New Accelerator Physics at New Accelerators

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June 15, 1992

Accelerator Physics:

The study of energy transfer between charged-particle beams and strong electromagnetic fields.

Heroic era of accelerator physics culminated in invention of the AGS and colliding beams in storage rings.

New Ideas: 1970-1990

1. Inverse Processes

Any reasonably coherent charged-particle radiation mechansim can be inverted to provide acceleration.

Present interest dates from the (re)invention of the free electron laser (Madey, 1970).

Inverse free-electron laser (laser + wiggler).

Inverse Čerenkov accelerator (laser + axicon focus + gas).

Inverse Smith-Purcell acclerator (laser + grating).

New Ideas: 1970-1990

2. Collective Effects

‘Smoke-ring’ accelerator.

Plasma beat-wave accelerator.

Wakefield accelerator.

New Ideas: 1970-1990

3. Power Sources

Lasers.

Laser-switched capacitors.

Gyroklystrons.

Relativistic klystrons.

Materials limitation: atoms ionize ‘instantly’ in fields of ~ 1 eV/Å $= 10$ GeV/m.

New Ideas: 1970-1990

4. Basic Interactions in Strong Fields

e or γ + laser: nonlinear Compton scattering, e^+e^- production.

e or γ + crystal: channeling, e^+e^- production.

e + colliding bunch: beamstrahlung, e^+e^- production.

High-energy/accelerator physics:

QED ($\gamma\gamma$) production of Higgs in heavy-ion collisions.

$\gamma + e \rightarrow W + \nu$ study of W magnetic moment.

$\gamma + \gamma \rightarrow X$ at high energies.

[Near-field gravitational radiation from bunched beams.]

Particles and Fields

1800's:

Experimentalists study fields (Ampere, Faraday...)

Theorists study particles [atoms] (Maxwell, Boltzmann...)

1900's:

Experimentalists study particles (Rutherford...)

Theoristis study fields (Einstein, Heisenberg, Weinberg...)

Particles are quanta of fields,

but in Standard Model, the Higgs **background field** is more important that the Higgs particle...

QED at Critical Field Strength
(SLAC Experiment 144)

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May 20, 1992

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:

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

- 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 $B_{\mathrm{crit}} = 4.4 \times 10^{13}$ Gauss.

- The maximum electric field experienced by an atomic electron near a nucleus of charge Z is

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

- During heavy-ion collisions where $Z_{\mathrm{total}} = 2Z > 1/\alpha$, 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.

DARMSTADT POSITRON PEAKS

IN U+Th COLLISIONS @ 6 MeV/c

NO QED EXPLANATION AS YET.

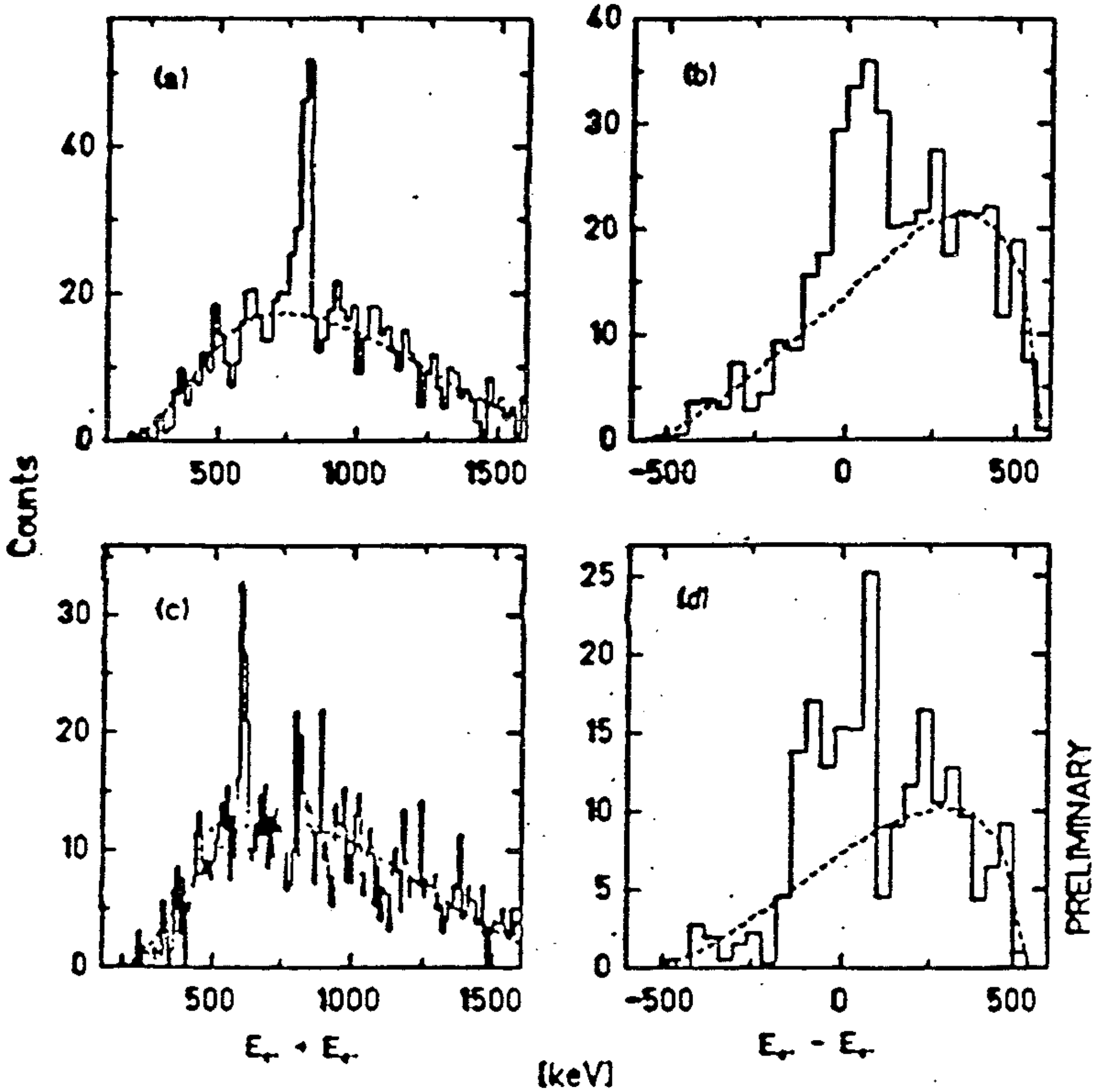

Figure 9: Results of a preliminary analysis of U + Th collisions near 5.87 MeV/c [4]. The $(E_{e^+} + E_{e^-})$ projections are for two subsets of data gated on beam energy, heavy-ion scattering angle and e^+ or e^- TOF chosen to enhance the prominent sum lines at ~ 810 keV and ~ 620 keV, respectively.

EXPTS BY JUDGE ET AL (1990) & HALLIN ET AL (1991) CLAIM NO EFFECT SEEN IN e^+e^- SCATTERING AT 1.8 MeV.

Phys. Lett B221 39 (1989)

IASSNS-HEP-88/50

November, 1988

A new embedding of quantum electrodynamics in a non-Abelian gauge structure

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ABSTRACT

Motivated by the anomalous electron-positron peaks observed at GSI, I propose a novel embedding of quantum electrodynamics in an $SU(2)$ non-Abelian gauge theory, inspired by quaternionic quantum mechanics. The construction eliminates the Dirac sea,. while keeping the electron-positron field as the only fermion field. The gauge partners of the photon are doubly charged gluons with the quantum numbers of di-fermions. The electron bare mass vanishes by virtue of the $SU(2)$ gauge symmetry. I postulate that a vacuum condensate breaks the $SU(2)$ down to $U(1)$, permitting the generation of a dynamical electron mass and leaving the photon as the only massless gauge gluon, and further conjecture that the GSI phenomenon arises from restoration of the unbroken vacuum in strong fields. The model avoids Witten's global $SU(2)$ anomaly when extended to contain the charged leptons in an even number of families.

To be submitted to Physics Letters.

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

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

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

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

  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/cm^2

  ($\Rightarrow \gtrsim 10^{27}$ photons/cm^3, $E_{\mathrm{lab}} = 7\times 10^{10}$ 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.

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

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

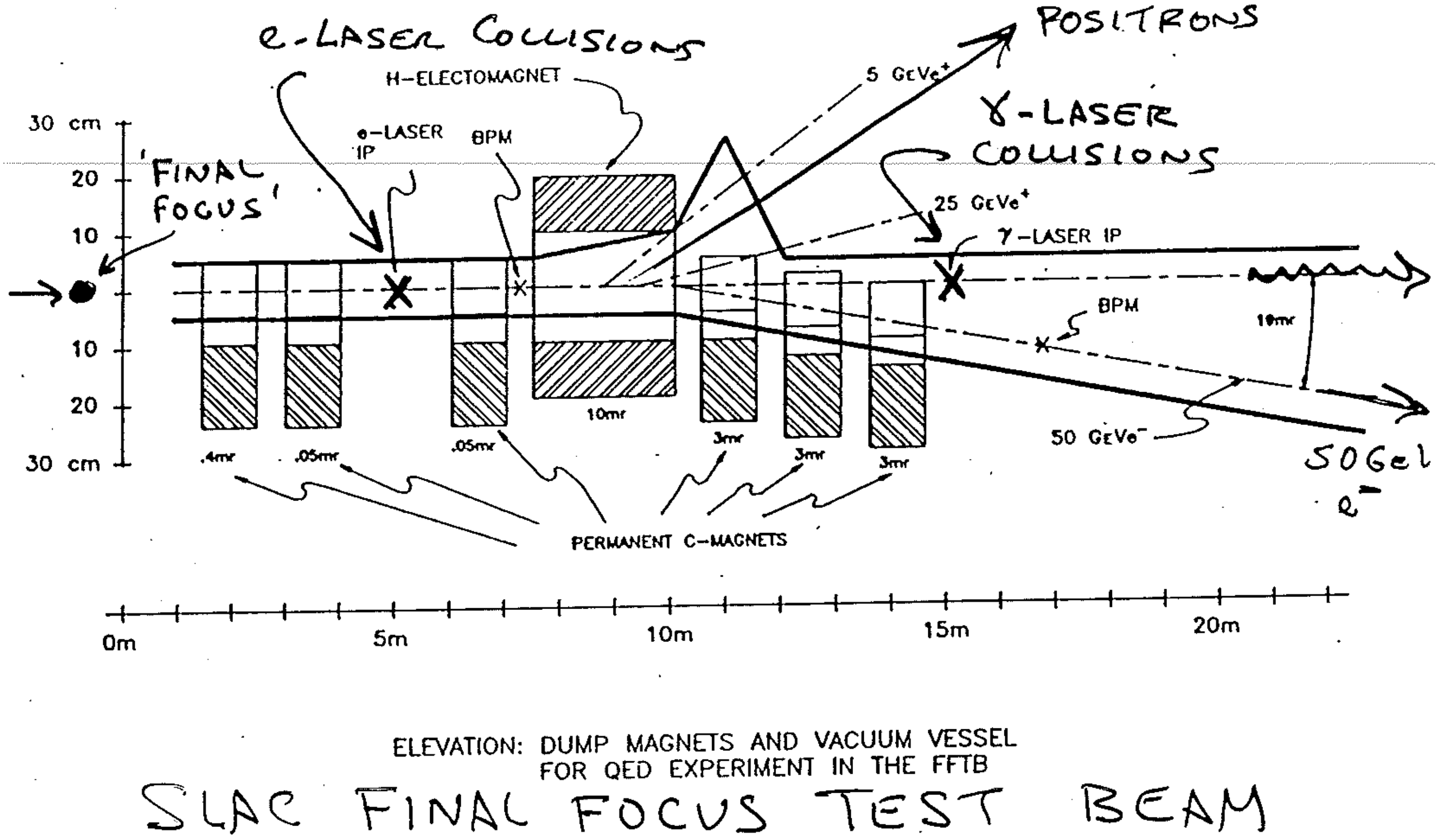


Figure 2: Proposed layout of the interaction region.

Table 1: Parameters of three beamline options for interaction point IP1 in the FFTB.

Parameter	FFTB Beam Tune		
	Nominal Low-β	Parallel	Point Focus
$\sigma_{x/y}$ (μm) at the FF	0.95/0.055	0.95/0.055	30/20
$\sigma_{x,\max}$ (μm) after FF (quad QP3)	2730	2700	121
$\sigma_{y,\max}$ (μm) after FF (quad QP5)	2883	2479	65
$\sigma_{x/y}$ (μm) at IP1	2314/1601	2479/1815	75/57
$\sigma_{x'/y'}$ (μrad) at IP1	54/88	1.0/0.5	3.2/6.6

E-144 Physics Program

1. 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.
2. Beamstrahlung
   - $E \approx 10^{11}$ 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.
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.'
- Multiple Compton scattering 'cools' the positrons.
- When $E \gtrsim E_{\mathrm{crit}}$ the laser beam is effectively more than a radiation length.
- Production is optimal for $\sim$ 150 GeV electrons.

Conditional Approval

"...demonstrate in the laboratory a laser power density adequate to achieve interesting values of the parameter Υ ($= 1.0 \pm 0.3$) in order to obtain final approval."

$$\Upsilon \equiv \frac{E^\star}{E_{\rm crit}} = \frac{2\gamma E_{\rm lab}}{E_{\rm crit}} = \sqrt{\frac{I}{1.4 \times 10^{19}\ {\rm Watts/cm^2}}}$$

for a 46-GeV electron beam.

Laser Progress to Date – June 1992

(D. Meyerhofer, *U. Rochester*)

- Laser system performs at diffraction limit.
- Pulse energy . . . . 2 J
- Pulse FWHM . . . . 1.4 ps
- Peak power . . . . 1.4 teraWatts
- Focal-spot area . . . . 26 μm^2
- Peak intensity . . . . 6×10^{18} Watts/cm^2
- Υ 0.7

FREE ELECTRONS IN A PLANE WAVE

1. TRANSVERSE VELOCITY, $V_\perp$

$$F = ma \Rightarrow eE = m\omega V_\perp \Rightarrow \frac{V_\perp}{c} = \frac{eE}{m\omega c} \equiv \eta$$

SO $V_\perp \rightarrow c$ AS $\eta \rightarrow 1$

NOTE: $\eta = \frac{1}{2\pi} \frac{eE\lambda}{mc^2} = \frac{1}{2\pi} \cdot \frac{\text{VOLTAGE DROP PER WAVELENGTH}}{\text{ELECTRON REST ENERGY}}$

2. EFFECTIVE MASS, $\bar{m}$

DUE TO THE $V_\perp$, THE ELECTRON HAS MASS

$$\gamma m = \frac{m}{\sqrt{1 - V_\perp^2/c^2}}$$

THEN REALLY $F = \gamma m a$ SO $\frac{V_\perp}{c} = \frac{\eta}{\gamma}$

$$\Rightarrow \gamma = \sqrt{1+\eta^2} \qquad \frac{V_\perp}{c} = \frac{\eta}{\sqrt{1+\eta^2}}$$

WE SAY $\bar{m} \equiv \gamma m = m\sqrt{1+\eta^2}$ = EFFECTIVE MASS OF THE ELECTRON IN THE WAVE

HIGHER HARMONIC RADIATION

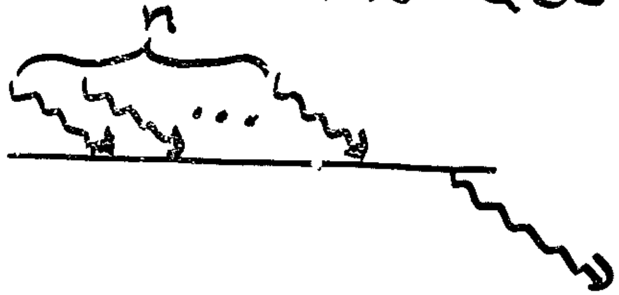
WHEN $v \to c$, HIGHER MULTIPOLE RADIATION BECOMES IMPORTANT

$$\frac{dU_n}{dt} \sim \left(\frac{v}{c}\right)^{2n-2} \cdot \text{DIPOLE RADIATION}$$

$\therefore$ CROSS SECTION FOR SCATTERING TO FINAL PHOTON OF FREQUENCY $n\omega$ IS

$$\sigma_n \sim r_0^2 (\eta^2)^{n-1} \qquad (\eta \lesssim 1)$$

COMPARE WITH 'NAIVE' QED ANALYSIS



$$\sigma \sim \frac{\alpha^{n+1}}{m^2} \sim r_0^2 \alpha^{n-1}$$

FOR $\eta \gg 1$ WE HAVE A KIND OF SYNCHROTRON RADIATION

$\Rightarrow$ MAX. INTENSITY AT HARMONIC

$$n\omega \sim \gamma^3 \omega \sim \eta^3 \omega$$

CLOSE ANALOGY TO WIGGLER RADIATION (SCATTERING OF VIRTUAL PHOTONS OF THE MAGNET)

– HIGHER HARMONICS WHEN $\eta = \frac{eB}{mc^2} \frac{\lambda_0}{2\pi} \gtrsim 1$

Nonlinear Compton Scattering

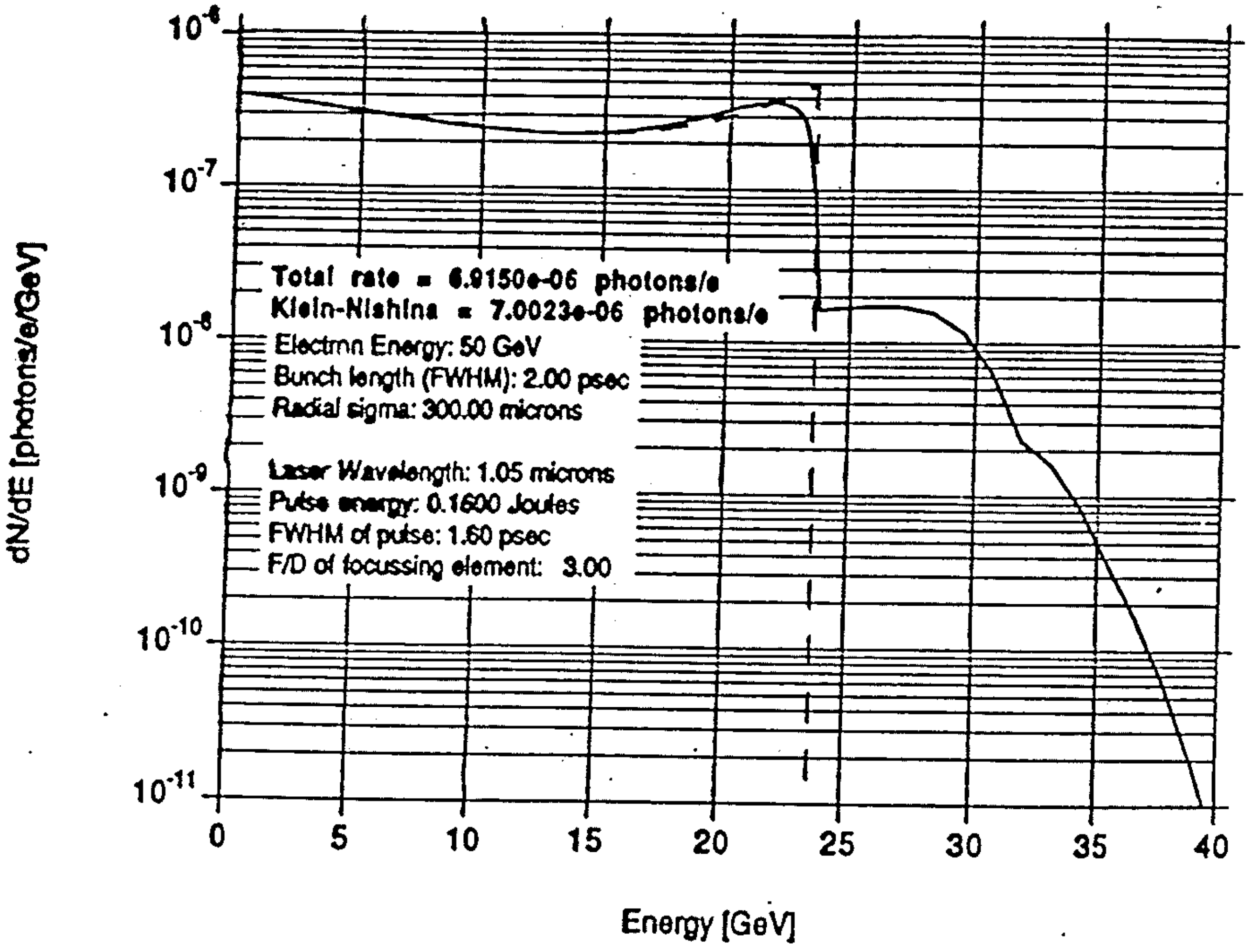
$$n\,\omega_0 + e \longrightarrow e' + \gamma$$

$$\frac{d\sigma_n}{dy} = \frac{2\pi r_0^2}{x}\left\{-\frac{4}{\eta^2}\,J_n^2(z) + \left(2 + \frac{u^2}{1+u}\right)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right]\right\} \qquad (19)$$

In the above equations the index n labels the number of photons absorbed from the field of the laser and the parameters u, z are defined through

$$u \simeq \frac{y}{1-y}, \qquad y_{\rm max} = \frac{nx}{1+\eta^2+nx}, \qquad z = \eta\sqrt{1+\eta^2}\,\frac{2}{x}\sqrt{u\left(\frac{nx}{1+\eta^2} - u\right)}. \qquad (20)$$

$$x = 4\omega_0 E_e/m^2, \qquad y = \frac{\omega}{E_e} \le y_{max} = \frac{x}{1+x}.$$



Total rate = 6.9150e-06 photons/e
Klein-Nishina = 7.0023e-06 photons/e
Electron Energy: 50 GeV
Bunch length (FWHM): 2.00 psec
Radial sigma: 300.00 microns

Laser Wavelength: 1.05 microns
Pulse energy: 0.1600 Joules
FWHM of pulse: 1.60 psec
F/D of focussing element: 3.00

Figure 4: Differential cross section for multiphoton scattering of a $\lambda =$ 1,054 nm laser pulse from 50-GeV electrons.

The Multiphoton Breit-Wheeler Process

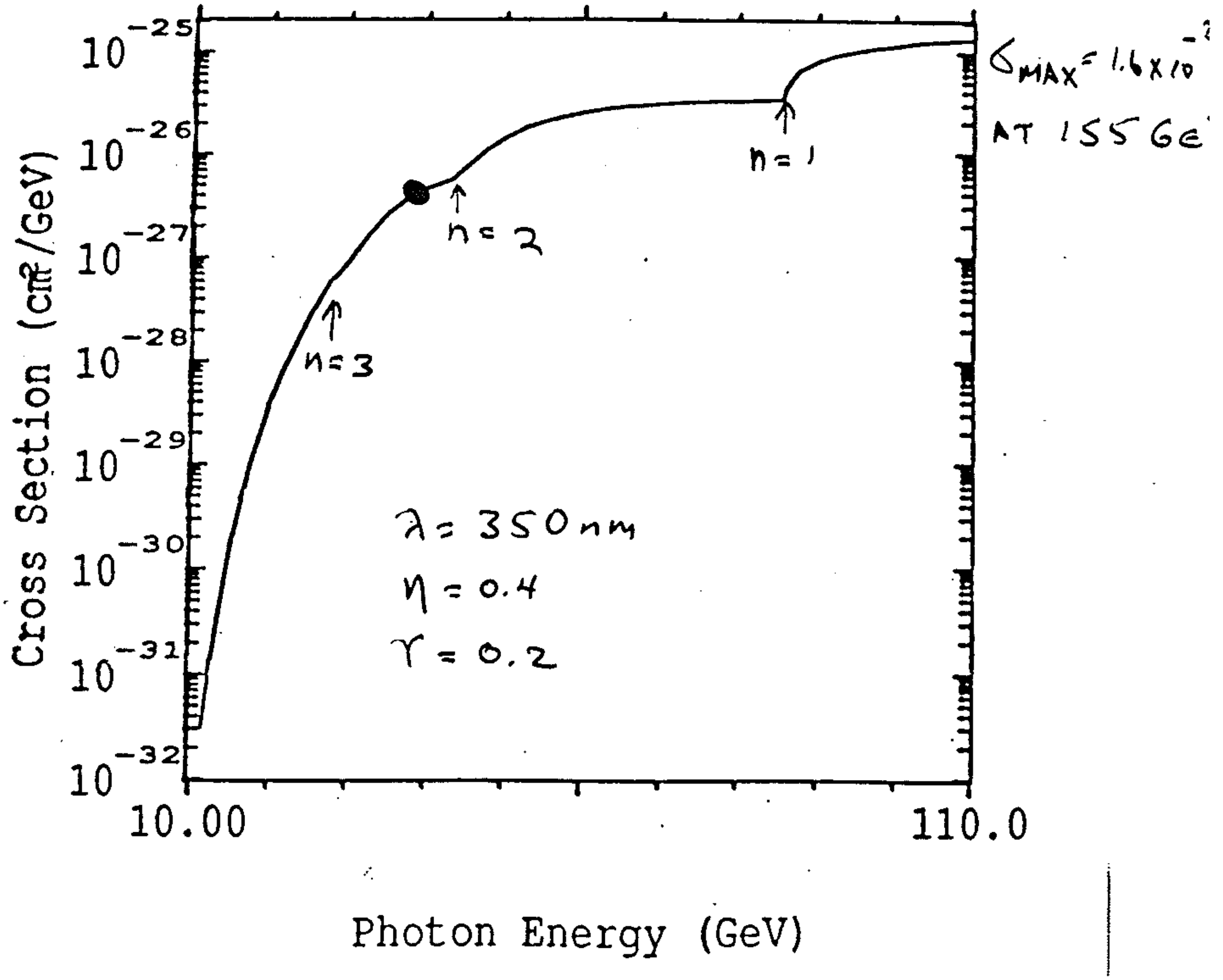
$$n\omega_0 + \omega \to e^+e^-$$

$$\frac{d\sigma_n}{dy} = \frac{2\pi r_0^2}{x} \left\{ \frac{4}{\eta^2} J_n(z) + (u-2)\left[J_{n-1}^2(z) + J_{n+1}^2(z) - 2J_n^2(z)\right] \right\}$$

where (for $n\omega_0 \ll \omega$)

$$x = \frac{4\omega_0\omega}{m^2}, \qquad y = \frac{E_e}{\omega}, \qquad y_{\mathrm{max,min}} = \frac{1}{2} \pm \sqrt{\frac{1}{4} - \frac{1+\eta^2}{nx}}, \qquad u = \frac{1}{y(1-y)},$$

$$z = \eta\sqrt{1+\eta^2}\,\frac{2}{x}\sqrt{u\left(\frac{nx}{1+\eta^2} - u\right)}.$$



The e^+e^- Mass Spectrum in High Fields

INSIDE LASER FIELD $\bar{M}^2_{e^+e^-} = 4n\omega_0\omega$

BUT AS e^+ & e^- LEAVE FIELD, THEIR MASSES DROP FROM $\bar{m} = m\sqrt{1+\eta^2}$ TO m

$\Rightarrow$ $M_{e^+e^-}$ IN FIELD-FREE REGION $< \bar{M}_{e^+e^-}$

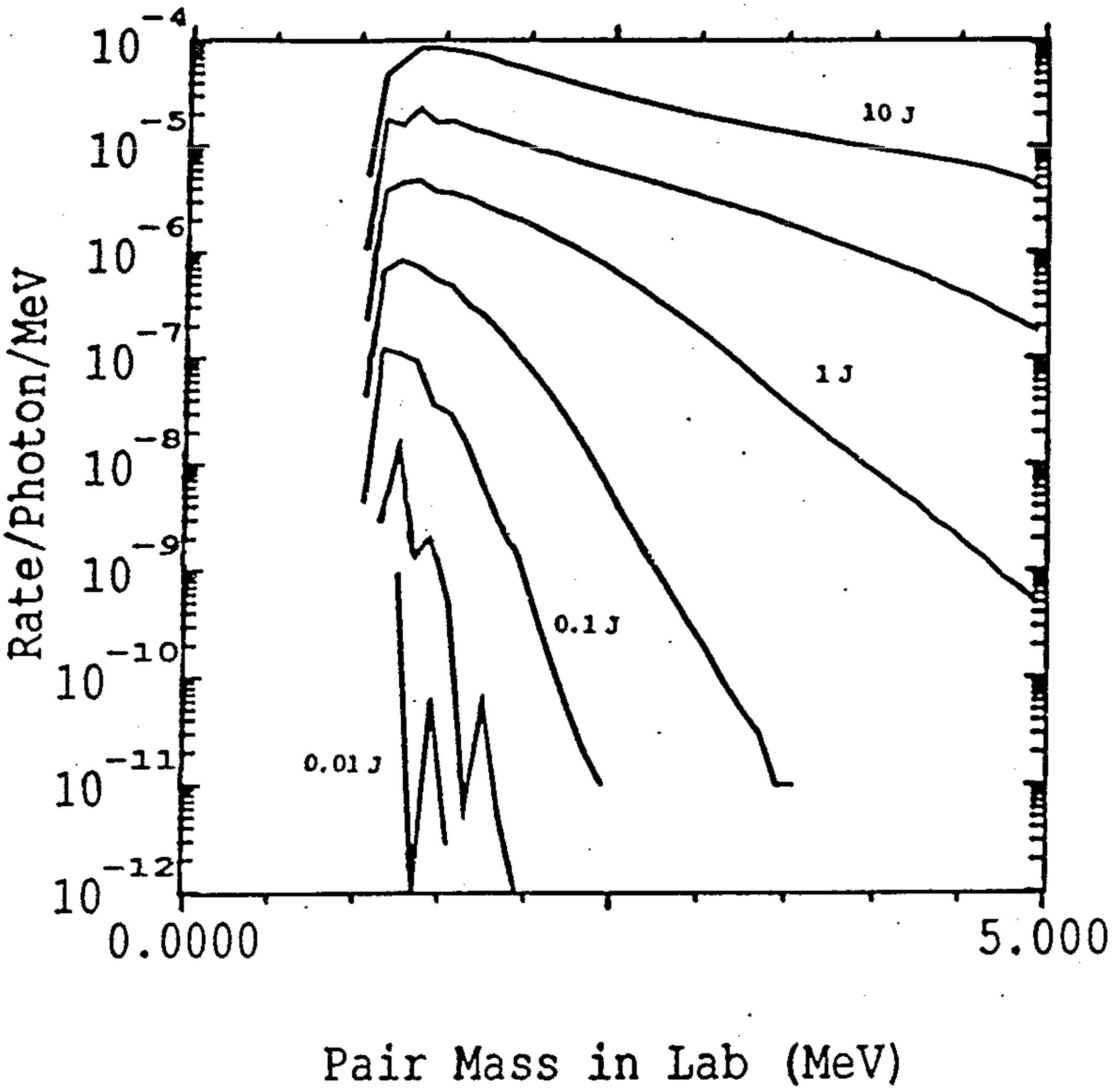


Figure 12: The calculated rate of pair production as a function of the pair mass as measured in the laboratory, for the conditions of Fig. 10. The intrinsic line spectrum is smeared into a continuum as the electrons leave the strong-field region.

Long-Lived e^+e^- State?

Darmstadt peaks could be due to an e^+e^- state with lifetime as long as 1 ns.

E-144 will have reduced sensitivity when $\gamma c\tau > 100$ m, *i.e.*, for $\tau > 10^{-11}$ s.

A sweeping magnet after the γ-laser interaction point would eliminate the 'background' from prompt e^+e^- pairs.

Rates

- When $E \approx E_{\text{crit}}$ all cross sections of interest are 10^{-26}-10^{-27} cm^2.
- With 1 laser pulse per second, and 10^{10} e's per bunch, typically have 0.1-10 events second.

Backgrounds

- The QED processes we study are the dominant ones in e-laser collisions.
- Detector backgrounds from synchrotron radiation and E-M showers must be suppressed by masking and collimation.

Responsibilities

- e-beam .... SLAC
  - e-beam diagnostics
  - RF timing
  - Laser & spectrometer buildings
- Pair Spectrometer .... Princeton
  - γ-beam diagnostics
- Positron spectrometer .... SLAC
- Laser systems .... Rochester
  - Laser-beam transport and diagnostics

E-144 Schedule

- Spring-Fall '92: build FFTB, modify beam dump, construct laser building.

  Rochester group begins residence at SLAC.

- Winter-Spring '93: Commission FFTB, begin accelerator physics program, build laser beam transport.

- Summer '93: Build extension to FFTB for pair spectrometer, first *e*-laser collisions (with detectors inside radiation area).

  Princeton group begins residence at SLAC.

- Fall '93: Initial running of E-144 with γ's from nonlinear Compton scattering into pair spectrometer.