UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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Winter College on Quantum Optics: Novel Radiation Sources

3-21 March 1997

Gain and noise fluctuations in a SASE FEL: the UCLA IR FEL

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The UCLA IR FEL: An Operating High Gain Free Electron Laser Experiment

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Presented at the ICTP Winter College on Quantum Optics
March 1997

Outline

The Cast

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http://pbpl.physics.ucla.edu/

[redacted] Areas of Study

- FEL Startup from Noise
- Output Fluctuations
- Quantum Effects
- Undulator Focusing
- Undulator Errors
- Microbunching
- Technical Challenges:
  undulator, diagnostics...

Uses of Microbunched Beams

- High frequency accelerators
  - Injection into plasma, dielectric accelerators
- Light sources
  - Radiation production
  - Compton backscattering
- Compressor
  - Replacement for magnetic compression

Start up

What is the effective input bandwidth which is amplified by the FEL?

Spontaneous emission calculations
Theory

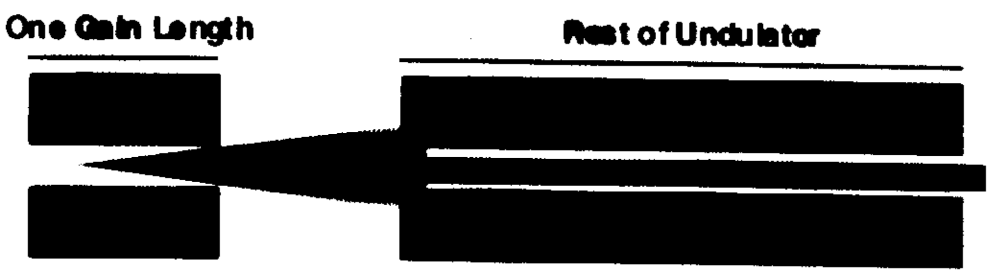
A charged particle traversing undulating magnetic field radiates.

We need to know

a) The total spontaneous emission from the undulator.
b) The total emission over the FEL bandwidth and solid angle.
c) The effective startup level for the FEL.

Four approaches to calculate spontaneous emission:

1) Larmor's formula.
2) From FEL 1D equations.
3) Integrated Liénard-Wiechert fields a lá Jackson.
4) Numerical model with "random" distribution.



Spontaneous emission calculations
Example From FEL 1D Equations

$$\left(\frac{dP}{d\omega d\Omega}\right) = \left(\frac{Ne\gamma K}{1+K^2/2}\right)^2 \frac{I}{4\pi\varepsilon_0 ce}.$$

where I is the beam current and here N is the number of undulator periods in one gain length.

This, along with the FEL bandwidth, yields

$P \approx 37$ milliwatts

(Spontaneous radiation power in one gain length within the **FEL** bandwidth and angular acceptance.)

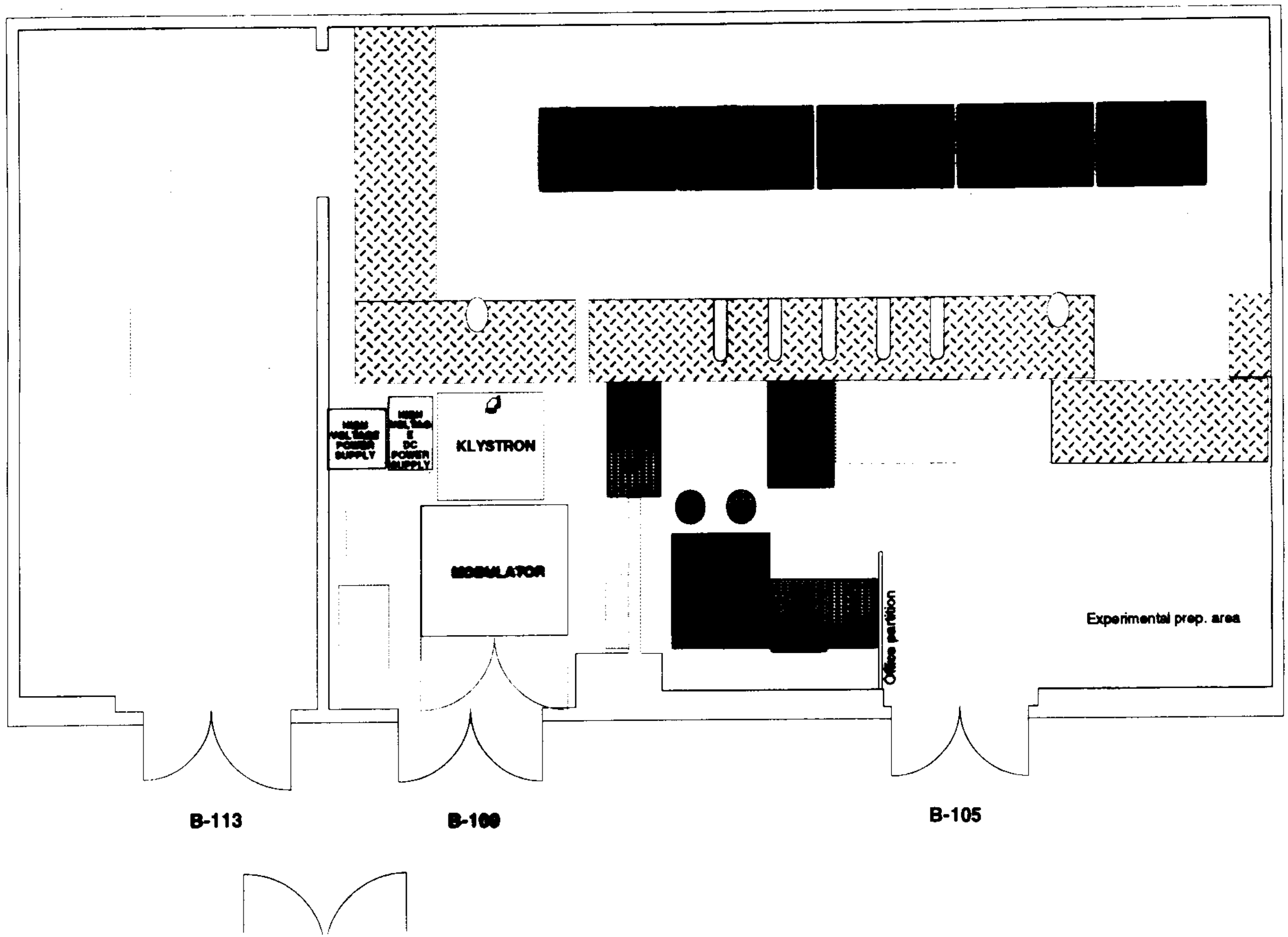
ON BOARD

PBPL is a test system!

FEATURE	REQUIREMENT	COST	PBPL REALITY
Tunability	tunable undulator tunable beam energy	complex mechanics/ undulator complex beam dynamics	Minimal tunability (not needed)
Wavelength	(FEL can operate in wavelengths not accessible to conventional lasers) Beam energy (high)	Large accelerator	Tests designed @ 10.6 μm (CO_2) / operated @ 10μm
Average Power	(FEL can operate at high average power) High beam power	Expensive accelerator- High beam power ⇒ High rf power- radiation shielding	Minimal power 5 Hz / single shot
High Peak Power	(FEL can reach GW range) Long undulator	Undulator	PBPL uses short undulator ⇒ low peak power

[redacted]

The UCLA Particle Beam Physics Laboratory



IR FEL Parameters

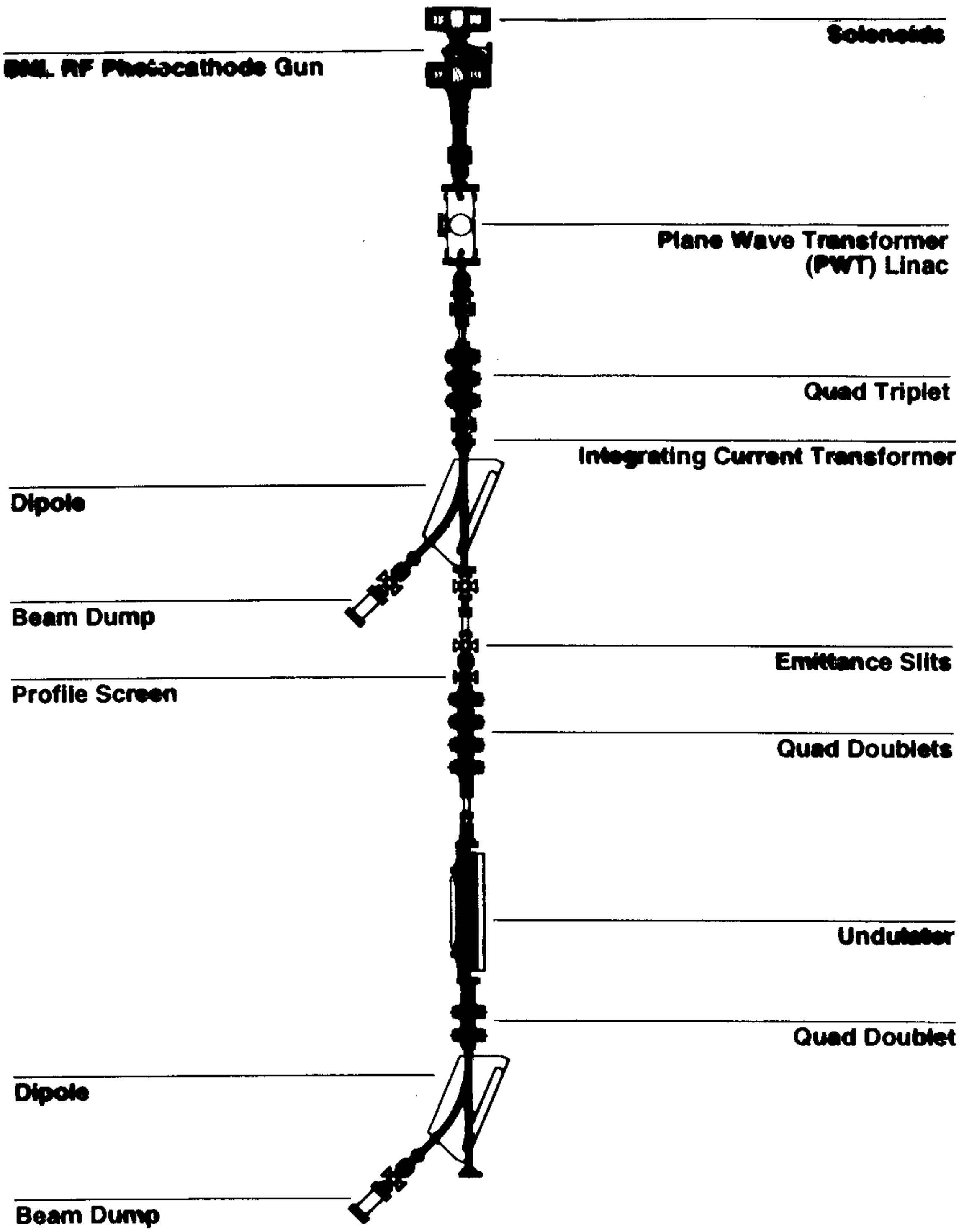
[Measured/Expected]

Single Shot Beam Parameters		Planar Hybrid Undulator Parameters	
Energy	13 MeV	Length	60 cm
Energy Spread (rms)	0.25%	Period	1.5 cm
Peak Current	150 A	Peak Field	0.75 T
Emittance (norm. rms)	12 mm-mrad @ 1/2nC	Undulator Parameter	1

High Gain SASE FEL Simulation Results

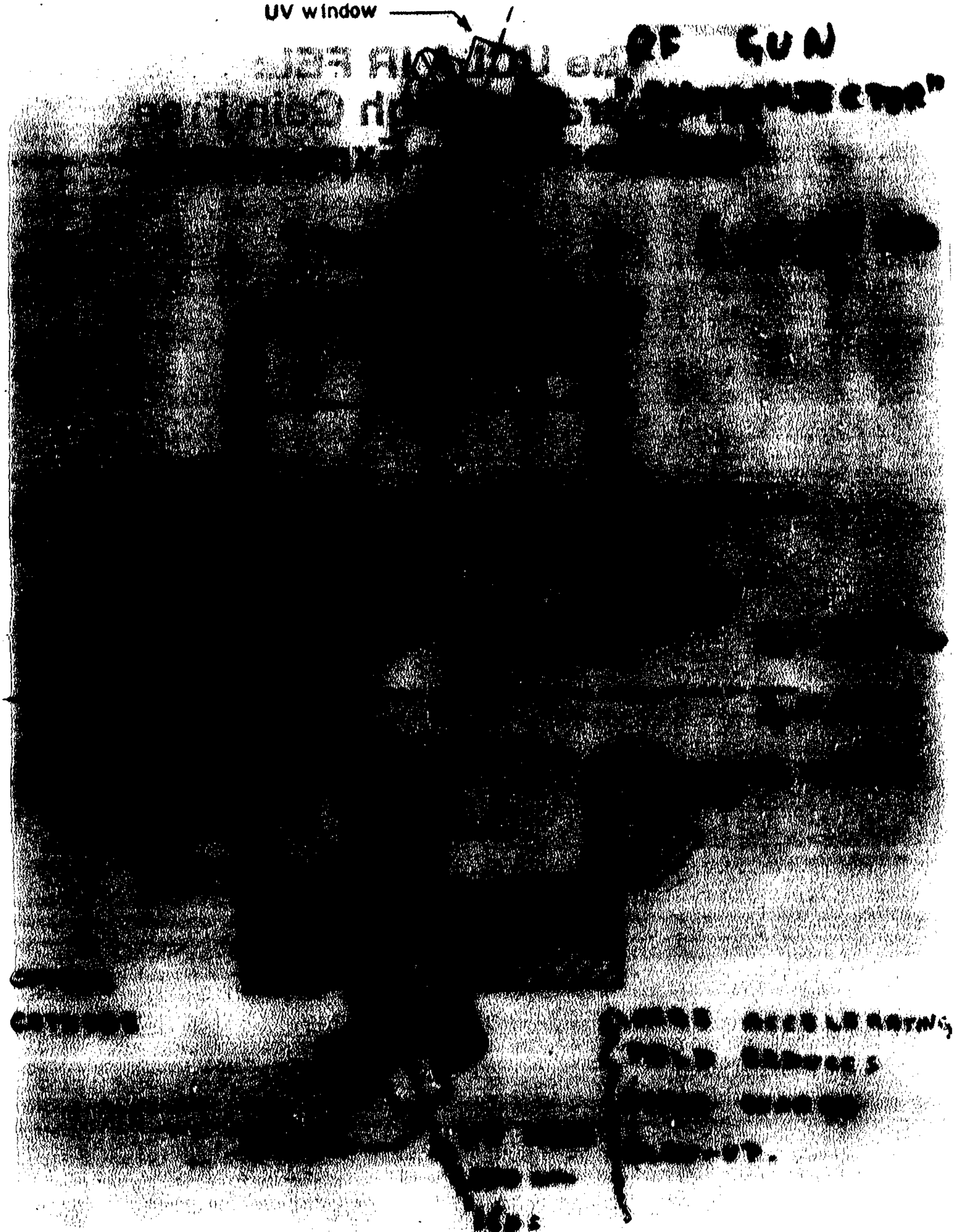
Total Gain @ 60 cm	~500
Peak Power	1 W
Nominal Wavelength	20 μm

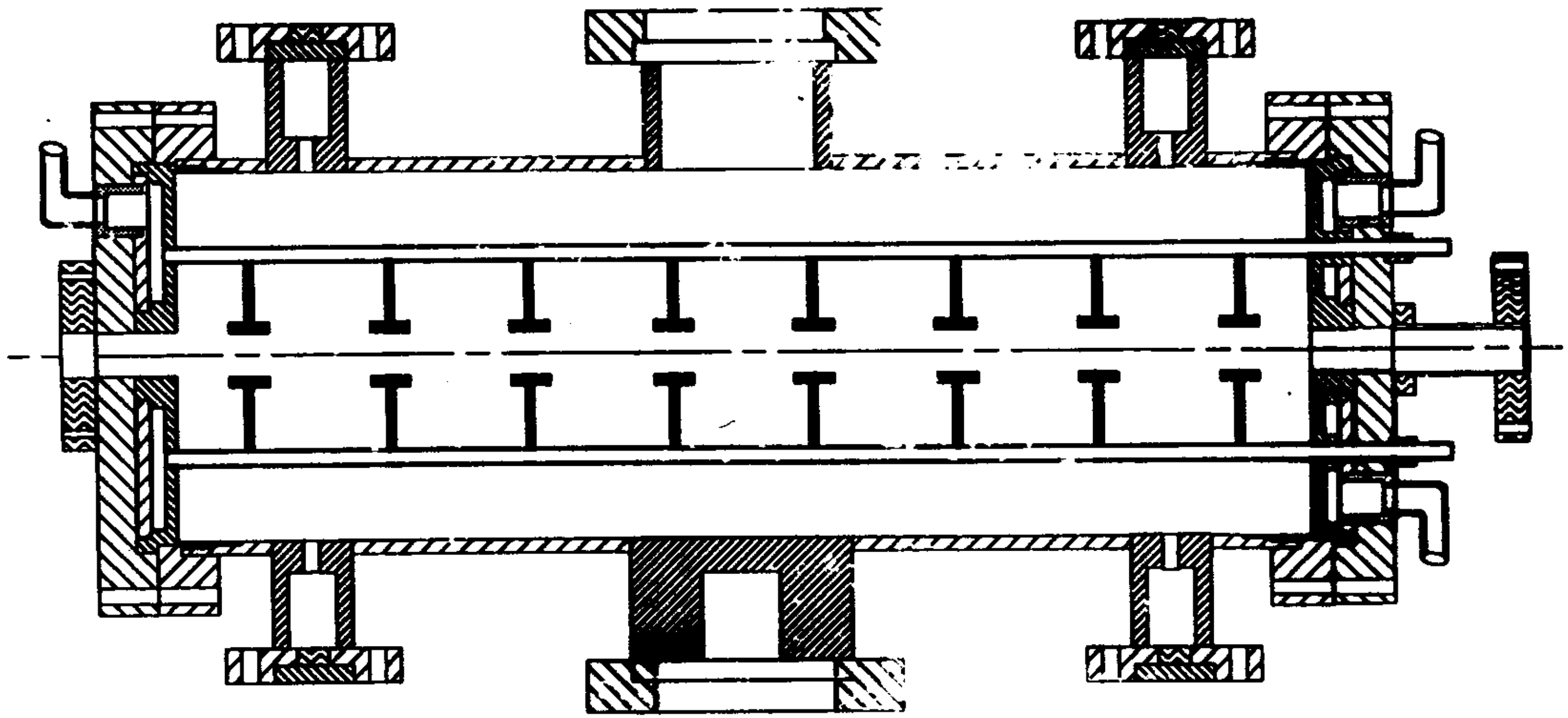
IR FEL Beamline



Revised
2/13/97

UCLA Particle Beam Physics Laboratory


UV window
RF GUN

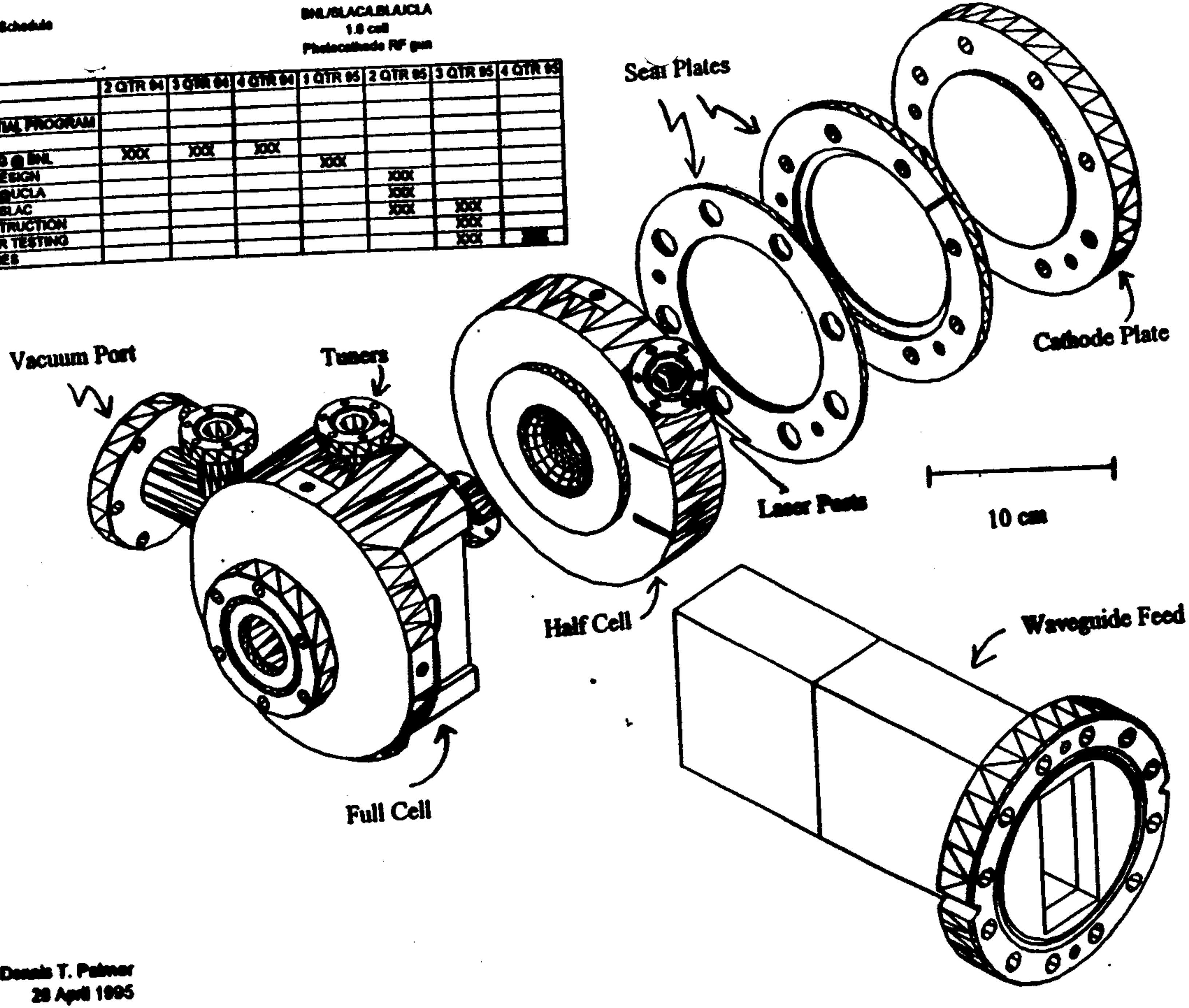


The Cross-Section Schematic of the Plane Wave Transformer (PWT) Linac.

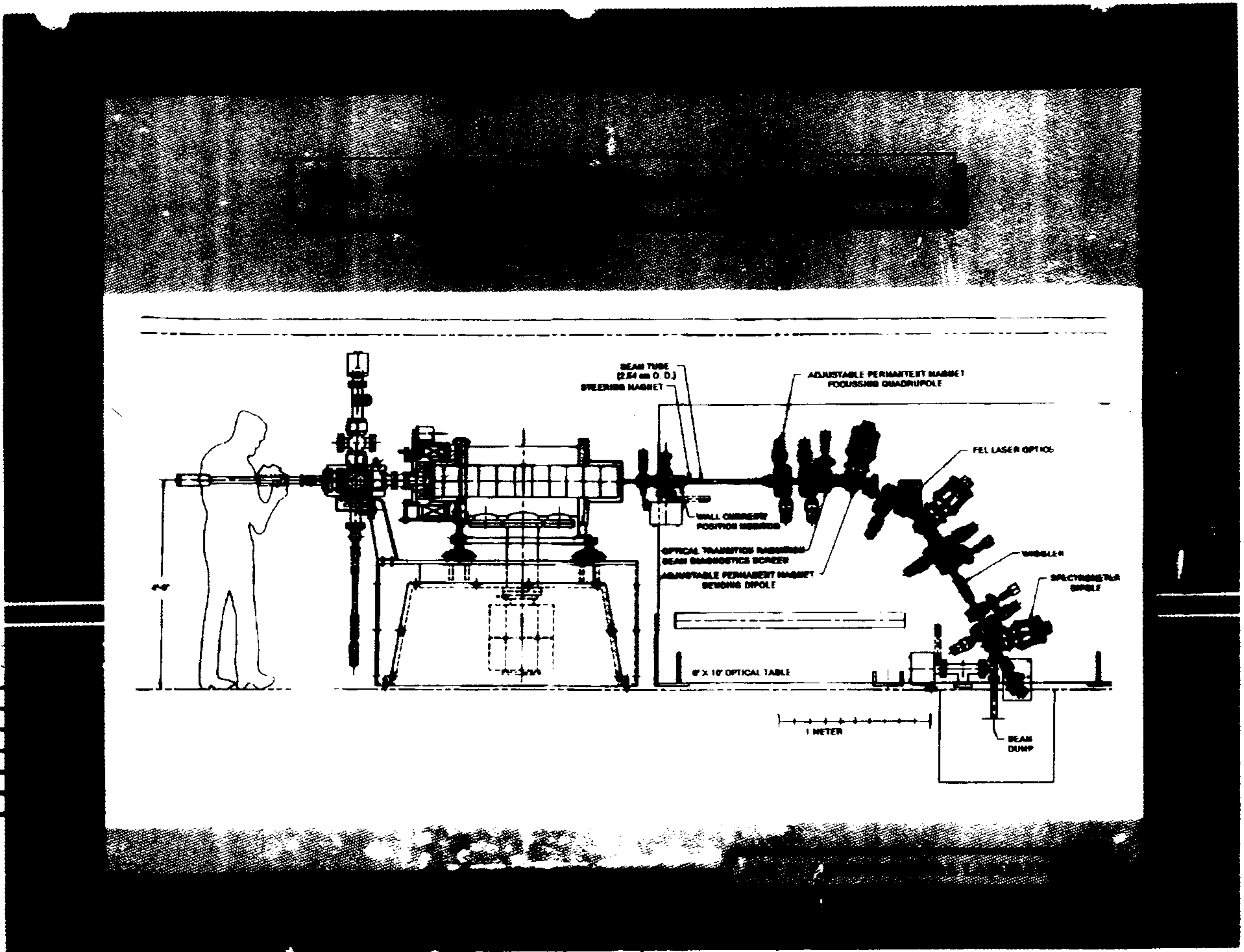
Development Schedule

BNL/SLAC/LBL/UCLA
1.6 cell
Photocathode RF gun

TIME LINE	2 QTR 94	3 QTR 94	4 QTR 94	1 QTR 95	2 QTR 95	3 QTR 95	4 QTR 95
EXPERIMENTIAL PROGRAM							
COLD TESTING @ BNL	XXX	XXX	XXX	XXX			
MACHINAL DESIGN					XXX		
MACHINING @UCLA					XXX		
BRAZING @ SLAC					XXX	XXX	
ZLINE CONSTRUCTION						XXX	
HIGH POWER TESTING						XXX	
BEAM STUDIES							



Dennis T. Palmer
28 April 1995



$Q = 1.3$ nC, $I = 150$ A, $\varepsilon_N = 1.8$ mm mrad (@ 16 MeV)

IR FEL Project Goals

Studies of a High Gain Self Amplified Spontaneous Emission FEL.

Present System

- 60 cm undulator
- Moderate gain
- Startup regime
- Dependence on beam charge
- Proof of principle for coherent transition radiation bunching monitor

Future Plans

- 2 m undulator
- High gain
- Saturation regime
- Gain versus emittance, current ...
- Measure highly bunched beam

Electron Beam Diagnostics

Need to know:

- Current
  - Charge
  - Pulse length
- Beam profile
  - Size
  - Position
  - Angular spread
- Emittance
- Energy
- Energy spread

Available tools:

- Current
  - ICT
  - BPMs (sum)
  - Screens (linear!)
  - Streak camera / Cerenkov
  - Pulse Length Monitor
- Beam Profile
  - BPMs (sum)
  - Screens (linear!)
  - Optical Transition Radiation
- Emittance
  - Slits
  - Collimator
- Energy
  - Dipole spectrometer

ON BOARD

Are the FEL conditions satisfied?

1. $\epsilon_n < \dfrac{\lambda_r}{4\pi}\gamma$?

   $\epsilon_n = 16 \times 10^{-6}$ m-rad

   $\lambda_r = 16 \times 10^{-6}$ m (16 μm)

   $\gamma = 24$ ($\sim$ 12 MeV)

   $$\frac{(16 \times 10^{-6})\,(24)}{4\pi} \approx \boxed{30 \times 10^{-6}} \checkmark$$

2. $\sigma_E < \rho$?

   $\rho \approx 10^{-2}$

   $\sigma_E \approx 0.2\,\%$ $\checkmark$

ON BOARD

(3) Beam wiggle amplitude $\lesssim$ Beam radius

$$\sigma_w \sim \frac{\lambda_u a_u}{2\pi\gamma}$$

$$= \frac{(1.5\times10^{-2})(1)}{2\pi(24)}$$

$$\approx 10^{-4}\,m$$

$$= \boxed{100\,\mu m}$$

$$\sigma_r = \sqrt{\frac{\beta\epsilon_n}{\gamma}}$$

$$\beta_n = \frac{\sqrt{2}\gamma\lambda_u}{2\pi a_u}$$

$$\approx \frac{\sqrt{2}(24)(1.5\times10^{-2})}{2\pi(1)}$$

$$\approx 8\ cm$$

$$\Rightarrow \sigma_r = \sqrt{\frac{(8\times10^{-2})(10\times10^{-6})}{24}} \approx 180\,\mu m$$

$100 < 180$ ✓

+ Look at SSB!

Estimates

$P_{SAT} \sim \rho P_{beam} = \rho I E$

$L_G \sim \frac{L_U}{2\pi\sqrt{3}\rho}$

$L_{SAT} \sim \cancel{1}0 L_G$

$N_{SAT} \sim \frac{1}{\rho}$

Average power in beam:

$\langle P \rangle_{beam} = \hat{P}_{beam} \times \text{Duty Cycle}$

$\hat{P}_{beam} = \gamma E_0 I$

$= (24)(5\times10^5)(10^2)$

$\approx 1.2 \text{ GW}$

Duty Cycle = repetition rate × pulse length

$= 5 \text{ Hz} \times 5\times10^{-12} \text{ sec}$

$= 2.5\times10^{-11}$!

$\Rightarrow \boxed{\langle P \rangle_{beam} = 30 \text{ mW}}$

radiation power

$P_r \sim 10^{-2} \times (1.2\times10^9) \text{W} \sim 10^7 \text{ W}$ $\boxed{10 \text{ MW}}$

$\Rightarrow \langle P_{SAT} \rangle = 300 \mu\text{W}$!

Record $\approx$ 1 kW

NO SDI

ON BOARD

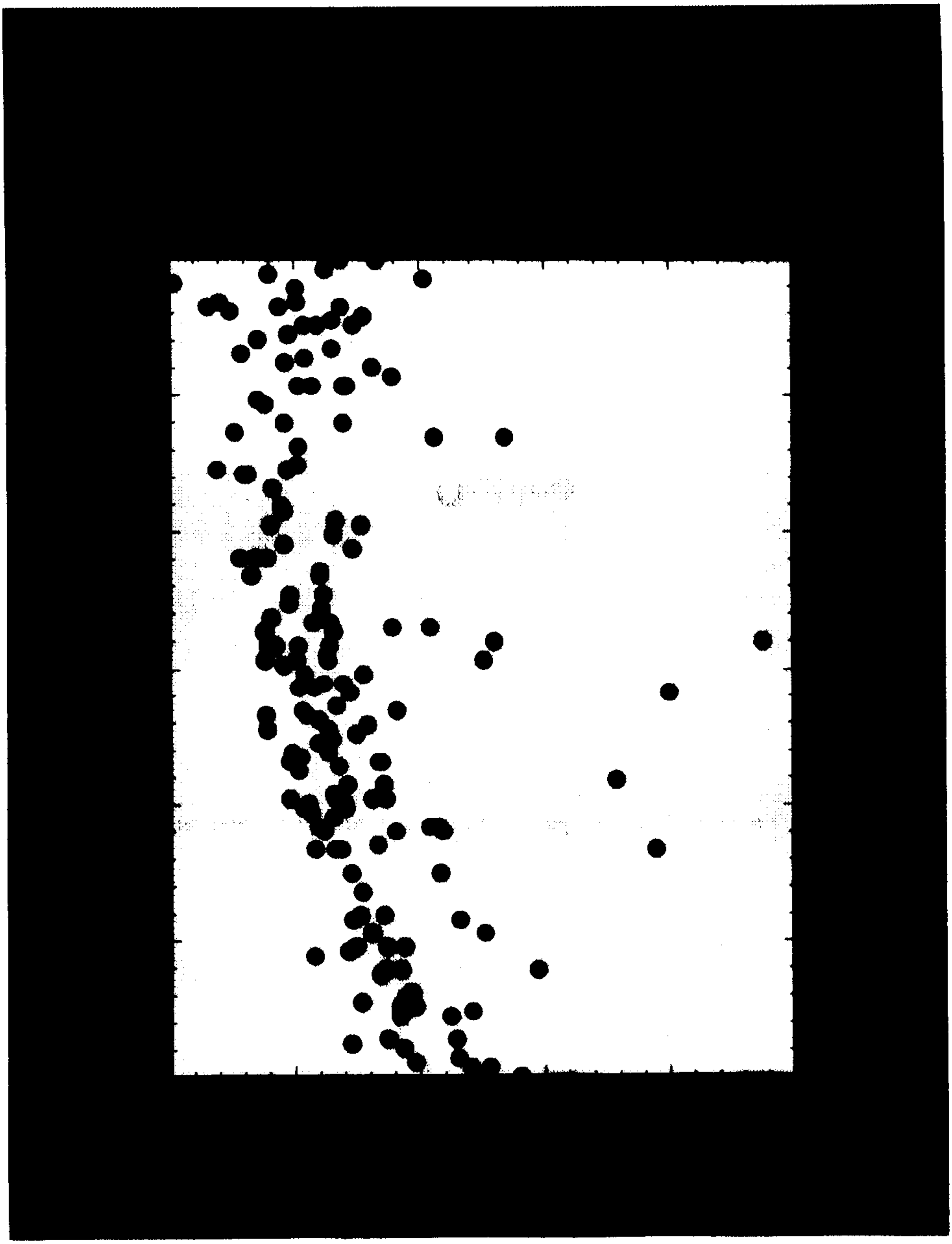
More Estimates

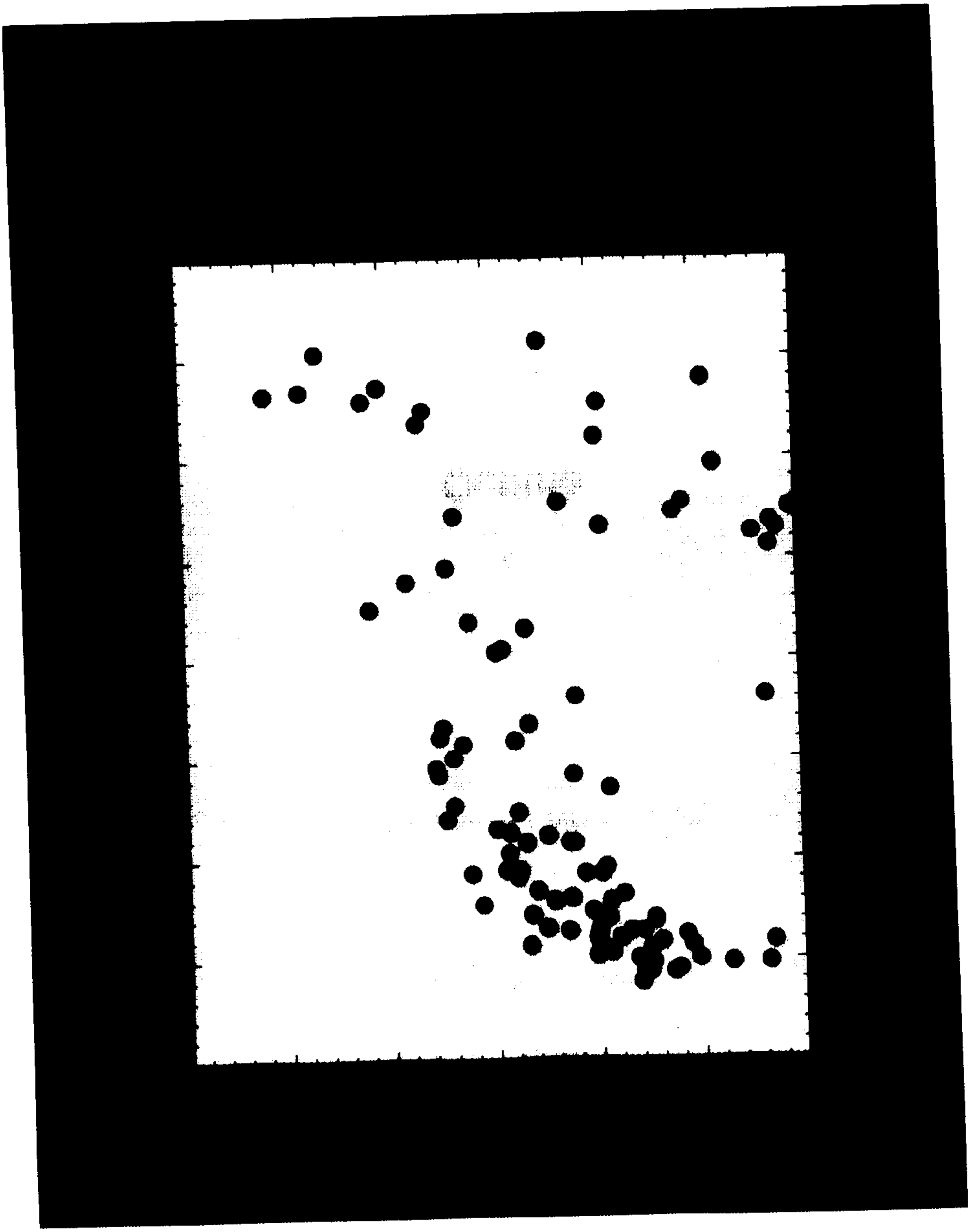
$N_{SAT} \sim 100$

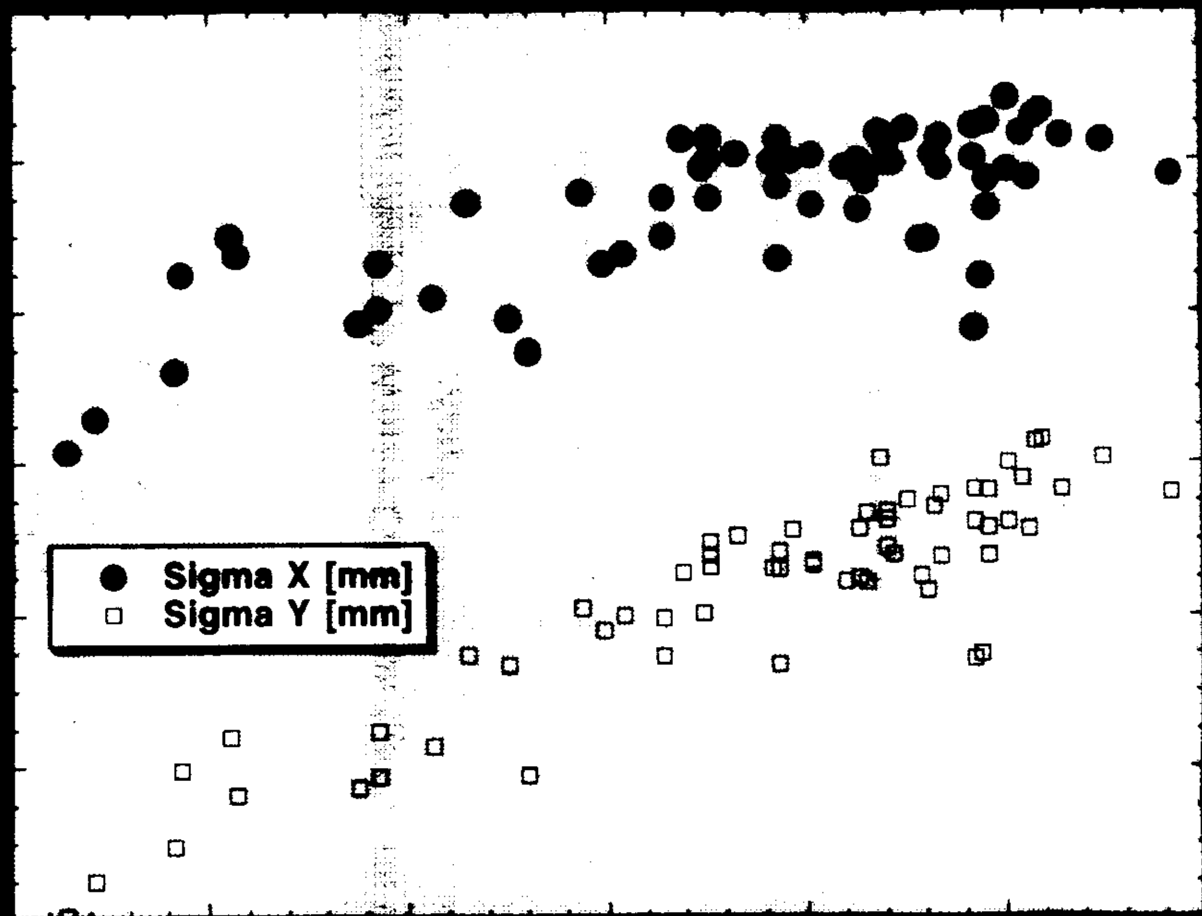
$L_U = 1.5\,cm$ $\Longrightarrow$ $\boxed{L_{SAT} \approx 1.5\,m}$

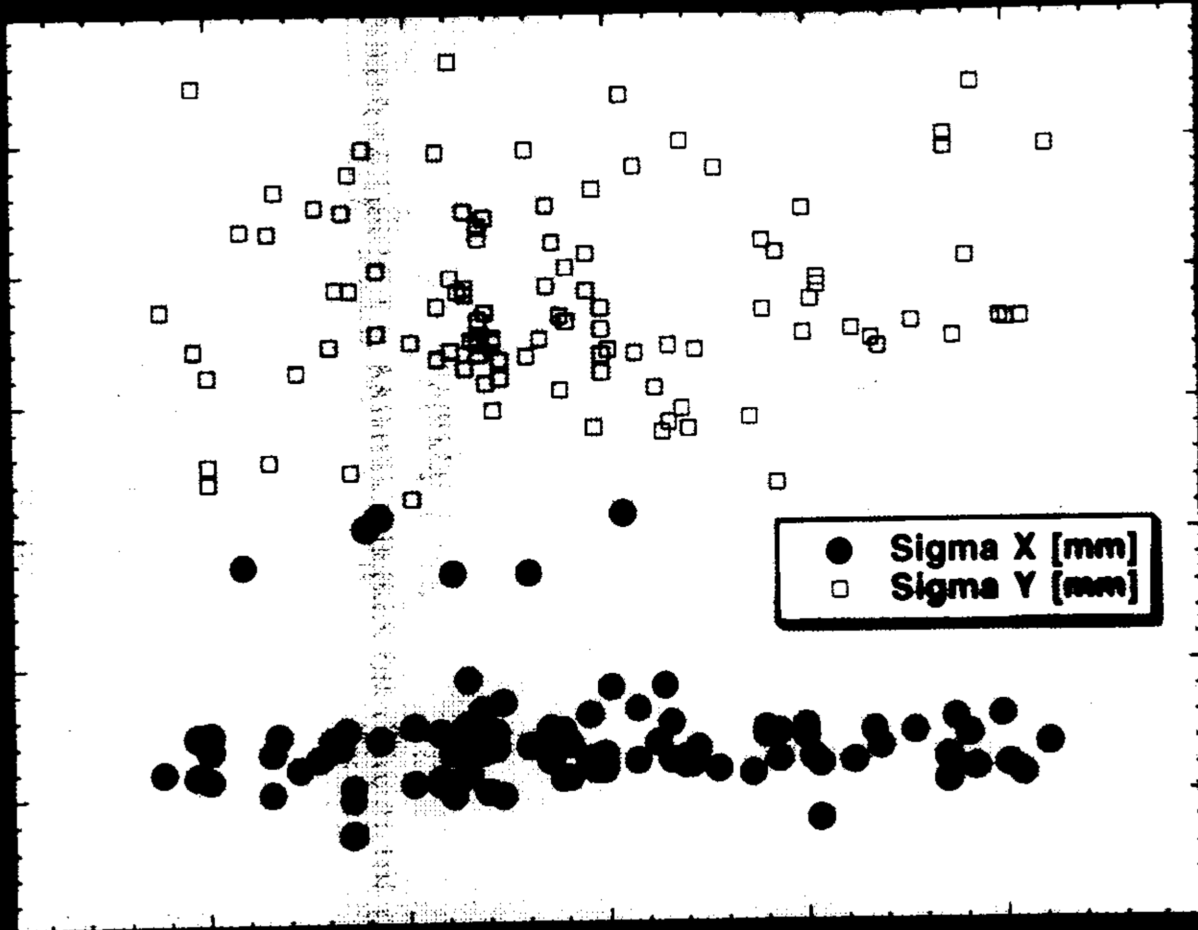
$$L_G \sim \frac{1.5 \times 10^{-2}}{4\pi\sqrt{3}(10^{-2})} \sim 8\,cm$$

$\Longrightarrow$ $L_{SAT} \sim 160\,cm$



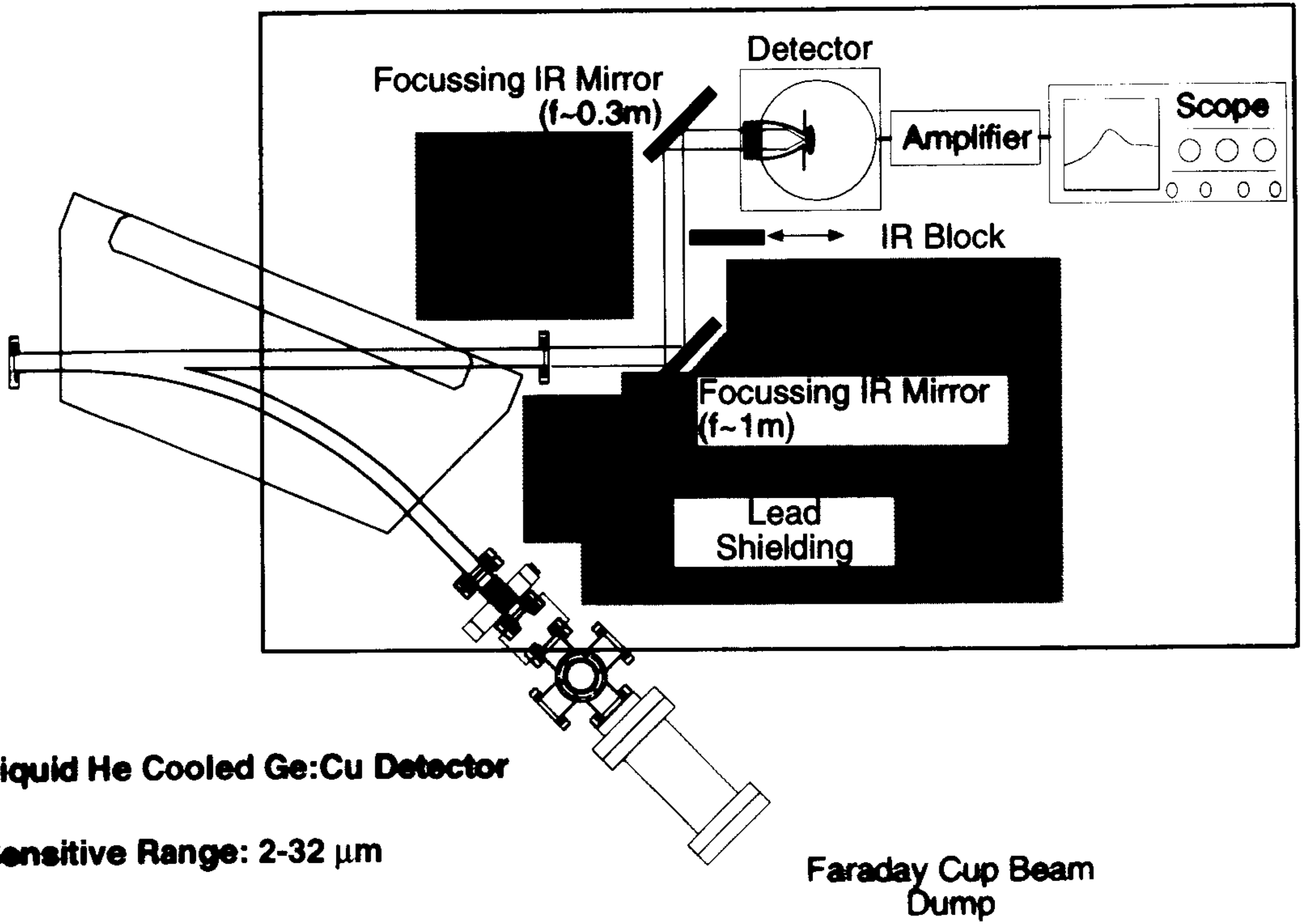



Sigma X [mm]
Sigma Y [mm]



Sigma X [mm]
Sigma Y [mm]

IR FEL Operational Diagnostic Layout



Liquid He Cooled Ge:Cu Detector

Sensitive Range: 2-32 μm

Rise Time: 5 ns

UCLA Particle Beam Physics Laboratory

I.R Diagnostics

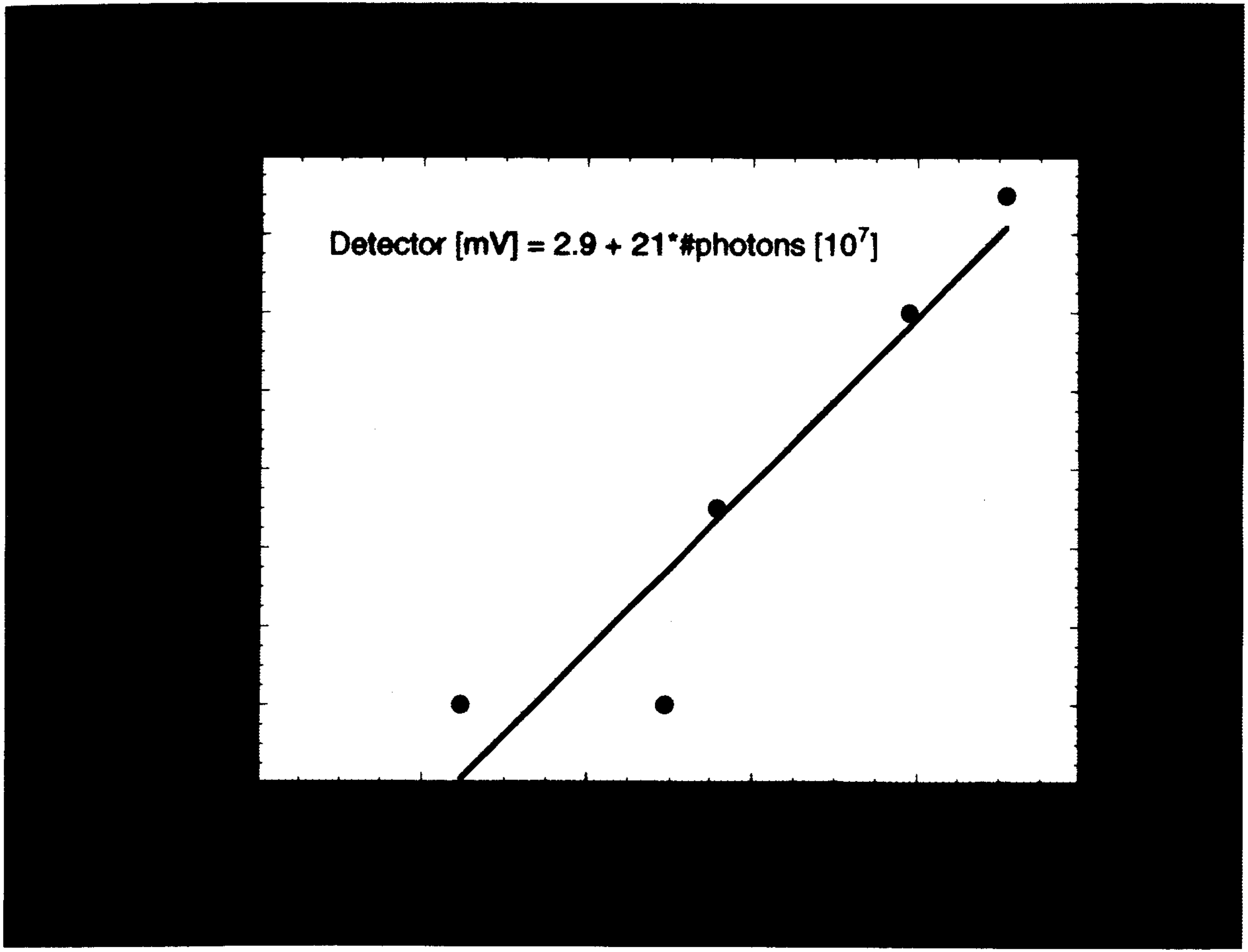
Wavelength: 16 μm IR $\Rightarrow$ Can't use Mer-cad detectors

Pulse length: 5ps $\Rightarrow$ Need fast detector to minimize Black body background.

$\Rightarrow$ Cryogenic detector

USE Ge:Cu LHe cooled detector

5nsec risetime
2-32 μm sensitivity range
BLIP Background limited


Detector [mV] = 2.9 + 21*#photons [10^7]

IR FEL Parameters

Single Shot Beam Parameters @ 1nC		Planar Hybrid Undulator Parameters	
Energy	13.5 MeV	Length	60 cm
Energy Spread (rms)	0.2%	Period	1.5 cm
Peak Current	150 A	Peak Field	0.75 T
Emittance (norm. rms)	15 mm-mrad	Undulator Parameter	1

SASE FEL Simulation Results (Ginger)

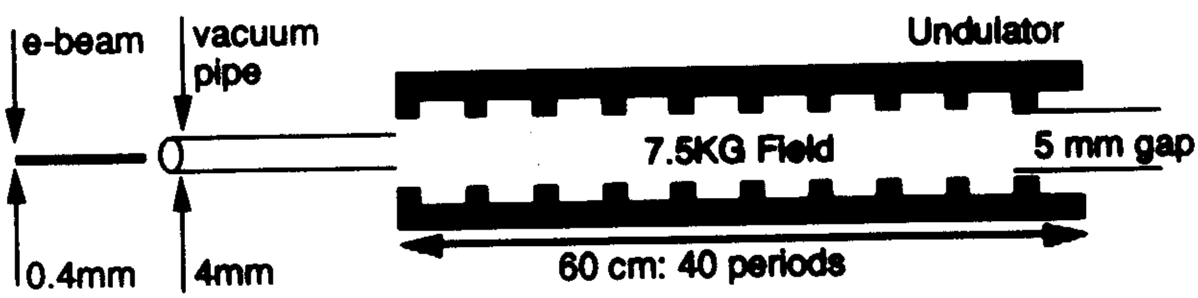
Total Gain @ 60 cm	~5
Peak Power	~2 W
Nominal Wavelength	16.5 μm

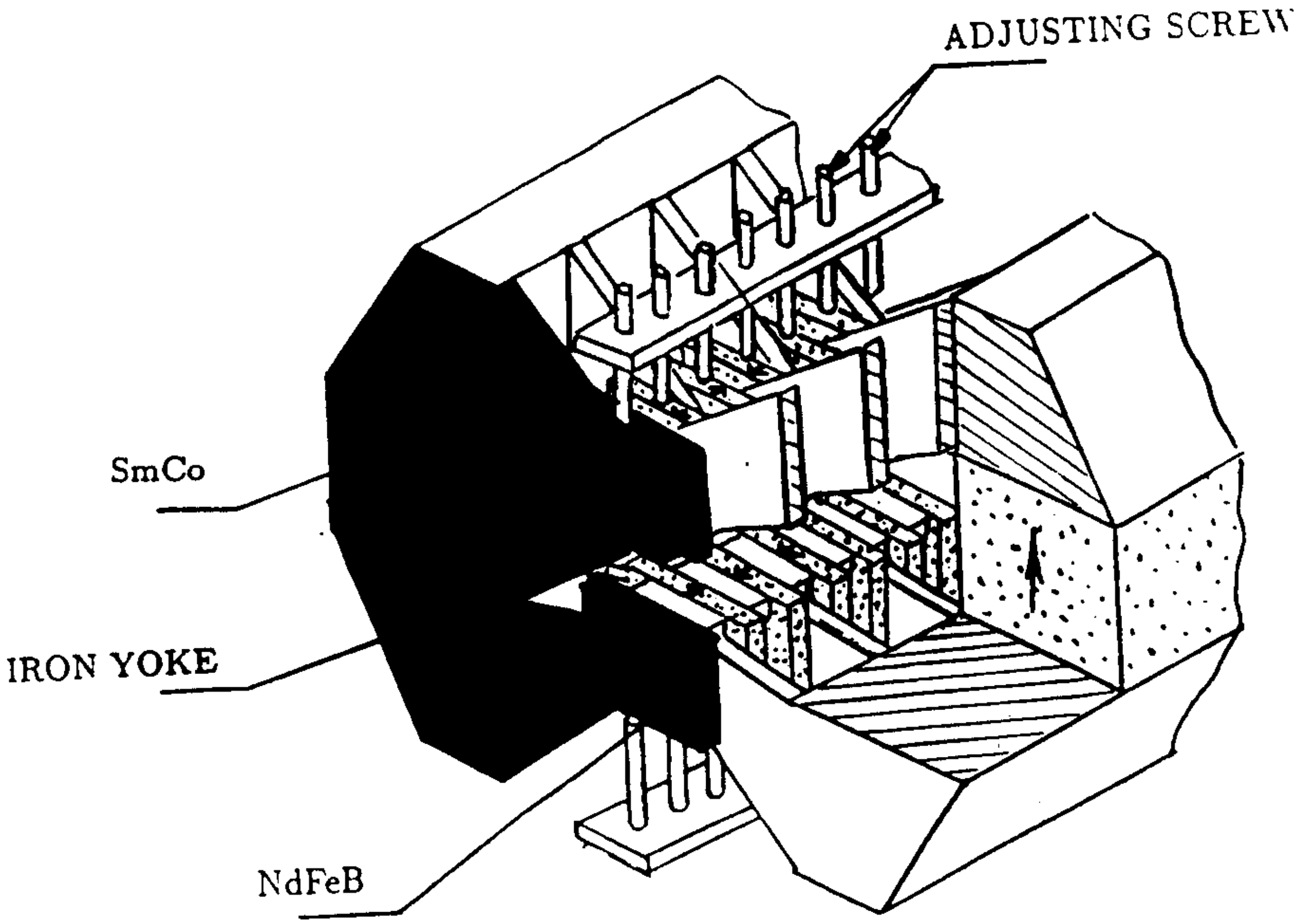
The Undulator

The Undulator

- Compact short period Hybrid design
  - Samarium-Cobalt main magnets
  - Vanadium-Permendur C-shaped yokes
  - Neodymium-Iron-Boron pole tip magnets

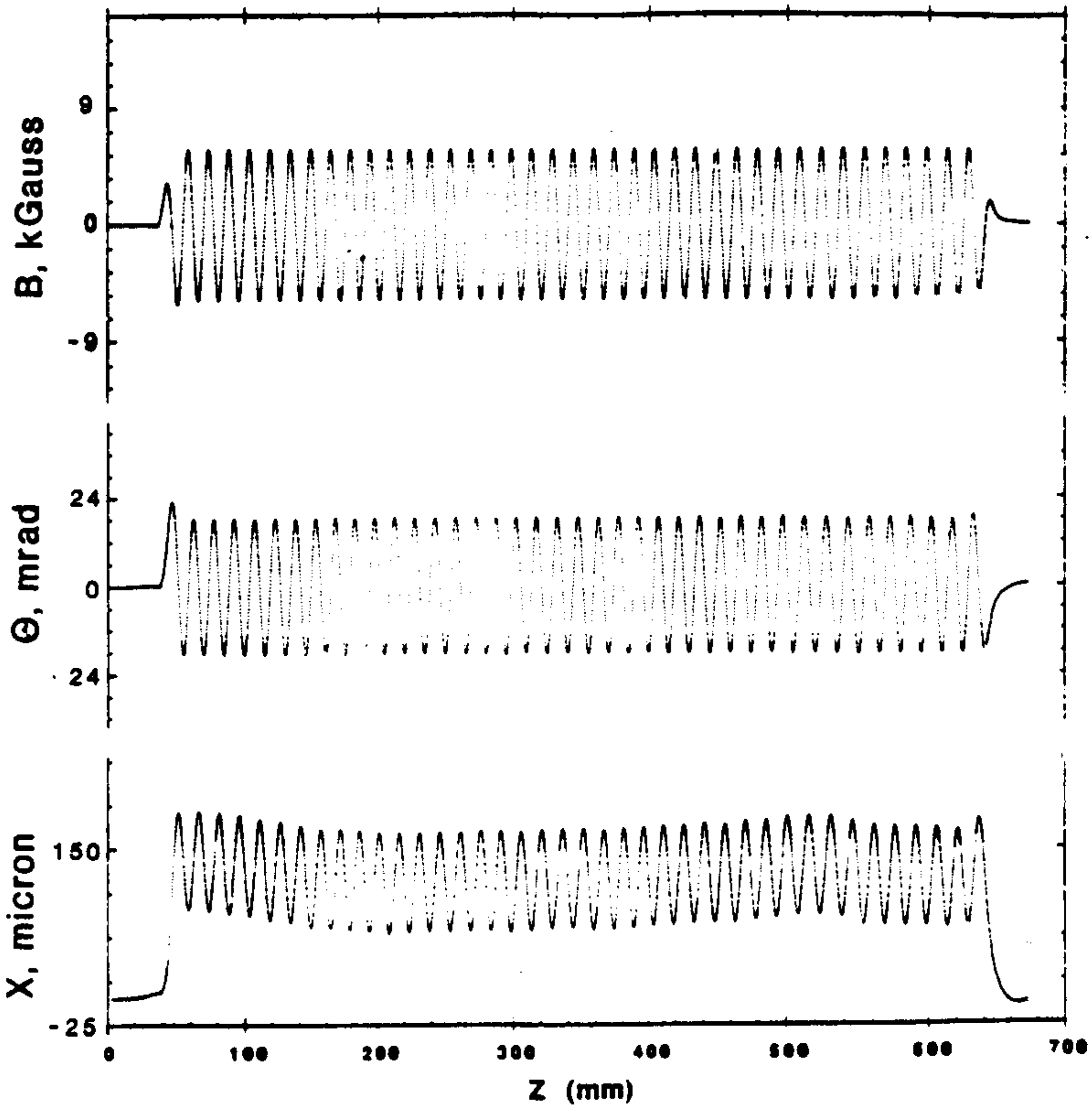
- Peak field of 7.5KG (> sum of fields)
- Pole tip field error 0.25% (peak).
- Second integral (e-beam orbit) good.
- Deviation of orbit < beam radius.



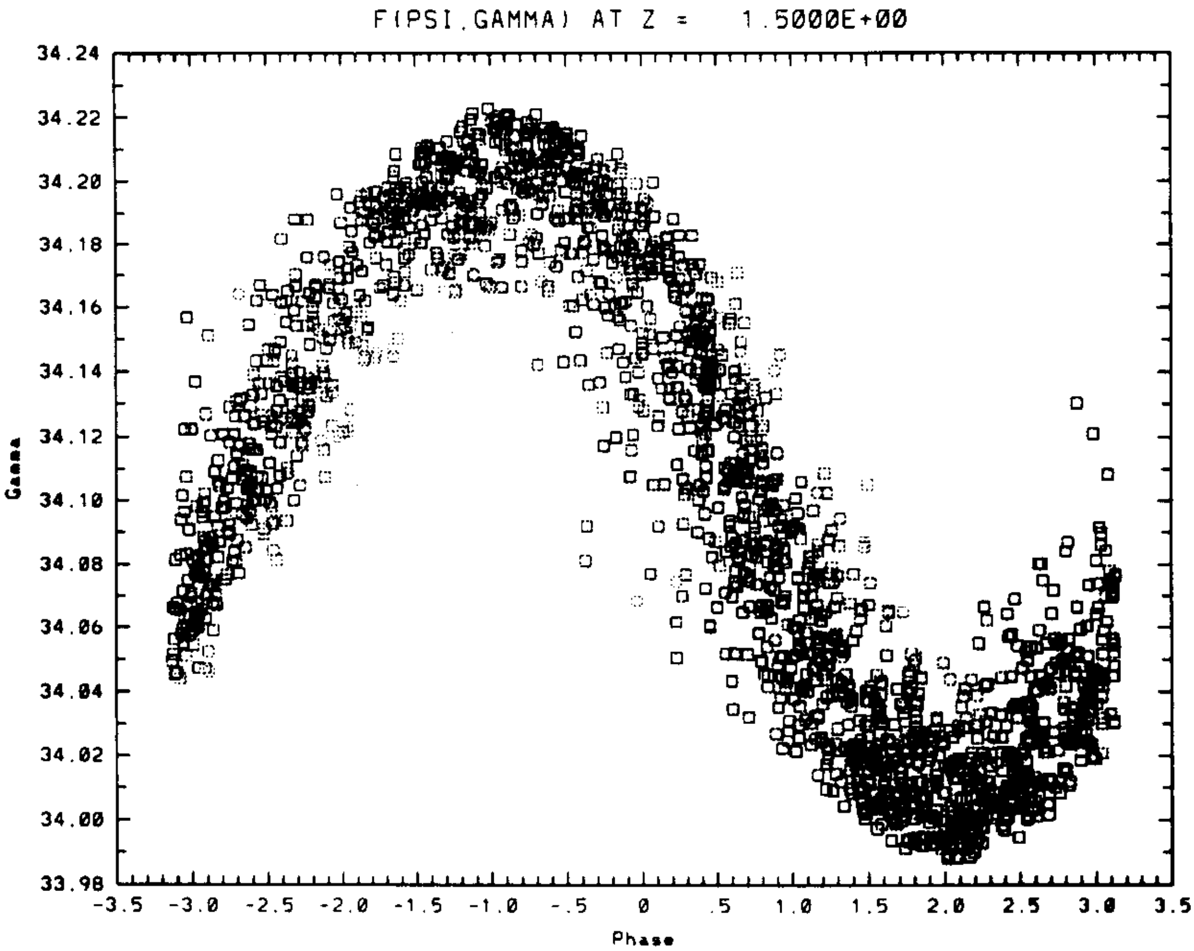


Cut-away view of the undulator

Mesured Magnetic Field, First and Second Integral
UCLA/Kurchatov Undulator



Bunching Effects



[redacted]

r= 1.9121E-08 r= 2.6660E-07 r= 5.1807E-07 r= 7.6755E-07 r= 1.0170E-06 r= 1.2665E-06 r= 1.5160E-06

[redacted]

Important Parameters:
Slippage

- **Slippage length:**

$$L_s = N_u \lambda_r$$
$$= 40(16 \times 10^{-6})$$
$$= 640 \mu m$$

- **Bunch length:**

$$L_b \approx 1000 \mu m$$

- Slippage parameter:

$$S = \frac{L_s}{L_b}$$
$$= \frac{640}{1000} \sim 1$$

Important Parameters: Cooperation Length

- **FEL Parameter:**

$$\rho = \left[\frac{I}{I_A} \frac{1}{64\pi^2} \left(\frac{a_u JJ \lambda_u}{\gamma} \right)^2 \frac{1}{\varepsilon_n \beta_n} \right]^{(1/3)}$$

$$\rho = \left[\frac{100}{17000} \frac{1}{64\pi^2} \left(\frac{1(0.9)(0.015)}{26} \right)^2 \cdots \frac{1}{10 \times 10^{-6}(0.09)} \right]^{(1/3)}$$

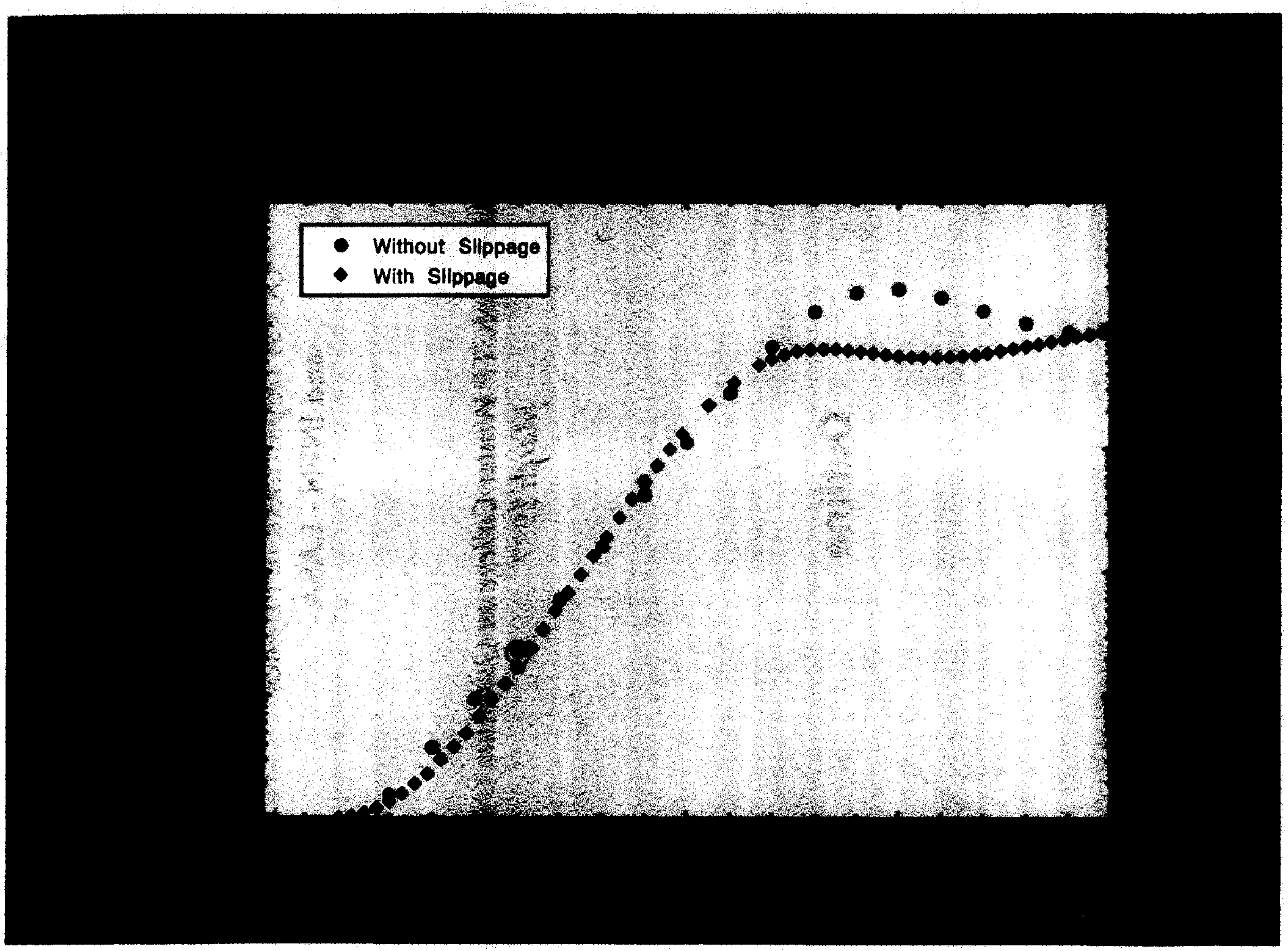
$$\rho \approx 1.4 \times 10^{-2}$$

- Cooperation length:

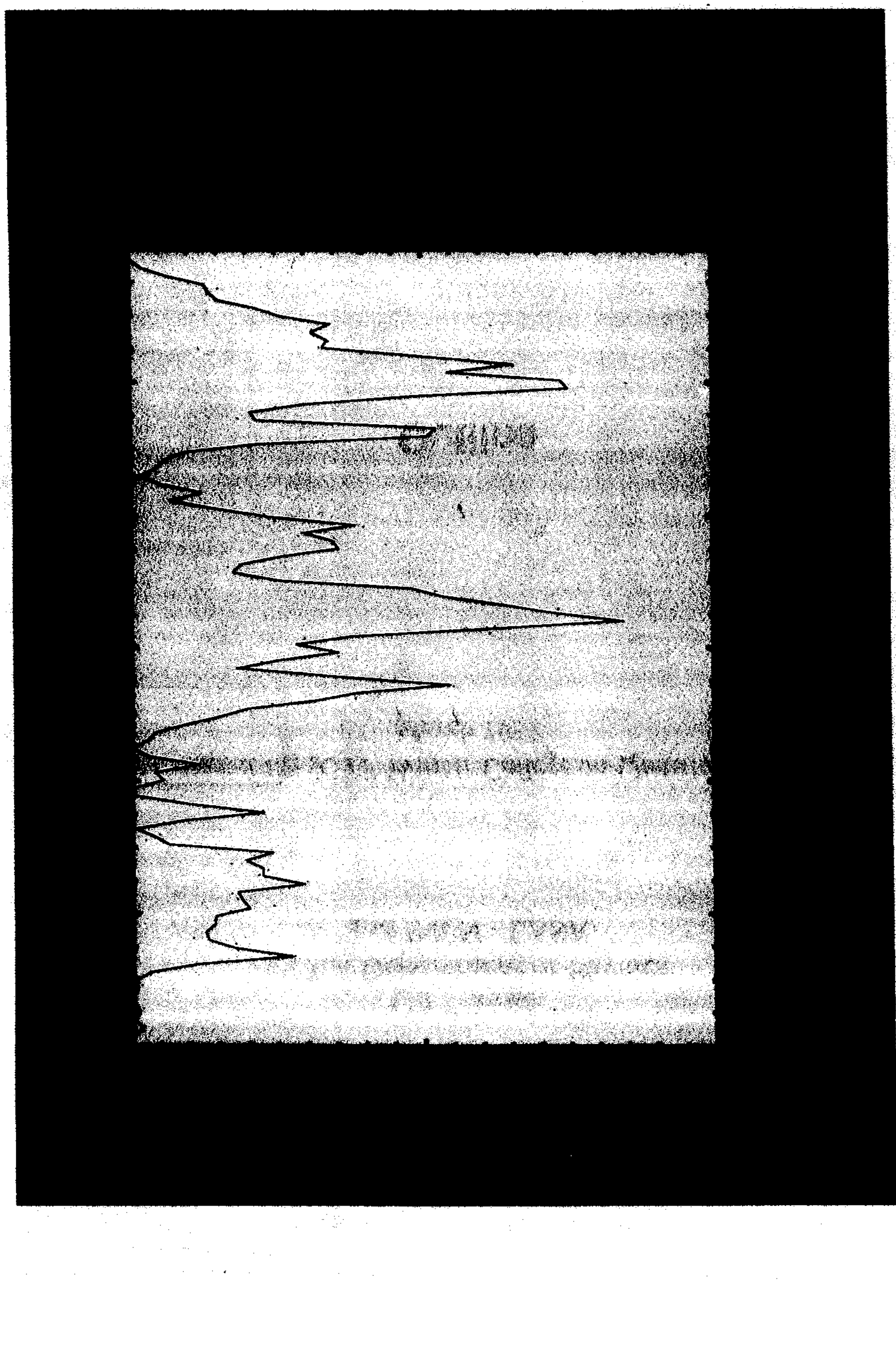
$$L_c = \frac{\lambda_r}{4\pi\rho} = \frac{16 \times 10^{-6}}{4\pi(1.4 \times 10^{-2})} \approx 100\mu m$$

- Cooperation Ratio:

$$\boxed{R = \frac{L_b}{L_c} = \frac{1000}{100} = 10}$$

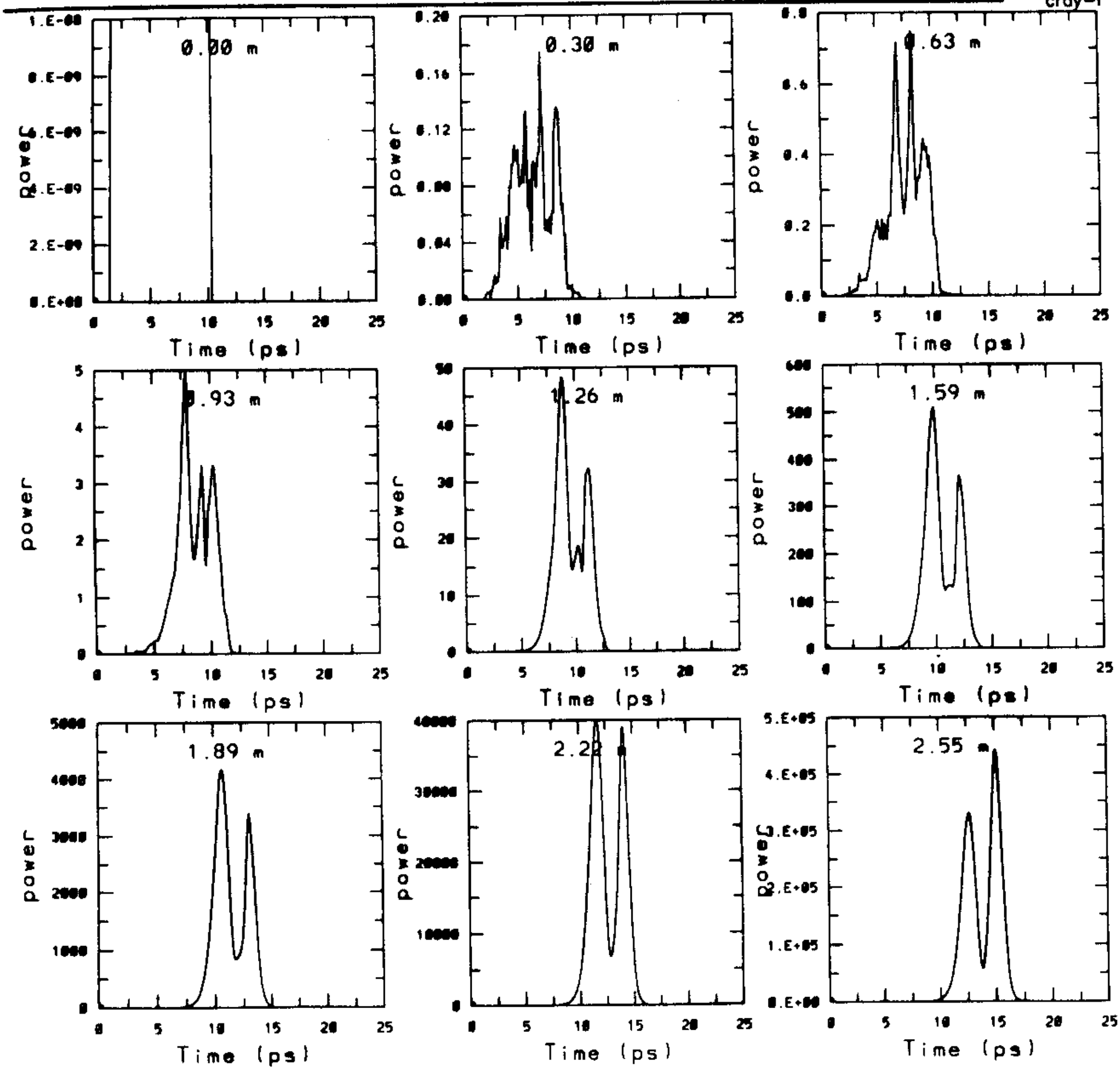


Without Slippage
With Slippage



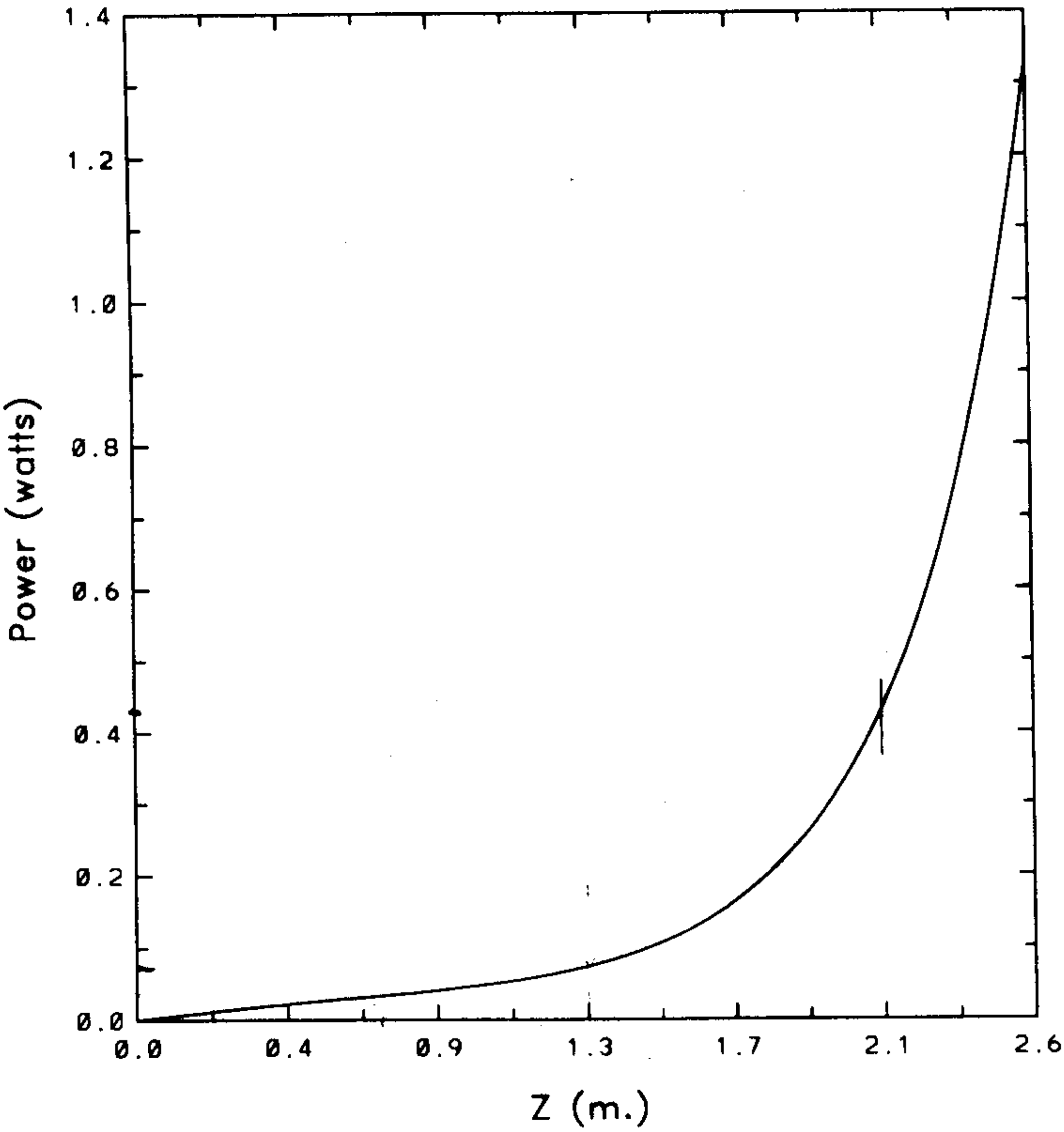
Laser Power (watts) vs. Time

17:18:02
12/02/96
testx2
cray-f

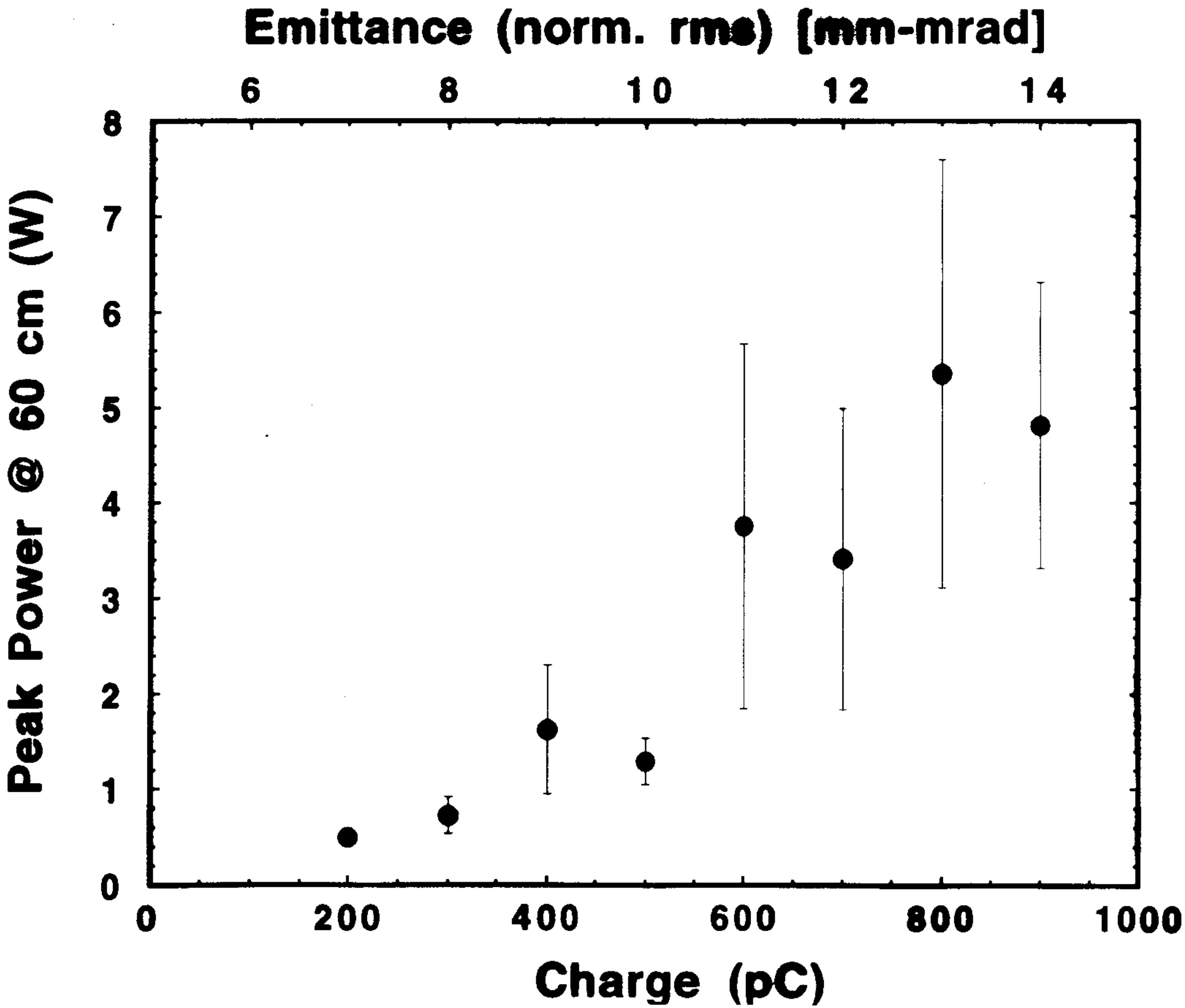


Avg. Field Power vs. Z

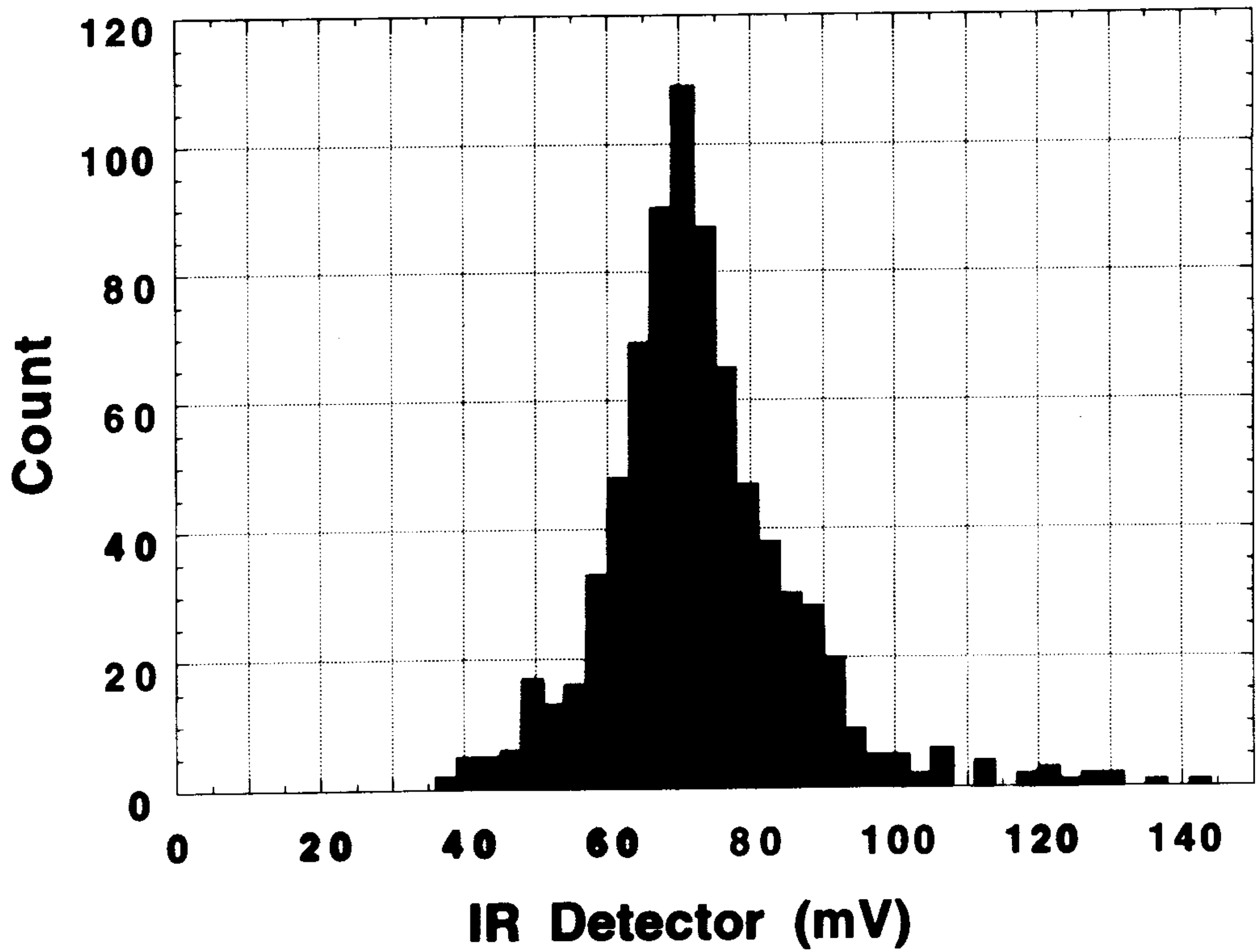
17:16:34
12/02/96
testy1
cray-b

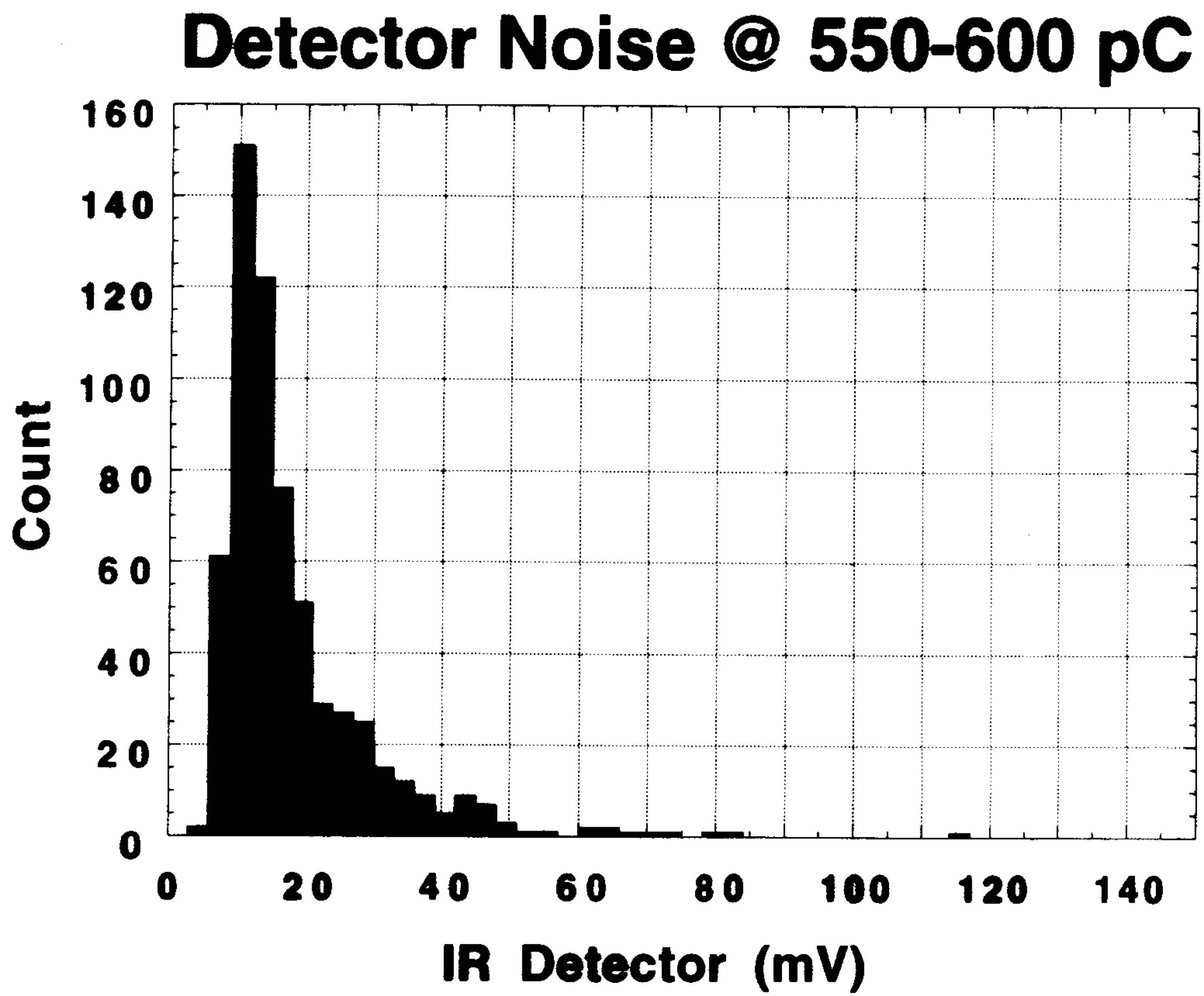


Ginger Simulation Results

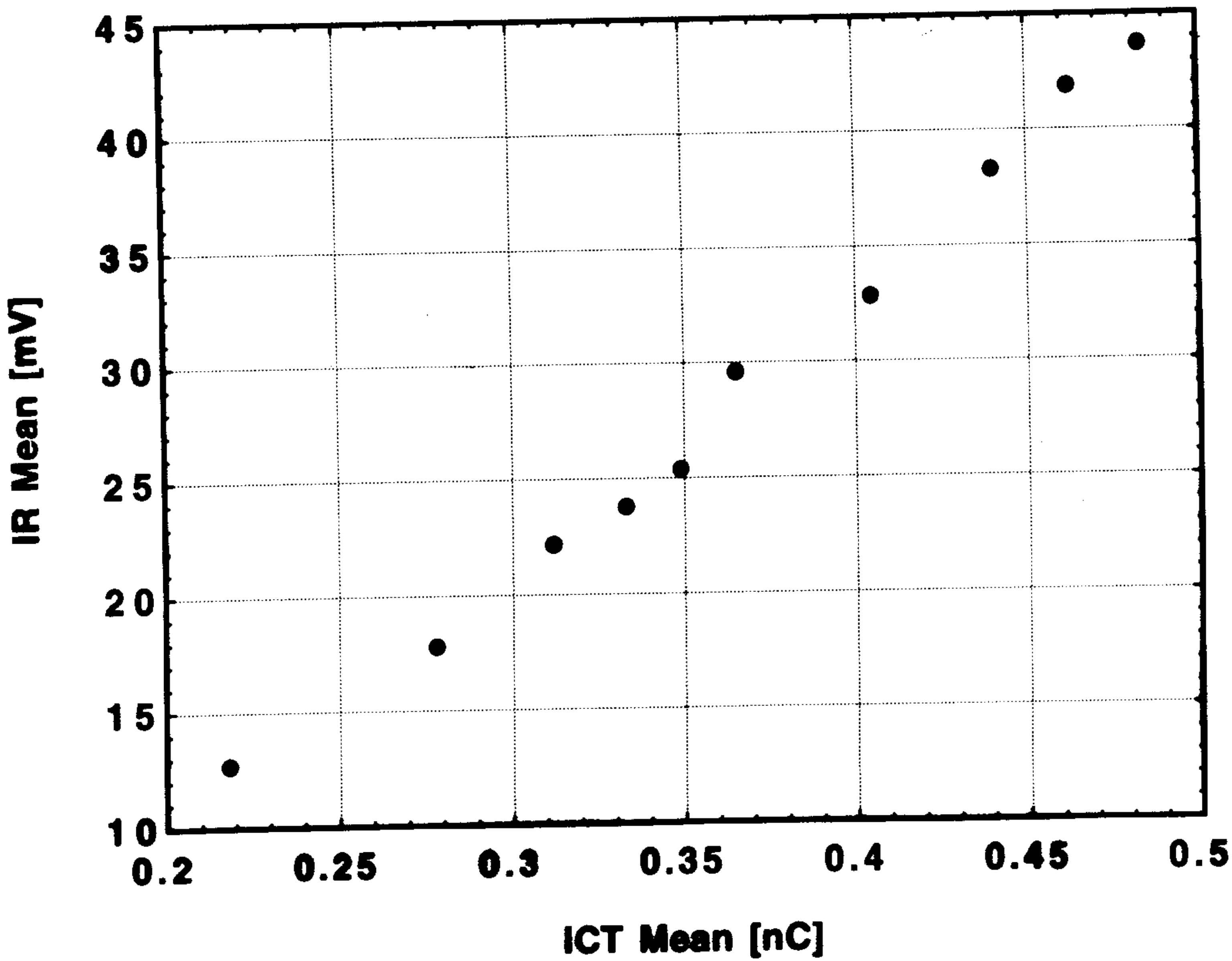


Signal Distribution @ 550-600 pC




Detector Noise @ 550-600 pC
Count
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
IR Detector (mV)

IR vs. Charge



IR Mean [mV]
45
40
35
30
25
20
15
10
0.2
0.25
0.3
0.35
0.4
0.45
0.5
ICT Mean [nC]

CONCLUSIONS

- PBPL WAS A STUDENT BUILT LABORATORY FOR DEMONSTRATING GAIN FROM NOISE IN AN FEL.
- MEASUREMENTS INDICATE GAIN FROM NOISE <u>AND</u> WITH LARGE FLUCTUATIONS.
- FLUCTUATIONS CAN BE CAUSED BY CHANGES IN THE BEAM MACROSCOPIC AND MICROSCOPIC DISTRIBUTIONS.
- EXAMINATION OF THE DATA WILL REVEAL THE VIABILITY OF NEAR FUTURE, SHORT WAVELENGTH MACHINES.

MUCH WORK REMAINS!

- STUDY FLUCTUATIONS
  - ➡ LONGER UNDULATOR / BETTER BEAM
- UNDERSTAND STARTUP THEORETICALLY
  - ➡ BETTER PROGRAMS / BETTER MODELS
- STUDY FLUCTUATIONS
  - ➡ BETTER DIAGNOSTICS
  - ➡ BETTER SYSTEMATICS (LASER, ETC.)
- MEASURE BUNCHING DIRECTLY

- GO TO SHORTER WAVELENGTHS