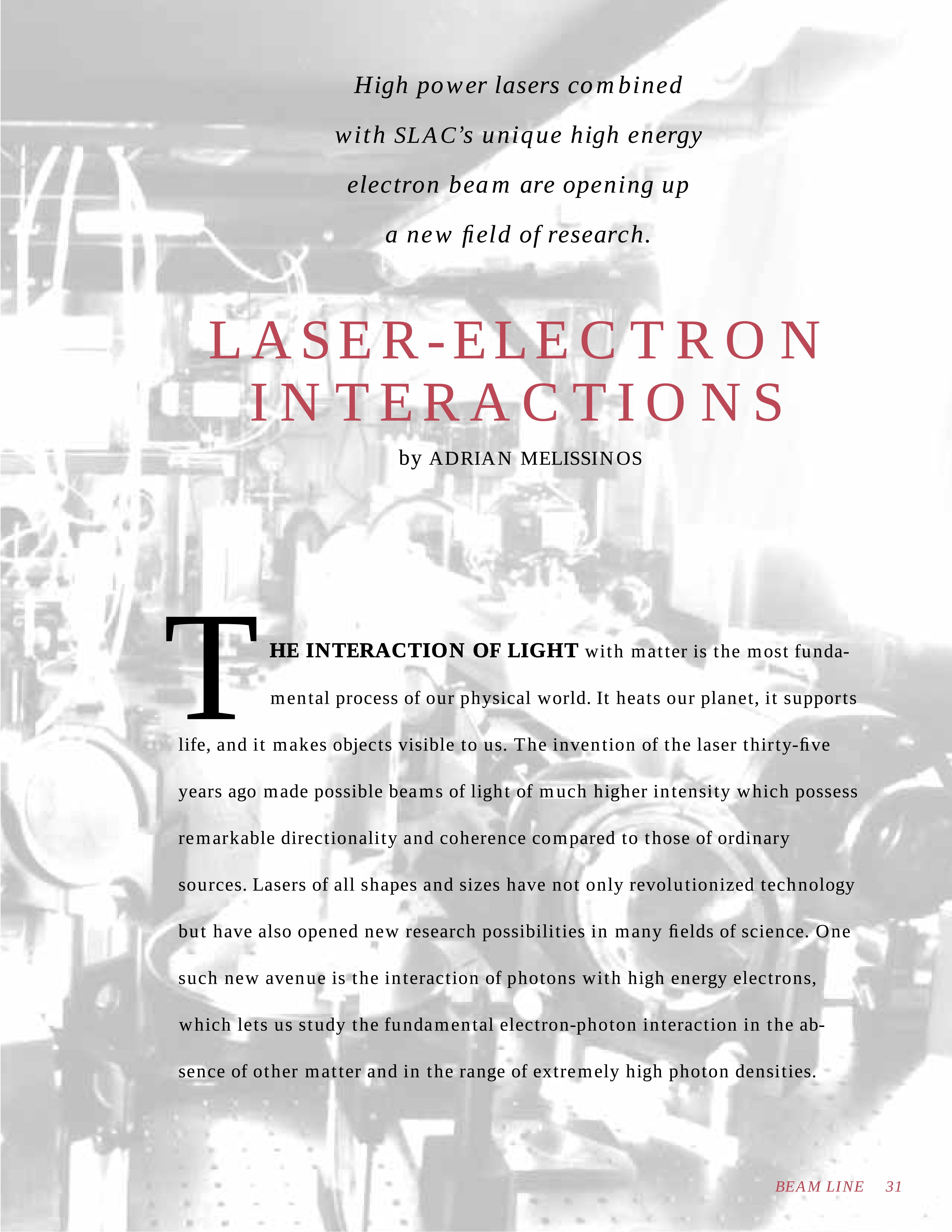


High power lasers combined with SLAC's unique high energy electron beam are opening up a new field of research.

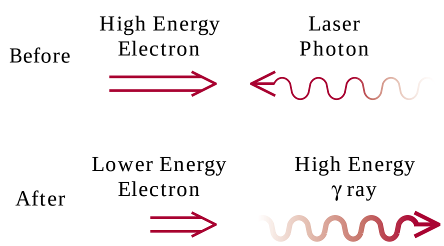
LASER-ELECTRON INTERACTIONS

by ADRIAN MELISSINOS

THE INTERACTION OF LIGHT with matter is the most fundamental process of our physical world. It heats our planet, it supports life, and it makes objects visible to us. The invention of the laser thirty-five years ago made possible beams of light of much higher intensity which possess remarkable directionality and coherence compared to those of ordinary sources. Lasers of all shapes and sizes have not only revolutionized technology but have also opened new research possibilities in many fields of science. One such new avenue is the interaction of photons with high energy electrons, which lets us study the fundamental electron-photon interaction in the absence of other matter and in the range of extremely high photon densities.

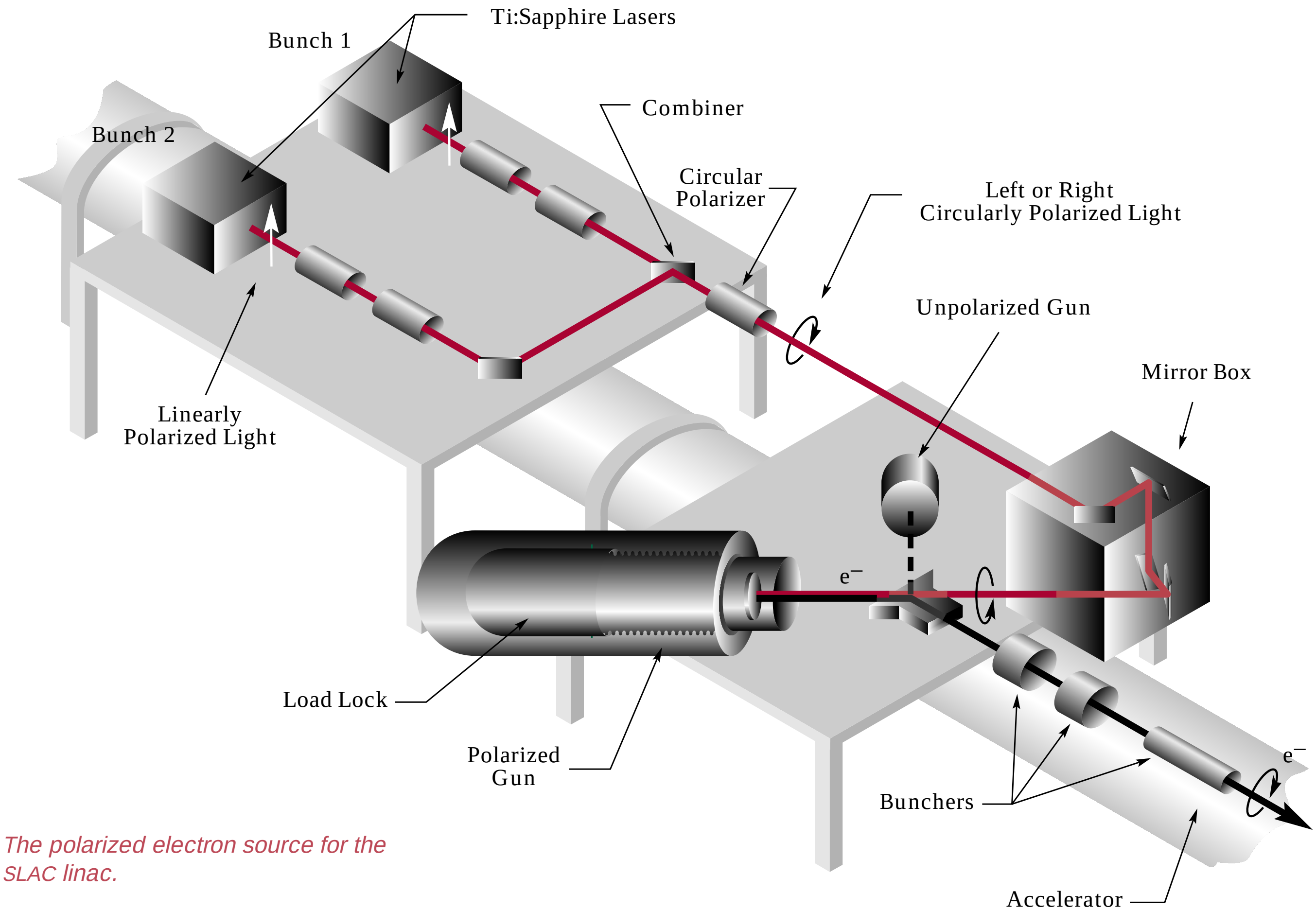
Right: Backscattering of a photon from a high energy electron.

Below: The 82-in. bubble chamber at SLAC in 1967. Top to bottom are Wolfgang Panofsky, Joseph Ballam, Robert Watt, and Louis Alvarez. This chamber was a modified version of the original 72-in. chamber built and operated by the Alvarez group at the Lawrence Radiation Laboratory.



That collisions will occur when a beam of electrons crosses through a counter-propagating beam of photons may seem obvious to some, but it could also be relegated to the domain of science fiction by others. The outcome of such an experiment depends on the density of the beams and on the duration of the crossing, as well as on the fundamental probability for the interaction to occur. If we compare the energy of an electron in the Stanford Linear Accelerator Center (SLAC) beam with that of a laser photon, a great disparity is evident. The electron energy is 50 billion electron volts, whereas the photon energy is typically 1 or 2 electron volts; the collision can thus be described by the proverbial analogy of a Mack truck colliding with a ping-pong ball. It is nevertheless true that under appropriate conditions the electron can transfer almost all its energy to the photon, as shown in the illustration above left. This process is referred to as Compton (or photon) backscattering.

BACKSCATTERING of a laser beam was first exploited at SLAC in 1969 to create high energy photons or gamma rays. The gamma rays were directed into the 82-inch bubble chamber, where their interactions in liquid hydrogen (on protons) were recorded and studied. An important aspect of high energy electron-photon collisions is that they depend on the state of polarization of the colliding beams. Electrons have spin that can point in one of two directions: along or against the direction of motion; the same is true for the photons. By measuring the rate of scattered events one can



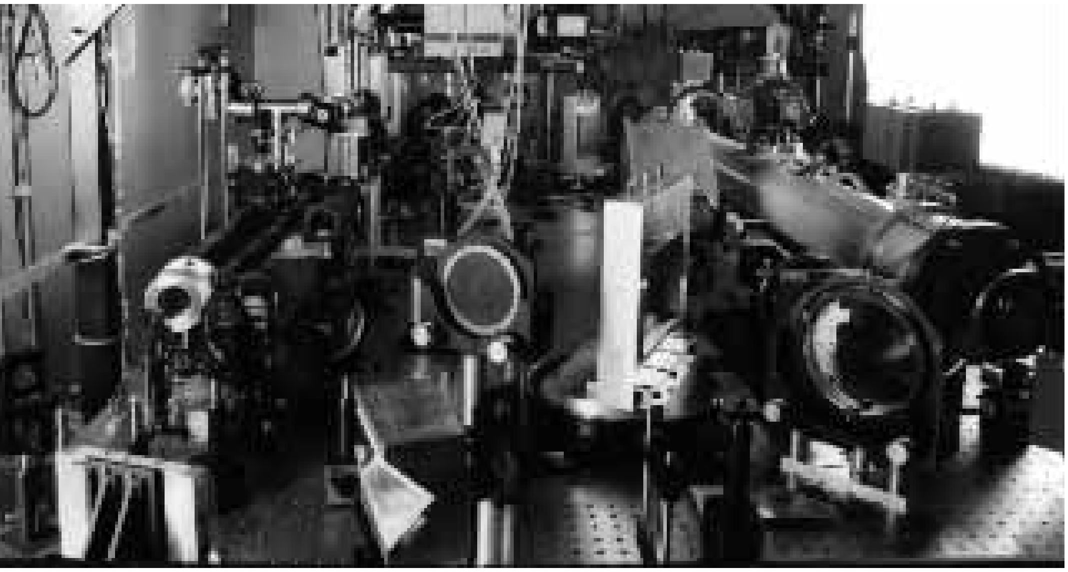
The polarized electron source for the SLAC linac.

determine the state of polarization of the electron beam, a technique that was pioneered at SLAC on the electron-positron ring SPEAR in the late 1970s.

An extension of the polarization-measurement technique, first used at Novosibirsk in Russia, allows the precise determination of the energy of the electrons in a storage ring. Three years ago such measurements revealed changes in the energy of the LEP electron-positron collider at CERN in Geneva, Switzerland, owing to the gravitational pull of the moon. The tidal force of the moon distorts the lattice of the 27 kilometer ring of magnets, resulting in a change of the beam energy at fixed radio-frequency and magnetic field values. What was first considered a puzzle was eventually resolved by the late Gerhard Fisher, a long-time SLAC accelerator physicist.

The energy spread of the photons in a laser beam is usually very small, and certain lasers can be tuned to deliver photons of a specific energy. This property in combination with the polarization dependence of the laser-electron interaction has made possible the highly successful polarized source that is now in use at the SLAC linac (see "The Heart of a New Machine" in the Summer 1994 issue of the *Beam Line*, Vol. 24, No. 2). In this case it is the laser photons that transfer energy to the electrons so that they can emerge from the semiconductor cathode and be accelerated in the electron gun and then injected into the linac. In the strained gallium arsenide crystal cathode, atomic levels corresponding to different polarization states have different energies and can be selectively excited by the laser. This has yielded polarizations as high as 85 percent. The same principle is used to achieve polarization in some of the targets for the electron-scattering experiments being carried out in End Station A at SLAC. Here a titanium sapphire laser operating at a wavelength of 790 nanometers excites rubidium atoms, which in turn collide with atoms of the helium isotope ^{3}He. This causes a significant polarization of the ^{3}He nuclei, and therefore of the two protons and neutron that form the nucleus.

Incidentally, Compton backscattering is not simply restricted to the laboratory but also plays an important role within our galaxy, and presumably in all of intergalactic space as well. Very high energy cosmic-ray protons scatter from the photons that form the microwave background radiation that permeates all of space. Although the density of the radiation is about 400 photons/cm^3, many orders of magnitude lower than that within a laser beam, the distances over which the interaction can occur are correspondingly enormous compared to terrestrial standards, so collisions do occur. In fact, it is believed that the highest energy of the cosmic rays is limited by their collision with the microwave background photons.



The T^3 laser facility used in SLAC Experiment 144.

AN EXPERIMENT currently in progress at SLAC (E-144) explores for the first time a different dimension of the electron-photon interaction—what happens if the photon density is extremely high? The experiment became possible because of recent advances in laser technology that can produce densities as high as 10^{28} photons/cm^3 at the focus of a short laser pulse. To suggest the scale of this number, we recall that the density of electrons in ordinary matter is in the range of 10^{24}/cm^3. High photon density corresponds to high electric field at the laser focus, approaching $E = 10^{11}$ volts/centimeter (V/cm). At such field strengths, atoms become completely ionized. More importantly, however, when an electron from the SLAC beam passes through the laser focus, it feels in its own rest frame an electric field multiplied by the ratio $\gamma = \varepsilon / mc^2$. This effect is a consequence of the special theory of relativity, which is applicable when the particle velocity approaches the speed of light. For the SLAC beam, the energy ε is about 50 GeV; since $mc^2 = 0.5$ MeV, the factor γ is of the order of 10^5. Thus the electric field seen by the electron is about $E = 10^{16}$ V/cm; this field strength is referred to as the critical field of quantum electrodynamics.

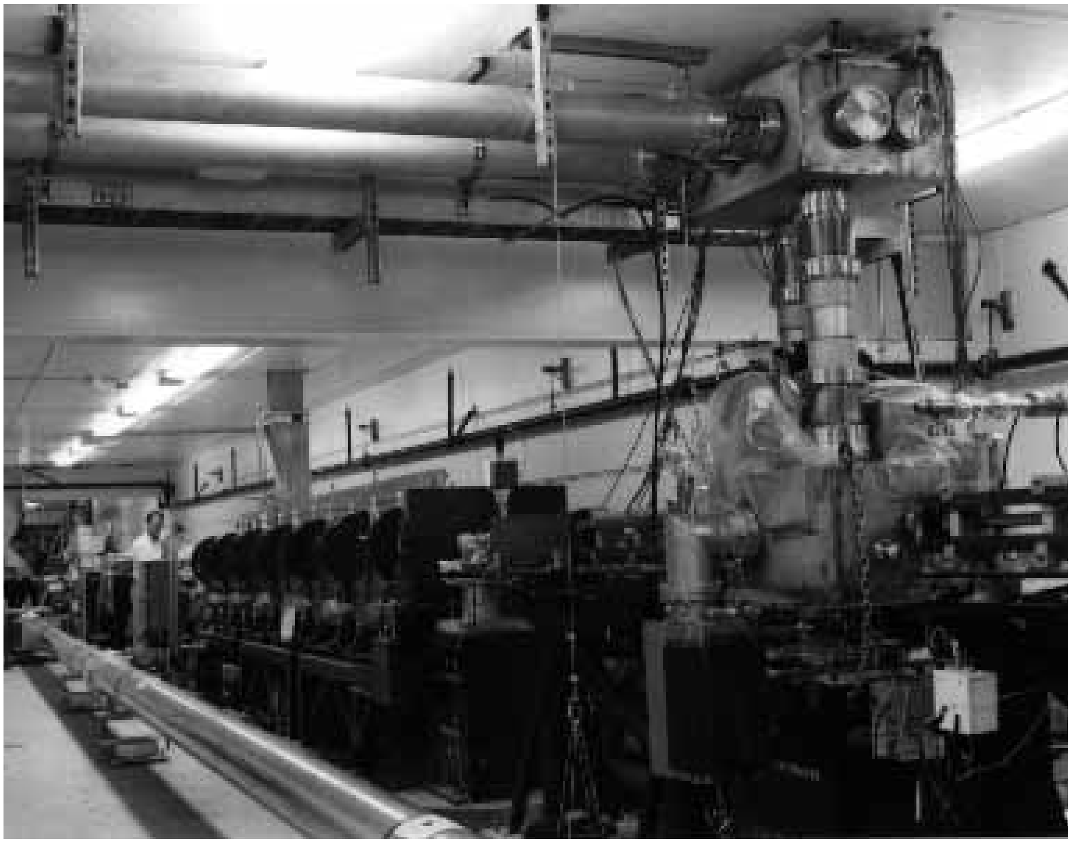
The interaction of electrons with such strong electric fields has hitherto been inaccessible to laboratory experiments (similar phenomena are thought to occur in very dense neutron stars). Just as atoms are torn apart in fields exceeding 10^9 V/cm, one can speculate that the electrons themselves may not withstand the critical field. What would be the manifestation of such a disruptive interaction? Presumably electron-positron pairs would be created out of the vacuum, the energy being supplied by the electric field. Experiment 144 has indeed observed positrons produced under such circumstances. Furthermore, the ordinary electron-photon scattering interaction is modified in the presence of strong electric fields by allowing for the simultaneous absorption of several laser photons. We will return to these experimental results.

The laser system for E-144 is based on the experience gained at the Laboratory for Laser Energetics of the University of Rochester; it uses neodymium embedded in a yttrium-lithium-fluoride crystal matrix (Nd:YLF laser) followed by neodymium in a glass matrix (Nd: glass laser). It has the advantage of being highly compact as compared to lasers of similar power and is nicknamed T^3, for Table-Top-Terawatt laser. Neodymium lases in the infrared at a wavelength of about 1060 nanometers; however, it is possible to double the frequency of the light with good efficiency to obtain beams in the green wavelength of about 530 nanometers. Typically the laser delivers 1–2 joules of energy in a single pulse, which is only 1.2 picoseconds (trillionths of a second) long. Thus the peak power is of the order of 10^{12} watts, to be contrasted with a common helium-neon laser that operates at a level of about 10^{-3} watts. Finally the laser pulse must be focused as tightly as possible. This implies the use of large beams and short focal length (to achieve a small *f*-number) and the absence of aberrations; nearly diffraction-limited spots of 20 mm^2 area have been achieved for green light using $f = 6$ optics.

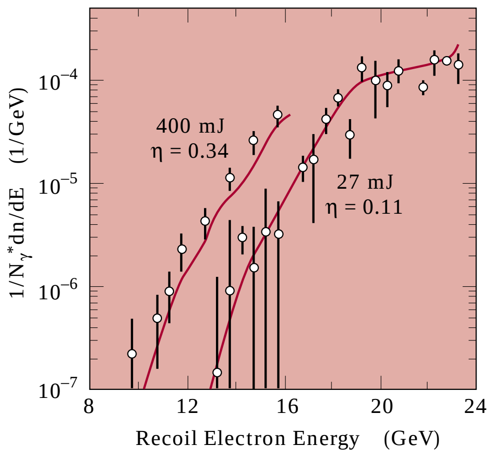
To reach joule energies in a single pulse, a chain of several laser amplifiers must be used. Initially a mode-locked oscillator produces a pulse train of short pulses, typically 50 picoseconds long. This is achieved by placing an acousto-optic switch that is driven by an external frequency with period equal to twice the time for one round trip of the pulse between the laser mirrors inside the laser cavity. As a result, the cavity can lase only for a short time when the switch is open and in phase with the external radio-frequency. This frequency has been chosen to be a sub multiple of the accelerator drive frequency, and in this way the pulses in the laser train are synchronized with the electron pulses in the linac. A single pulse is selected out of the pulse train by a Pockels cell, but the energy in the pulse is only a few nanojoules. The pulse is then stretched in time and chirped in frequency before being injected into a regenerative amplifier. After 100 round trips in the regenerative amplifier, the pulse energy is at the millijoule level, at which point the pulse is ejected from the regenerative amplifier and further amplified in two additional stages. The last stage is of special construction using a slab of lasing material instead of the usual rods to permit a repetition rate of 1 hertz. Finally, the pulse is compressed in time in a pair of diffraction gratings to achieve the desired short length.

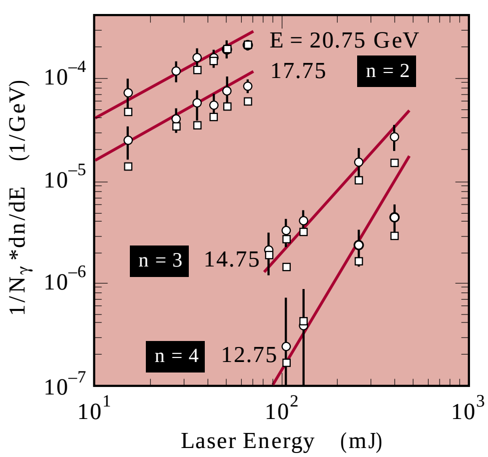
The experiment is installed in the Final Focus Test Beam (FFTB) line (See “The Final Focus Test Beam,” in the Spring 1995 issue of the *Beam Line*, Vol. 25, No. 1), just downstream of the primary focus. This location is particularly advantageous because the tight focal area and short duration of the laser pulse must be matched by an electron pulse of corresponding quality. The laser beam is transported by high performance mirrors to the interaction point, where it crosses the electron-beam line at a 17 degree angle. Immediately after the interaction point, a string of six permanent magnets deflects the electron beam into a beam dump; these magnets also serve to disperse the electrons that have interacted and the positrons that have been produced in the interaction so that their momenta can be measured. Electrons and positrons are detected in silicon calorimeters placed below and above the original beam line. These detectors measure the total energy deposited in a narrow range of electron (positron) momenta. The high energy gamma rays continue in the forward direction and are detected in a separate calorimeter 40 meters downstream from the interaction point.

One of the concerns during the planning of the experiment was whether the synchronization of the laser pulses with the electron beam could be established and maintained. The length of the laser pulse is 300–600 micrometers, and the electron pulse is only slightly longer; furthermore, the two beams cross at an angle. Thus the timing and the path lengths traversed by these two pulses originating from very different sources must be kept to a tolerance of a fraction of a millimeter. This was successfully accomplished with a phase-locked loop between the laser mode locker and the linac radio-frequency, as well as by careful construction of the transport line. A computer-controlled delay inserted in the laser line was used to set and maintain optimal timing.



The laser-electron interaction point and the analyzing spectrometer for Experiment 144 inside the Final Focus Test Beam cave.





Top: The normalized cross section for multiphoton Compton scattering plotted as a function of momentum for laser energies of 27 and 400 millijoules. The laser wavelength was λ = 1054 nanometers and the electron energy ε = 46 GeV.

Bottom: The normalized cross sections for 2, 3,and 4 photon absorption as a function of laser energy (λ = 1054 nanometers and ε = 46 GeV). For linear processes the cross section is independent of laser energy. The open circles show the predictions of the theory.

NOT EVERY BEAM electron crosses through the laser focus, but at high laser density every electron that does cross through the laser focus interacts, giving rise to a backscattered gamma ray with energy between 0 and 21 GeV (for infrared light and for 46 GeV incident electrons). Some 5×10^7 gammas were produced by each electron pulse, corresponding to conversion of approximately 1 percent of the incident electron flux (as expected from the relative size of the two beams). Interactions that involve the absorption of two or more photons are much less common but still copious. In this case it is the recoil electrons that are being detected; if a single (infrared) photon is absorbed, the recoil electron energy is always greater than 25 GeV. Thus electrons with energy below 25 GeV are a measure of interactions where two or more photons were absorbed (there is also a finite probability that the electron scattered twice at different positions within the laser focus). The measured spectrum of recoil electrons for two different laser energies is shown in the top graph on the left. Recoil electrons in the range between 18 and 25 GeV result from the absorption of two photons, between 13 and 18 GeV from the absorption of three photons, and so on.

The absorption of a single photon is a linear process; this implies that if the laser intensity is doubled, the scattering rate also doubles. In contrast, the absorption of several photons is a nonlinear process. When the laser intensity is doubled the rate of 2-photon absorptions increases by a factor of four, the rate of 3-photon absorptions by a factor of eight, and in general the rate of n-photon absorptions increases as the nth power of the laser energy. That this is true can be seen in the bottom graph on this page where the observed rate for two-, three-, and four-photon absorption is plotted as a function of laser energy. The nonlinear behavior for these processes is clearly evident.

The rate for the production of electron-positron pairs is relatively low at present laser intensities; approximately one positron is detected in 1000 laser shots. The physical mechanism in this case is the following: an electron enters the laser focus and produces a high energy gamma ray; the gamma ray interacts simultaneously with several (at least four) laser photons to produce the pair. This result is the first demonstration of light-by-light scattering involving physical photons. There was little doubt that this process, which has been amply verified for virtual photons, would occur; however, the stage has now been set for further precision experiments that can probe quantum electrodynamics in the critical field regime.

IT SHOULD COME as no surprise that an understanding of the electromagnetic interaction in high electric fields is essential for the design of the next generation of linear colliders. To achieve the required luminosity, the beams at the collision point of these new machines must have dimensions of only a few nanometers. This results in an extremely high electric field inside the electron (or positron) bunch; the incoming positron (electron) that

Steve Boege

enters the oppositely moving bunch is affected by the field and can lose a significant amount of energy in the form of radiation and/or pair production. This effect is already observable in the collisions at the Stanford Linear Collider and has been given the name "beamstrahlung." It will be much more important for future linear colliders, and designers are making every effort to minimize its impact.

Finally, it is desired to include in future electron-positron colliders the option of operating them as gamma-gamma colliders. This has certain advantages in identifying the particles produced in the collision, especially scalar particles such as the hypothesized Higgs boson. The high energy electron and positron beams can be converted to gamma-ray beams by backscattering laser photons from each of the beams. In this respect E-144 has been the pilot experiment for future gamma-gamma colliders both in terms of the hardware involved and in measuring the fundamental processes that govern such collisions. There are still many unanswered questions and much work to be done before gamma-gamma colliders can be designed with certainty.

Investigation and exploitation of the electron-photon interaction has had a long tradition at SLAC. Higher energies, new technology, and new ideas have confirmed theoretical predictions that, in some cases were made decades ago. The recent experiments present an opportunity for probing this fundamental interaction in a new regime. No doubt the answers will continue to be important.

Experiment 144 group photograph. Pictured left to right are (kneeling) Glenn Horton-Smith, SLAC; Theofilos Kotseroglou, Wolfram Ragg, and Steve Boege, University of Rochester; (standing) Kostya Shmakov, University of Tennessee; David Meyerhofer and Charles Bamber, University of Rochester; Bill Bugg, University of Tennessee; Uli Haug, University of Rochester; Achim Weidemann, University of Tenessee; Dieter Walz, David Burke, and Jim Spencer, SLAC; Christian Bula and Kirk McDonald, Princeton; Adrian Melissinos, University of Rochester. Not pictured are Clive Field and Allen Odian, SLAC; Steve Berridge, University of Tennessee; Eric Prebys, Princeton; and Thomas Koffas, University of Rochester.