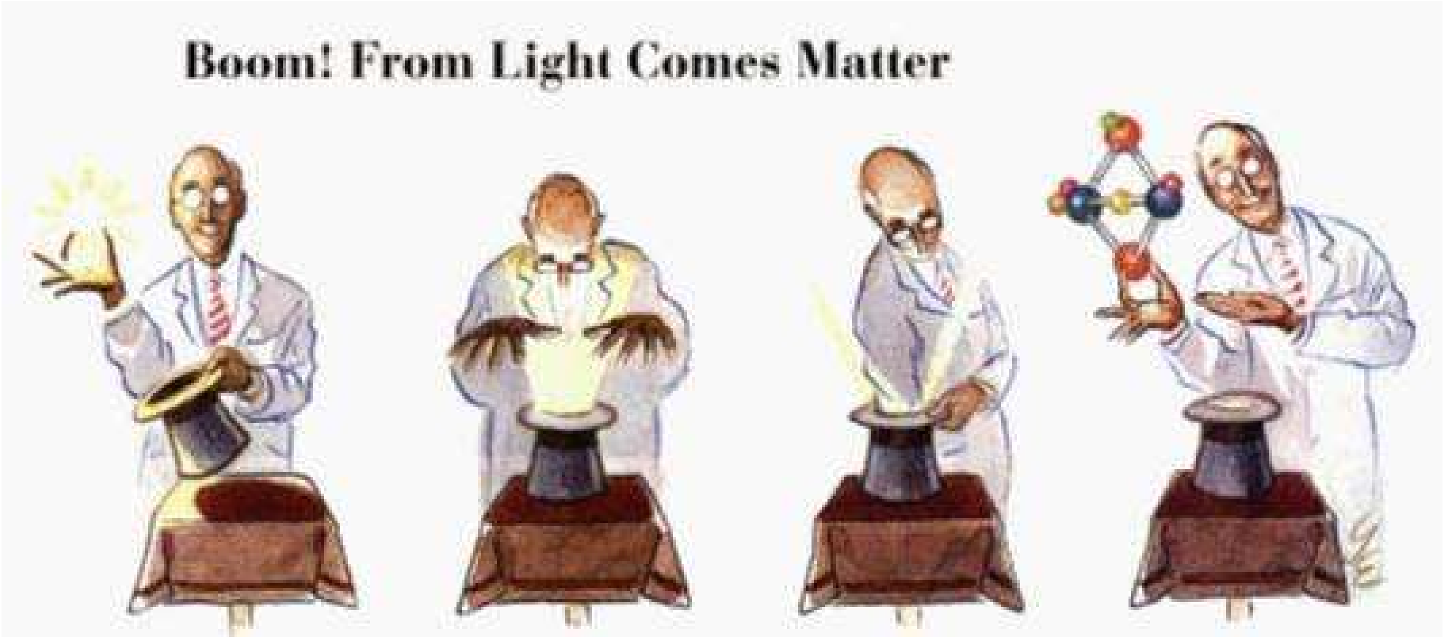


Positron Production by Laser Light

K.T. McDonald

Princeton U.

September 30, 1998

Seminar at U. Maryland

Sonoluminescence

In 1850, the Navier-Stokes equation was the "theory of everything", but it doesn't predict sonoluminescence. [Erber]

[Sonoluminescence is what makes nitroglycerine explode.]

- Preparata (1998): QED theory of water vapor predicts emission of light when water vapor condenses at density near 1 g/cm^3.
- Schwinger (1992): a bubble is an electromagnetic cavity; an imploding bubble will radiate away the changing, trapped zero-point energy.
- Liberati (1998): Imploding bubble ⇒ rapidly changing index ⇒ associated radiation.

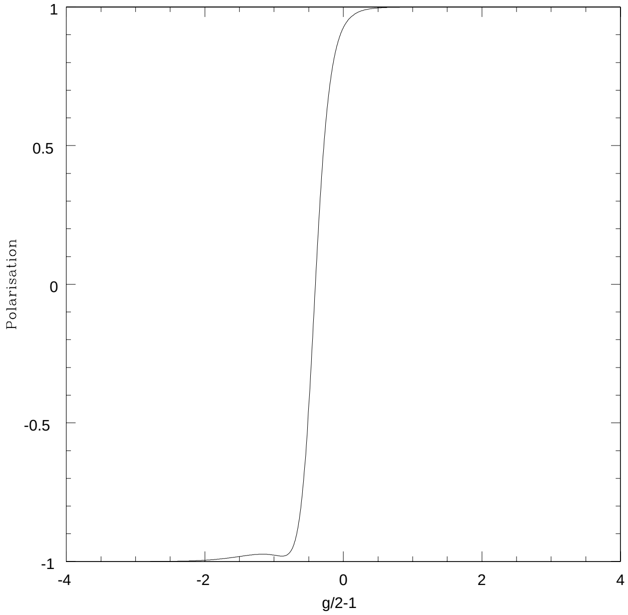
  This relates to an earlier idea:
- Yablonovitch (1989): An accelerating boundary across which the index of refraction changes is a possible realization of the Hawking-Unruh effect, leading to conversion of QED vacuum fluctuations into real photons.

The Hawking-Unruh Effect

Hawking (1974): An observer outside a black hole experiences a bath of thermal radiation of temperature $T = \frac{\hbar g}{2\pi c k}$, where g is the local acceleration due to gravity.

Unruh (1976): According to the equivalence principle an accelerated observer in a gravity-free region should also experience a thermal bath with: $T = \frac{\hbar a}{2\pi c k}$, where a is the acceleration of the observer as measured in his instantaneous rest frame.

Bell (1983), Leinaas (1998), Unruh (1998): Incomplete polarization of electrons in a storage ring is explained in detail by Hawking-Unruh excitation.



Unruh Radiation (?)

Suppose the observer is an electron, accelerated by a field E.

Thomson scattering off photons in the apparent thermal bath implies a radiation rate:

$$\frac{dU_{\text{Unruh}}}{dt} = \text{thermal energy flux} \times \text{Thomson cross section} = \frac{\hbar r_e^2 a^4}{90\pi c^6}.$$

[Stefan-Boltzman: flux $\propto T^4$, Unruh: $T^4 \propto a^4$.]

This equals the Larmor radiation rate, $dU/dt = 2e^2a^2/3c^3$, when the acceleration $a = eE/m$ is about 10^{31} g, *i.e.*, when

$$E = \sqrt{\frac{60\pi}{\alpha}} \left(\frac{m^2c^3}{e\hbar}\right) \approx 3 \times 10^{18} \text{ V/cm}.$$

Can we do the experiment?

Strong-Field QED

For high acceleration, need strong electromagnetic field.

Strongest macroscopic electromagnetic fields are in lasers.

Tabletop teraWatt lasers can be focused to $> 10^{19}$ W/cm^2.

$\Rightarrow$ Electric fields > 100 GeV/cm.

[Photon number density $> 10^{27}$/cm^3.]

(Nonperturbative) physics described by two dimensionless measures of field strength:

$$\eta = \frac{e\sqrt{\langle A_\mu A^\mu \rangle}}{mc^2} = \frac{eE_{\text{rms}}}{m\omega_0 c} = \frac{eE_{\text{rms}}\lambda_0}{mc^2},$$

governs the importance of multiple photons in the initial state, and characterizes the "mass shift": $\overline{m} = m\sqrt{1+\eta^2}$. [Kibble, 1996]

$$\Upsilon = \frac{\sqrt{\langle (F^{\mu\nu} p_\nu)^2 \rangle}}{mc^2 E_{\text{crit}}} = \frac{2p_0}{mc^2}\frac{E_{\text{rms}}}{E_{\text{crit}}} = \frac{2p_0}{mc^2}\frac{\lambda_C}{\lambda_0}\eta,$$

governs the importance of "spontaneous" pair creation, where $E_{\text{crit}} = m^2c^3/e\hbar = mc^2/e\lambda_C = 1.3 \times 10^{16}$ V/cm.

The QED Critical Field Strength

- O. Klein (Z. Phys. **53**, 157 (1929)) noted that the reflection coefficient exceeds unity 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:

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

- At the critical field, the energy gain across a Compton wavelength is the electron rest energy:

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

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

$$\text{Dimensionless measure of criticality: } \Upsilon = \frac{E}{E_{\mathrm{crit}}}.$$

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.

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

  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

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

$$\text{so} \qquad \Upsilon = \frac{E^\star}{E_{\rm crit}} = \frac{2\gamma E_{\rm lab}}{E_{\rm crit}} = \frac{\sqrt{(F_{\mu\nu}p^\nu)^2}}{mc^2 E_{\rm crit}}.$$

- 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 $\sim 10^{27}$/cm^3, and the radiation length of this 'photon solid' is $\sim \lambda_0/\alpha \approx 100\ \mu$m.

Another Aspect of Electrons in Strong Wave Fields

Simplest to consider a circularly polarized laser beam incident on an electron at rest. Laser field is E, frequency is ω_0.

Classical response of electron is transverse motion in a circle with angular velocity ω_0 and velocity described by

$$\frac{v_\perp}{c} = \frac{eE}{m\omega_0 c} \equiv \eta.$$

$[\eta = e\sqrt{\langle A_\mu A^\mu \rangle}/mc^2$ where A_μ is the vector potential.]

The accelerating electron emits multipole radiation.

$\mathrm{Rate}_n \propto \eta^{2n} \propto I^n$ for nth-order multipole ($\eta \lesssim 1$).

nth order $\Leftrightarrow$ absorption of n photons before emitting a single higher-energy photon $\Leftrightarrow$ nonlinear Compton scattering.

Υ and η are related by

$$\Upsilon = \frac{2\gamma E_{\mathrm{lab}}}{E_{\mathrm{crit}}} = \frac{2\gamma\hbar\omega_0}{mc^2}\eta \quad \approx \quad \eta \ \text{ in our experiment.}$$

$\Rightarrow$ Two classes of strong-field effects to be untangled.

The Mass Shift Effect

An electron propagating in a (periodic) wave field of strength $\eta = eE/m\omega_0 c$ takes on an effective mass

$$\overline{m} = m\sqrt{1+\eta^2}.$$

Classical view: the transverse oscillations of the electron are relativistic, so it becomes 'heavier'.

As a result the kinematic limits in nonlinear Compton scattering (and threshold for pair creation) are shifted.

Pedagogic paradox: An electron with 4-momentum p_μ in the absence of the field takes on quasimomentum q_μ once in a field of 4-momentum k_μ:

$$q_\mu = p_\mu + \frac{\eta^2 m^2}{2k\cdot p}k_\mu, \qquad q^2 = \overline{m}^2.$$

In our experiment $\eta^2 m^2/2k\cdot p$ takes on a fractional value.

Summary of 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'

$$E_{\text{crit}} = m^2c^3/e\hbar = 1.6 \times 10^{16}\ \text{V/cm}.$$

- Explore QED in the realm where multiphoton interactions dominate, *i.e.*, when $\eta \equiv eE/m\omega_0 c \approx 1$.

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

E-144 Home Page on World Wide Web

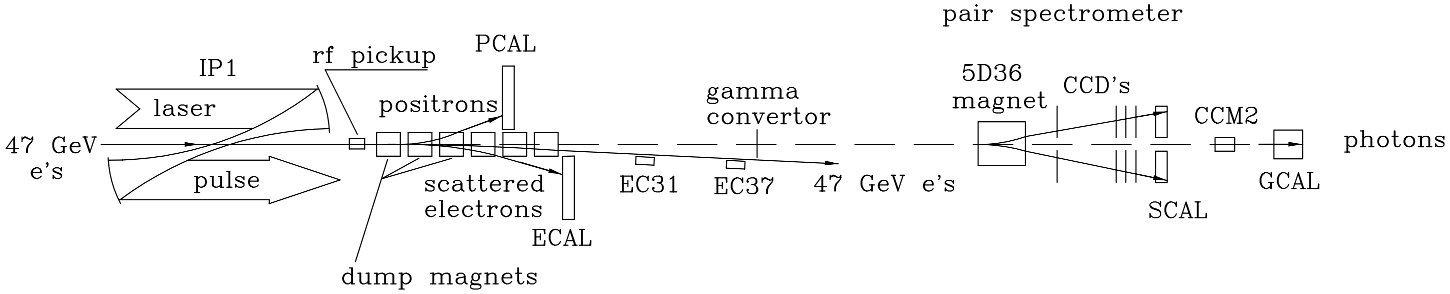
http://www.slac.stanford.edu/exp/e144/e144.html

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. Nonlinear Compton Scattering: $e + n\omega_0 \to e' + \omega$
    - Semiclassical theory $\Rightarrow$ data will diagnose laser intensity.
    - Provides high-energy-photon beam for light-by-light scattering.
3. Multiphoton Breit-Wheeler Process: $\omega + n\omega_0 \to e^+e^-$
    - Might show anomalous structure in e^+e^- invariant mass when $E > E_{\text{crit}}$.

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-grain' measurements.
- Data-acquisition system based on PC's interconnected via a local ethernet.



E-144 is at the End of the FFTB

TeraWatt Laser Via Chirped-Pulse Amplification

1 Joule in 1 ps ⇒ 10^{12} Watt.

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

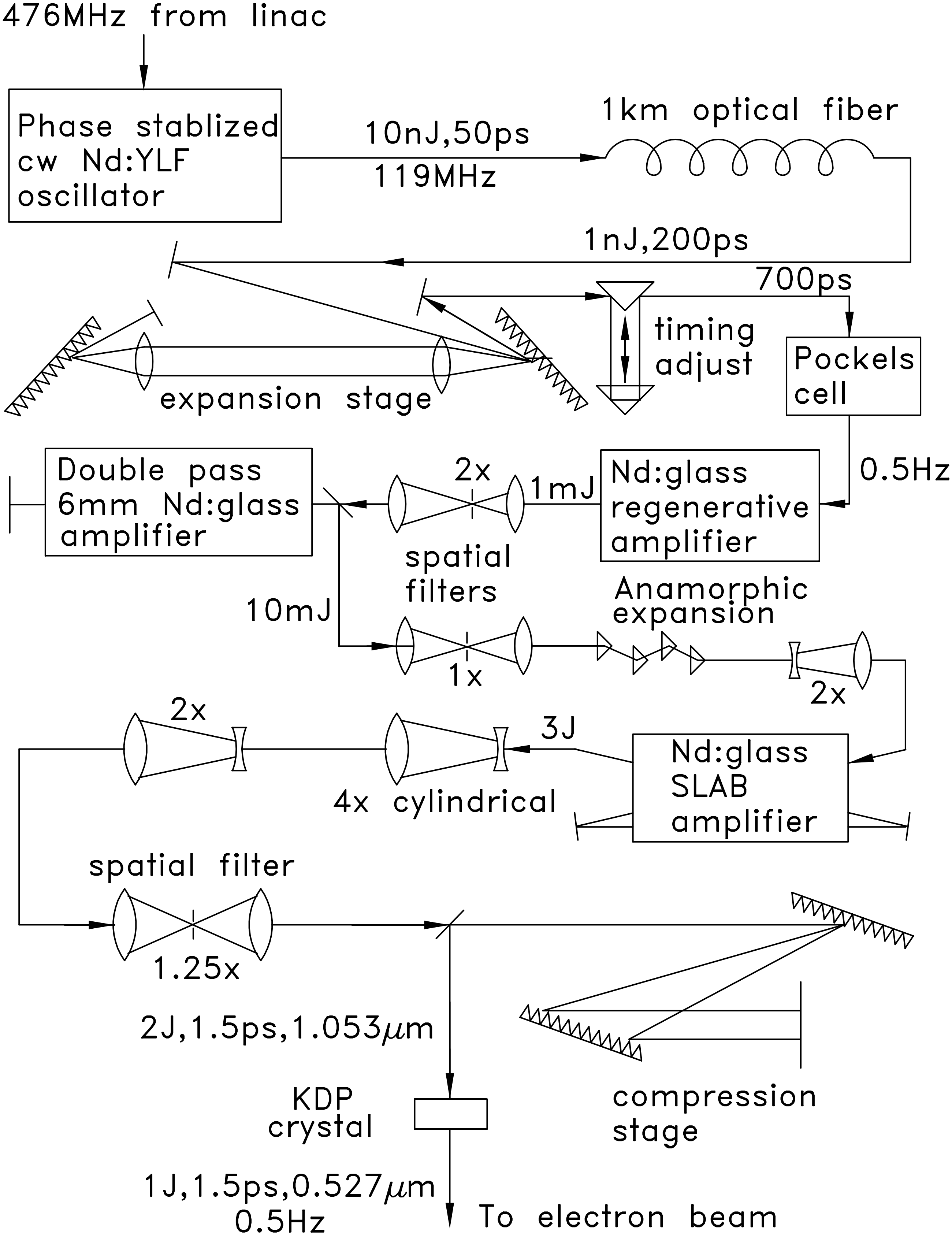
$\Rightarrow I \approx 10^{19}\ \mathrm{W/cm^2}$.

High power pulses can damage optics!

⇒ stretch pulse, then amplify and compress.

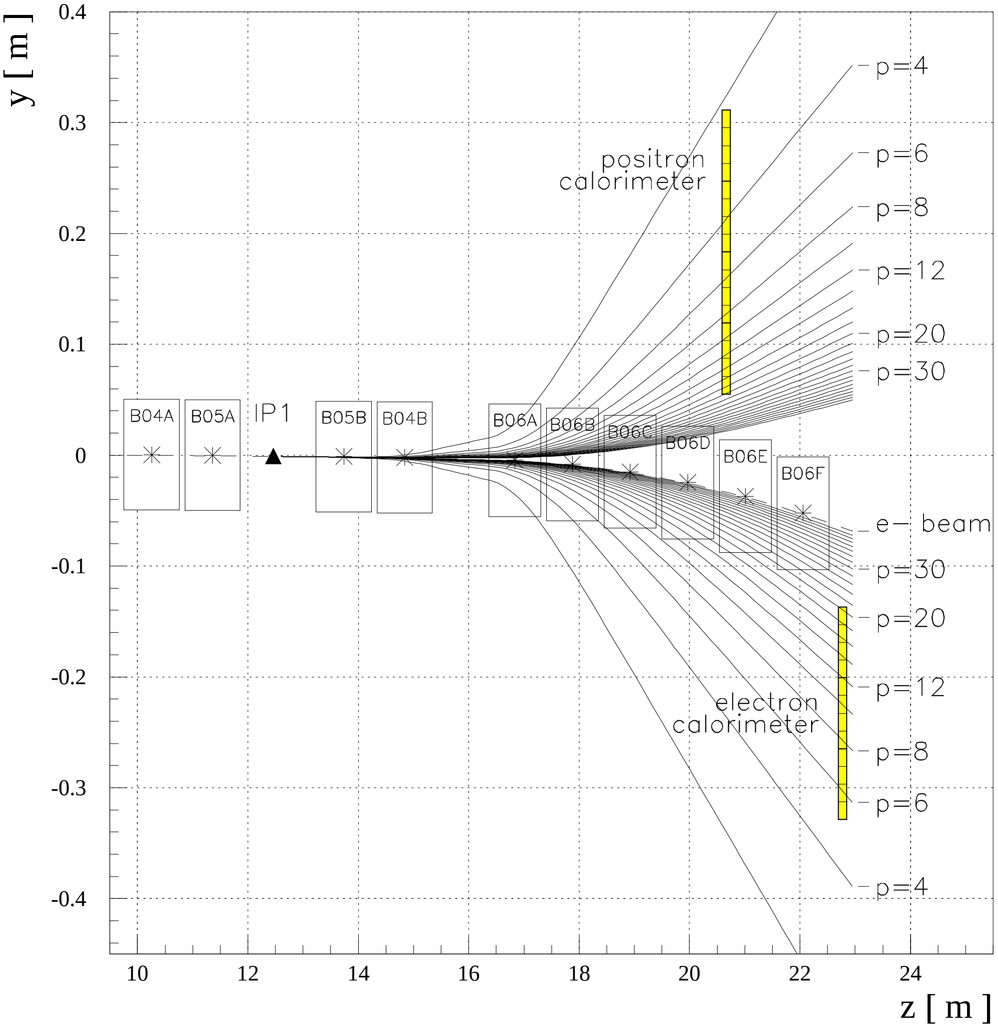
[D. Strickland and G. Mourou, Opt. Comm. **55**, 447 (1985).]

E-144 Laser Schematic



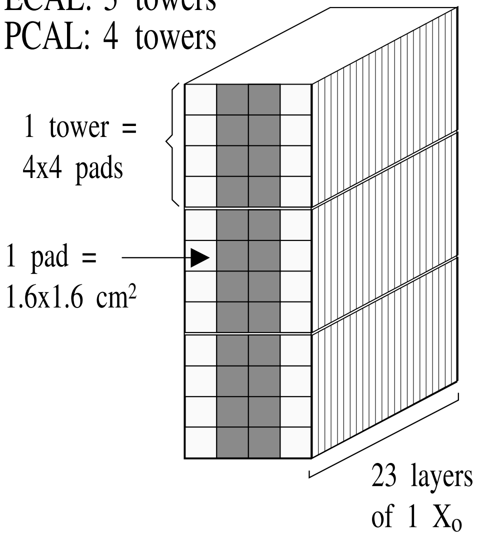
synchronization block diagram

Electron & Positron Spectrometers



ECAL, PCAL: silicon-tungsten

ECAL: 3 towers
PCAL: 4 towers


1 tower =
4x4 pads

1 pad =
1.6x1.6 cm^2

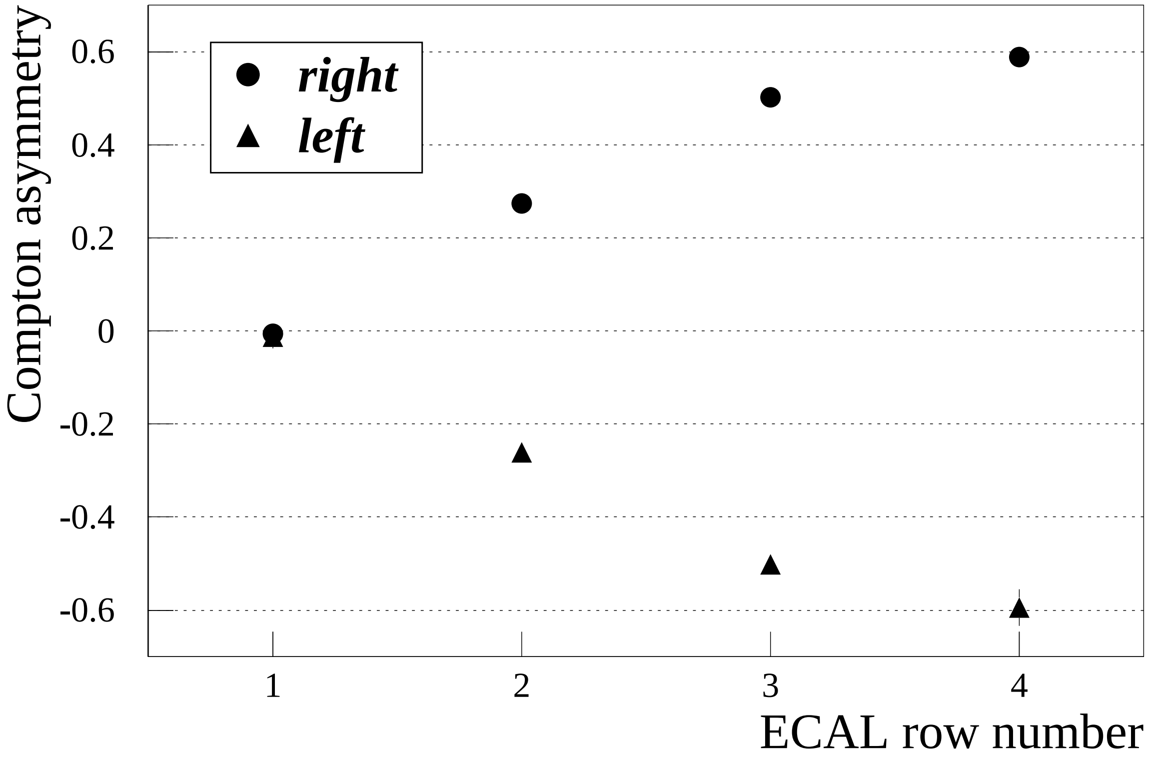
23 layers
of 1 X_0

Measurement of e-Beam Polarization (May ’94)

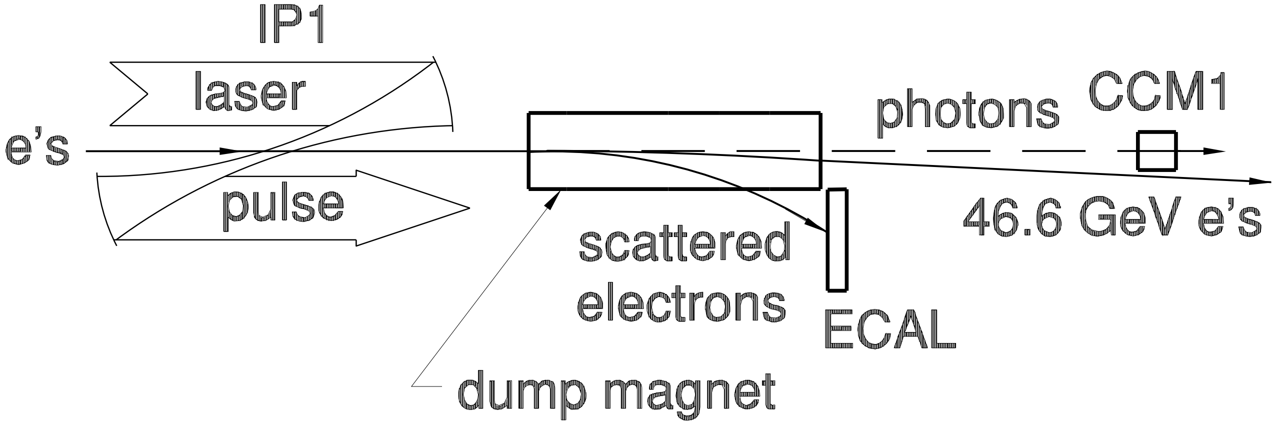
Fit to measured polarization asymmetry in 4 energy bins yields

$$P_e P_{\text{laser}} = 0.81 \pm 0.01.$$

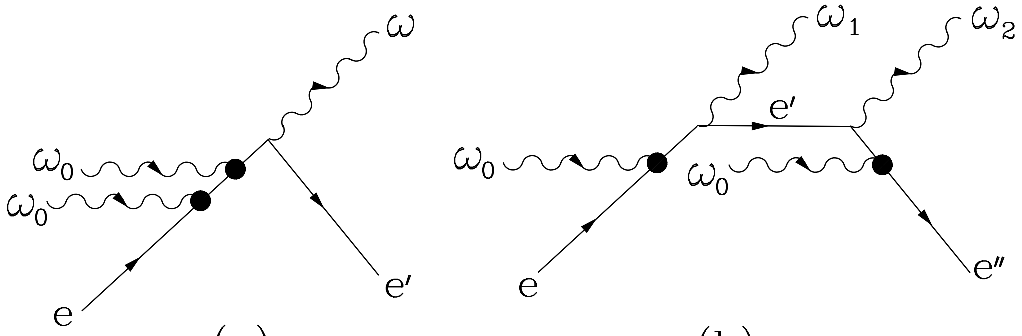
Laser polarization $> 0.96 \Rightarrow P_e = 0.81^{+0.04}_{-0.01}$.



Nonlinear Compton Scattering



$$(a) \qquad e + n\omega_0 \rightarrow e' + \omega$$



(a) (b)

(b) Background: multiple Compton scattering

Can distinguish process (a) from (b) by detecting scattered photon.

In first experiments, only the scattered electron was detected.

Theoretical Predictions for $e + n\omega_0 \to e' + \omega$

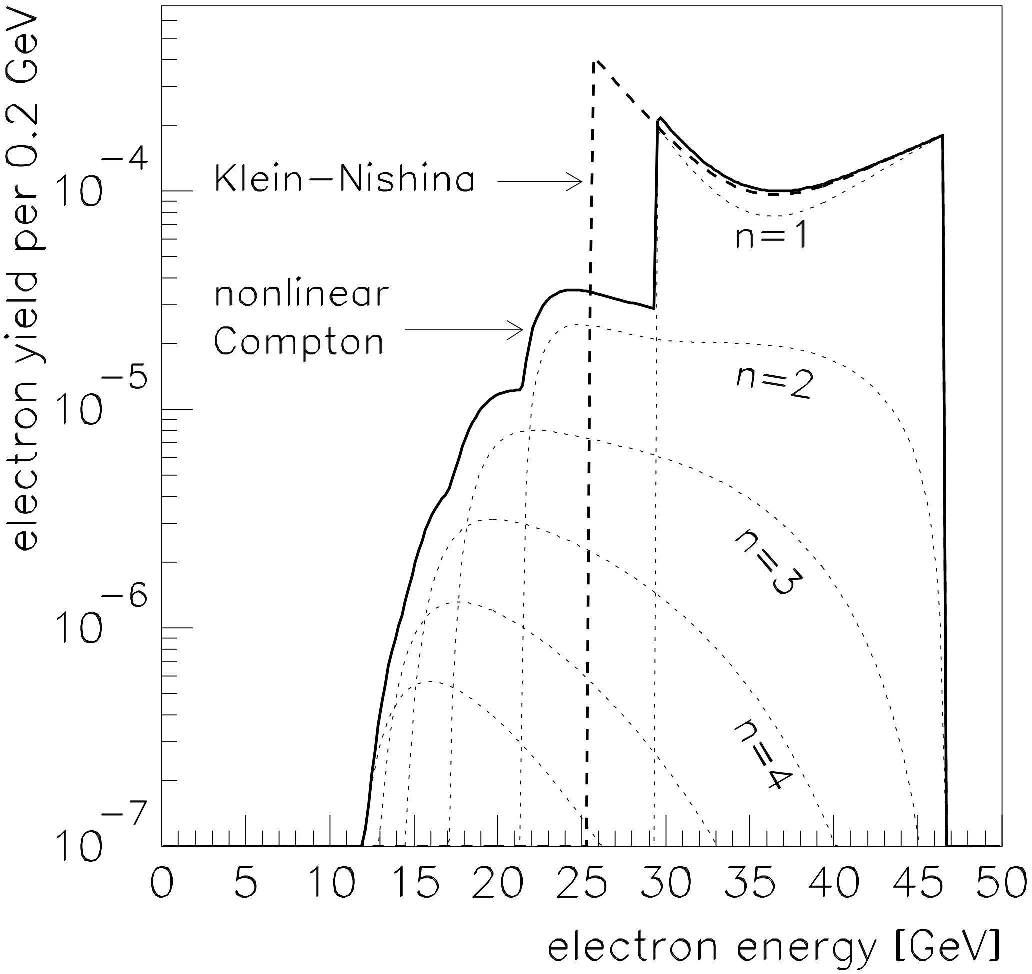
Circular polarization (Nikishov *et al.*, JETP **20** (1965) 622).

$$\frac{d\mathrm{Rate}_n}{dE_{e'}} = \frac{4\pi r_0^2 N_{\mathrm{laser}} N_e}{x E_e} \times$$

$$\left\{ \left(2 + \frac{u^2}{1+u}\right) \left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right] - \frac{4}{\eta^2} J_n^2(z) \right\},$$

$$x = \frac{4\omega_0 E_e}{m^2}, \qquad u \approx \frac{E_e}{E_{e'}} - 1, \qquad z = \frac{2\eta}{x}\sqrt{nux - u^2(1+\eta^2)}.$$

Case of linear polarization is more intricate.



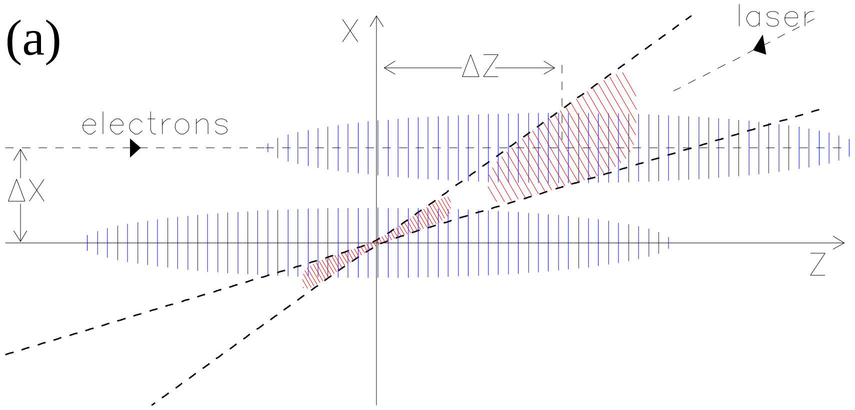
$\eta = 0.64$

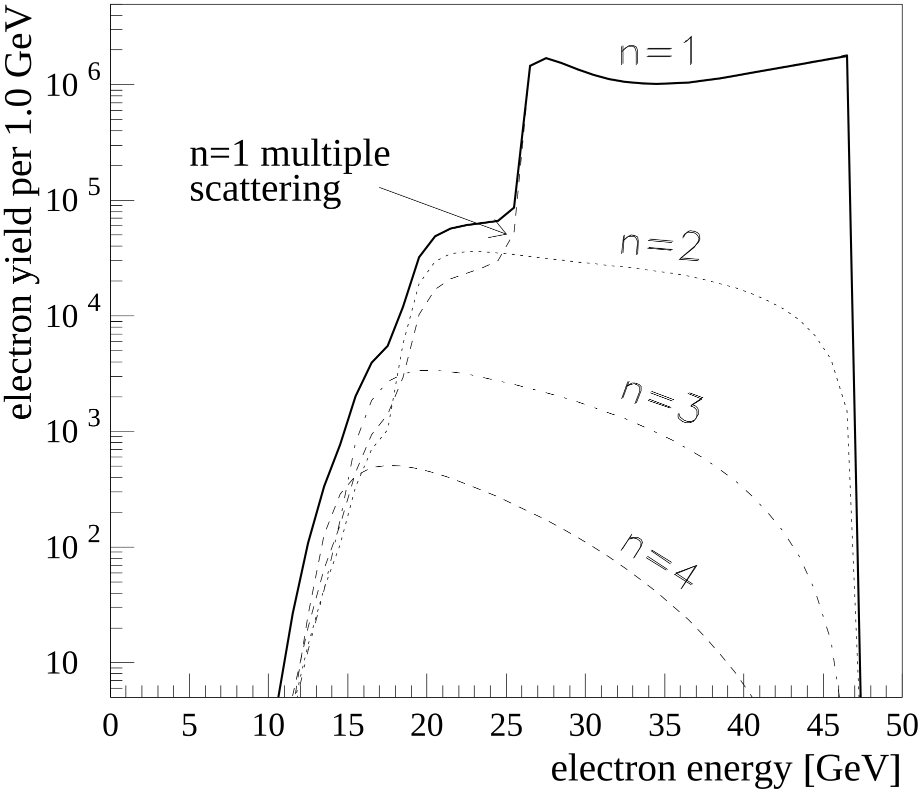
Effect of Laser and Electron Beam Spots

Beams cross at 17°.

Laser pulse is ≈ 2 ps long, focussed to $\approx 5\lambda_0$.

Electron pulse is ≈ 5 ps long.



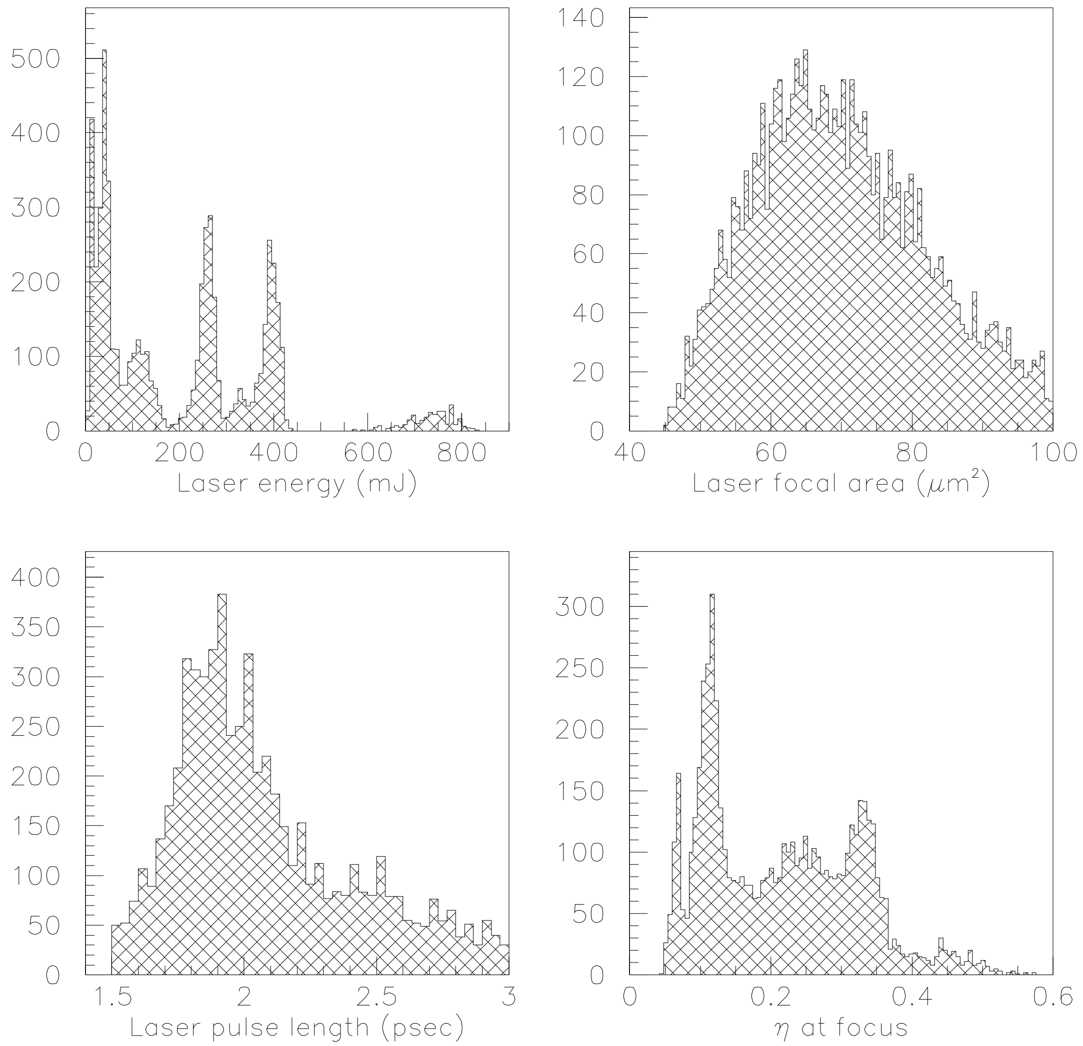


$$\eta_{\rm max} = 0.64$$

Measurements of Nonlinear Compton Scattering

[C. Bula *et al.*, Phys. Rev. Lett. **76**, 3116 (1996)]

18,000 infrared laser shots ($\omega_0 = 1.15$ eV):

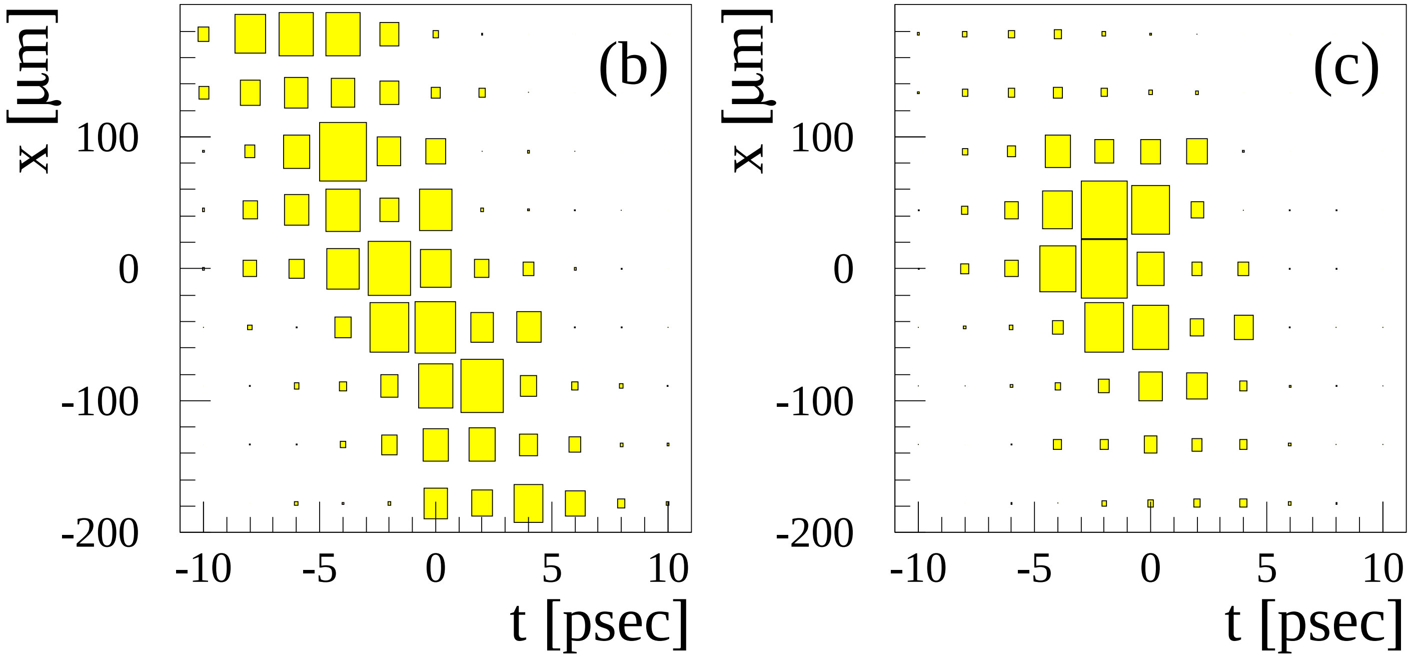


16,000 green laser shots ($\omega_0 = 2.3$ eV).

x-t Scans

Vary x and t offsets between laser and electron beam.

Detect scattered electrons in (a) $n = 1$ region and (b) $n = 2$ region.



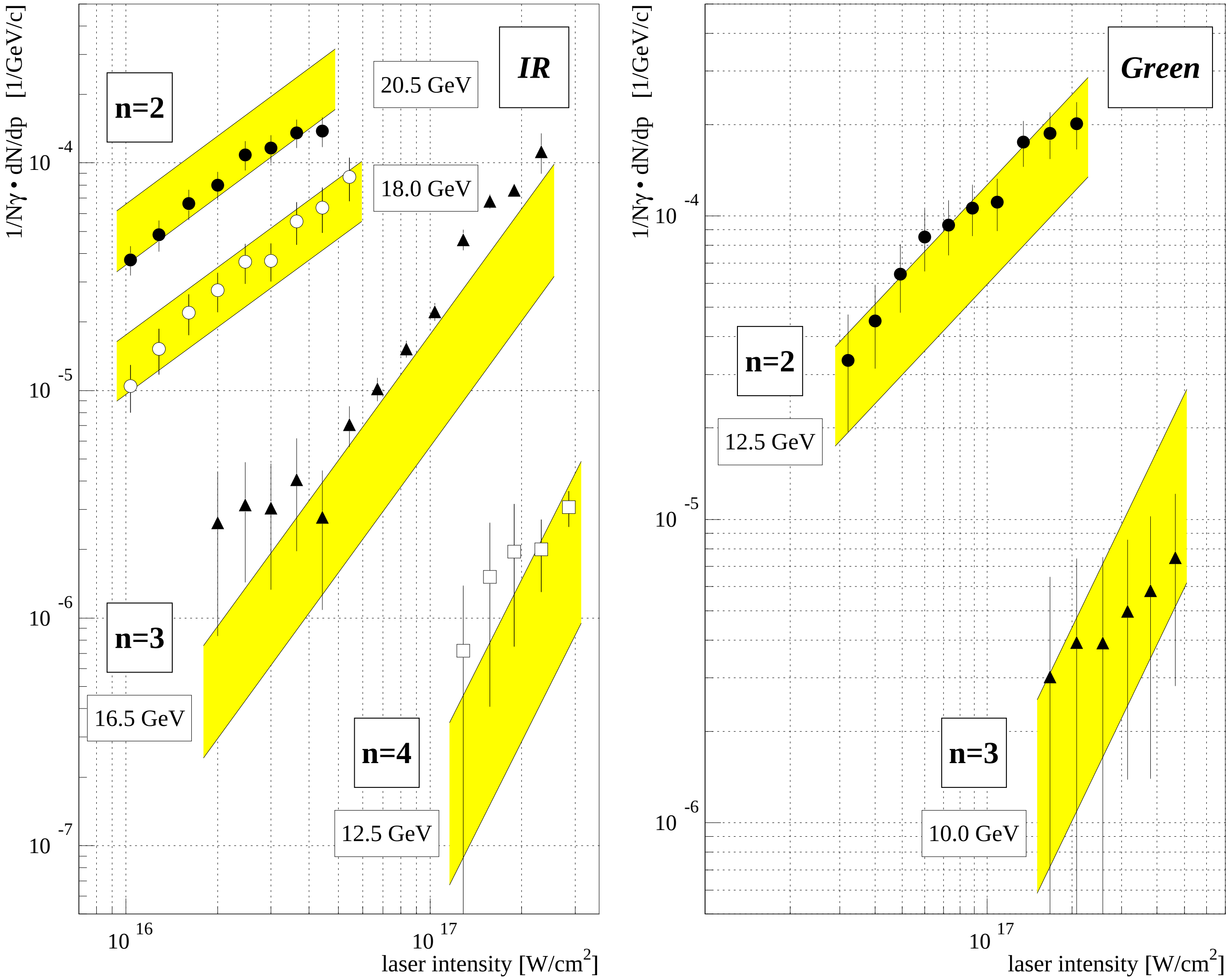
Nonlinear scattering confined to core of laser spot where intensity is the highest.

Observed Rates *vs.* **Laser Intensity**

Cross-section not a useful concept for nonlinear scattering.

Plot differential rates normalized to total scattering rate

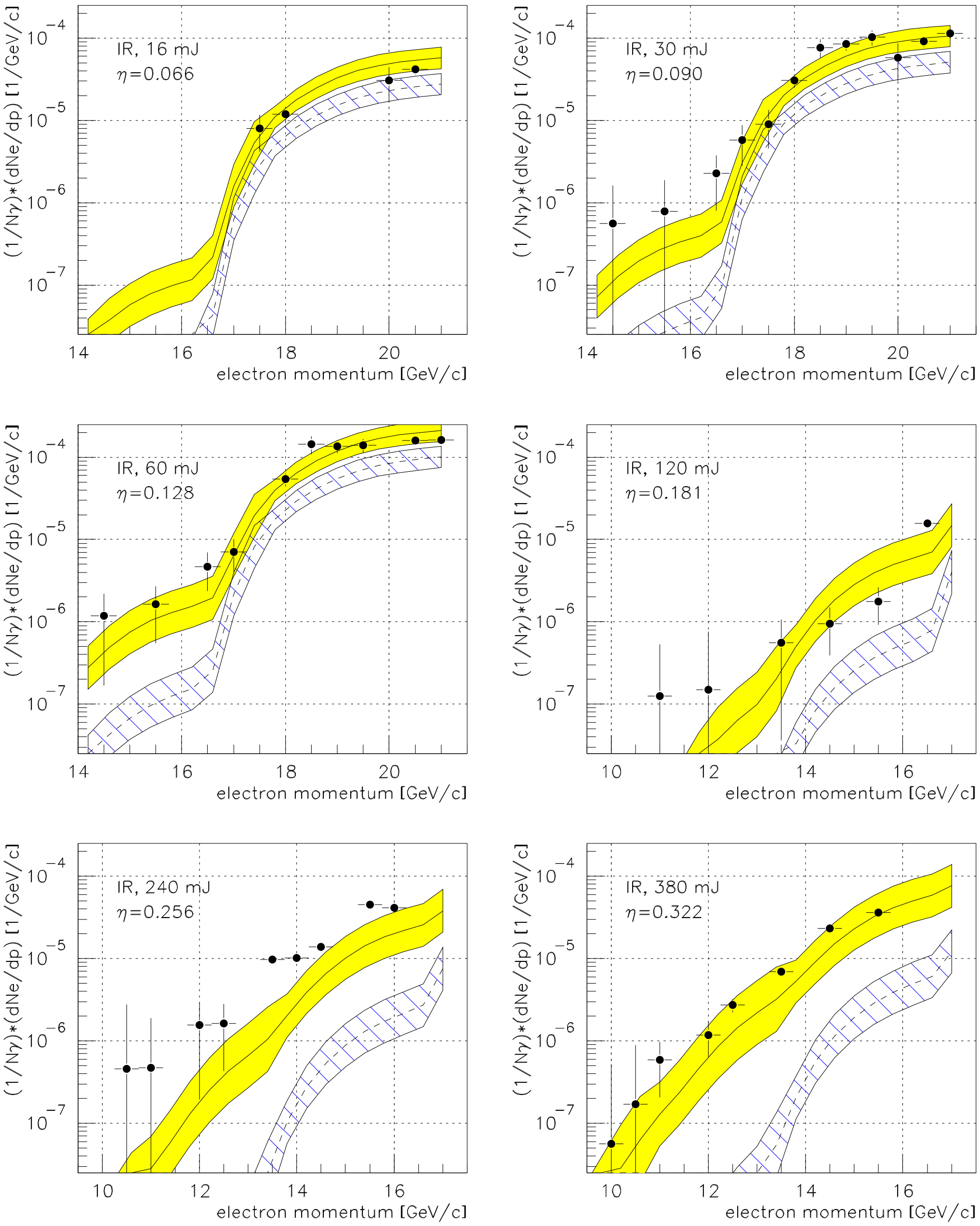
(= total rate of scattered photons).



Normalized to total scattered photon rate

$\Rightarrow$ Rate(order n) $\propto I^{n-1}$.

Observed Scattering Rates *vs.* Electron Energy



$n = 2$ edge at 17.6 GeV, $n = 3$ edge at 13.5 GeV.

Shaded = full simulation.

Striped = multiple-$(n = 1)$ scattering only.

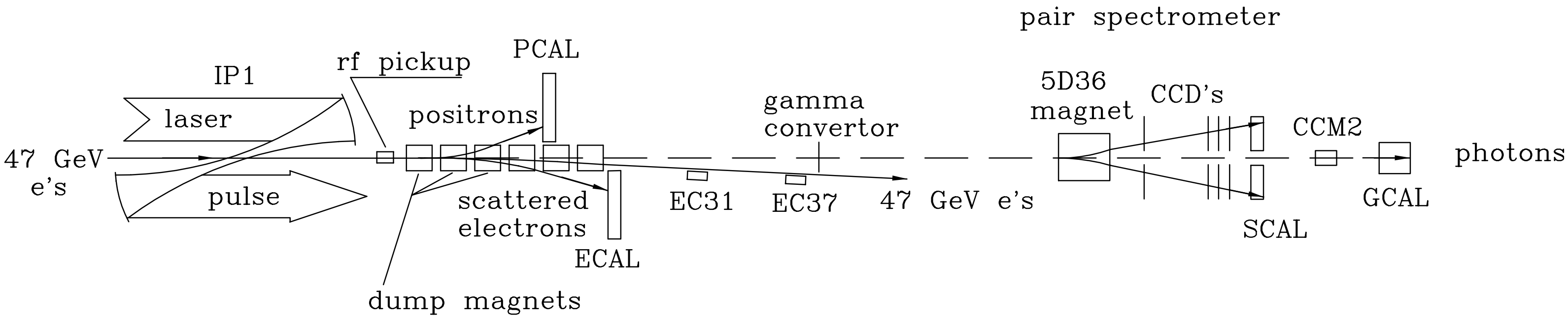
Measurements of the Scattered Photon

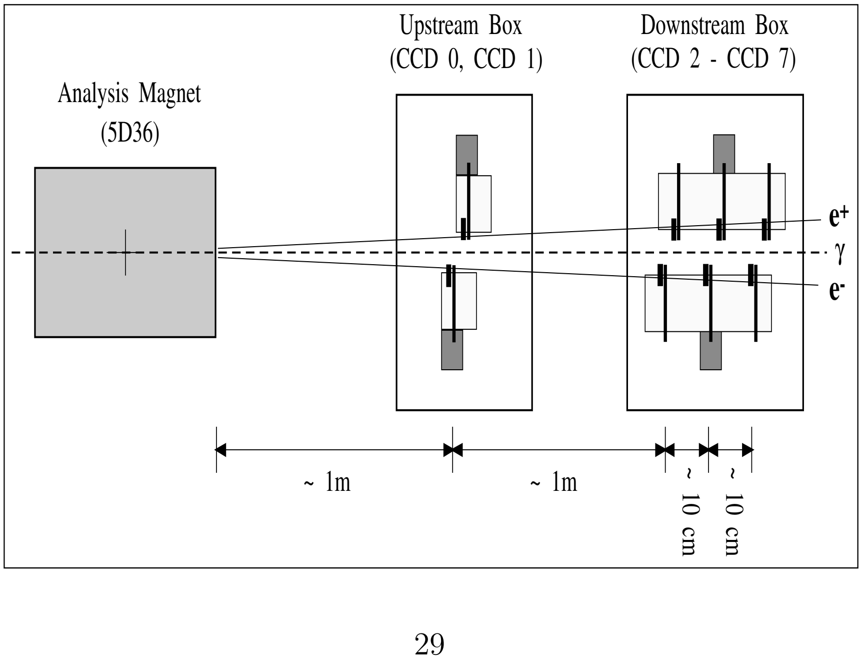
Multiple Compton scatters produce no photons with energy above the maximum for a single scatter.

$\Rightarrow$ No backgrounds for $n > 1$ nonlinear Compton Scattering

However, no simple spectrometer for high-energy photons:

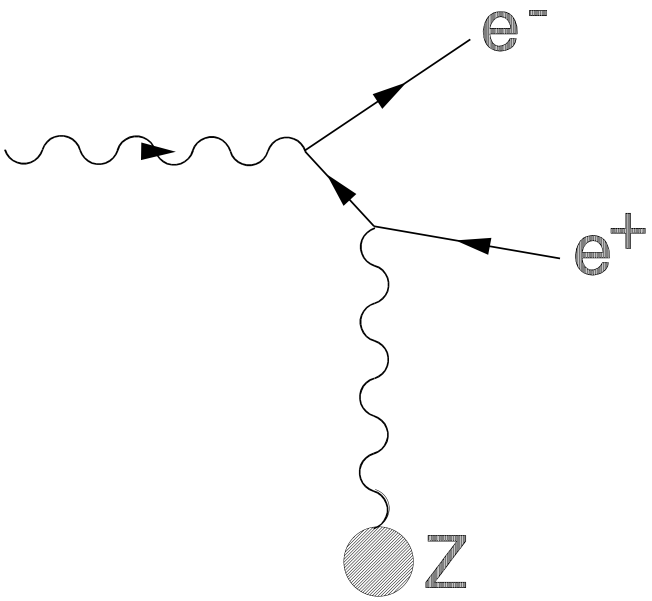
We convert the photons to e^+e^- pairs and analyze the latter in a magnetic spectrometer with CCD detectors





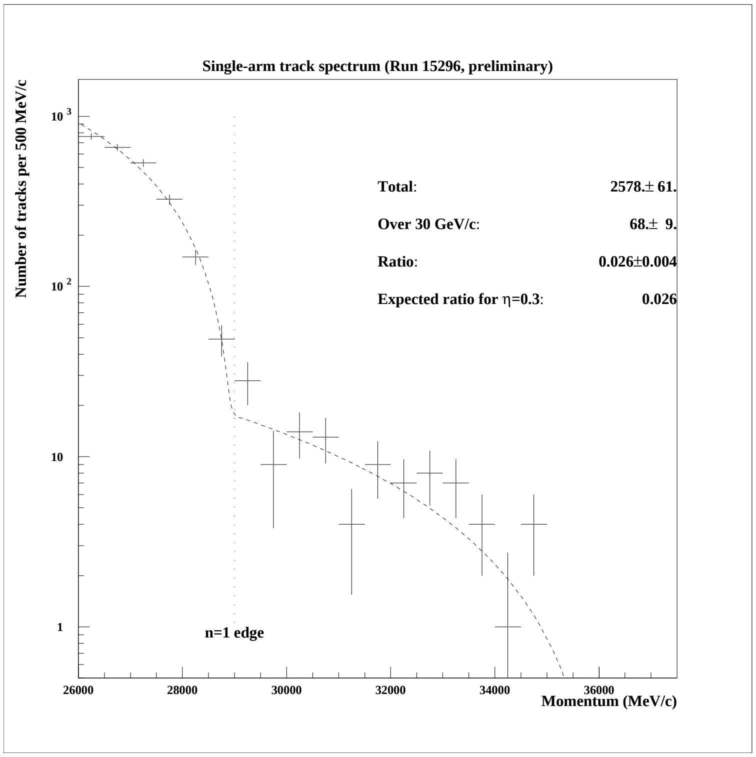
Making Positrons the Old-Fashioned Way

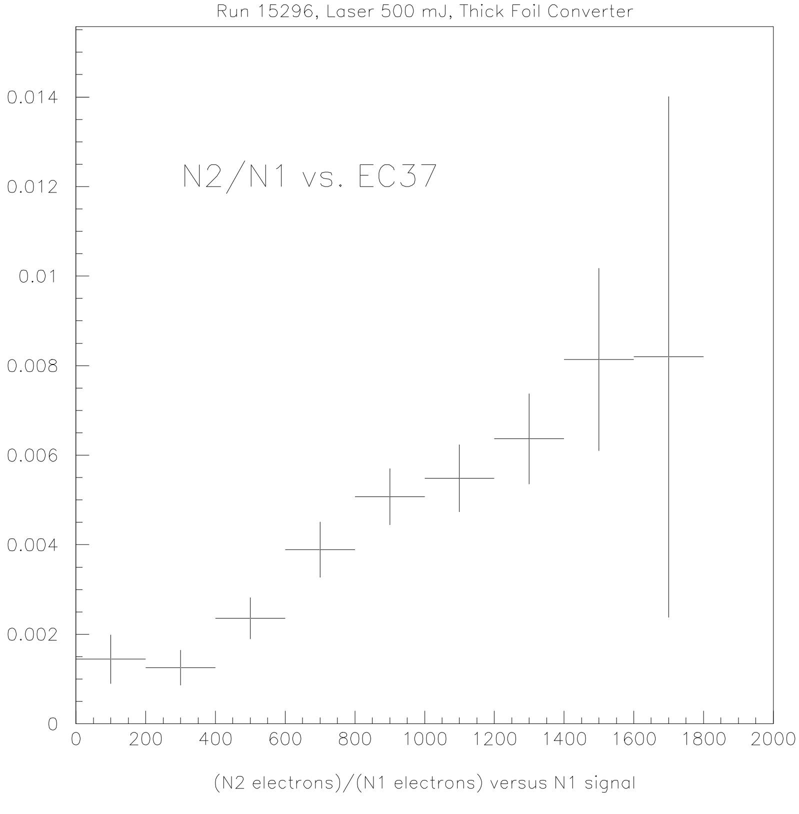
Bethe-Heitler (1934): A real photon combines with a virtual photon from the field of a nucleus to create an e^+e^- pair.



Nuclear electric fields are strong but not critical; Bethe-Heitler pair creation is well described in perturbation theory involving a single virtual photon.

e^+ and e^- from Converted Compton Photons



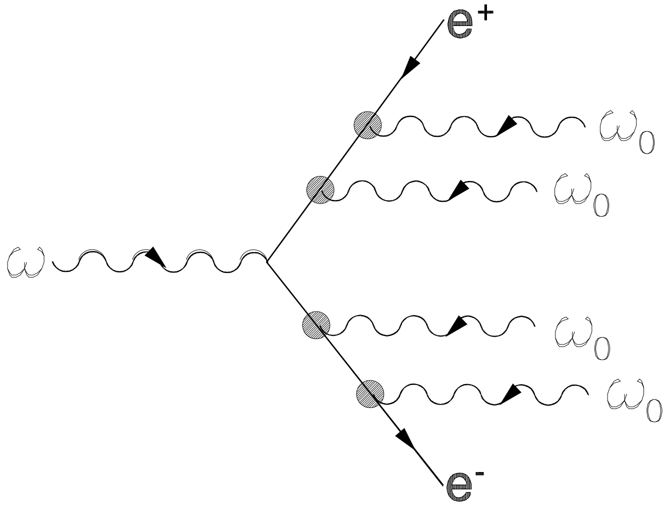


Threshold: $\hbar\omega_1\,\hbar\omega_2 = (mc^2)^2$

Cross section near threshold : $\sigma_{\text{B-W}} \approx \pi r_e^2 \sqrt{1 - \frac{m^2c^4}{\hbar\omega_1\,\hbar\omega_2}}.$

Pair Creation by Light

Two step process: $e + \omega_0 \to e' + \omega$, then $\omega + n\omega_0 \to e^+e^-$.



Multiphoton pair creation is cross-channel process to nonlinear Compton scattering.

$\Rightarrow$ Similar theories [sums of Bessel functions whose arguments depend on η^2].

$\Rightarrow$ Breit-Wheeler cross section in weak-field limit.

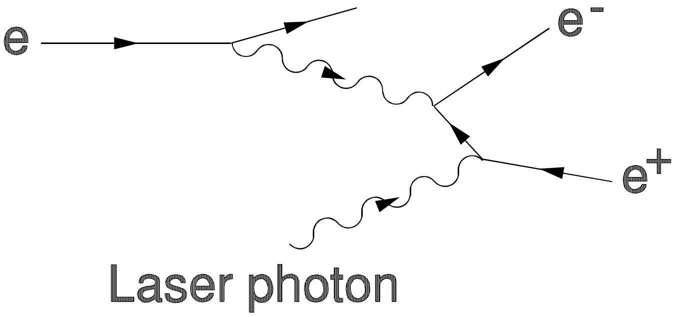
$\omega_{\max} \approx 29$ GeV for 46.6-GeV electrons + $(n = 1)$ green laser.

Then need at least $n = 4$ laser photons to produce a pair.

$\Leftrightarrow$ Below threshold for 2-photon pair creation.

Trident Production

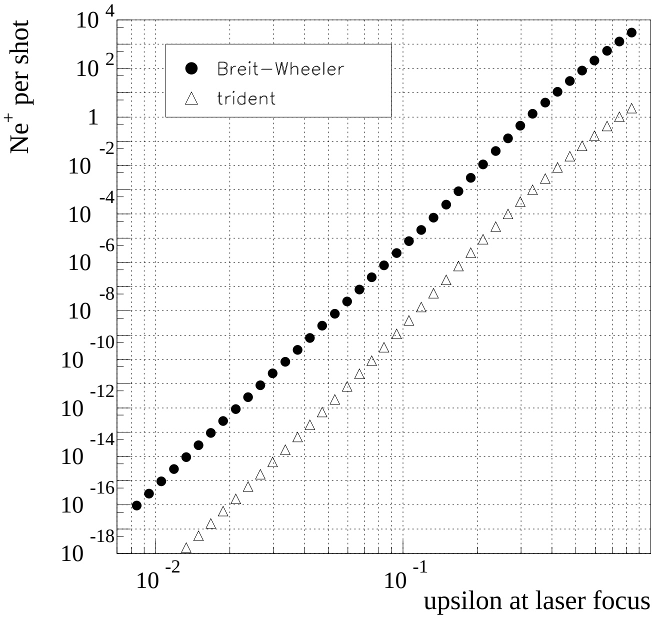
$$e + n\omega_0 \to e' e^+ e^-$$



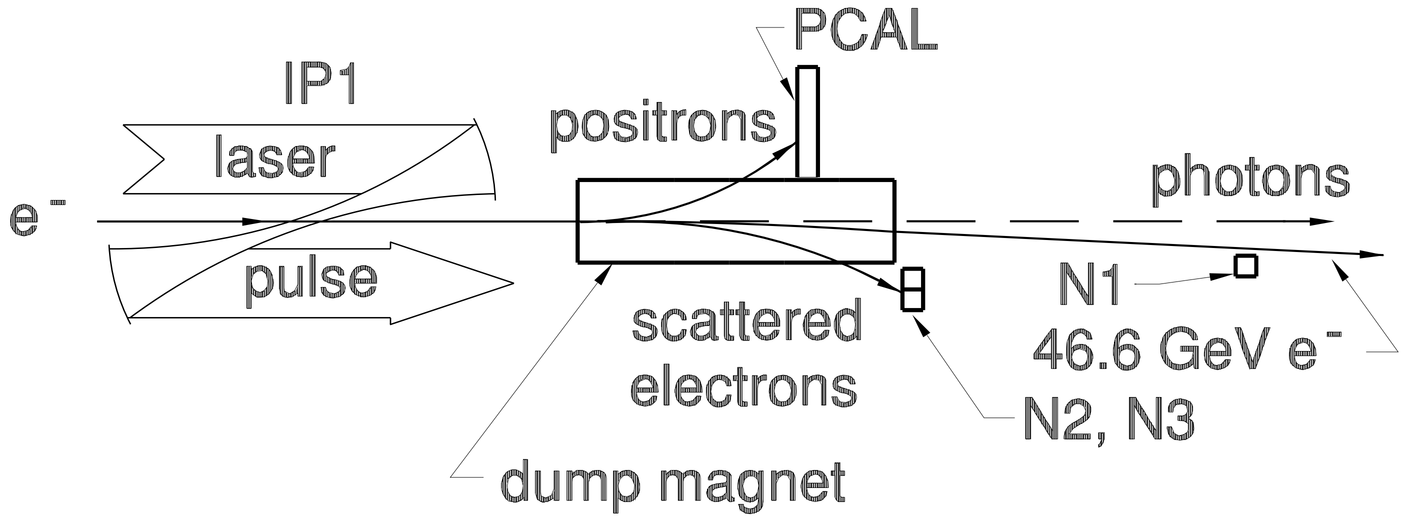
Background when scattering occurs in presence of electron beam.

Theory only approximate: Weizsäcker-Williams + multiphoton Breit-Wheeler.

Predicted to have rate only 1% that of the two-step process.



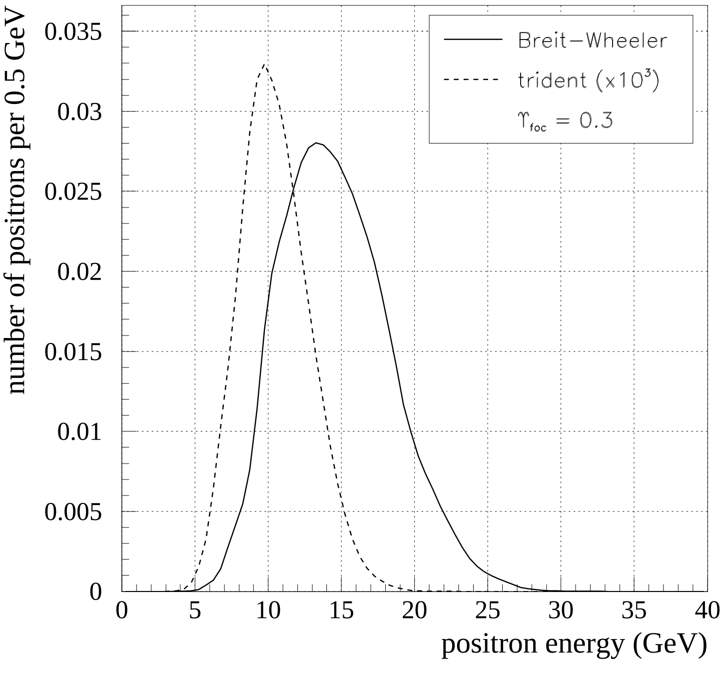
Positrons from e-Laser Interaction Region



$\approx 10^7$ electrons per laser shot from Compton scattering,

$\Rightarrow$ Only detect e^+ from e^+e^- pair.

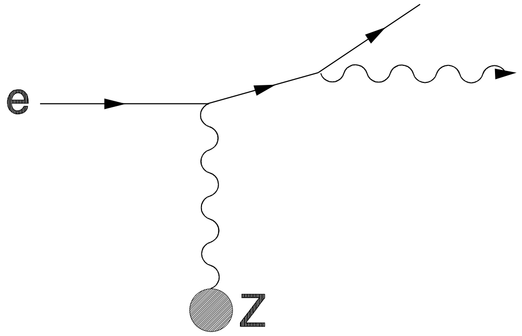
Predicted positron spectra:



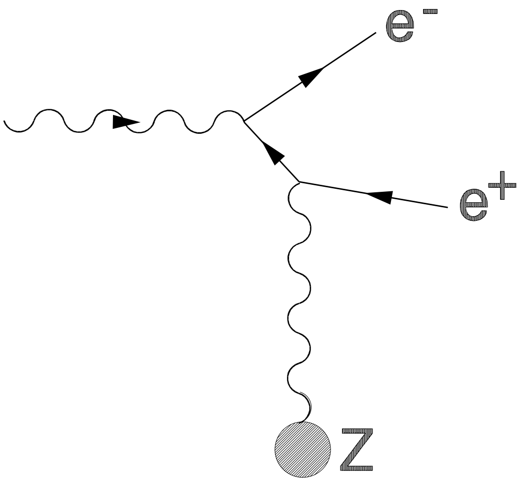
Laser-Off Positron Backgrounds

Laser-off positrons are from showers caused by electrons that have fallen out of the beam.

1. Bremsstrahlung.



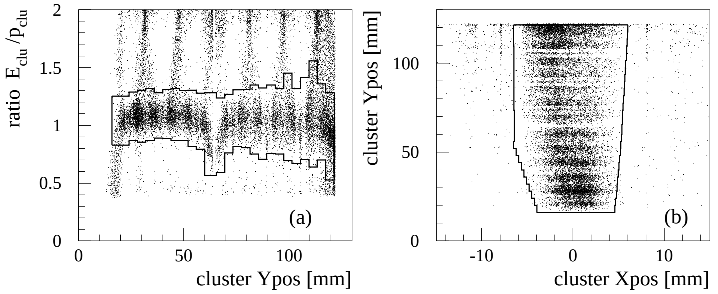
2. Bethe-Heitler pair creation.



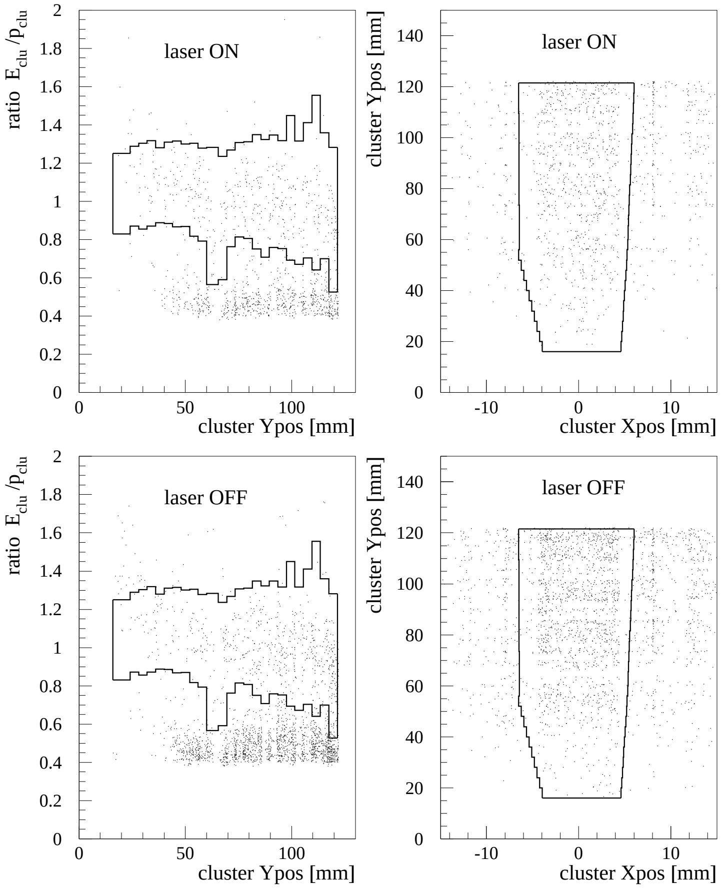
Study with data collected with laser off but electron beam on.

Signal Processing

1. 'Signal' positrons from a wire at IP1 (no laser)



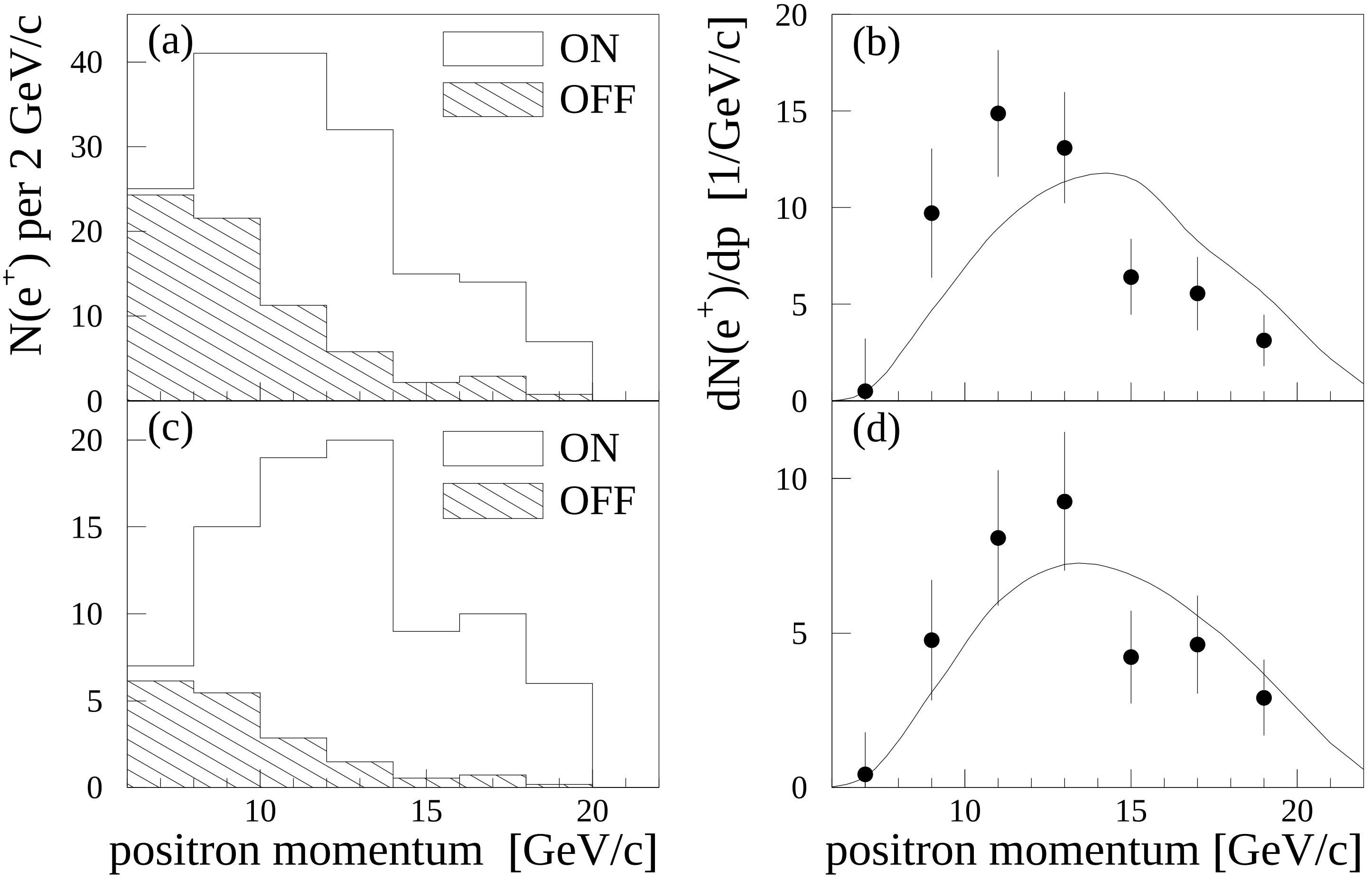
2. Define signal region for laser-on and -off data.



Evidence for Positron Production (August '96)

178 laser-on candidates - 0.175 × 398 laser-off candidates,

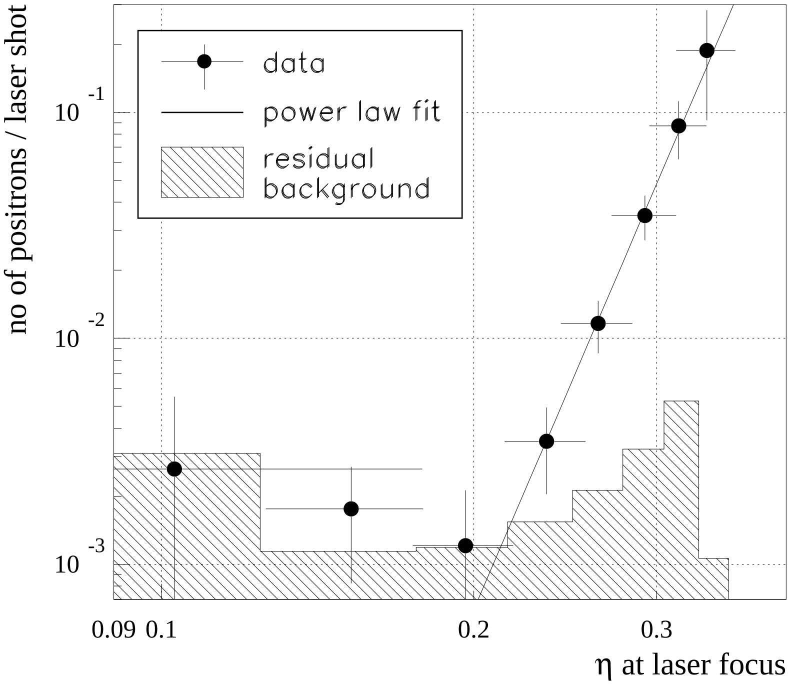
$\Rightarrow 106 \pm 14$ signal positrons (upper plots, no η cut)



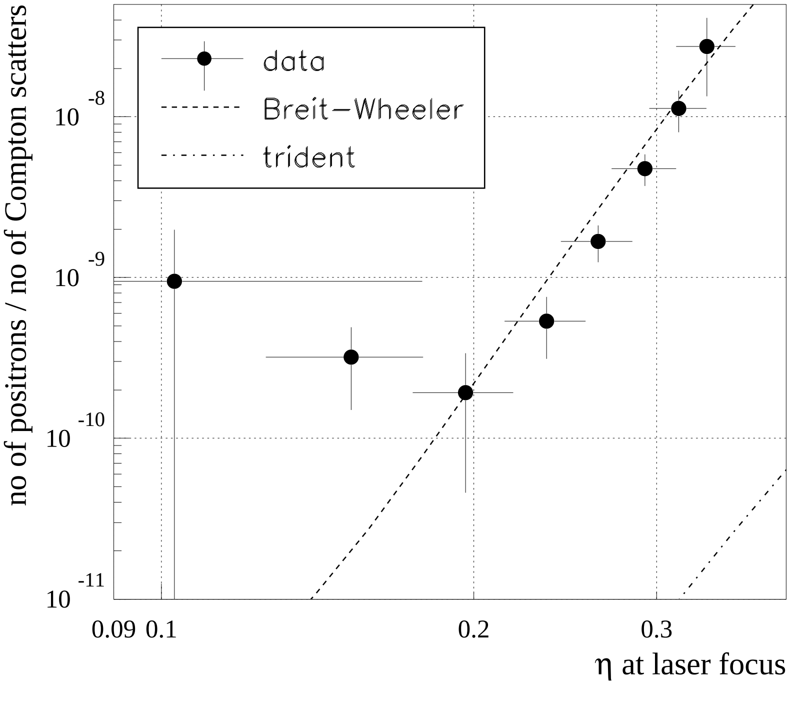
Lower plots: $\eta > 0.216 \Rightarrow 69 \pm 9$ signal positrons.

Positron Rate *vs.* η

Rate $\propto \eta^{2n}$ where $n = 5.1 \pm 0.2$ (stat.) ${}^{+0.5}_{-0.8}$ (syst.):



Normalized to Compton scattering rate:



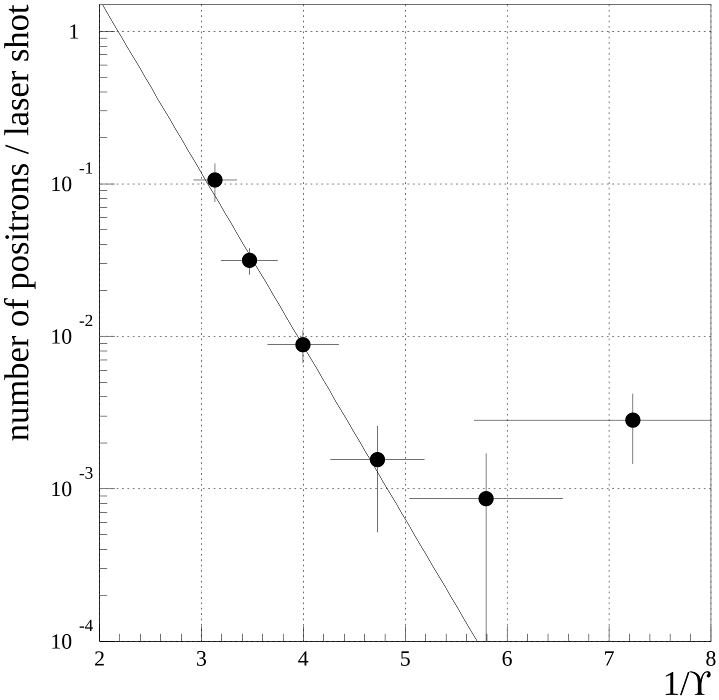
Strong Field Pair Creation as Barrier Penetration

For a virtual e^+e^- pair to materialize in a field E the electron and positron must separate by distance d sufficient to extract energy $2mc^2$ from the field:

$$eEd = 2mc^2.$$

The probability of a separation d arising as a quantum fluctuation is related to penetration through a barrier of thickness d:

$$P \propto \exp\left(-\frac{2d}{\lambda_C}\right) = \exp\left(-\frac{4m^2c^3}{e\hbar E}\right) = \exp\left(-\frac{4E_{\rm crit}}{E}\right) = \exp\left(-\frac{4}{\Upsilon}\right).$$



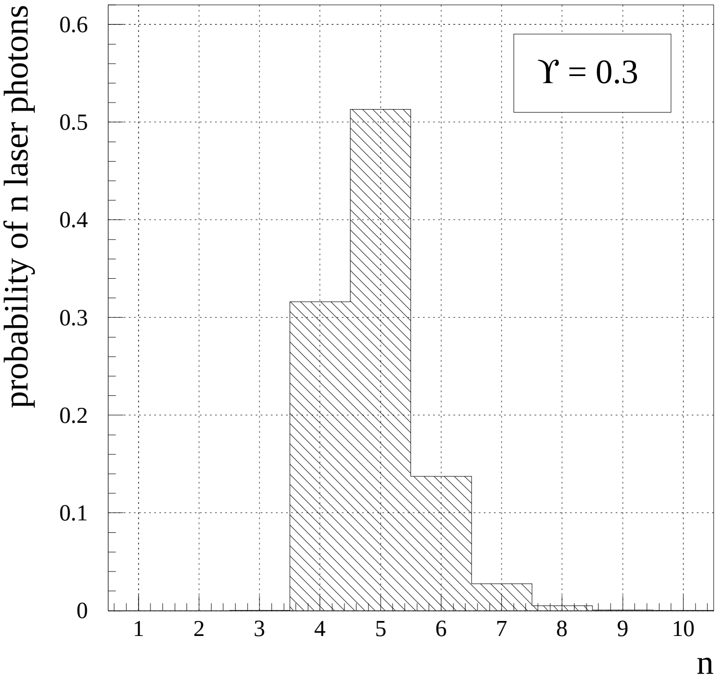
$$R_{e^+} \propto \exp[(-2.8 \pm 0.2\,(\text{stat.}) \pm 0.2\,(\text{syst.}))/\Upsilon].$$

Comments on Positron Observations

Signal rate ≈ 1 positron per 10 e-laser collisions at highest Υ.

The laser-induced positrons are $> 99\%$ from light-by-light scattering and $< 1\%$ from trident production.

In $n\omega_0 + \omega \to e^+e^-$ the average number n of laser photons is 5 (plus 1 more to produce the high-energy photon by Compton backscattering).



This is the first observation of positron production in light-by-light scattering with only real photons.

Reports in the Popular Media

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

Presto! Light Creates Matter, Science Now Online, Aug. 20, 1997.

Conjuring Matter from Light, Science magazine, 29 Aug. 1997, p. 1202.

Scientists Use Light to Create Matter, N.Y. Times, Sept. 16, 1997.

Real Photons Create Matter, AIP Physics News, Sept. 18, 1997.

Dalla luce e nata la materia, Corriere della Sera, Sept. 21, 1997.

Materie aus Licht, Neue Zuricher Zeitung, Sept. 26, 1997;
Materie aus Licht erschaffen, Oct. 1, 1997,

Light Work, New Scientist magazine, Sept. 27, 1997.

Amerikanische Physiker schufen erstmals Materie aus reinem Licht, Die Zeit, Oct. 17, 1997.

Matter Created from Pure Light, OE Reports, No. 167, Nov. 1997.

Boom! from Light comes Matter, Photonics Spectra online, Nov. 1997, also, p. 31 of Photonics Spectra, Nov. 1997.

Matter from Light, CERN Courier, Nov. 1997, p. 4.

$E = mc^2$, *Really*, Scientific American, Dec. 1997.

Let There Be Matter, Discover magazine, Dec. 1997, p. 40.

Researchers Create Matter from Light, Laser Focus World, Dec. 1997, p. 29.

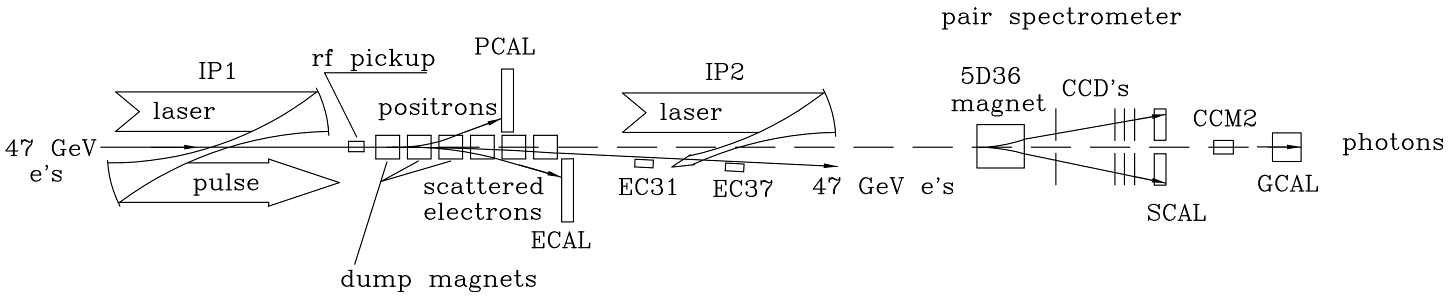
Out of Pure Light, Physicists Create Particles of Matter, SLAC Interaction Point magazine, Dec. 1997.

Let There Be Matter, a 2:04 min. interview by Karen Fox for the AIP Science Report

Gamma Rays Create Matter Just by Plowing into Laser Light, Physics Today, Feb. 1998, p. 17.

To Do: Basic Physics

1. Study the mass-shift effect in nonlinear Compton scattering.
   - Continue at SLAC, or use 50-Mev electrons and CO_2 laser at BNL.
2. Study pair creation in a pure light-by-light scattering situation:



   - No trident production.
   - Search for structure in the e^+e^- invariant-mass spectrum.
   - Upgrade laser to 10-Hz, 100-femtosecond pulses with $\Upsilon_{\rm max} \approx 5$.

To Do: Applied Physics

1. 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 $E^\star > E_{\rm crit}$.
   - Production with visible laser is optimal for $\sim$ 500 GeV electrons.

     [Or use a 50-nm FEL with 50-GeV electrons.]
2. High-energy e-γ and γ-γ colliders.
   - e-laser scattering can convert essentially all of an electron beam to a photon beam.
3. Picosecond/femtosecond pulsed-γ sources from Compton backscattering.

Vacuum Laser Acceleration?

- A Maxwellian view: acceleration (energy gain) of a charge is due to interference between the drive field and the "spontaneous radiation" of the charge.
- Ex: The energy gained by a electron as it moves across the gap of a capacitor is compensated by a loss of field energy due to the interference between the DC field and the dipole field of charge + image.
- Ex: The energy gained by an electron in an rf cavity is compensated by the energy of interference between the cavity field and transition radiation of the charge.
- In these examples, the energy gain is linear in the strength of the external field.
- ⇒ No vacuum linear acceleration (*i.e.*, linear in the laser field strength).
- Weak quadratic acceleration is possible in vacuum.
- http://puhep1.princeton.edu/˜mcdonald/accel/