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## **Nonlinear Compton Scattering**

K.T. McDonald and D.P. Russell

Princeton University

Presentation at DOE Headquarters, Germantown

(October 12, 1990)

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# I.

## The Nonlinear Compton Scattering Experiment

# PARTICLES & FIELDS

1800's

EXPERIMENT  $\Rightarrow$  FIELDS EXIST  
(AMPÈRE, FARADAY, HERTZ...)

THEORY  $\Rightarrow$  ELEMENTARY PARTICLES SHOULD EXIST  
(MAXWELL, BOLTZMANN...)

1900's

EXPERIMENT  $\Rightarrow$  ELEMENTARY PARTICLES EXIST  
(THOMSON, RUTHERFORD...)

THEORY  $\Rightarrow$  NEW FIELDS SHOULD EXIST  
(GLUON, HIGGS...)



PARTICLE PROPERTIES ARE GREATLY AFFECTED  
BY A STRONG BACKGROUND FIELD

(MORE FAMILIAR IN CONDENSED-MATTER PHYSICS)

HAWKING: QED AFFECTED BY STRONG GRAVITATIONAL  
FIELD

INTEREST: QED IN STRONG E-M WAVES,

# Laser Acceleration of Particles

(Malibu, California, 1985)

## Fundamental Physics During Violent Accelerations

KIRK T. McDONALD

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Princeton University  
Princeton, New Jersey 08544*

### ABSTRACT

When a powerful laser beam is focussed on a free electron the acceleration of the latter is so violent that the interaction is non-linear. We review the prospects for experimental studies of non-linear electrodynamics of a single electron, with emphasis on the most accessible effect, non-linear Thomson scattering. We also speculate on the possibility of laboratory studies of a novel effect related to the Hawking radiation of a black hole.

## NONLINEAR EFFECTS

### A. MULTIPHOTON IONIZATION OF ATOMS

- VOLTAGE ACROSS BOHR RADIUS  $\sim 1 \text{ eV}$

$$E_{\text{LASER}} \sim 10^8 \text{ Volts/cm}$$

$$I_{\text{LASER}} = \frac{E^2}{8\pi} \sim 10^{13} \text{ Watts/cm}^2$$

### B. MULTIPHOTON INTERACTIONS OF FREE ELECTRON

- VOLTAGE ACROSS LASER WAVELENGTH  $\sim 1 \text{ MeV}$

$$eE\lambda \sim mc^2 \Rightarrow E \sim 3 \times 10^9 \text{ V/cm} \text{ for } \lambda \sim 10 \mu\text{m}$$

$$I \sim 10^{16} \text{ Watts/cm}^2$$

### C. PAIR CREATION; LIGHT-BY-LIGHT SCATTERING

- VOLTAGE ACROSS COMPTON WAVELENGTH  $\sim 1 \text{ MeV}$

$$eE \frac{\lambda}{mc} \sim mc^2$$

$$E \sim 10^{16} \text{ Volts/cm}$$

- BUT, ONLY NEED THIS IN PAIR REST FRAME!

$$- \text{AT SLAC, } \gamma_e \sim 10^5, \text{ so } E_{\text{LAB}} \sim \frac{E}{10^5} \sim 10^{11} \text{ V/cm}$$

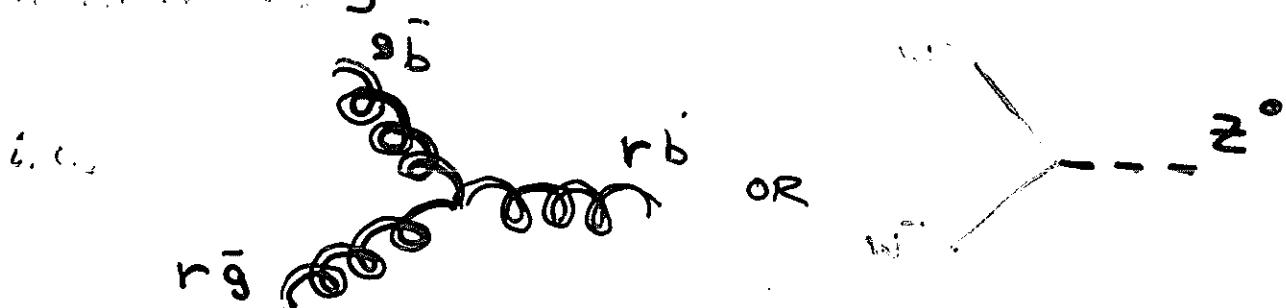
$$I \sim 10^{19} \text{ Watts/cm}^2$$

# FUNDAMENTAL    NONLINEAR    FORCES

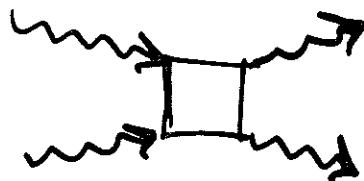
ELECTROMAGNETIC  $\rightarrow$  LINEAR  $\leftrightarrow$  SUPERPOSITION  
OF FIELDS

STRONG }  
WEAK }  
} - NONLINEAR  $\leftrightarrow$  SELF-COUPLING  
OF GAUGE BOSONS

GRV, POMERANZEN



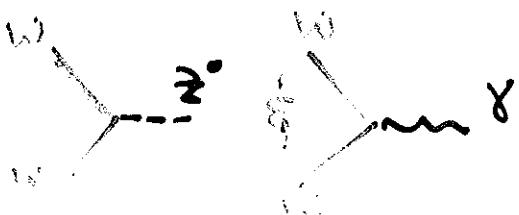
BUT, VACUUM POLARIZATION  $\Rightarrow$  NONLINEARITY IN QED



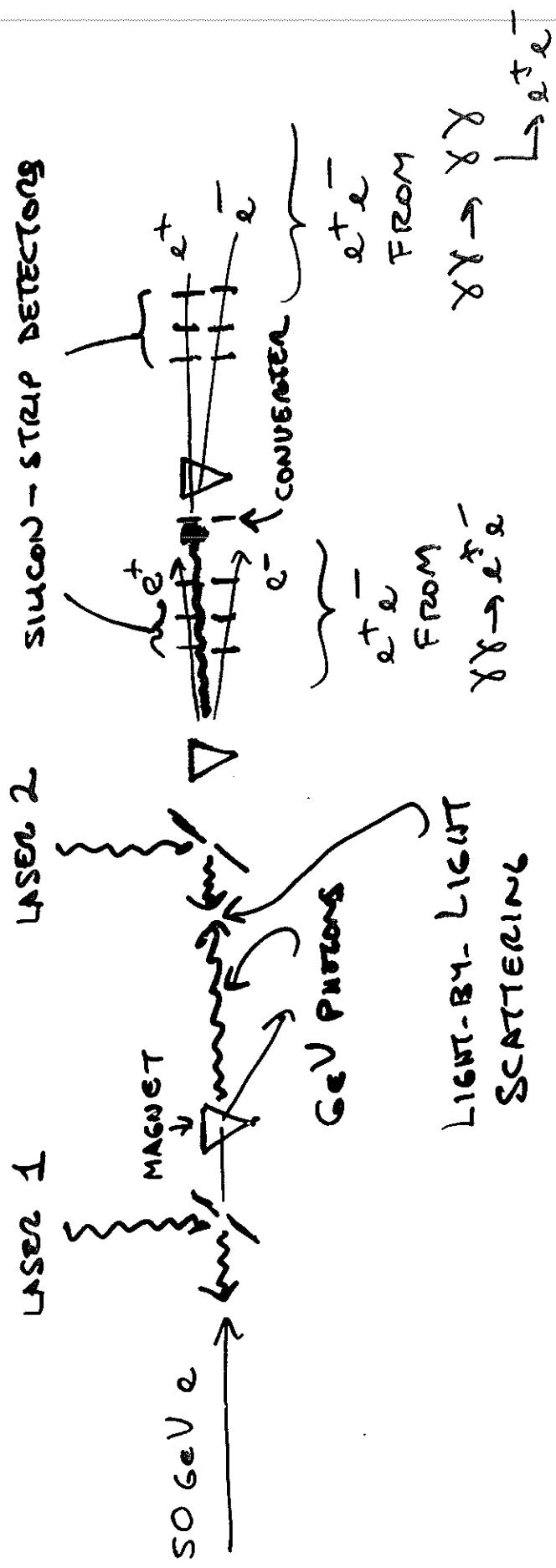
LIGHT-BY-LIGHT SCATTERING (1935)

No DIRECT EVIDENCE FOR ANY FUNDAMENTAL  
NONLINEAR INTERACTION!

LEP II:  $\sqrt{s} = 100 \text{ GeV}$  TO STUDY



LIGHT - BY - LIGHT SCATTERING EXPERIMENTS



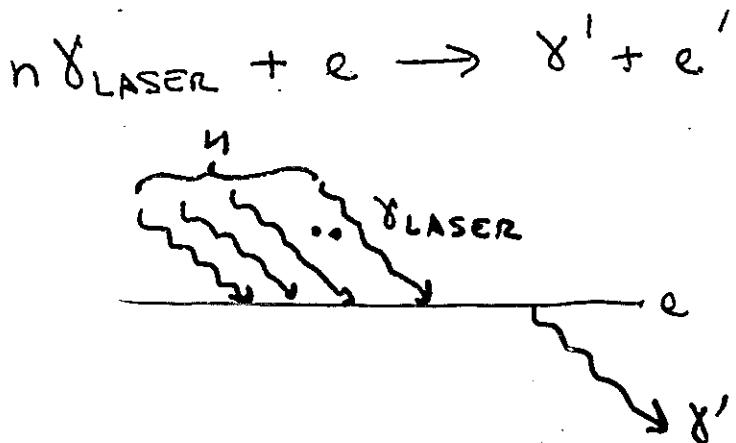
DOE/ER/3072-39  
September 9, 1986

**PROPOSAL FOR AN EXPERIMENTAL STUDY OF  
NONLINEAR COMPTON SCATTERING**

R.C. FERNOW and H.G. KIRK  
*Brookhaven National Laboratory*

I.J. BIGIO and N.A. KURNIT  
*Los Alamos National Laboratory*

K.D. BONIN, K.T. McDONALD,<sup>†</sup> and D.P. RUSSELL  
*Princeton University*



*Submitted to Brookhaven National Laboratory*

<sup>†</sup> Spokesperson

# FREE ELECTRONS IN A PLANE WAVE

## 1. TRANSVERSE VELOCITY, $v_{\perp}$

$$F = ma \Rightarrow eE = m\omega v_{\perp} \Rightarrow \frac{v_{\perp}}{c} = \frac{eE}{mc^2} \equiv \eta$$

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

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

$$\text{THEN REALLY } F = \gamma ma \quad \text{so} \quad \frac{v_{\perp}}{c} = \frac{\eta}{\gamma}$$

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

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

## HIGHER HARMONIC RADIATION

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

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

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

$$\sigma_n \sim r_0^2 (\eta^2)^{n-1} \quad (\eta \ll 1)$$

COMPARE WITH 'NAIVE' QED ANALYSIS



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

For  $\eta \gg 1$  WE HAVE A KIND OF SYNCHROTRON RADIATION  
 ⇒ MAX. INTENSITY AT HARMONIC

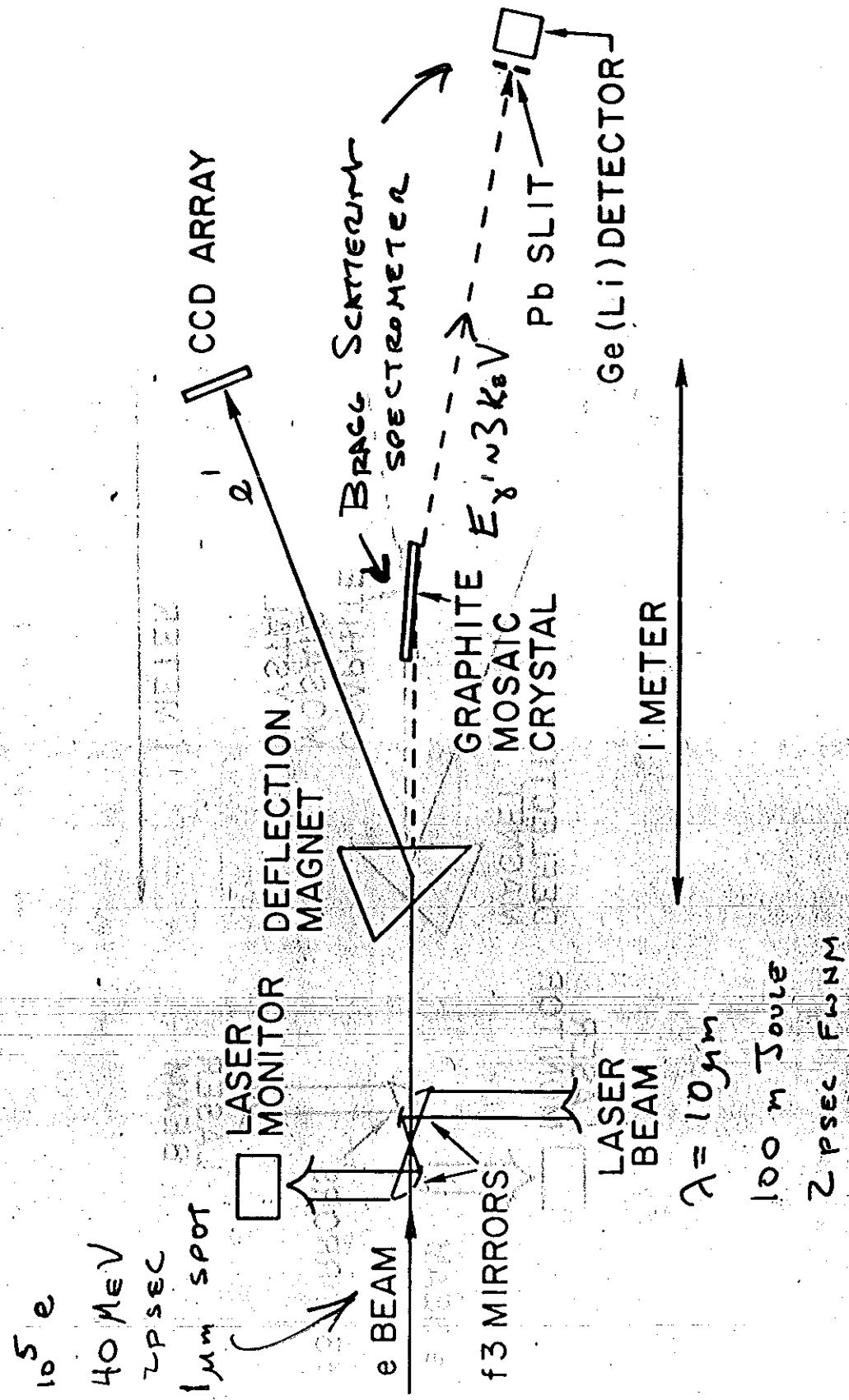
$$n\omega \sim \gamma^3 \omega \sim \eta^3 \omega$$

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

- HIGHER HARMONICS WHEN  $\eta = \frac{eB}{mc^3} \frac{\lambda_0}{2\pi} \gtrsim 1$



# Nonlinear Compton Scattering Experiment



MUST DISTINGUISH | 6-KeV X-RAY FROM  
 . 2. 3-KeV X-RAYS, ARRIVING WITHIN 2 PS!

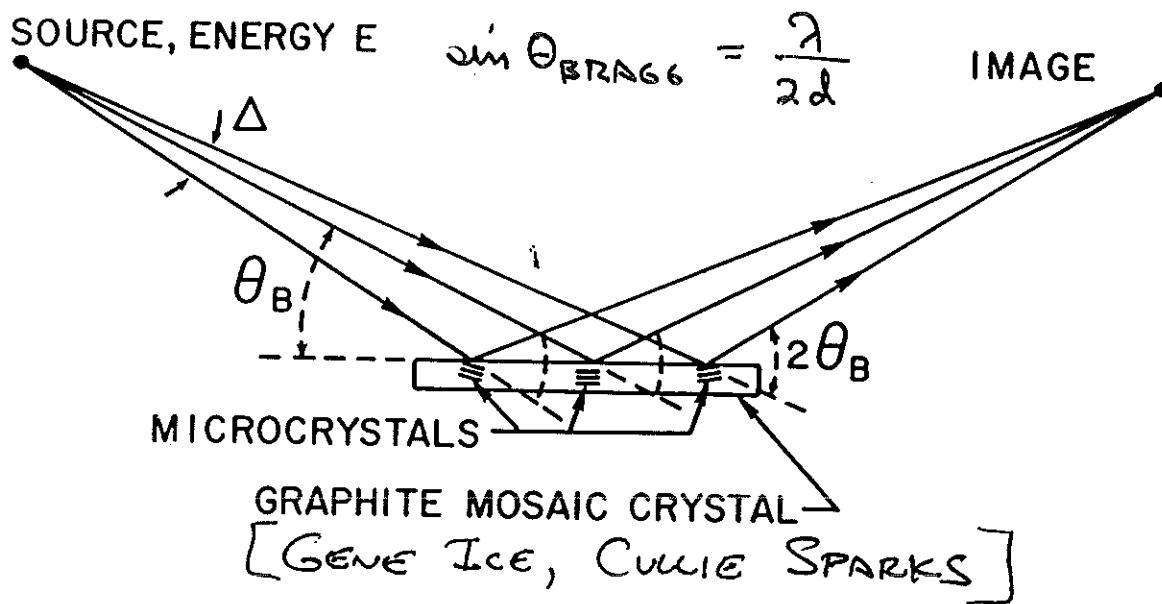


Figure 6. The scattering of monoenergetic x-rays by a graphite mosaic crystal. The scattering angle is always twice the Bragg angle  $\theta_B$ . The mosaic spread,  $\Delta$ , of orientations of the microcrystals results in a focusing geometry with angular acceptance  $\Delta$ .

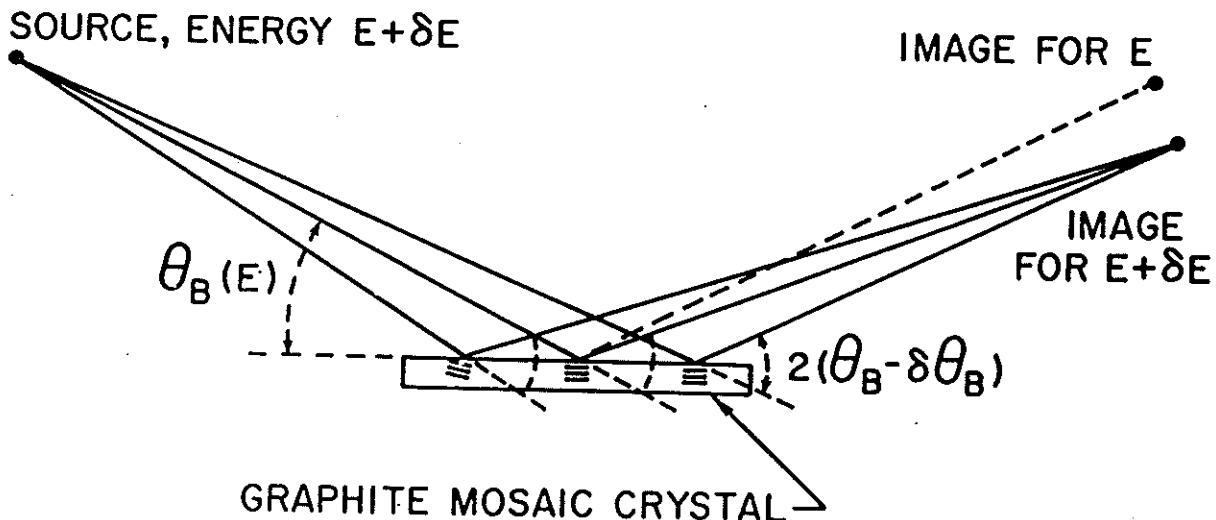
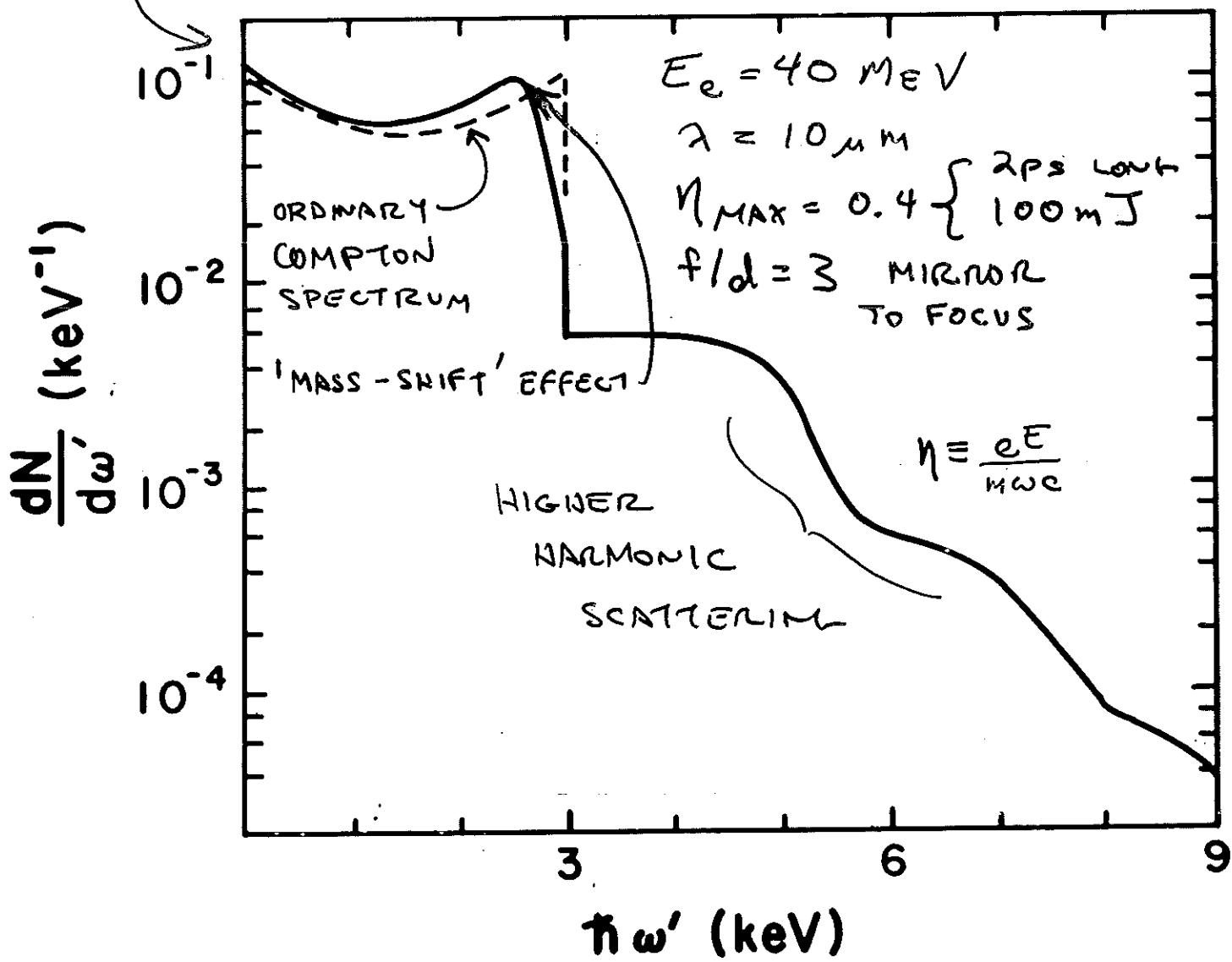


Figure 7. X-rays of energy  $E + \delta E$  are focused by Bragg reflection off a graphite mosaic crystal to a different point than those of energy  $E$ .

DATA COLLECTION  $\sim$  1 WEEK (ONCE DEBUGGED)

# NONLINEAR COMPTON SCATTERING

TOTAL SCATTERING PROBABILITY  
= 0.25 PER ELECTRON



X-RAY PRODUCTION = BASIC TEST OF  
SYNCHRONIZATION OF LASER AND LINAC.

DOE/ER/3072-55

October 27, 1989

## PROPOSAL FOR AN EXPERIMENTAL STUDY OF NONLINEAR COMPTON SCATTERING

R.C. FERNOW, H.G. KIRK, and J. ROGERS

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I.J. BIGIO, N.A. KURNIT, and T. SHIMADA

*Los Alamos National Laboratory*

K.T. McDONALD,† D.P. RUSSELL, and M.E. WALL

*Princeton University*

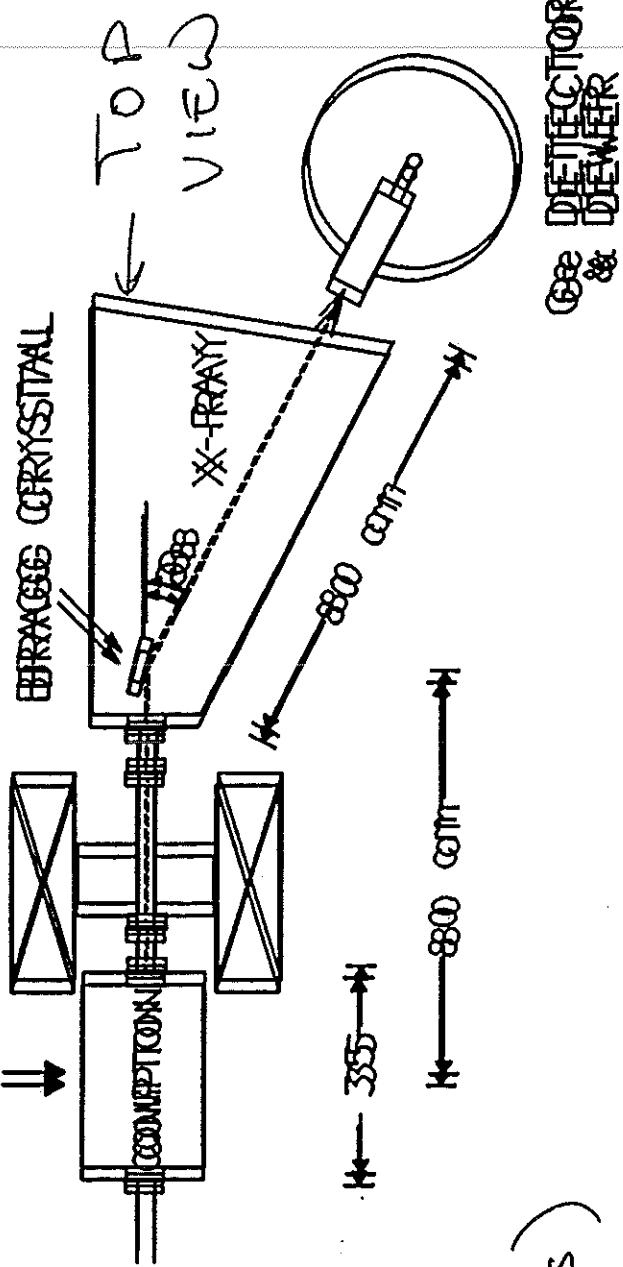
*Submitted to the Center for Accelerator Physics, Brookhaven National Laboratory*

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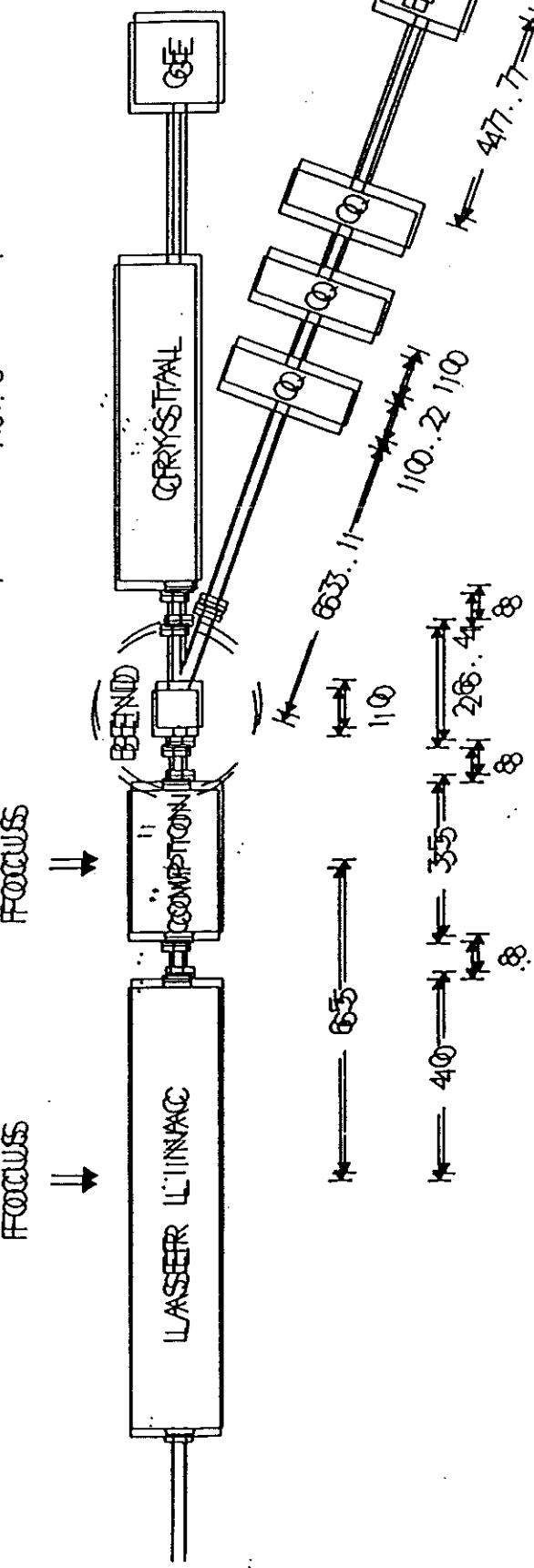
† Spokesperson

Coexistence of  
the laser - grating &  
the nonlinear  
Compton Experiment  
(needs 8<sup>th</sup> adjustment  
of CO<sub>2</sub> path lengths  
between experiments)

Focusus profile



SIDE VIEW →



## BACKGROUNDS?

I. X-RAYS THAT COULD REACH THE Ge DETECTOR  
AFTER SCATTERING OFF THE BRAGG CRYSTAL

A. SCATTERING OF THE e-BEAM OFF RESIDUAL GAS

$$10^7 \text{ e}^-/\text{s} ; 10^{-5} \text{ TORR} \Rightarrow 250 \text{ keV}$$

BUT ONLY  $\frac{1}{4}$  keV IN 1% BIN  $\approx 4 \text{ keV}$

B. SYNCHROTRON RADIATION OF e-BEAM IN DUMP MAGNET

$$20^\circ \text{ BEND} ; 50-\text{MeV} e^-/\text{s} \Rightarrow \omega_0 \sim 0.6 \text{ eV} \\ N \sim 0.2/\text{ELECTRON}$$

$\Rightarrow$  NO TAIL INTO 1keV REGION

II. X-RAYS THAT COULD REACH THE Ge DETECTOR  
WITHOUT SCATTERING OFF THE BRAGG CRYSTAL

A. X-RAYS FROM THE BEAM DUMP  $\sim 3$  FEET BELOW  
THE Ge DETECTOR

B. X-RAYS FROM THE COLLIMATORS IN THE UPSTREAM  
e-BEAM LINE

$\Rightarrow$  MUST SHIELD Ge DETECTOR WITH LEAD  
IF WANT TO DETECT  $\approx 1$  NONLINEAR COMPTON  
X-RAY PER  $10^7 e^-/\text{s}$ .

## DATA COLLECTION

- GOAL : - 1% BINS IN X-RAY ENERGY
- SCAN UPPER 30% OF ENERGY SPECTRA OF FIRST 4 HARMONICS
  - 2% STATISTICAL ACCURACY PER BIN

RATE AT 3RD HARMONIC \*

- $\sim 10^{-7}$  SCATTERS PER ELECTRON INTO 1% BIN
- $\Rightarrow$  RUN WITH  $\sim 10^7$  ELECTRONS / PULSE
- $\Rightarrow$   $\sim 150$  HOURS TO SCAN 4 HARMONICS

CALIBRATION S (OF ACCEPTANCE VIA ORDINARY  
COMPTON SCATTERING)  
 $\sim 50$  HOURS

TOTAL  $\sim \underline{200}$  HOURS

\* CO<sub>2</sub> LASER PERFORMANCE IS CRITICAL TO  
OBSERVE NONLINEAR EFFECTS

GOAL : 50mJ / PULSE

6 PS FWHM

FOCUSABLE IN f/2 MIRROR

1 Hz OPERATION

BROOKHAVEN NATIONAL LABORATORY  
ASSOCIATED UNIVERSITIES, INC.

Upton, Long Island, New York 11973

(516) 282  
FTS 666 2842

Department of Physics

6 December 1989

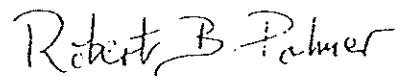
Dr. Kirk T. McDonald  
Princeton University  
Jadwin Hall  
P.O. Box 708  
Princeton, NJ 08544

Dear Kirk:

Thank you for your clear presentation of the proposal *The Nonlinear Compton Scattering Experiment* which has been given the experiment number "4". The committee recommended approval of this experiment. Congratulations!

The committee did feel that there may be a severe background from beam halo colliding with walls. It was felt however that the best way to find out was to try. Thought should, never-the-less, be given to the problem.

Yours sincerely



Robert B. Palmer

RBP:kt

cc: CAP Steering Committee:

E. Courant  
H. Foelsche  
S. Krinsky  
V. Radeka  
A. Sessler  
P. Thieberger

M. Blume  
H. Kirk  
N. Samios  
D. Sutter, DOE

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**II.**  
**Princeton Involvement with the**  
**BNL Accelerator Test Facility**

# PARTICLE ACCELERATORS

MAXWELL: PLANE WAVES HAVE  $\vec{E} \perp \vec{k}$   
SO CAN'T GIVE NET ACCELERATION TO A CHARGE

NEED  $\vec{E} \parallel \vec{k} \Rightarrow$  WALL OR MEDIUM

BUT, WALL DESTROYED IN 1 CYCLE IF

$$E \gtrsim \frac{\text{ION. POT.}}{\text{SIZE OF ATOM}} \sim \frac{10 \text{ VOLTS}}{1 \text{ Å}} \sim 10^9 \text{ VOLTS/cm}$$

MATERIALS LIMIT:  $E_{\text{WALL}} \lesssim 10^7 \text{ VOLTS/cm}$

so  $E_{||} \sim E_{\text{WALL}} \lesssim \underline{1 \text{ GeV/meter}}$

(LIMIT IN A PLASMA MAY BE SOMEWHAT HIGHER!)

STANFORD LINEAR COLLIDER: 15 MeV/meter

'TABLETOP' CO<sub>2</sub> LASER: ~ 100 GeV/meter

'TABLETOP' Nd:GLASS (QUADRUPOLE): ~ 1 TeV/meter

$\Rightarrow$  LASER - GRATING ACCELERATOR

INVERSE FEL

INVERSE ČERENKOV

PLASMA BEAT WAVE

⋮

# Design of the Laser-Driven RF Electron Gun for the BNL Accelerator Test Facility

KIRK T. McDONALD

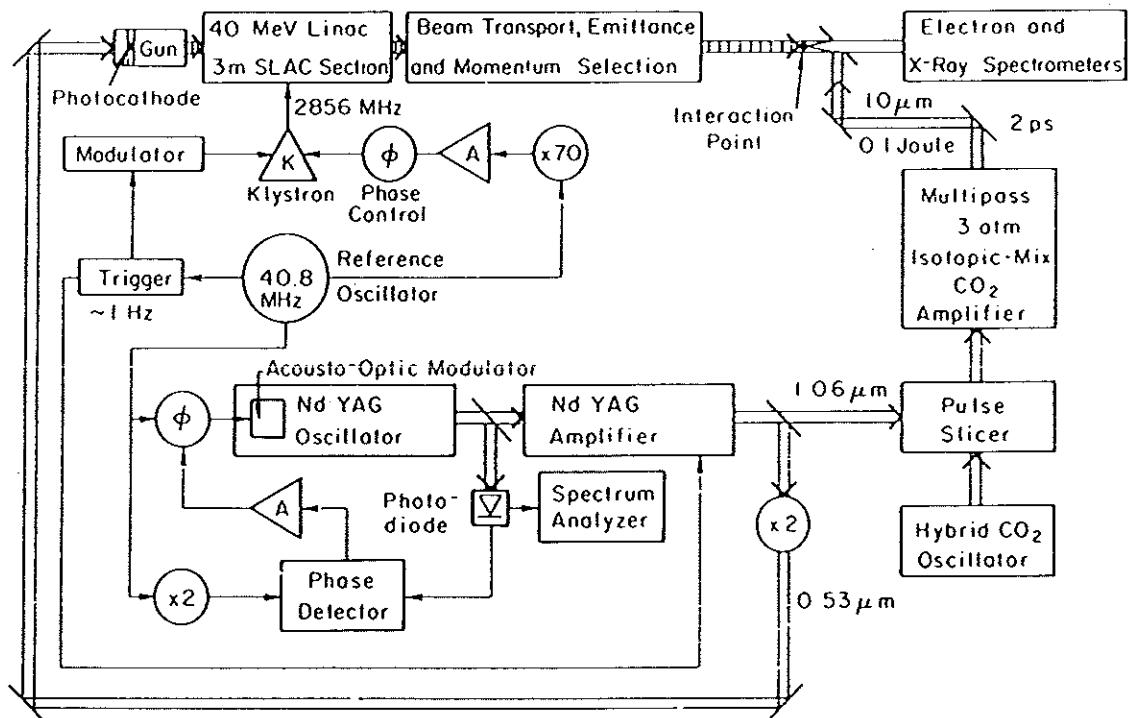


Fig. 1. Block diagram of the Brookhaven Accelerator Test Facility.

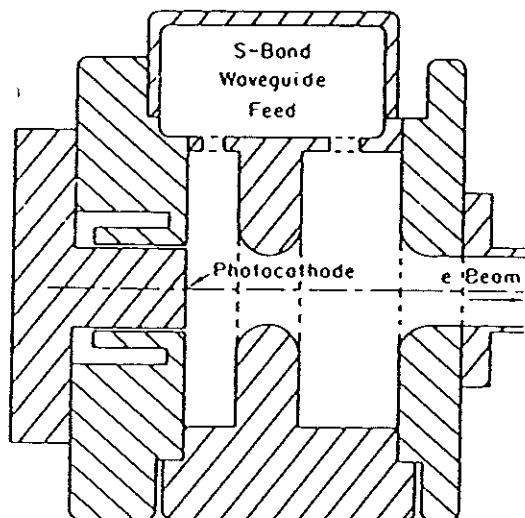


Fig. 2. Section through the RF gun. Except for the waveguide feed, the gun is axially symmetric. The  $1\frac{1}{2}$ -cells of the gun are 8 cm long.

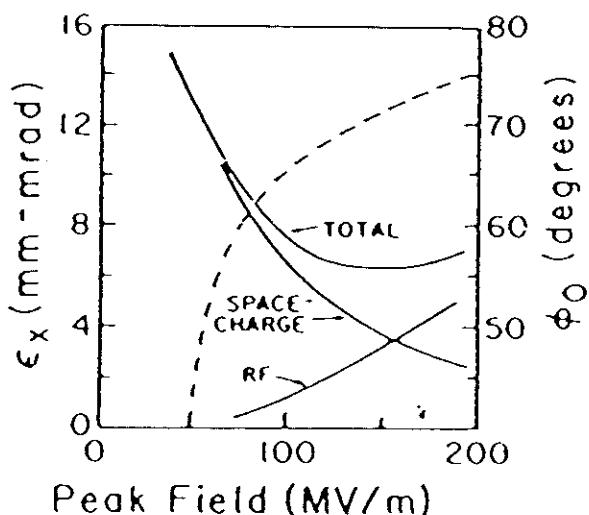


Fig. 8. The transverse emittance (solid curves) as a function of the peak RF field on the cathode, and the optimum phase (dashed curve) for the laser pulse to strike the cathode. Other parameters are as in Table I.

# Methods of Emittance Measurement

K.T. McDonald and D.P. Russell

## Frontiers of Particle Beams; Observation, Diagnosis and Correction

Proceedings of a Topical Course  
Held by the Joint US-CERN School on Particle Accelerators  
at Anacapri, Isola di Capri, Italy, October 20-26, 1988

M. Month S. Turner (Eds.)

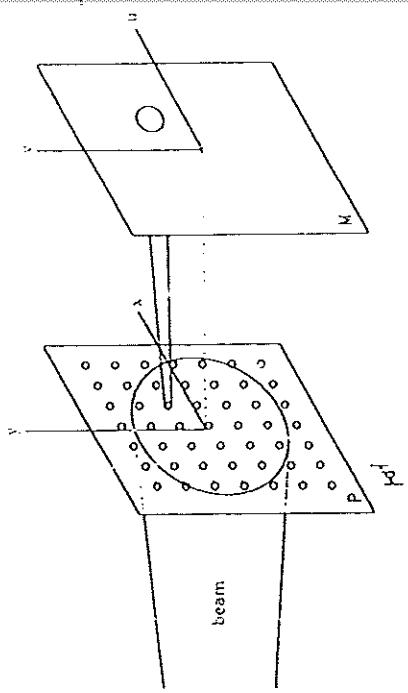


Fig. 3. Pepper-Pot Technique

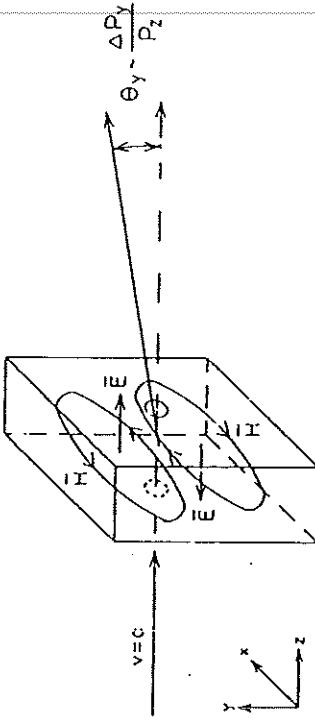


Fig. 4. A TM<sub>120</sub> rf cavity used to impart a time-dependent transverse deflection to a particle beam.

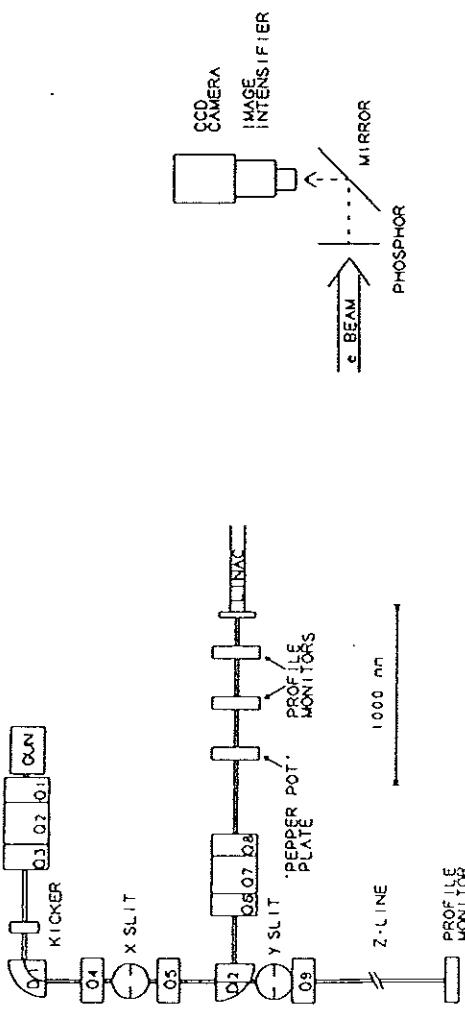


Fig. 1. ATF Beamline.

Fig. 2. A Phosphor-Screen Beam-Profile Monitor.

A BEAM-PROFILE MONITOR  
FOR THE BNL ACCELERATOR TEST FACILITY (ATF)

D. P. Russell and K. T. McDonald

*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*

Proceedings of the  
1989  
IEEE Particle Accelerator  
Conference

*Accelerator Science  
and Technology*

March 20-23, 1989  
Chicago, IL

Proceedings Editors  
Floyd Bennett  
and  
Joyce Kopra  
Argonne National Laboratory

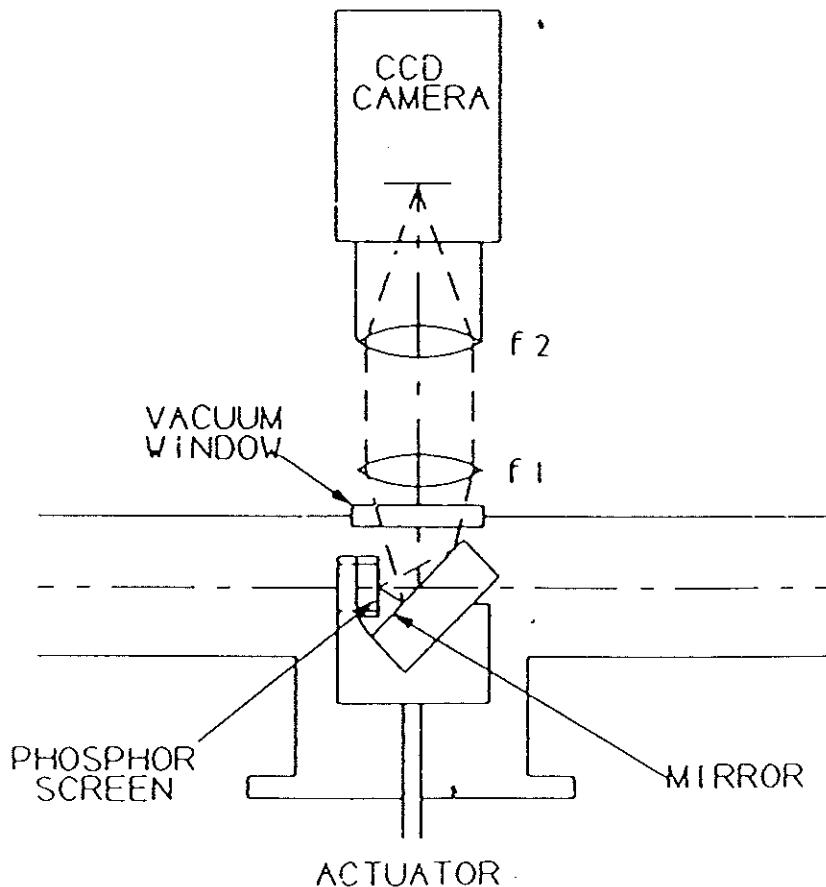
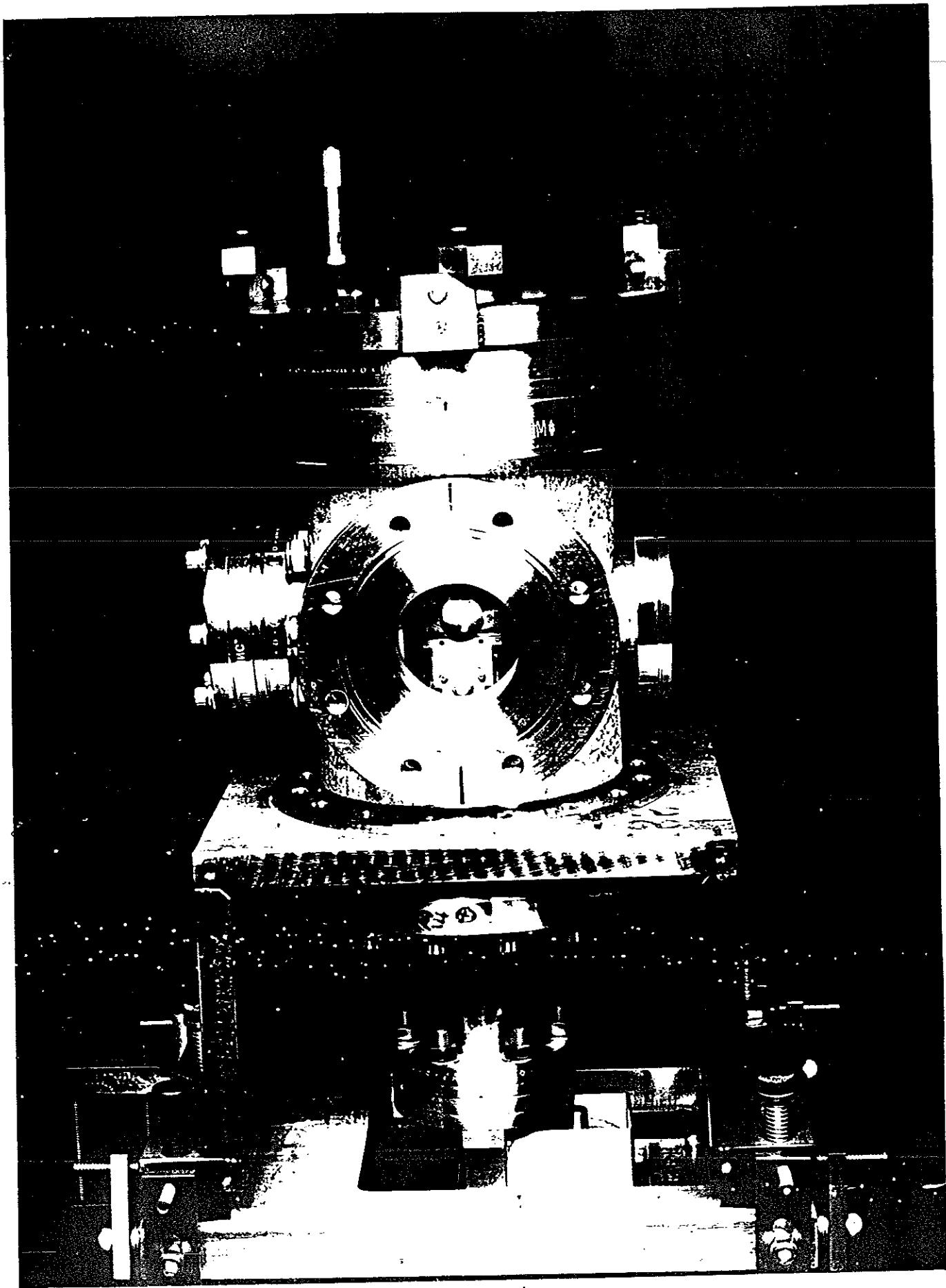
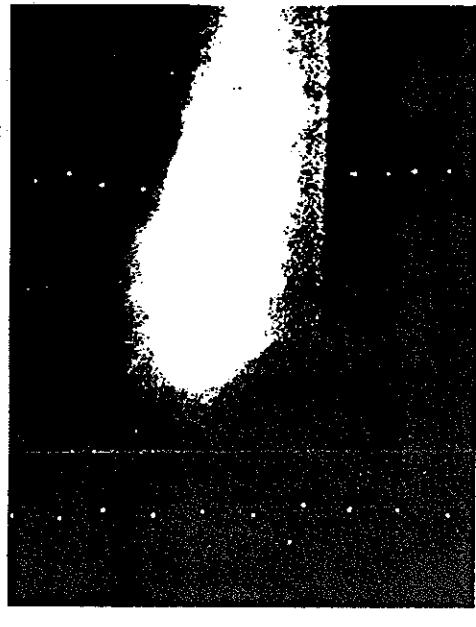


Fig. 1. The ATF beam-profile monitor

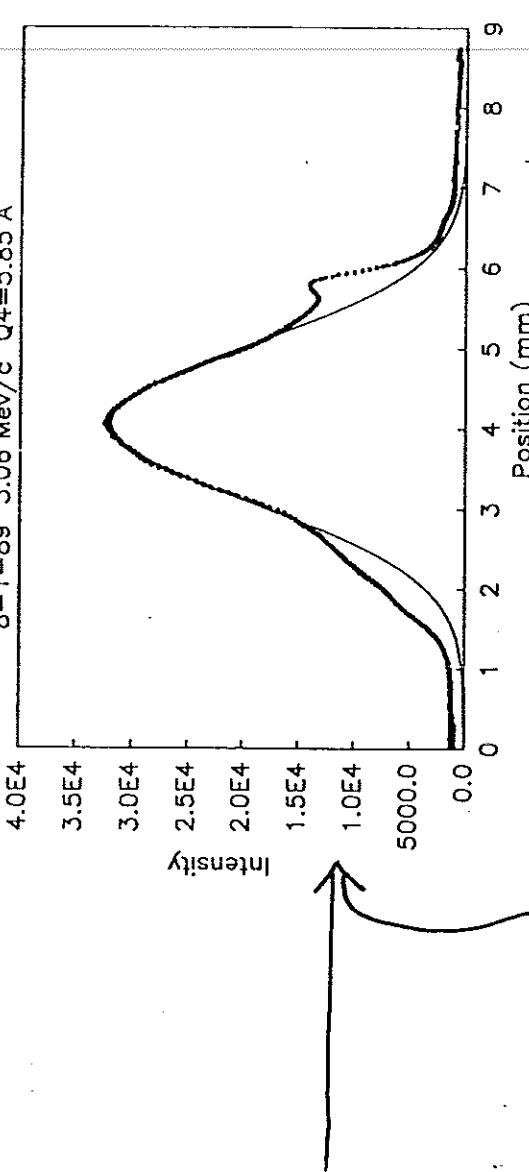


## Initial Emittance Measurements

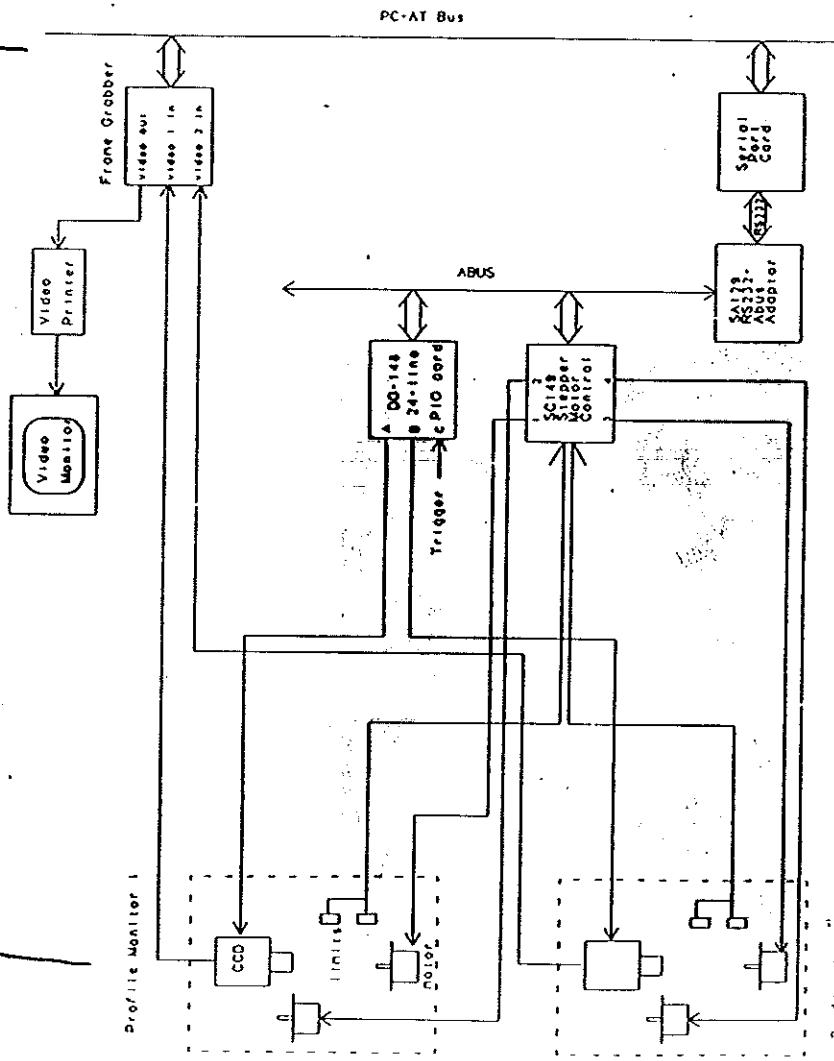


Vertical Beam Profile

8-1-89 3.06 Mev/c Q4=5.85 A

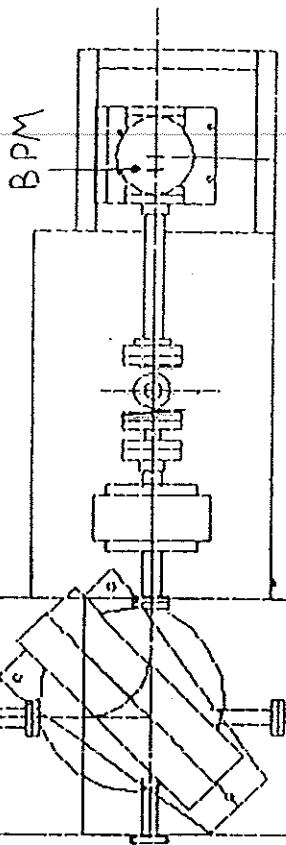
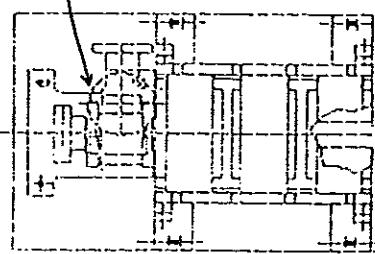


Beam-Profile Monitor System (2 Monitors)

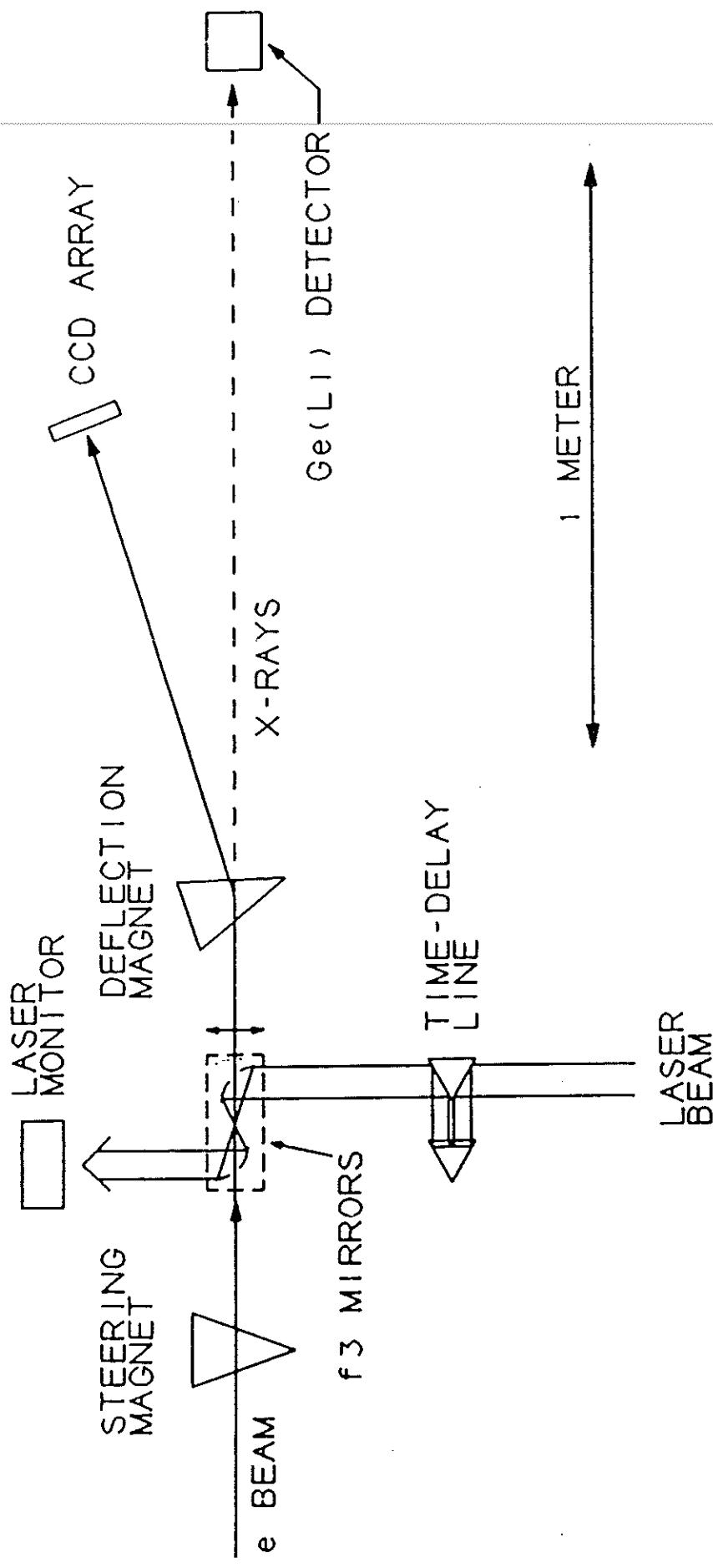


$$\epsilon_N = 8\pi \text{ mm-mrad}$$

RF Gun



# X-RAY DIAGNOSTIC OF ELECTRON - CO<sub>2</sub> LASER INTERACTIONS



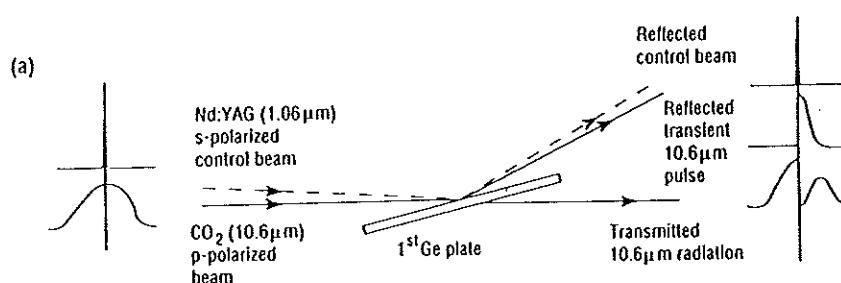
VERIF: PICOSECOND SYNCHRONIZATION OF e BEAM WITH LASER.

# Preliminary Tests and Modeling of the 10.6 $\mu\text{m}$ Picosecond Pulse-Formation System Experiment

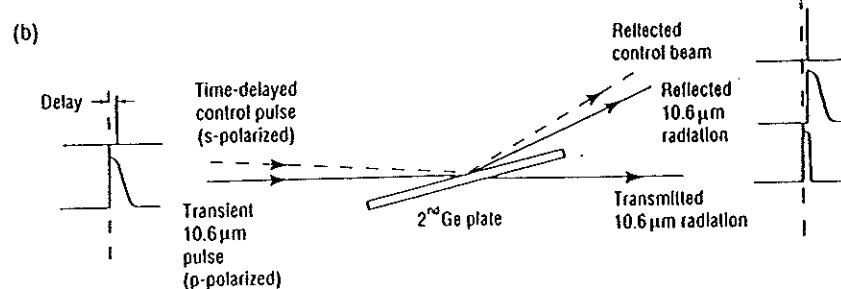
CAP-ATF-Tech. Note #7

I. Pogorelsky  
Brookhaven National Laboratory  
and Spectra Technology, Inc.

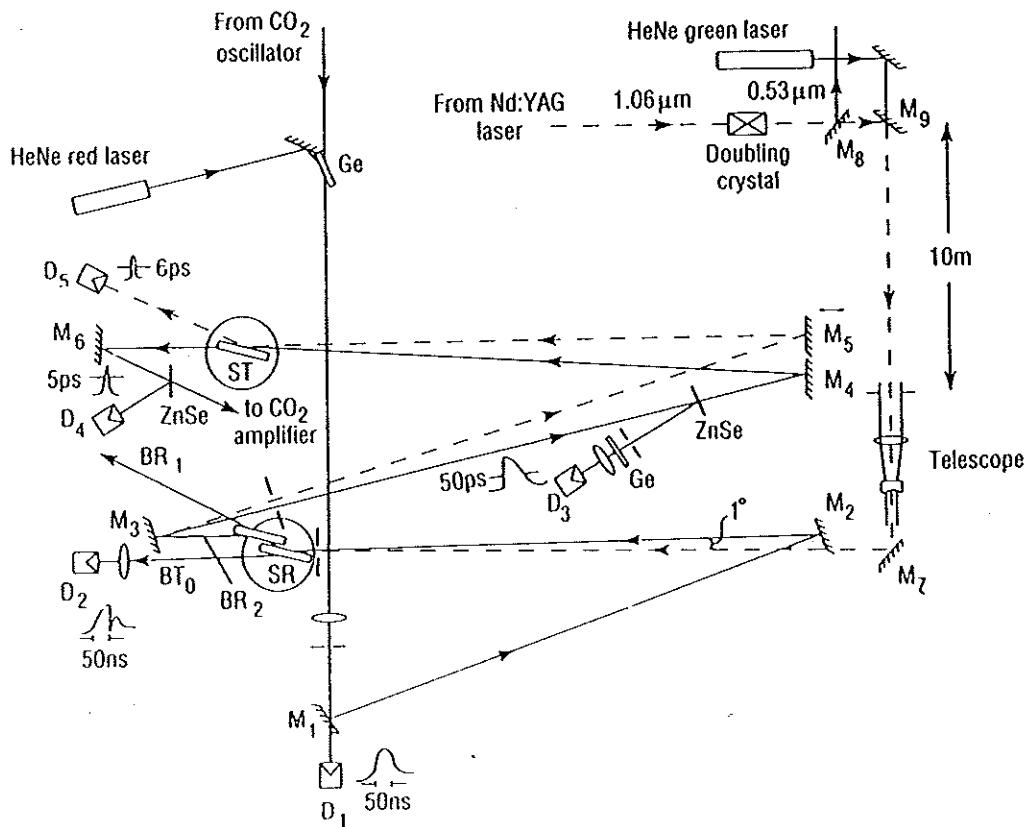
P. Russell  
Princeton University



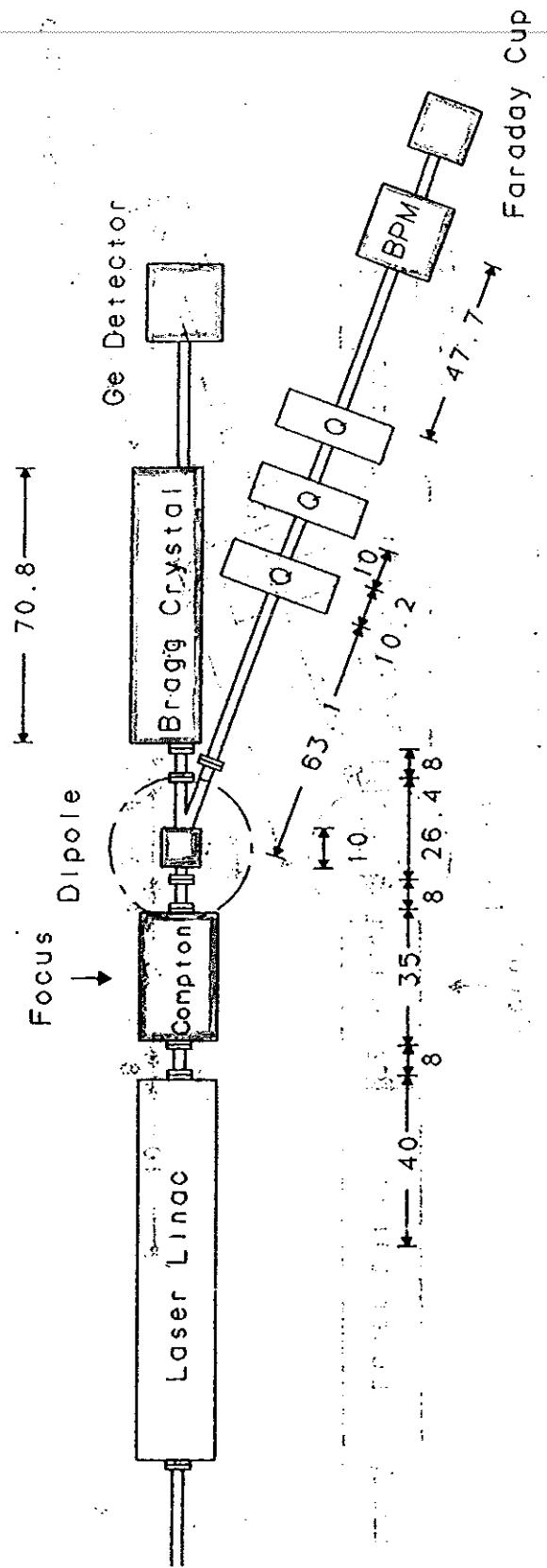
ONE-STAGE REFLECTION SWITCHING



TRANSMISSION SWITCHING

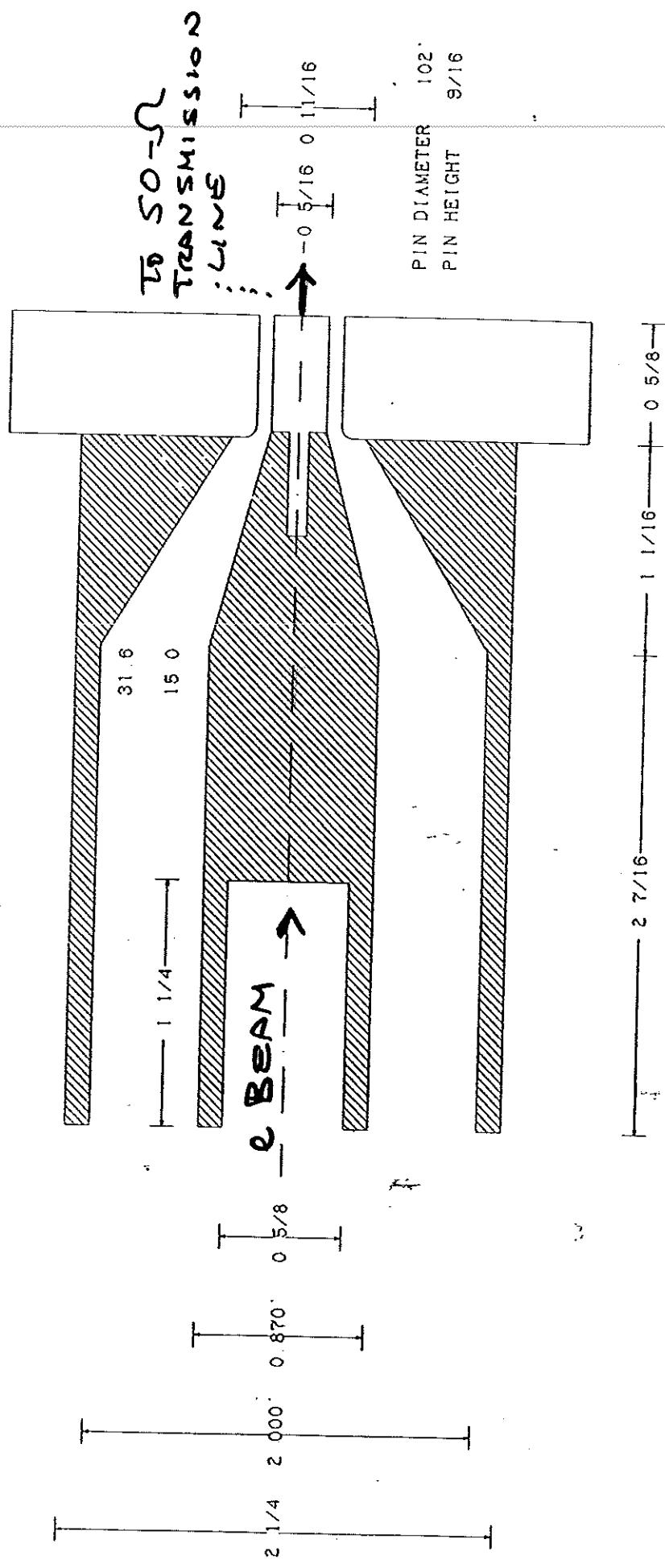


# ATF Experimental Beamline



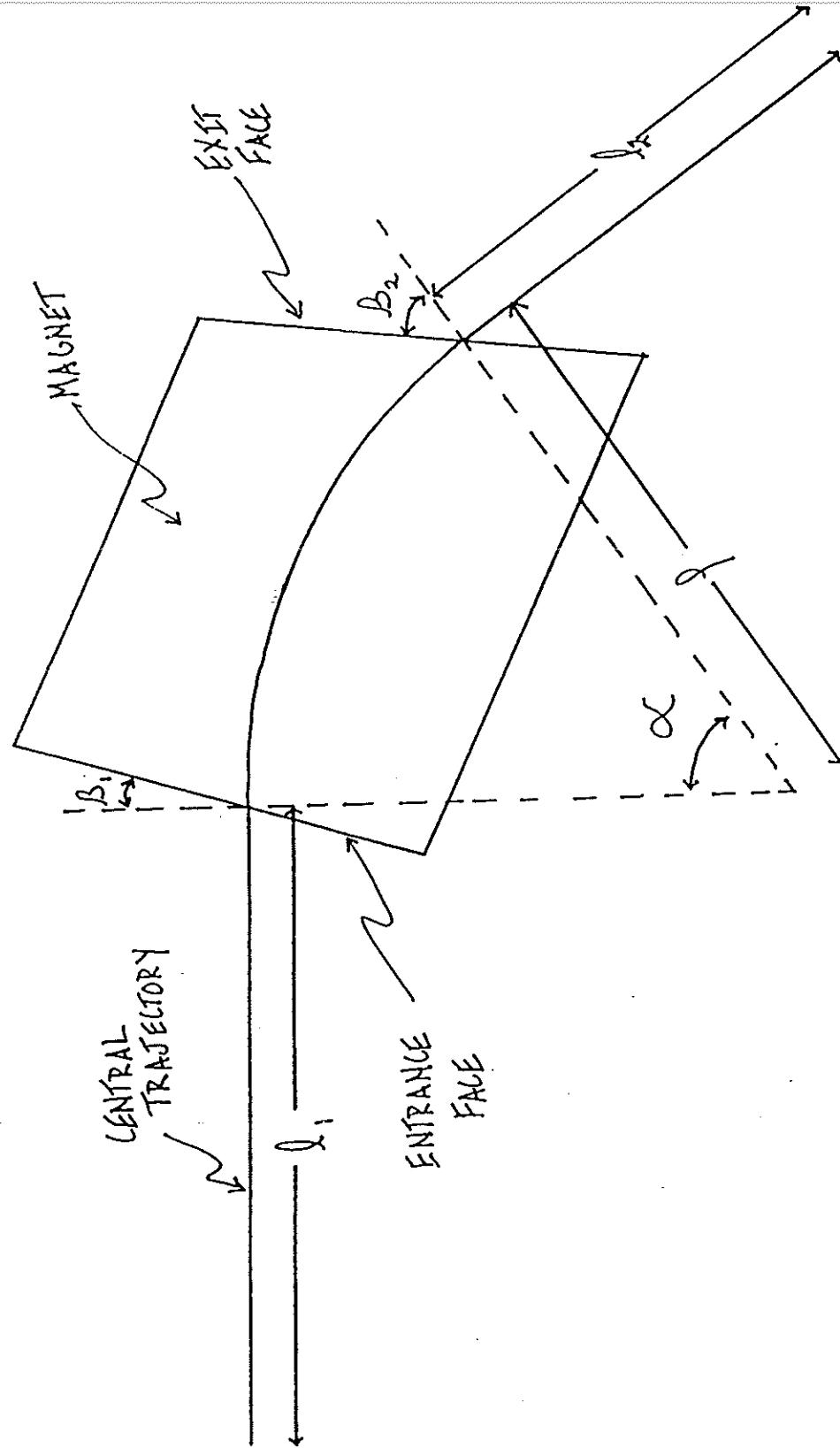
□ = BUILT BY PRINCETON U.

# 3-GHz Faraday Cup



Simultaneous x- and y-Focusing with a Single Bend Magnet

(M. WU)



	α [deg]	20.5	30.0	40.0
	ρ [cm]	13.9	16.7	16.7
	B [kgauss]	12	10	10
	l <sub>1</sub> [cm]	91	91	91
	l <sub>2</sub> [cm]	216	88.5	41.2
	β <sub>1</sub> [deg]	0	0	0
	β <sub>2</sub> [deg]	8.24	9.5	9.24
	∂R <sub>12</sub> / ∂β <sub>2</sub> [mm/mrad/deg]	0.265	0.0945	0.0450
	∂R <sub>44</sub> / ∂β <sub>2</sub> [deg <sup>-1</sup> ]	-0.123	-0.107	-1.110

# The Brookhaven Accelerator Test Facility

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J. Fischer,<sup>(a)</sup> A.S. Fisher,<sup>(a)</sup> J. Gallardo,<sup>(a)</sup> Xie Jialin,<sup>(a)</sup> Z.Y. Jiang,<sup>(d)</sup>  
H.G. Kirk,<sup>(a)</sup> N. Kurnit,<sup>(b)</sup> K.T. McDonald,<sup>(c)</sup> Z. Parsa,<sup>(a)</sup> R.B. Palmer,<sup>(a)</sup>  
C. Pellegrini,<sup>(e)</sup> T. Rao,<sup>(a)</sup> J. Rogers,<sup>(a)</sup> J. Sheehan,<sup>(a)</sup> T. Shimada,<sup>(b)</sup>  
T.Y.F. Tsang,<sup>(a)</sup> S. Ulc,<sup>(a)</sup> A. Van Steenbergen,<sup>(a)</sup> X.J. Wang,<sup>(e)</sup>  
M. Woodle,<sup>(a)</sup> R.S. Zhang<sup>(a)</sup>

<sup>(a)</sup>Brookhaven National Laboratory; <sup>(b)</sup>Los Alamos National Laboratory;  
<sup>(c)</sup>Princeton University; <sup>(d)</sup>SUNY, Stony Brook; <sup>(e)</sup>UCLA

The following is a partial list of experiments planned for the ATF:

- Laser-grating accelerator experiment.
- Inverse free-electron laser demonstration stage.
- Inverse Čerenkov accelerator experiment.
- Visible free-electron laser.
- Nonlinear Compton scattering experiment.

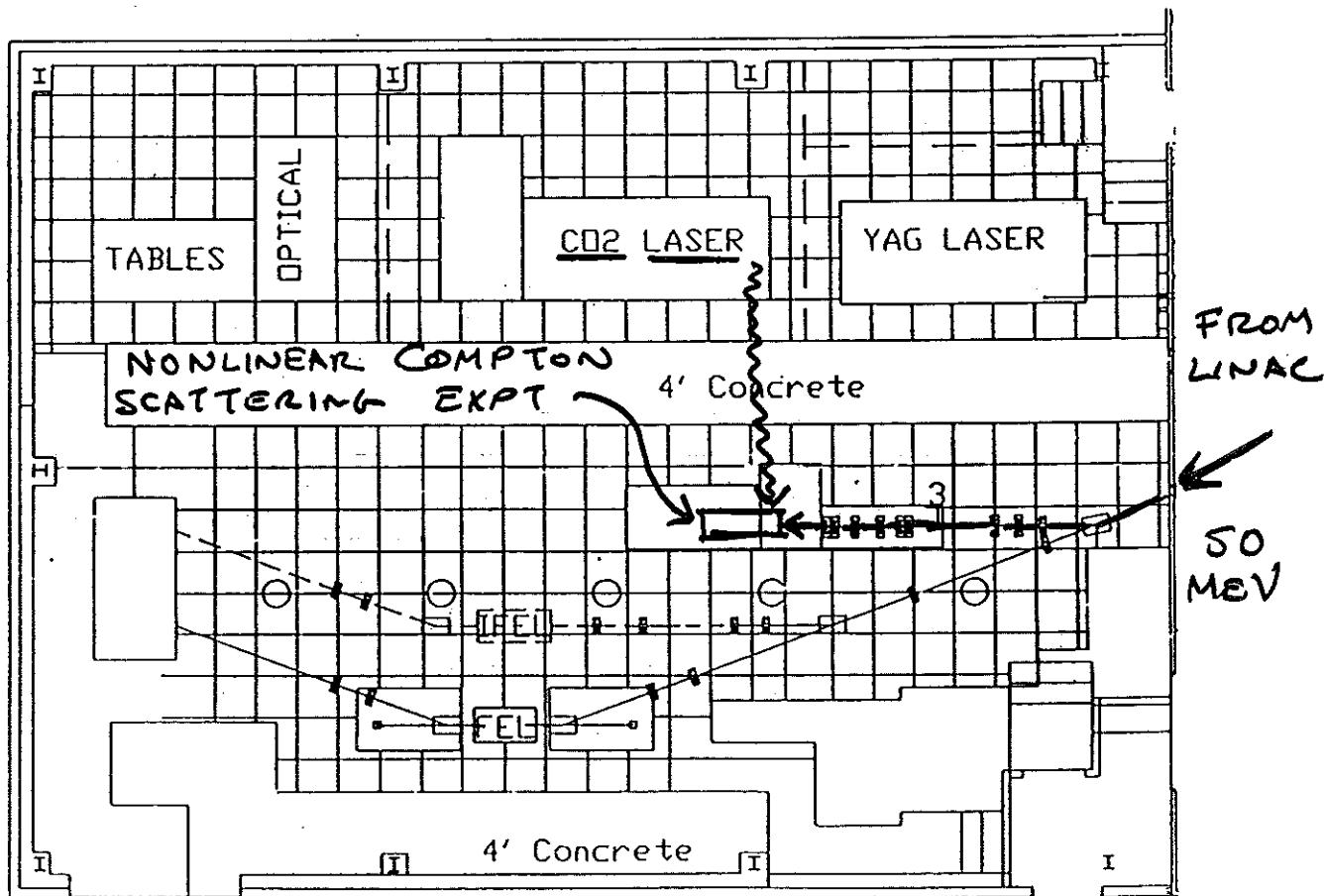
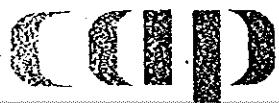


Figure 1. The proposed experimental beamlines of the ATF.



BNL-43465

CAP #52  
LL-89R

Proposal for a Study of  
Laser Acceleration of Electrons  
Using Micrograting Structures  
at ATF (Phase I)

29 October 1989

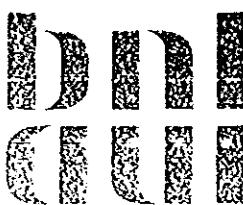
W. Chen, J. Claus, R. C. Fernow , J. Fischer,  
J. C. Gallardo, H. G. Kirk, H. Kramer, Z. Li,  
R. B. Palmer, J. Rogers, T. Srinivasan-Rao,  
T. Tsang, S. Ulc, J. Veligdan and J. Warren  
*Brookhaven National Laboratory*

I. Bigio, N. Kurnit and T. Shimada  
*Los Alamos National Laboratory*

K. T. McDonald and D. P. Russell  
*Princeton University*

X. Wang  
*UCLA*

**CENTER FOR ACCELERATOR PHYSICS**



BROOKHAVEN NATIONAL LABORATORY  
ASSOCIATED UNIVERSITIES, INC.

Under Contract No DE-AC02-76CH00016 with the

UNITED STATES DEPARTMENT OF ENERGY

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## **Summary of DOE Support for Princeton U. at the ATF**

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### **I. Operating Expenses (1987-)**

Ongoing travel and salary support, including use of technical staff.

### **II. Supplement (1988-89) ..... \$50k**

Construction of the CCD-camera emittance monitors.

### **III. Supplement (1989-1990) ..... \$50k**

Construction of the backscattered x-ray diagnostic.

### **IV. Budget Request for the Fiscal Year 1991**

Construction of the nonlinear Compton scattering experiment.

- a. Pyrolytic graphite crystals ..... \$5k
- b. X-ray scattering chamber ..... \$5k
- c. Motion control for the graphite crystal and x-ray detector ..... \$10k
- d. Vacuum system for the x-ray spectrometer and x-ray beam diagnostic ..... \$20k

**Total ..... \$40k**