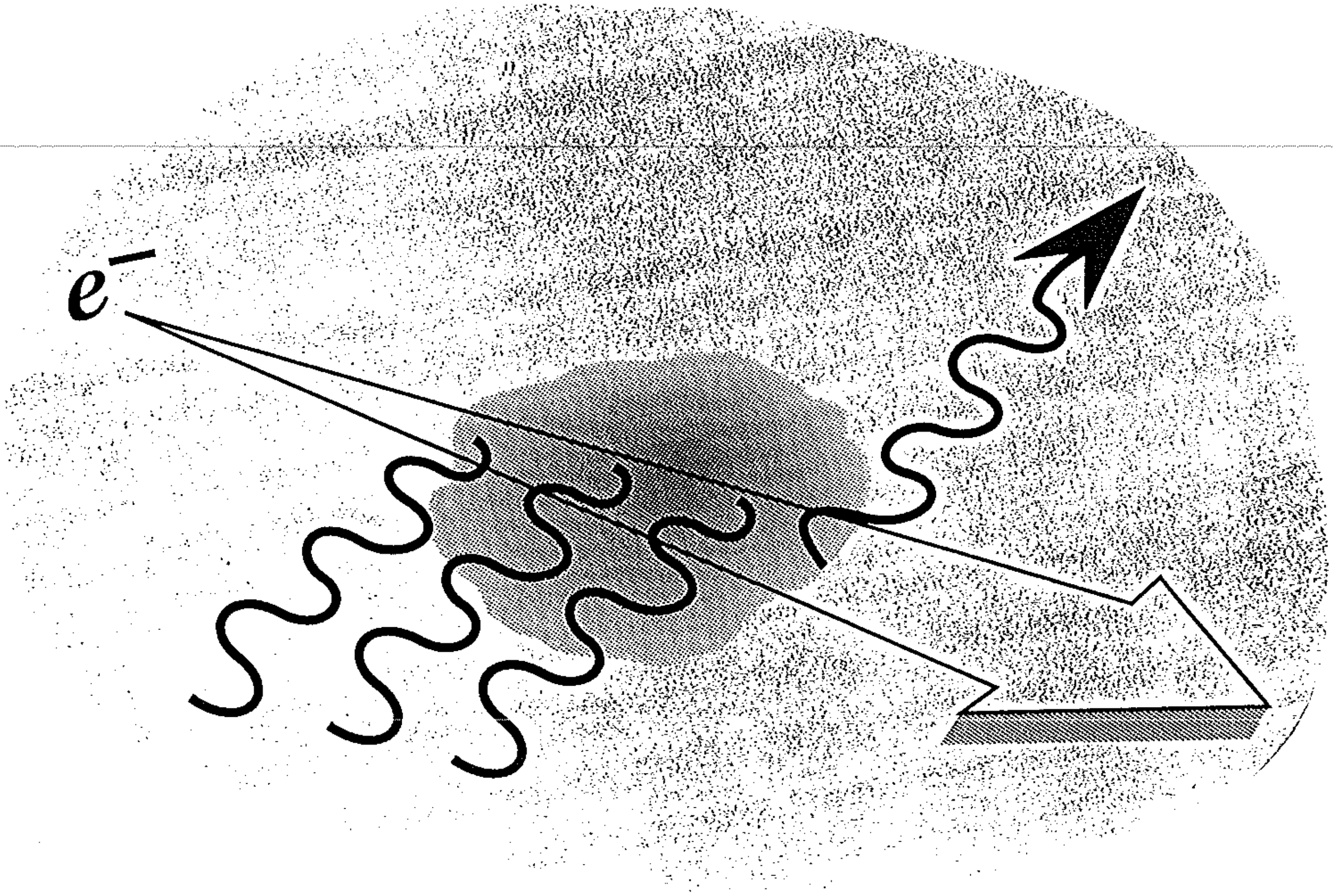

QED at Critical Field Strength
(SLAC Experiment 144)

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Princeton U.

May 3, 1993

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.

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)

E-144 Physics Program

1. 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.
   - $e{+}n\omega \to e'e^+e^-$ is analog of important pair-production backgrounds in future colliders.
2. Nonlinear Compton Scattering: $e + n\omega \to e' + \gamma'$
   - Semiclassical theory ⇒ data will diagnose laser intensity.
   - Provides γ beam for light-by-light scattering.
3. The Multiphoton Breit-Wheeler Reaction:

   $\gamma + n\omega \to e^+e^-$
   - Might show anomalous structure in e^+e^- invariant mass when $E > E_{\text{crit}}$.

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.’
- 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.]

5. e-laser technolgy of E-144 is precursor of e-γ and γ-γ colliders.

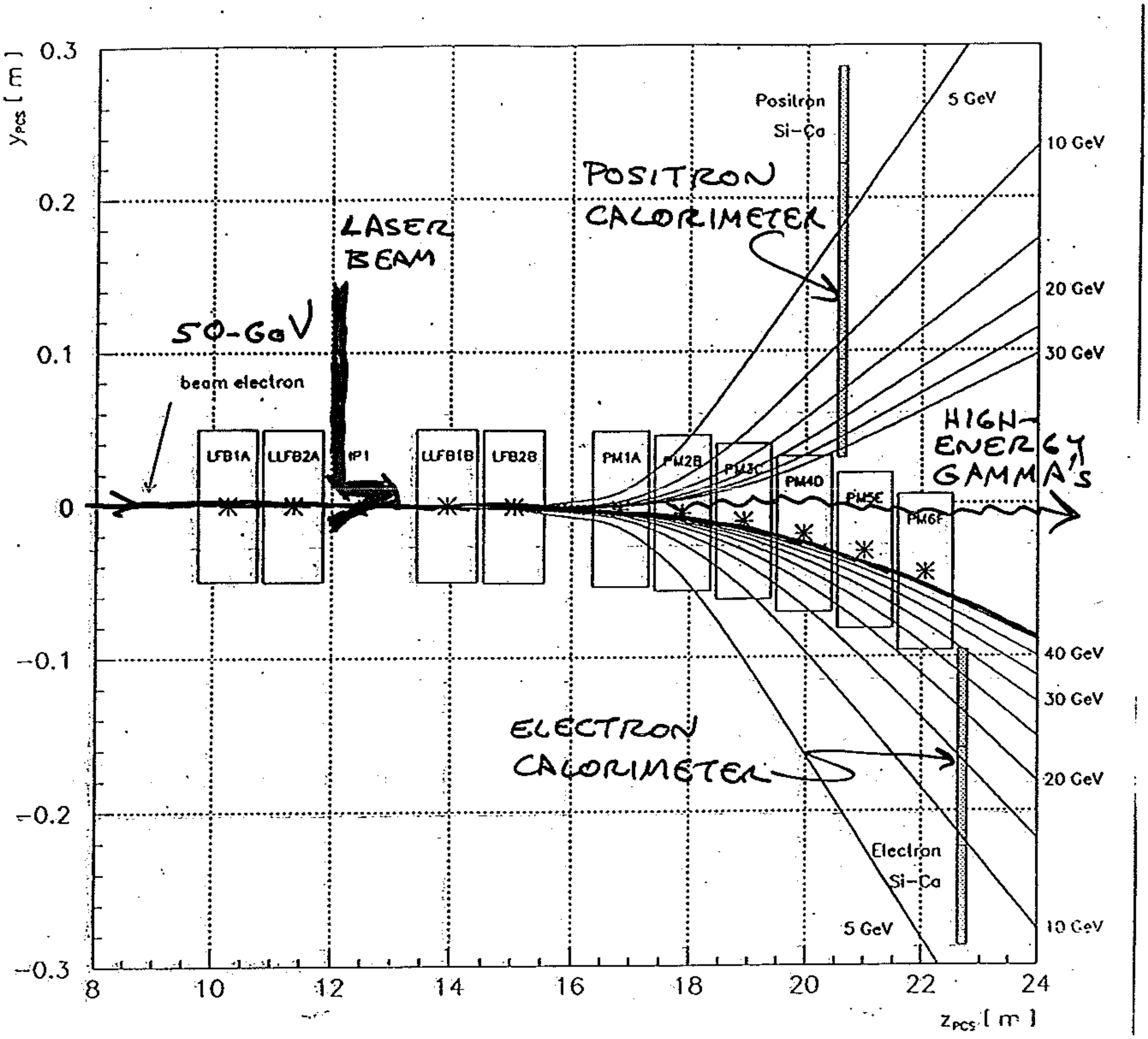
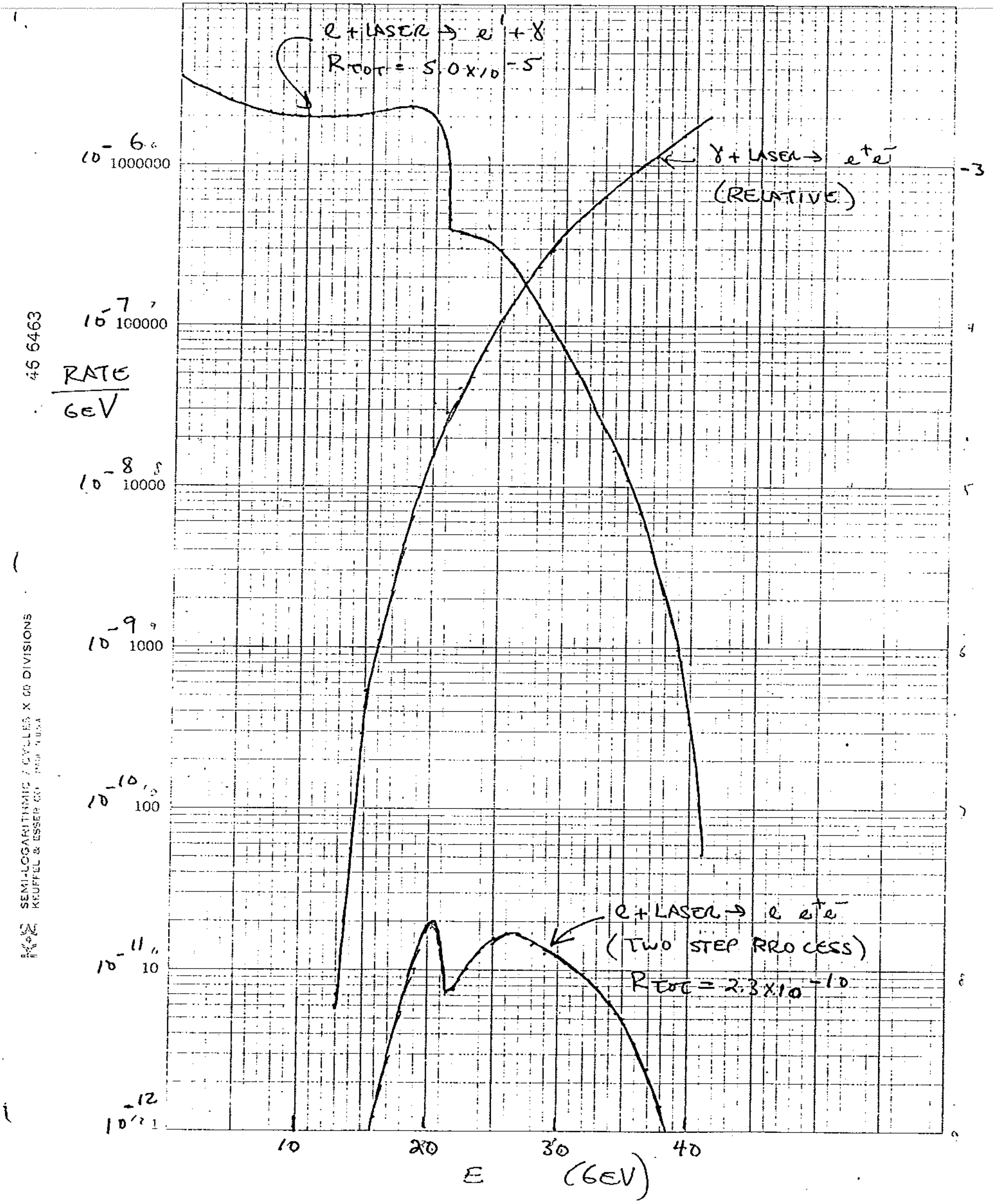


Figure 4.4: Trajectories of electrons and positrons through the FFTB dump magnets.

$\lambda = 1.06\ \mu m$ $\eta = 2.2$ $\tau_{LASER} = 1\ ps$ $\sigma_{\gamma, LASER} = 2.4\ \mu m$ $\Upsilon = 1.0$ AT $E = 50\ GeV$

$U = 3$ JOULES $f/D = 5$ $\tau_e = 3\ ps$ $\sigma_{y,e} = 1000\ \mu m$

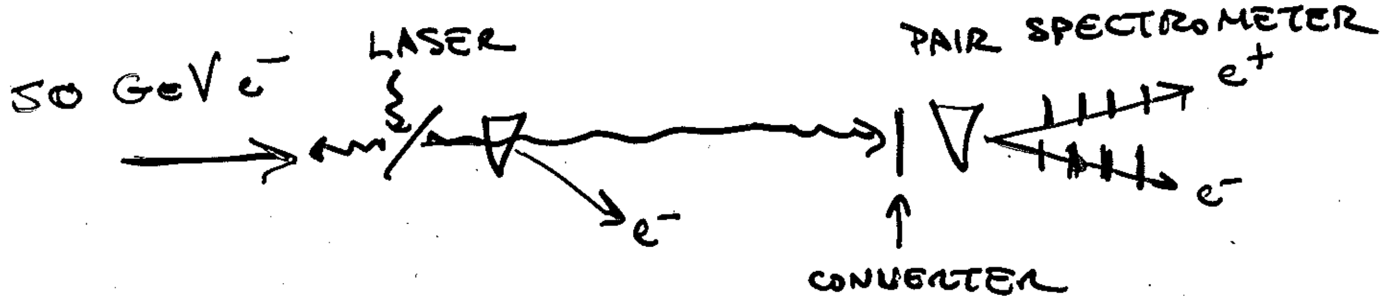
MODEL DATE



STRONG-FIELD QED EXPERIMENTS

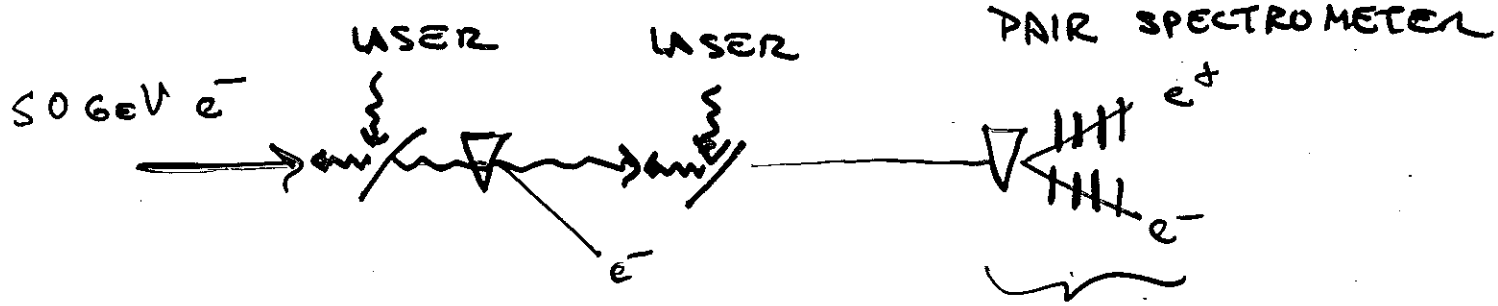
① NONLINEAR COMPTON SCATTERING

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



② PAIR CREATION BY LIGHT

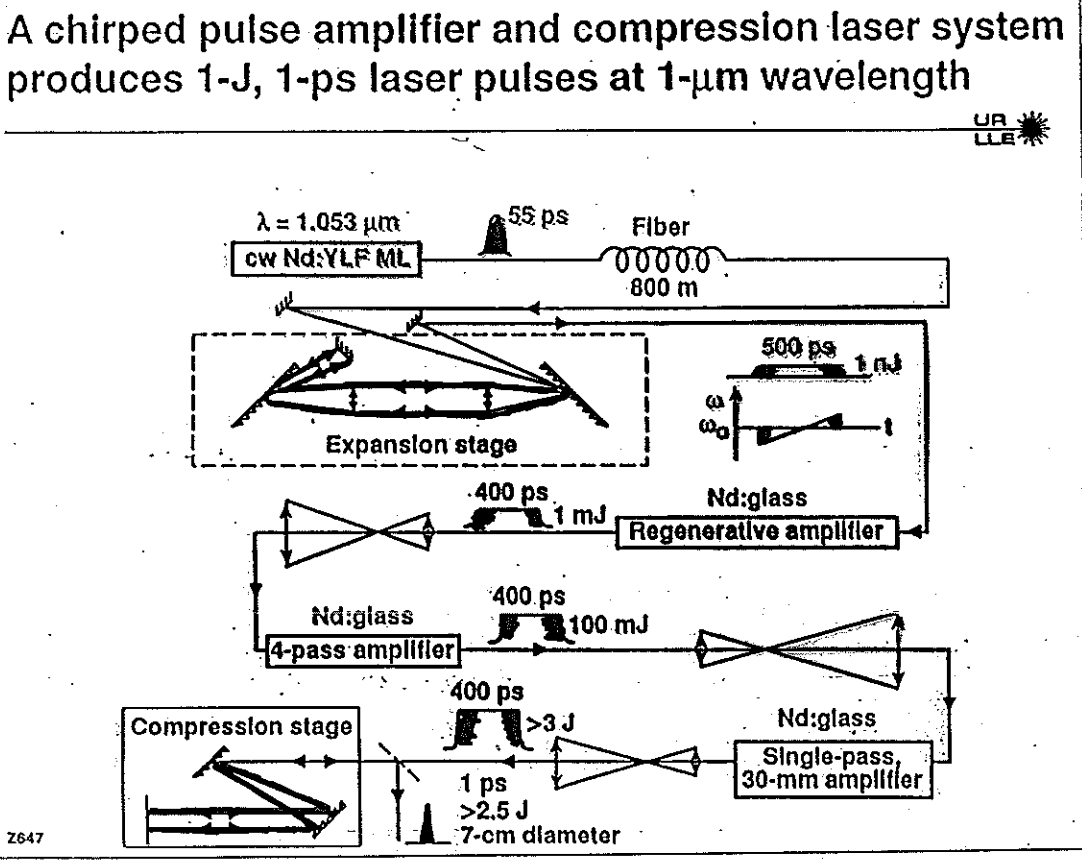
$$\gamma + n\,\omega_{\text{LASER}} \rightarrow e^+e^-$$



10 keV RESOLUTION ON $M_{e^+e^-}$ AT 1.8 MeV/c^2

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

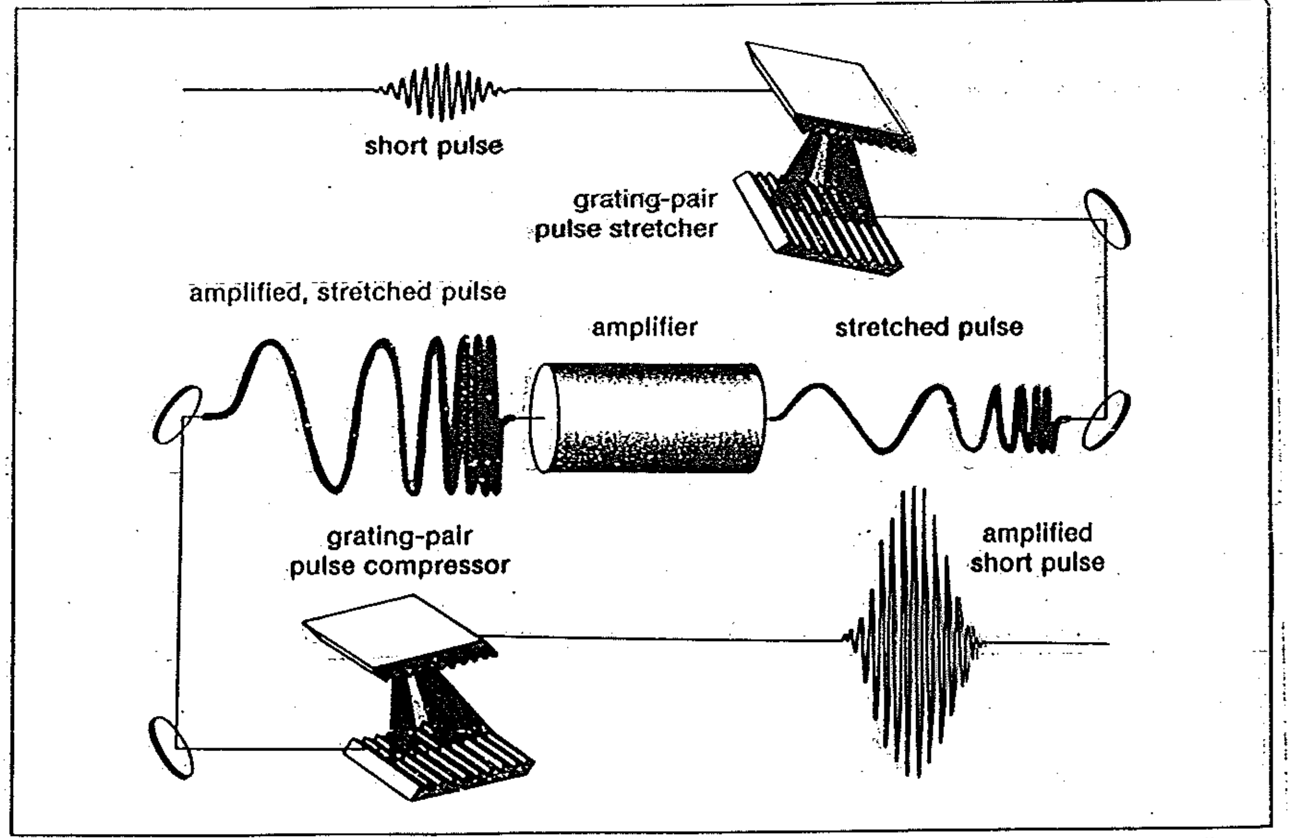


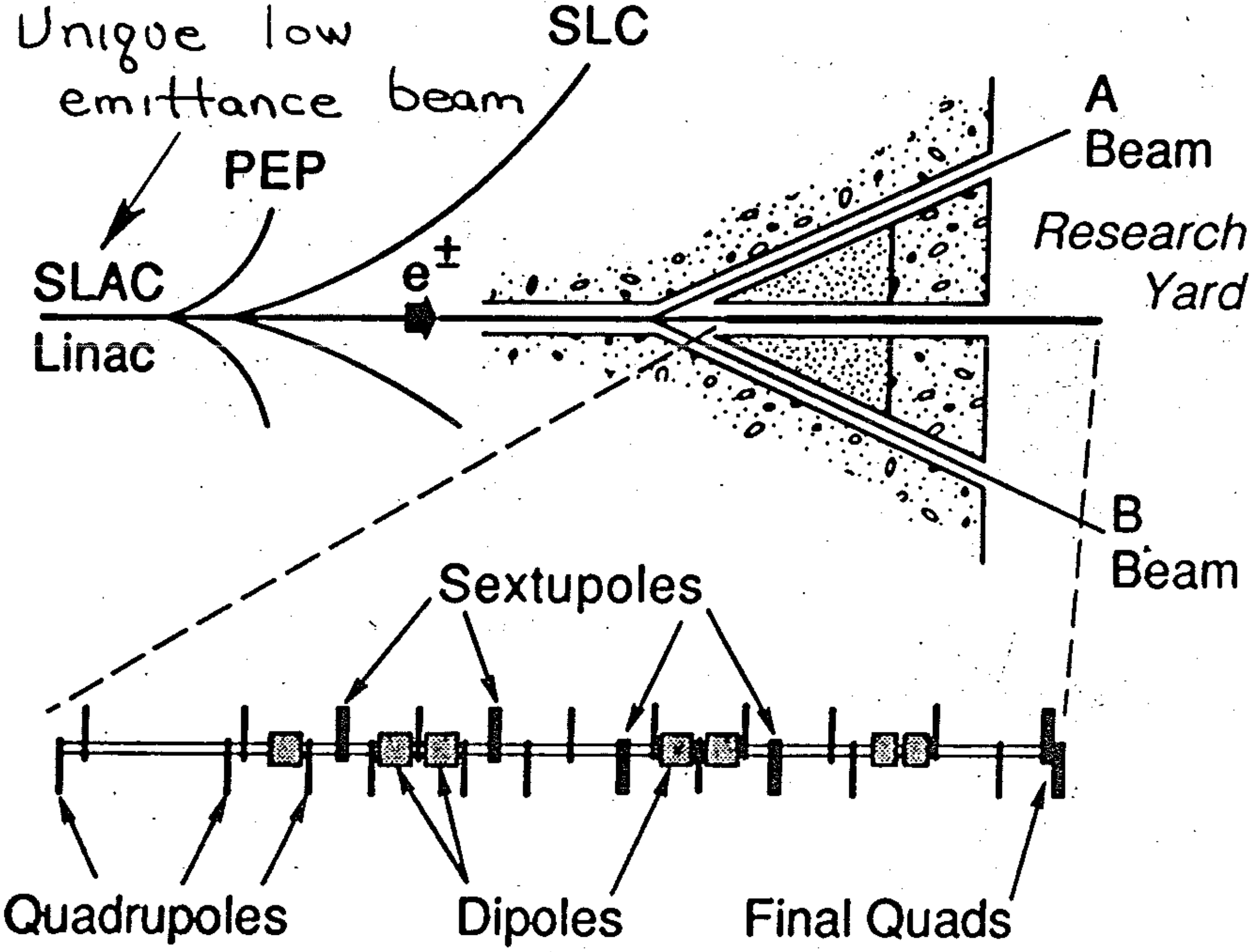
FIGURE 1. In chirped pulse amplification a short optical pulse is stretched and compressed by two compensating grating pairs.

Laser Demonstration – June 1992

(D. Meyerhofer, *U. Rochester*)

- Laser system performs at diffraction limit.
- Pulse energy . . . . 2 J
- Focal-spot area . . . . 26 μm^2
- Pulse FWHM . . . . 1.4 ps
- Peak intensity . . . . 6×10^{18} Watts/cm^2
- $\Upsilon = 2\gamma E/E_{\text{crit}}$ 0.7

Satisfied requirements of the EPAC for full approval of E-144, which was granted in Sept. 1992.



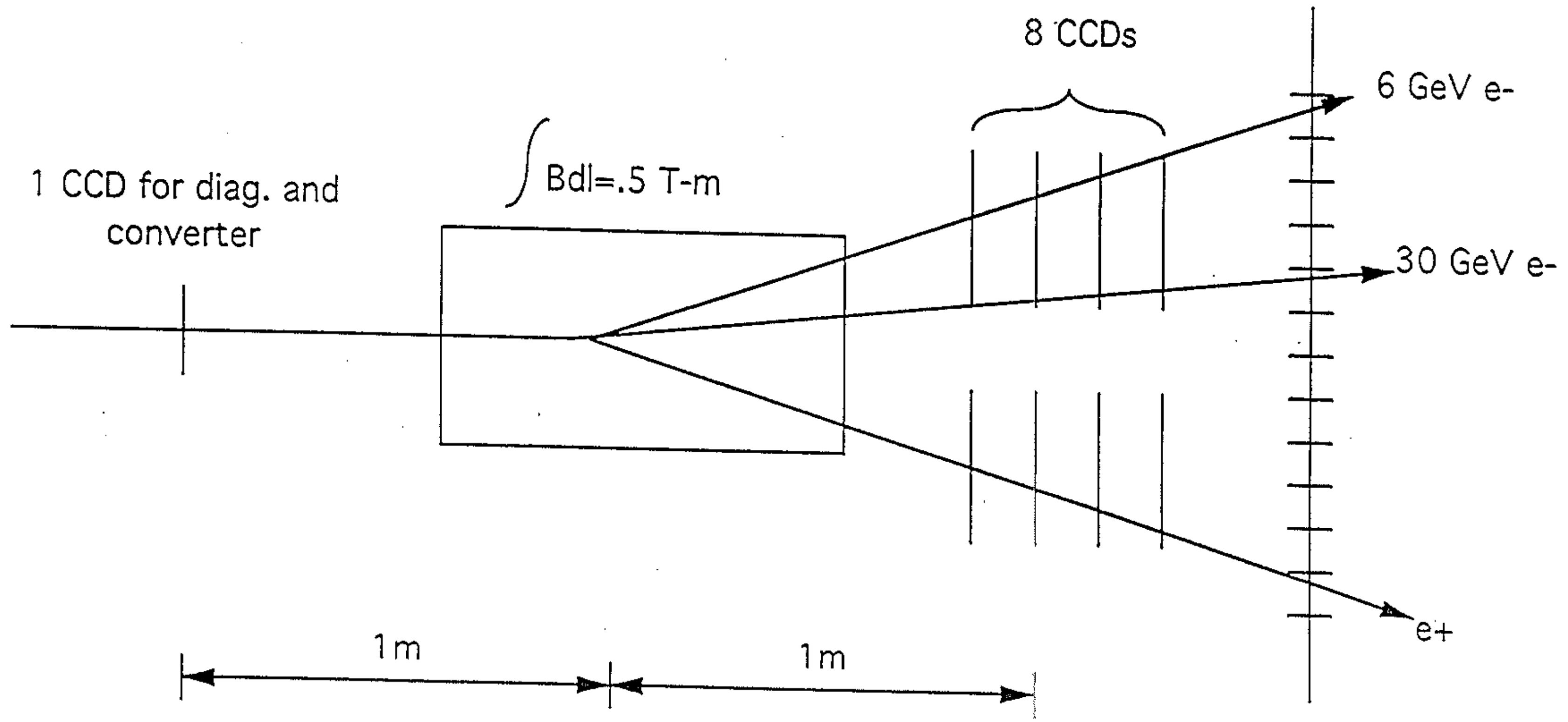
8-90

Final Focus Test Beam

6700A2

Prototype final focus for a future linear collider.

CCD Pair Spectrometer



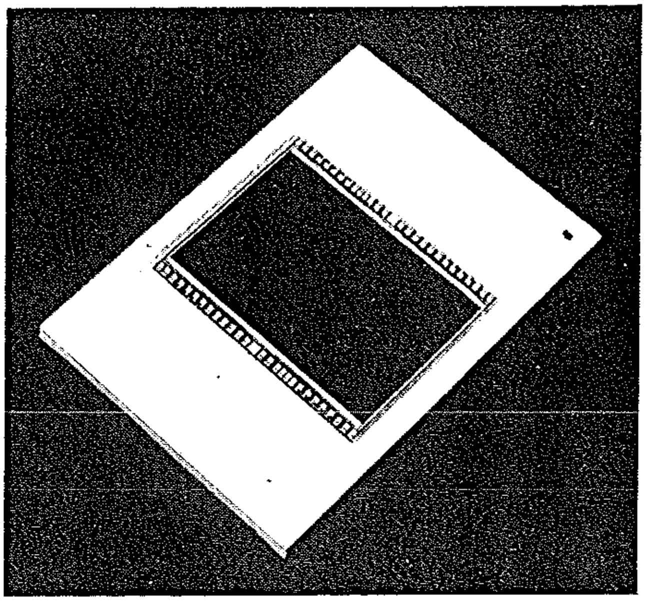
Pair Spectrometer with CCD's

Large Area CCD Image Sensor
Slow Scan Scientific Version

CCD05-20 Series
Scientific Image Sensor

FEATURES

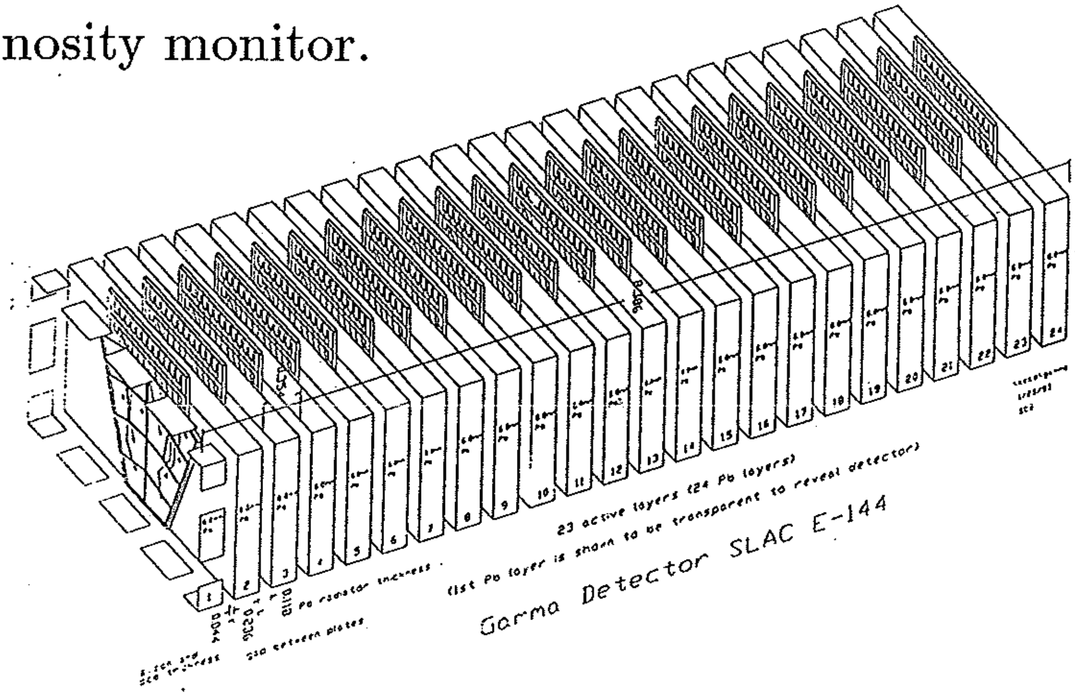
- 770 (H) x 1152 (V) pixel format
- 17.3 x 26 mm active area
- Extremely low pixel readout noise
- Visible light and X-ray sensitive
- Two readout registers
- Uniform response over whole image area
- Two low noise amplifiers for slow scan systems and two large signal amplifiers for high speed applications
- Symmetrical anti-static gate protection
- Long life expectancy
- Low voltage operation
- Radiation tolerant



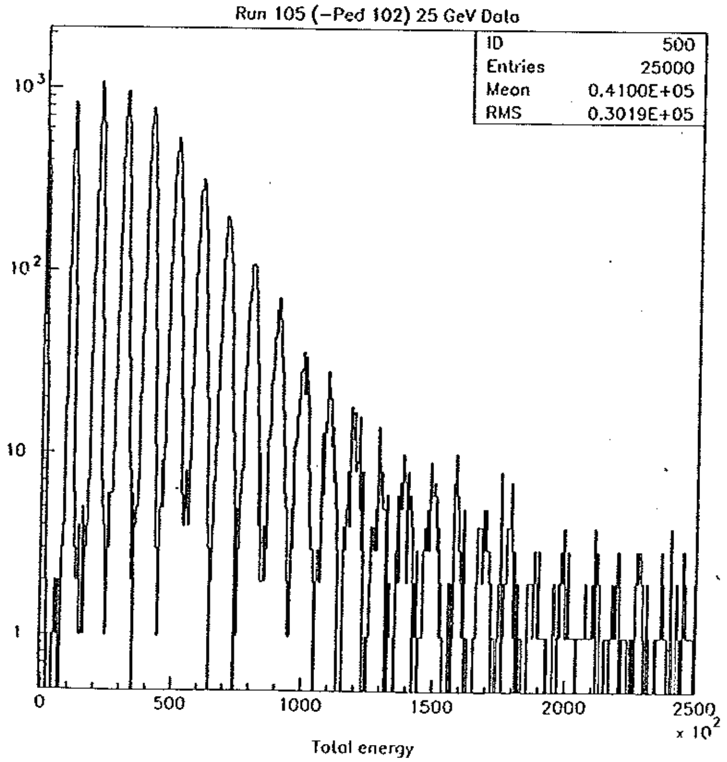
- Pixel size $22.5 \times 22.5\ \mu\text{m} \Rightarrow \sigma_x = 5\text{-}6\ \mu\text{m}$.
- $17 \times 26\ \text{mm}^2$ active area per CCD.
- 4 CCD's in each arm of pair spectrometer.
- Mass resolution ≈ 10 keV at $M_{e^+e^-} = 1.8$ MeV.
- 1 CCD + converter can be put in beam:
  - Diagnose beam position.
  - Convert γ's in Compton experiment.
- Readout based on commerical frame grabbers.

Silicon Calorimeter Beam Test – April 1993

Pb-Si calorimeter assembled from spare Si detectors for SLD luminosity monitor.



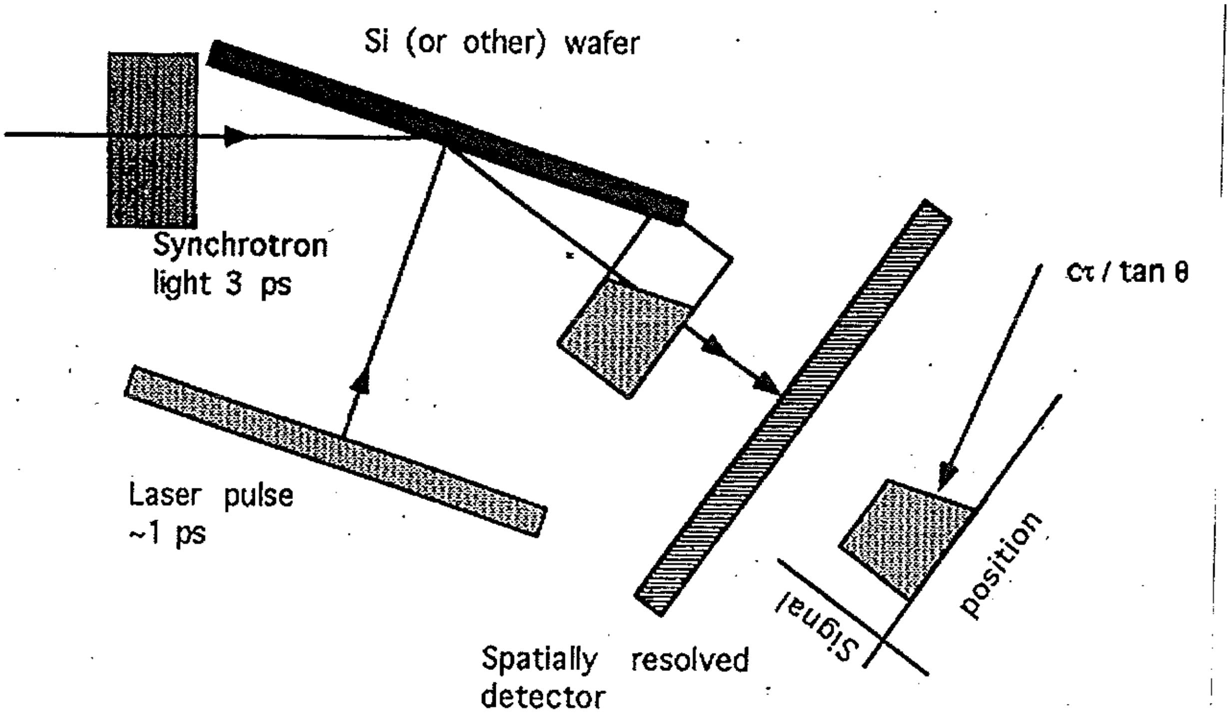
Readout using RABBIT electronics from FNAL E-706.



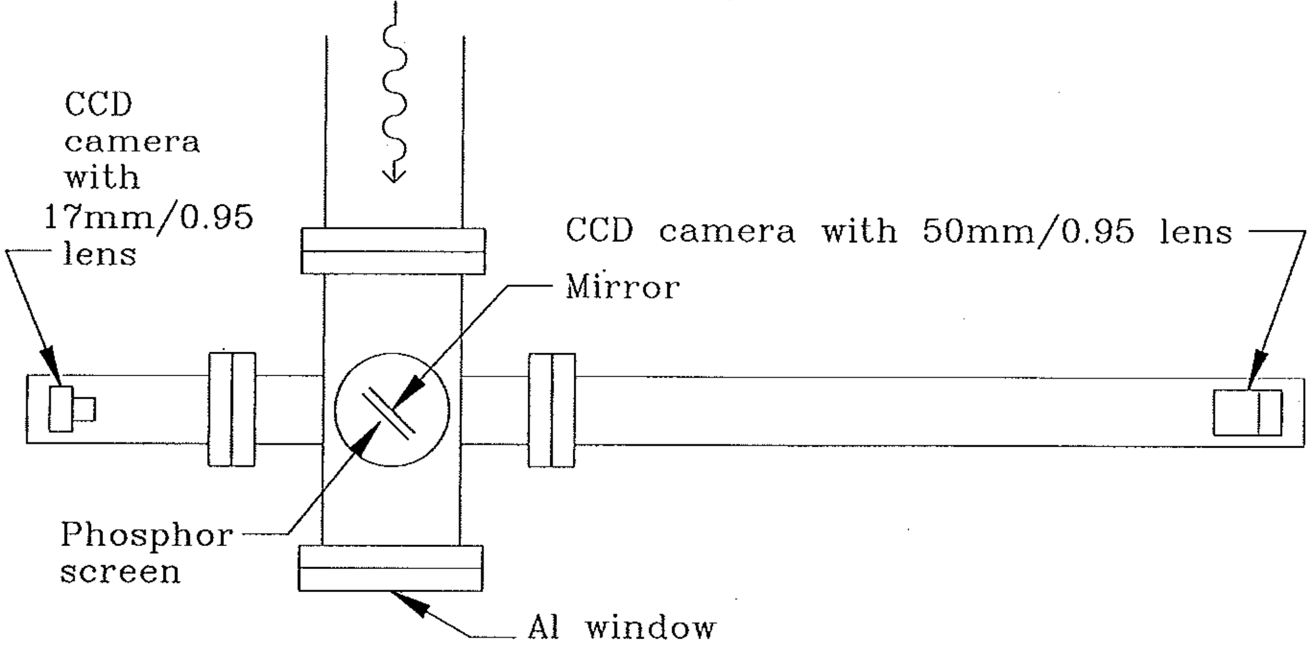
RESOLUTION
(ON-LINE)
~ 26% /√E

Monitor for Time Structure of the Electron Beam

Cross-correlation of optical synchrotron radiation with the psec laser pulse (D. Meyerhofer)



Summer 1993: Monitor optical synchrotron radiation.



Responsibilities

- e-beam .... SLAC
  e-beam diagnostics
  RF timing
  Laser & spectrometer buildings
- Laser systems .... Rochester
  Laser-beam transport and diagnostics (with SLAC)
- Silicon calorimeters (e^+, e^-, γ) .... Tennessee
  Calorimeter readout (with Princeton)
- CCD Pair Spectrometer .... Princeton

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.

E-144 Schedule

May 1993: Laser shipped to SLAC from U. Rochester.

June 1993: FFTB commisioning begins.

Aug. 1993: Engineering test of e-laser collisions

Fall 1993: Double laser frequency.

Winter/Spring 1994: Beamstrahlung experiments with silicon calorimeters.

Summer 1994: Install CCD spectrometer.

Summer/Fall 1994: Nonlinear Compton experiments

Fall 1994: Install γ-laser interaction region.

Winter/Spring 1995: Pair-production experiments.

E-144 Princeton Equipment Budget

FY92 (Supplement)	$35k
FY93	$125k
FY94 (proposed)	**$105k**

1. Two 486-PC computers	$10k
2. 10 custom CCD carrier boards	$20k
3. 10 CCD readout boards (Dipix)	$30k
4. Oil-free vacuum pump	$10k
5. Workstation (DEC α-VAX)	$15k
6. Digital oscilloscope	$15k
7. Power supplies	$5k