- Continue Search for positrons at IP1 using Si calorimeter.
- Detailed study of nonlinear Compton scattering with CCD spectrometer.

May 1996 (and beyond):

- FFTB/E-144 runs possible at beginning and end of SLD runs.
- After copious pair created has been demonstrated at IP1, commision the second interaction region, IP2, for pure light-by-light interactions.
- Study details of e^+e^- spectrum with CCD pair spectrometer.
- Major laser upgrade if warranted by the physics.

Proposed Task G FY96 Equipment Budget

Additional computing power needed as data accumulates.

The CCD spectrometer should be made more robust, particularly the cooling system.

1.	Three Pentium computers for online/offline analysis	\$12k
2.	Laser printer	\$2k
3.	4 new CCD's	\$4k
4.	1 new CCD readout board (DIPIX)	\$4k
5.	Upgrade to CCD cooling system	\$5k
6.	Upgrade to CCD vacuum system	\$3k
7.	Tek TDS684A digital scope	\$25k
8.	Test equipment for detector developmet	\$10k
Total		**\$65k**

The operating budget is considered elsewhere; please note the significant travel costs associated with operating at SLAC.