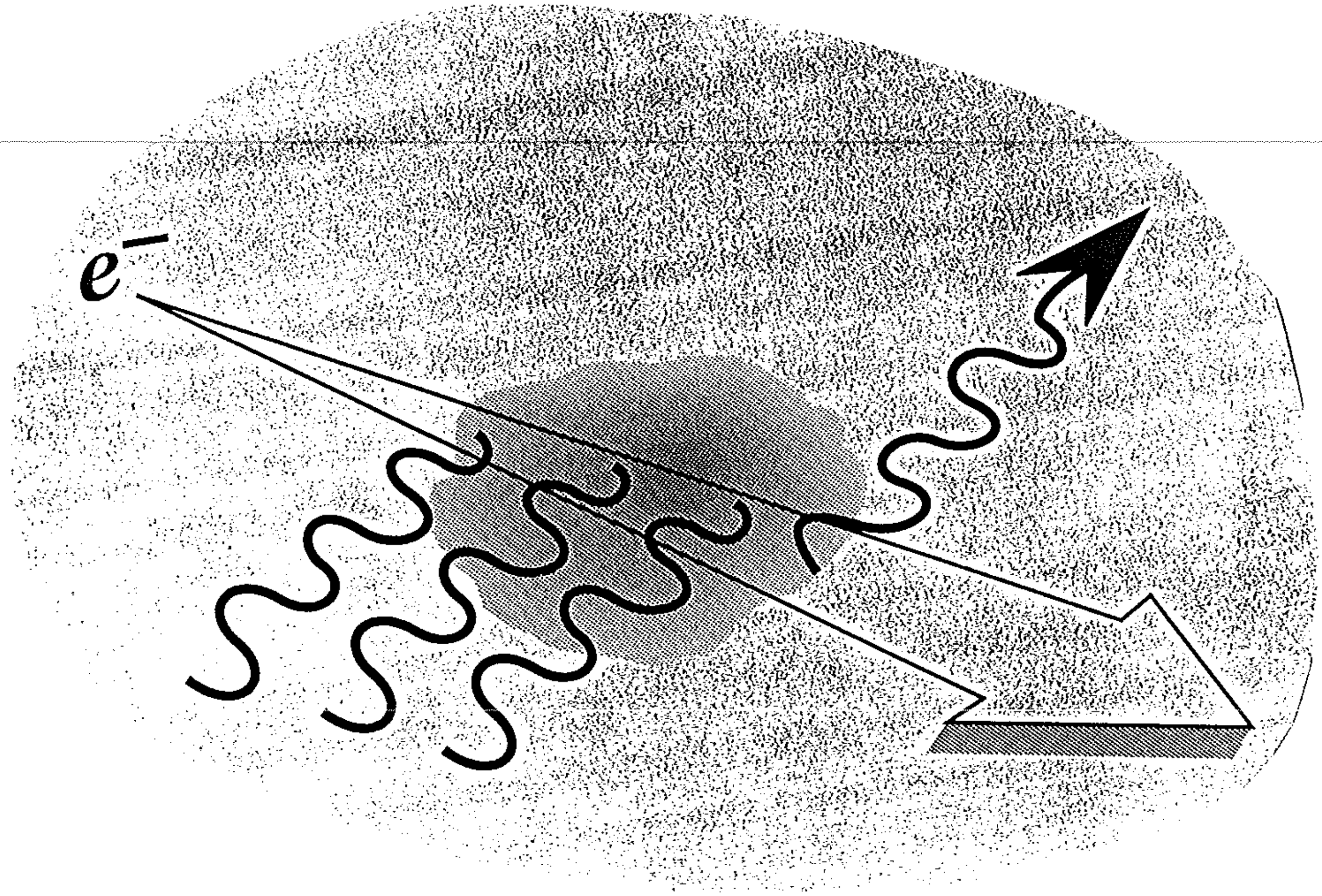

Readiness Review
Experiment 144
QED at Critical Field Strength

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Princeton U.

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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

Goals

- 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 $eE/m\omega c \geq 1$.

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 $B_{\text{crit}} = 4.4 \times 10^{13}$ 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

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

- 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 1.43×10^{19} Watts/cm^2 ($\Rightarrow \gtrsim 10^{27}$ photons/cm^3, $E_{\rm lab} = 7 \times 10^{10}$ 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.

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.
   - $e + n\omega \to e'e^+e^-$ is analog of important pair-production backgrounds in future colliders.

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

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

4. The Multiphoton Breit-Wheeler Reaction:

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

- 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 $\sim$ 500 GeV electrons.

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

6. e-laser technolgy 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.

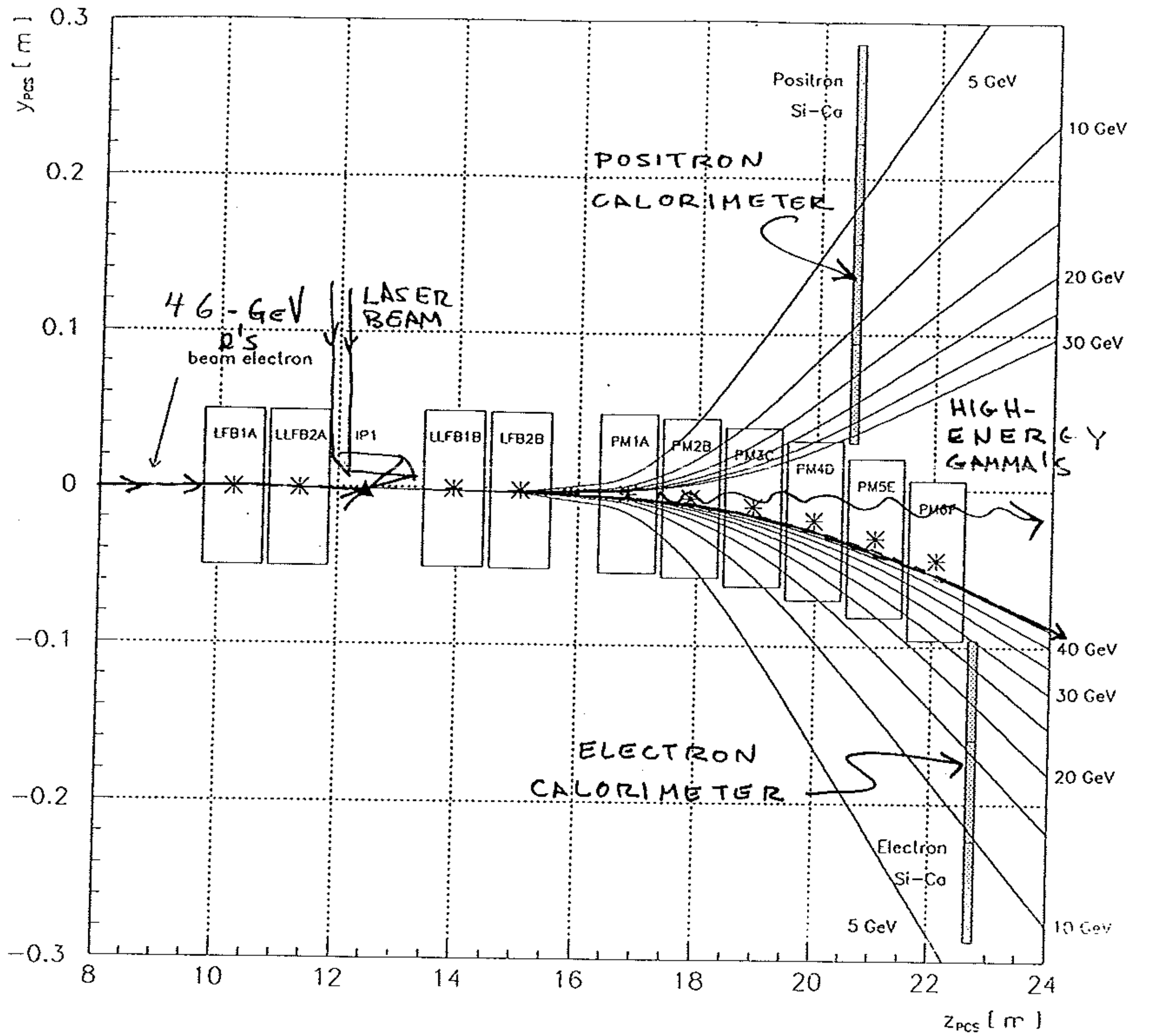
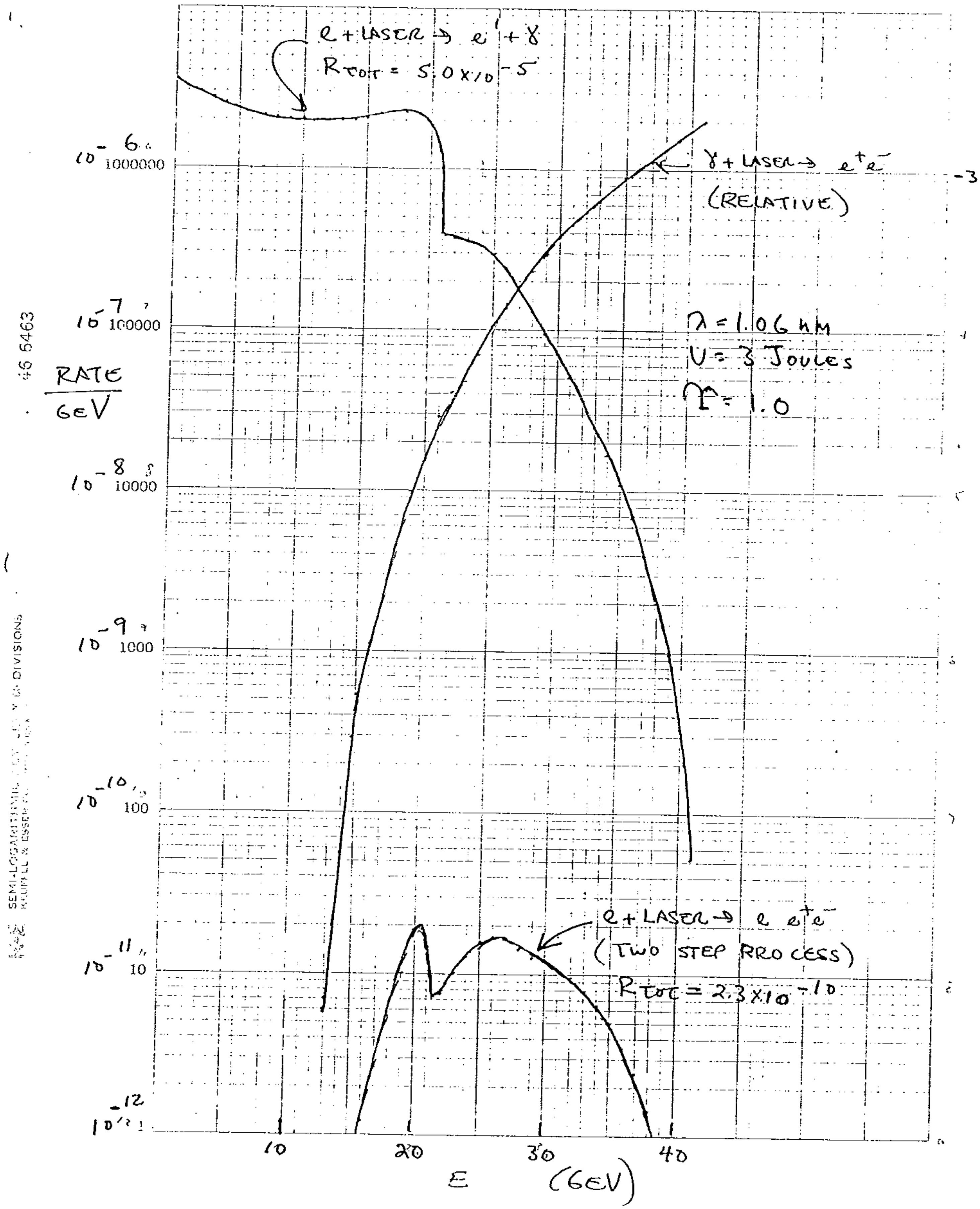


Figure 4.4: Trajectories of electrons and positrons through the FFTB dump magnets.

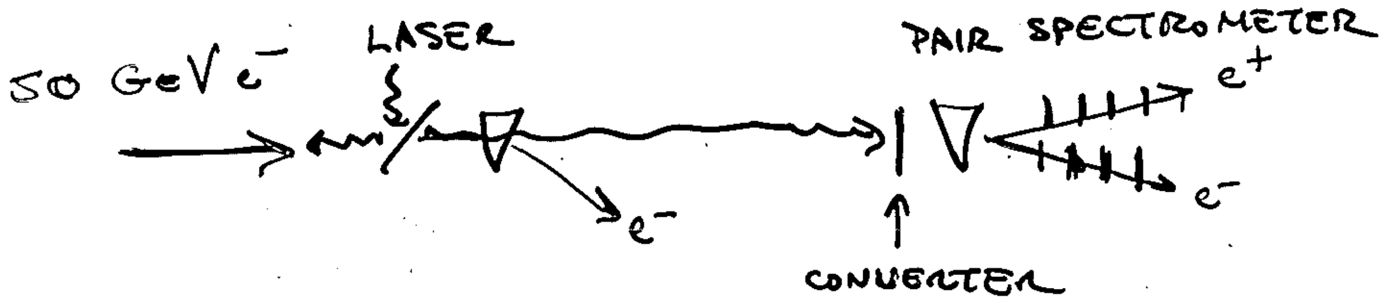
Beamstrahlung Signals



Strong-field QED Experiments

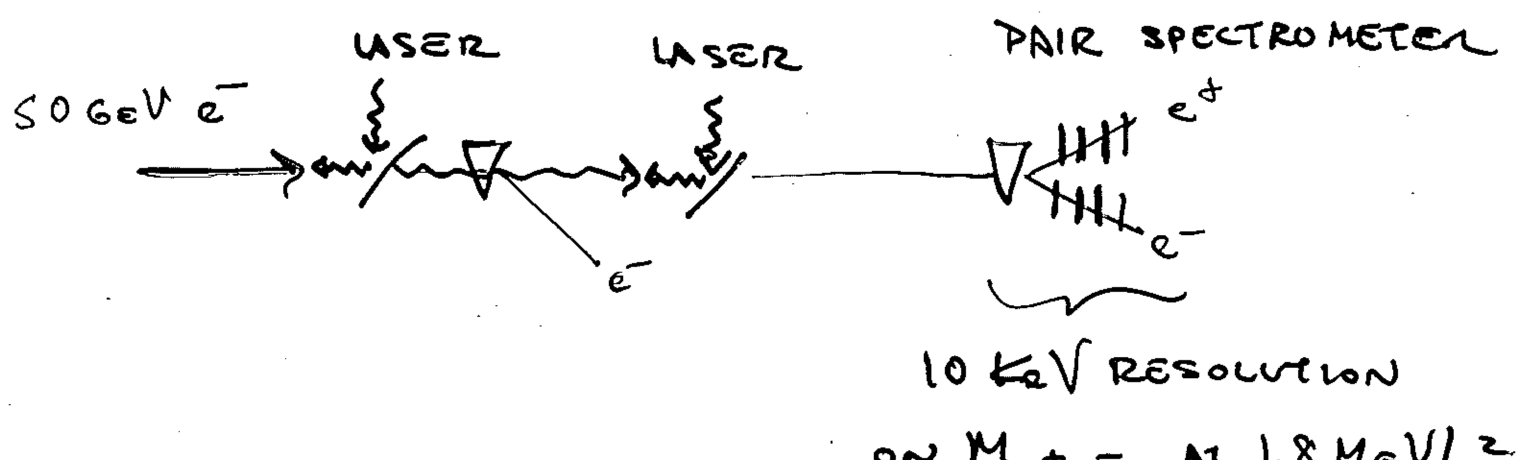
1. Nonlinear Compton Scattering

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

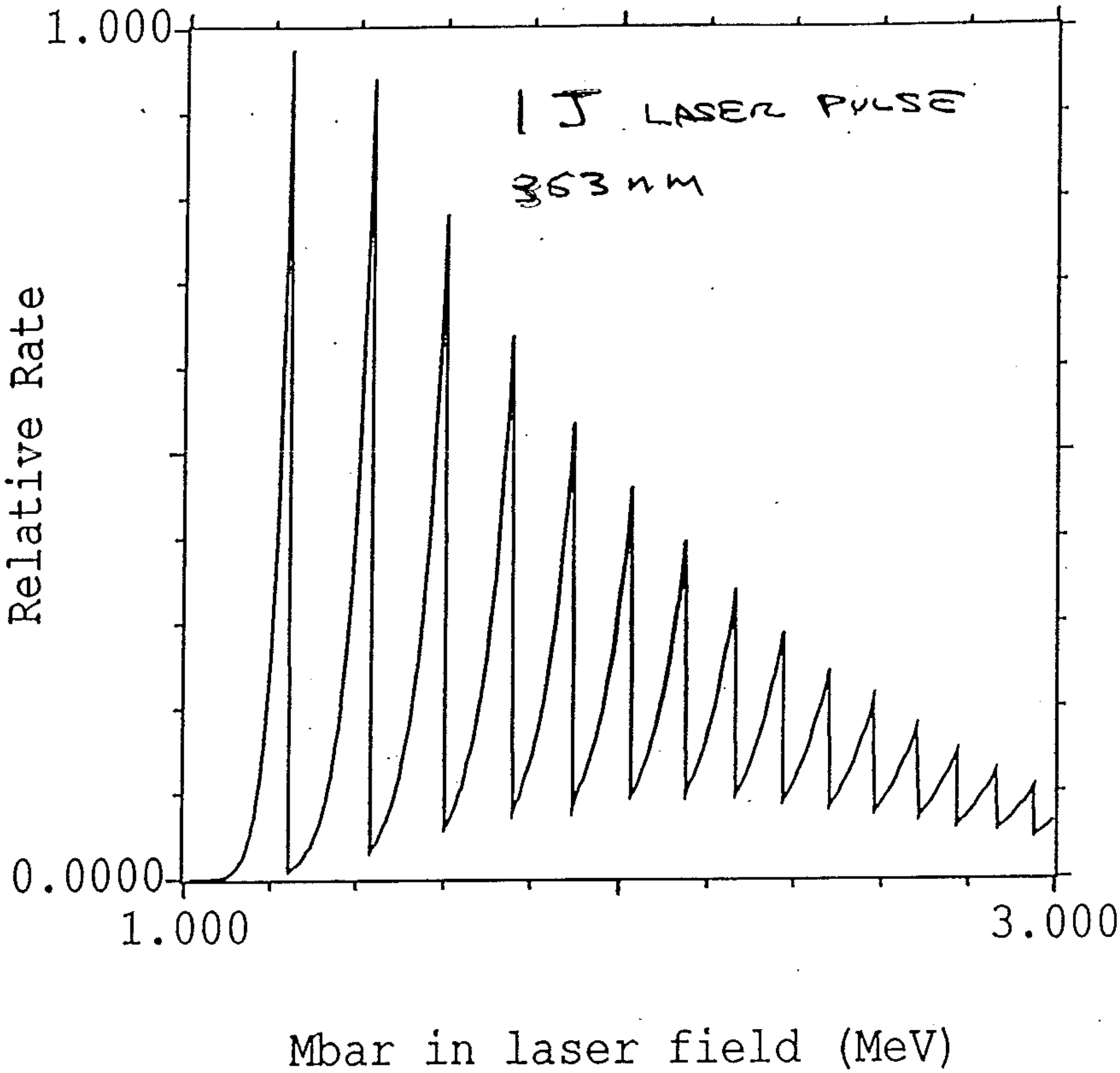


2. Pair Creation by Light

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



Expected e^+e^- Mass Spectrum



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.

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

Mar. 1994: Readiness Review

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

Readiness Review Presentations

Status of the laser system .... D. Meyerhofer

Optical transport and *e*-laser synchronization .. C. Bamber

Polarization Measurment .... M. Woods

Primary- and scattered-electron optics ... G. Horton-Smith

Silicon Calorimeters .... W. Bugg

Data-acquisition network .... C. Bula

CCD spectrometer .... E. Prebys

Schedules .... A. Melissinos/D. Burke