LEUTL/FEL Project

- Joint Project Between
  - Accelerator Systems Division
  - Experimental Facilities Division

- Actively Involved Groups

Accelerator Systems Division	Experimental Facilities Division
Controls	Insertion Devices
Diagnostics	
Mechanical	
Operations	
Operations Analysis	
Accelerator Physics	
Power Supplies	
RF	
Survey	
Vacuum	

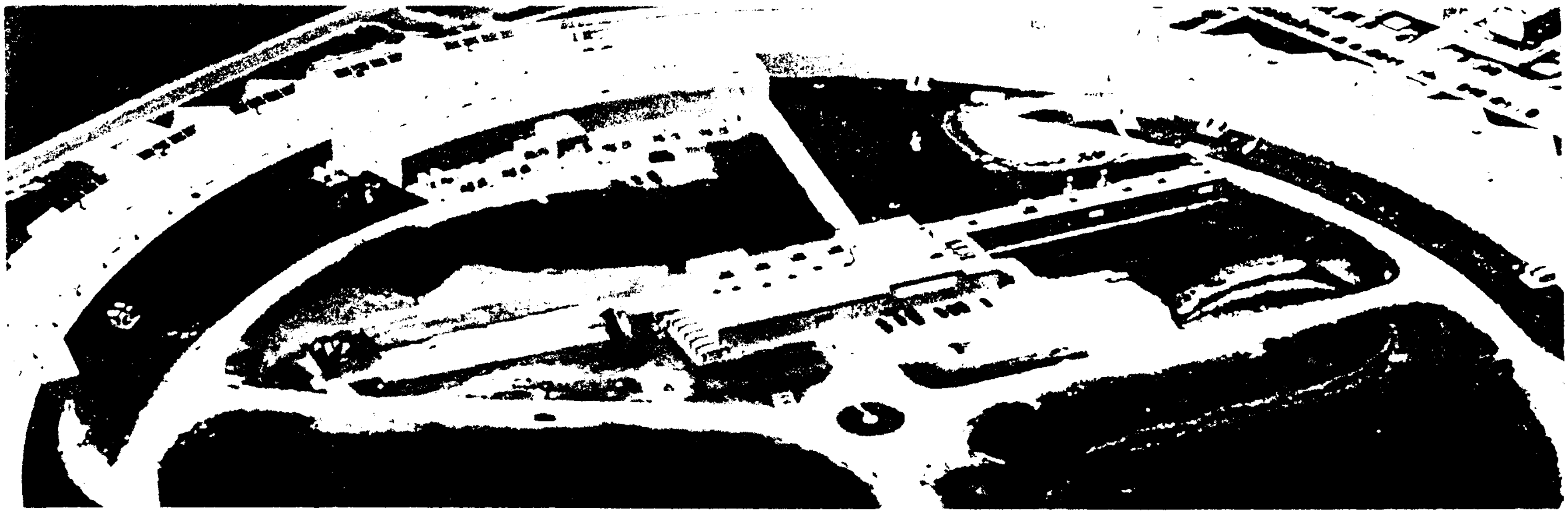
LEUTL/FEL Project

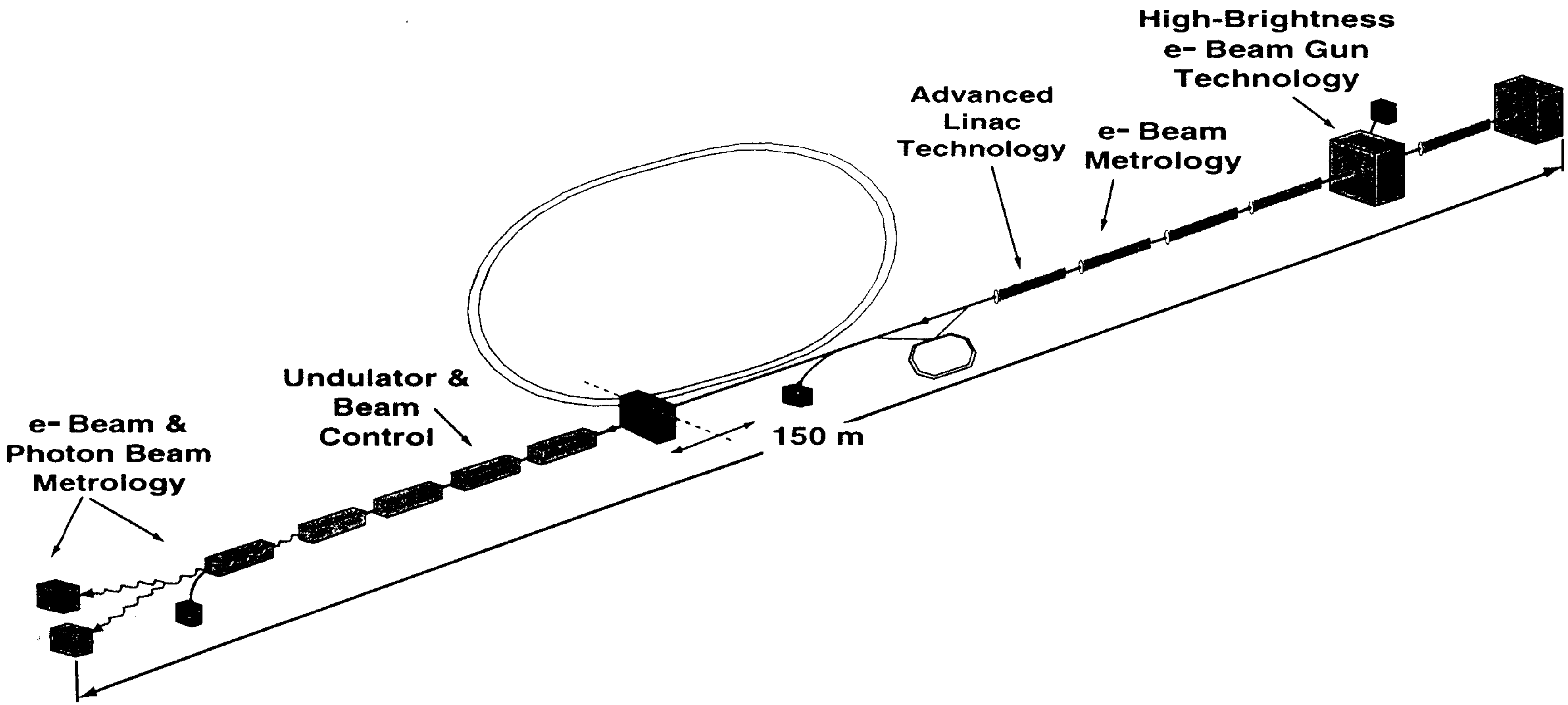
- Project Leadership
  - S. Milton (ASD)
  - E. Gluskin (XFD)

- The Hard Working Commissioning Team
  - N. Arnold (ASD)
  - S. Biedron (ASD)
  - M. Borland (ASD)
  - P. Den Hartog (XFD)
  - K. Harkay (ASD)
  - J. Lewellen (ASD)
  - A. Lumpkin (ASD)
  - E. Moog (XFD)
  - A. Nassiri (ASD)
  - V. Sajaev (ASD)
  - N. Sereno (ASD)
  - G. Travish (ASD)

- Others
  - BNL Accelerator Test Facility
    - PC RF Gun
    - XJ Wang

ADVANCED PHOTON SOURCE LOW-ENERGY UNDULATOR TEST LINE





APS Low-Energy Undulator Test Line (LEUTL)

R&D program for UV FEL

- Goal is to study the process of self-amplified spontaneous emission (SASE)
- Pursue scientific demonstration experiments impossible with existing sources
- Novel beam characteristics (50 -> 500 nm)
  - Pulse duration 1 -> 5 psec @ 10 Hz
  - Peak power of 100 MW (1st harmonic)
  - Time-average power 0.1 W (1st harmonic)
  - Time-average brilliance 10^{20}
  - Peak brilliance 10^{28}
- Schedule is to begin SASE experiments at 530 nm in August '99

FEL Operation Requirements

- SASE MODE: Basic Description

Spontaneous emission + bunch irregularities

↓

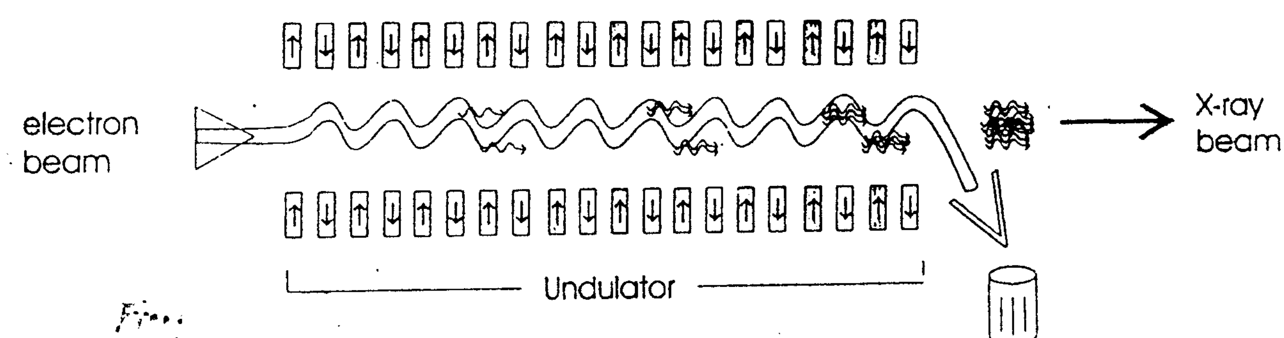
Bunching begins

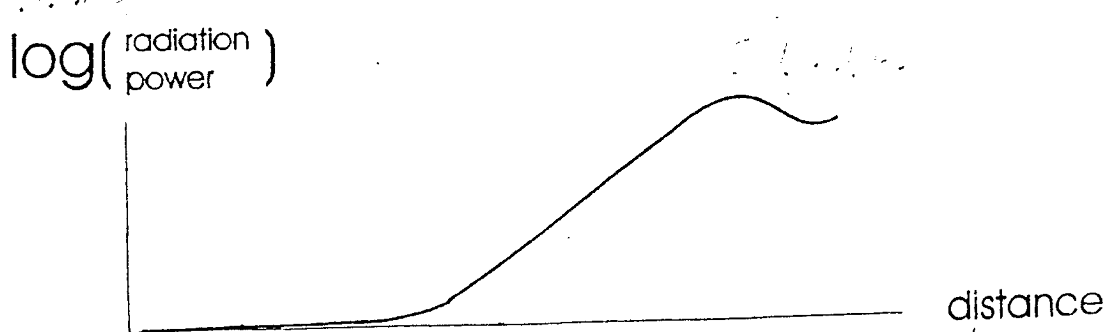
↓

Field strength increase

↓

Exponential growth of coherent field





Free Electron Laser in the Self Amplified Spontaneous Emission (SASE) mode

- SASE PARAMETERIZATION

  - The Pierce Parameter

$$\rho \propto \left[\frac{I_{peak} K^2 \lambda_w^2}{\sigma_{trans}^2 \gamma^3}\right]^{1/3} = \left[\frac{I_{peak}}{\sigma_{trans}^2} \frac{\lambda^2 \gamma K^2}{\left(1 + K^2/2\right)^2}\right]^{1/3}$$

  - The Gain Length

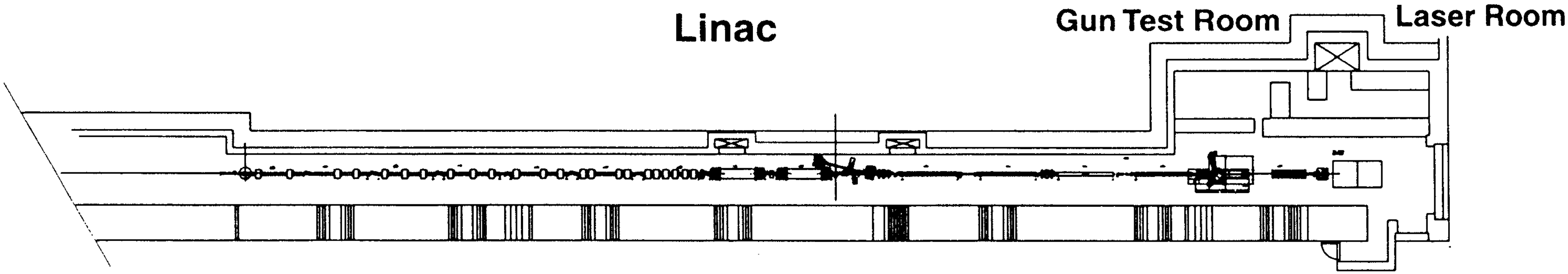
$$L_{gain} = \frac{1}{1+\eta} L_{gain}^{1-D} = \frac{1}{1+\eta} \frac{\lambda_w}{4\pi\sqrt{3}\rho}$$

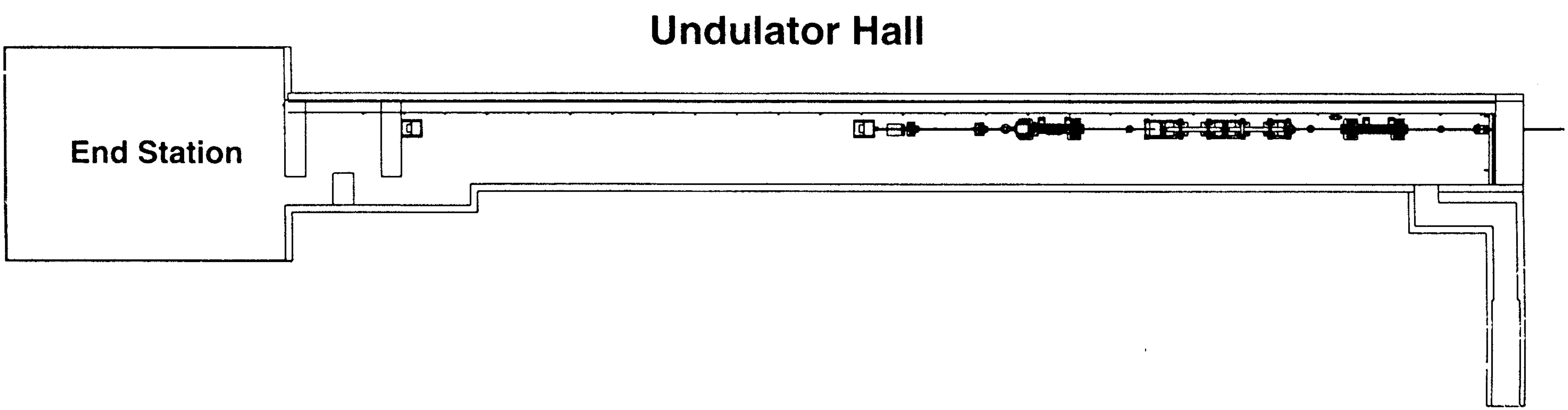
  - Efficient Operation

$$\frac{4\pi\varepsilon}{\lambda_{light}} \leq 1 \qquad \frac{L_{gain}}{L_R} \leq 1 \qquad \frac{\sigma_\gamma}{\gamma} \leq \rho$$

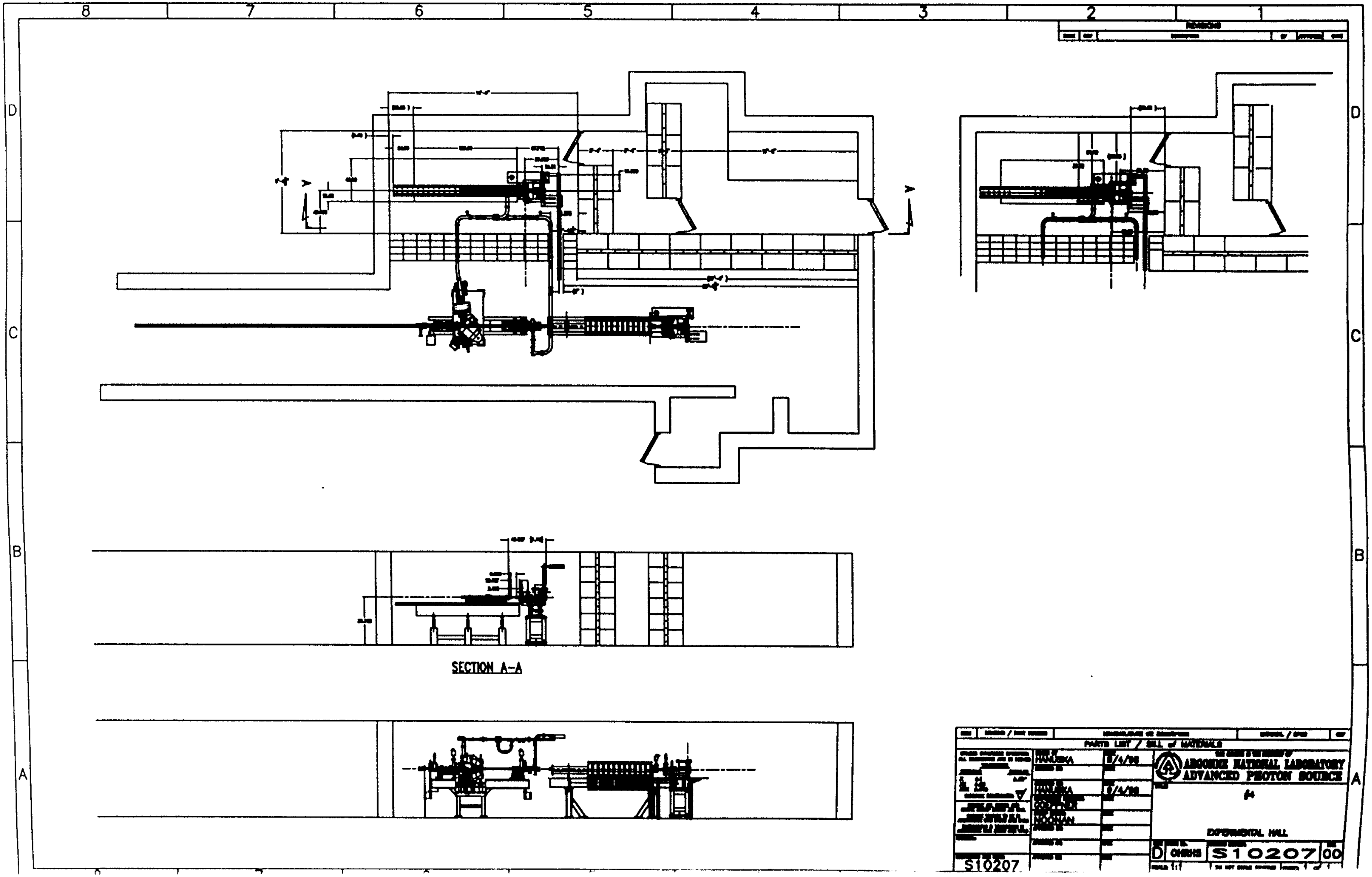
  - Quickly Summing Up

    Make ρ as large as possible without violating conditions for efficient operation.



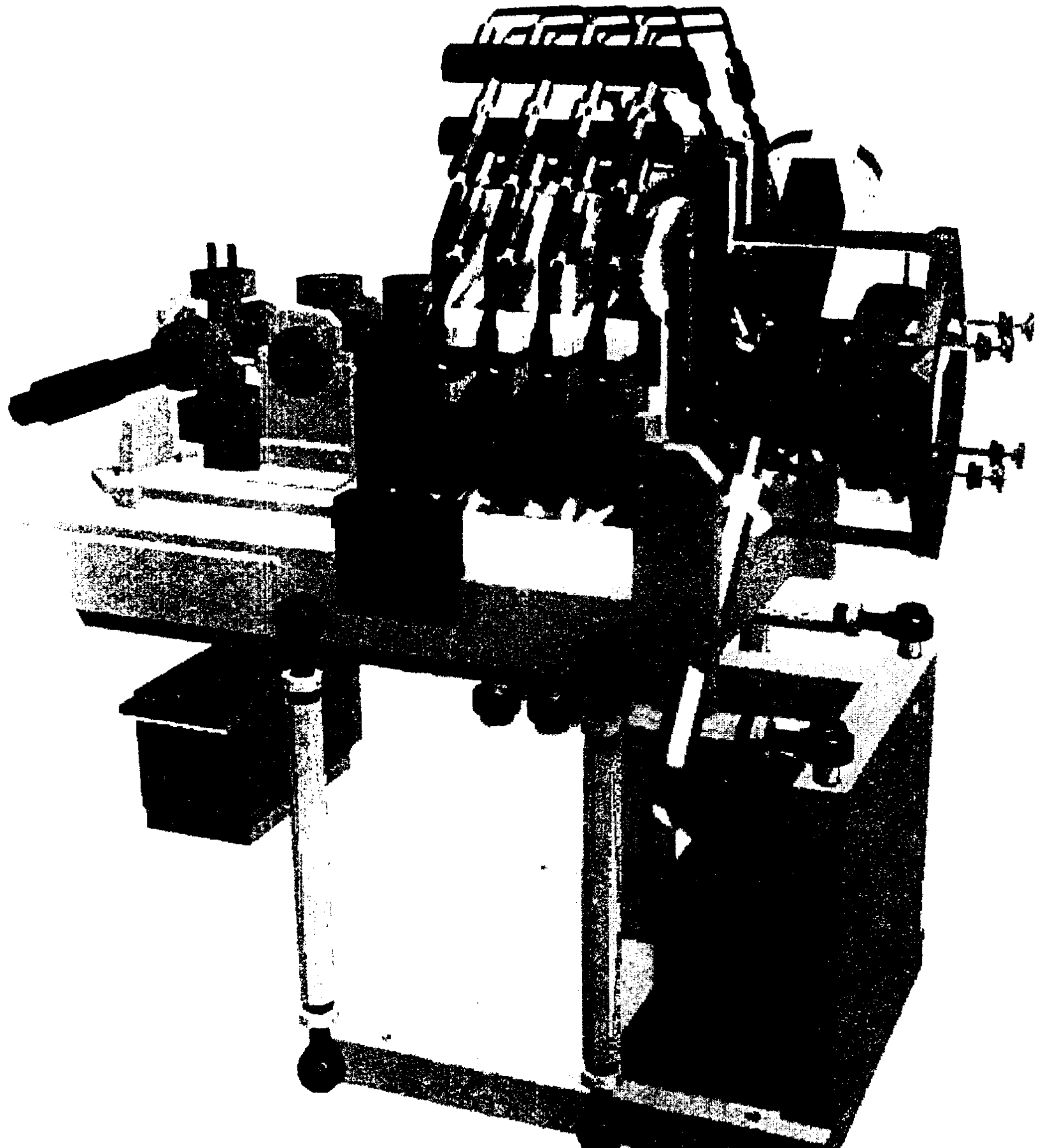


99.1.17



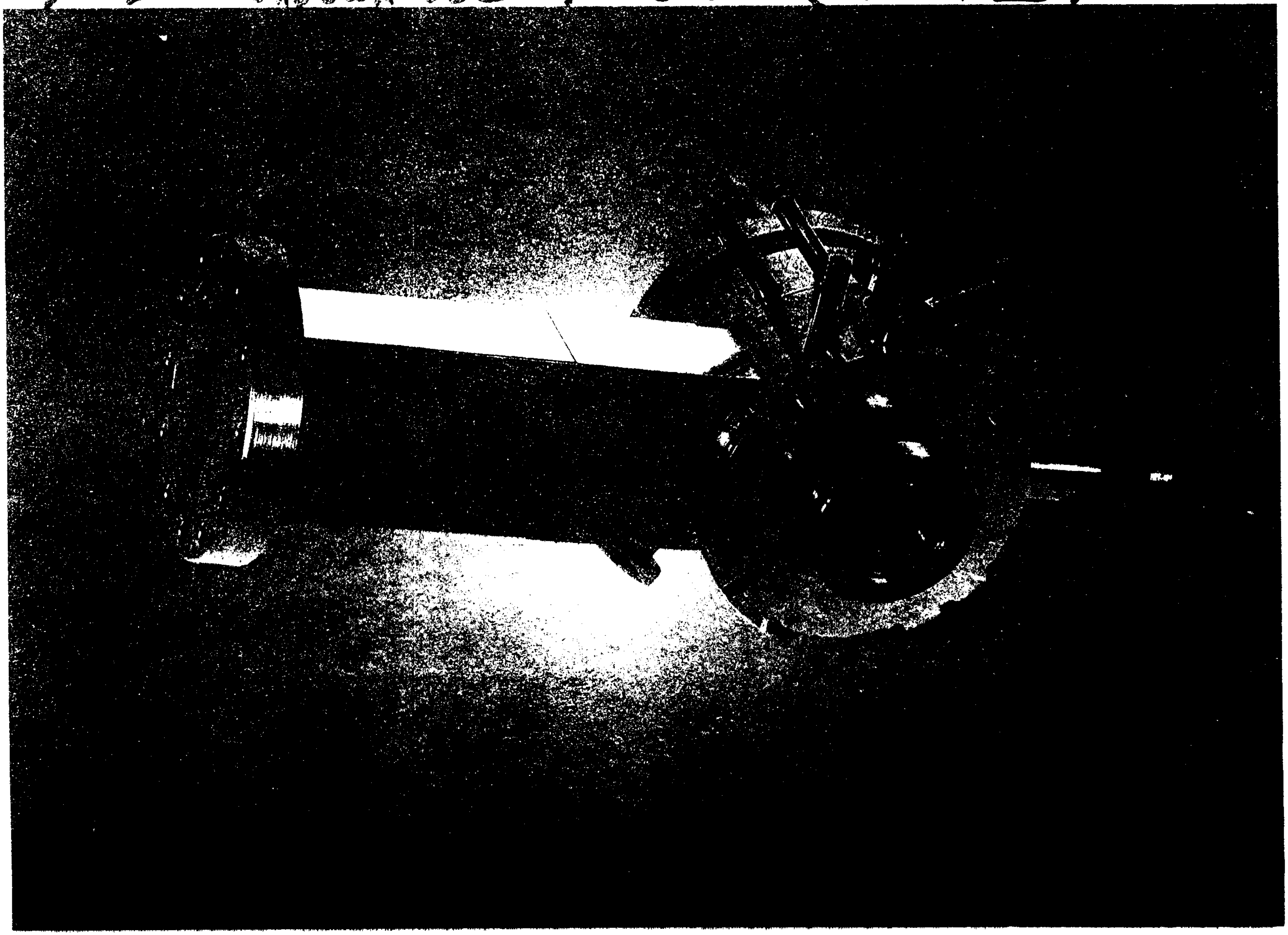
SECTION A-A
PARTS LIST / BILL of MATERIALS
HANUSKA
HANUSKA
NOONAN
ARGONNE NATIONAL LABORATORY
ADVANCED PHOTON SOURCE
EXPERIMENTAL HALL
D
S10207
00
S10207
SCALE 1:1

BNL Photocathode RF gun System

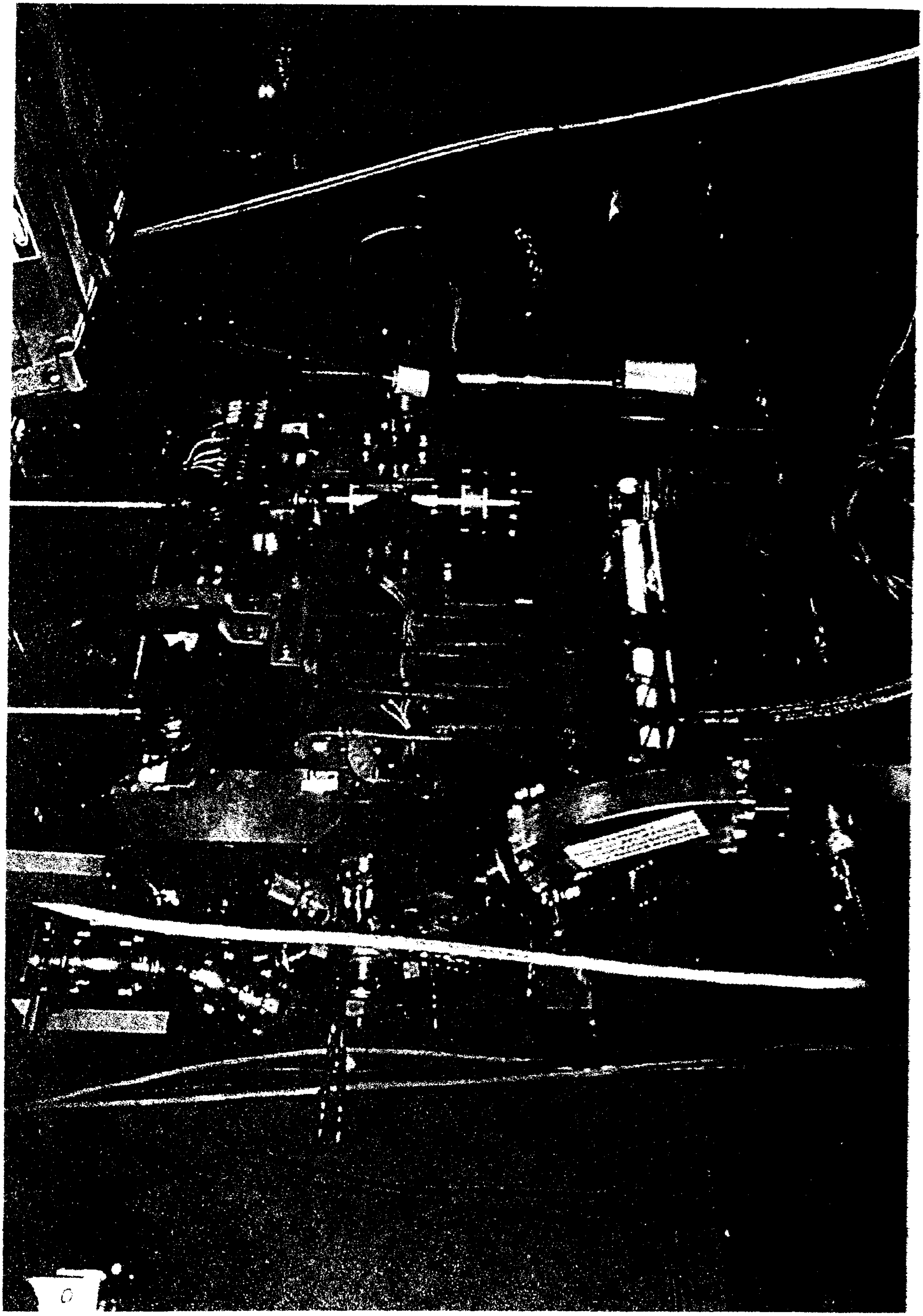


...telmach & S. Pjerov

BNL Photocathode RF Gun (Mark IV)

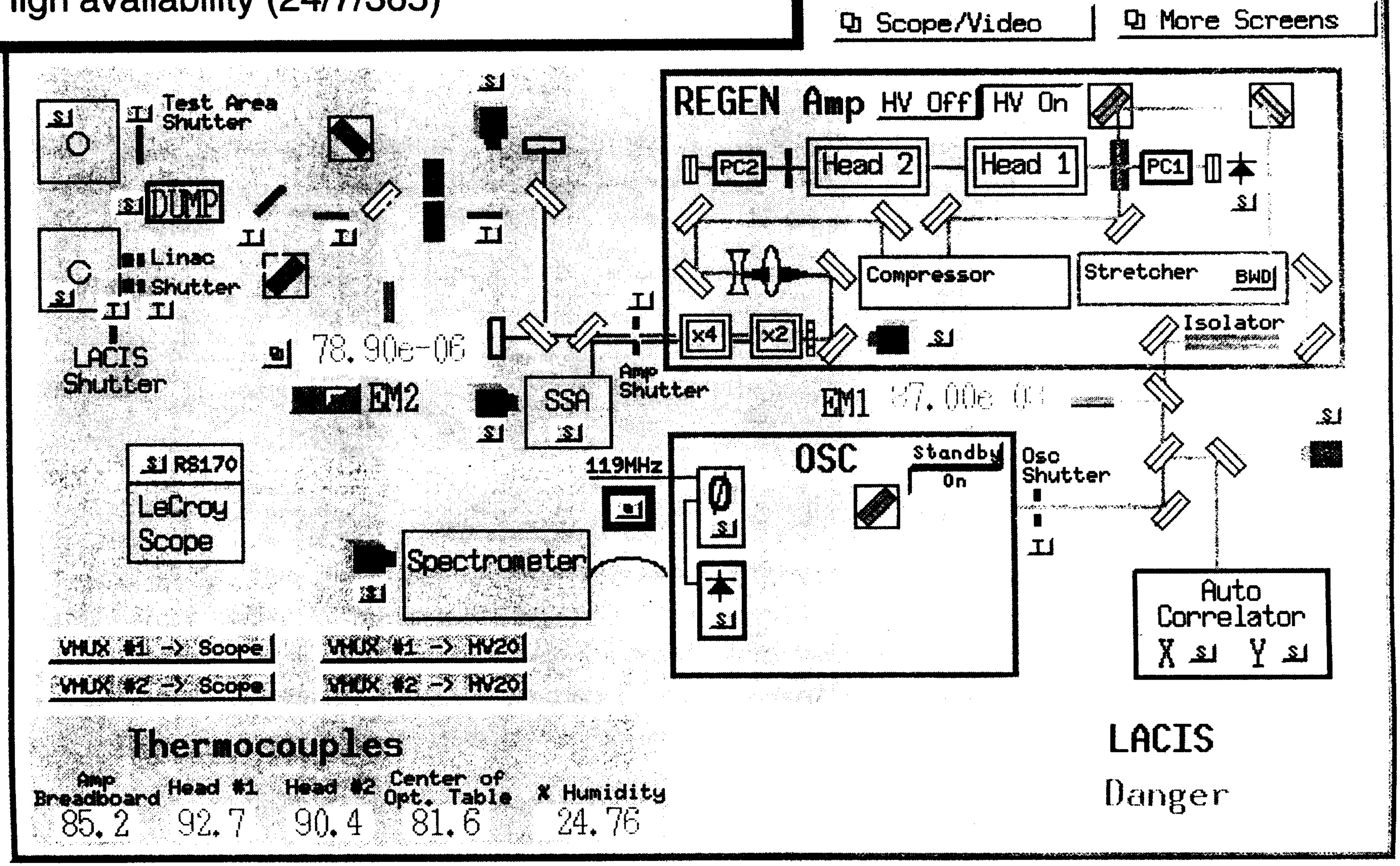


CAP-108-91



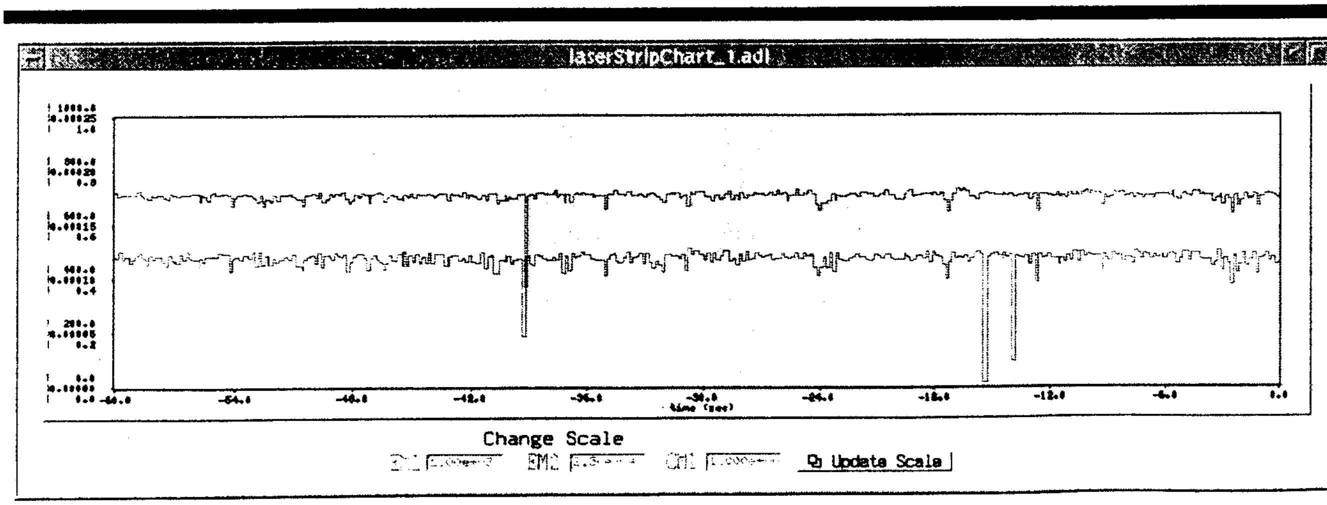
LEUTL Drive Laser: System Goals

- Provide light for an S-band, 1.6-cell gun
- Single shot 1 nC, 10 Hz with copper cathode
- Remotely controlled
- Integrated into EPICS control system
- Near "hands off" operation
- High availability (24/7/365)

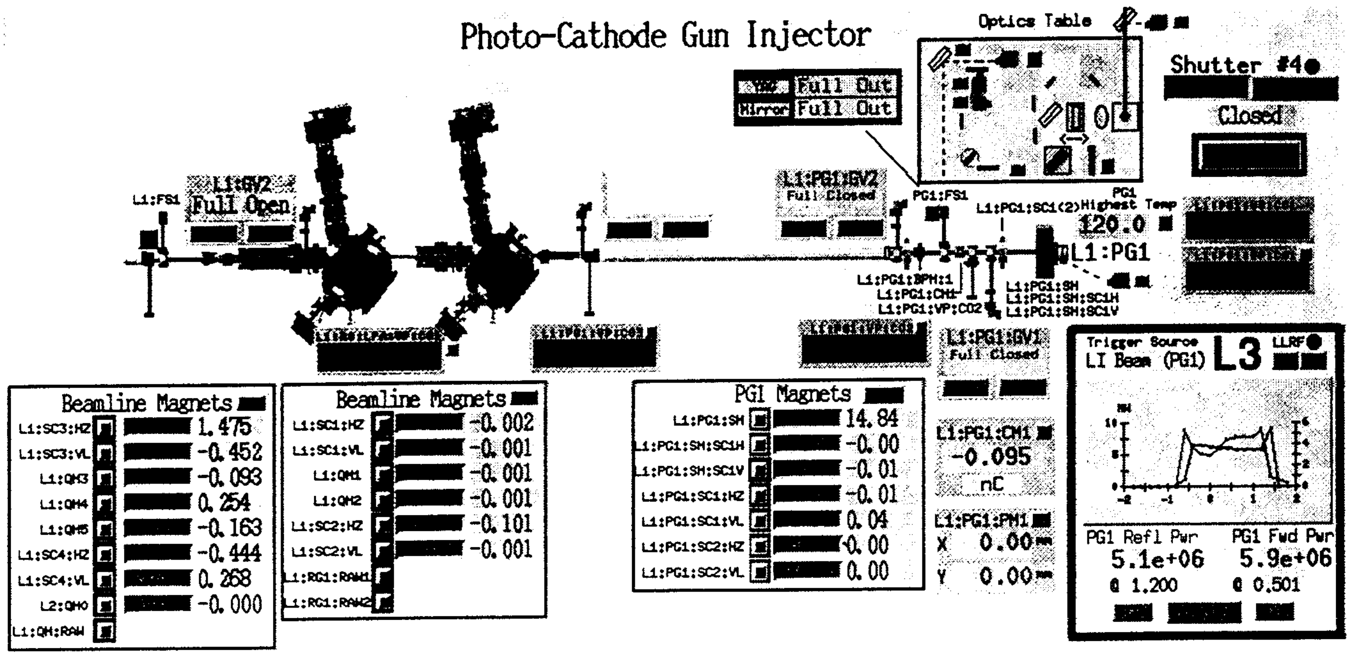


LEUTL Drive Laser:
Measured and Operating Parameters

Oscillator	
Wavelength	1053 nm
Pulse Length	200 fs
Avg. Power	~80 mW
Timing Stability	~1/3 ps
Amplifier	
Repetition Rate	6 Hz
Pulse Energy	9 mJ
Lamp Pump Power (x2)	36 J
Shot-to-shot jitter	±5%
Compressor	
Efficiency	42%
Output energy	<4 mJ
Pulse length (SSA)	2-6 ps
UV	
Conversion efficiency	<10%
Energy	<500 μJ
Energy Jitter (saturated)	±5%
Phase Stability (streak)	< 1.5 ps
Pointing jitter @ Cathode	< 0.3 %



Sep 22, 1999 08:10:24

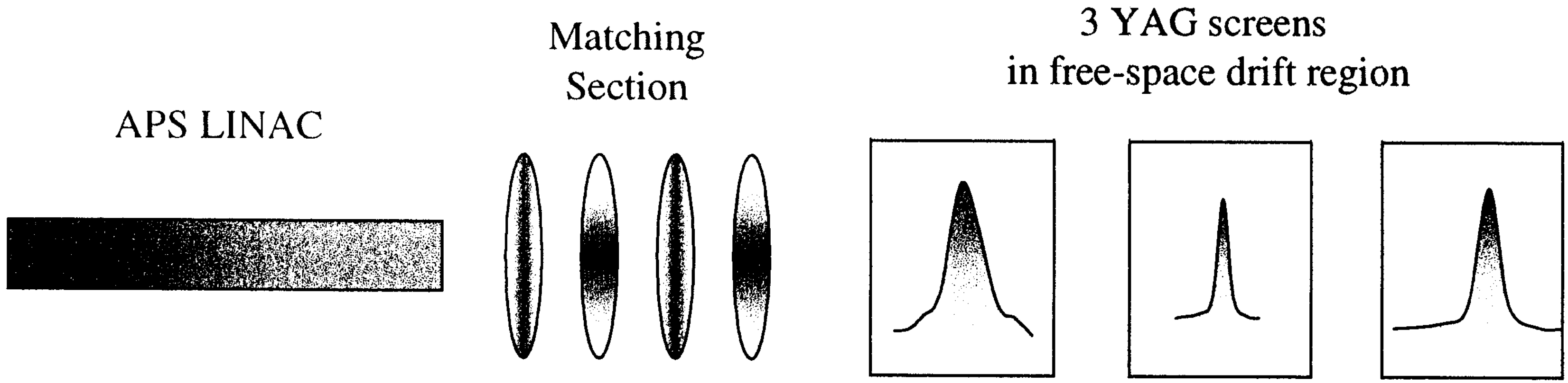


Beam Properties – 530 nm

Beam Property	Required Value*	Measured Value
ε_n	5 π mm mrad	4 - 6 π mm mrad (x and y planes, averaged)
I_p	150 A	50 - 100 A $\sigma_z = 3 - 6$ ps Q = 0.3 nC

* for saturation at 530 nm in 14 m of undulator

3-Screen Beam Property Measurement



Given	Obtain
Profile measurements Distance between screens	Beam parameters α, β, ε
Beamline Geometry Quad Settings	Settings for "perfect" match into LEUTL line

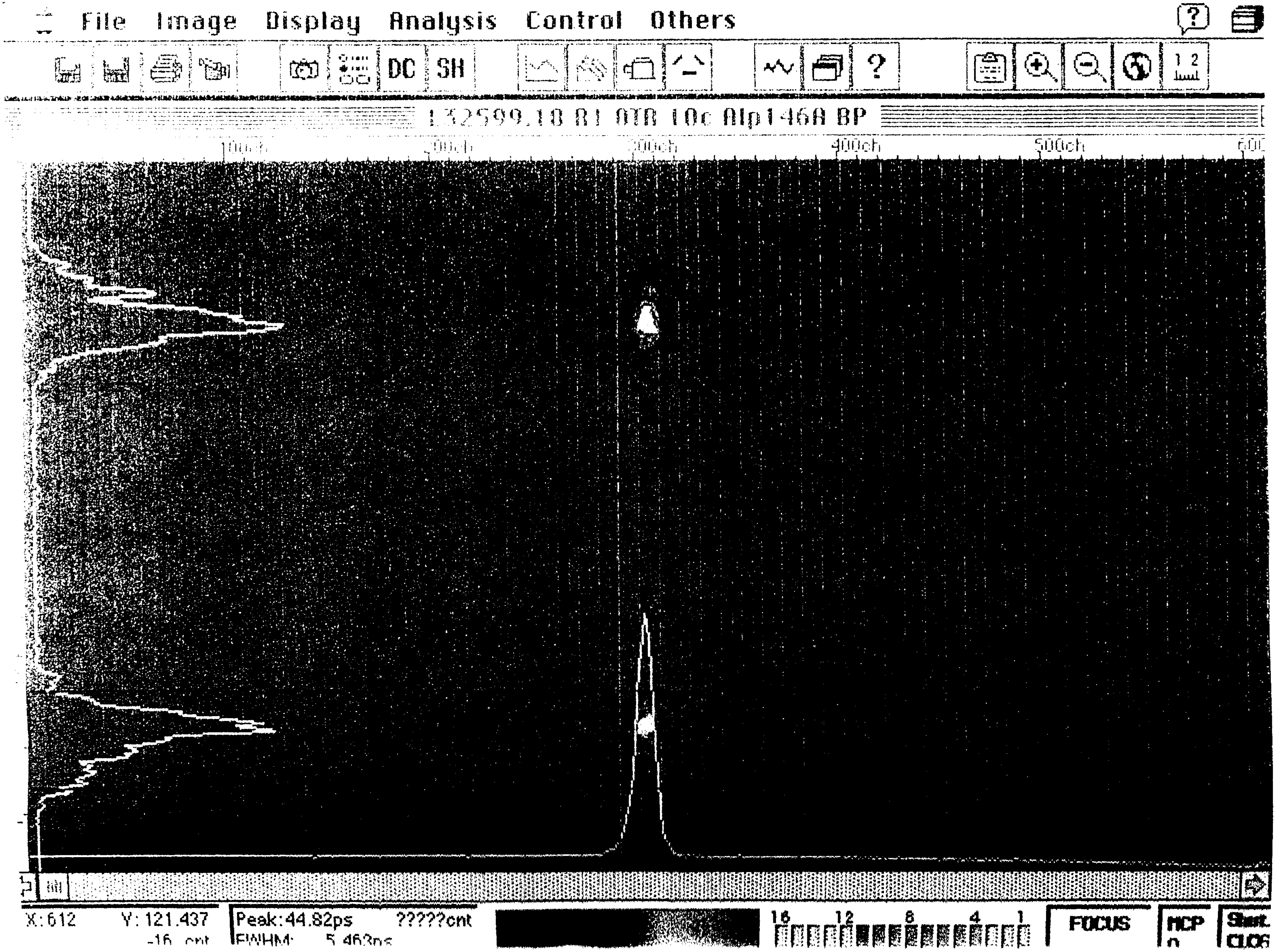
Experimental Background

Streak Camera Measurements

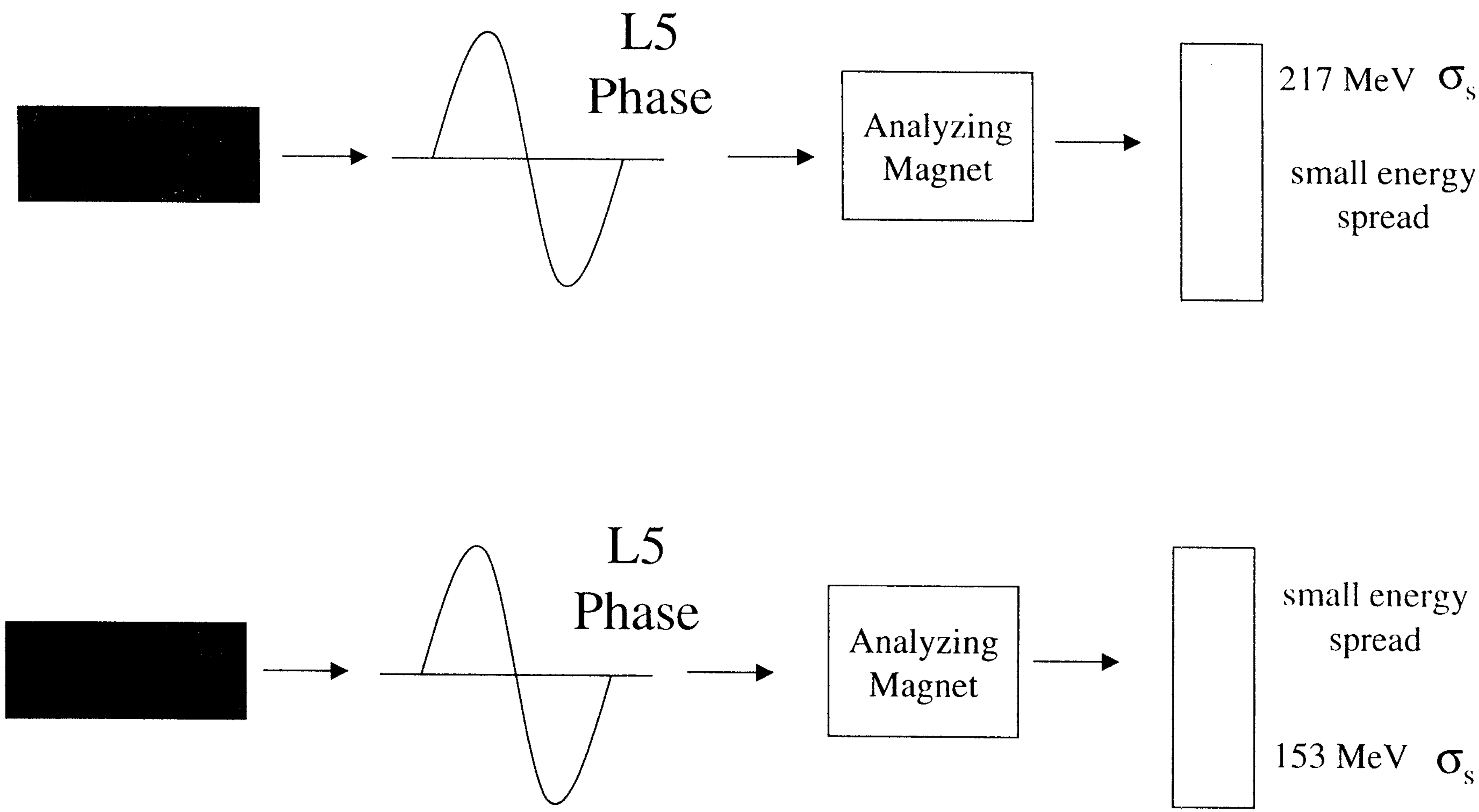
- Optical transition radiation (OTR) converter
- Hamamatsu C5680 mainframe
- Synchroscan, 119.0 MHz
- 220-MeV e-beam energy
- 200-mA macropulse average current
- Data (March 1999)

Michelson Interferometer

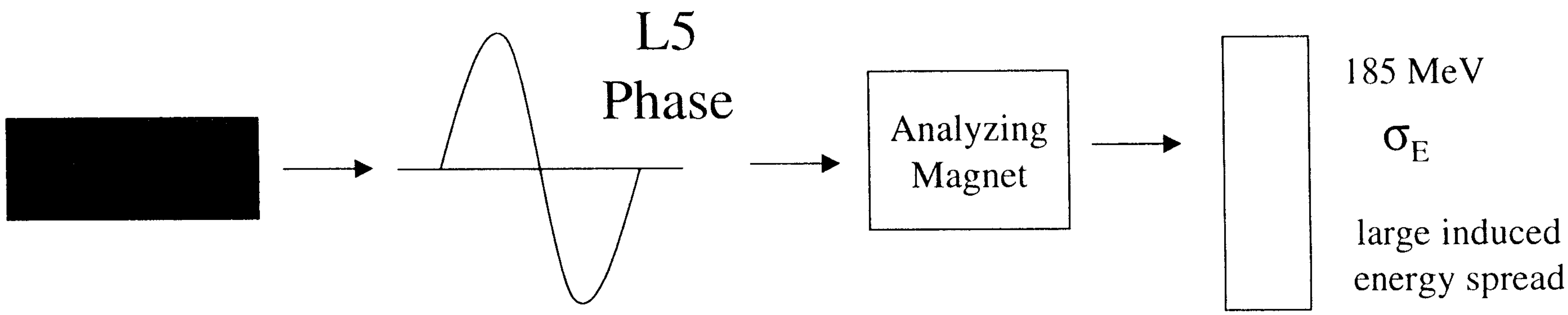
- Coherent transition radiation (CTR) mechanism
- Novel compact design
- Inconel-coated beamsplitter
- Constructed at Univ. of Georgia under ANL contract
- Golay cell as FIR detector
- 40-MeV e-beam energy
- 200-mA macropulse average current
- Data (May and August 1999)


File Image Display Analysis Control Others
DC SH
132599.18 R1 ATR 10c Alp146A BP
100ch
200ch
300ch
400ch
500ch
X: 612
Y: 121.437
-16 cnt
Peak:44.82ps
?????cnt
FWHM: 5.463ps
FOCUS
MCP

Linac-Based Bunch Length Measurements



Linac-Based Bunch Length Measurements



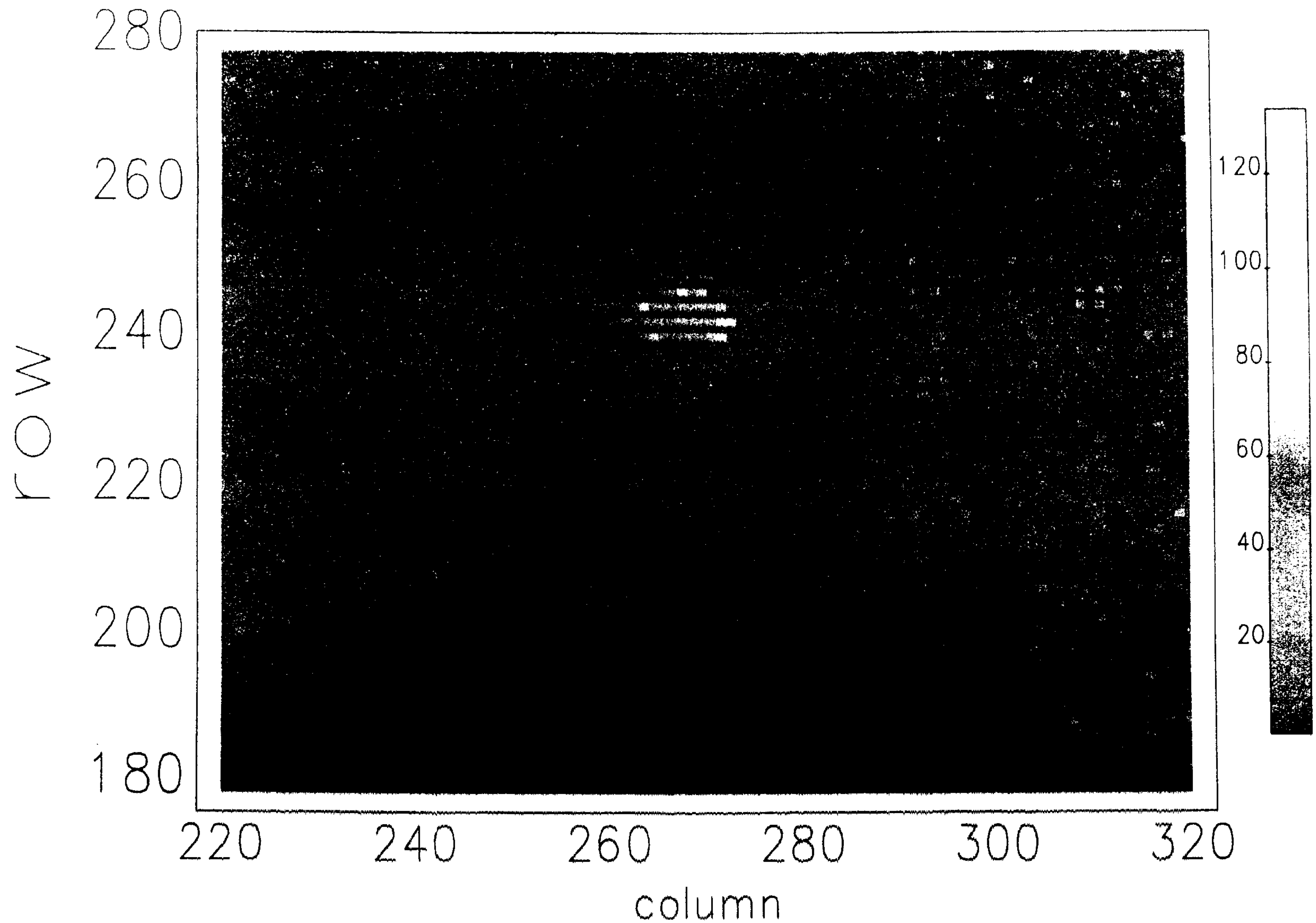
Energy gain = A sin (ϕ)

$\Delta E \sim A\, \Delta\phi$ for small ϕ (near zero crossing)

$$\sigma_L = \sqrt{\sigma_E^2 - \sigma_s^2} \Big/ A$$

"On Crest"

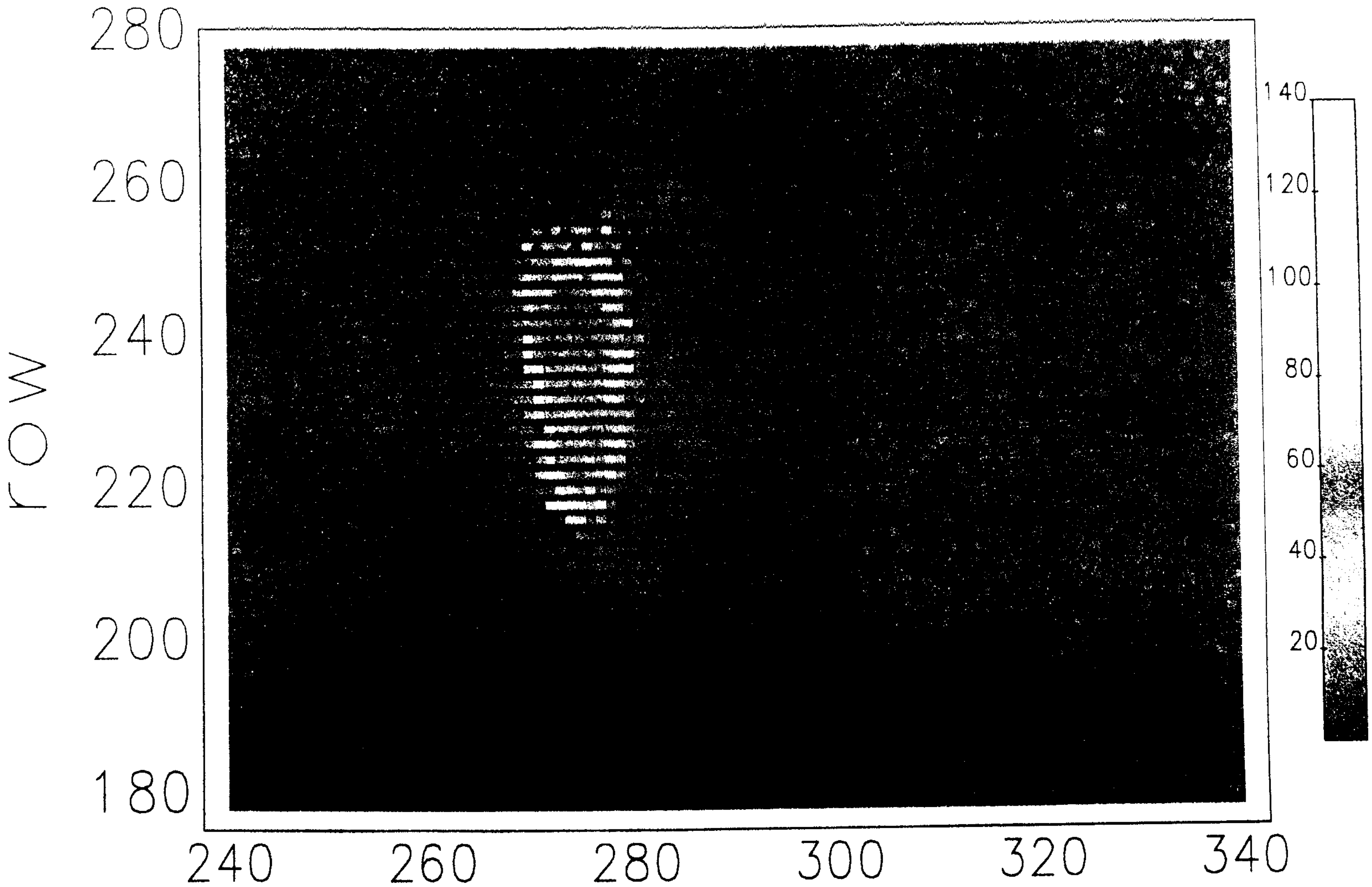
Data from SDDS file /home/helios/LEUTL/daily/9908/08/Screen10NoStreak.sdds, table 1



contours of constant Intensity

"Zero Crossing"

Data from SDDS file Screen10Streaked.sdds, table 1



column

contours of constant Intensity

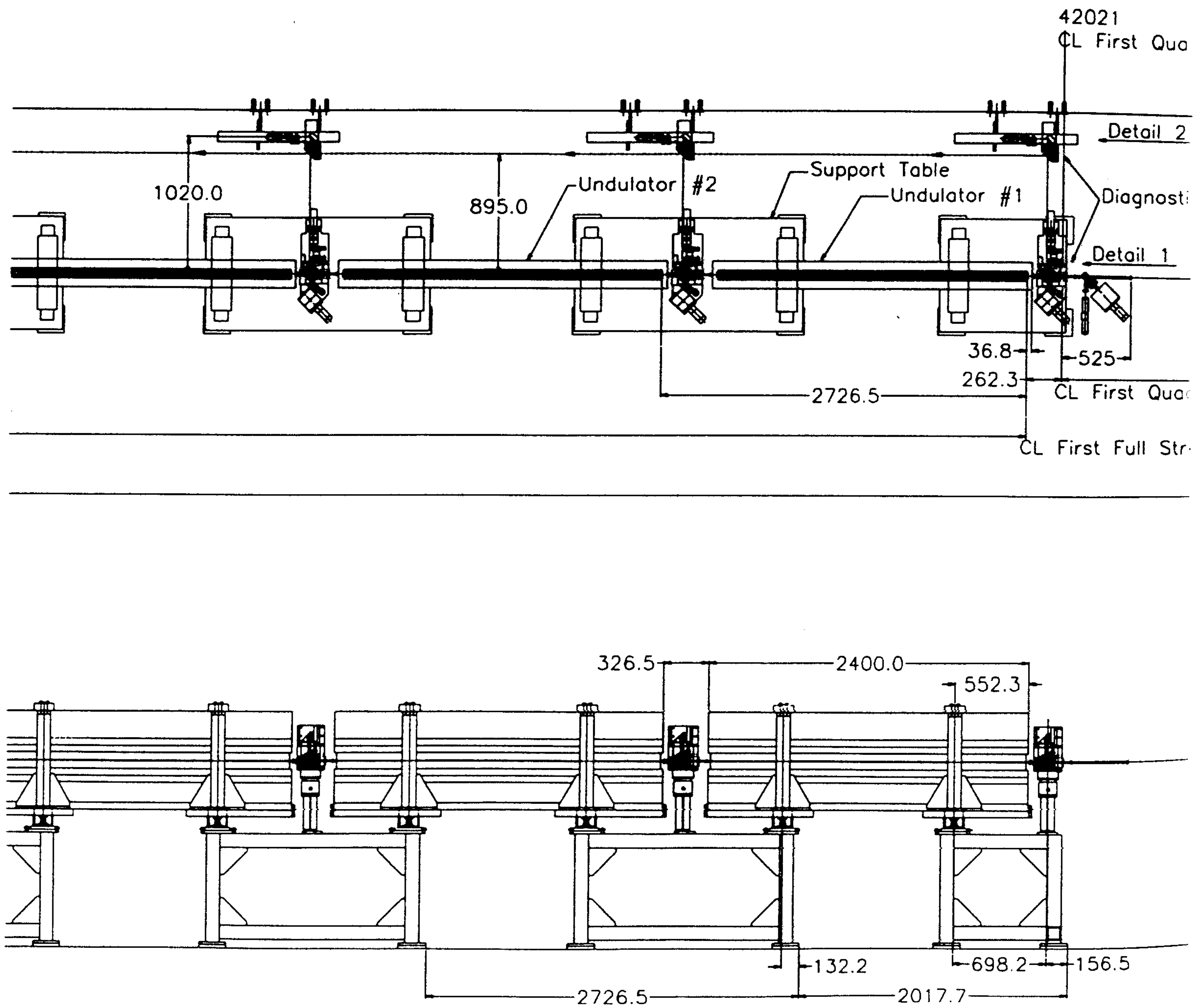
≈ 5ps FWHM

Beam Transport Issues

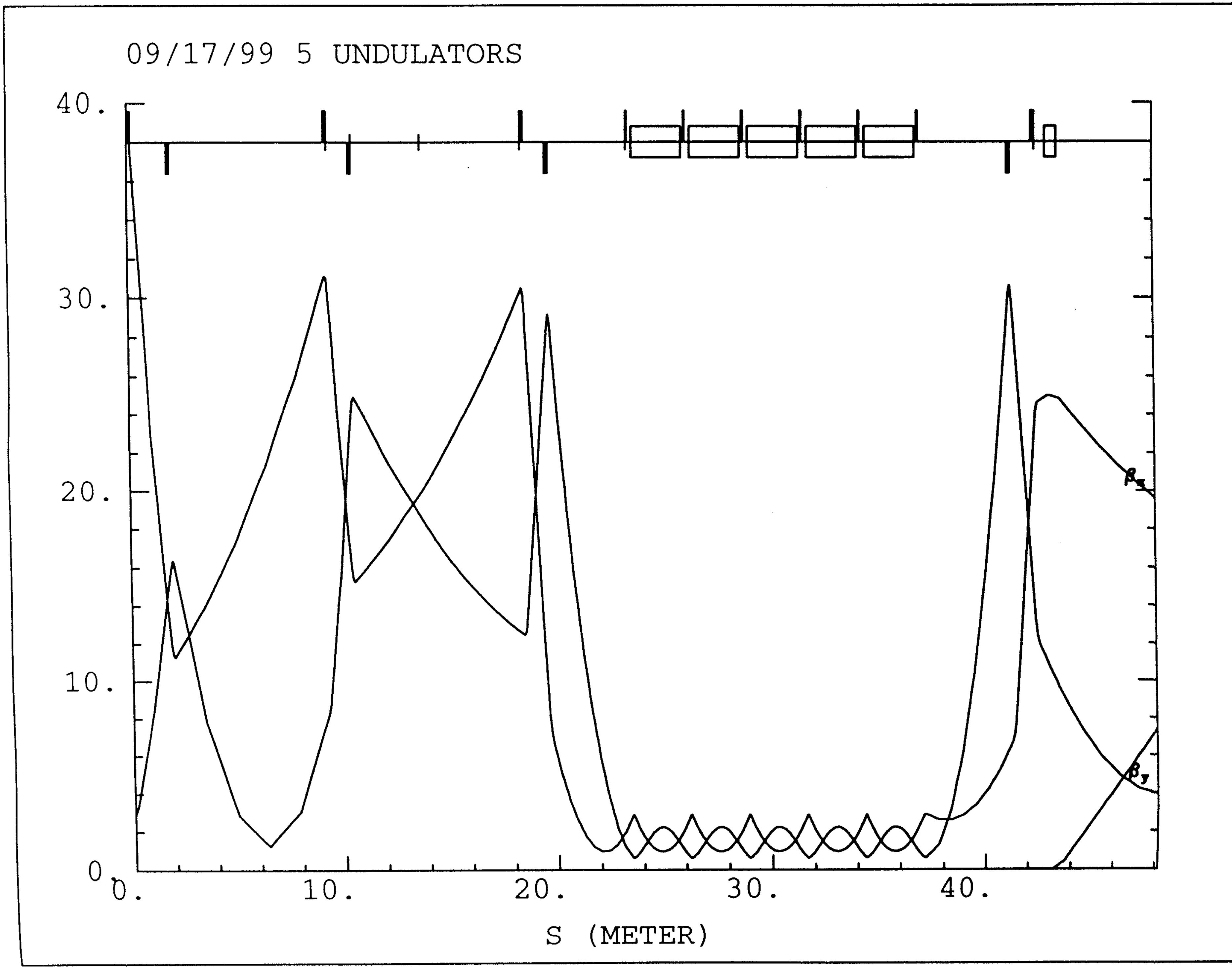
Issue	Causes	Solutions
Linac beam jitter	laser performance	improve power, reduce jitter, clean transverse profile
	rf phase & power jitter	new LLRF system
		rf system cross-comparison to localize jitter sources
	transverse wakefields (amplifying effect)	trajectory studies for wakefield minimization
		identification of suspected "bad" linac sections

Beam Transport Issues

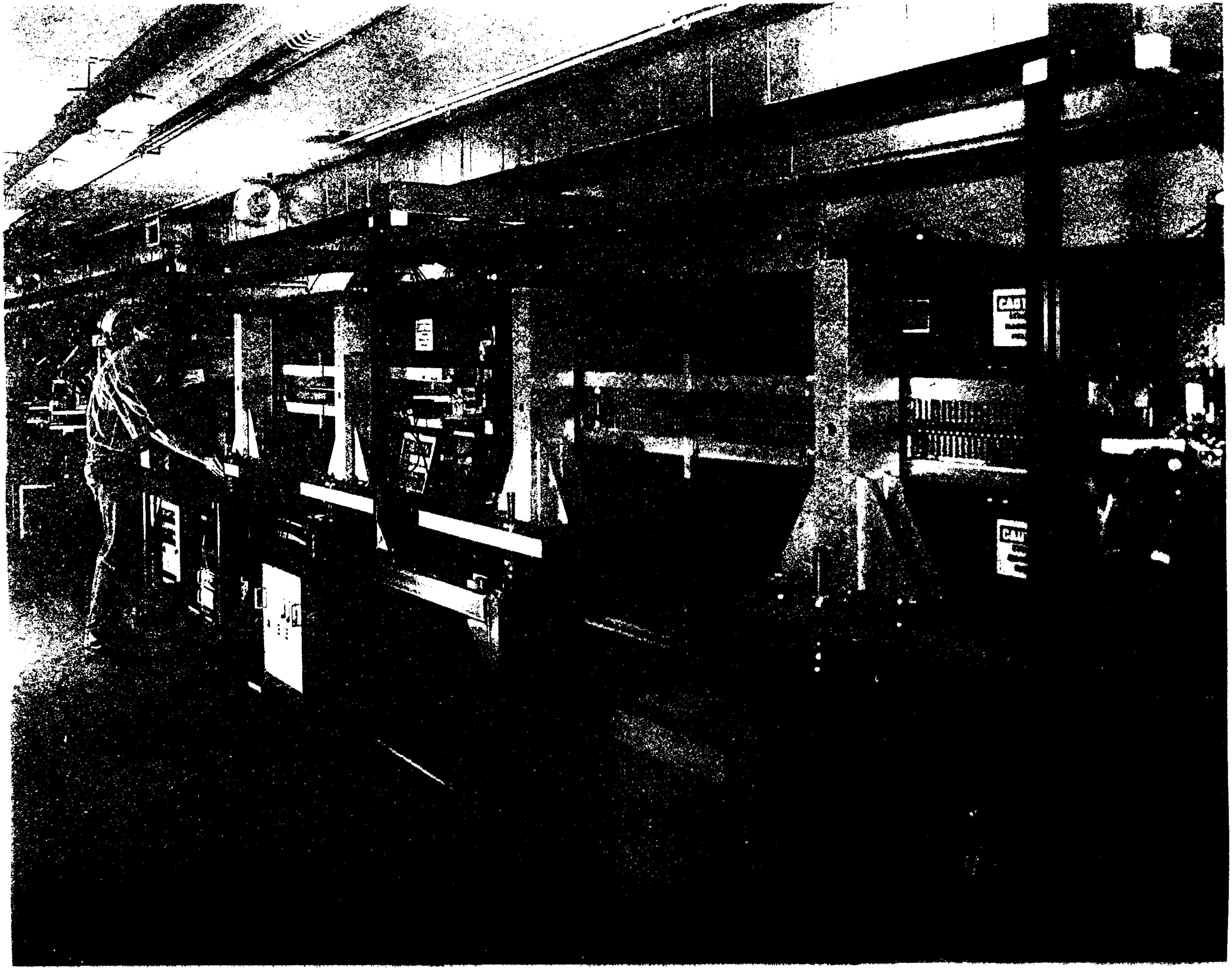
Issue	Causes	Solutions
Transport line mismatch into bypass and undulator lines	off-energy injection into matching section	recalibrate the linac spectrometers
		use BB:BD for spectrometer (higher resolution)
		use undulator light for energy measurement
	“hard” beam parameters at entrance to matching section	search parameter space for better initial conditions
		wakefield reduction

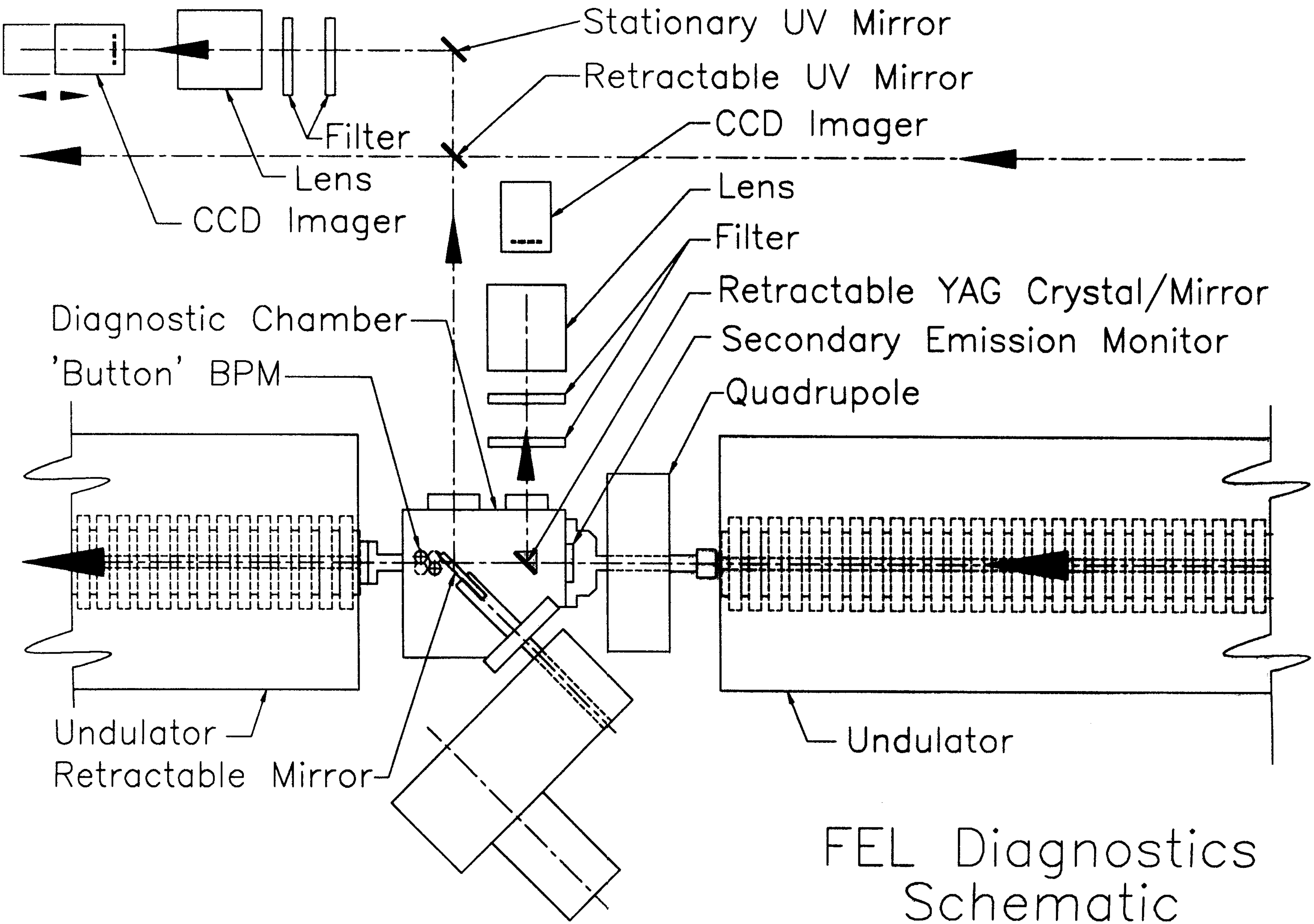


FEL Undulator Assy
Sketch: Assy-9-16
C. Benson 9/16/98

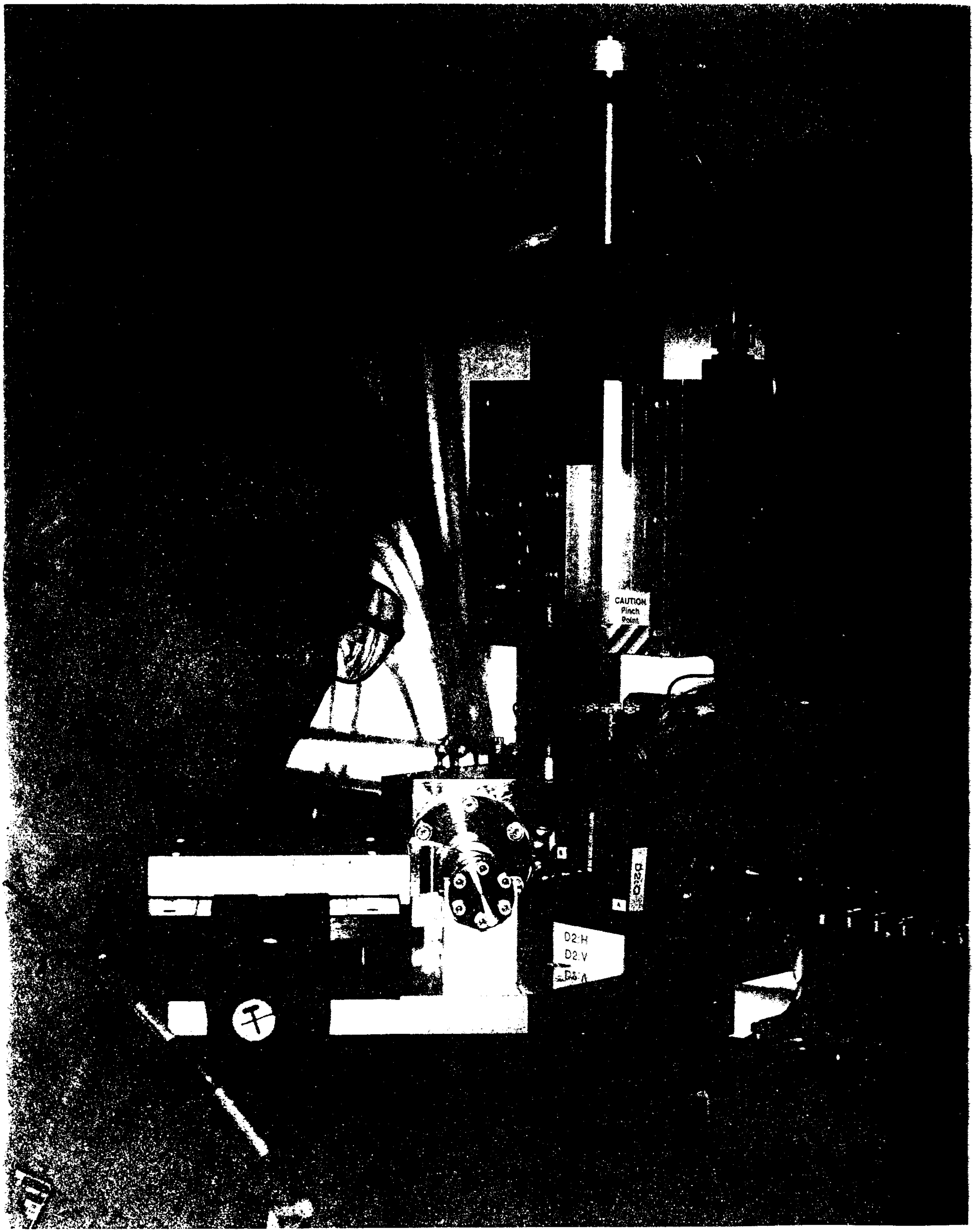


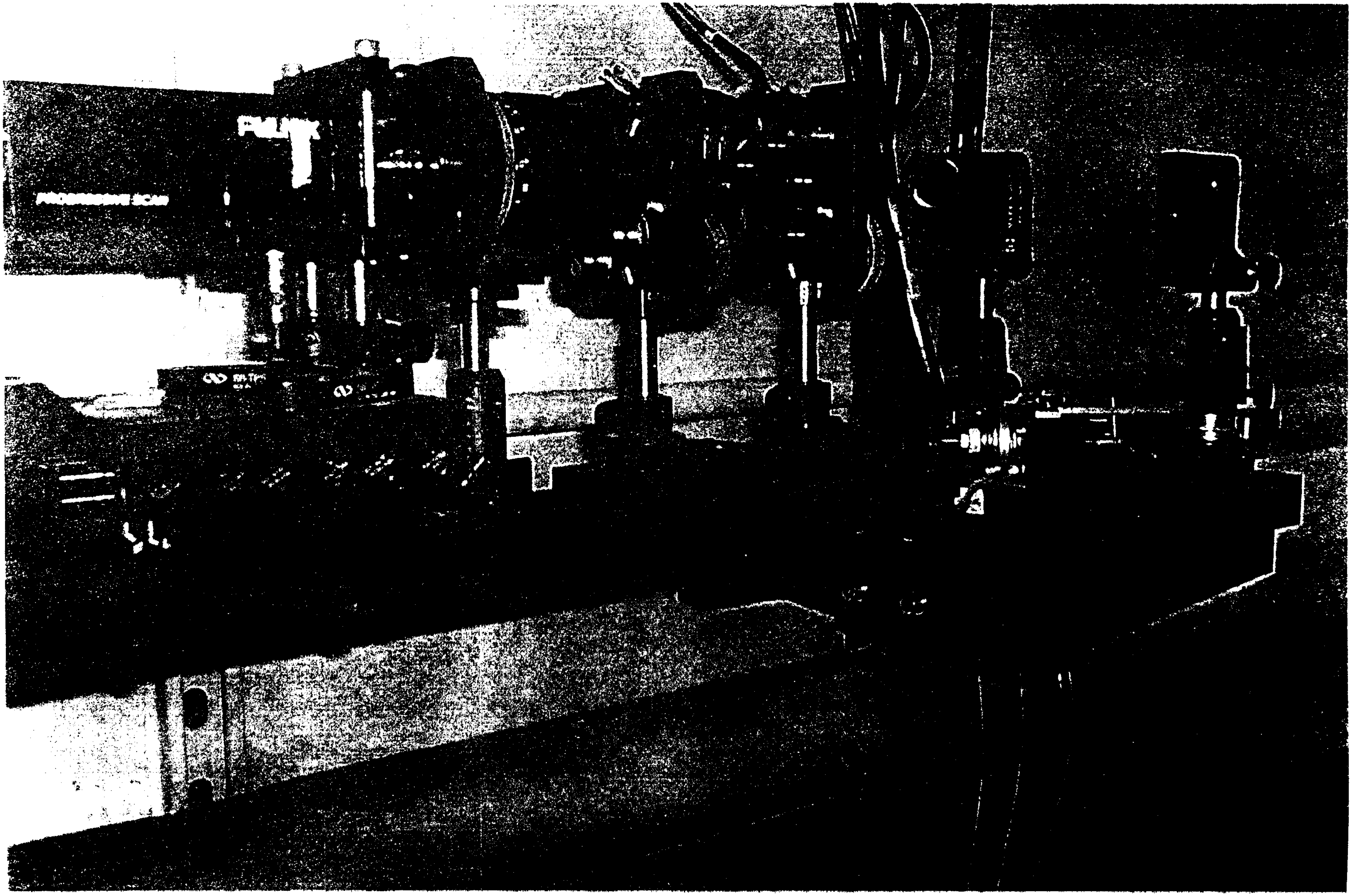
09/17/99 5 UNDULATORS
40.
30.
20.
10.
0.
0.
10.
20.
30.
40.
S (METER)
β_x
β_y



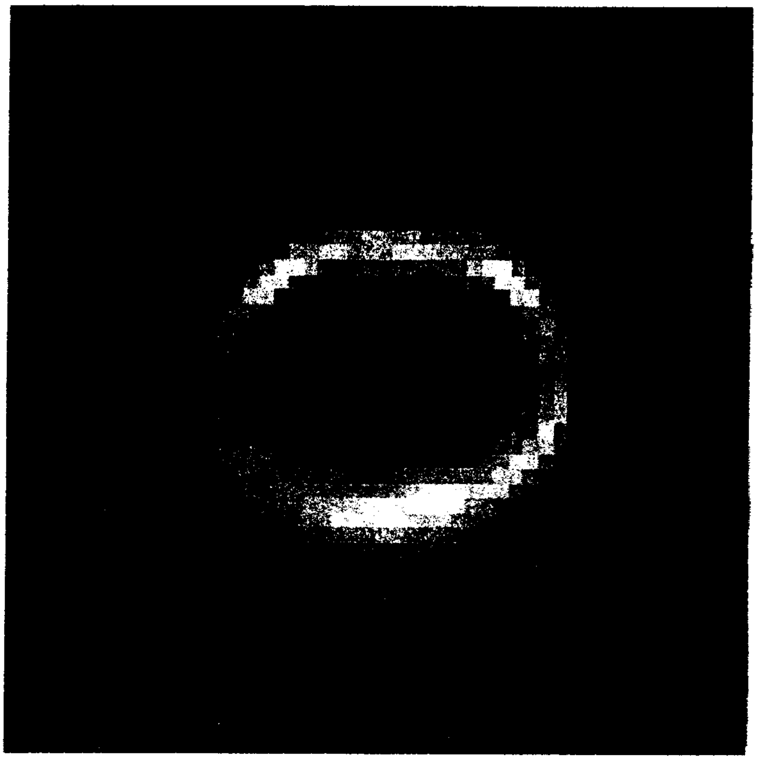


FEL Diagnostics Schematic


CAUTION
Pinch
Point
D2:H
D2:V

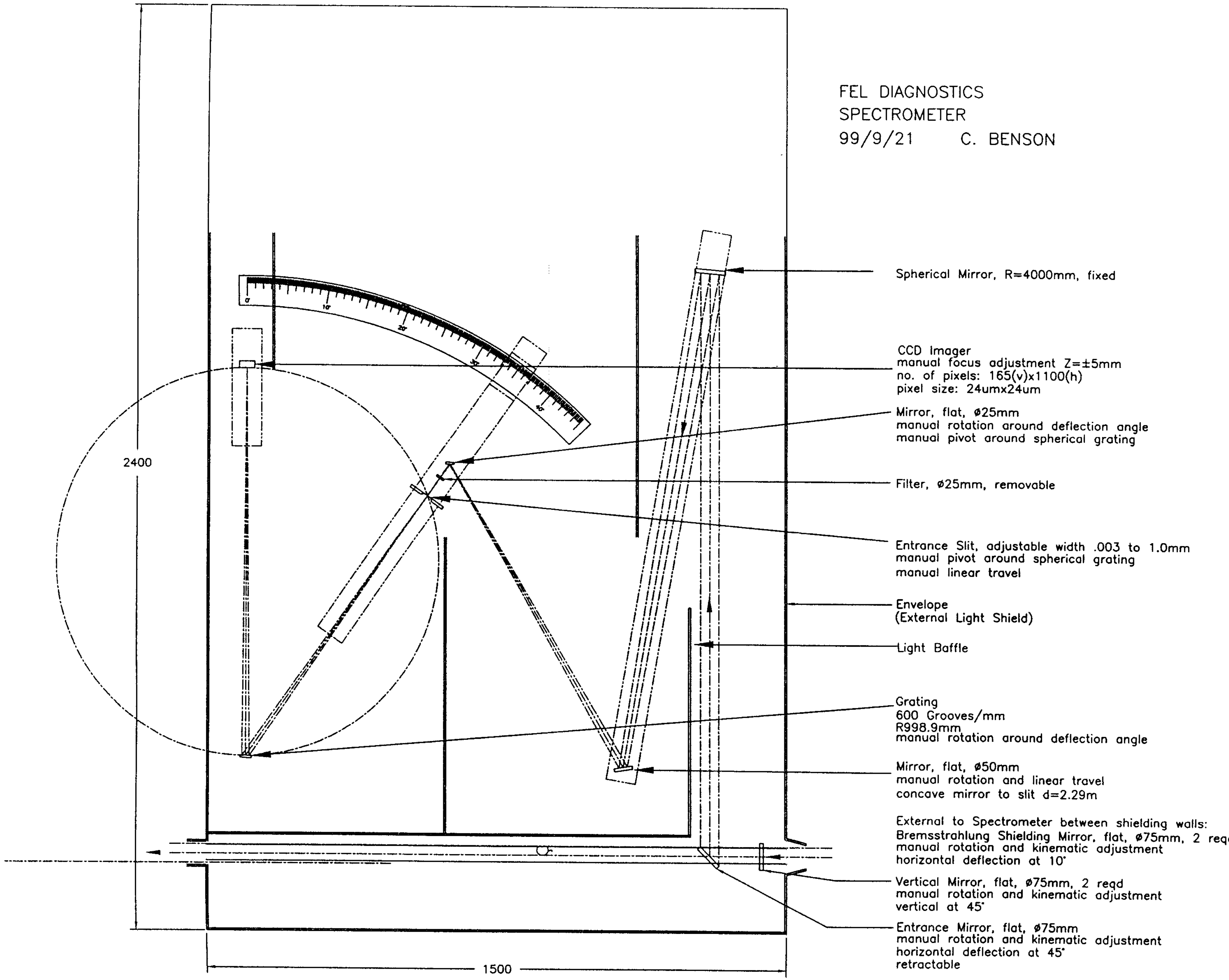


Advanced Photon Source

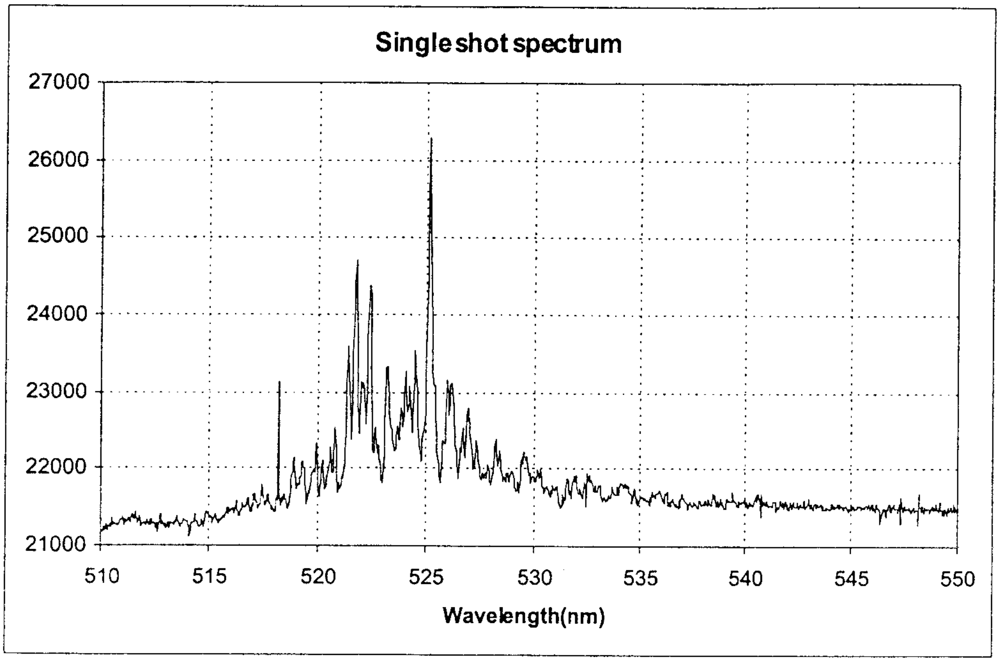


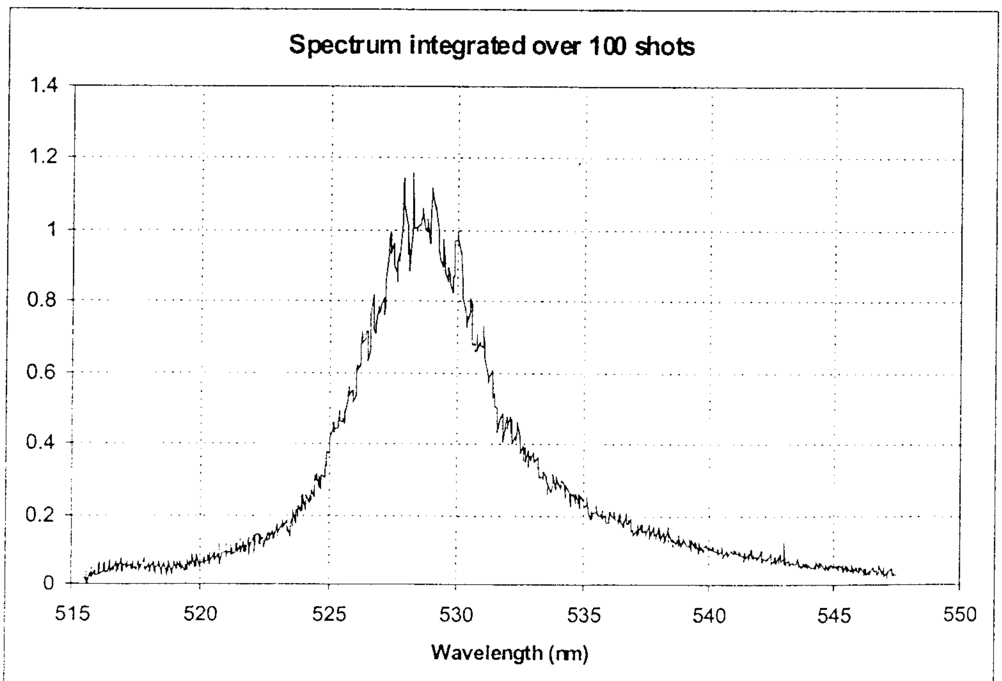
CCD image obtained with. E= 217 MeV, λ=570 nm. The non-circular aspect ratio is from the rectangular camera pixels, 11.6 μm x 13.6 μm.

FEL DIAGNOSTICS
SPECTROMETER
99/9/21 C. BENSON

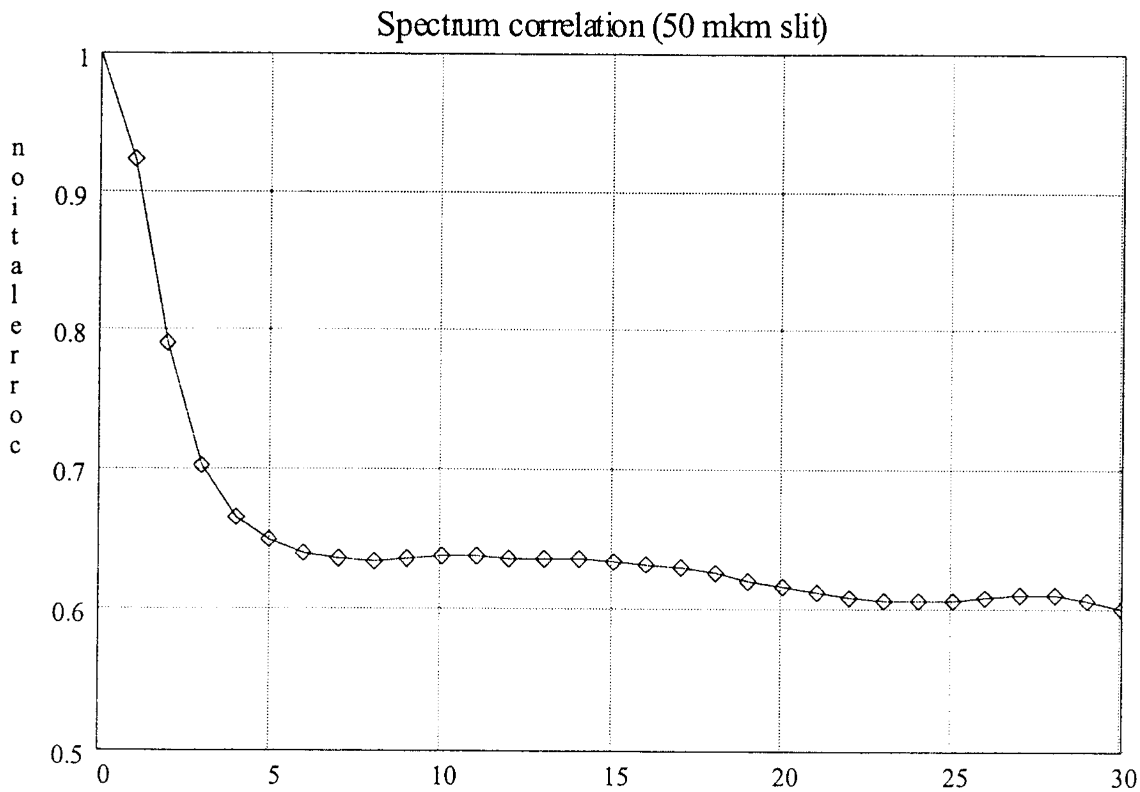


Advanced
Photon
Source





Advanced Photon Source



The spectrum correlation was calculated, then averaged over 100 spectra. The bunch length was determined* from the correlation to be 2 ps (1 sigma, assuming a Gaussian).

* method of P. Catravas et al., Phys. Rev. Lett. 82, 5261 (1999)

Near-Term Goals

- Installation of Three More Undulators (5 Total)
  - Installation following the October 1999 maintenance period
  - Total length of undulator 12 m
  - Total length of undulator system 13.63 m

- Measurements to Be Made
  - Trajectory and matching verification through undulators
  - Gain measurement at 530 nm
  - Basic measurements of SASE properties
    - Power vs. Length
    - Spectral properites
    - Temporal properties
    - Fluctuations
    - Transverse coherence

- Installation of Four More Undulators (9 Total)
  - Ready for installation January 2000
  - Total length of undulator 21.6 m
- Total length of undulator system 24.53 m
  - Full saturation at 530 nm
  - Measurement of harmonics

Intermediate Goal

- 380 nm (265 nm) Operation to Saturation
  - Requirements
    - $E = 256$ MeV (307 MeV)
    - $I_{peak} = 100$ A
    - $\varepsilon\gamma = 4\,\pi$ mm-mrad
    - $\delta = 0.01\%$
    - $L_{und} = 18.1$ m (21.7 m) (Undulator/Saturation Length)
  - Does not require vacuum transport of light

- Schedule
  - Summer 2000

Long-Term Goals

- Additional Undulators
  - Have room for up to 13 undulator cells
    - 31.2 m of undulator
    - 35.4 m total length of undulator system
  - Buncher/Radiator Operation

- Operation to Saturation at 120 nm
  - Requires vacuum transport system
  - Experimental (user) group already expressing interest
  - Earliest date envisioned to start: January 2001

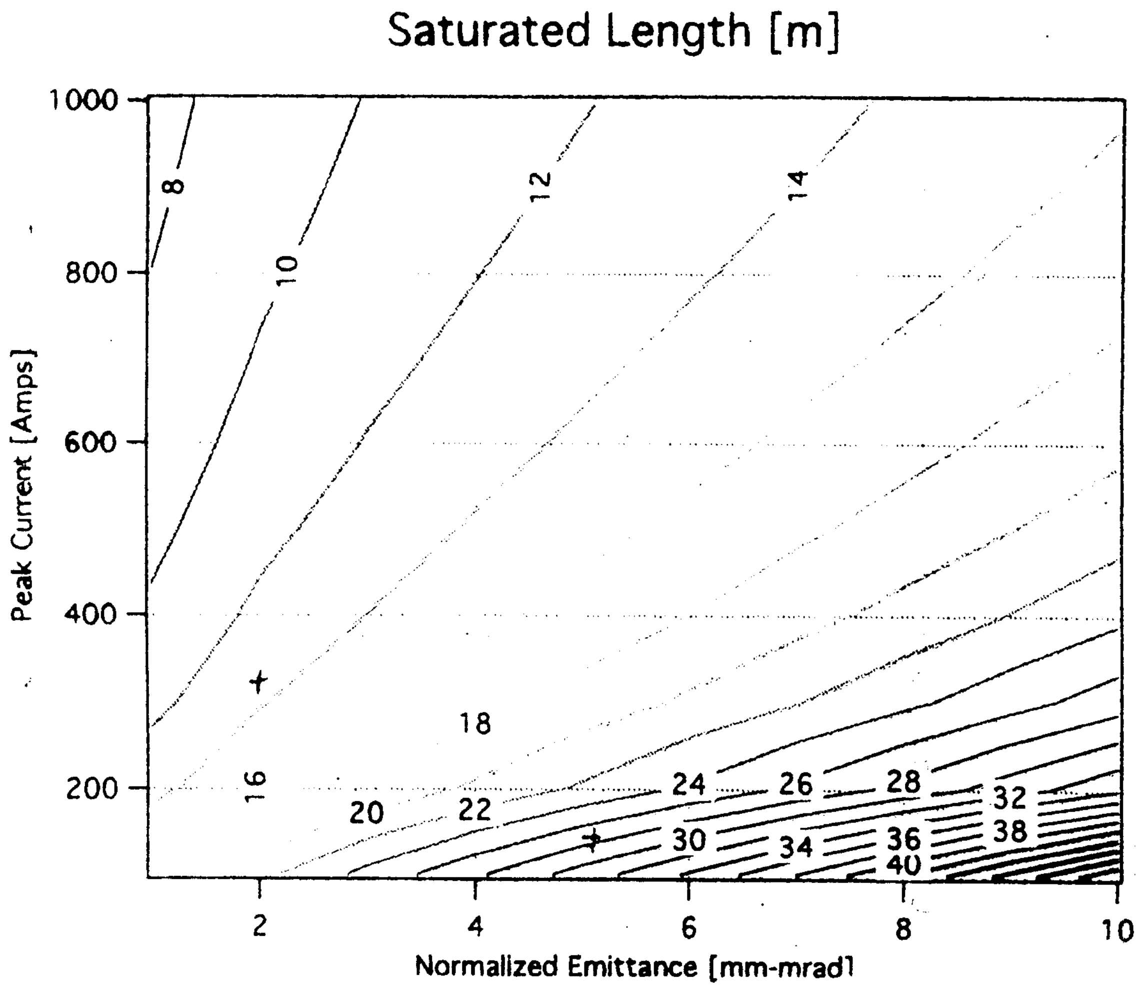
- Reduce Wavelength to Limit of Linac Energy
  - 70 nm (600 MeV) -> 50 nm (700 MeV) range possible

- Parallel Beamline
  - LEUTL tunnel capable of supporting a second parallel beamline
  - Could attempt fast switching experiments envisioned for 4th generation light sources

Bunch Compressor Overview: Project Decription

- Primary objective and motivation
  - Improve the performance, i.e., "brightness" of the electron beam in order to reduce the length of undulator needed to reach saturation in a single pass FEL
- Requires
  - Induced correlated energy spread on the bunch
  - Controlled dispersion bump
  - Diagnostics
- To be installed into the APS linac
  - The design **MUST** be compatable with APS operations
- Secondary objectives
  - To study the coherent synchrotron radiation (CSR)
  - To build a bunch compression system similar enough to that planned for the LCLS that the results could be used to improve the LCLS bunch compressor 1 (BC1) base design

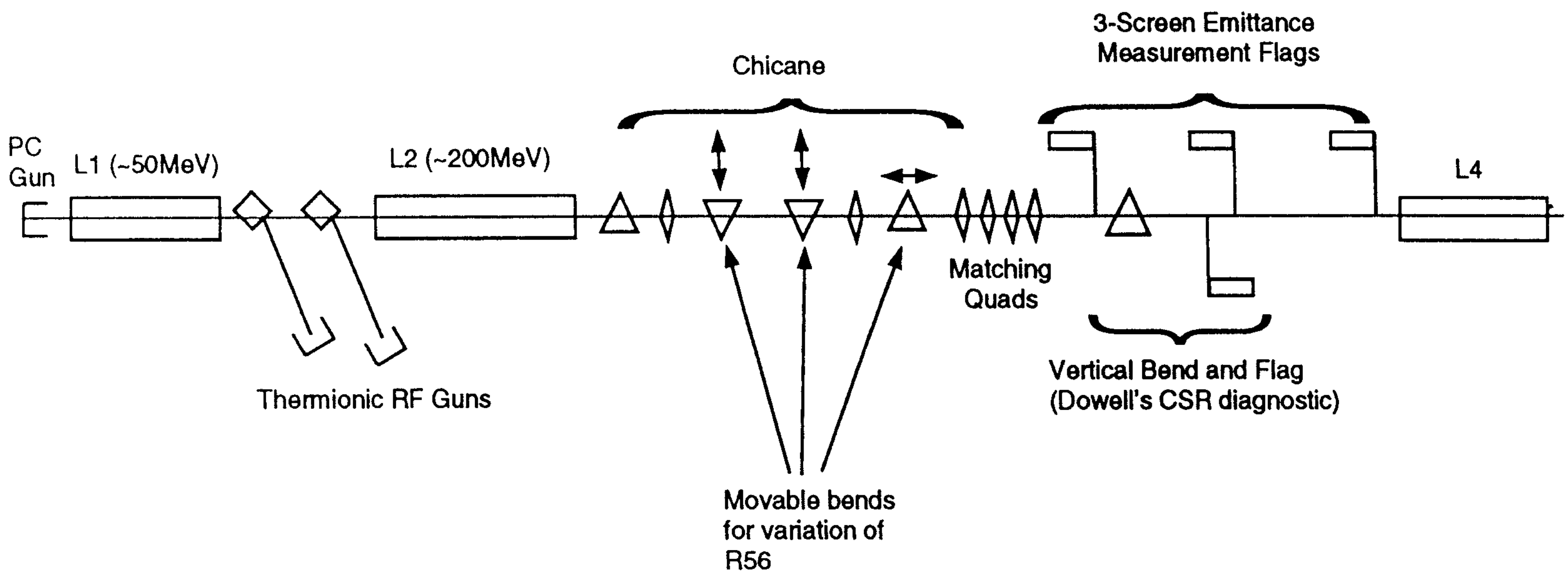
SASE FEL Performance



$\lambda = 120$ nm
$\lambda_{und} = 3.3$ cm
$K = 3$
$\beta_{avg} = 3.0$ m

Operations Analysis Group
Michael Borland borland@aps.anl.gov

Schematic of the APS Linac and Proposed Bunch Compressor



Operations Analysis Group
Michael Borland borland@aps.anl.gov

Addition of CSR to elegant

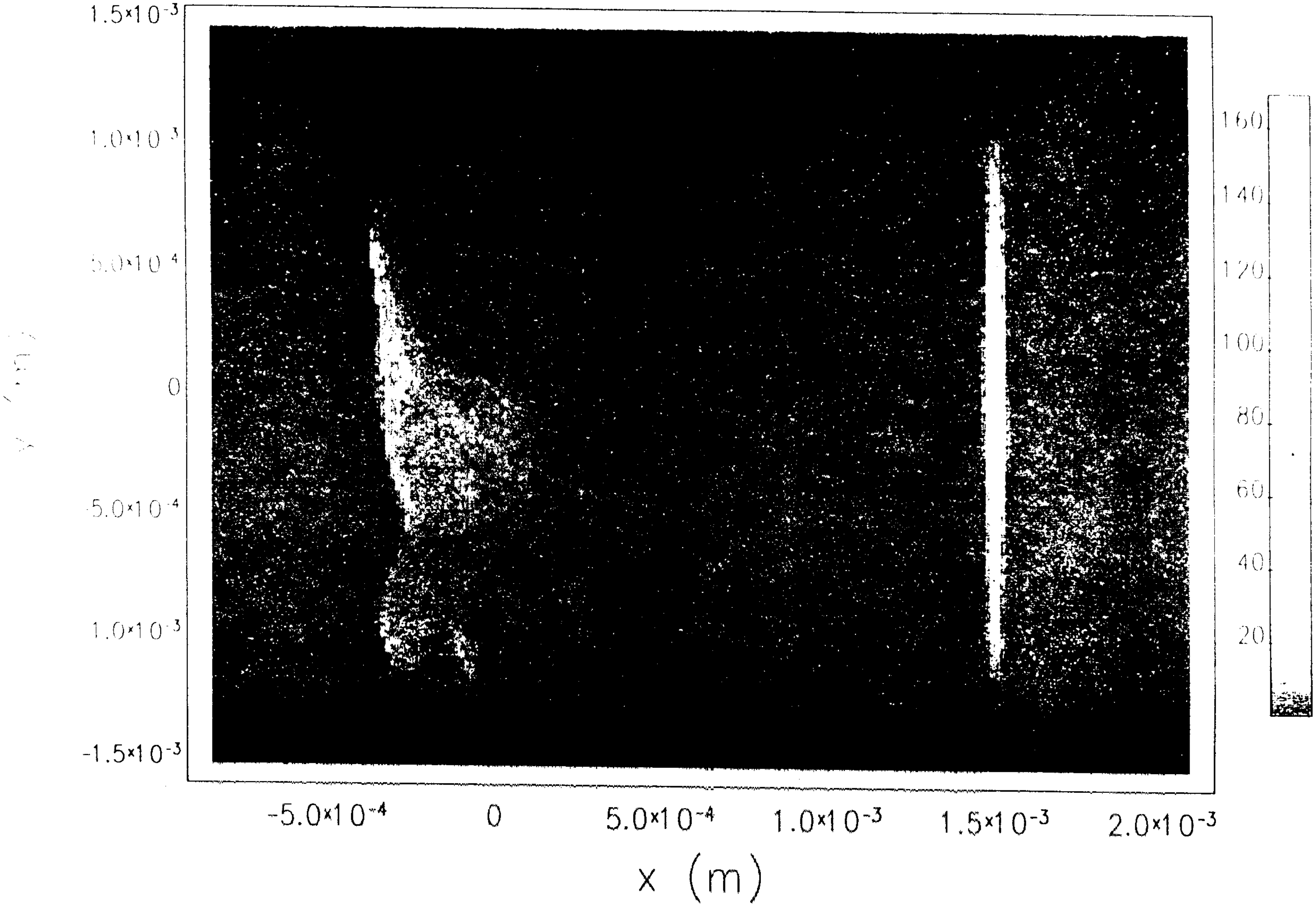
- Based on the work of E. L. Saldin, *et. al.,* in NIM A 398 (1997). They give,

$$\frac{dE(s,\phi)}{cdt} = \frac{-2e^2}{3^{1/3}R^{2/3}}\left\{\left(\frac{24}{R\phi^3}\right)^{1/3}[\lambda(s-s_L)-\lambda(s-4s_L)] + \int_{(s-s_L)}^{s} \frac{1}{(s-z)^{1/3}}\lambda(z)'dz\right\}$$

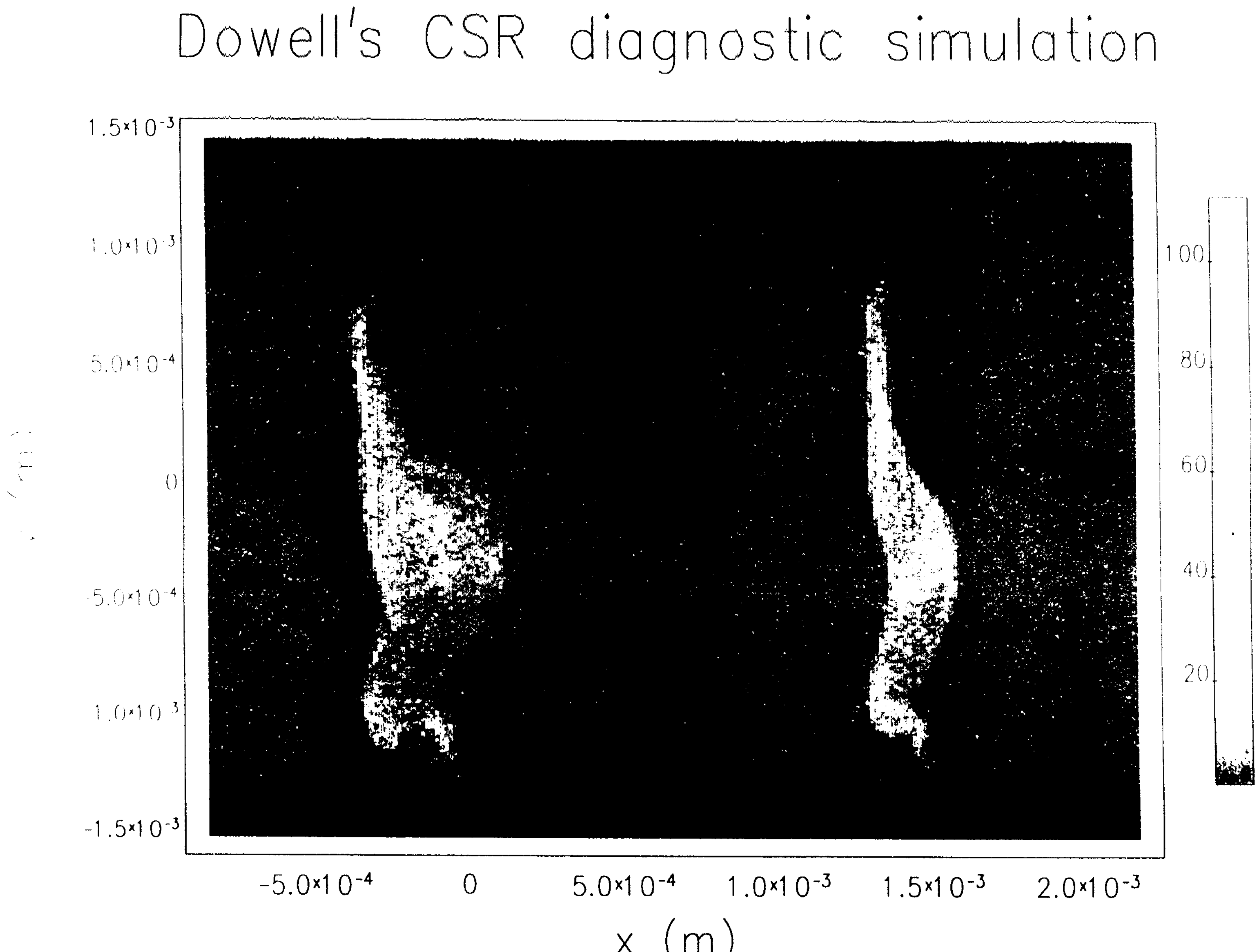
  where R is bend radius, ϕ is the angle into the bend, $s = ct$, s_L is the slippage length, and $\lambda(s)$ is the linear density of the bunch.

- Algorithm:
  - The dipole is divided into a user-specified number of pieces. 60 is adequate but 100 is better.
  - For each piece, a fourth-order canonical integration is done for the dipole fields.
  - Following this, the CSR energy kicks are applied.

Dowell's CSR diagnostic simulation



CSR on/off for 50mm/1 case



50mm/1 and 50mm/2

Very Long-Term Goals

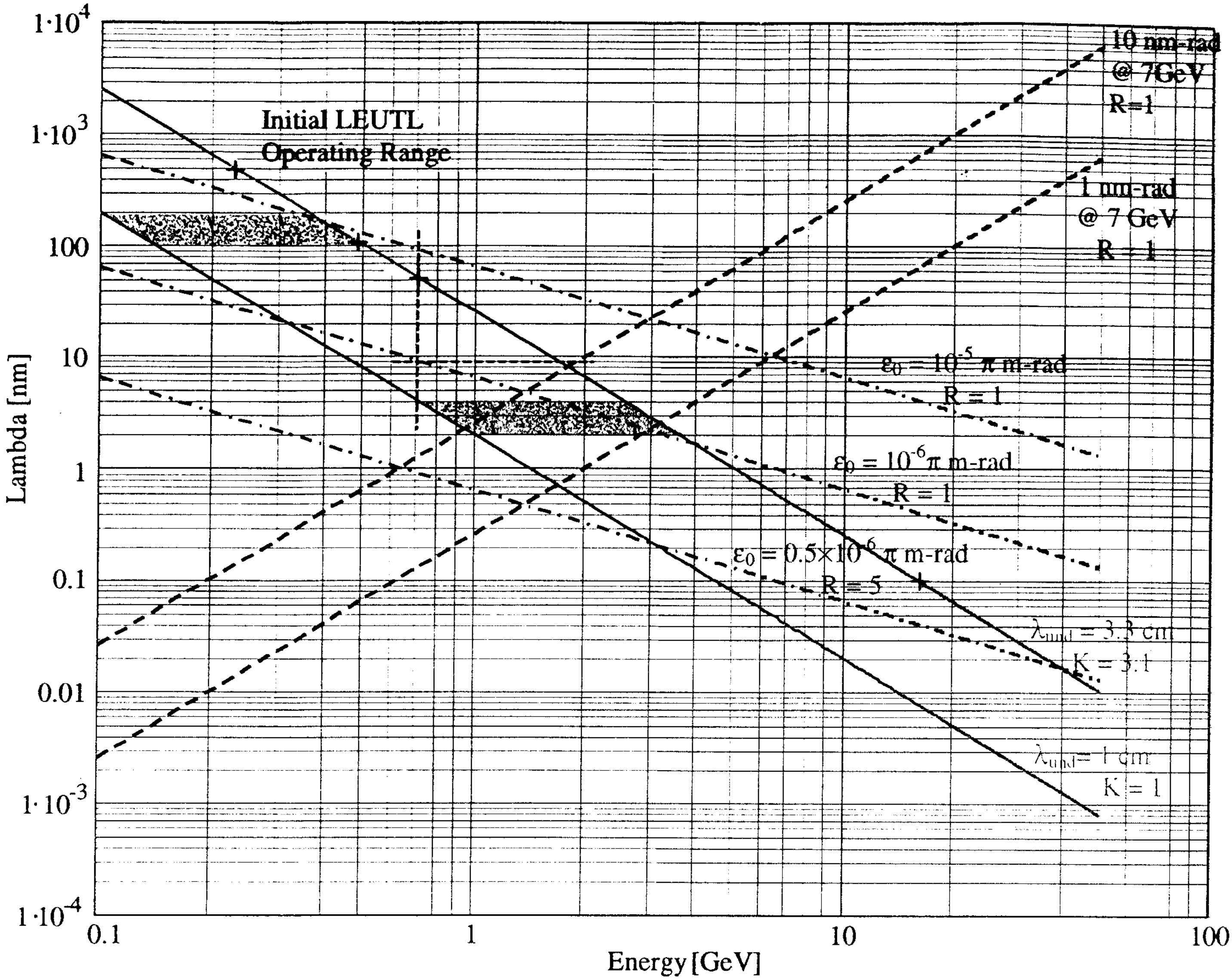
- Linac Energy Upgrade
  - Motivation
    - To push to the "water window" (~ 4 nm -> 2 nm)

ADVANCED PHOTON SOURCE

	Energy [MeV]						
	217	[redacted]	457	[redacted]		1000	[redacted]
Beam Parameters							
emit [pi mm-mrad]	5	5	[redacted]	3	[redacted]	1.5	1.5
Ipeak [A]	150	150	[redacted]	300	[redacted]	800	800
delE/E [%]	0.1	0.1	0.1	0.1	[redacted]	0.05	0.05
Undulator Parameters							
LambdaU [cm]	3.3	3.3	3.3	3.3	3.3	[redacted]	[redacted]
K	3.1	3.1	3.1	3.1	3.1	[redacted]	[redacted]
FEL Output							
Lambda [nm]	530	**120**	120	**51**	**25**	**3**	3
Lgain [m]	0.64	1.6	0.72	1.2	0.73	1.4	1.5
Lsat [m]	13.8	**31**	**15**	**24**	**15.3**	**27**	28
Ppeak [MW]	73	41	**270**	200	**1980**	230	**560**
Brightness [x10^28]	1.4	4	20	37	**263**	60	**278**

Items in [redacted] are changes made.

Items in yellow are some significant results of the changes made.



Undulator Resonant Condition: $$\lambda_L = \frac{\lambda_{und}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

Diffraction Limit Requirement: $$\lambda_L > \lambda_{diff} = \frac{4\pi\varepsilon}{R}$$

Linac Emittance Scaling: $$\varepsilon = \frac{\varepsilon_o}{\gamma}$$

$$\gamma = \frac{E}{m_e c^2}$$

Storage Ring Emittance Scaling: $$\varepsilon \propto \gamma^2$$