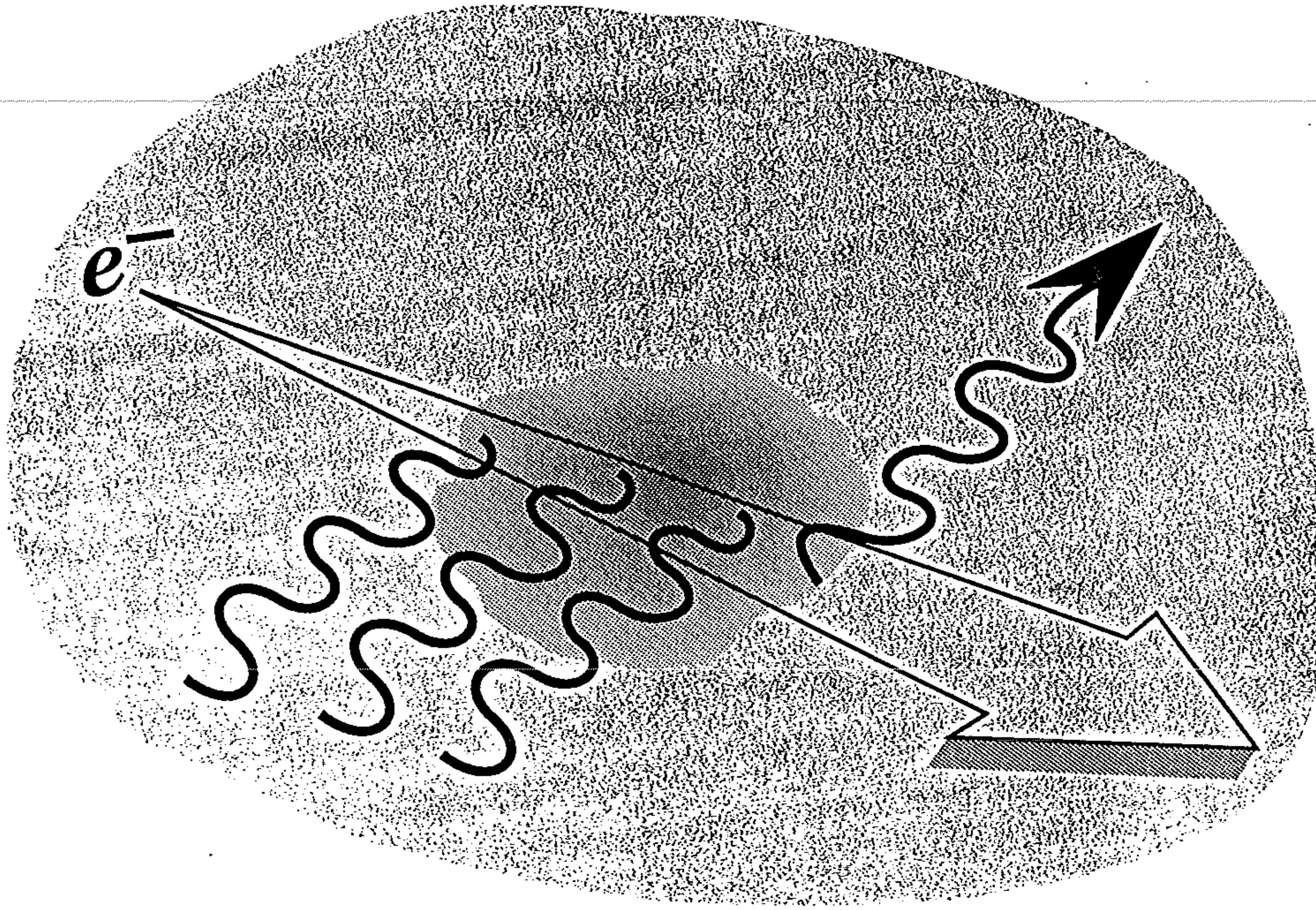

SLAC Experiment 144

QED at Critical Field Strength

A Progress Report

K.T. McDonald

Princeton U.

February 7, 1995

E-144 Home Page on World Wide Web

http://www.slac.stanford.edu/~prebys/e144/home.html

E144

cranked beyond the limit

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

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

- Explore QED in the realm where multiphoton interactions dominate, *i.e.*, when $eE/m\omega c \geq 1$.

PHYSICS

Inertia: Does Empty Space Put Up the Resistance?

As a child, the Nobel Prize–winning physicist Richard Feynman asked his father why a ball in his toy wagon moved backward whenever he pulled the wagon forward. His father said that the answer lay in the tendency of moving things to keep moving, and of stationary things to stay put. "This tendency is called inertia," said Feynman senior. Then, with uncommon wisdom, he added: "But nobody knows why it is true."

THE GRANGER COLLECTION

Seeking a reference frame. Mach defined inertia with respect to the distant stars.

That's more than even most physicists would say. To them, inertia does not need explaining, it simply "is." But since the concept was first coined by Galileo in the 17th century, some scientists have wondered if, perhaps, inertia is not intrinsic to matter at all, but is somehow acquired. Those who have tried to come to grips with inertia include Feynman junior, once he had grown up, and Albert Einstein, who tried—and failed—to show that inertia was related to the arrangement of matter in the universe.

Now three researchers think they have found the source of inertia—and it turns out to be much closer to home. Inertia, they say, comes from the apparently empty space that surrounds us all—or rather, from the buzz of activity that, according to quantum theory, fills even a perfect vacuum, where subatomic particles are being created and annihilated in the blink of an eye. It is this ever-present sea of energy that the researchers believe resists the acceleration of mass, and so creates inertia.

UPI/BETTMANN

Another try. Einstein tried to incorporate Mach's principle into general relativity.

Reaching this conclusion took more than just a simple application of quantum theory for Bernhard Haisch of the Lockheed Palo Alto Research Laboratory, Alfonso Rueda of the California State University at Long Beach, and Hal Puthoff at the Institute for Advanced Studies at Austin, Texas. Their idea, published in the 1 February issue of *Physical Review A*, is based on an esoteric mathematical treatment of the vacuum and a long-forgotten attempt by the Soviet theorist and dissident Andrei Sakharov to explain another great mystery, gravity. These unfamiliar foundations, together with the new proposal's boldness, would be more than enough to stir up controversy. But the paper raises an even more provocative notion: that inertia, once understood, might be controlled.

It is a bit too early to be talking about building inertia-free starships, the researchers say, but they maintain that there may soon be hard evidence supporting their claim, from experiments that will search for changes in the mass of electrons when they are exposed to powerful laser beams. Certainly many of their colleagues are intrigued. Says Stanford University astrophysicist Peter Sturrock, "No one would say that it's the last word, but I think it may really be one of the first words in what could be a very interesting approach."

One inspiration for the effort was a much earlier try, by the German philosopher-physicist Ernst Mach. In 1872, Mach argued that acceleration—and hence inertia—is not absolute, but only has meaning within a frame of reference. For Mach, that frame of reference consisted of the other matter in the universe: After all, in utterly empty space, how do you know you are moving? Einstein later tried and failed to work that notion into general relativity. Haisch and his colleagues also invoke a frame of reference: not the distant stars, but the quantum vacuum.

The seething activity of the vacuum is an upshot of Heisenberg's uncertainty principle, one of the key results of quantum theory. The principle is best known for setting limits to the accuracy with which it is possible to measure simultaneously certain attributes of a particle, such as its position and momentum. But the flip-side of this uncertainty is that a particle and a matching antiparticle can spontaneously appear out of thin air, so long as they recombine and annihilate each other so fast no one would know. During their fleeting existence, these "virtual particles" make their presence felt in many ways, including slight shifts in the spectrum of hydrogen, the irreducible electronic noise in semiconductors and, Haisch and his colleagues now claim, inertia.

Meeting with resistance. Their argument draws on a curious quantum vacuum phenomenon first described by the British physicist Paul Davies (now at the University of Adelaide in Australia) and William Unruh of the University of British Columbia in the mid-1970s. If you move at a constant speed through the quantum sea of virtual particles, it looks the same in all directions. But as soon as you start to accelerate through it, theory predicts that the vacuum gives the appearance of being a tepid "sea" of heat radiation.

Although far too small to measure, the Davies-Unruh effect led Haisch, a high-energy astrophysicist, and Puthoff, a quantum theorist, to wonder independently about a connection with inertia. Could it be that accelerating through the vacuum produces other effects, too—like the resistance to acceleration that we call inertia? While still mulling over the idea, Haisch met with Rueda, an electrodynamics theorist with considerable experience in the techniques needed to attack such a question. When they learned of Puthoff's similar ideas, Haisch and Rueda decided to join forces with him.

In their analysis, the trio set aside conventional quantum theory. Instead, they opted for an approach known as stochastic electrodynamics (SED), which accepts the existence of the vacuum fluctuations *a priori*, then applies an entirely classical (i.e., nonquantum) approach to particles and electromagnetism. Since the 1960s, a number of theorists, including Rueda, have shown that SED can give a perfectly accurate account of bizarre quantum effects without becoming embroiled in complex quantum theory.

In their intensely mathematical paper, Haisch and his colleagues wield SED to argue that inertia results from a Lorentz force, familiar to physicists as the force that deflects a charged particle moving through a magnetic field. For inertia, it is the vacuum fluctuations that produce the magnetic field, and it is the charged subatomic particles making up objects that feel the Lorentz force. The larger the object, the more particles it contains, and hence the stronger the resistance, and the greater the object's inertia.

Predictably for a grand claim based on obscure theory, peer reaction is mixed. On the one hand is Stanford's Sturrock, who calls it "very interesting, and potentially very important." On the other is Peter Milonni, a specialist on quantum vacuum processes at the Los Alamos National Laboratory, who says, "I don't think much of the work," complaining "I see a lot of claims being made that are just not backed up."

Cosmologist Paul Wesson of the University of Waterloo, Canada, an authority on the links between the subatomic and cosmic worlds, is "glad that someone is trying to return to the question of inertia again." But he is concerned about "the astrophysical and cosmological implications" of the work. Wesson's concerns center on the cosmological constant, best known as an add-on to Einstein's equations of general relativity that endows free space with extra energy and gives it a gravitational effect. Einstein eventually dropped the constant because it was inelegant, but some cosmologists would like to resurrect it because it would solve some of their most intractable problems, such as the age of the universe and its missing mass (*Science*, 5 November 1993, p. 846).

The new vacuum-based theory of inertia devised by Haisch and his colleagues does just that: It requires an energy-rich vacuum, which implies a cosmological constant. The problem is that the constant implied by the new theory is much bigger than the one required to solve the other problems of cosmology. Says Wesson: "The vacuum has so much energy associated with it that it would have negative astrophysical implications. Those would have to be cleared up."

A new tack. Haisch, Rueda, and Puthoff, shown from left to right, think they have found the source of inertia in the fluctuations of the quantum vacuum.

Overcoming inertia. Haisch and his colleagues agree that there is a problem and suggest an answer, in the form of a controversial theory of gravity proposed by Sakharov in the late 1960s. One consequence of Sakharov's theory is that vacuum energy can't generate a gravitational field—and so cannot create a problematic cosmological constant. Solving one unconventional theory's problems by invoking another unconventional theory is unlikely to win many converts, and Haisch agrees that the team's work needs refining. But he hopes to do it with the help of other researchers, who might be lured by the tantalizing implications of the theory—among them the possibility that by altering the properties of the vacuum, researchers might control inertia.

Physicists have known for years that the quantum vacuum can be manipulated. In the so-called Casimir effect, two metal plates brought close together distort the quantum vacuum, which responds by producing an attractive force between the plates. If the quantum vacuum could be distorted on a larger scale, says Haisch, "then we open a door on a way of perhaps someday controlling inertia—and we had no inkling that was even possible in principle before."

Experiments slated for later this year at the Stanford Linear Accelerator Center (SLAC) may provide Haisch and his colleagues with the evidence they need to convince skeptics. Physicist Kirk McDonald of Princeton University and colleagues from a number of other universities plan to expose high-energy electrons produced at SLAC to a terawatt beam from a neodymium-YAG laser. Testing the inertia theory isn't the main aim of the experiment. But if the theory is correct, the intense electromagnetic field experienced by the electrons as they enter the beam will affect their interaction with the quantum vacuum's own field—and so change their inertia.

A favorable outcome, Haisch thinks, might be just what he and his colleagues need to overcome any resistance—or is it inertia?—they are meeting in the scientific community. "If nothing else," he says, "controlling inertia is a possibility that might just encourage others to dig deeper."

–Robert Matthews

Robert Matthews writes for The Sunday Telegraph *in London.*

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:

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

- 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

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

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

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

  Thus for 46-GeV electrons ($\gamma = 9 \times 10^4$) we can achieve E_{crit} with a focused laser intensity of 1.4×10^{19} Watts/cm^2 ($\Rightarrow E_{\text{lab}} = 7 \times 10^{10}$ 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 $\sim 10^{27}/\text{cm}^3$, and the radiation length of this 'photon solid' is $\sim \lambda/\alpha \approx 100\ \mu$m.

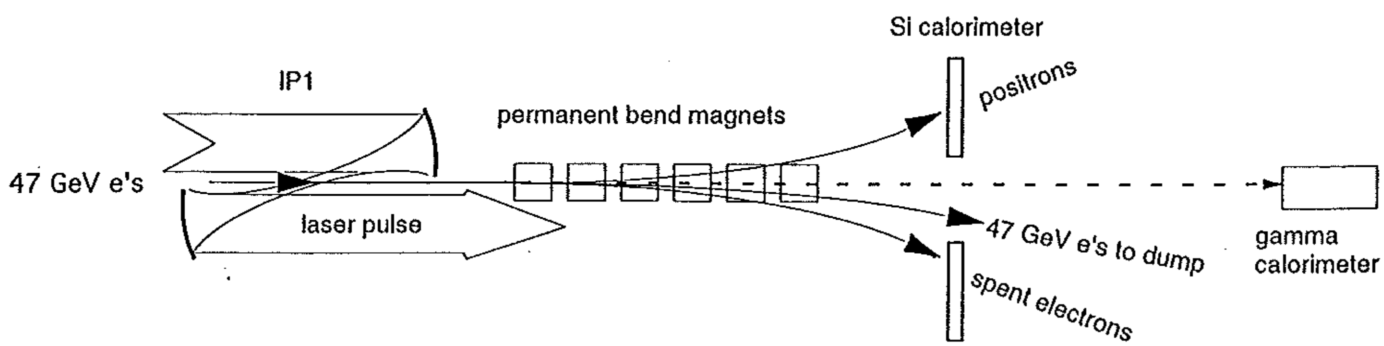
E-144 Physics Program

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.

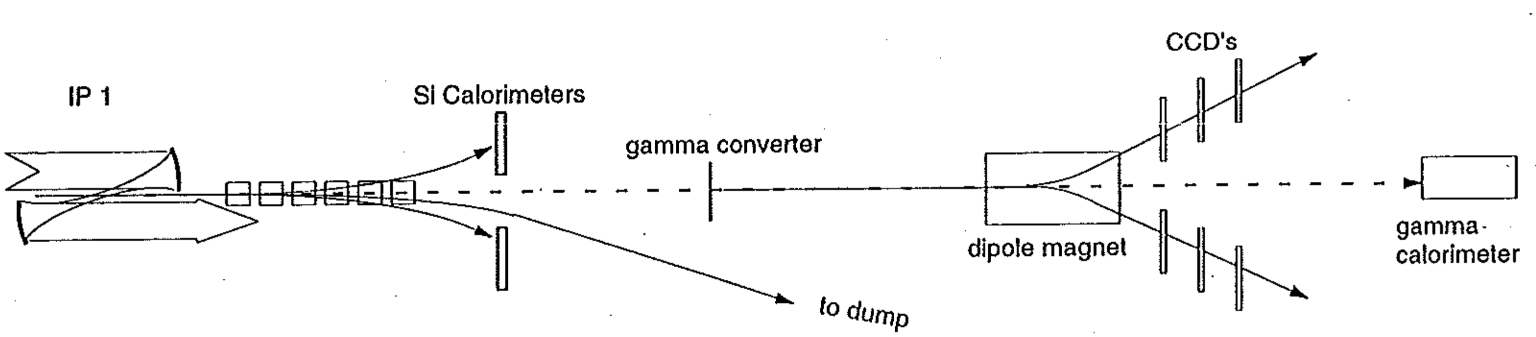
2. Beamstrahlung

   - $E \approx 10^{11}$ V/cm for the E-144 laser, and for electron bunches at future e^+e^- colliders.
   - $e + n\omega_{\text{laser}}$ interactions with large n mimic beamstrahlung.
   - $e + n\omega \to e'e^+e^-$ is analog of important pair-production backgrounds in future colliders.



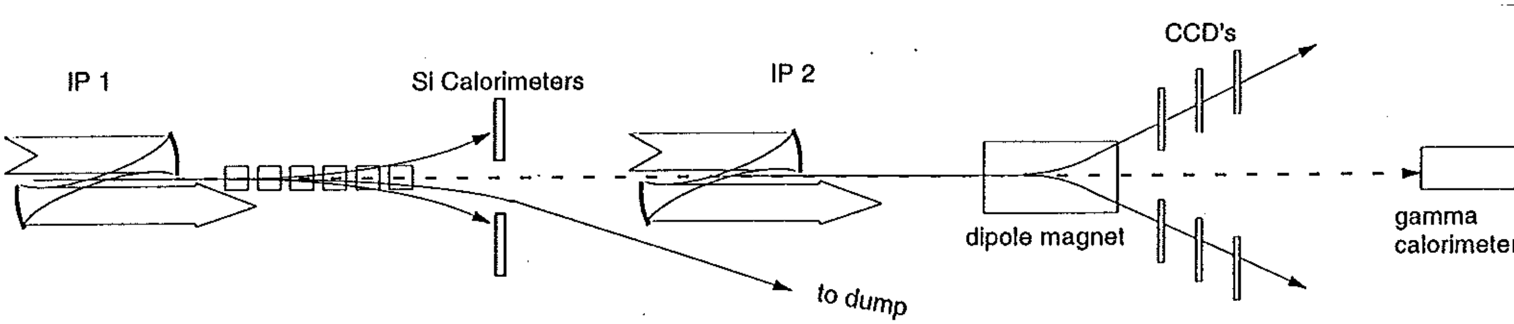
3. Nonlinear Compton Scattering: $e + n\omega \rightarrow e' + \gamma'$

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



4. Multiphoton Breit-Wheeler Process: $\gamma + n\omega \rightarrow e^+e^-$

- 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 ⇒ 'cooling' of invariant emittance.
- Can produce 1 positron per electron if $E^\star > E_{\mathrm{crit}}$.
- Production with visible laser is optimal for $\sim$ 500 GeV electrons.

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

6. e-laser technology of E-144 is precursor of e-γ and γ-γ colliders.

7. Accelerator-physics spinoffs:

- Nonlinear-optics diagnostic of electron-bunch length.
- Possible demonstration of laser acceleration with gradient of 1 TeV/m (but only for a few μm).

E-144 History

Oct. 1991: Strong-field QED experiment proposed to SLAC.

Dec. 1991: Conditional approval of E-144 by SLAC EPAC.

June 1992: Demonstration of laser focused to 10^{19} Watts/cm^2 at U. Rochester.

June 1992: Memorandum of Understanding between Princeton, Rochester and SLAC.

Sept. 1992: Full approval of E-144.

Oct. 1992: U. Tennessee joins E-144 collaboration.

Apr. 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.

Apr. 1994: First data taking by E-144 at the FFTB:
e-beam polarization measurement;
evidence for quadratic effects in Compton scattering

Sept. 1994: Further studies of nonlinear Compton scattering: evidence for 2-, 3- and 4-photon effects.

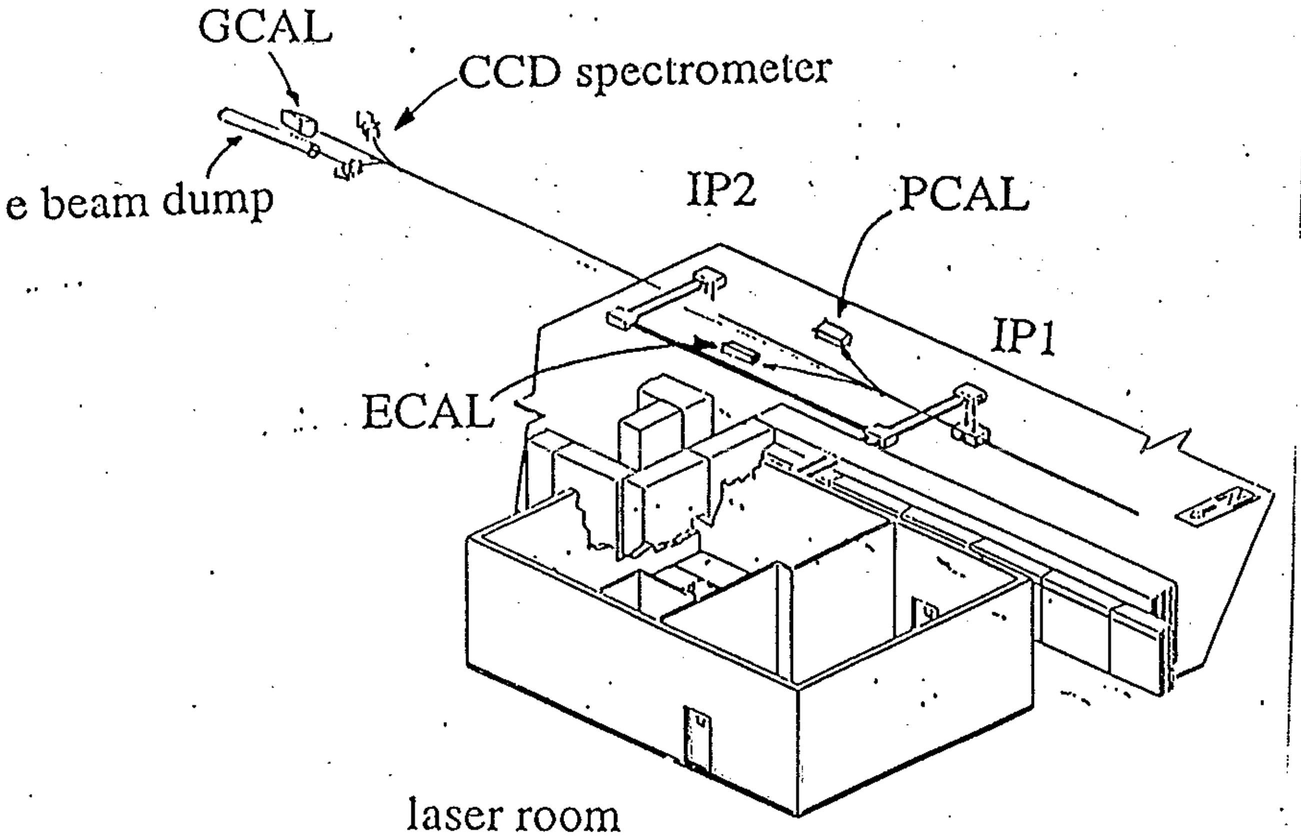
Mar. 1995: 5-day run to study nonlinear Compton scattering, and search for positron production.
First use of CCD pair spectrometer.

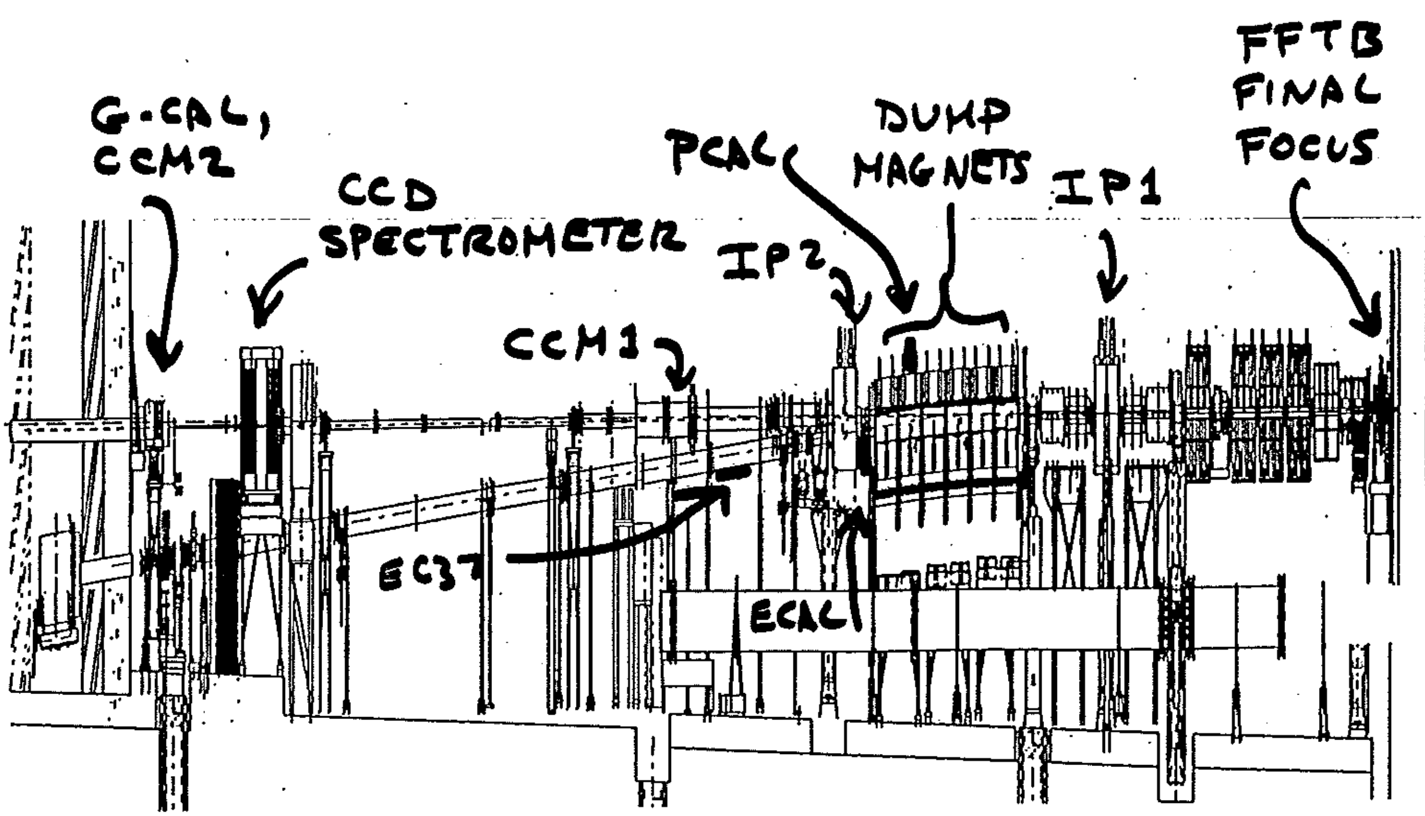
Jan. 1996: Study pair creation by light at IP2.

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





Retune FFTB Quads for Small Spot at IP1

Beam energy = 46.6 GeV.

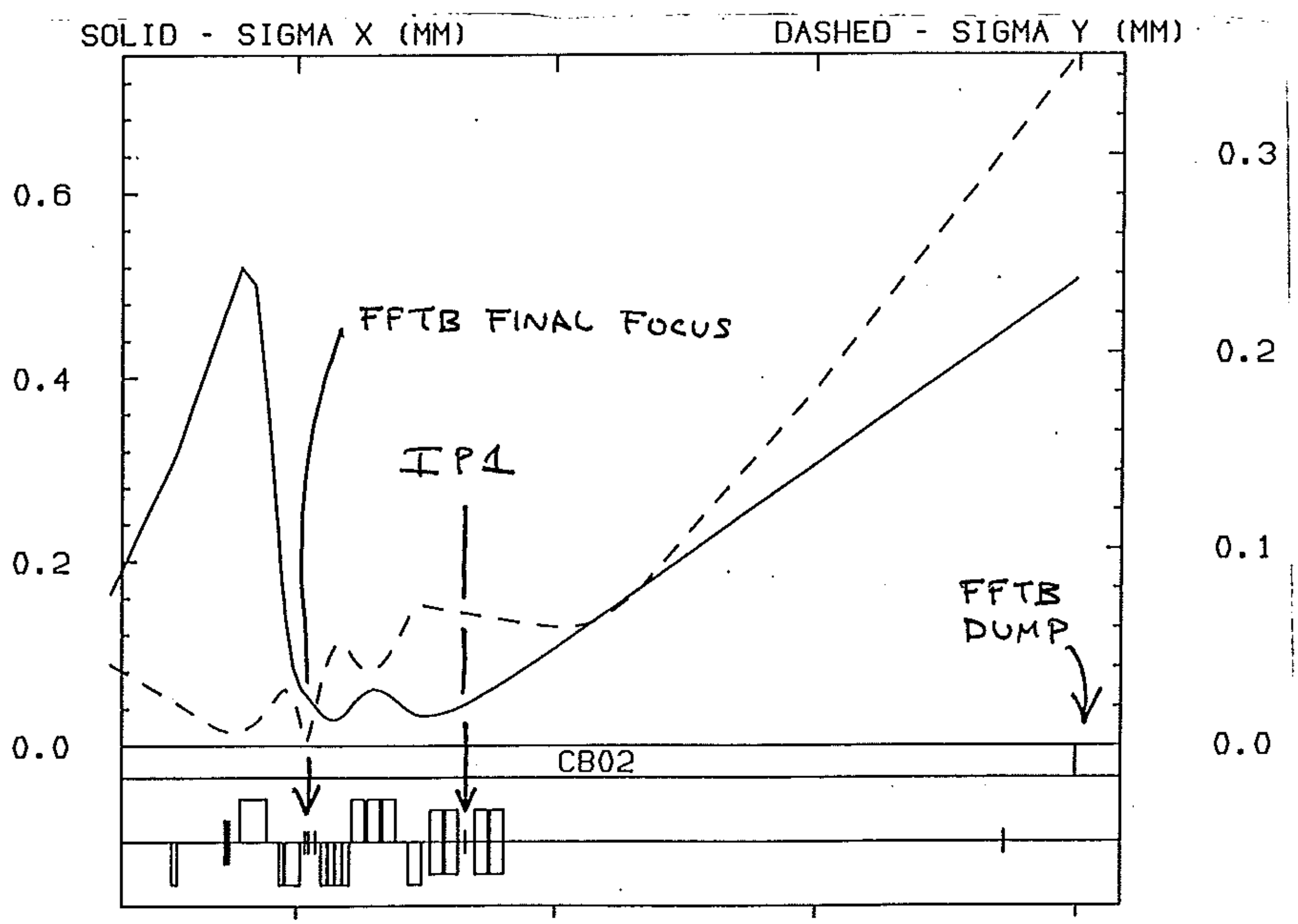
QED scattering angle $\lesssim 1/\gamma \approx 10\ \mu$rad.

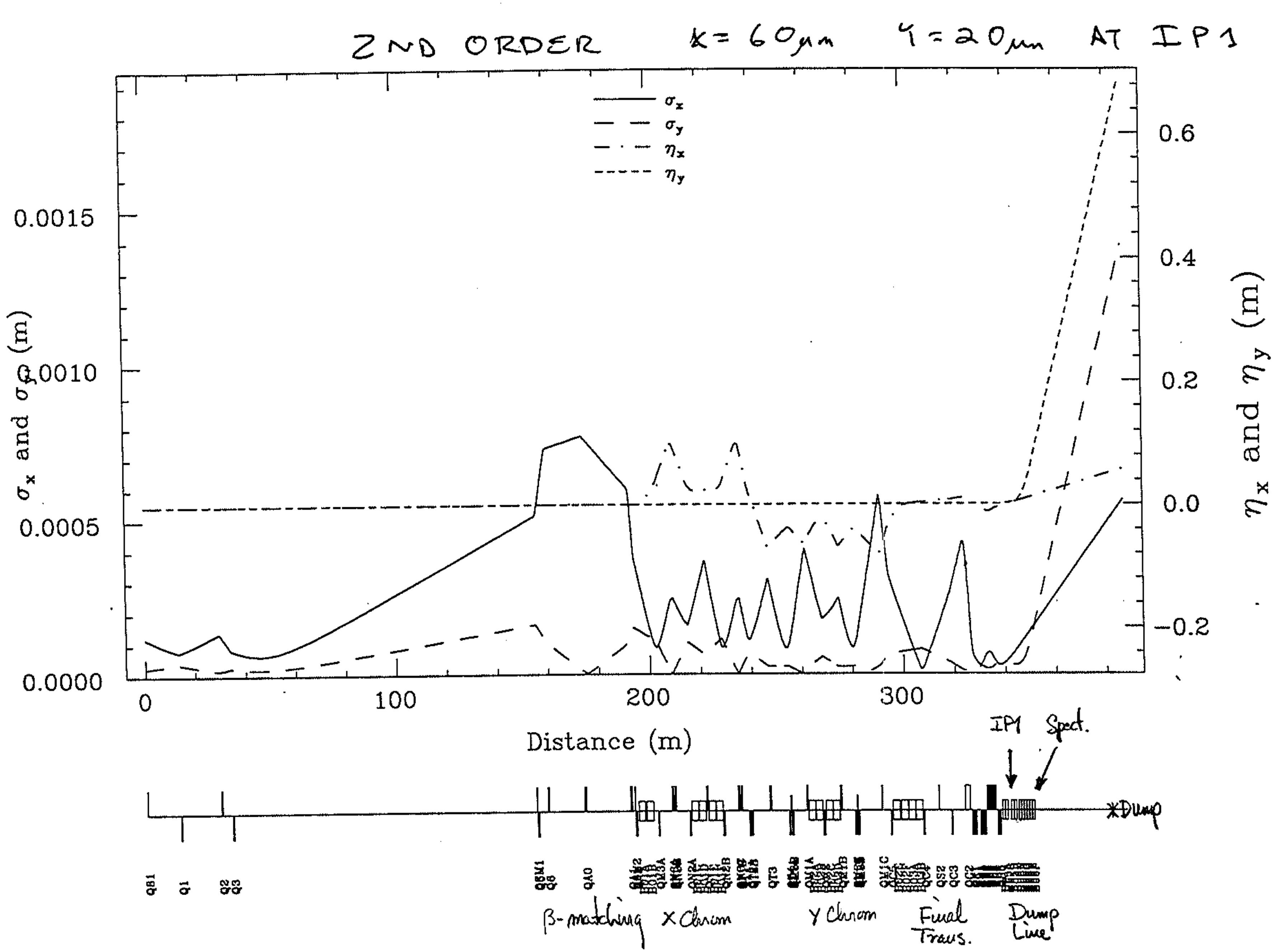
Laser spot size $\approx 3\ \mu$m.

$\Rightarrow$ Desired emittance $\approx 3 \times 10^{-11}$ m-rad.

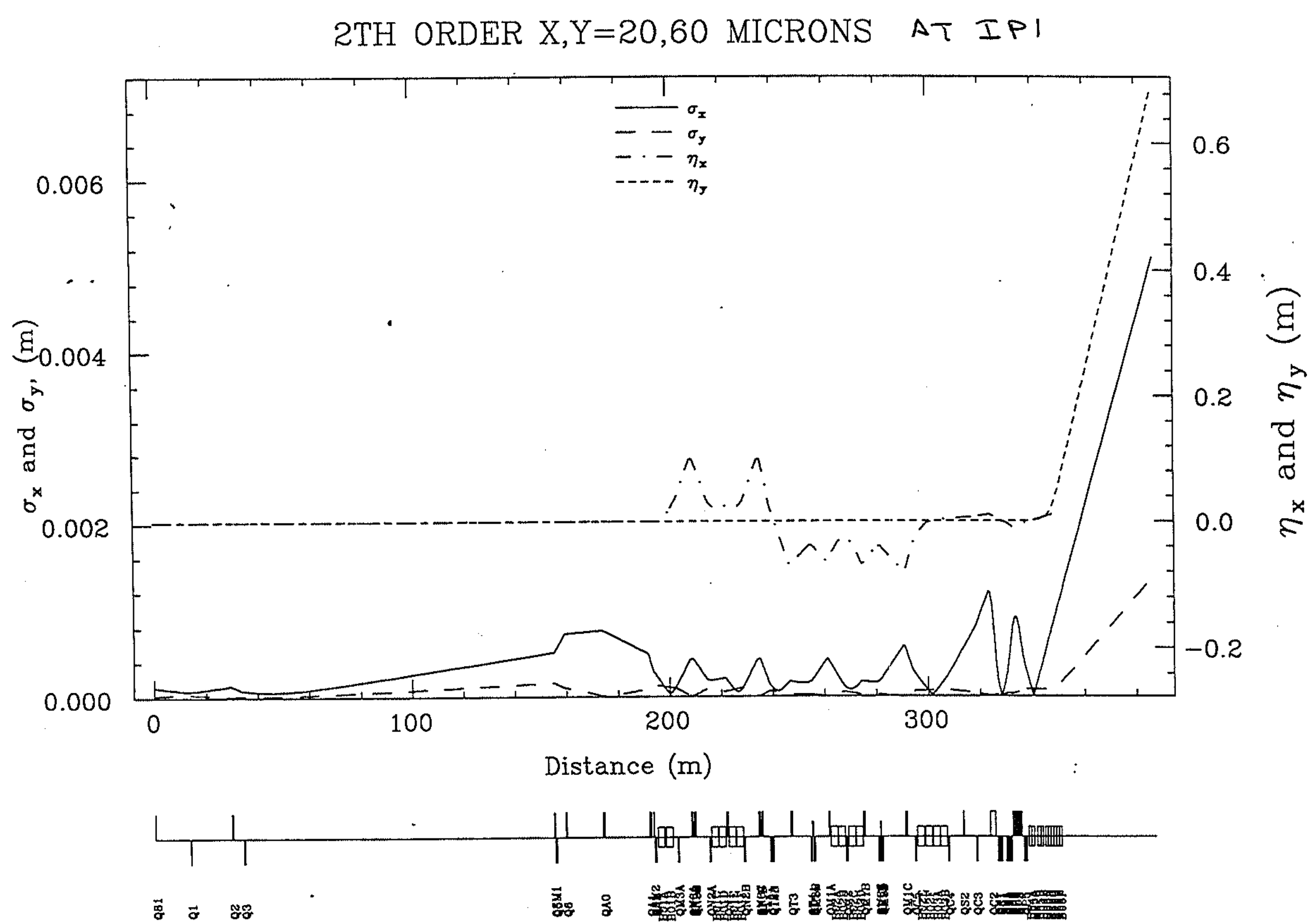
FFTB emittance $\approx 3 \times 10^{-10}$ m-rad.

E-144 tune: 100 μm (x) $\times$ 30 μm (y), θ_x, $\theta_y \sim 10\ \mu$rad.





2ND ORDER x = 60µm y = 20µm AT IP1
σx
σy
ηx
ηy
0.0015
0.0010
0.0005
0.0000
σx and σy (m)
0.6
0.4
0.2
0.0
−0.2
ηx and ηy (m)
0
100
200
300
Distance (m)
IP1
Spect.
*Dump
QS1
Q1
Q2
Q3
QSM1
Q8
QA0
QT3
QS2
QC3
β-matching
X Chrom
Y Chrom
Final Trans.
Dump Line

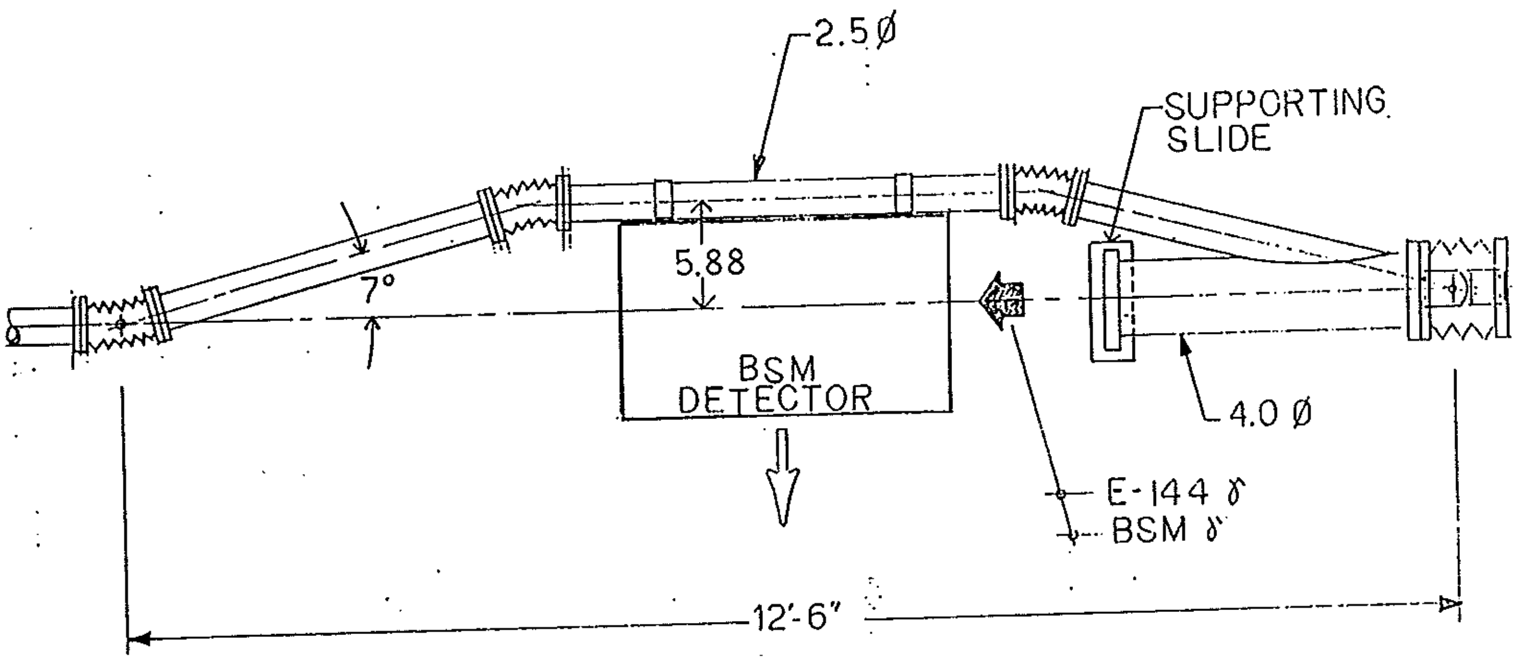


2TH ORDER X,Y=20,60 MICRONS AT IP1
σ_x
σ_y
η_x
η_y
σ_x and σ_y, (m)
0.006
0.004
0.002
0.000
η_x and η_y (m)
0.6
0.4
0.2
0.0
−0.2
0
100
200
300
Distance (m)
QB1
Q1
Q2
Q3
QSM1
Q8
QA0
QT3
QS2
QC3

Sliding Vacuum Pipe

The FFTB/Shintake beam size monitor blocks the E-144 γ-line to the CCD spectrometer.

Solution: An articulated section of vacuum pipe permits push-pull operation of both systems.



DW/BB
6-3-94

TeraWatt Laser Via Chirped-Pulse Amplification

1 Joule in 1 ps $\Rightarrow 10^{12}$ Watt.

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

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

Desired rep. rate 1 Hz.

High power pulses can damage optics!

$\Rightarrow$ stretch pulse, then amplify and compress.

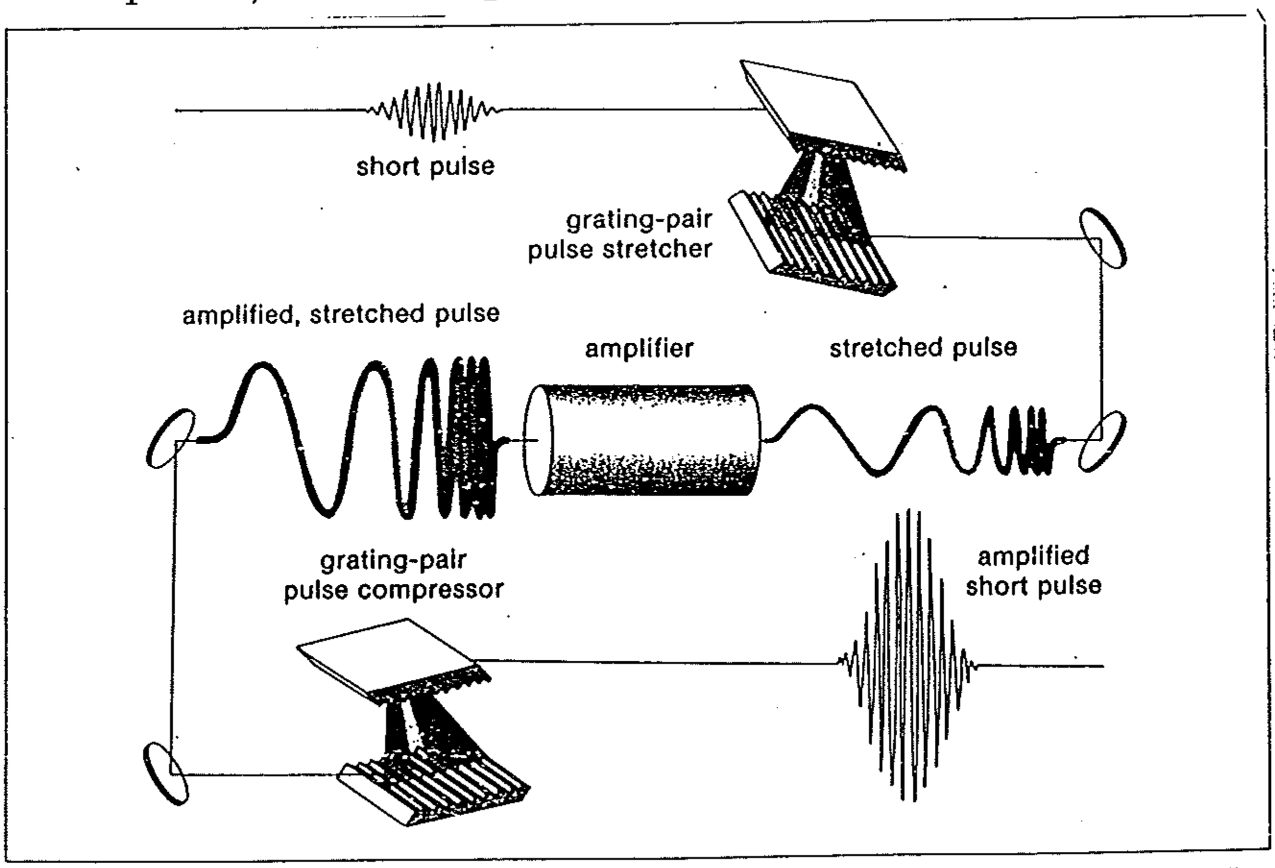
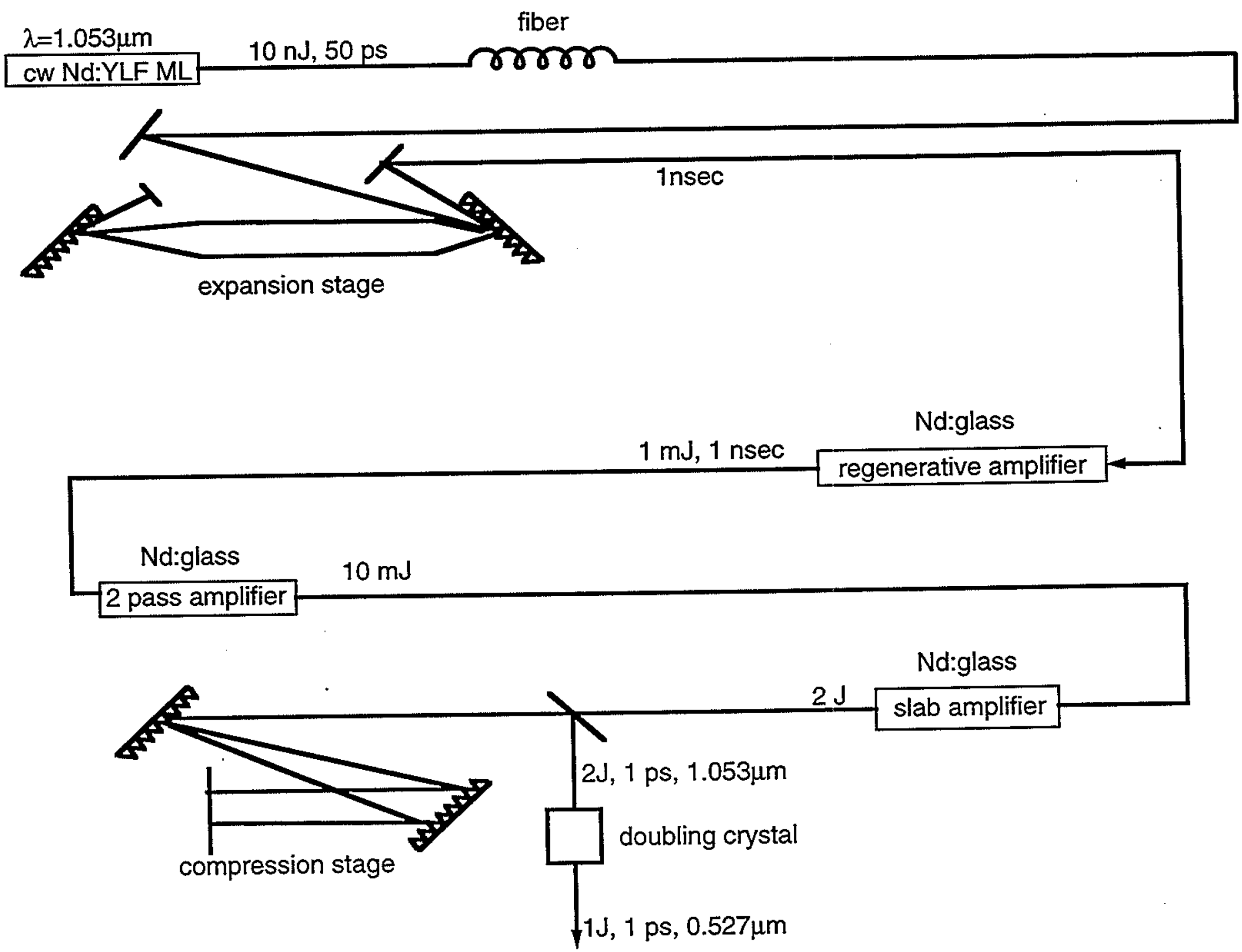
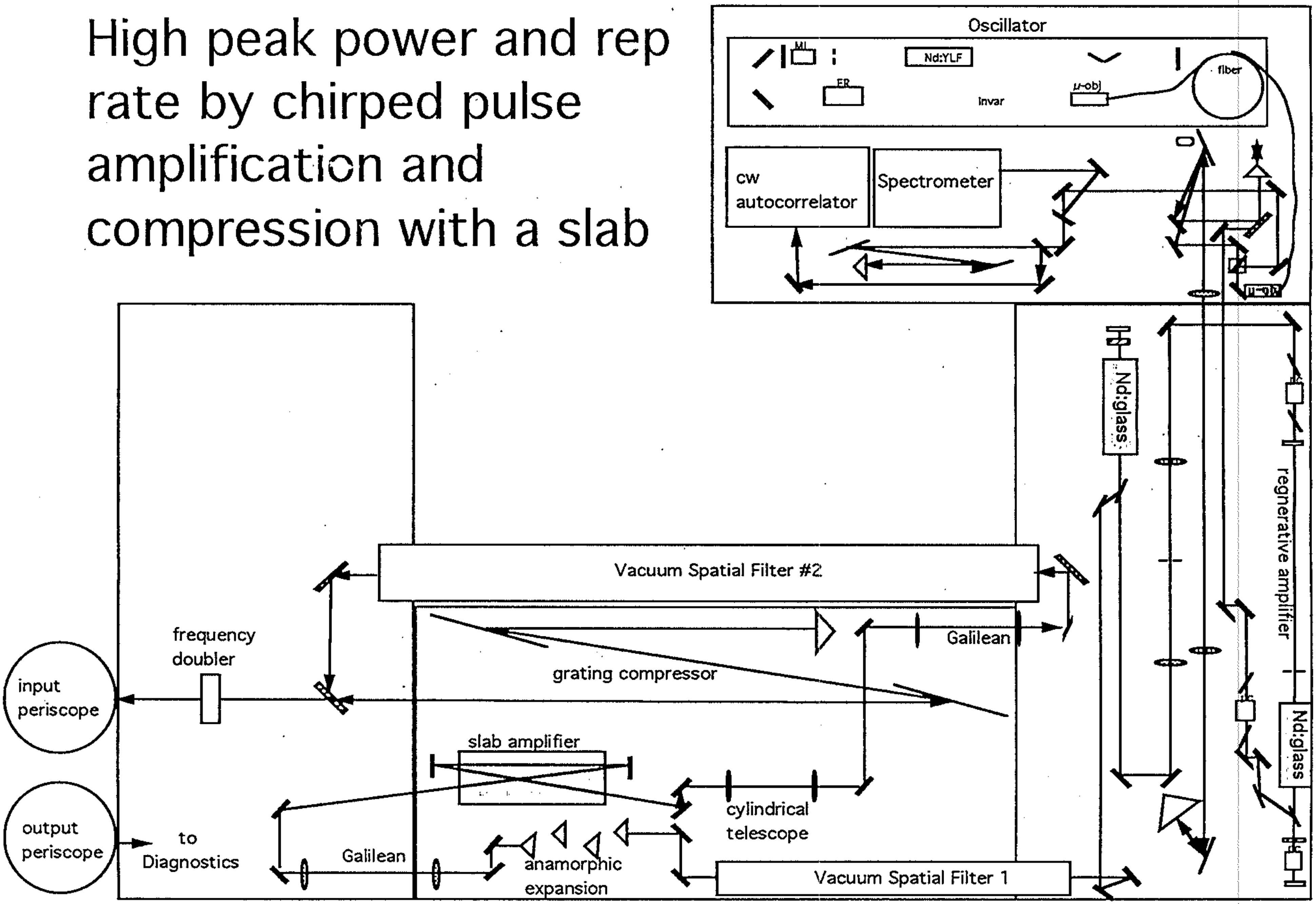


FIGURE 1. In chirped pulse amplification a short optical pulse is stretched and compressed by two compensating grating pairs.

The laser system is designed to produce terrawatt pulses at a 1 Hz repetition rate.



High peak power and rep rate by chirped pulse amplification and compression with a slab



The Laser Front End

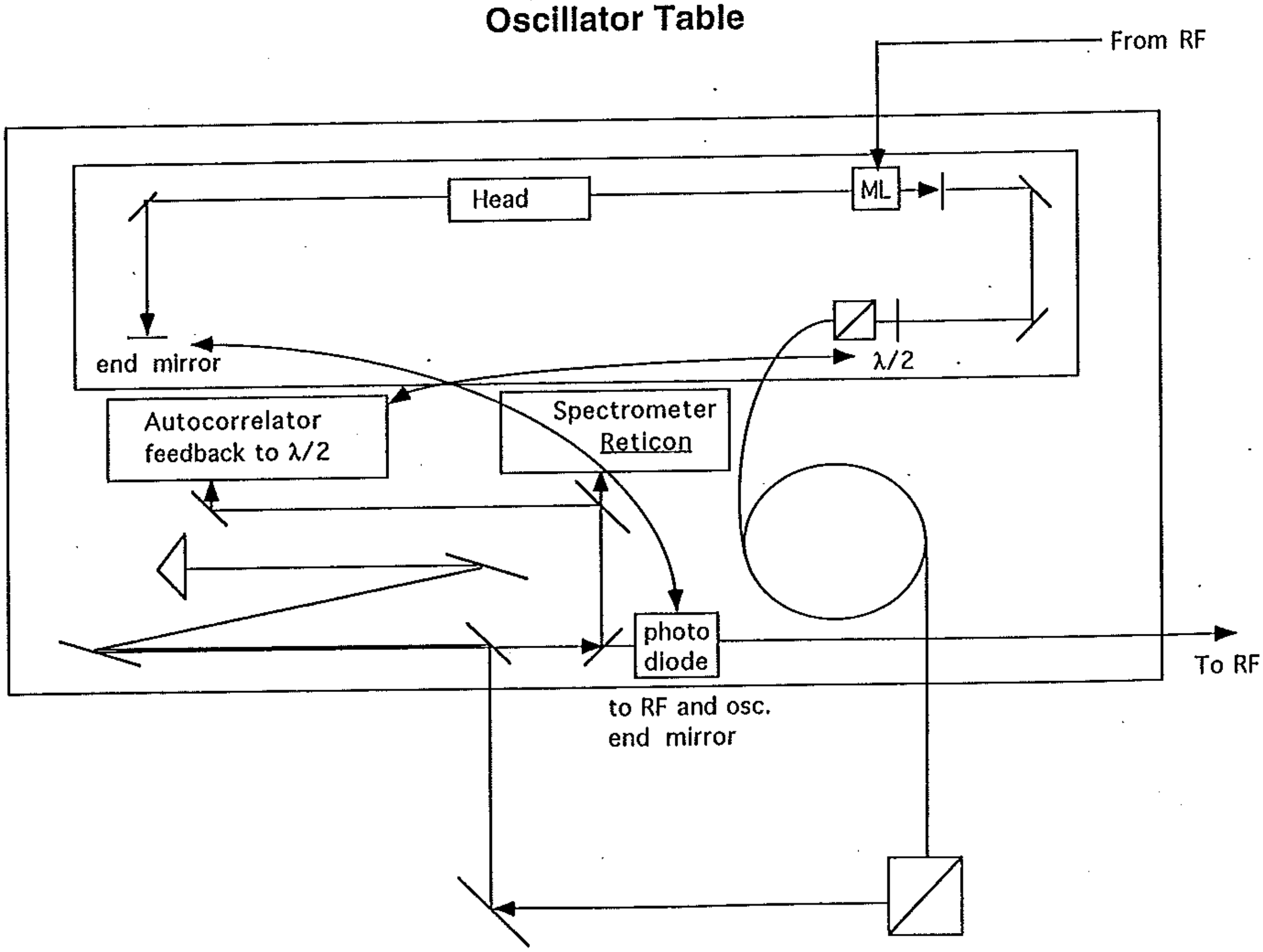
The oscillator is controlled by an acousto-optic modulator (modelocker) driven by 119-MHz RF.

⇒ pulse period is 8 nsec.

The oscillator can be stabilized to 1 psec.

Output pulse 1 nJ, 50 psec.

Oscillator Table



Fiber Optic Transport

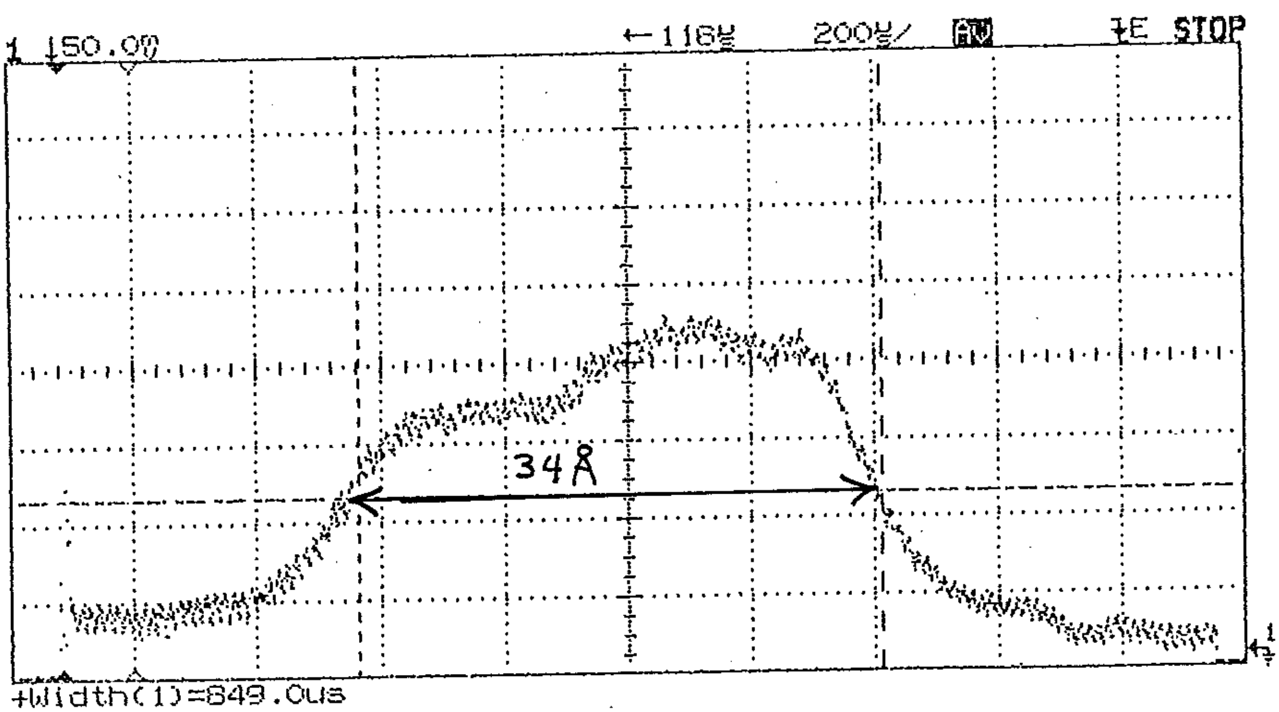
Oscillator output coupled into a 1-km-long optical fiber.

Dispersion in fiber ⇒ frequency chirp.

High intensity ⇒ nonlinear pulse propagation.

⇒ Broadening of frequency spectrum.

Output pulse 150 psec.



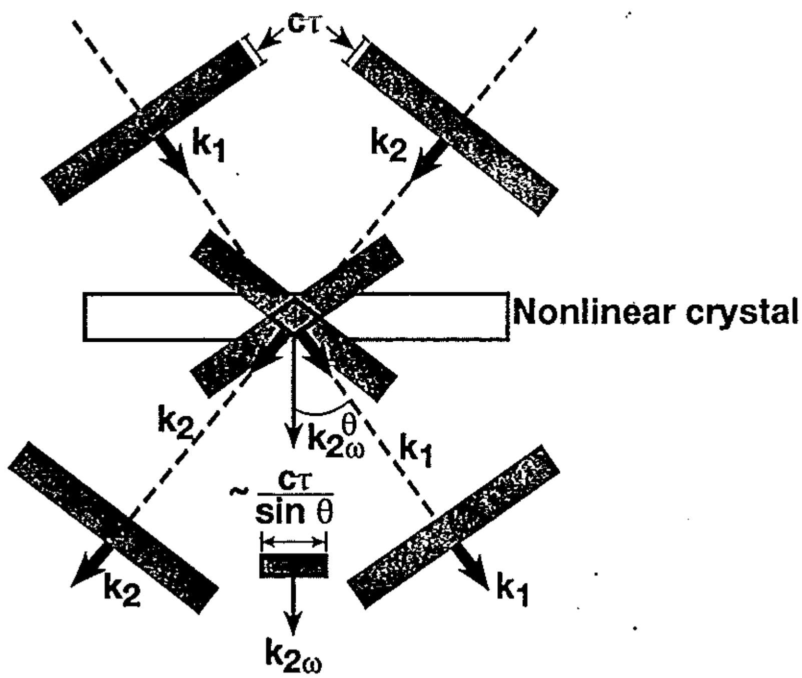
SHOULD BE ABLE TO COMPRESS TO $\Delta\tau \sim \frac{1}{\Delta\nu} = 1.1$ psec

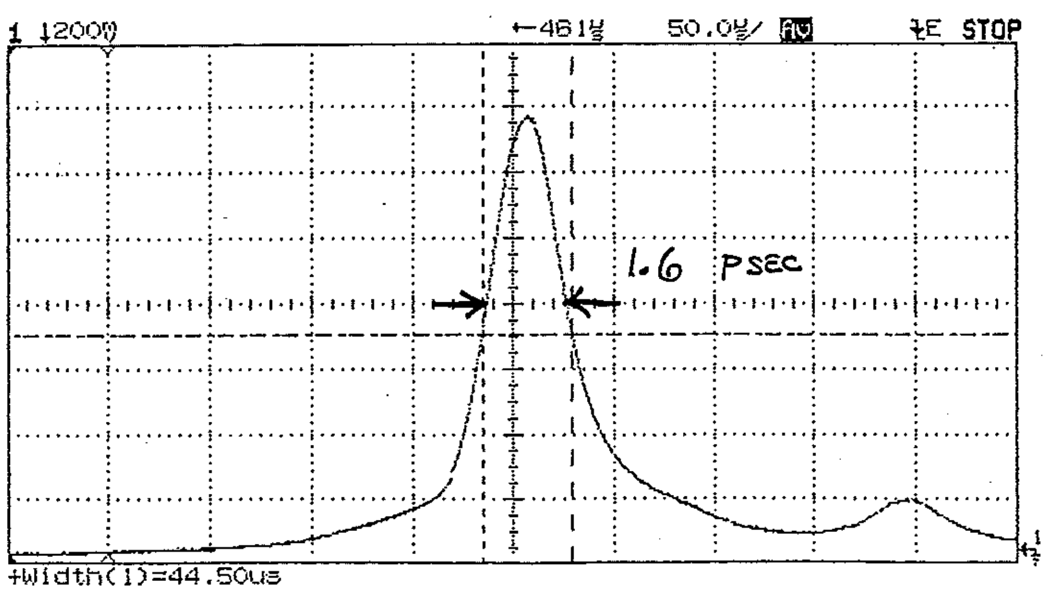
Pulse Length Measurement by Autocorrelation

Compress output from fiber via gratings for monitor.

Autocorrelation: combine pulse with delayed copy.

Frequency doubling in a nonlinear crystal is sensitive to the intensity overlap of two beams.

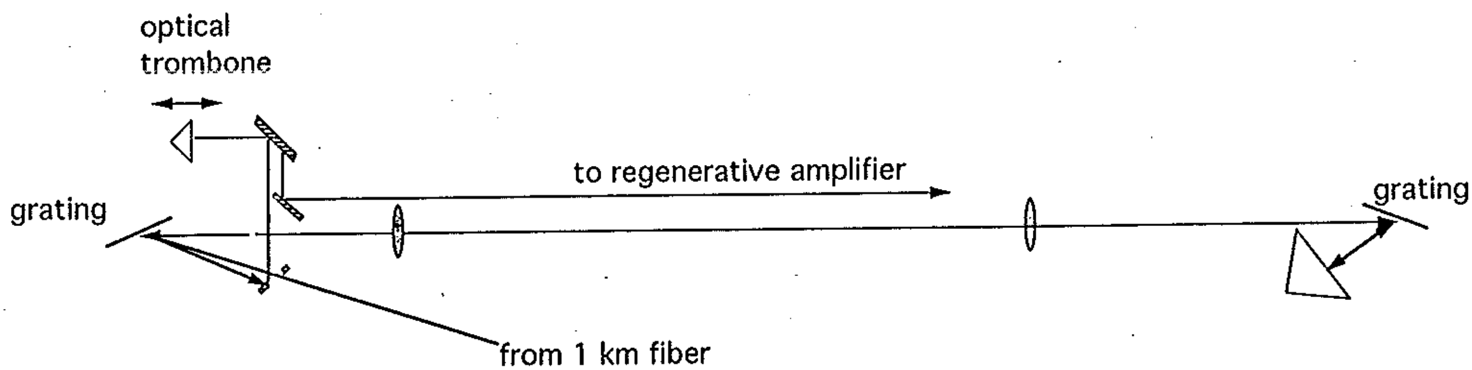




Expansion Gratings and Optical Trombone

Grating pair expands pulse to 1 nsec and completes the chirp.

Optical trombone provides psec adjustment of laser timing.

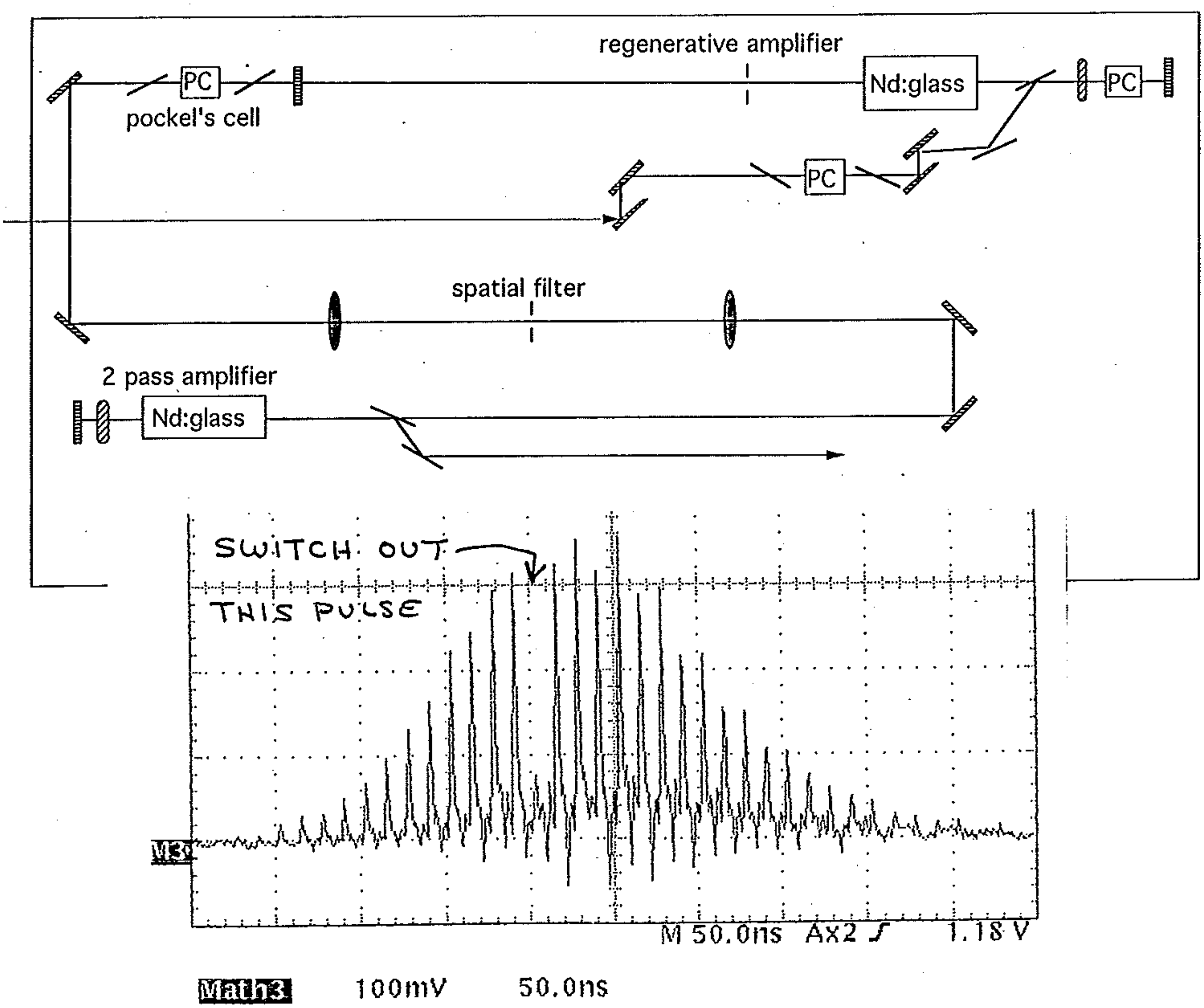


Regenerative and 2-Pass Amplifiers

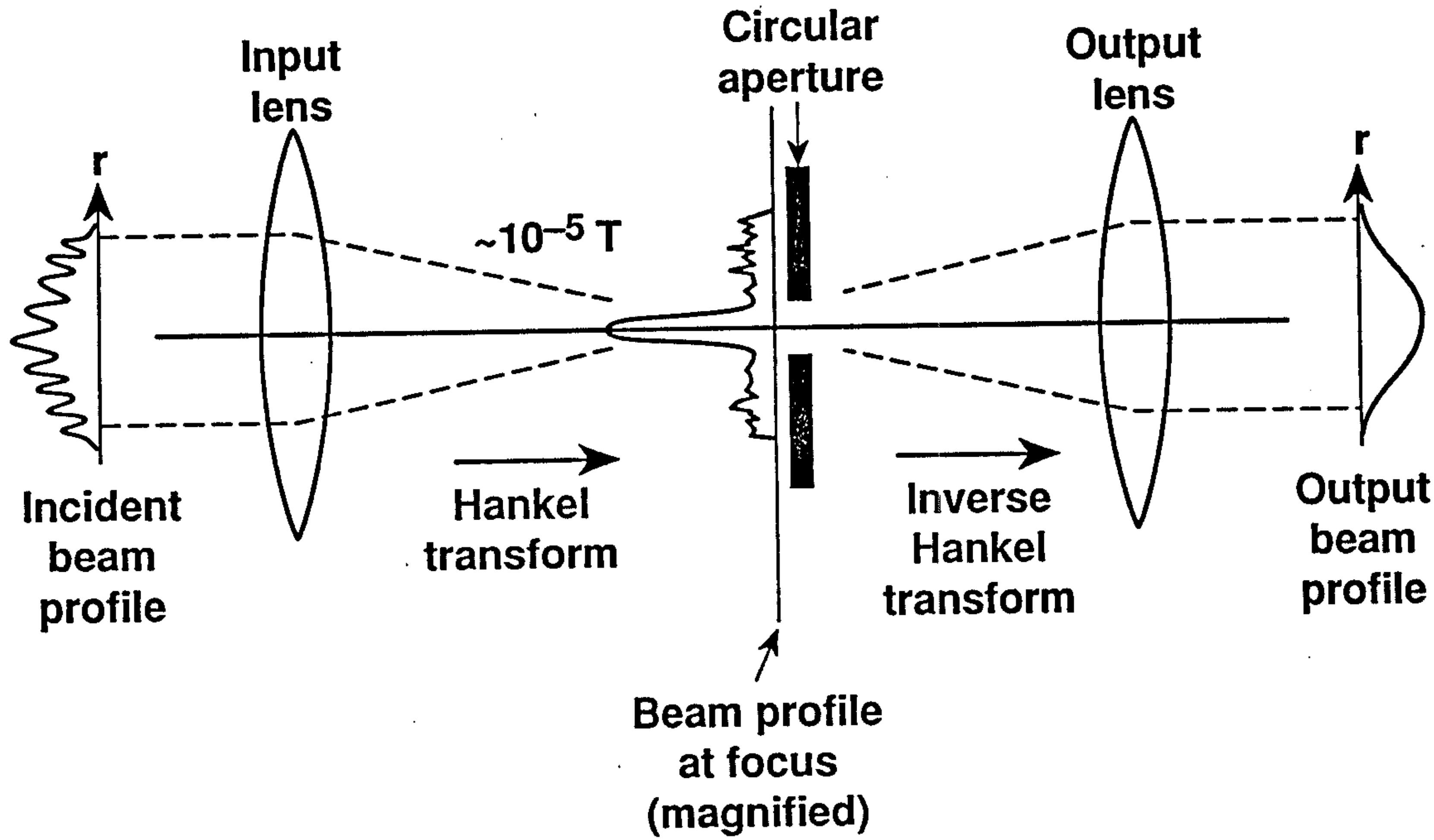
Pockel's cell switches one pulse per sec into the regenerative amplifier.

Gain is 10^6 in 60 passes $\Rightarrow \sim 1$ mJ.

Additional gain of 10 in 2-pass amplifier $\Rightarrow \sim 10$ mJ.



A spatial filter removes the nonfocusable parts of the propagating laser beam

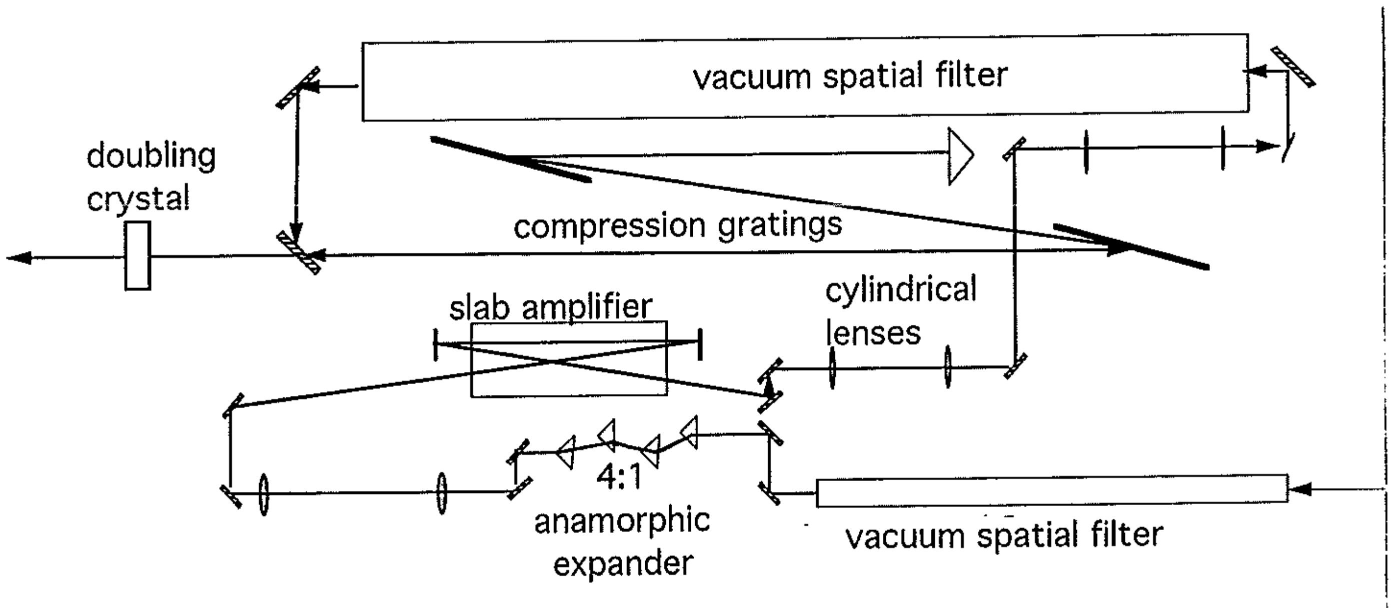


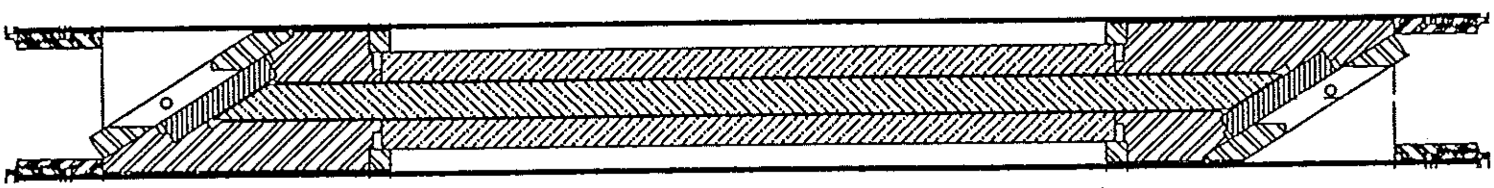
E6291

Slab Amplifier

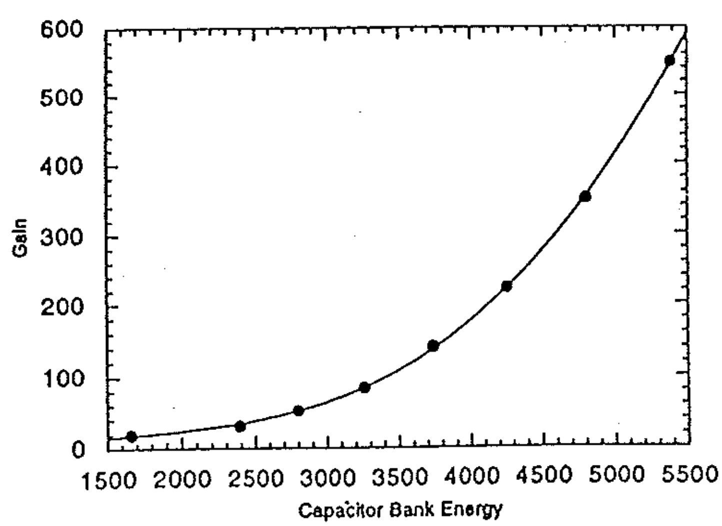
Slab geometry maximizes material near surface for cooling.

Elliptical beam makes 3 passes through slab.





Slab Triple-Pass Gain



Frequency Doubling

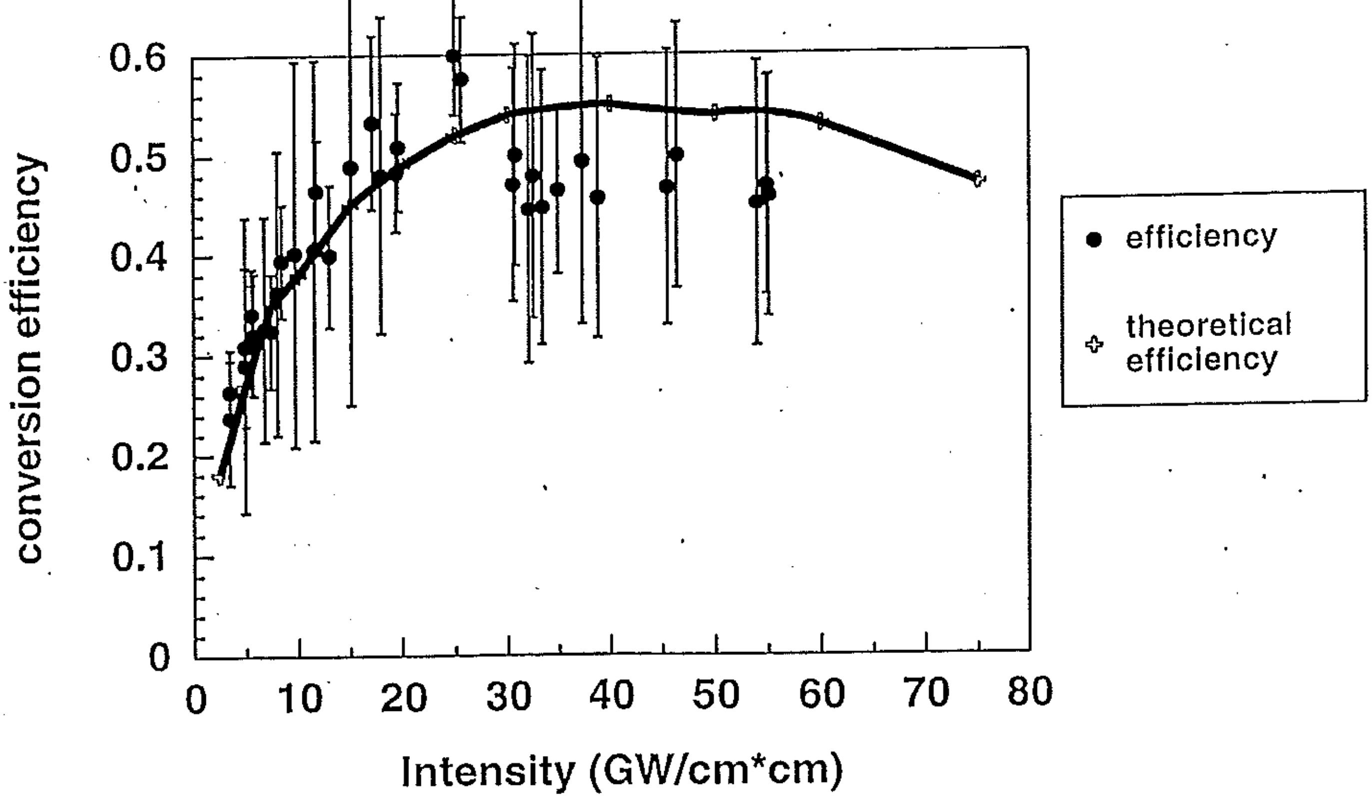
Focused intensity $\propto U/\lambda^2$.

$E \propto \sqrt{I} \propto \sqrt{U}/\lambda$.

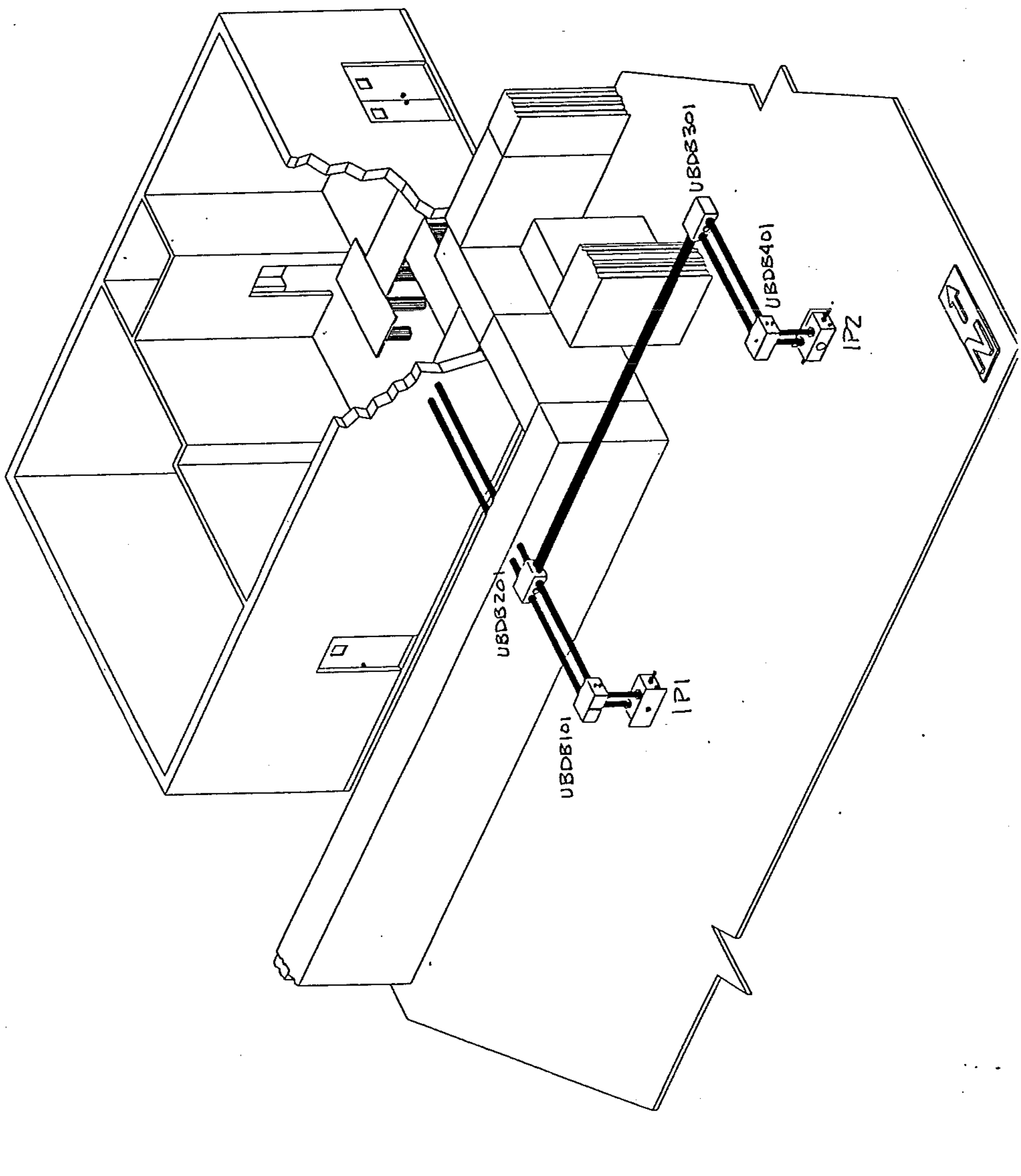
$\Rightarrow$ Gain in peak field if can double frequency with $> 25\%$ efficiency.

Frequency doubling conversion efficiencies of up to 50% were obeserved with a 8 mm thick KDP crystal

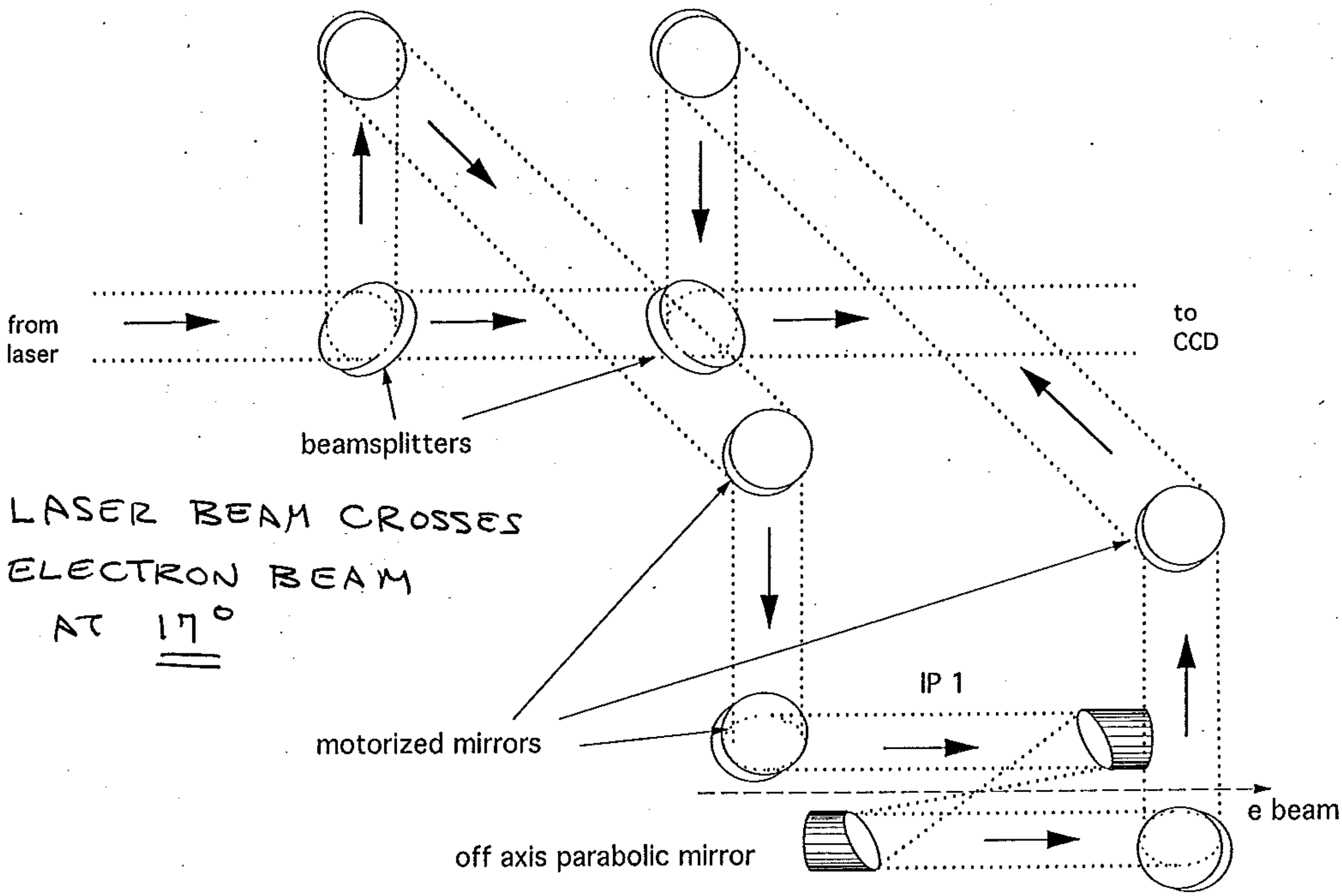
UR LLE



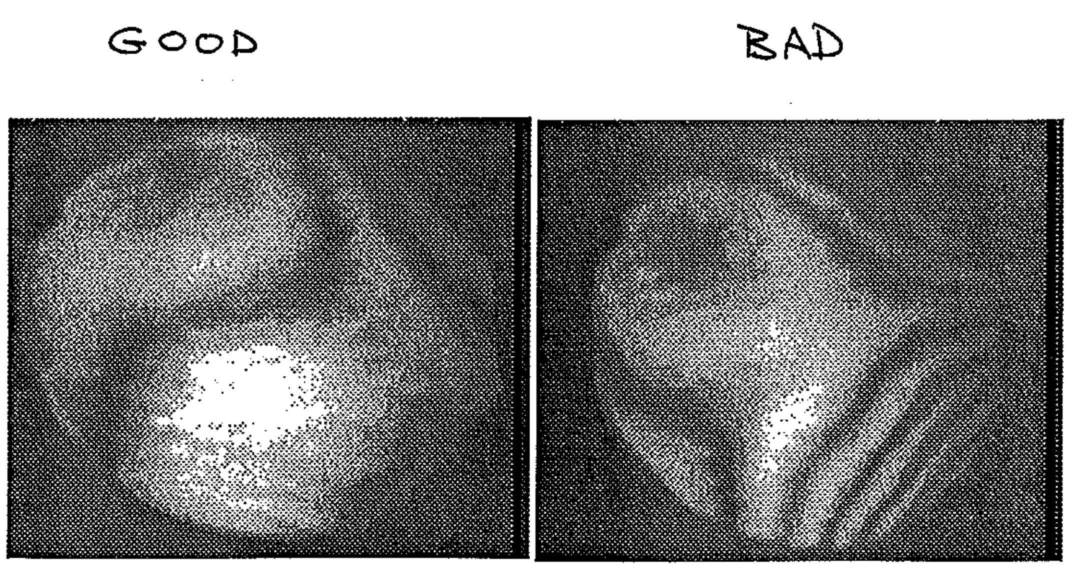
perspective view of optics transport



Laser Focus Via Off-Axis Parabolic Mirror



Interferometer monitors quality of optics transport.



What is the Laser Intensity?

$I = 10^{19}$ W/cm$^2 \Rightarrow E = 1000$ V/Å.

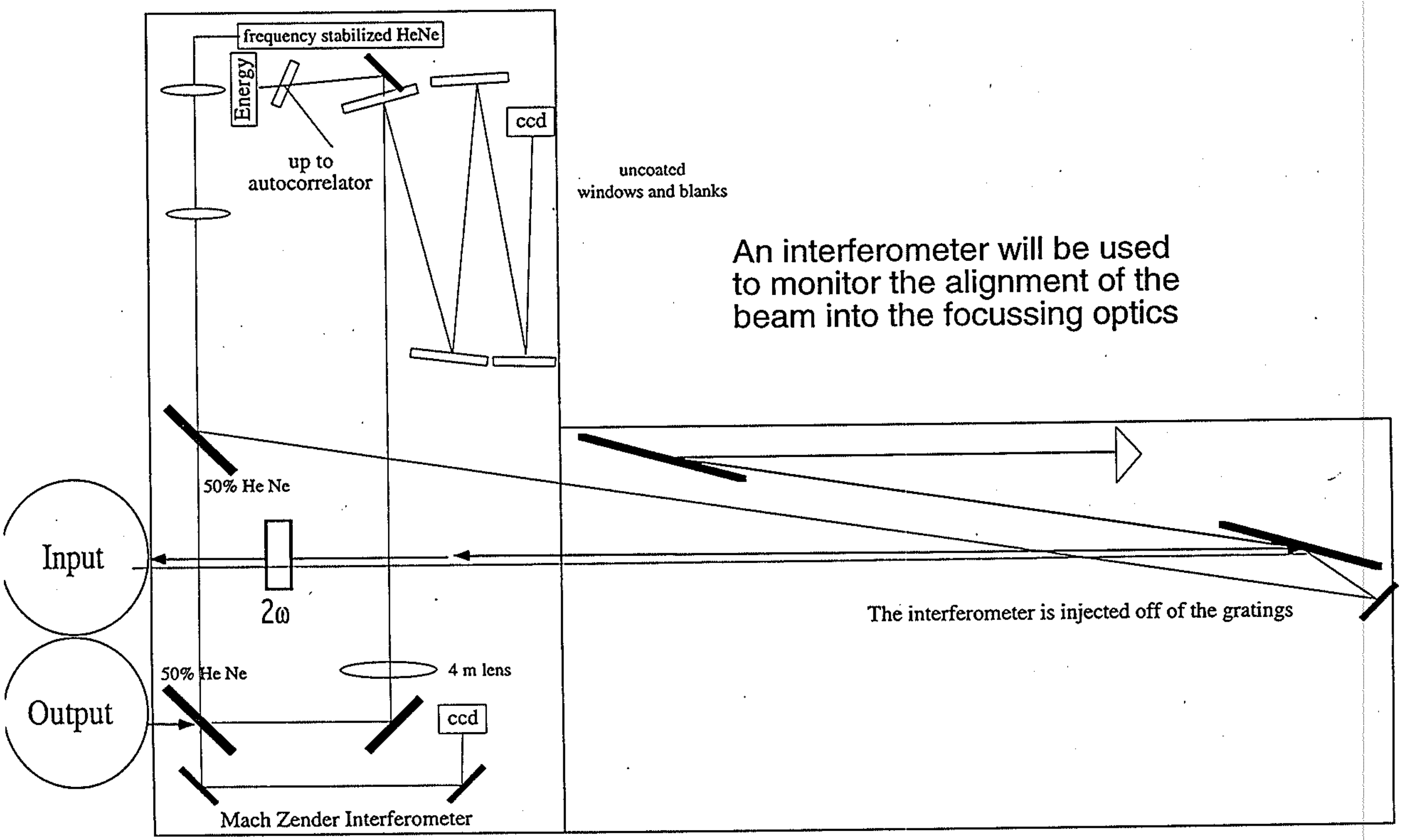
$\Rightarrow$ atoms cannot survive in laser focus!

1. Indirect measurement: $I = U/A\Delta t$.

   Measure U, A and Δt separately.

2. Direct measurement: multiphoton ionization of gas.

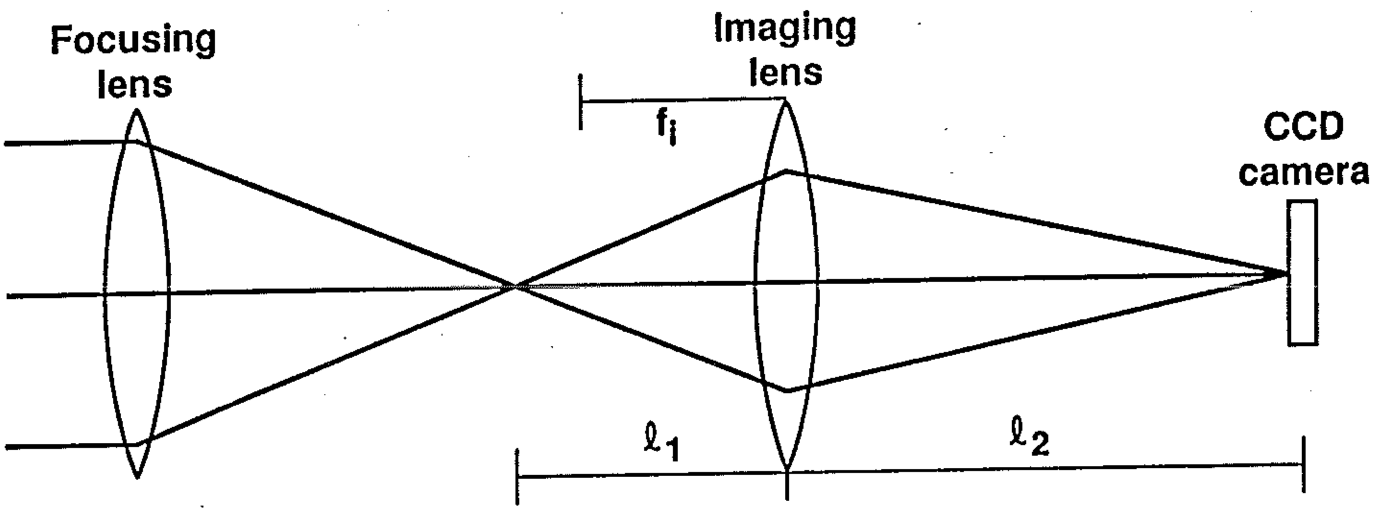
The energy, pulse width, and focal spot area of the 1 Hz, 2 TW laser system will be measured every shot



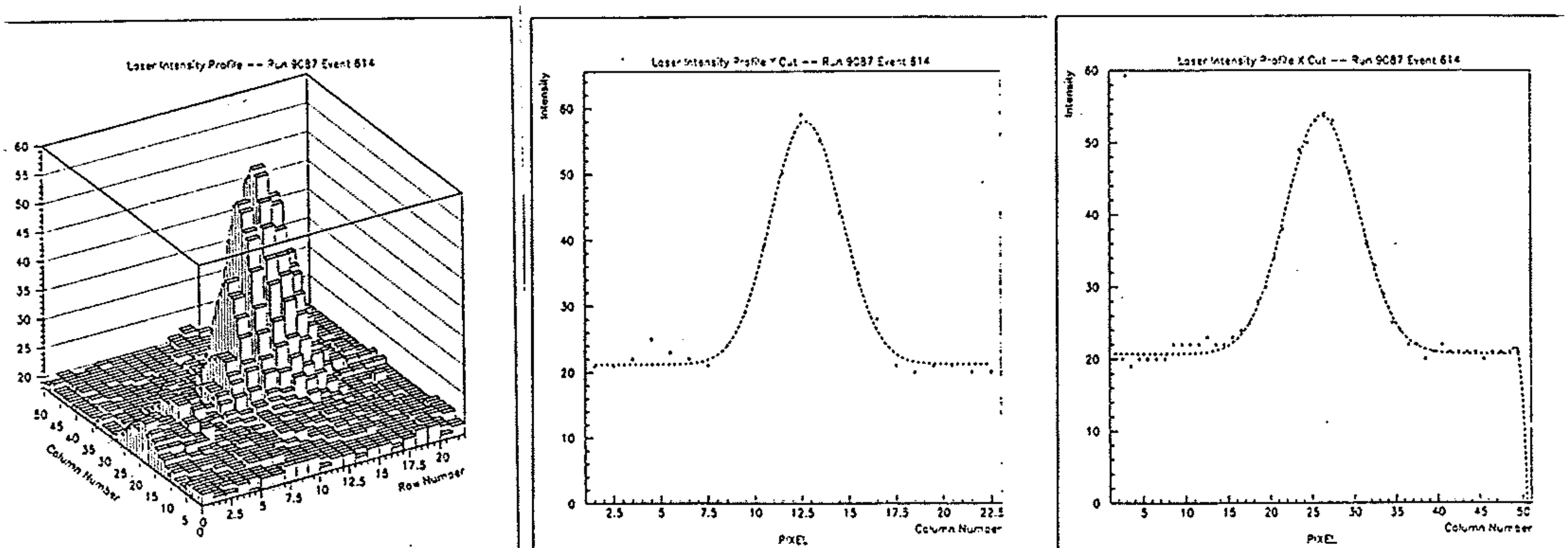
An interferometer will be used to monitor the alignment of the beam into the focussing optics

Spot-Area Measurement

The focal spot area is measured by imaging the focal plane



$$\text{Magnification} = \frac{\ell_2}{\ell_1} = \frac{\ell_2 - f_i}{f_i}$$



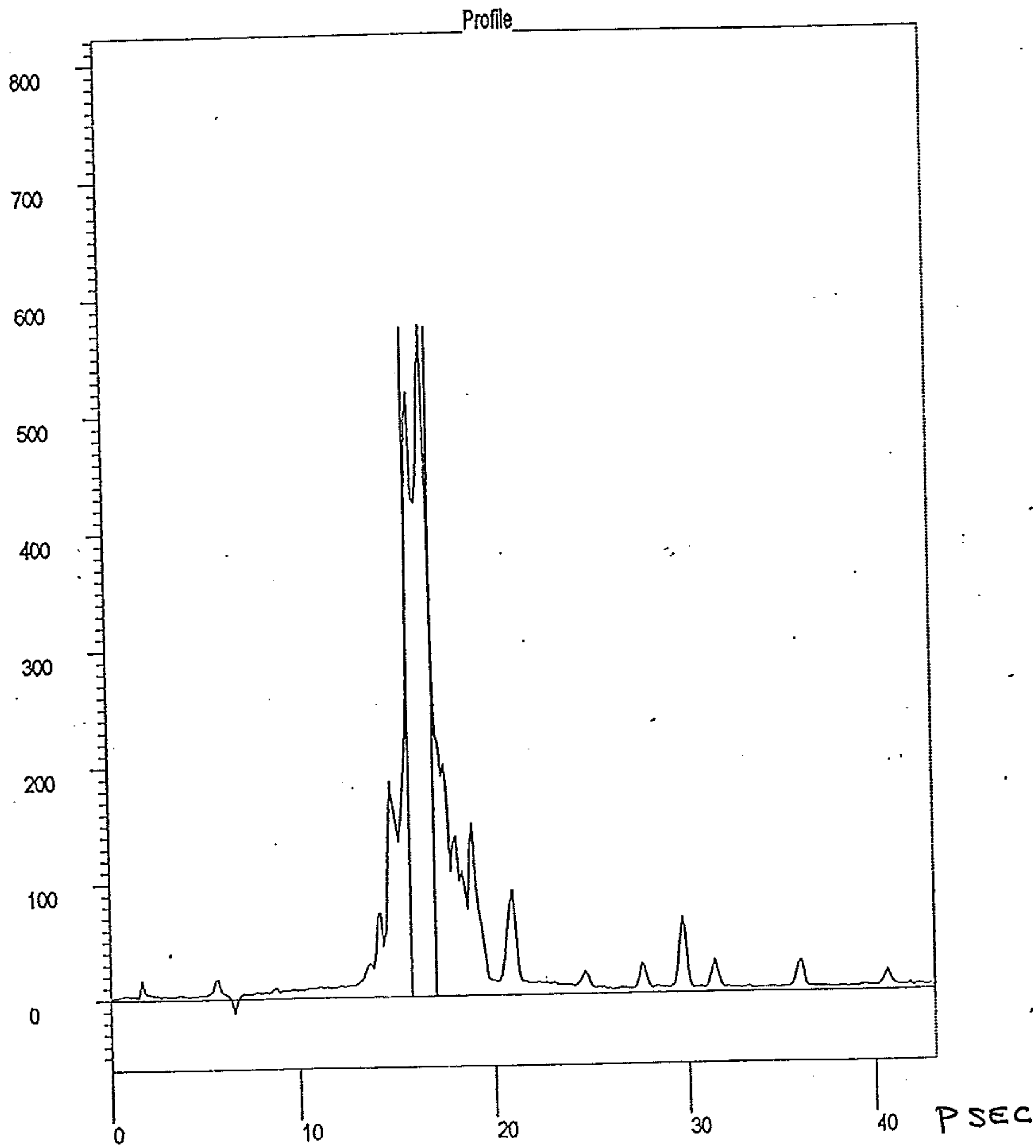
↖ SPOT AREA = $30\ \mu m^2$

Steak Camera Measurement of Pulse Width

Can only be made occasionally.

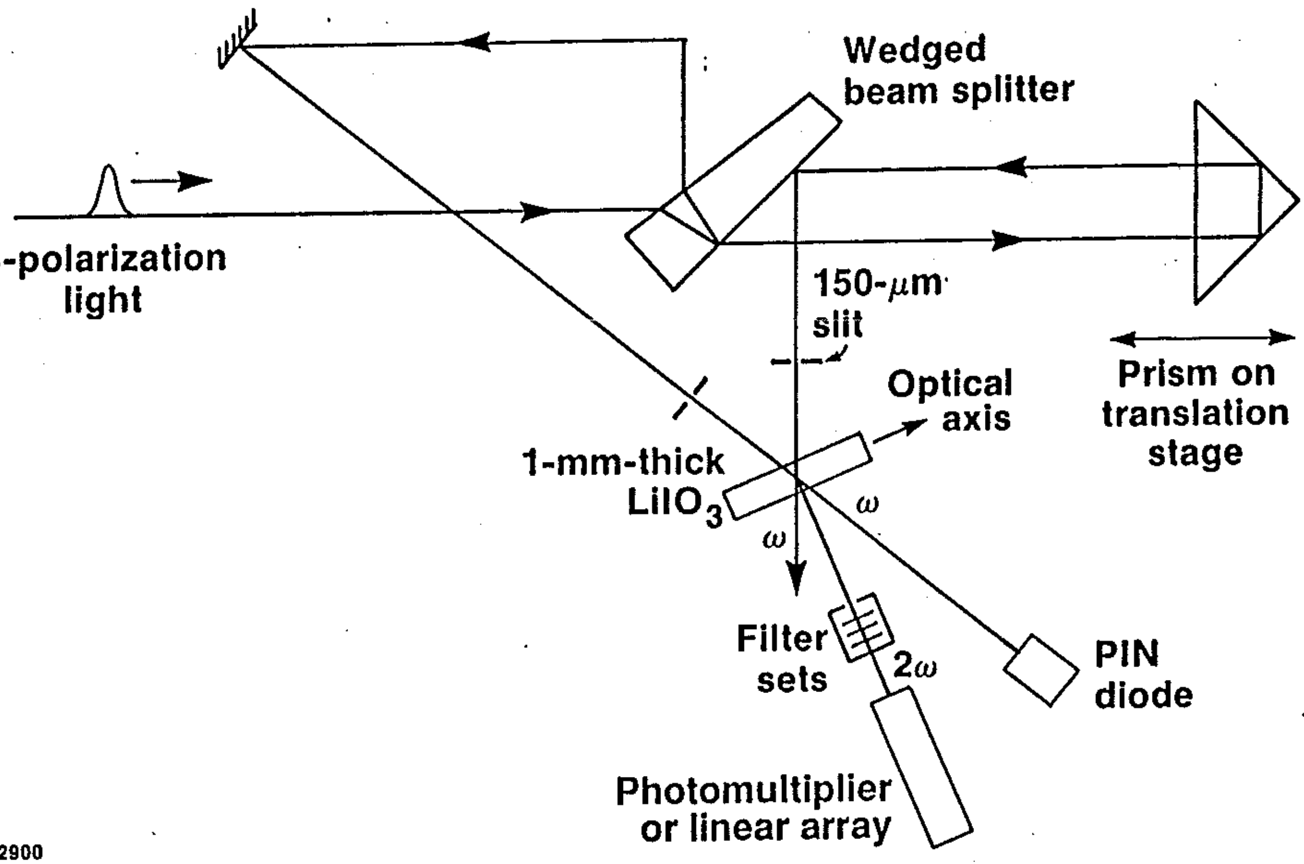
Hamamatsu FESCA 500

FWHM=1.3 ps

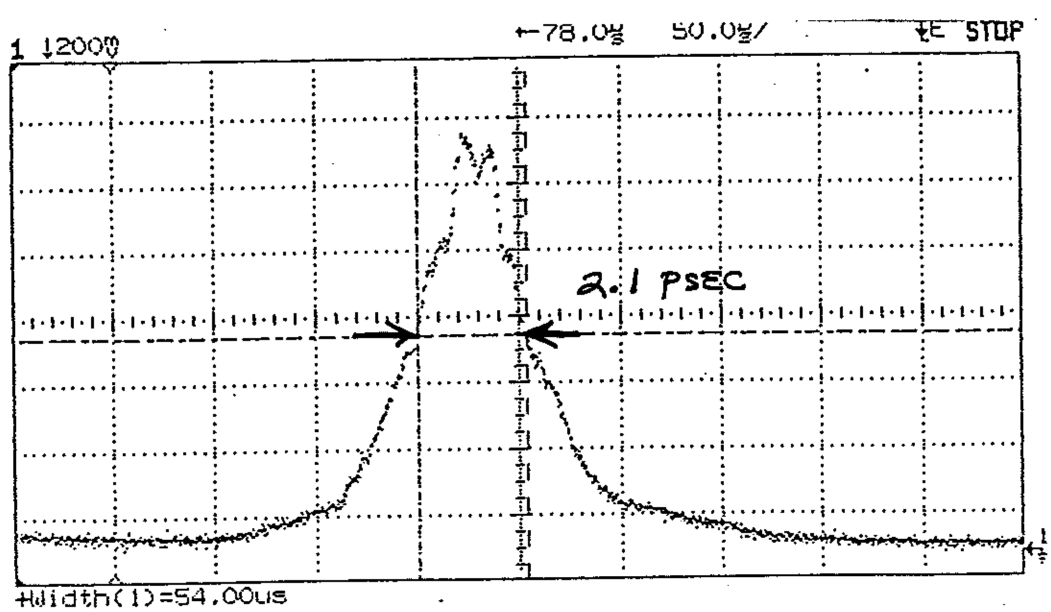


Shot-by-Shot Pulse Width Measurement

The pulse width is measured using a single shot autocorrelator

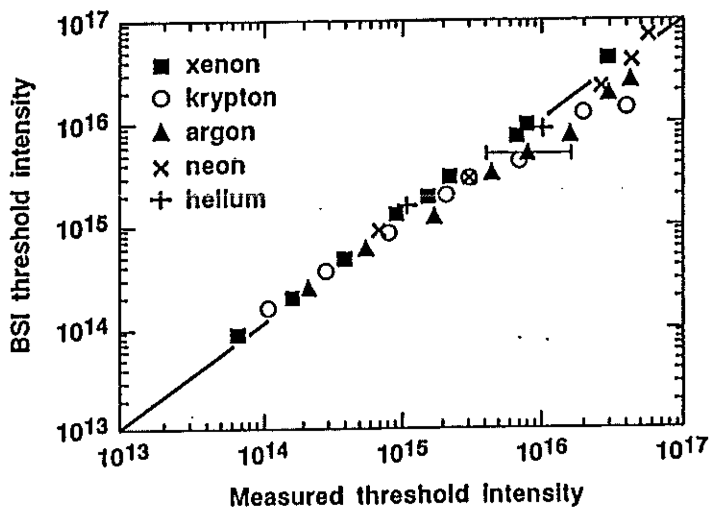


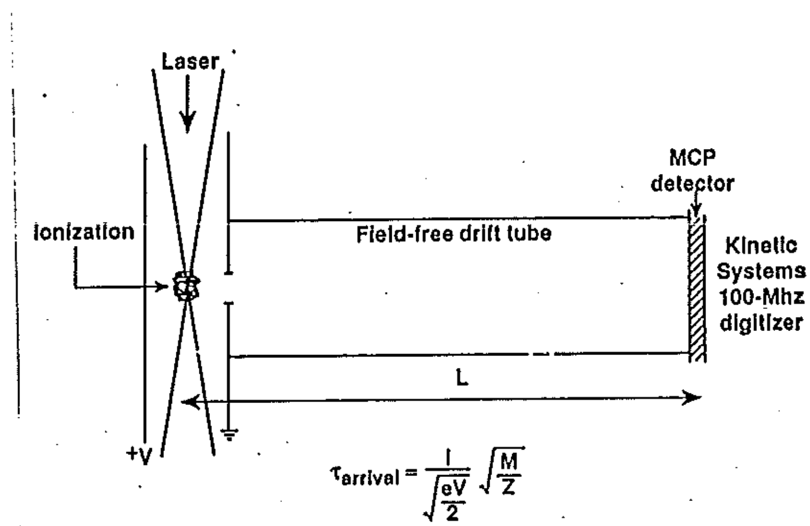
G2900



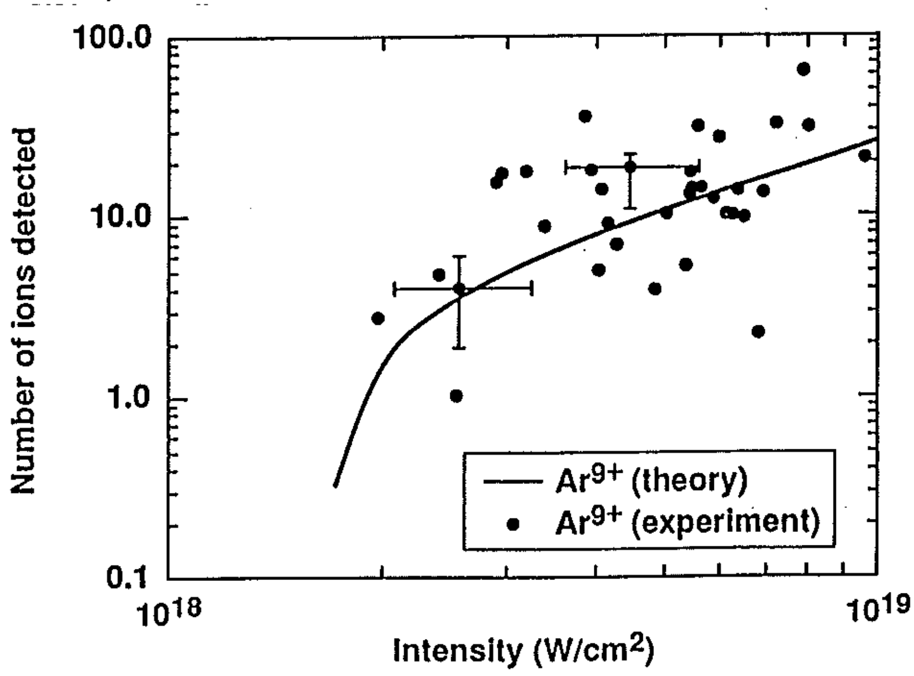
Multiphoton Ionization of Noble Gases

'Barrier suppresion ionization' model well confirmed up to $I = 10^{17}$ W/cm^2.





Data for ionization at I up to 10^{19} W/cm^2 (indirect measurement) agree well with model.



How Well Do Laser and e-Beams Overlap?

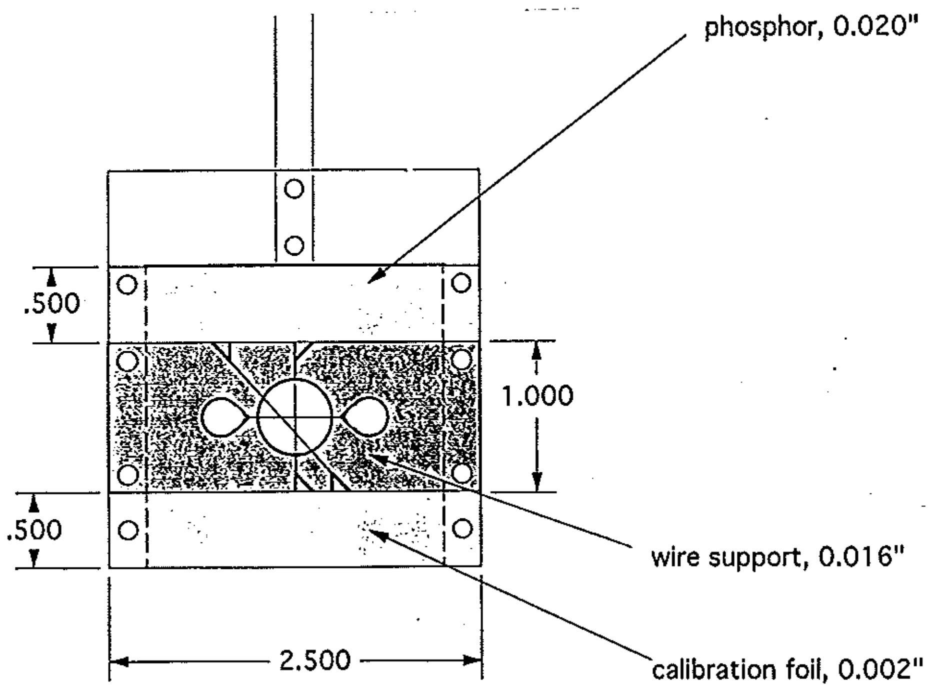
Spatial Overlap

IP1 box moves 10's of μm diurnally relative to e-beam.

Past: Initial alignment via phosphor screen.

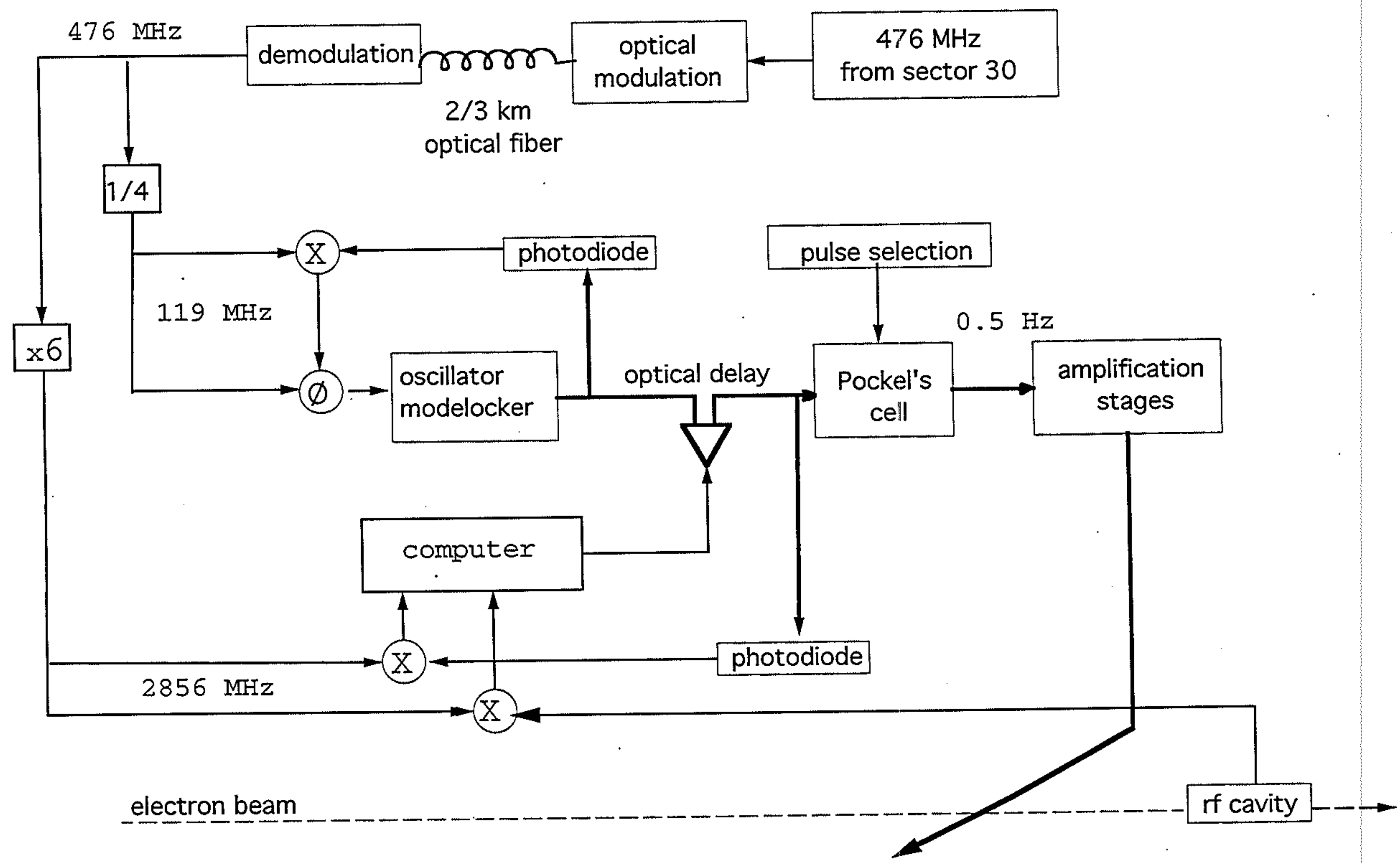
Occasional x and y scans of e-beam across laser.

Future: Precision cross hair at IP1 will locate laser focus in x, y and z, and e-beam in x and y.



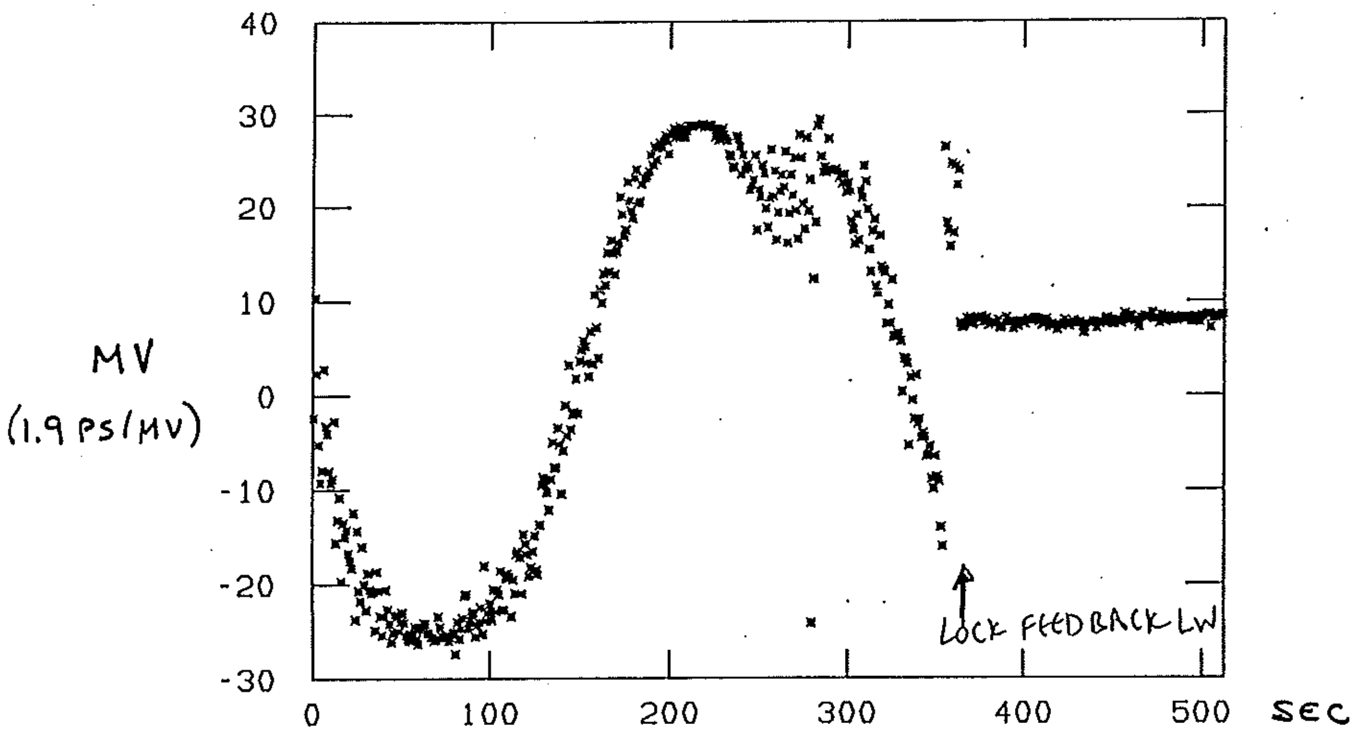
Needed: beam position monitor fixed relative to IP1 box for shot-by-shot measurement.

Laser - electron synchronization
Goal: 1 ps

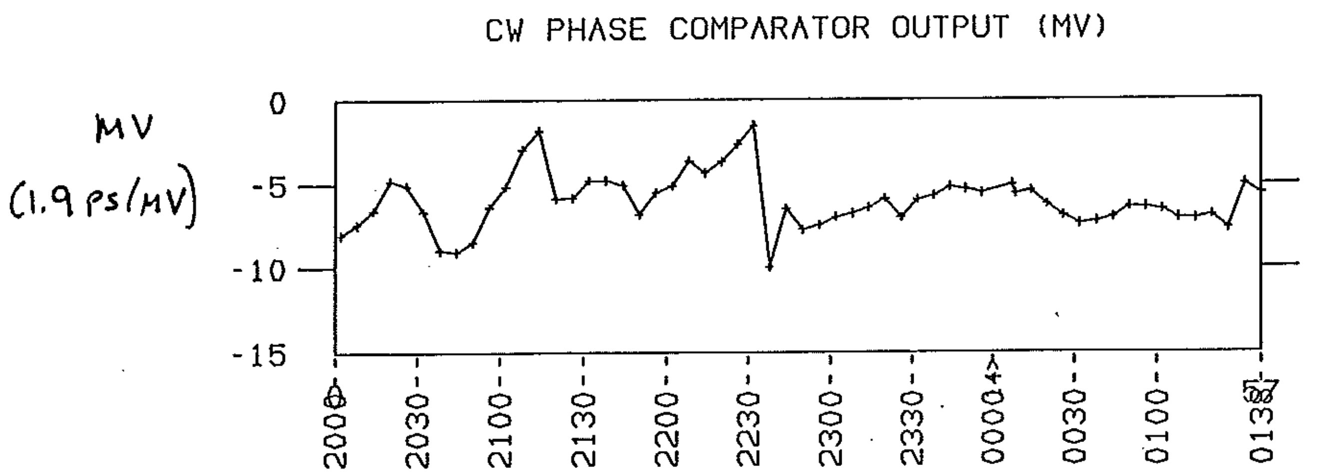


The Laser is Locked to the Linac RF

Phase locking via output of phase comparator between RF and photodiode observing laser beam.

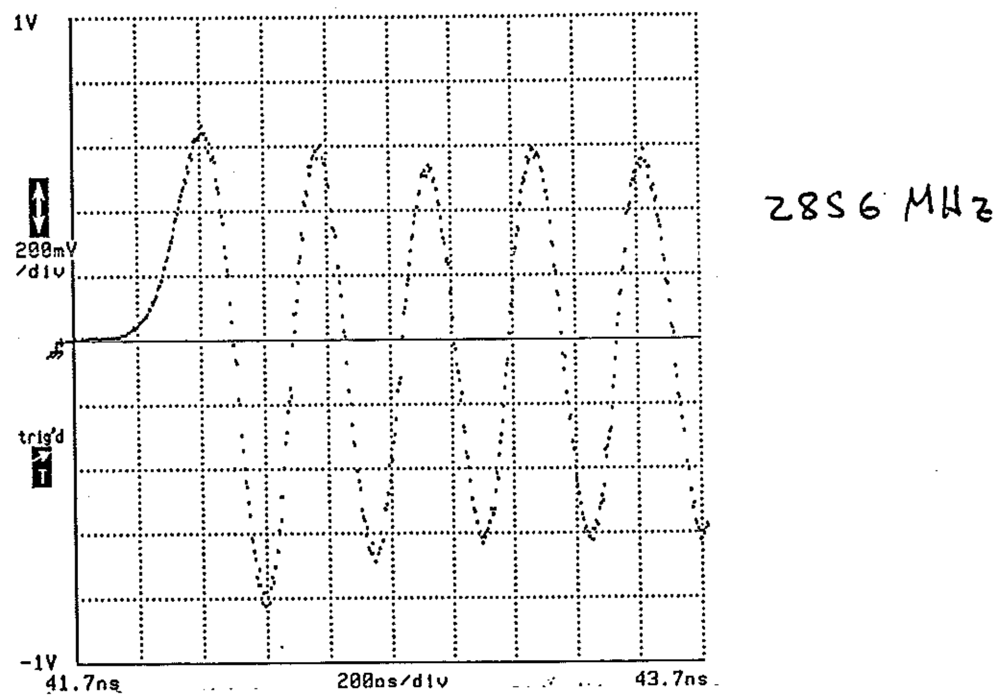


1-psec locking obtained on scale of minutes, but long term drifts.

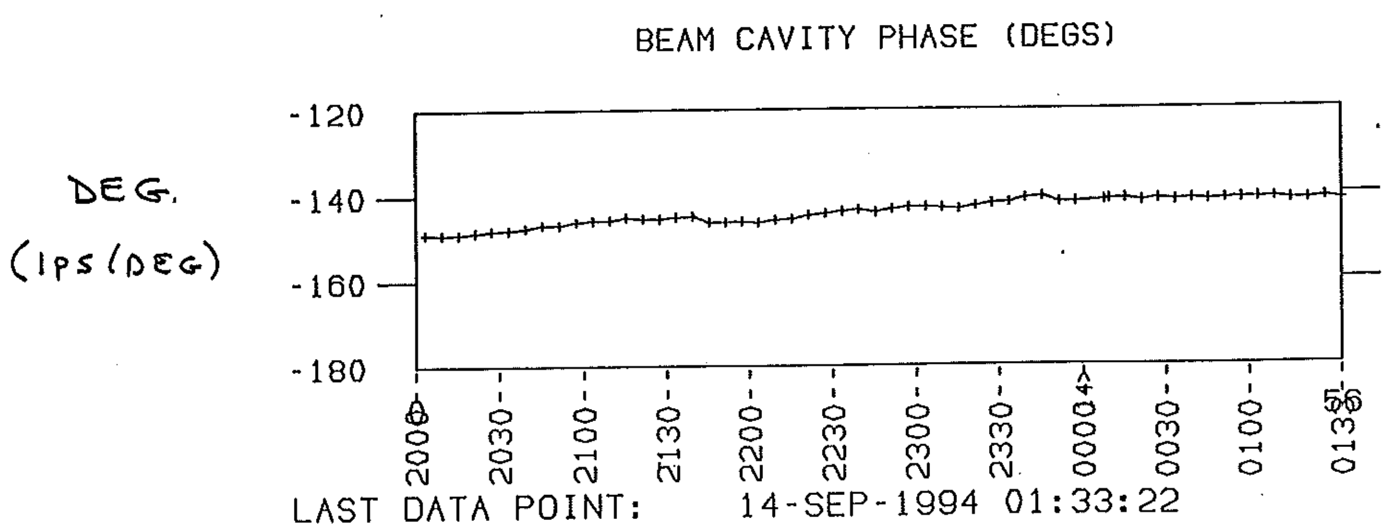


The Ringing Cavity

An RF cavity downstream of IP1 is excited by the *e*-beam to provide a shot-by-shot phase reference.



The 476-MHz RF derived from Sector 30 is well locked to the ringing cavity in the short term, but long-term drifts.

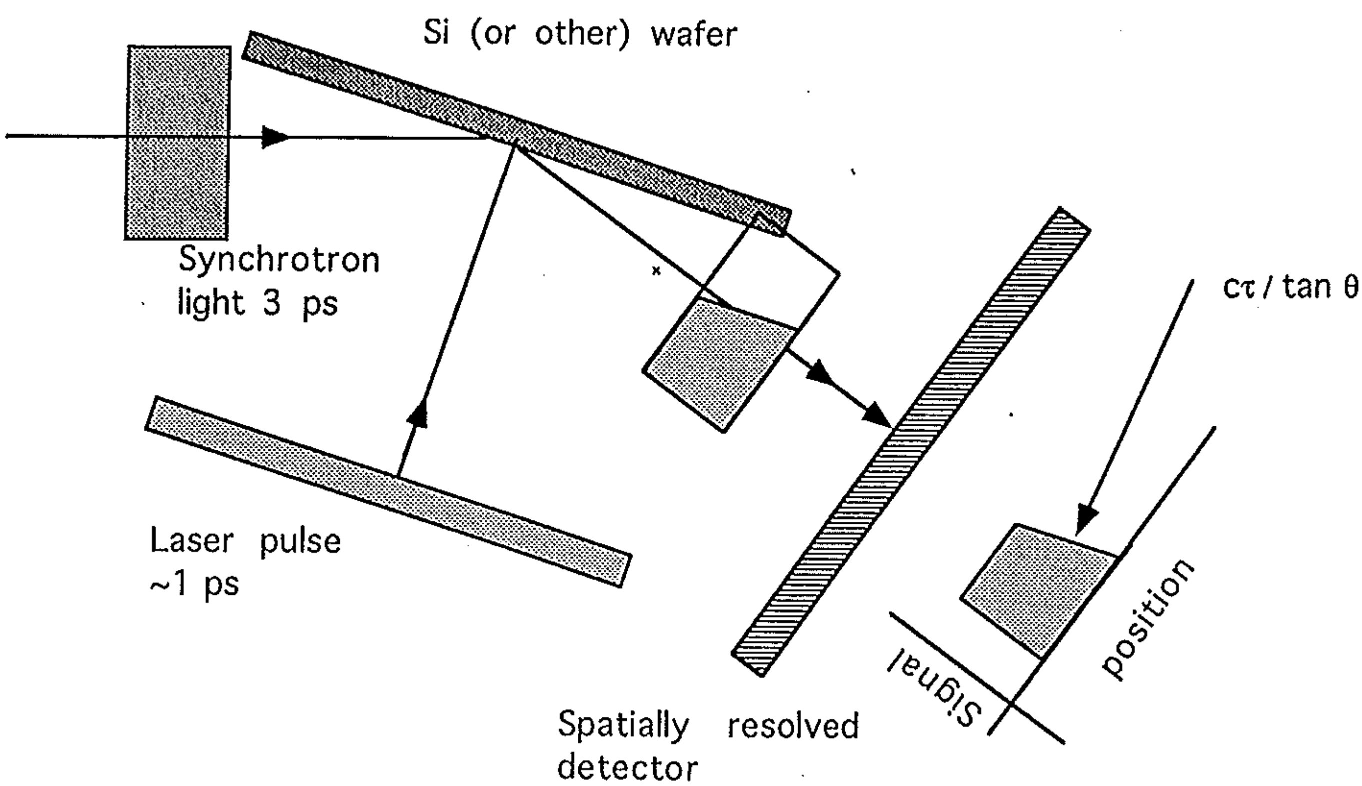


Needed: Shot-by-Shot Timing Measurement

Proposal: Measure time of optical synchrotron radiation of e-beam (largely due to the Earth's magnetic field!).

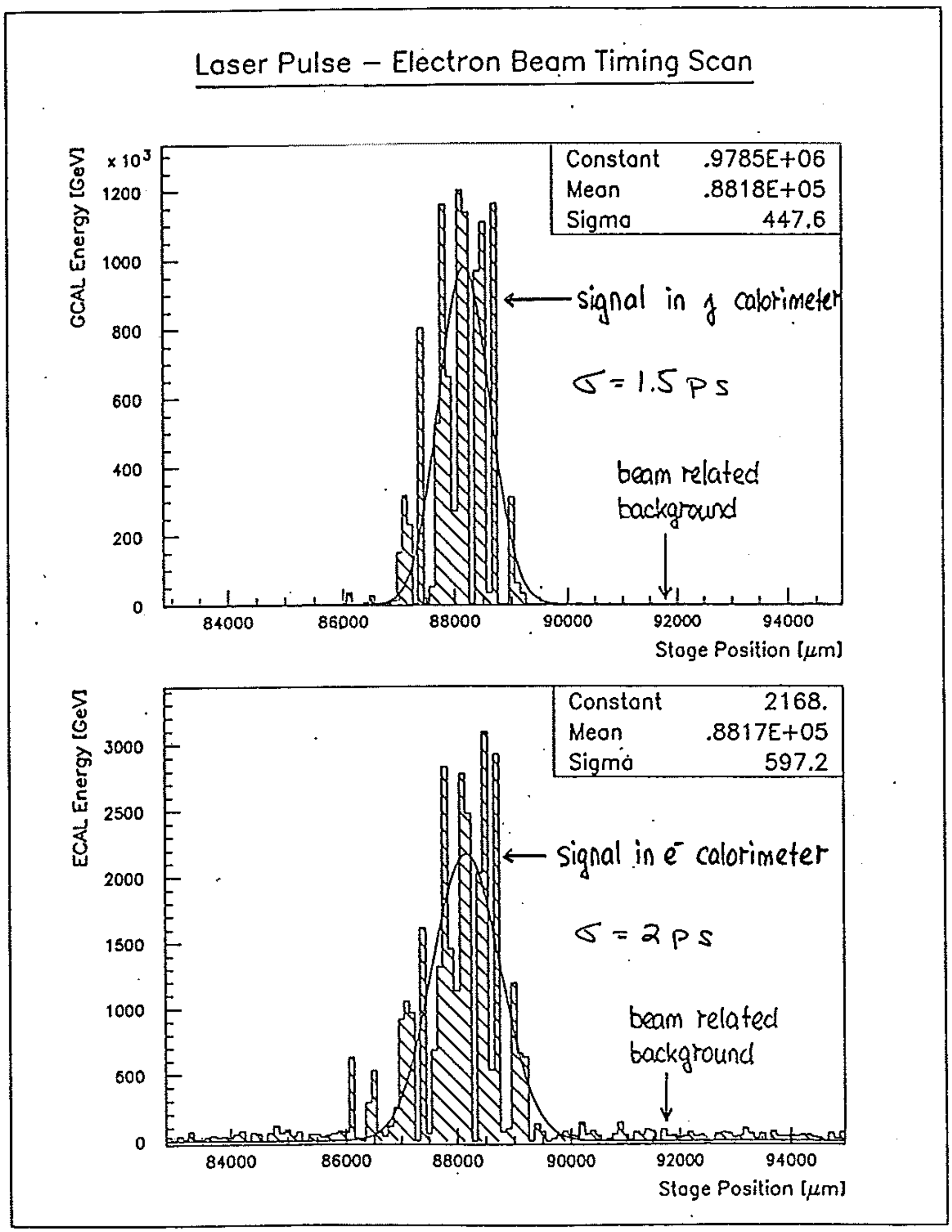
Laser pulse will be used to switch reflectivity of a Si wafer on psec time scale.

Tilted, time-dependent mirror $\Rightarrow$ translate time into space.

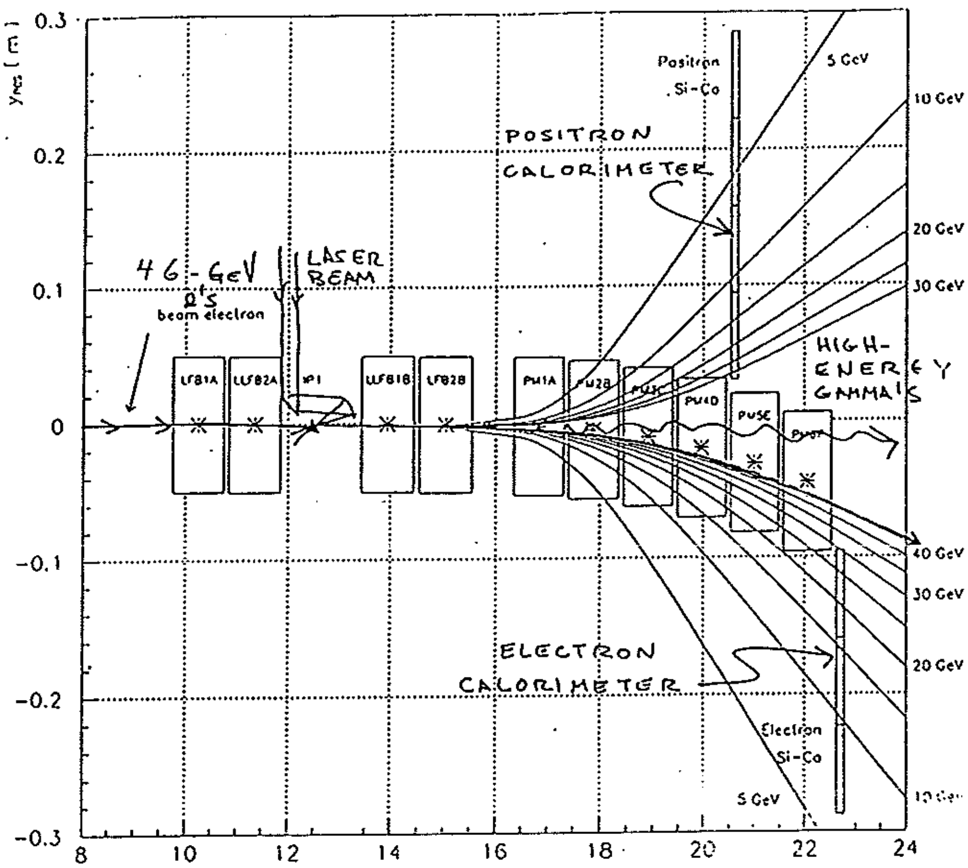


Overlap Strategy

In absence of shot-by-shot confirmation of space-time overlap, we must do frequent (continuous?) scans in both time and space during data taking.



Silicon Calorimeters

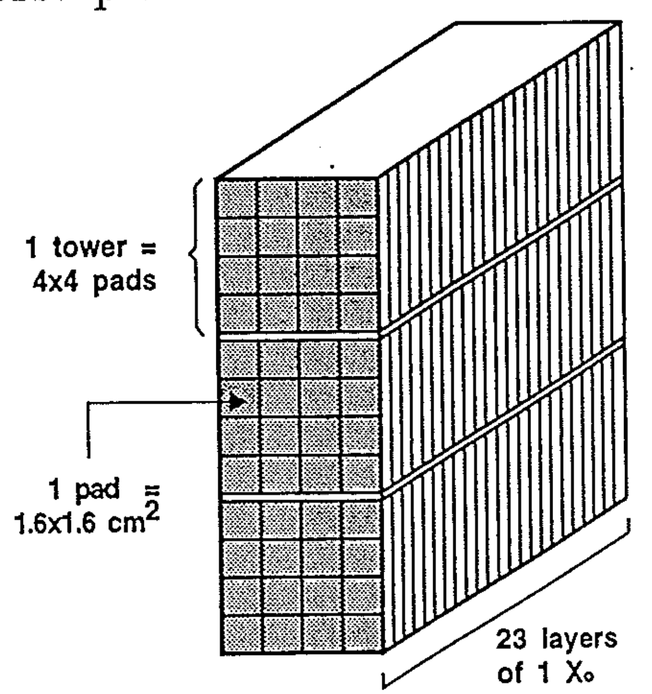


Silicon-tungsten calorimeters: pads 1.6×1.6 cm^2.

E-cal: 48 towers

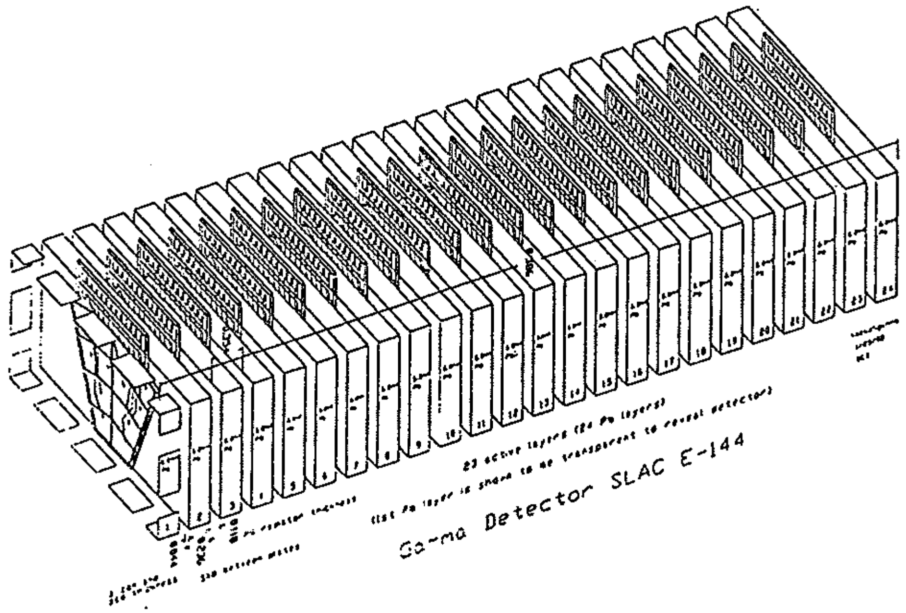
P-cal: 64 towers

3 longitudinal segments



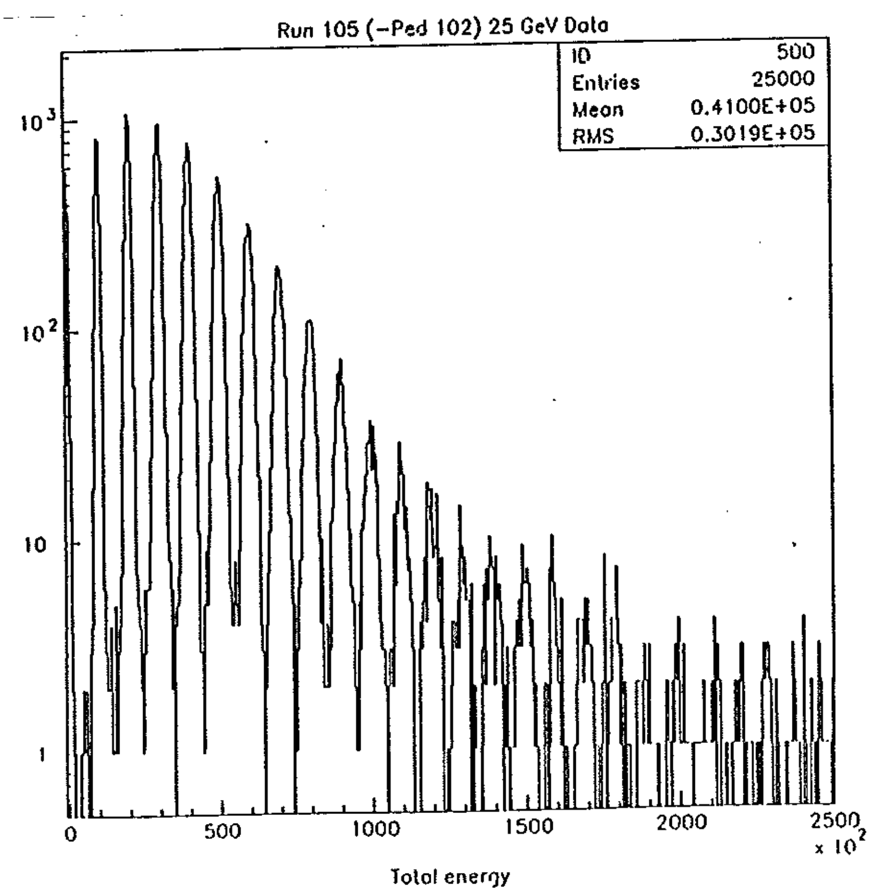
Readout using RABBIT electronics from FNAL E-706.

G-cal = Pb-Si, assembled from SLD spares.



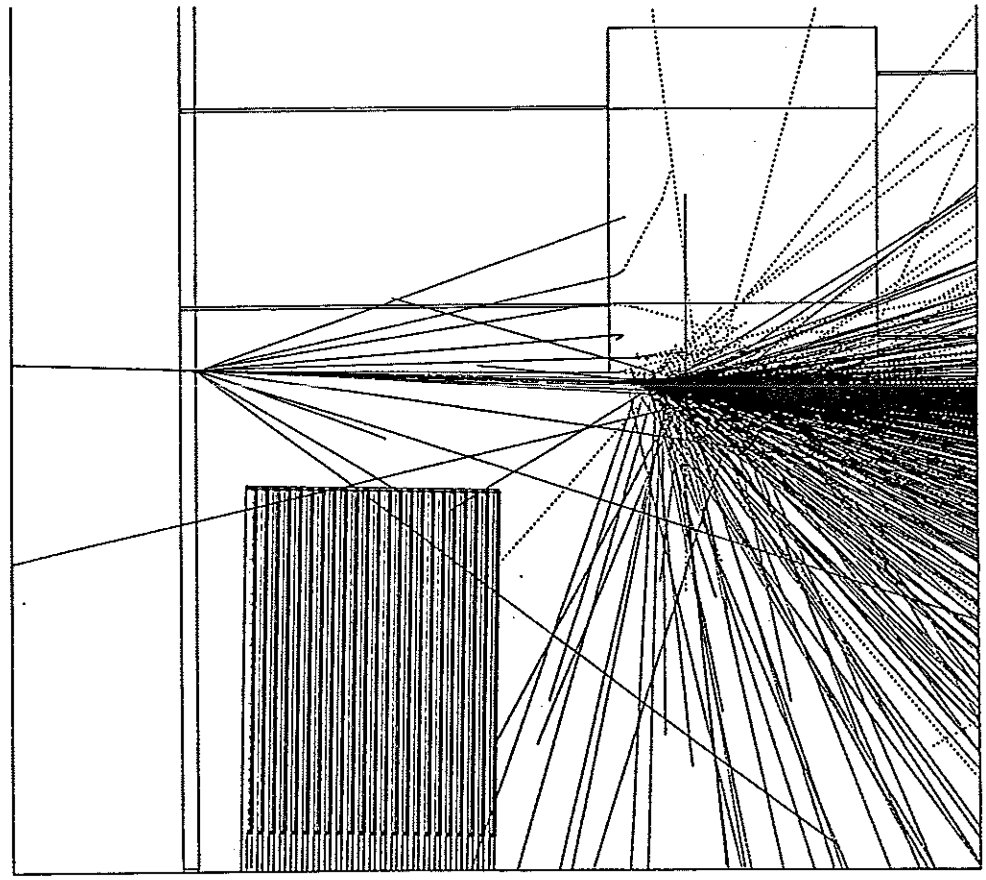
Calibrations in A-line and FFTB parasitic to SLD running.

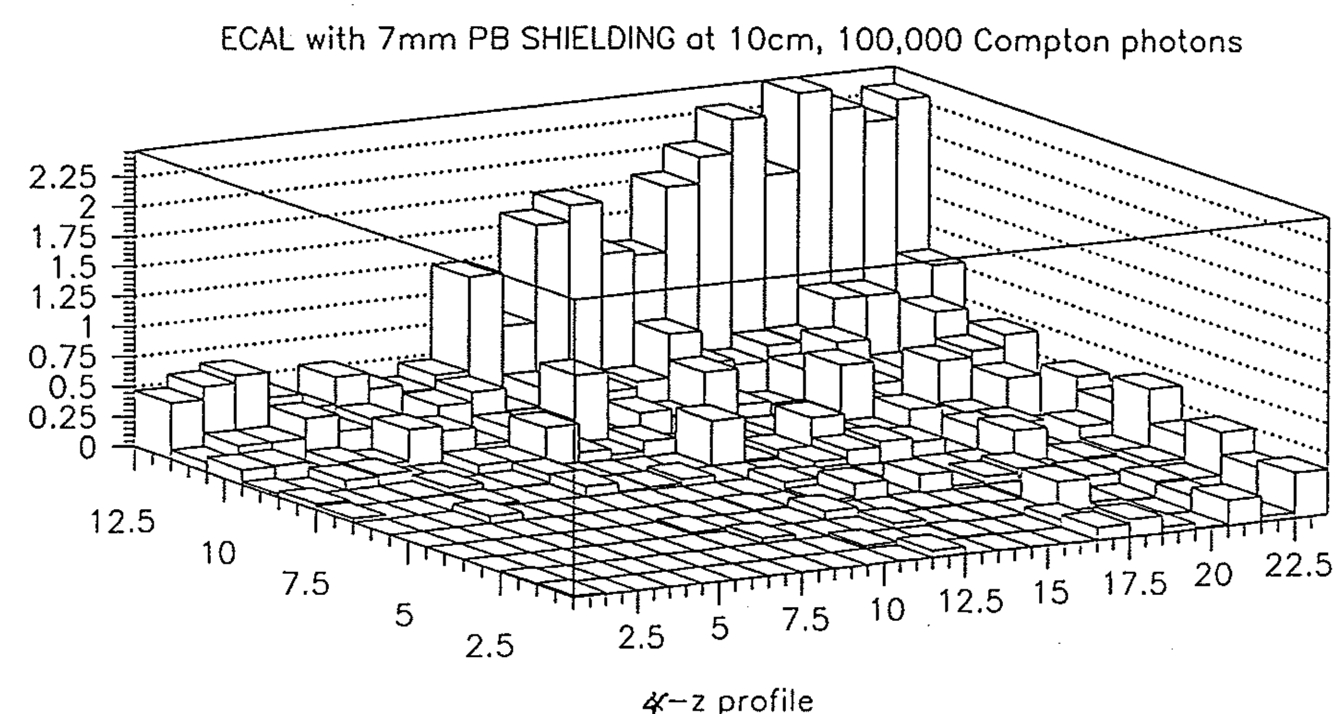
Resolution $\approx 26\%/\sqrt{E}$.



Compton-Scatter Electrons Hit the Beampipe

Even with shielding have ~ 300 GeV/10^6 Comptons.





CCD Pair Spectrometer

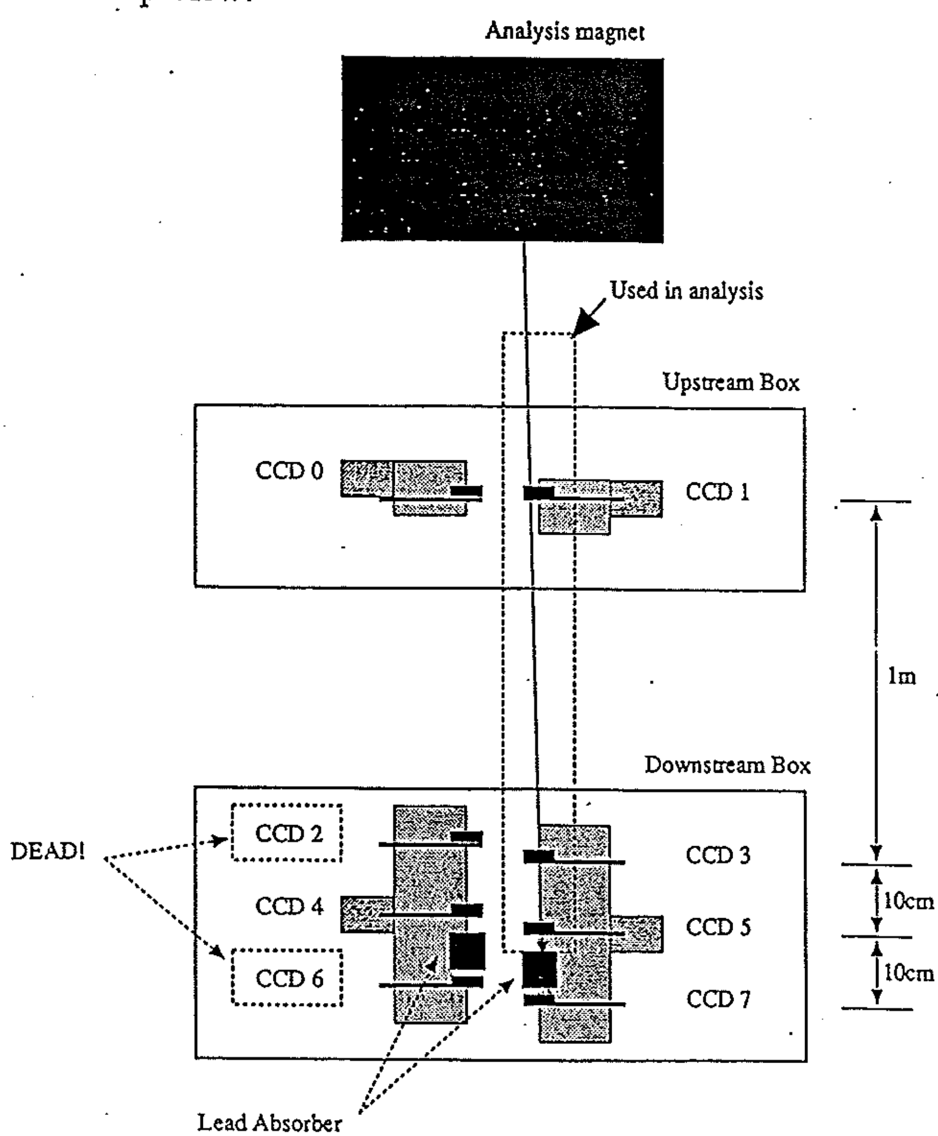
5D36 magnet followed by two arms of 4 CCD's each.

770 × 1150 pixels per CCD; pixel size = 22.5 μm.

$\Rightarrow$ Mass resolution $\approx$ 15 keV at $M_{e^+e^-} = 2$ MeV/c^2.

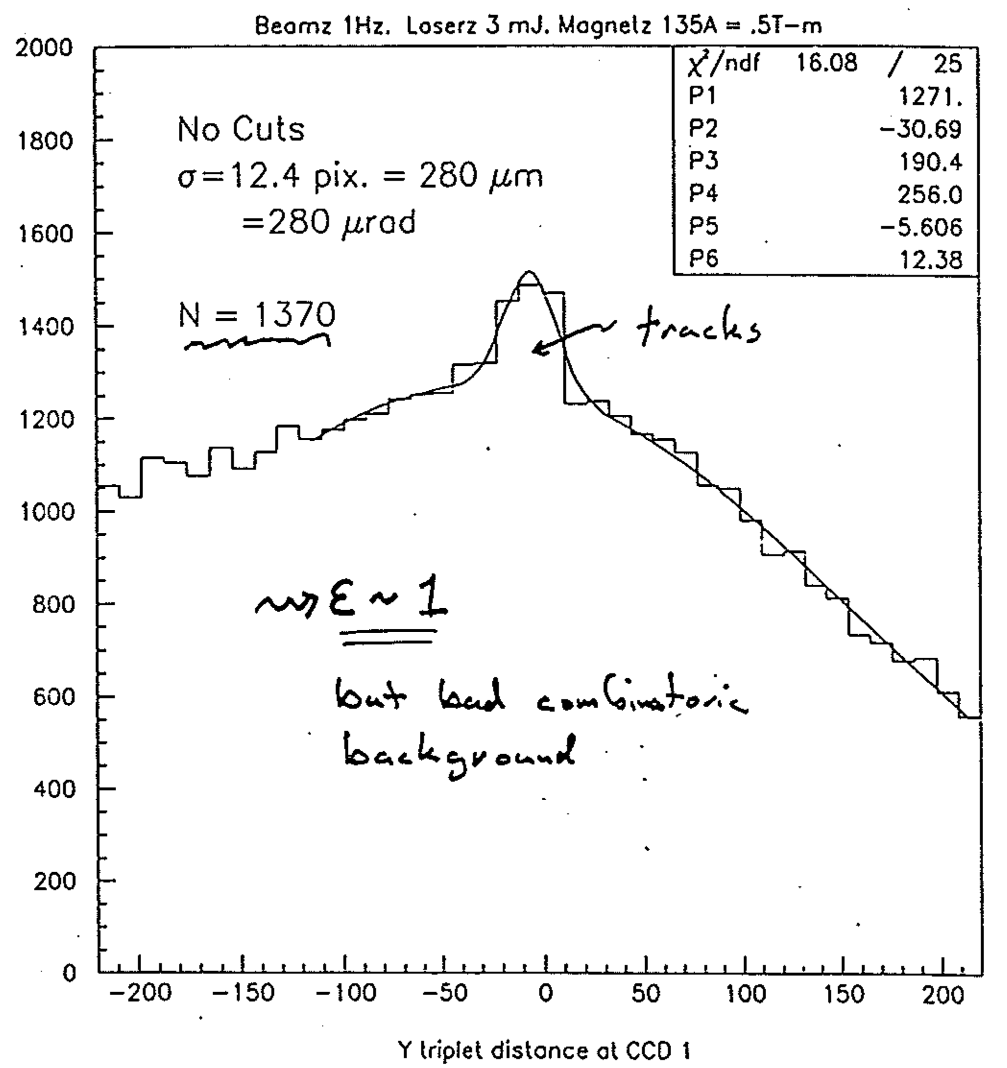
Readout via PC-based frame grabbers.

Top View:



CCD Test

Can find tracks in events with $\sim$ 100 tracks/CCD.



But will not be able to correlate e^+ and e^- tracks in events with more than 2-3 pairs.

Full CCD spectrometer to be installed for March '95.

Compton-Rate Monitors

The linear Compton-scatter rate is our primary measure of e-laser overlap.

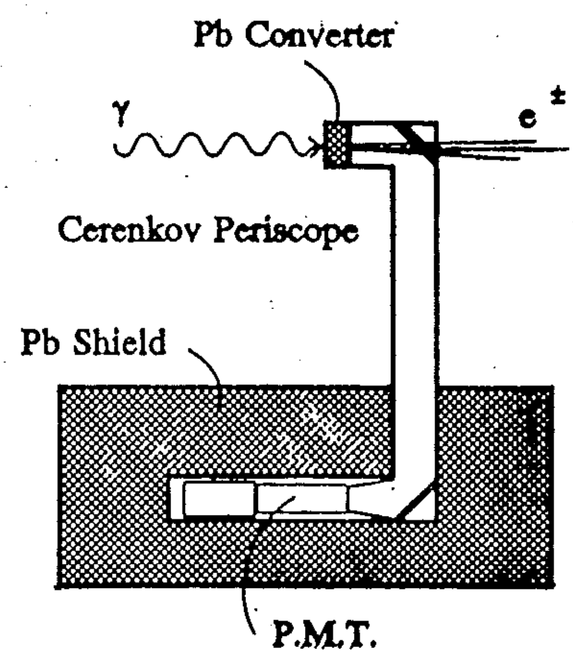
It is used to normalize the nonlinear signal.

At high rates, E-cal must be removed from path of linear Compton scatters.

G-cal, CCM1 and CCM2 monitor Compton photons.

EC31 and EC37 monitor scattered electrons.

CCM1, CCM2, EC31 and EC37 are gas Čerenkov counters.

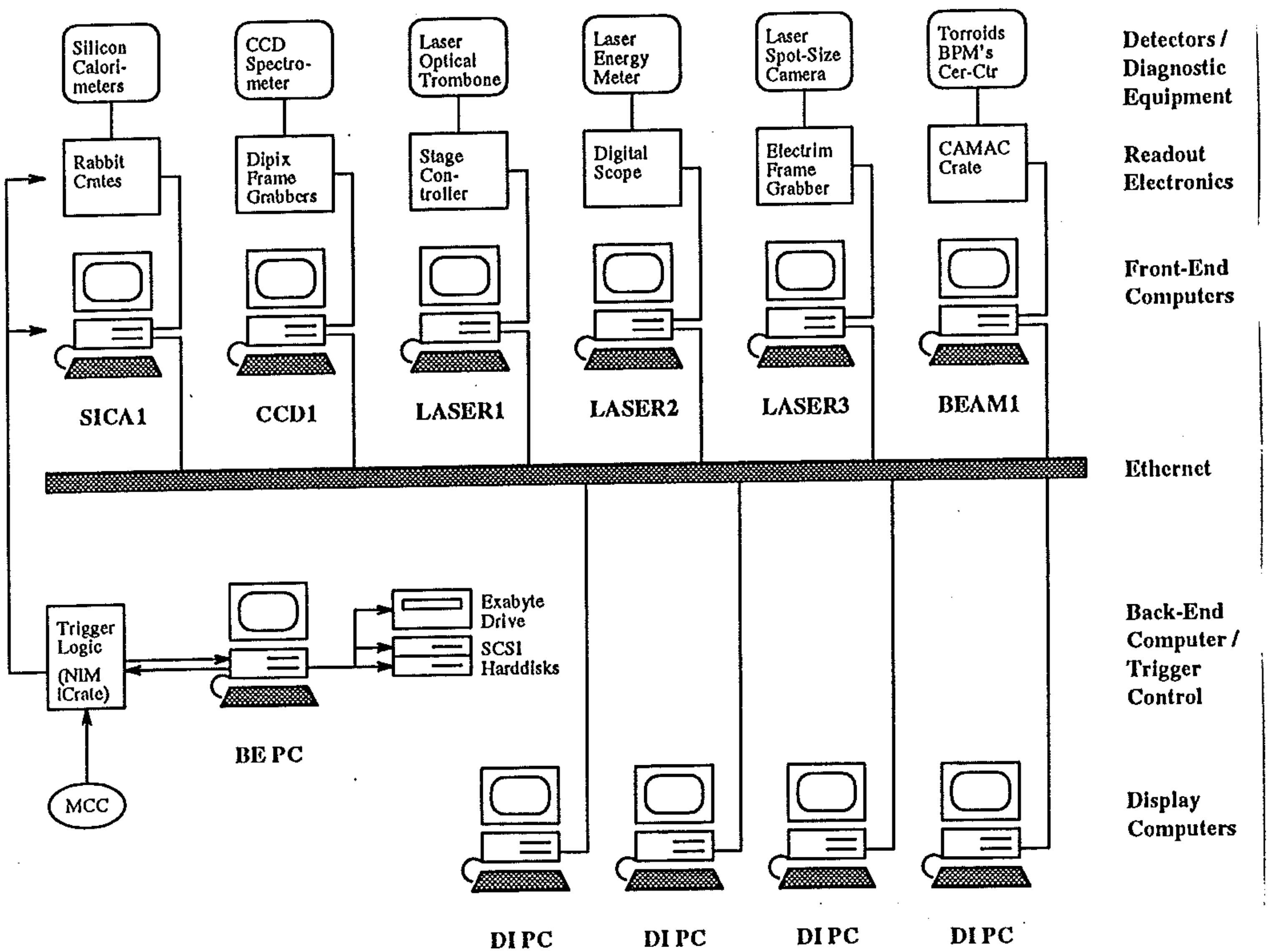


Data-Acquisition System

Detector elements are interfaced to several 'front-end' PC's.

Data from the 'front-end' PC's is collected via a local ethernet by a 'back-end' PC.

Data can also be examined online by 'display' PC's.



Measurement of e-Beam Polarization (May '94)

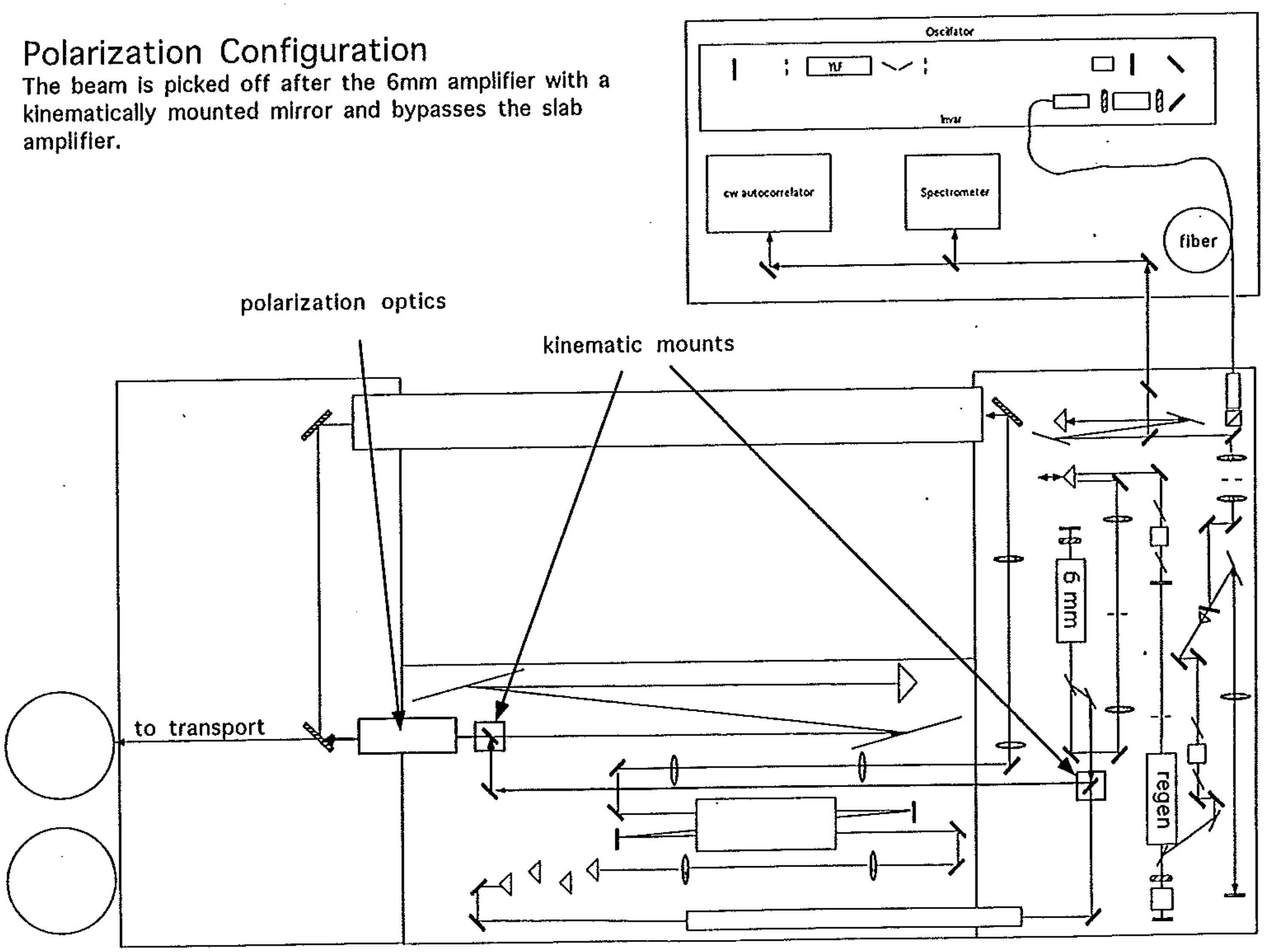
Laser pulse energy $\sim$ 3 mJ.

Scattered electrons observed in E-cal.

Laser frequency doubled to 537 nm so that zero of polarization asymmetry at 25.4 GeV is in top row of E-cal.

Polarization Configuration

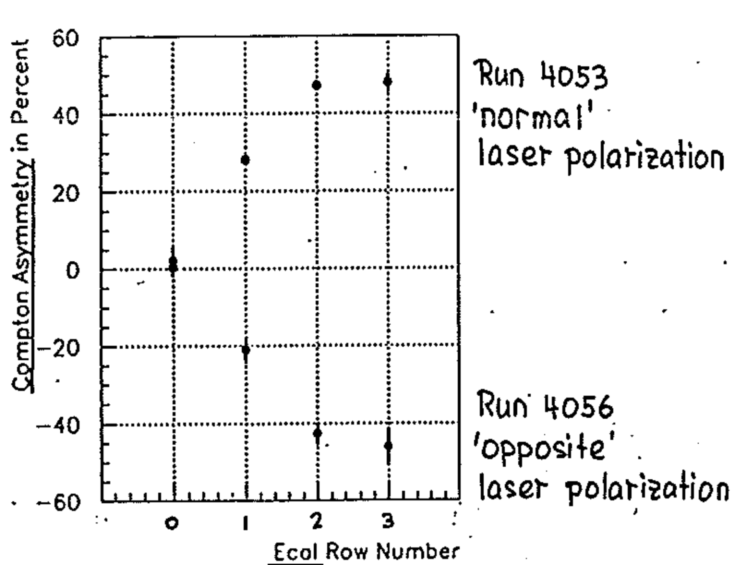
The beam is picked off after the 6mm amplifier with a kinematically mounted mirror and bypasses the slab amplifier.

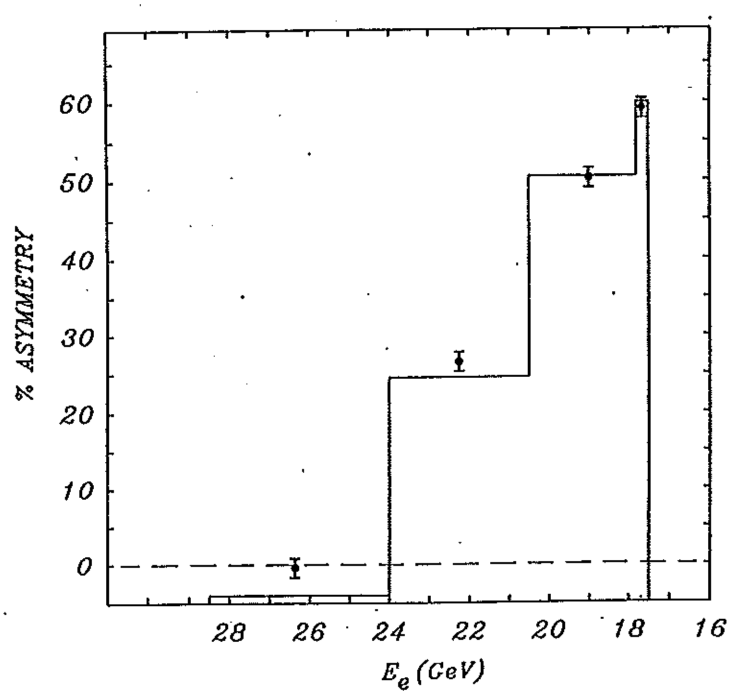


Polarization Result

Fit to measured polarization asymmetry in 4 energy bins yields $$P_e P_{\text{laser}} = 0.81 \pm 0.01.$$

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

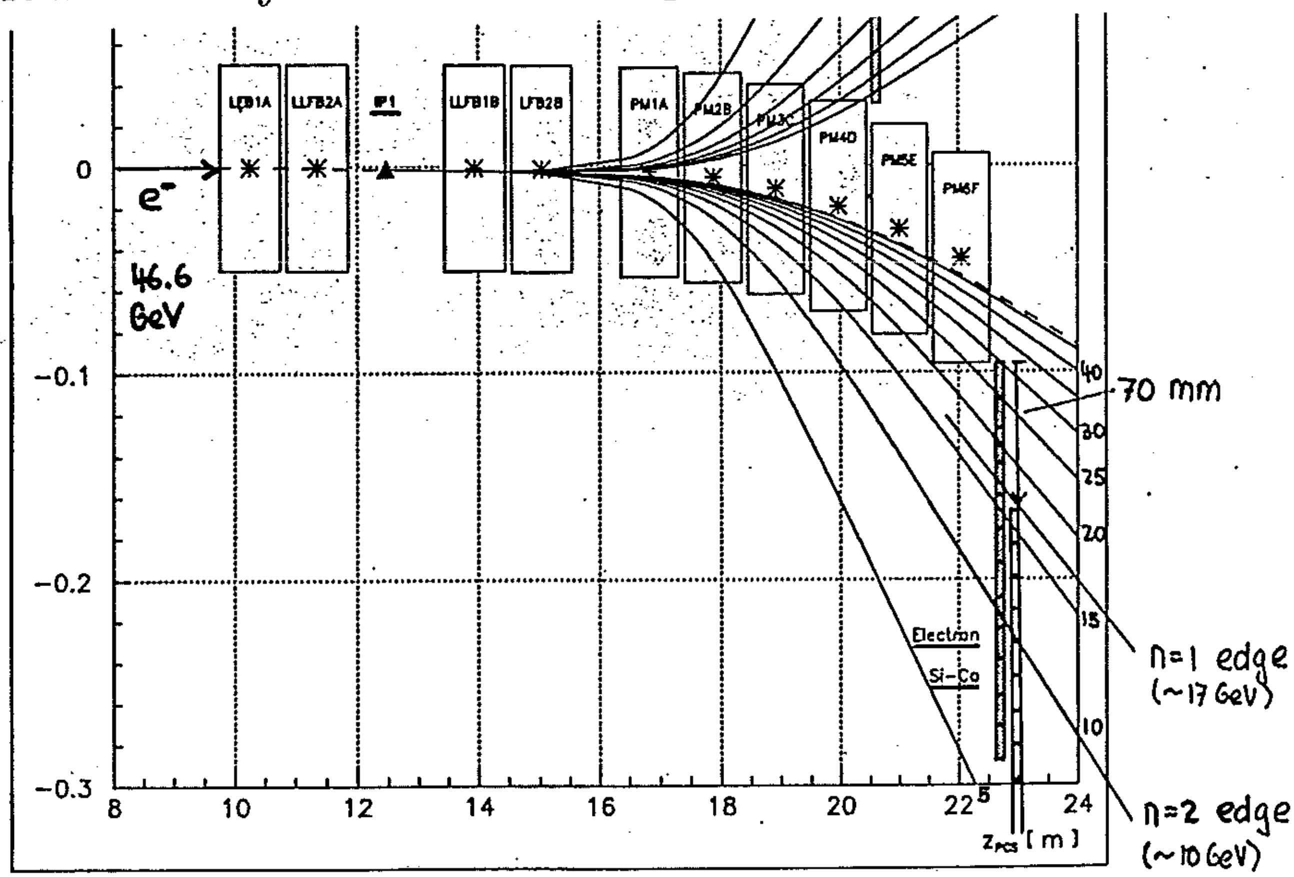


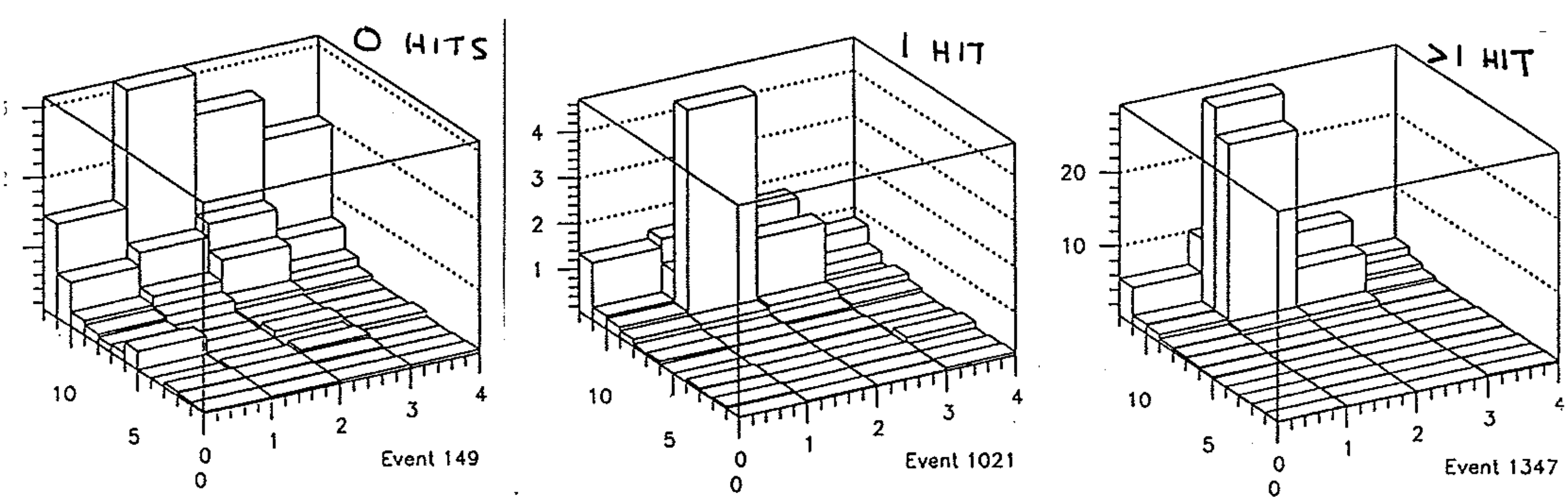


First Evidence for Nonlinear Compton Scattering

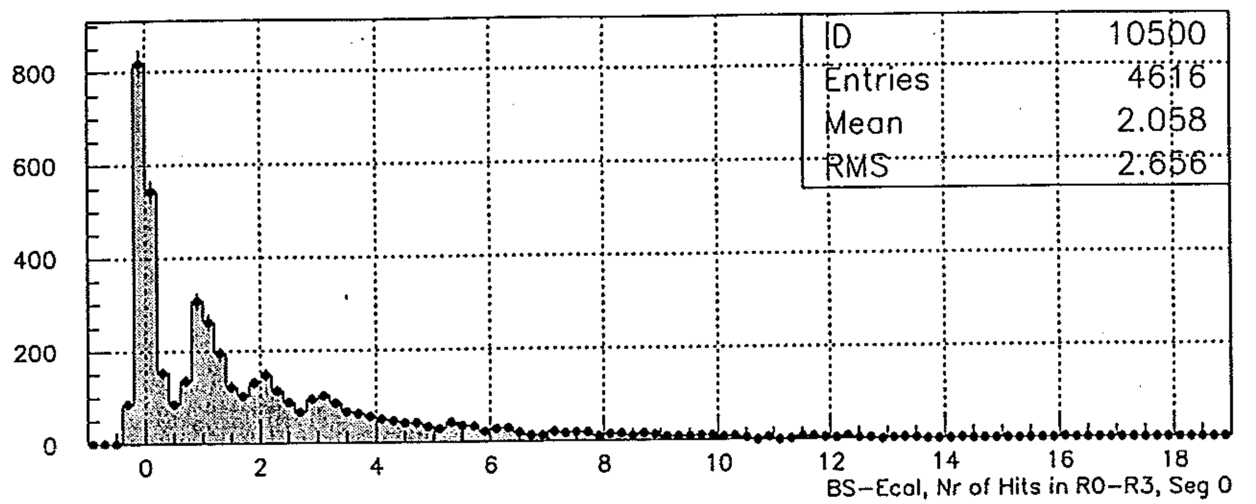
Laser pulse energy varied from 10 to 50 mJ (May '94).

E-cal lowered beyond linear Compton edge.

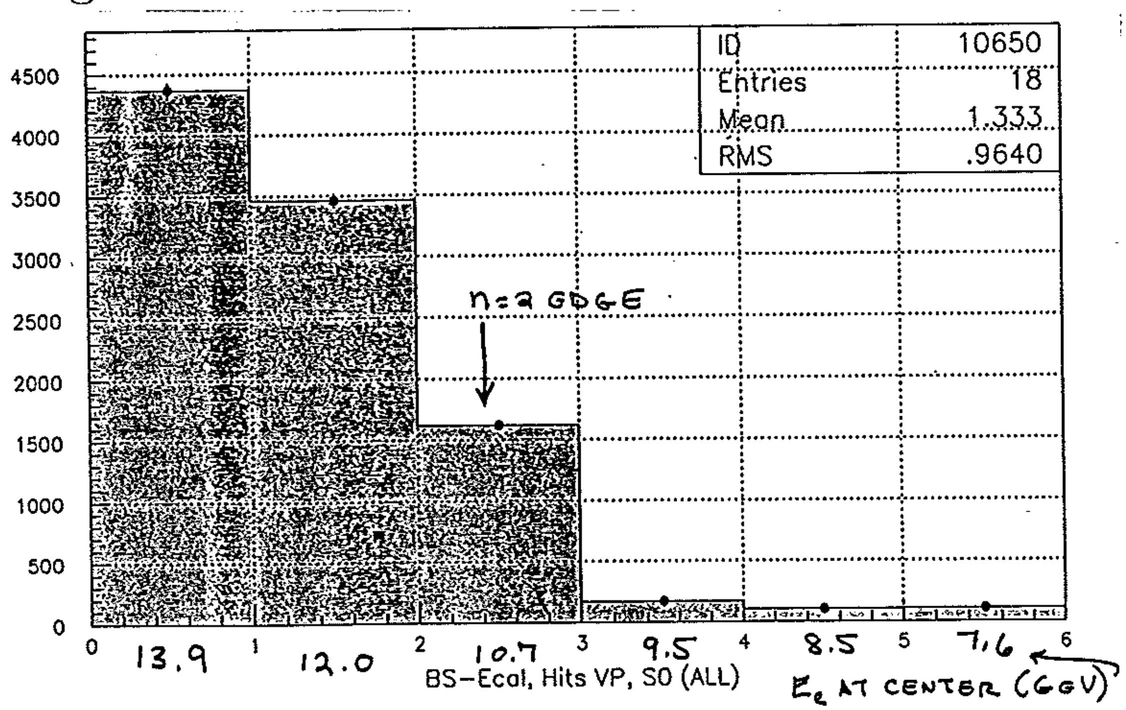




Analysis of first longitudinal segment resolves 1, 2 and 3 electron peaks.



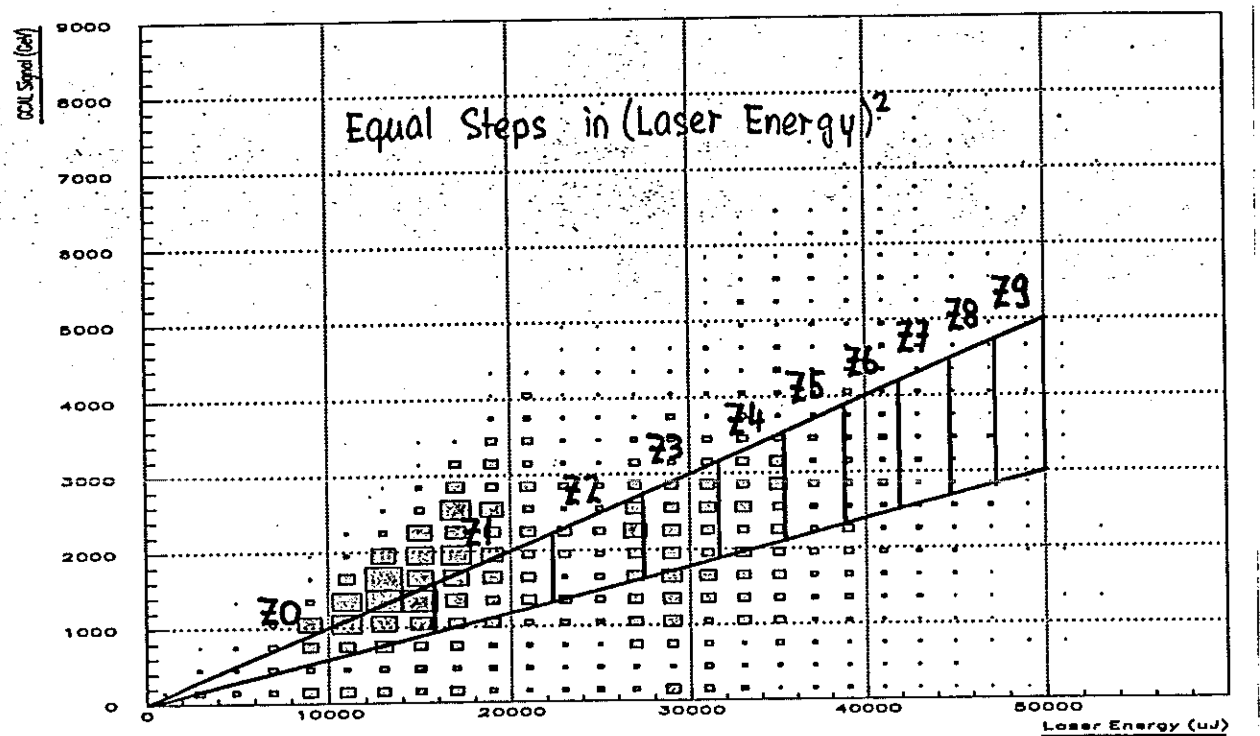
Number of hits decreases with electron energy to zero at $n = 2$ edge.



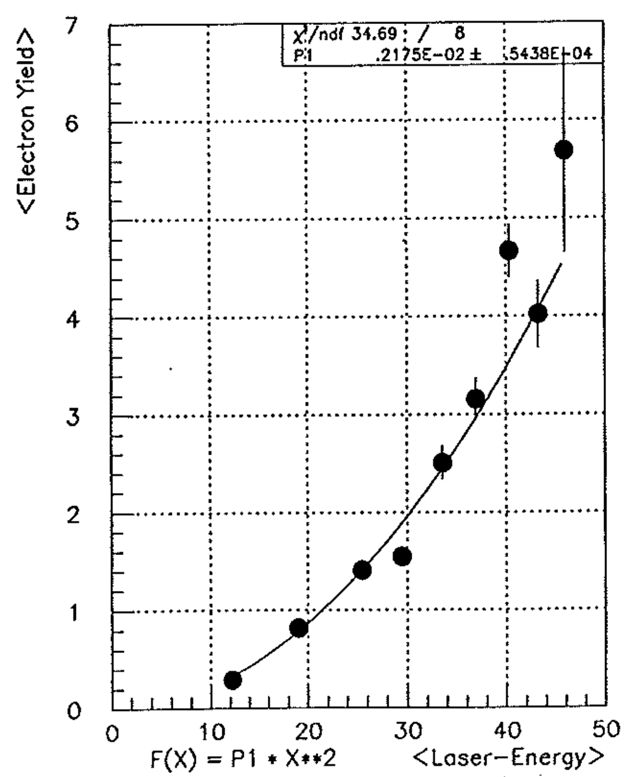
$$E_{\rm min}(n) = \frac{E_0}{1 + n\frac{4\gamma\omega_0}{m}}, \qquad \frac{4\gamma\omega_0}{m} = 1.65,$$

$$\Rightarrow E_{\rm min}(n) = 17.6,\ 10.8,\ 7.8,\ 6.1\ \text{GeV},\ \ldots$$

e-laser overlap problem: restrict analysis to region where laser energy correlates with linear Compton rate.



Number of hits varies quadratically with laser pulse energy.



$\Rightarrow$ nonlinear scattering.

Double Compton Scattering *vs.* Nonlinear Compton Scattering

Nonlinear Compton scattering: $e + 2\gamma_{\text{laser}} \rightarrow e' + \gamma$.

Double Compton scattering: $e + \gamma_{\text{laser}} \rightarrow e' + \gamma_1$,

$$e' + \gamma_{\text{laser}} \rightarrow e'' + \gamma_2.$$

Both processes are quadratic in laser intensity.

Kinematics of the final-state electrons are identical.

Spectra of final-state electrons are similar.

Rates are similar in conditions of E-144.

Best distinguished via the final-state photon:

nonlinear Compton scattering $\Rightarrow$ one, higher-energy γ;

double Compton scattering $\Rightarrow$ two, normal-energy γ's.

$\Rightarrow$ need CCD spectrometer to resolve the two processes.

Nonlinear Compton Scattering

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 and velocity described by

$$\gamma\beta = \frac{eE}{m\omega_0 c} \equiv \eta.$$

[$\eta = eA/mc^2$ where A is magnitude of vector potential.]

The accelerating electron emits multipole radiation.

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

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

Nonlinear Compton scattering becomes prominent as $\eta \to 1$ and the transverse motion of the electron becomes relativistic.

Theory of Nonlinear Compton Scattering

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

$$n\omega_o + e \rightarrow e' + \omega .$$

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

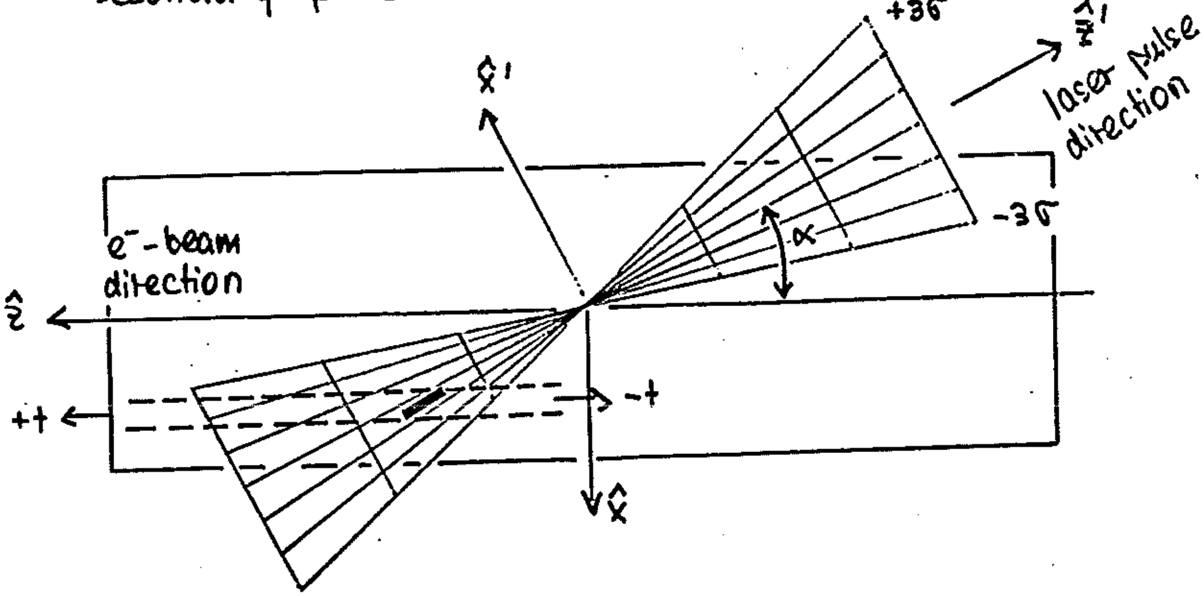
$$x = \frac{4\omega_0 E_e}{m^2}, \qquad y = \frac{\omega}{E_e}, \qquad u \approx \frac{y}{1-y},$$

$$z = \frac{2\eta}{x}\sqrt{nux - u^2(1+\eta^2)}.$$

Case of linear polarization is more intricate.

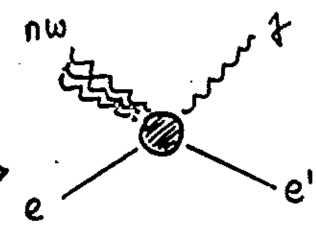
Numeric Integration over "Space"-Time Grid, taking into account:

- crossing angle between e^--beam and laser pulse
- laser focusing angle
- attenuation of e^--beam due to laser field
- secondary processes

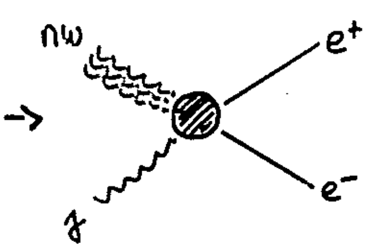


For each Space-Time Volume:

- calculate attenuated beam electron density, using the Klein-Nishina Approximation
- calculate primary process rates for:
  - Klein-Nishina Approximation
  - Non-Linear Compton Scattering ------>

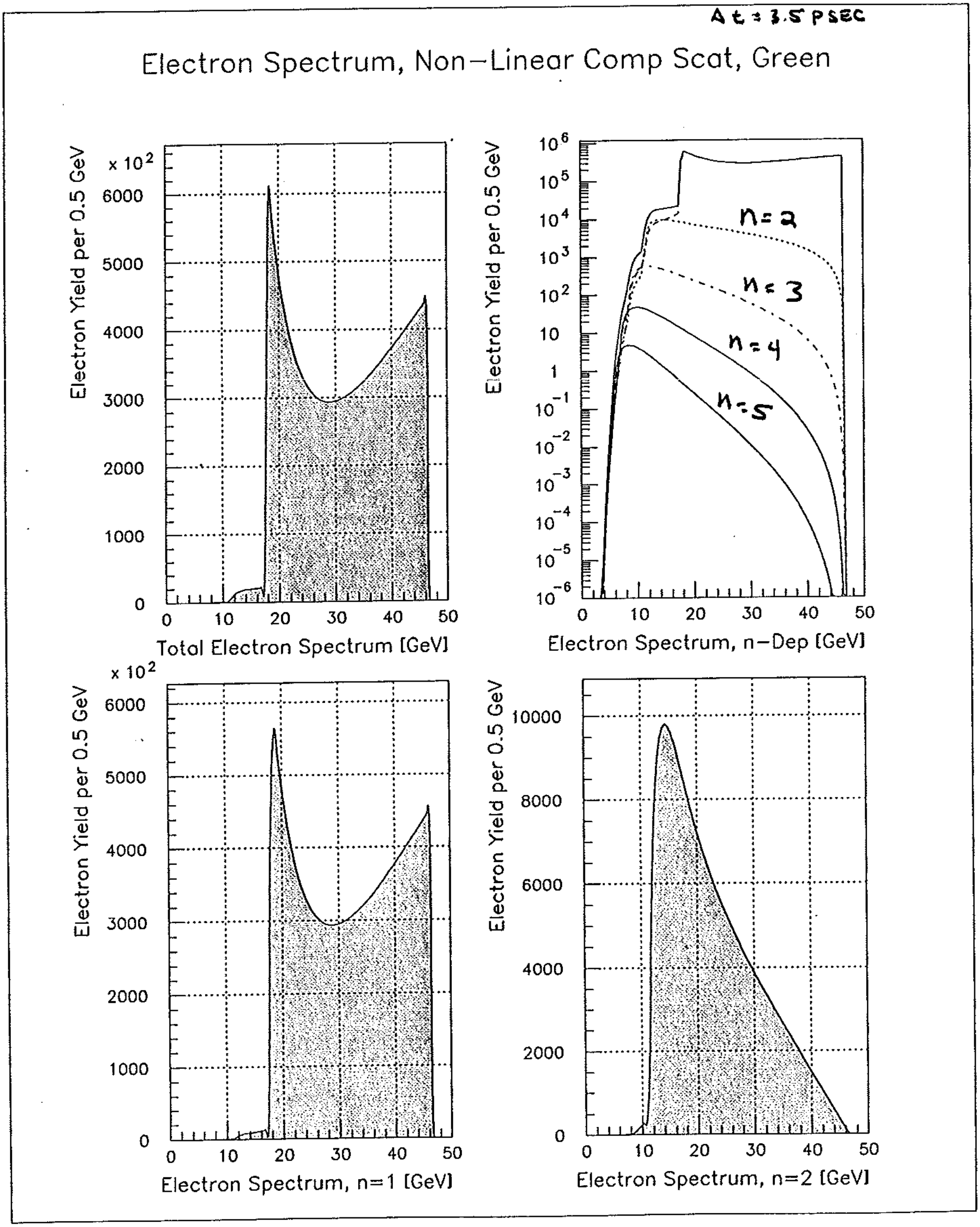


- integrate secondary process rates along $\hat{z}$ (forward in time), with fixed space volume, for:
  - Klein-Nishina Approximation
  - Non-Linear Compton Scattering
  - Breit-Wheeler Pair Production ------>



LASER: U = 700 mJ
Δt = 2.5 psec
f/D = 12

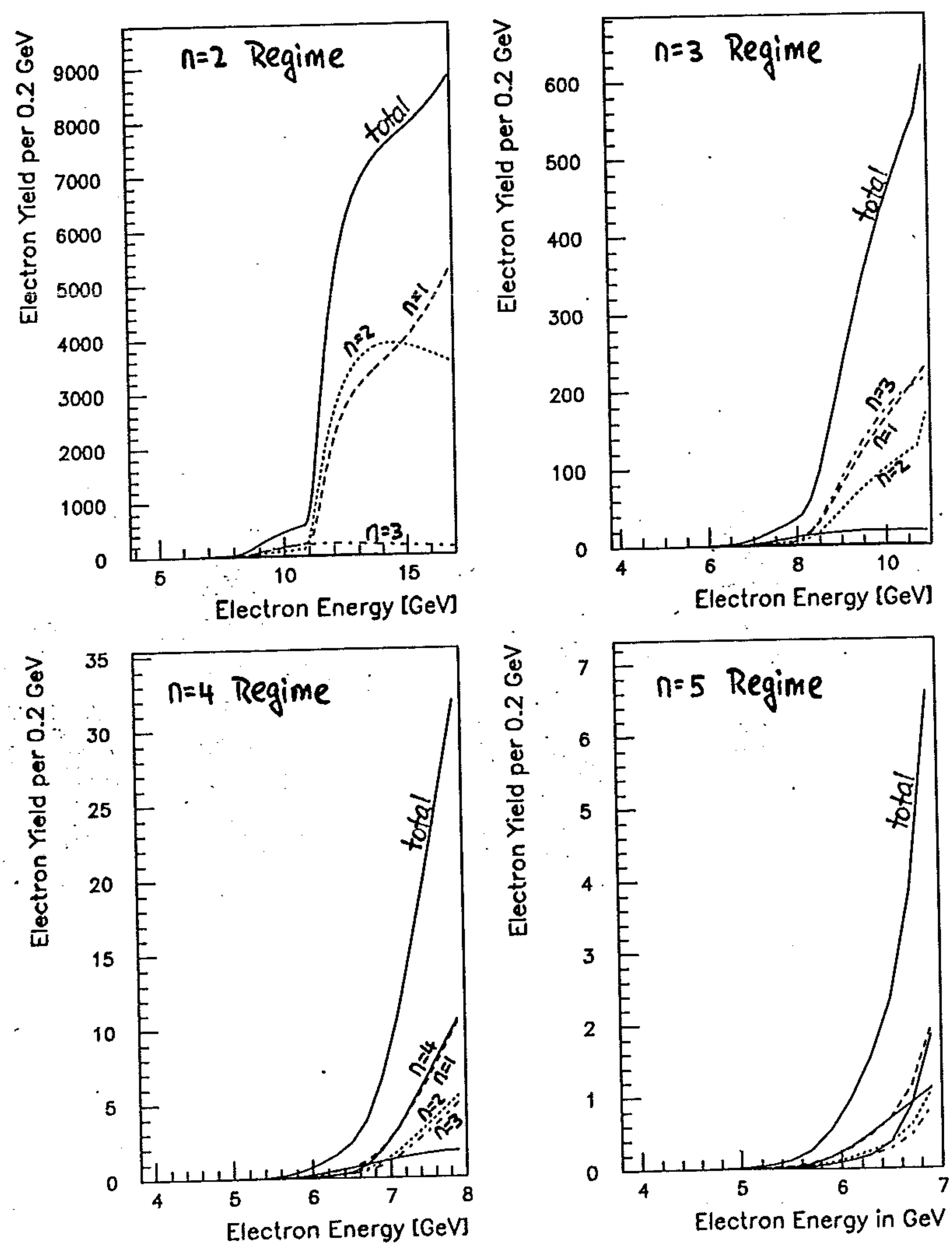
e-BEAM: $n_e = 5 \times 10^9$
σ_x = 60 μm
σ_y = 20 μm
Δt = 3.5 psec



Laser: 700 mJ
2.5 psec
f-Nr = 12

e-Beam: 5×10^9
$\sigma_x = 60\,\mu m$
$\sigma_y = 20\,\mu m$
3.5 psec

Electron Spectrum Beyond Linear Compton Edge, Green

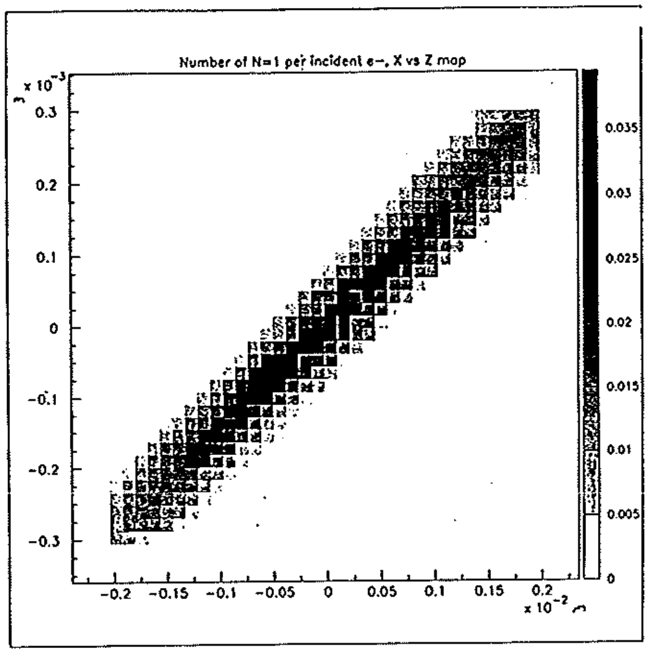


Spatial Dependence of Scattering Rates

300 μm

x

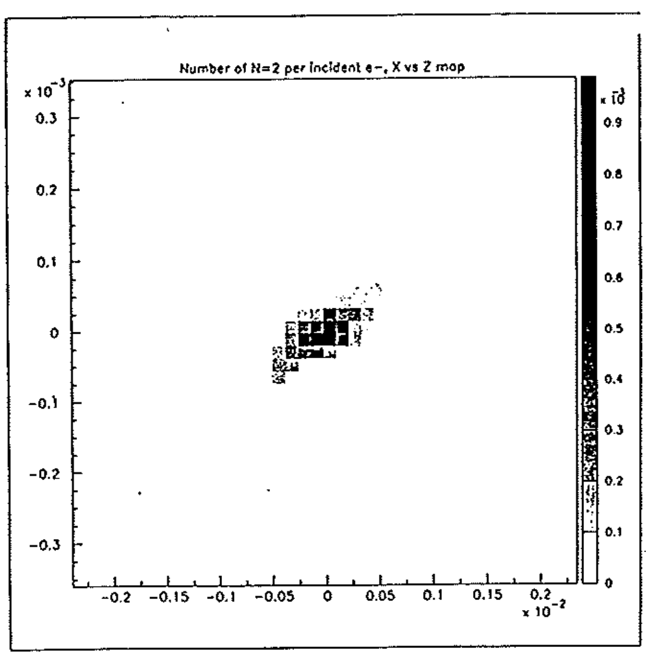
-300μm



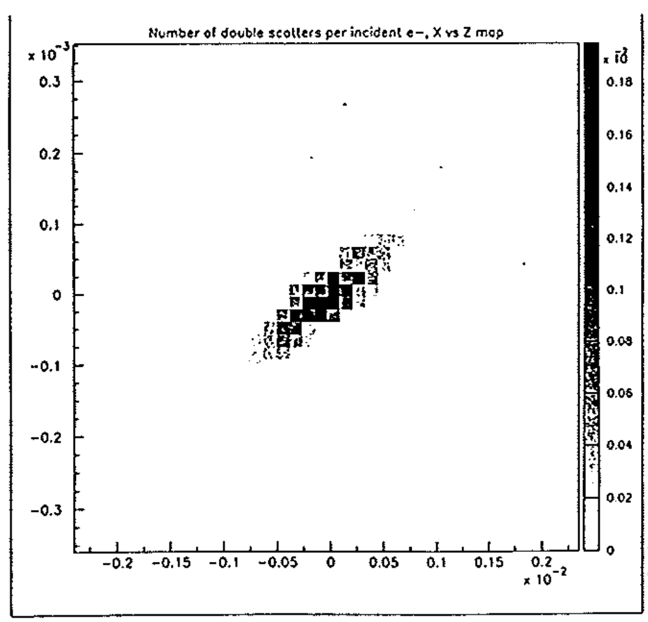
LINEAR COMPTON SCATTERS

-2mm z 2 mm

n=2 NONLINEAR COMPTON SCATTERS



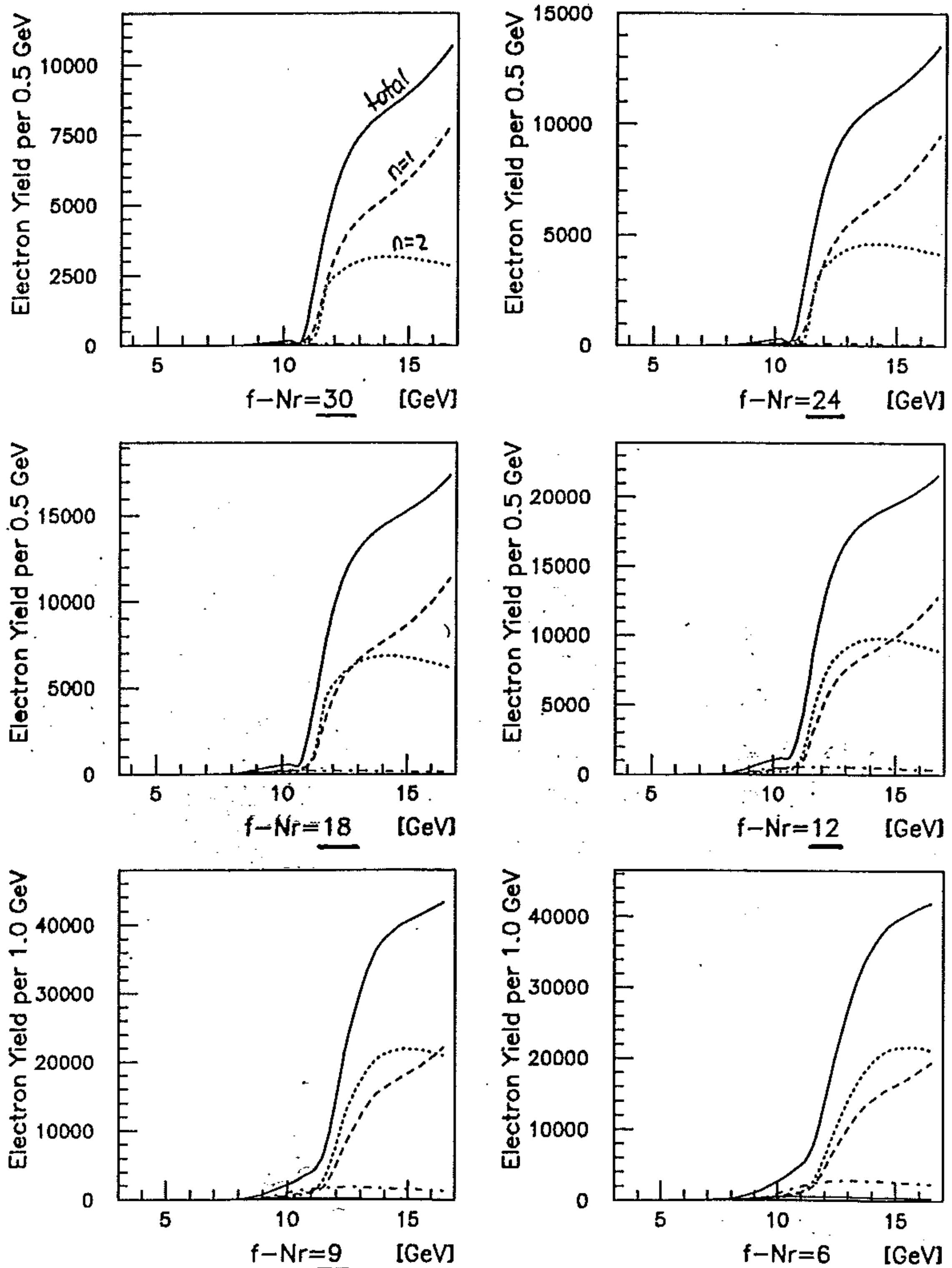
DOUBLE COMPTON SCATTERS



Laser: Green
700 mJ
2.5 psec

e-Beam: 5×10^9
$\sigma_x = 60 \mu m$
$\sigma_y = 20 \mu m$
3.5 psec

Effect of f–Number on Double Scattering and n=2



Sept. '94 Run

Improved doubling efficiency $\rightarrow$ up to 1 J at 527 nm.

Shot-by-shot spot-area measurement for latter part of run.

$A \approx 20\ \mu\text{m}^2$ at low pulse energy.

Observed $20 < A < 100\ \mu\text{m}^2$ at larger pulse energies.

Measurement gives only a upper limit.

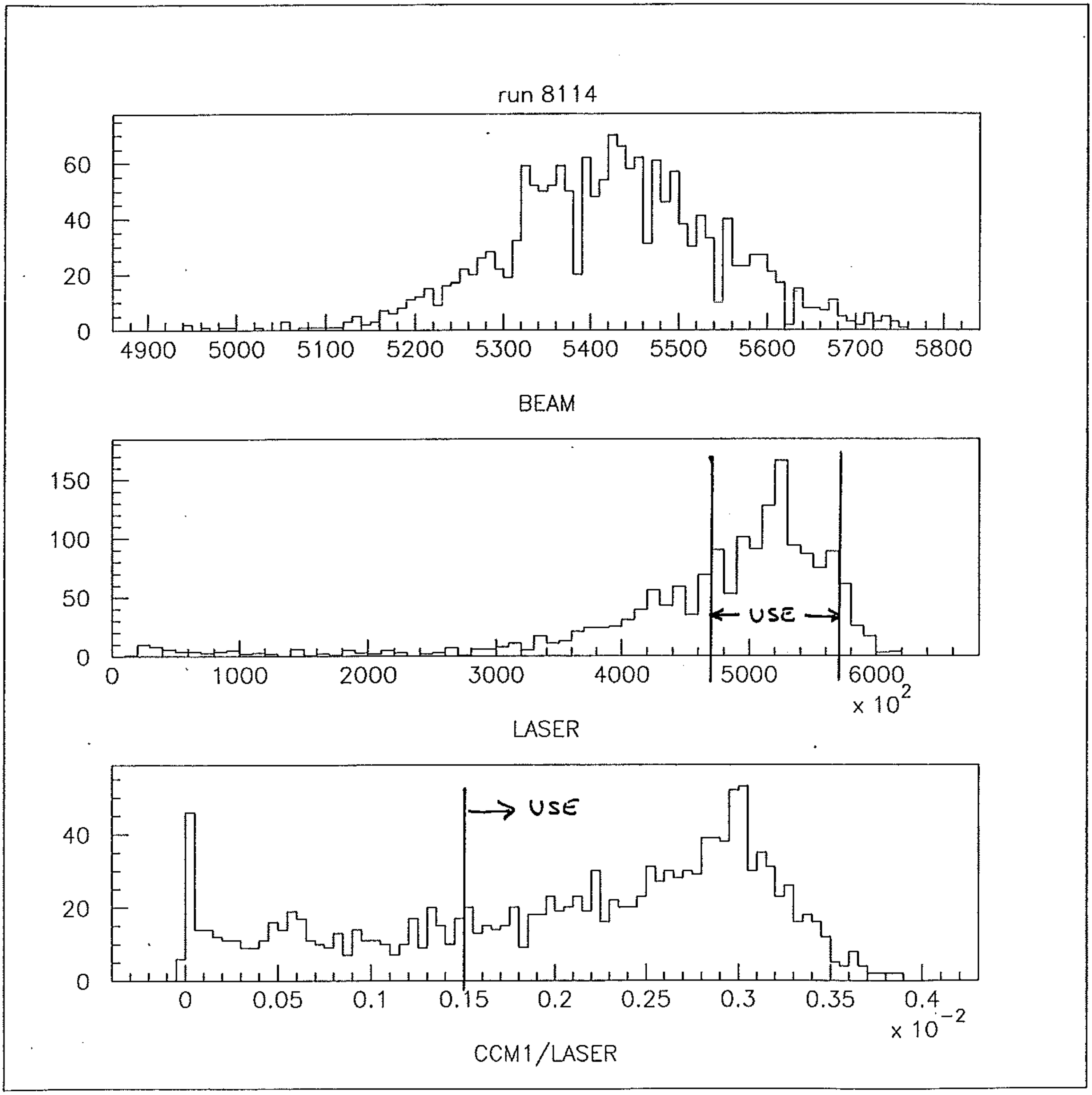
Shot-by-shot pulse length measurement not available.

Streak camera showed $\Delta t = 1.5$ ps at low pulse energy, up to 3 ps at high pulse energy.

$$I_{\text{max,optimistic}} = \frac{1}{(1.5 \times 10^{-12})(2 \times 10^{-5})} = 3 \times 10^{18}\ \text{W/cm}^2.$$

$$I_{\text{max,pessimistic}} = \frac{1}{(3 \times 10^{-12})(10^{-4})} = 3 \times 10^{17}\ \text{W/cm}^2.$$

e-Laser Overlap Problems



Remarks on the Data

High laser energy $\Rightarrow$ up to 10^6 scatters/pulse.

$\Rightarrow$ must lower E-cal out of $n = 1$ range.

Backsplash from beampipe, crosstalk $\Rightarrow$ can use only top 4 rows of E-cal.

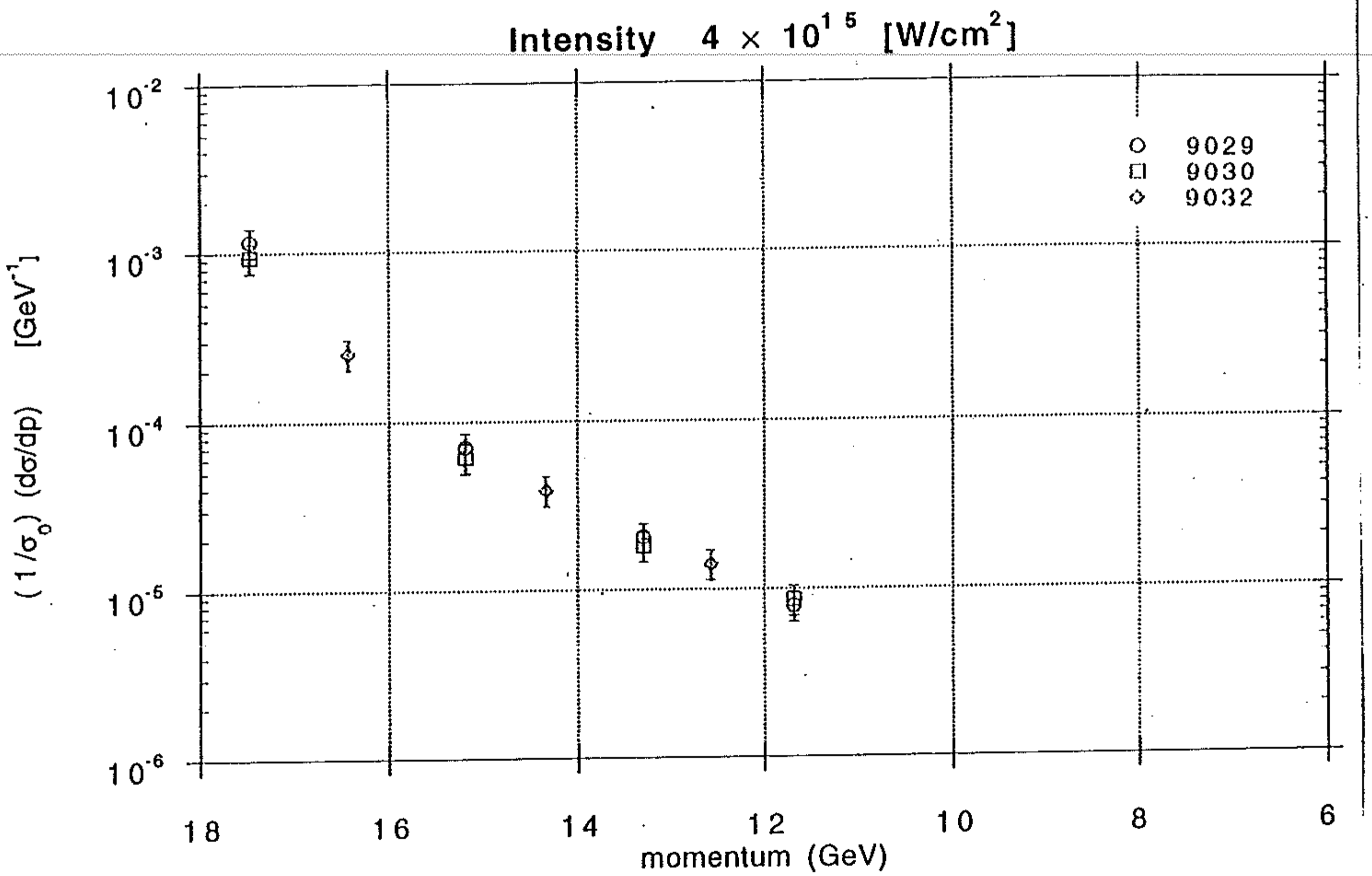
Use events only with good e-laser overlap:
CCM1/$U_{\text{laser}} > 0.5\times$ peak.

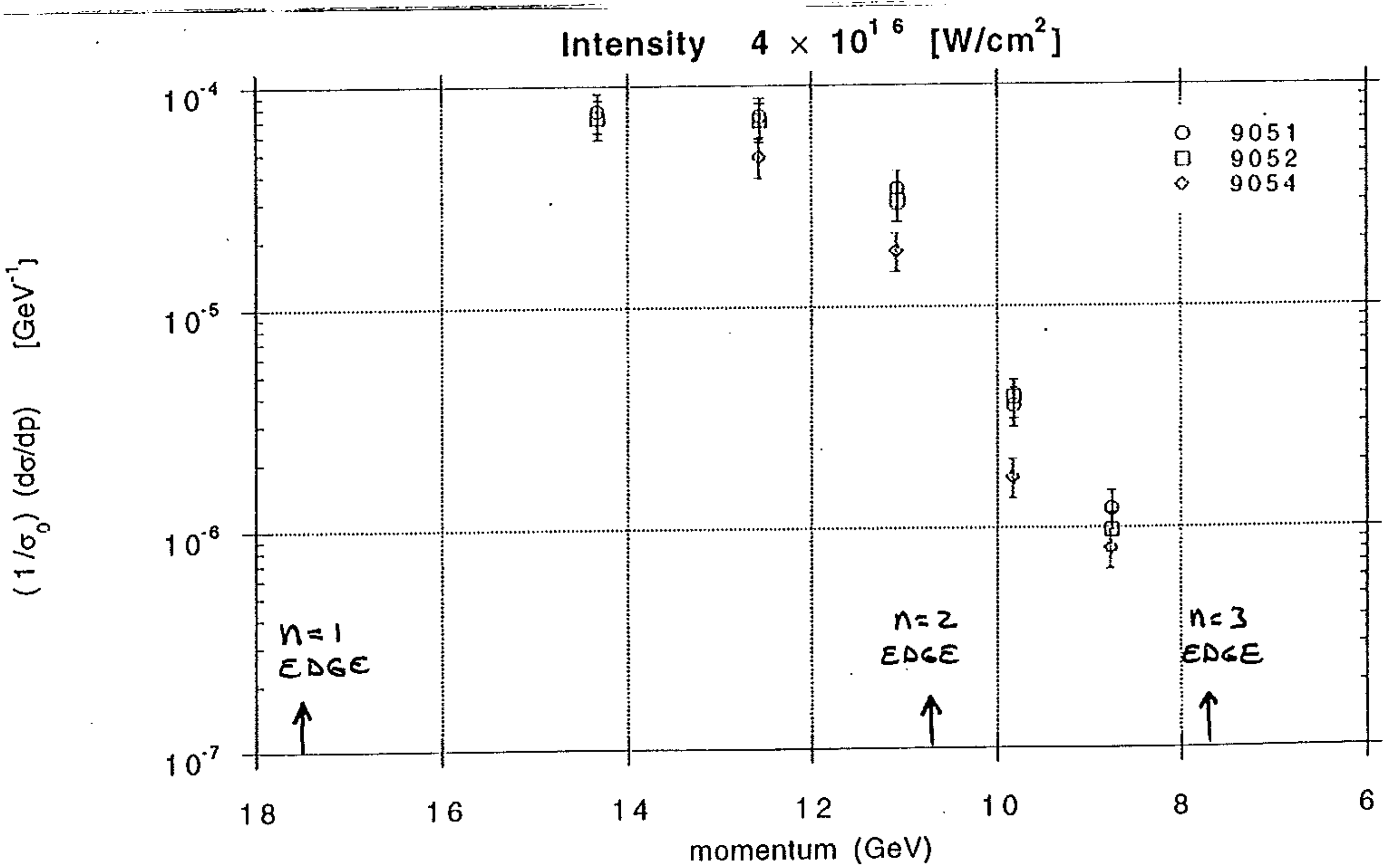
We report

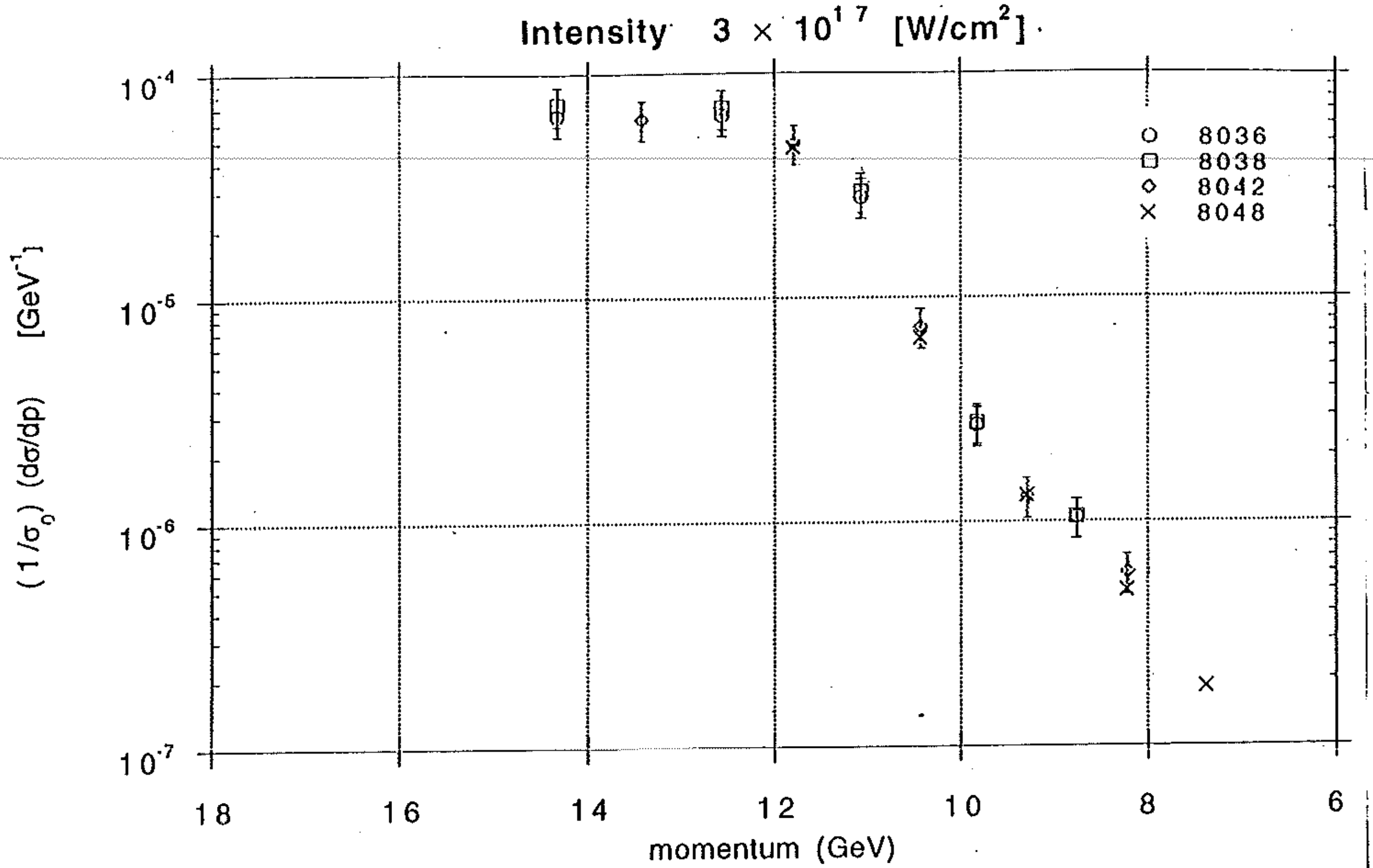
$$\frac{1}{N_\gamma}\frac{dN_e}{dP_e} = \frac{1}{\sigma_0}\frac{d\sigma}{dP_e}$$

where N_γ = number of scattered γ's, and
$N_e = U_e/P_e$ = number of electrons in a row of E-cal.

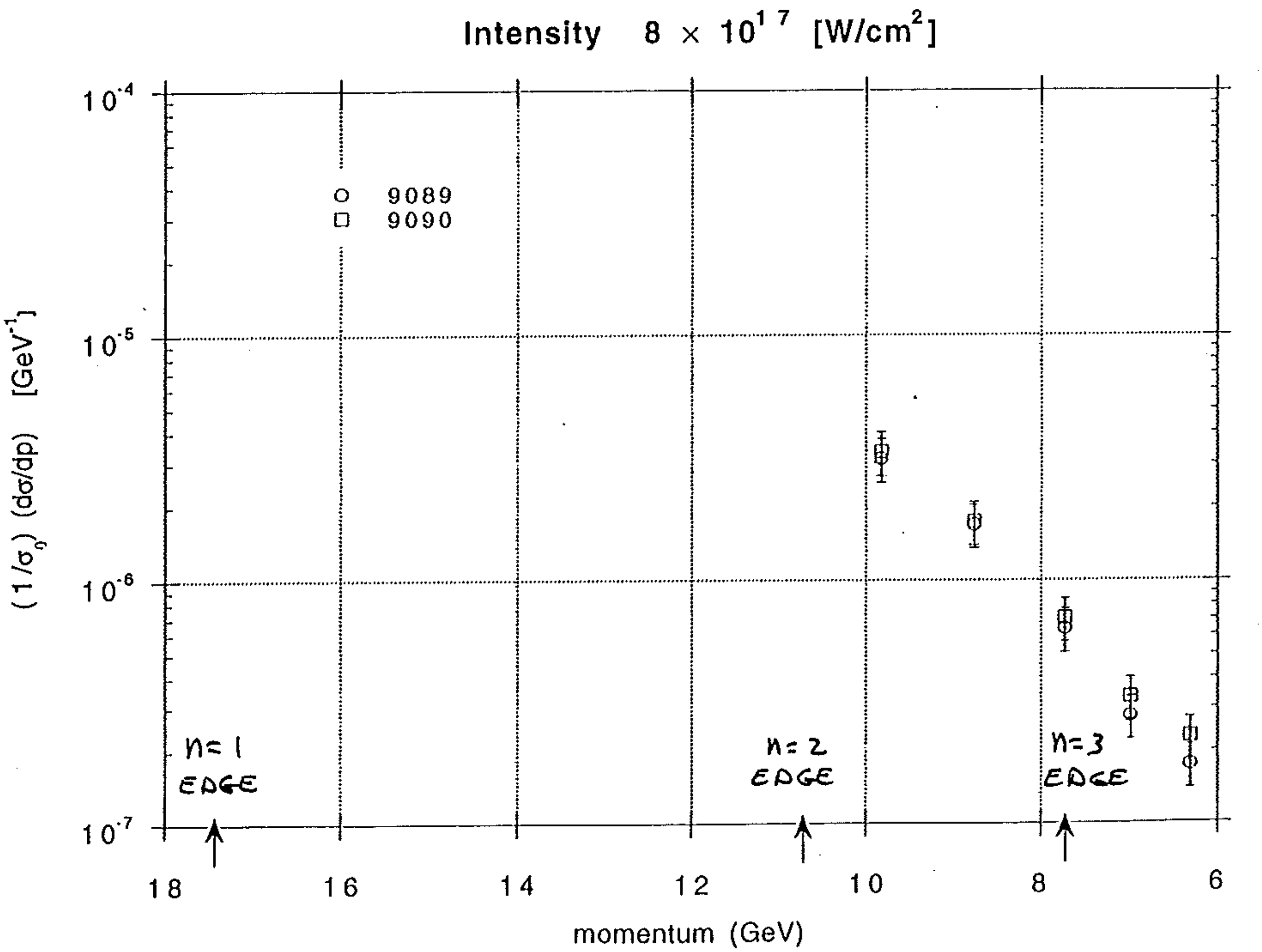
N_γ is inferred from the CCM1 Čerenkov monitor.


Intensity 4 × 10^15 [W/cm^2]
(1/σ0) (dσ/dp) [GeV^-1]
10^-2
10^-3
10^-4
10^-5
10^-6
9029
9030
9032
18
16
14
12
10
8
6
momentum (GeV)

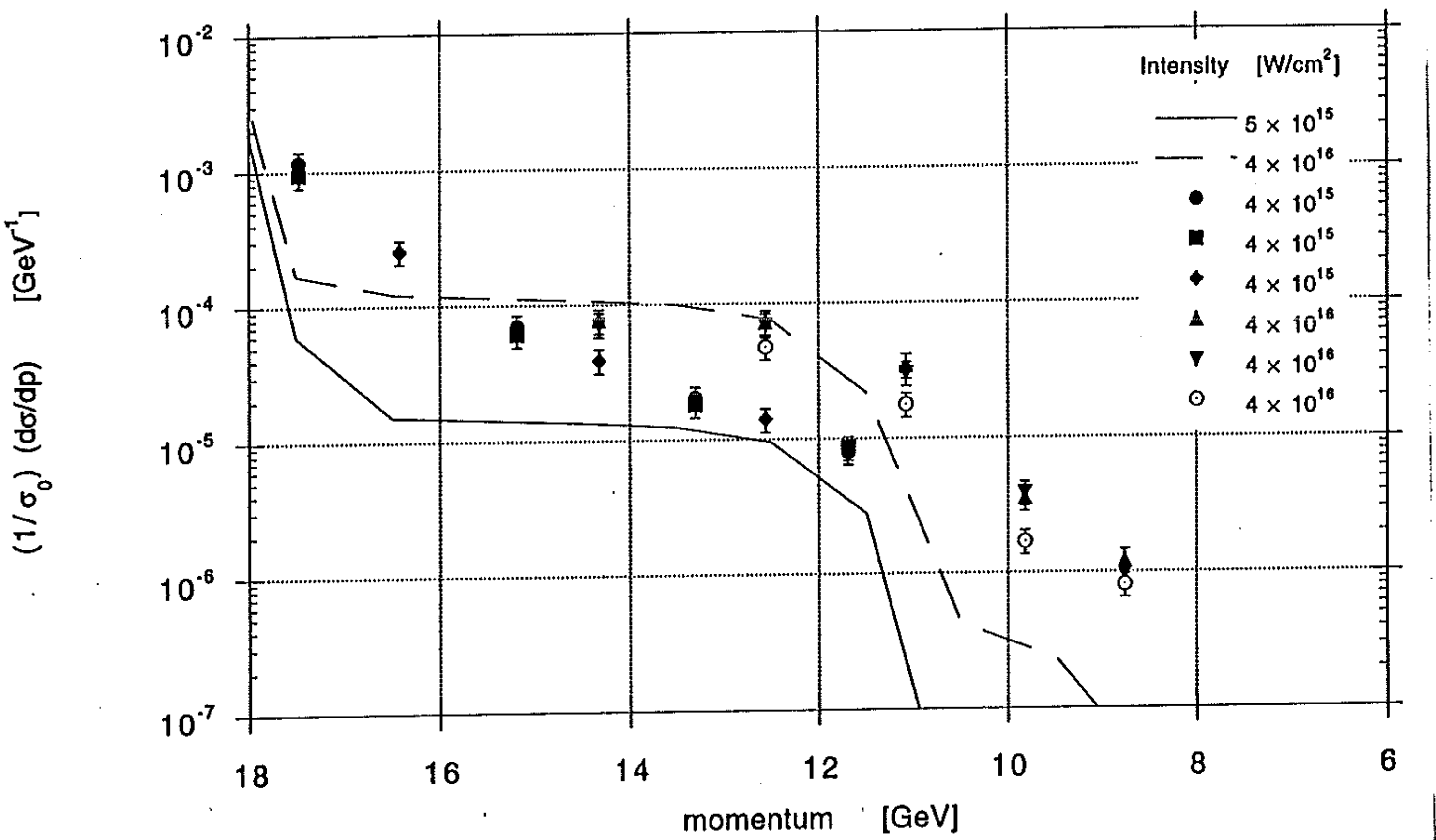

Intensity 4 × 10^16 [W/cm^2]
(1/σ0) (dσ/dp) [GeV^-1]
10^-4
10^-5
10^-6
10^-7
9051
9052
9054
n=1 EDGE
n=2 EDGE
n=3 EDGE
18
16
14
12
10
8
6
momentum (GeV)



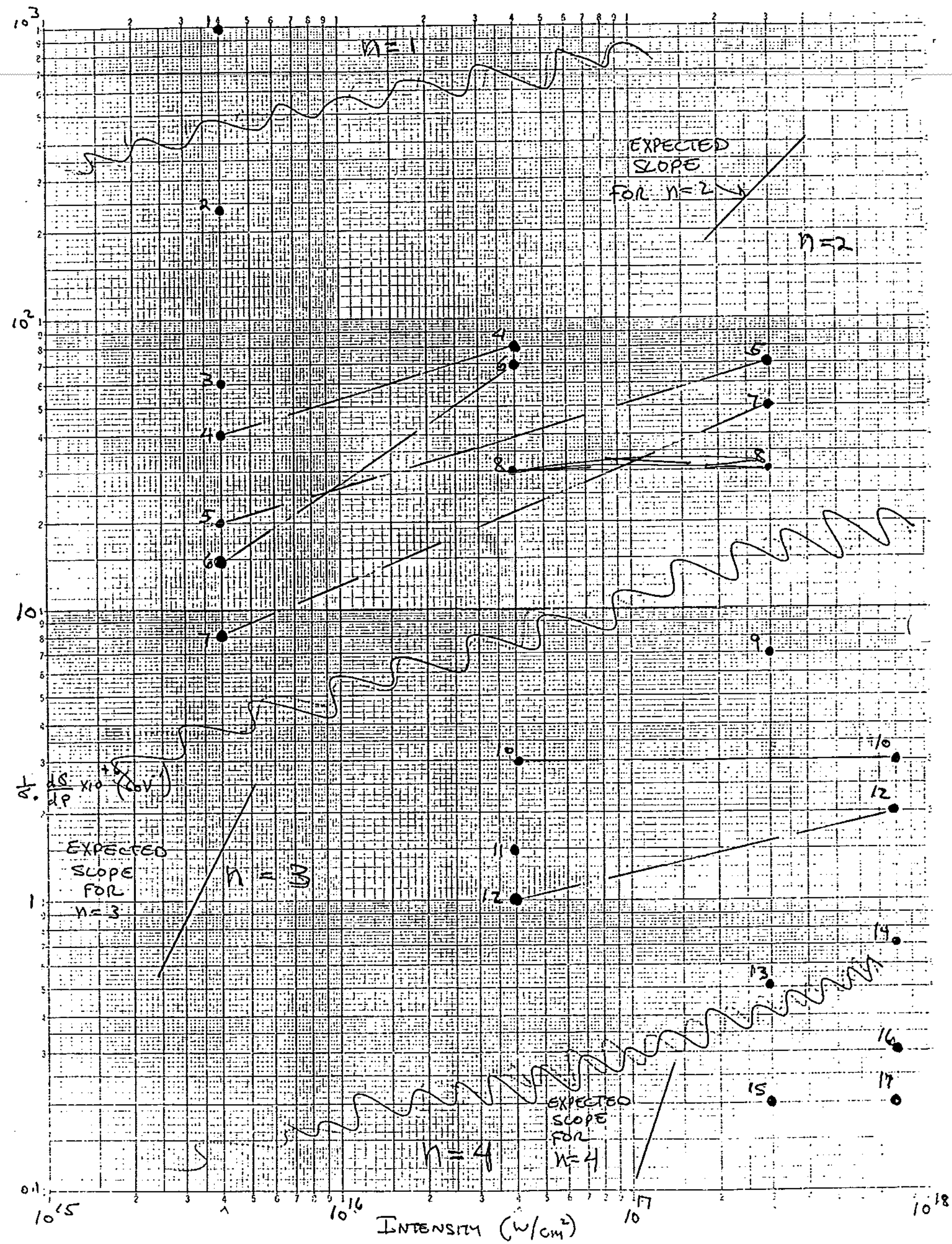
Intensity 3 × 10¹⁷ [W/cm²]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
(1/σ₀) (dσ/dp) [GeV⁻¹]
8036
8038
8042
8048
18
16
14
12
10
8
6
momentum (GeV)



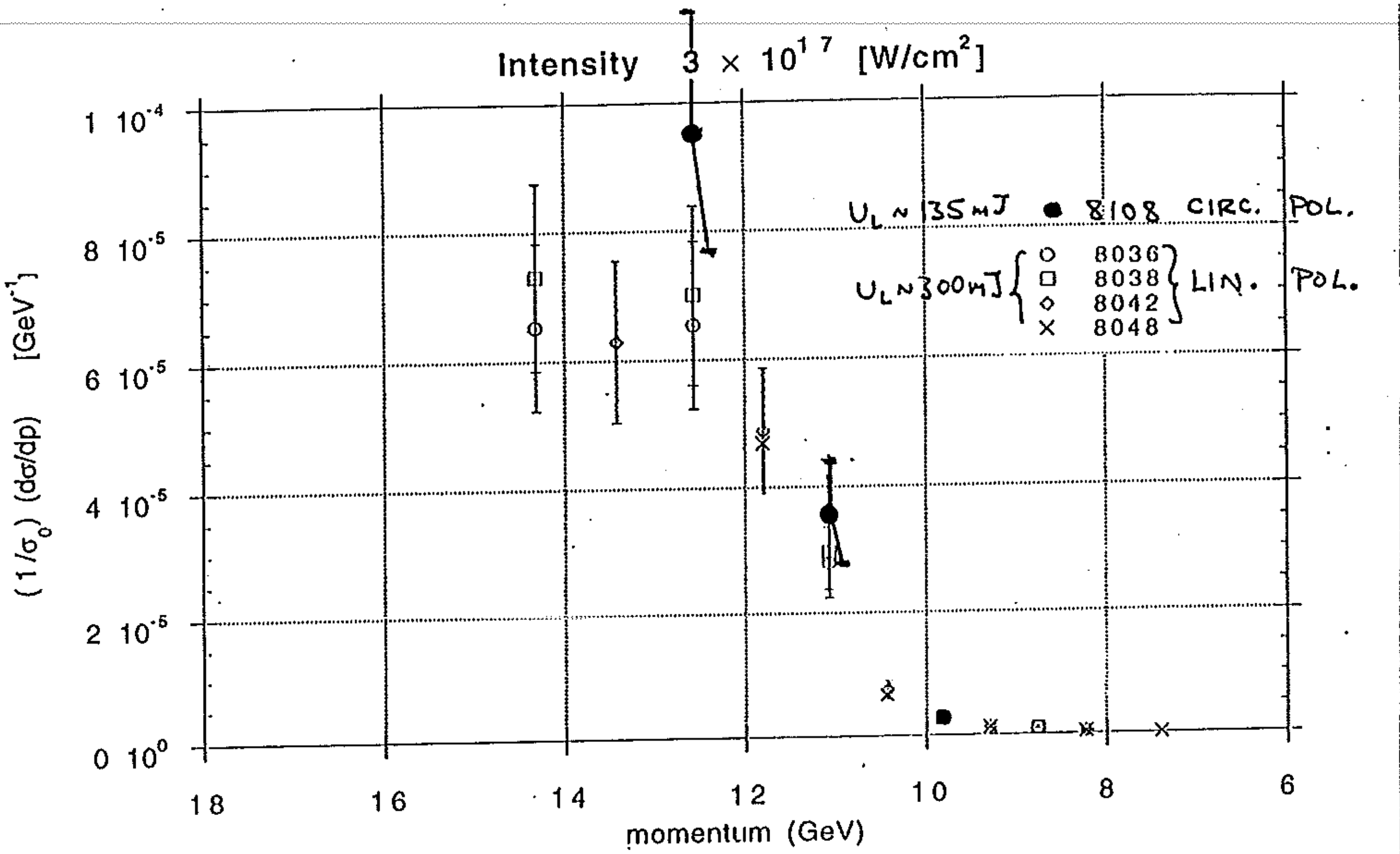
Intensity 8 × 10¹⁷ [W/cm²]
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
(1/σ₀) (dσ/dp) [GeV⁻¹]
9089
9090
n=1
EDGE
n=2
EDGE
n=3
EDGE
18
16
14
12
10
8
6
momentum (GeV)



$(1/\sigma_0)$ $(d\sigma/dp)$ [GeV^{-1}]
momentum [GeV]
Intensity [W/cm^2]
5×10^{15}
4×10^{16}
4×10^{15}
4×10^{15}
4×10^{15}
4×10^{16}
4×10^{16}
4×10^{16}



n=1
EXPECTED SLOPE FOR n=2
n=2
n=3
EXPECTED SLOPE FOR n=3
n=4
EXPECTED SLOPE FOR n=4
INTENSITY (W/cm²)



Intensity 3 × 10¹⁷ [W/cm²]
1 10⁻⁴
8 10⁻⁵
6 10⁻⁵
4 10⁻⁵
2 10⁻⁵
0 10⁰
(1/σ₀) (dσ/dp) [GeV⁻¹]
18
16
14
12
10
8
6
momentum (GeV)
U_L ~ 135 mJ ● 8108 CIRC. POL.
U_L ~ 300 mJ
○ 8036
□ 8038
◇ 8042
× 8048
LIN. POL.

Positrons?

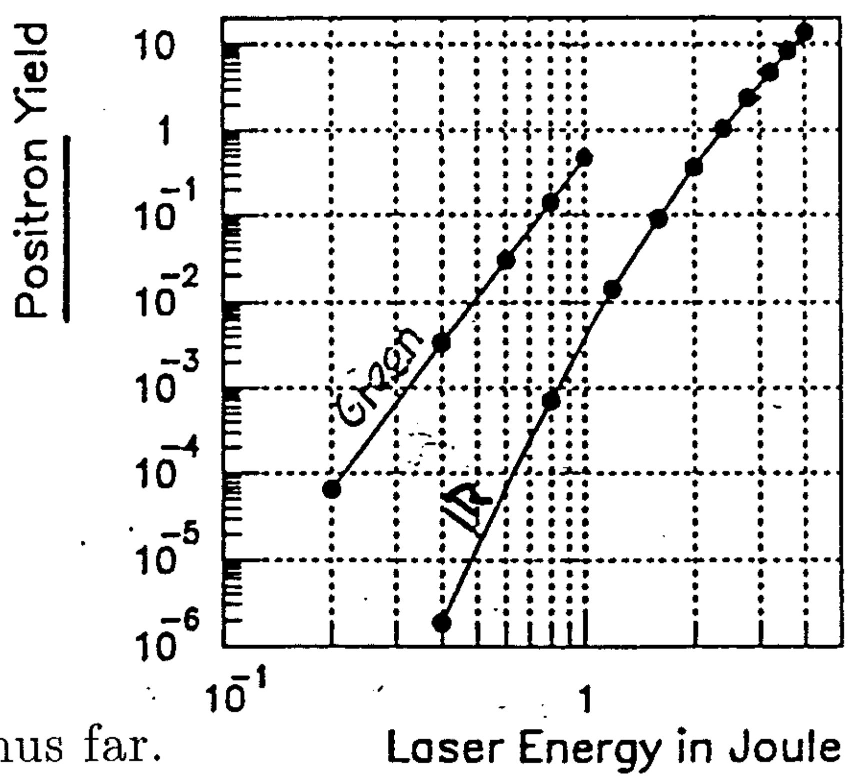
$$\omega + n\omega_0 \to e^- + e^+$$

Cross-channel reaction to nonlinear Compton scattering,

$\Rightarrow$ Theory exists.

In E-144, need $n = 4$ to cross threshold at 527 nm (need $n = 8$ at 1053 nm).

$\Rightarrow$ Rate $\propto I^5$ at 527 nm ($\propto I^9$ at 1053 nm).



No positrons observed thus far.

Preparations for March '95 Run

Install wire scanner in IP1 box.

Install beam position monitor in IP1 box.

Install IP2 box and wire scanner (no laser optics).

Laser oscillator rebuilt $\Rightarrow$ improved timing stability.

CW autocorrelator installed to monitor oscillator pulse length.

New slab amplifier.

Optics installed to deliver both 527 and 1053 nm to IP1.

Single-shot autocorrelators installed for 527 and 1053 nm.

Install CCD pair spectrometer.

Explore use of 'hi-lo' e-beam to reduce scattering rates.

Run plan with extensive x-y-z-t scans of e-laser overlap.

Electron Mass Shift

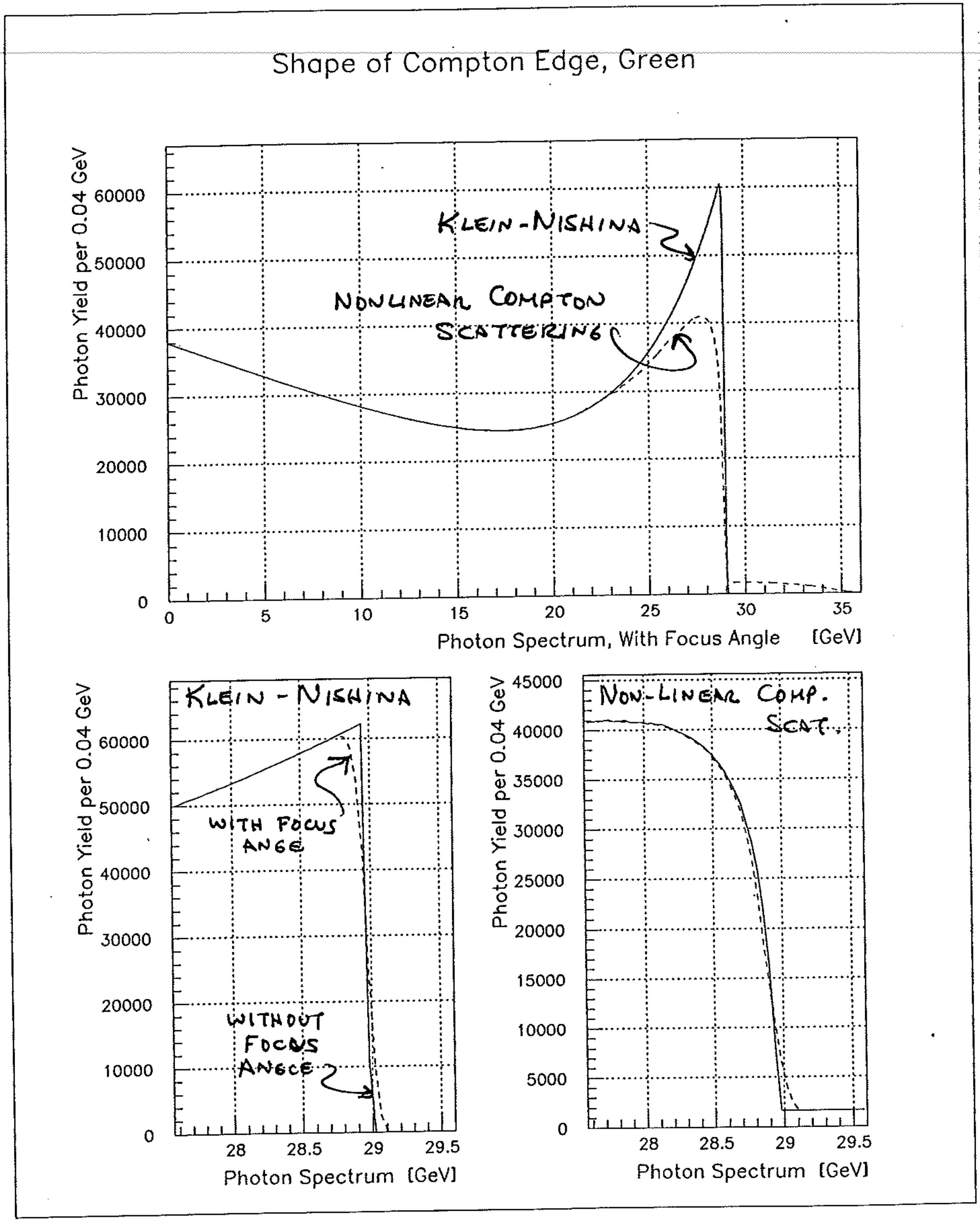
Classically, an electron in a strong wave field undergoes relativistic transverse oscillations which increase its mass.

Quantum mechanically, the electron is in a 'dressed' state (Volkov solution to Dirac equation) which appears to have a higher mass.

$$m_{\text{eff}} = m\sqrt{1+\eta^2}.$$

Most prominent effect is shift of the endpoint of the $n = 1$ Compton scattering spectrum.

Can measure this for converted Compton γ's in the CCD pair spectrometer.



Shape of Compton Edge, Green
Photon Yield per 0.04 GeV
60000
50000
40000
30000
20000
10000
0
0
5
10
15
20
25
30
35
Photon Spectrum, With Focus Angle [GeV]
KLEIN-NISHINA
NONLINEAR COMPTON SCATTERING
WITH FOCUS ANGE
WITHOUT FOCUS ANGLE
28
28.5
29
29.5
Photon Spectrum [GeV]
NON-LINEAR COMP. SCAT.
45000
35000
25000
15000
5000

Summary

We have crossed the threshold of nonlinear QED.

Incremental improvements to the apparatus are still to be made, leading to large additional physics reach.