A diagram illustrating a quantum electrodynamics (QED) process. An electron, labeled e^- , is shown as a straight line entering from the left. It interacts with a central shaded region representing a nucleus. After the interaction, the electron is shown as a straight line exiting towards the right. A wavy line, representing a photon, is emitted from the interaction point and travels towards the upper right. The entire scene is set against a background of a stippled, circular field.

SLAC Experiment 144
QED at Critical Field Strength

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

Princeton U.

June 15, 1994

Proposal for a

STUDY OF QED AT CRITICAL FIELD STRENGTH

IN INTENSE LASER-HIGH ENERGY ELECTRON COLLISIONS

AT THE STANFORD LINEAR ACCELERATOR

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

C. Bamber⁽¹⁾, S. Boege⁽¹⁾, T. Kotseroglu⁽¹⁾, A.C. Melissinos⁽¹⁾, D. Meyerhofer⁽²⁾ and W. Ragg⁽¹⁾
*Department of Physics⁽¹⁾, Department of Mechanical Engineering⁽²⁾,
University of Rochester, Rochester, NY 14627*

D.L. Burke, P. Chen, R.C. Field, G. Horton-Smith, A.C. Odian, S.H. Rokni, J.E. Spencer, D. Walz and
M.S. Woods
Stanford Linear Accelerator Center, Stanford University, Stanford, CA 94309

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

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.
- Explore QED in the realm where multiphoton interactions dominate, *i.e.*, when $eE/m\omega c \geq 1$.

Inertia: Does Empty Space Put Up the Resistance?

As a child, the Nobel Prize-winning physicist Richard Feynman asked his father why a ball in his toy wagon moved backward whenever he pulled the wagon forward. His father said that the answer lay in the tendency of moving things to keep moving, and of stationary things to stay put.



"This tendency is called inertia," said Feynman senior. Then, with uncommon wisdom, he added: "But nobody knows why it is true."

That's more than even most physicists would say. To them, inertia does not need explaining, it simply "is." But since the concept was first coined by Galileo in the 17th century, some scientists have wondered if, perhaps, inertia is not intrinsic to matter at all, but is somehow acquired. Those who have tried to come to grips with inertia include Feynman junior, once he had grown up, and Albert Einstein, who tried—and failed—to show that inertia was related to the arrangement of matter in the universe.

Now three researchers think they have found the source of inertia—and it turns out to be much closer to home. Inertia, they say, comes from the apparently empty space that surrounds us all—or rather, from the buzz of activity that, according to quantum theory, fills even a perfect vacuum, where subatomic particles are being created and annihilated in the blink of an eye. It is this ever-present sea of energy that the researchers believe resists the acceleration of mass, and so creates inertia.



Another try. Einstein tried to incorporate Mach's principle into general relativity.

found the source of inertia—and it turns out to be much closer to home. Inertia, they say, comes from the apparently empty space that surrounds us all—or rather, from the buzz of activity that, according to quantum theory, fills even a perfect vacuum, where subatomic particles are being created and annihilated in the blink of an eye. It is this ever-present sea of energy that the researchers believe resists the acceleration of mass, and so creates inertia.

one of the key results of quantum theory. The principle is best known for setting limits to the accuracy with which it is possible to measure simultaneously certain attributes of a particle, such as its position and momentum. But the flip-side of this uncertainty is that a particle and a matching anti-particle can spontaneously appear out of thin air, so long as they recombine and annihilate each other so fast no one would know. During their fleeting existence, these "virtual particles" make their presence felt in many ways, including slight shifts in the spectrum of hydrogen, the irreducible electronic noise in semiconductors and, Haisch and his colleagues now claim, inertia.

Meeting with resistance. Their argument draws on a curious quantum vacuum phenomenon first described by the British physicist Paul Davies (now at the University of Adelaide in Australia) and William Unruh of the University of British Columbia in the mid-1970s. If you move at a constant speed through the quantum sea of virtual particles, it looks the same in all directions. But as soon as you start to accelerate through it, theory predicts that the vacuum gives the appearance of being a tepid "sea" of heat radiation.

Although far too small to measure, the Davies-Unruh effect led Haisch, a high-energy astrophysicist, and Puthoff, a quantum theorist, to wonder independently about a connection with inertia. Could it be that accelerating through the vacuum produces other effects, too—like the resistance to acceleration that we call inertia? While still mulling over the idea, Haisch met with Rueda, an electrodynamics theorist with considerable experience in the techniques needed to attack such a question. When they learned of Puthoff's similar ideas, Haisch and Rueda decided to join forces with him.

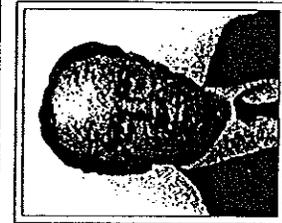
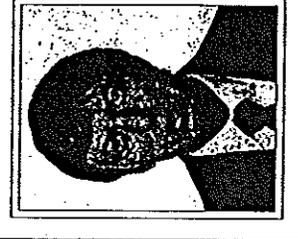
In their analysis, the trio set aside conventional quantum theory. Instead, they opted for an approach known as stochastic electrodynamics (SED), which accepts the existence of the vacuum fluctuations *a priori*, then applies an entirely classical (i.e., non-quantum) approach to particles and electromagnetism. Since the 1960s, a number of theorists, including Rueda, have shown that SED can give a perfectly accurate account of bizarre quantum effects without becoming embroiled in complex quantum theory.

In their intensely mathematical paper, Haisch and his colleagues wield SED to argue that inertia results from a Lorentz force, familiar to physicists as the force that deflects a charged particle moving through a magnetic field. For inertia, it is the vacuum fluctuations that produce the magnetic field, and it is the charged subatomic particles making up objects that feel the Lorentz force. The larger the object, the more particles it contains, and hence the stronger the resistance, and

the greater the object's inertia. Predictably for a grand claim based on obscure theory, peer reaction is mixed. On the one hand is Stanford's Sturrock, who calls it "very interesting, and potentially very important." On the other is Peter Millman, a specialist on quantum vacuum processes at the Los Alamos National Laboratory, who says, "I don't think much of the work," complaining "I see a lot of claims being made that are just not backed up."

Cosmologist Paul Wesson of the University of Waterloo, Canada, an authority on the links between the subatomic and cosmic worlds, is "glad that someone is trying to return to the question of inertia again." But he is concerned about "the astrophysical and cosmological implications" of the work. Wesson's concerns center on the cosmological constant, best known as an add-on to Einstein's equations of general relativity that endows free space with extra energy and gives it a gravitational effect. Einstein eventually dropped the constant because it was inelegant, but some cosmologists would like to resurrect it because it would solve some of their most intractable problems, such as the age of the universe and its missing mass (*Science*, 5 November 1993, p. 846).

The new vacuum-based theory of inertia devised by Haisch and his colleagues does just that: It requires an energy-rich vacuum,



A new tack. Haisch, Rueda, and Puthoff, shown from left to right, think they have found the source of inertia in the fluctuations of the quantum vacuum.

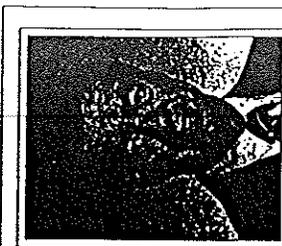
which implies a cosmological constant. The problem is that the constant implied by the new theory is much bigger than the one required to solve the other problems of cosmology. Says Wesson: "The vacuum has so much energy associated with it that it would have negative astrophysical implications. Those would have to be cleared up."

Overcoming inertia. Haisch and his colleagues agree that there is a problem and suggest an answer, in the form of a controversial theory of gravity proposed by Sakharov in the late 1960s. One consequence of Sakharov's theory is that vacuum energy can't generate a gravitational field—and so can't create a problematic cosmological con-

stant. Solving one unconventional theory's problems by invoking another unconventional theory is unlikely to win many converts, and Haisch agrees that the team's work needs refining. But he hopes to do it with the help of other researchers, who might be lured by the tantalizing implications of the theory—among them the possibility that by altering the properties of the vacuum, researchers might control inertia.

Physicists have known for years that the quantum vacuum can be manipulated. In the so-called Casimir effect, two metal plates brought close together distort the quantum vacuum, which responds by producing an attractive force between the plates. If the quantum vacuum could be distorted on a larger scale, says Haisch, "then we open a door on a way of perhaps someday controlling inertia—and we had no inkling that was even possible in principle before."

Experiments slated for later this year at the Stanford Linear Accelerator Center (SLAC) may provide Haisch and his colleagues with the evidence they need to convince skeptics. Physicist Kirk McDonald of Princeton University and colleagues from a number of other universities plan to expose high-energy electrons produced at SLAC to a terawatt beam from a neodymium-YAG laser. Testing the inertia theory isn't the main aim of the experiment. But if the theory



is correct, the intense electromagnetic field experienced by the electrons as they enter the beam will affect their interaction with the quantum vacuum's own field—and so change their inertia.

A favorable outcome, Haisch thinks, might be just what he and his colleagues need to overcome any resistance—or is it inertia?—they are meeting in the scientific community. "If nothing else," he says, "controlling inertia is a possibility that might just encourage others to dig deeper."

—Robert Matthews

Robert Matthews writes for The Sunday Telegraph in London.

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_{crit} with a focused laser intensity of 1.43×10^{19} Watts/cm² ($\Rightarrow \gtrsim 10^{27}$ photons/cm³, $E_{\text{lab}} = 7 \times 10^{10}$ Volts/cm).

- Such intensities are now attainable in table-top teraWatt (T³) lasers in which a Joule of energy is compressed into one picosecond and focused into a few square microns.

E-144 Physics Program

1. Compton Polarimetry

- Both the E-144 laser and electron beams are polarized.
- A measurement of the polarization asymmetry in Compton scattering 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 $\Upsilon > 1$
- Production with visible laser is optimal for ~ 500 GeV electrons.

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

6. e-laser technology of E-144 is precursor of $e-\gamma$ and $\gamma-\gamma$ colliders.

7. Accelerator-physics spinoffs:

- (a) Nonlinear-optics diagnostic of electron-bunch length
- (b) Possible demonstration of laser acceleration with gradient of 1 TeV/m (but only for a few μm).

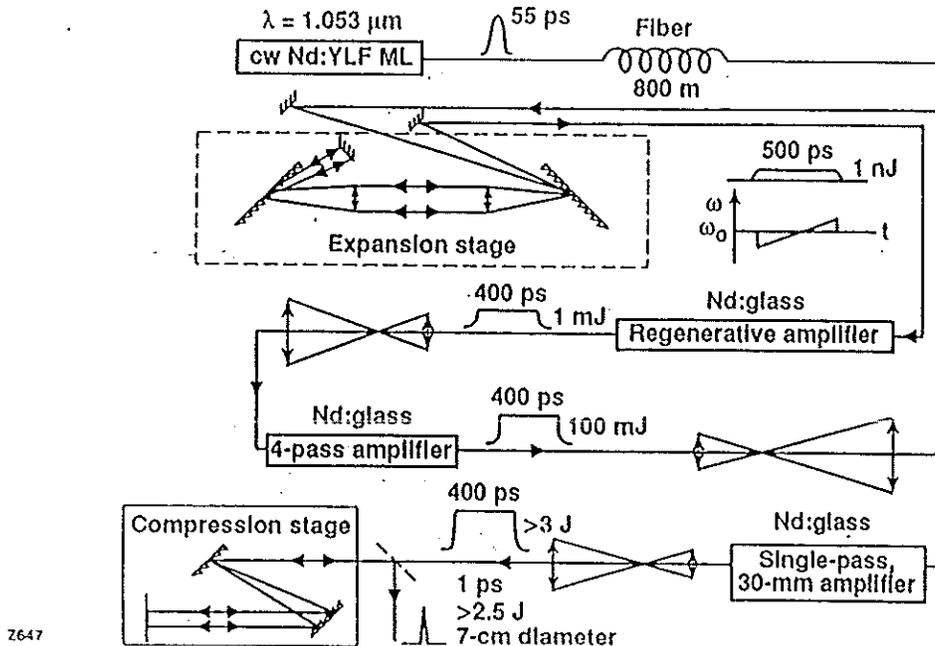
Experimental Ingredients

- 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.

HIGH-INTENSITY LASER PULSES EXTEND THE REALM OF OPTICAL PHYSICS

By J.H. Eberly, P. Maine, D. Strickland, and G. Mourou

A chirped pulse amplifier and compression laser system produces 1-J, 1-ps laser pulses at 1- μm wavelength



2647

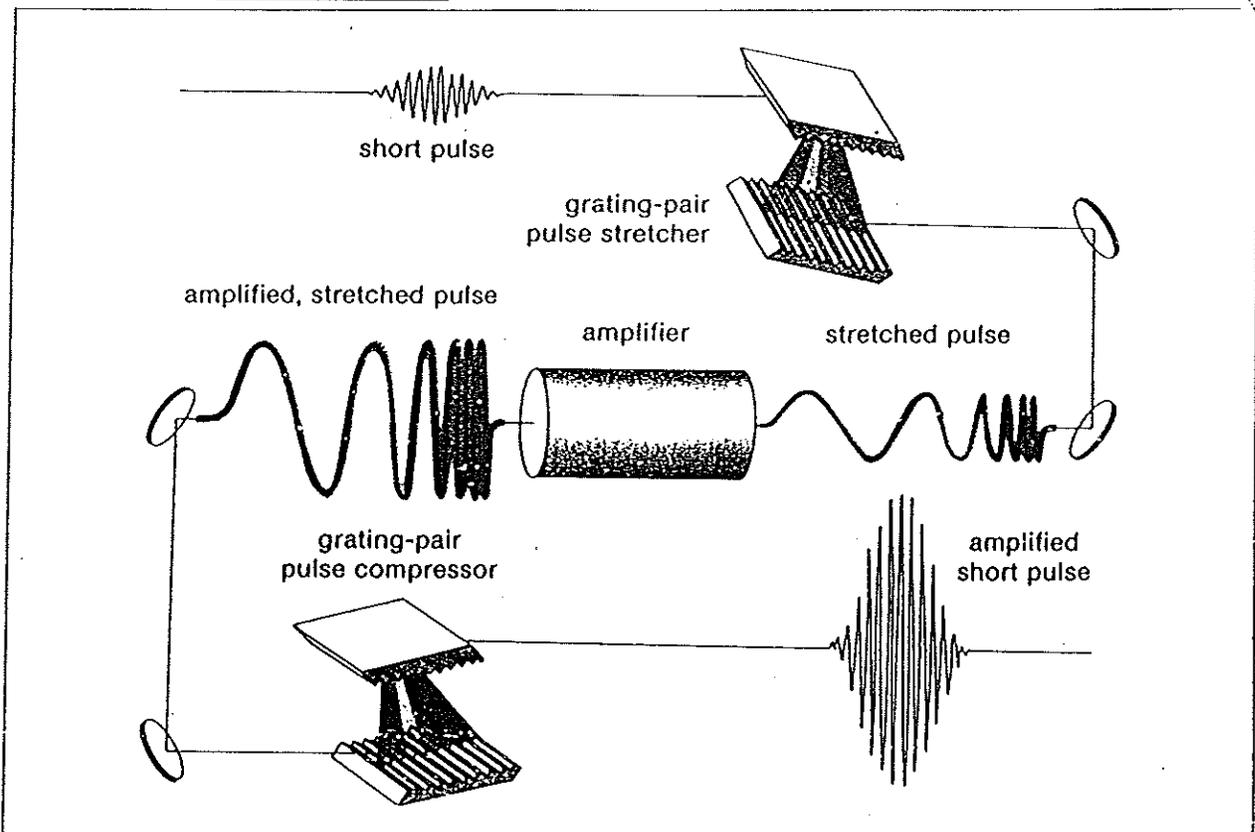


FIGURE 1. In chirped pulse amplification a short optical pulse is stretched and compressed by two compensating grating pairs.

Beamstrahlung and Polarimetry Experiments

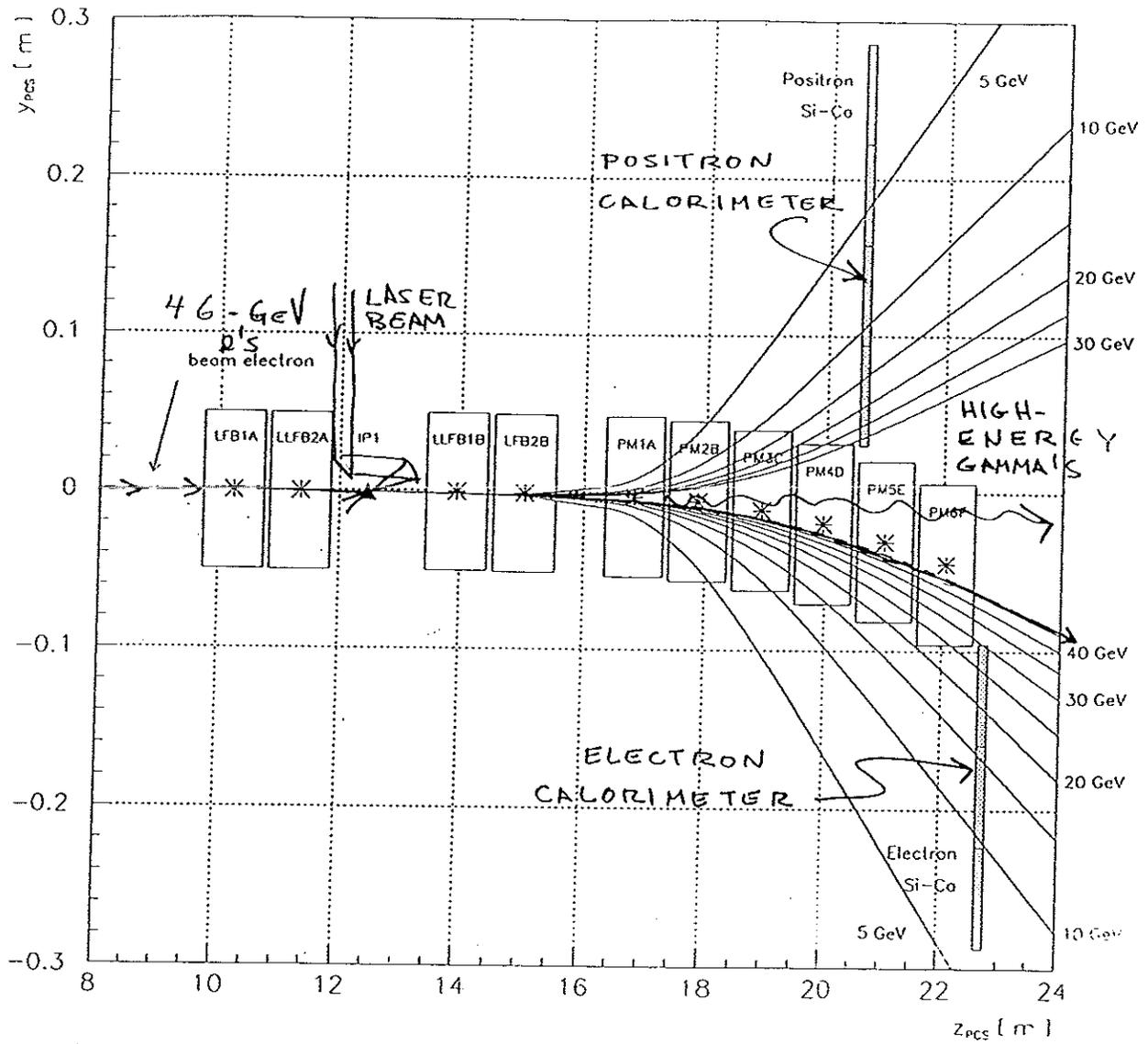
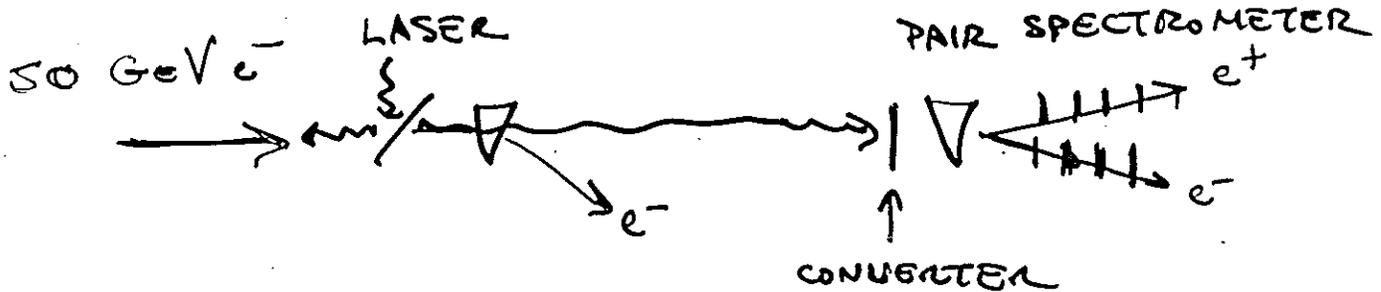


Figure 4.4: Trajectories of electrons and positrons through the FFTB dump magnets.

Strong-field QED Experiments

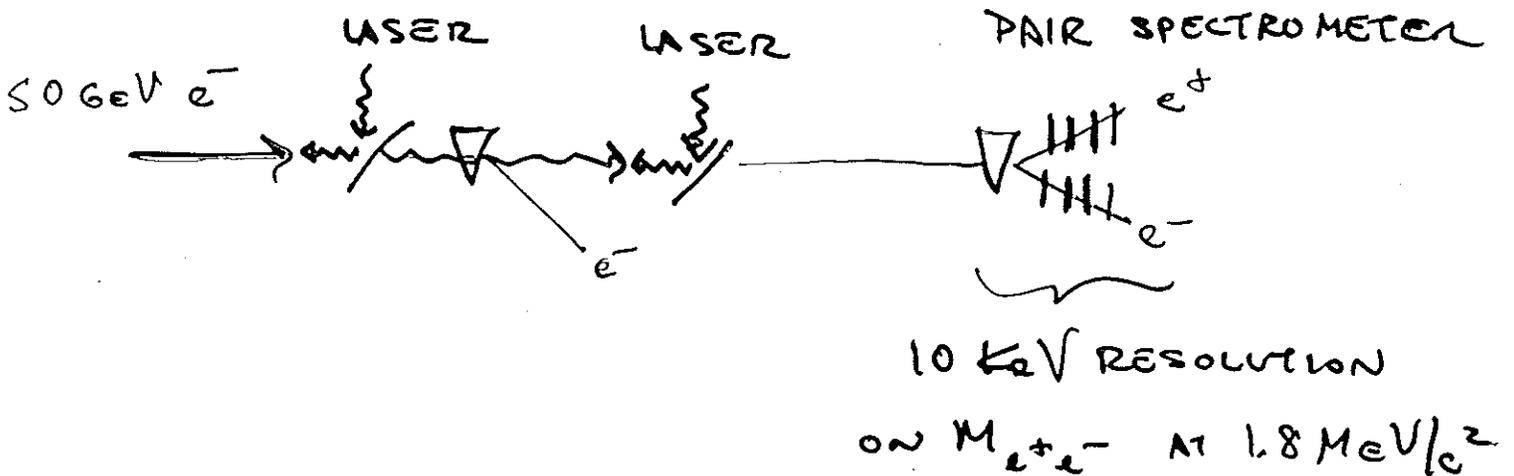
1. Nonlinear Compton Scattering

$$e + n \omega_{\text{LASER}} \rightarrow e' + \gamma$$



2. Pair Creation by Light

$$\gamma + n \omega_{\text{LASER}} \rightarrow e^+ e^-$$



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/cm² at U. Rochester.

Sept. 1992: Full approval of E-144.

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

April 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.

~~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.

Double Compton Scattering vs. Nonlinear Compton Scattering

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

Double Compton scattering: $e + \gamma_{\text{laser}} \rightarrow e' + \gamma_1 : e' + \gamma_{\text{laser}} \rightarrow e'' + \gamma_2$.

Both processes are quadratic in laser intensity.

Double Compton scattering has somewhat higher rate in conditions of E-144.

Kinematics of the final-state electrons are identical.

Spectrum of final-state electron is \sim flat for nonlinear Compton scattering, triangular for double Compton scattering.

Best distinguished via the final-state photon:

nonlinear Compton scattering \Rightarrow one, higher-energy γ ;

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

\Rightarrow need CCD spectrometer to resolve the two processes.

Future Run Schedule

- **Sept. '94:** \sim 15 shifts during 2 weeks of FFTB running.

Laser energy \rightarrow 0.5-1 J.

Positron production via 2-step process; observe in Si cal.

Install CCD spectrometer in air inside FFTB tunnel, with magnet, protection collimators and vacuum line extension.

Study nonlinear Compton spectrum with CCD spectrometer.

- **Feb. '95:** 15-25 shifts during FFTB run after SLD run.

Install 2nd interaction region for studies of light-by-light scattering.

Observe e^+e^- pairs in CCD spectrometer in vacuum.

- **?? '96**

Precision measurements of e^+e^- mass spectrum.

Relocate CCD spectrometer outside FFTB tunnel if necessary.

Responsibilities

- e-beam SLAC
 - e-beam diagnostics
 - RF timing
 - Laser & spectrometer buildings
 - Polarimetry optics (with Rochester)
- Laser systems Rochester
 - Laser-beam transport and diagnostics (with SLAC)
 - e-bunch-length monitor
- Silicon calorimeters (e^+ , e^- , γ) Tennessee
 - Calorimeter readout (with Princeton)
- CCD Pair Spectrometer Princeton
 - Data-acquisition system
 - Optical-synchrotron-radiation monitor

Future Hardware Tasks (Princeton)

Modest expansion of the data-acquisition system.

Assemble spectrometer with 8 CCD's on custom driver boards, mounted on motion stages.

Construct CCD spectrometer house: in air for Sept. '94, but stainless-steel vacuum box for Feb. '95.

Commission custom, low mass CCD carrier boards for Feb. '95.

Machine heavy stainless-steel parts for the IP2 optical beam transport, needed for Feb. '95.

Remarks on Laser Diagnostics

The laser consists of 4 amplifiers, each a laser in its own right.

Only the first amplifier (oscillator) is reasonably well instrumented.

'Turn-key' performance of laser can only be achieved with greater investment in diagnostics (as well as a few improvements underway).

Princeton could play a role in time-domain diagnostics:

1. 6-GHz single-shot sampling module (LLNL design, ~ \$15k)
2. 1-GHz real-time digital oscilloscope (Tektronix TDS 684A, ~ \$25k)

Proposed FY95 Equipment Budget

Stainless-steel vacuum chamber and accessories \$20k

Additional online/offline computer system \$10k

Total \$30k

Highly desirable for improved timing diagnostics:

LLNL 2-ch, 30-Gsample/sec, 6-GHz module \$15k

Tektronix TDS684A 4-ch, 5-Gsample/sec, 1-GHz
oscilloscope \$25k