Diagnostic Imaging Issues and Challenges

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Outline

I. Introduction

II. Experimental Background

III. Examples of Demonstrations

- Longitudinal Profiles
- Transverse Profiles
- Scaling Issues

IV. Summary and Projections

Background on Relevant Parameters

Linac: Support efforts towards a few Å self-amplified spontaneous emission (SASE) experiment

Emittance (σ, normalized)	~1-2 π mm mrad
Bunch Length (σ)	~100 fs
Peak Current	~1-5 kA
Energy Spread (σ_E/E)	2×10^{-4}
Beam Energy	10's of GeV

Storage Ring: Support efforts to a diffraction-limited soft x-ray source: $\varepsilon \leq \lambda/4\pi$

Emittance	(ε)	~10×10^{-12} m rad
Beam Width	(σ_x)	~10 μm
Divergence	$\sigma_{x'}$	~1 μrad
Bunch Length (σ)		~1 ps
Beam Stability		<1 μm
Energy Spread		<0.1%
Brilliance		~10^{23}

LCLS Undulator Electron Beam Parameters

H.-D. Nuhn et al., SSRL/SLAC

Energy:	4.5 GeV	14.4 GeV
Emittance (normal):	2 π mm-mrad	1.5 π mm-mrad
Charge/bunch:	1 nC	1 nC
Peak current:	3400 A pk	3400 A pk
Bunches/pulse:	1	1
Pulse rep rate:	10-120 Hz	10-120 Hz
Bunch radius:	37 μm rms	31 μm rms
Bunch divergence:	6.1 μrad	1.7 μrad
Bunch length:	20 μm rms (67 fs rms)	20 μm rms
dE/E (uncorrelated):	0.07%	0.02%
dE/E (correlated):	0.2%	0.1%

LCLS Undulator Photon Beam Parameters

H.-D. Nuhn et al., SSRL/SLAC

Electron energy:	4.5 GeV	14.4 GeV

Spontaneous Radiation:

1st undulator peak:	15 Å (0.8 keV)	1.5 Å (8.2 keV)
Peak power/pulse:	8.1 GW	81 GW
Average power:	0.27 W	2.7 W
Beam radius:	52 µm rms	33 µm rms
Beam divergence:	6.2 µrad rms	2 µrad rms
Critical energy:	22 keV	200 keV

FEL Radiation:

Wavelength:	15 Å (0.82 keV)	1.5 Å (8.2 keV)
Peak sat. power/pulse:	11 GW	9 GW
Average saturation power:	0.36 W	0.51 W
Peak brightness:	1.2×10^{32}	12×10^{32}
Average brightness:	0.42×10^{22}	4.2×10^{22}
Peak flux:	81×10^{24} ph/s	7.1×10^{24} ph/s
Coherent photons/pulse:	22×10^{12}	2.0×10^{12}
Beam radius:	37 µm rms	31 µm rms
Beam divergence:	3.2 µrad rms	0.38 µrad rms
Pulse duration:	67 fs rms	67 fs rms

Examples of Recent Results
"On the Path"

Beam Position Monitors (submicron)

- Linac: cavity-based BPM (SLAC)
- Storage ring rf BPM (APS)
  0.1 μm at 1 mA and 1 Hz BW

Beam Profile

- Transition Radiation Meas. at 3.25 GeV
  (P. Piot, CEBAF)
- Storage ring, x-ray pinhole
  (P. Ellaume, ESRF)
  $\varepsilon_y \sim 25$ pm rad

Beam Divergence

- Linac beam at 650 MeV, ~50 μrad (calc.)
- Storage ring at 7 GeV, ~ ~~9~~5 μrad (meas.)
  (Z. Cai, E. Gluskin et al., APS/XFD)

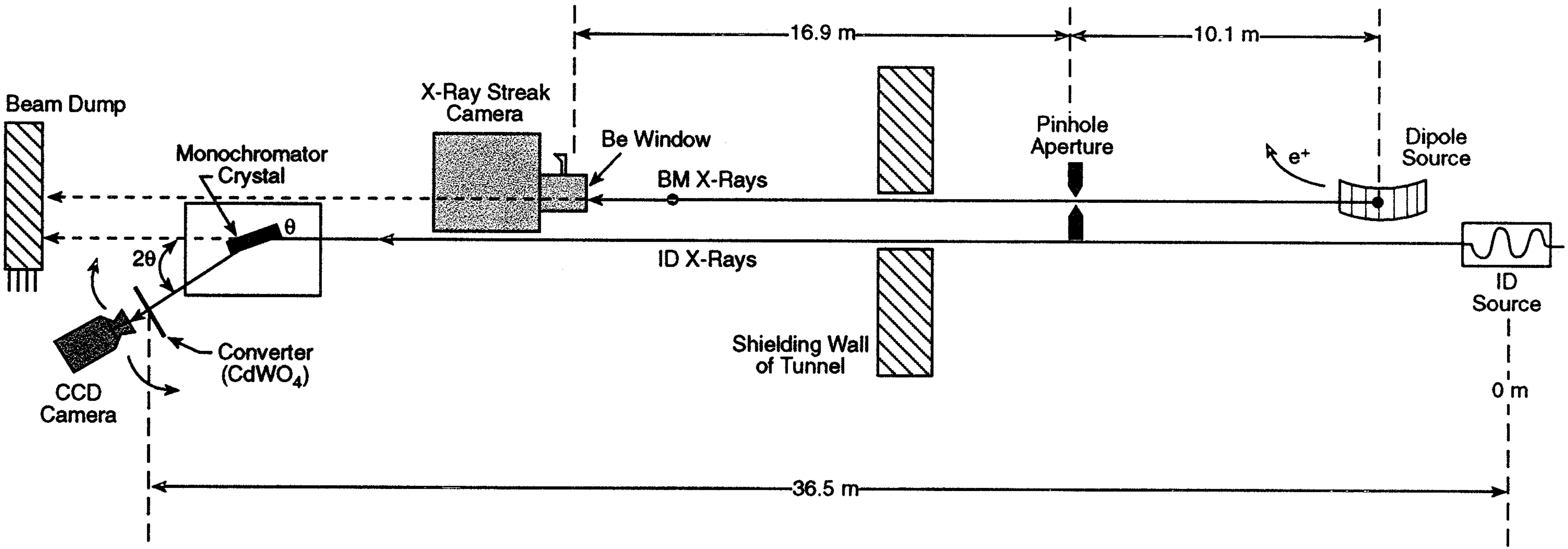
Bunch Length

- Linac beam at 50 fs using coherent transition radiation
  (Lihn, Stanford)
- Storage ring beam at few ps (ALS, ESRF)
- Sub-ps streak cameras on market

Circa 1996
(AHL)

Schematic of the S35 Sources and Beamlines

Top View



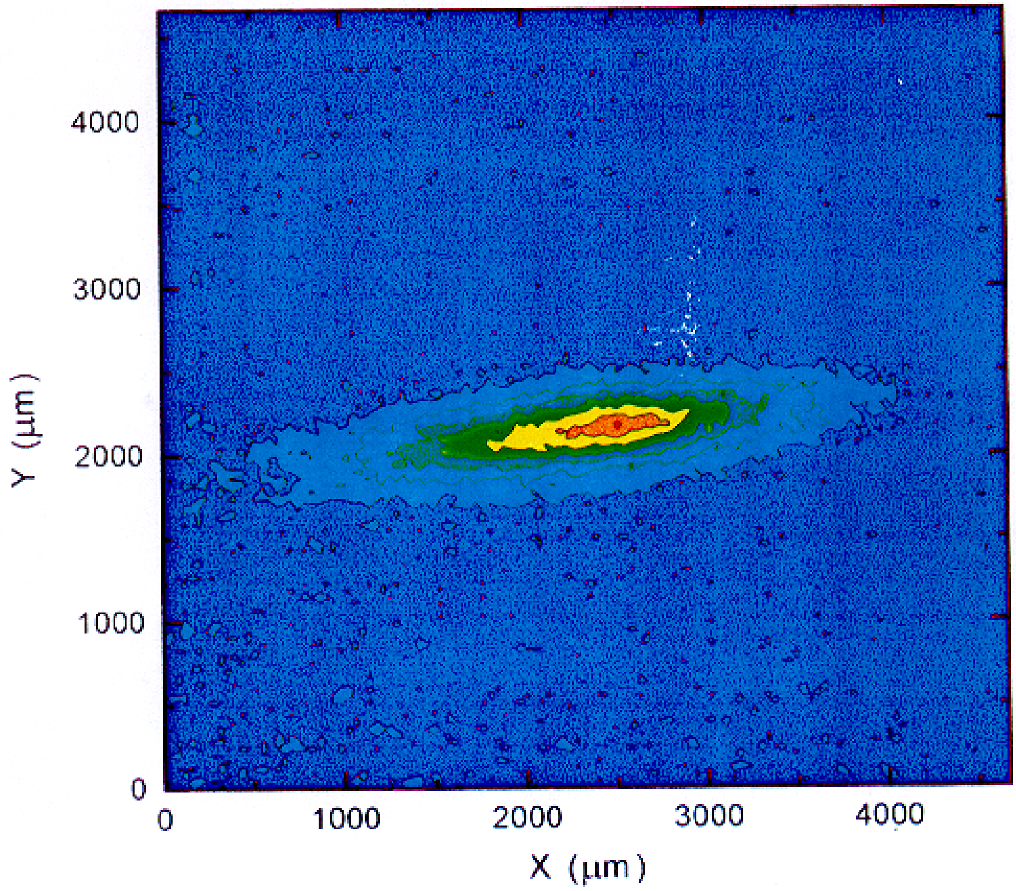
Operation Plan for the Diagnostic Undulator Beamline

Positron Beam Vertical Coupling	10%	1%	0.1%
β_y (m)	10.1	10.1	10.1
Undulator Gap (mm)	15.5	12.3	12.3
X-ray energy (keV) ω_n	25.3	73.1	73.1
Harmonic number n	1	3	3
Ideal Undulator Photon Beam			
size (µm)	1.4	2.4	2.4
divergence (µrad)	2.9	1.7	1.7
Trajectory Random Walk			
size (µm)	0.9	0.9	0.9
divergence (µrad)	0.6	0.6	0.6
Optical Instrument Resolution	(pin-hole)		
size (µm)	30	9	1.5
divergence (µrad)	< 1.0	< 0.8	< 0.5
Total Instrument Resolution			
size (µm)	30	10	3
divergence (µrad)	< 3.1	< 2	< 1.9
Positron Beam			
vertical size (µm)	87	29	8.7
divergence (µrad)	8.6	2.8	0.9
Resolution / Beam Size			
vertical size	0.35	0.35	0.35
vertical divergence	0.36	0.71	2.1

ADVANCED PHOTON SOURCE

SR BEAM DIVERGENCE MEASUREMENT (35-ID)

(After minimizing vertical divergence @ 25 mA, 6/16/97 2:30 PM)



SUMMARY OF MEASUREMENT*

	Horizontal Beam Size	Vertical Beam Size
Total measured value	870 μm	157 μm
Undulator cone	95 μm (2.6 μrad)	95 μm (2.6 μrad)
e^+-beam	314 μm	34 μm
e^+-beam divergence	806 μm (**22 μrad**)	122 μm (**3.3 μrad**)

* The transverse beam size was measured at 36.5 m from the e^+-beam waist. The beta functions were assumed to be at the design value: β_x = 14.2 m, β_y = 10.1 m.

TOTAL EMITTANCE = 7.1 ± 0.5 nm-rad

VERTICAL COUPLING = 1.6%

Some Scaling Factors for the Diagnostics Undulator

APS Diagnostics Undulator Results:

- 7-GeV stored positron beam with 3.3 μrad divergence measured using about 2.4 mC integrated charge in the 30-ms CCD camera image

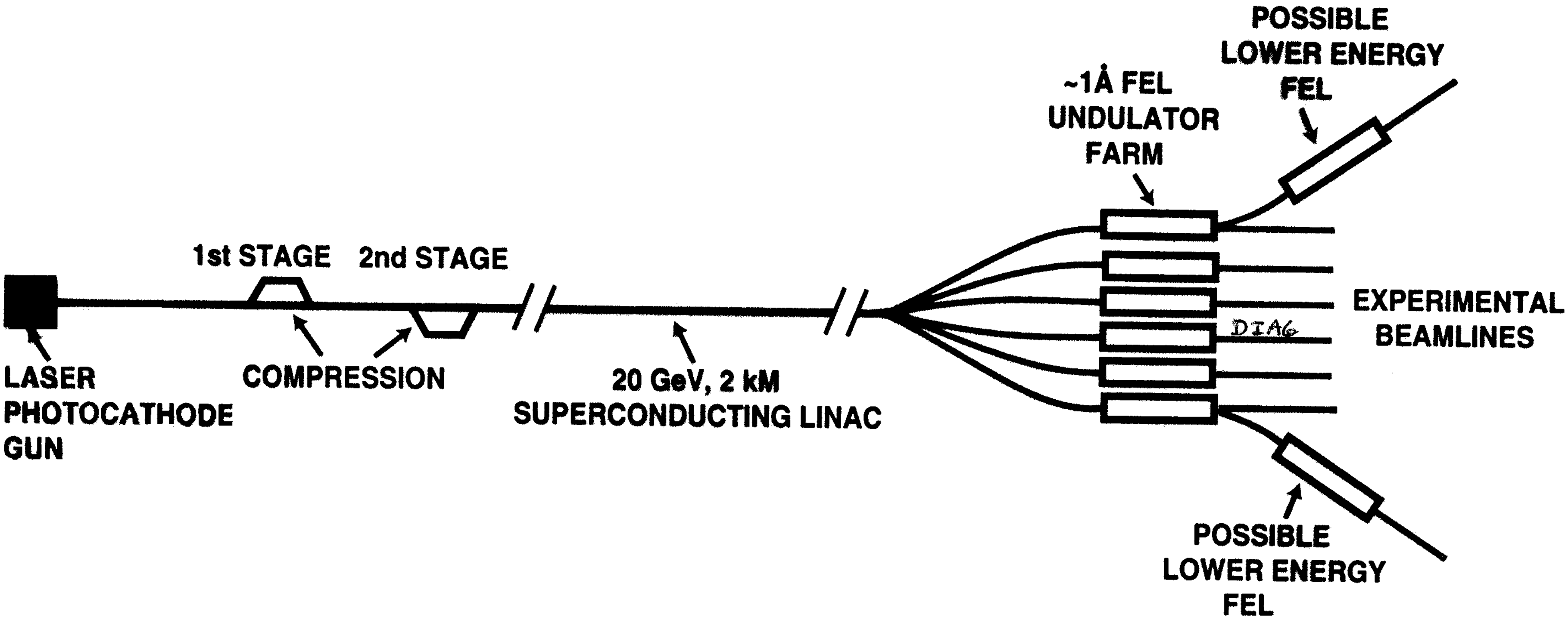
- Close ID gap from 34 mm with 0.2W in the fundamental to 14mm (6mm) to gain a factor of 10^3 (10^4) increase in power from the source

- Undulator on-axis, cone angle ~ 1.2 μrad for E = 15 GeV, fundamental at 110 keV

- Use cryo-cooled or image intensified CCDs to gain 10^2 in sensitivity in detector

- Have low horizontal emittance as well for photon density enhancement at detector

Combined factors support measurements of about 1 μrad for Q ≅ 1nC beam at 15 GeV



POSSIBLE FOURTH-GENERATION SYNCHROTRON FACILITY USING SELF-AMPLIFIED SPONTANEOUS EMISSION (SASE) FELS

Some Issues for X-ray Streak Tubes

- Photocathode quantum efficiency for x rays (lower than for visible light)
- Photocathode robustness in the x-ray tube
- Geometry of the tube relative to high fields
- Vacuum integrity of the tube
- "Windowless" operation of the tube
- Separate vacuum pump-out system
- Angle in photoelectron trajectory to put the phosphor off-axis to transmitted x-rays

Some Chronology

- Motivations often lasers, time-resolved spectrometer, plasma, diagnostics, etc. because of the number of users

- Our motivation is to study sub-50-μm beam spot sizes with ps-domain resolution. X-ray field provides better spatial resolution than visible

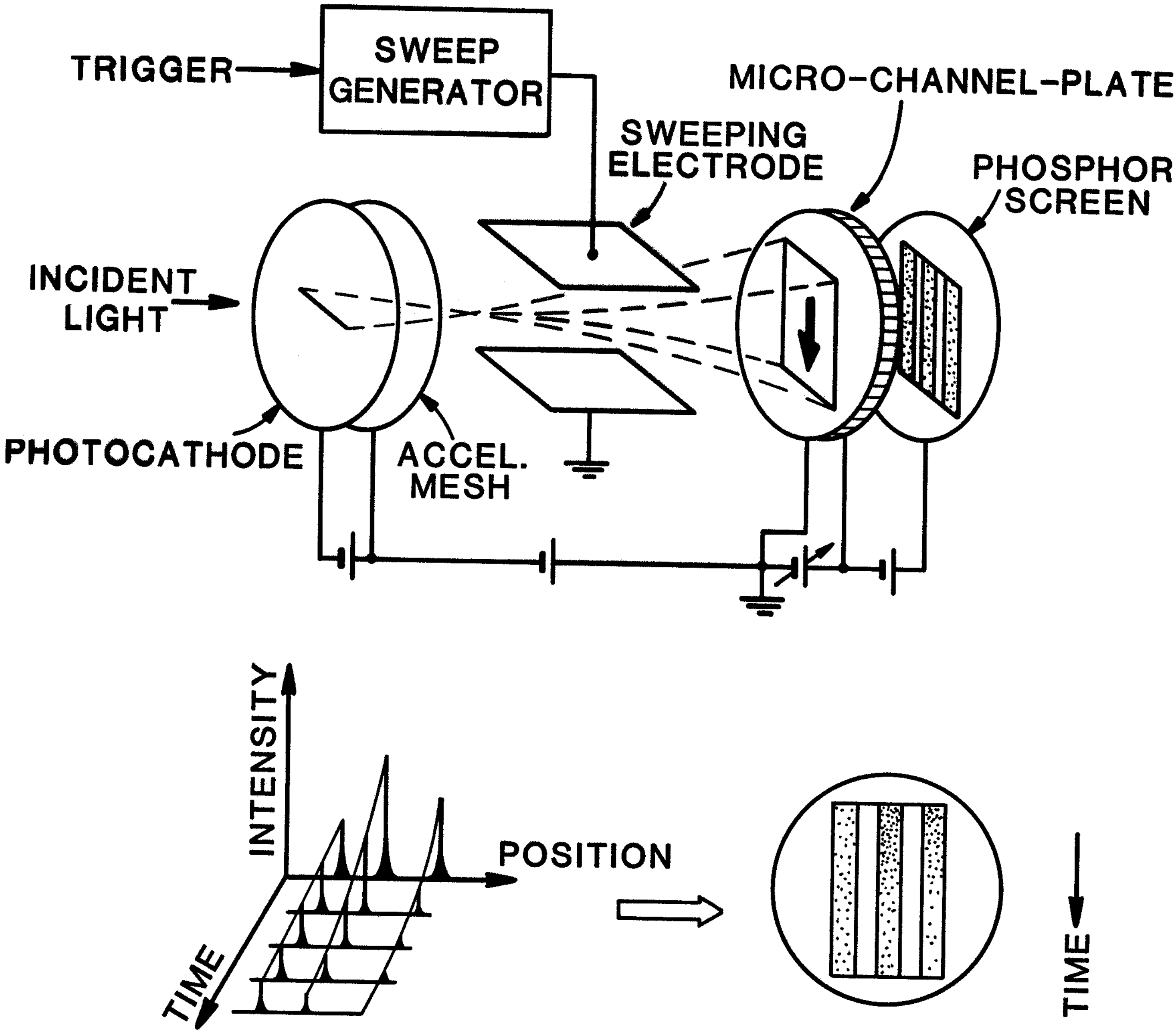
  - Development of single-sweep visible streak cameras using electro-optics ~ 1960s

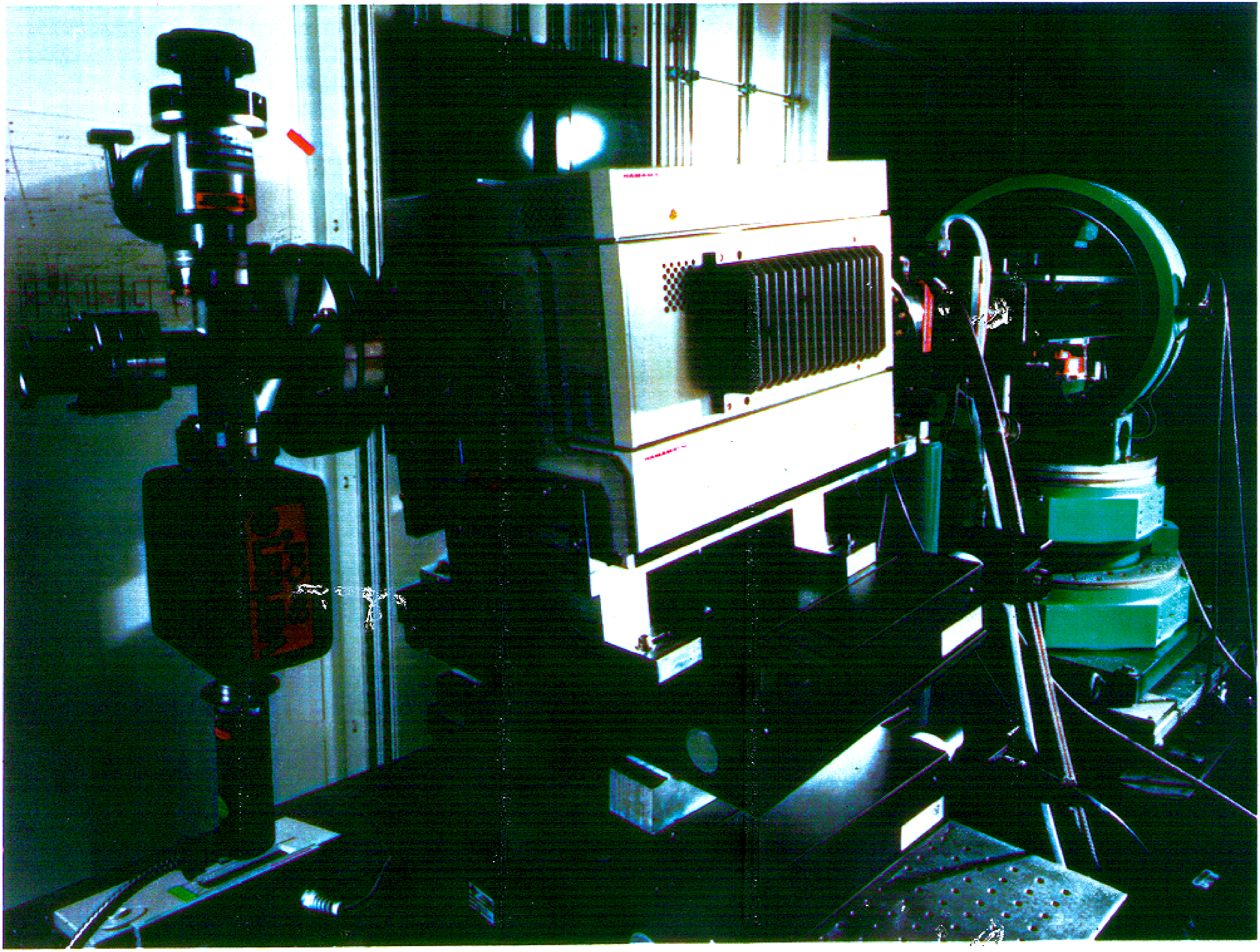
  - Extension of single-sweep streak camera to the soft x-ray regime ~ 1970s

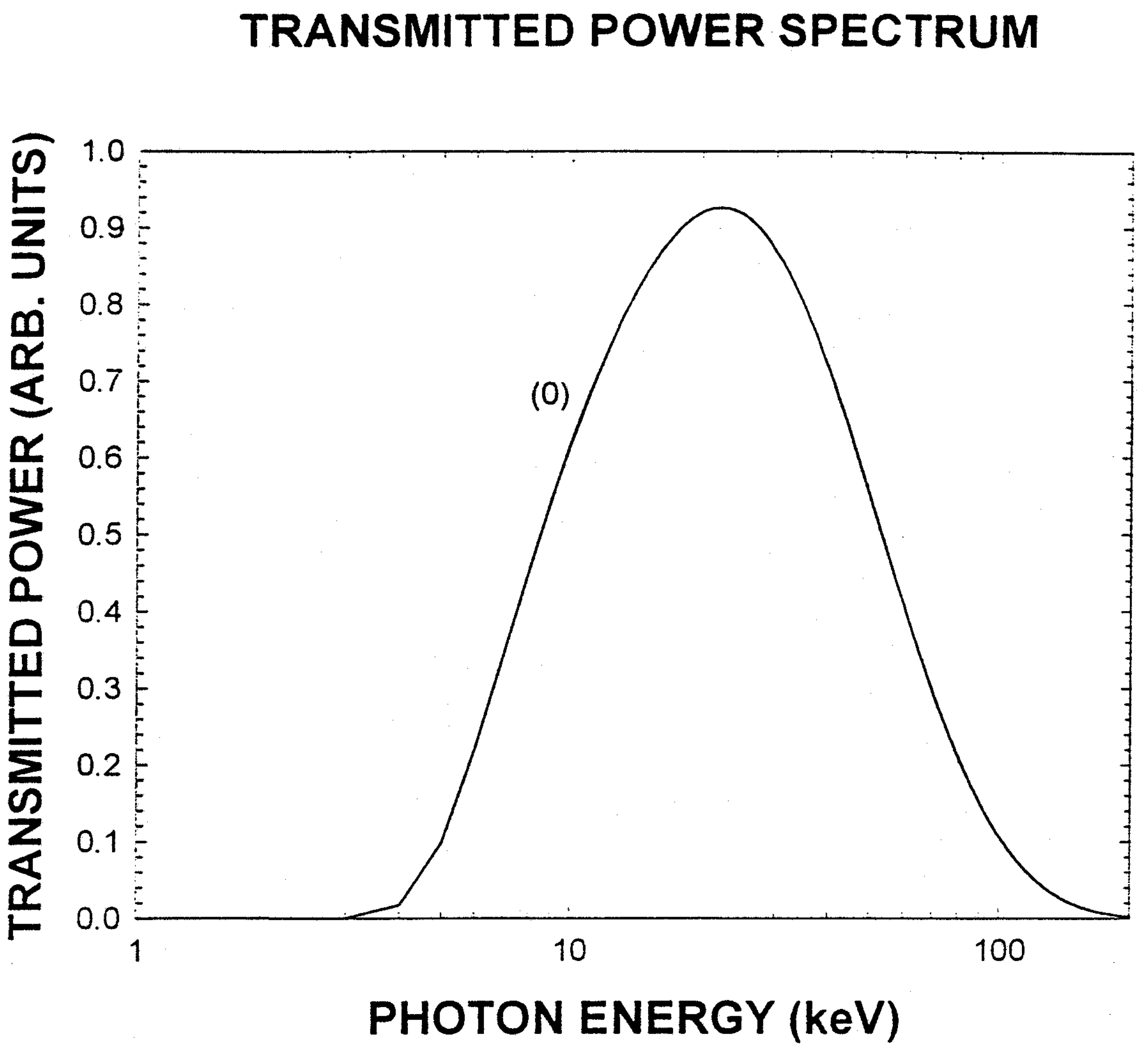
  - Developments of synchroscan and dual-sweep visible streak camera ~ 1980s

  - Extension of synchroscan and dual-sweep features to the x-ray streak camera ~ 1990s

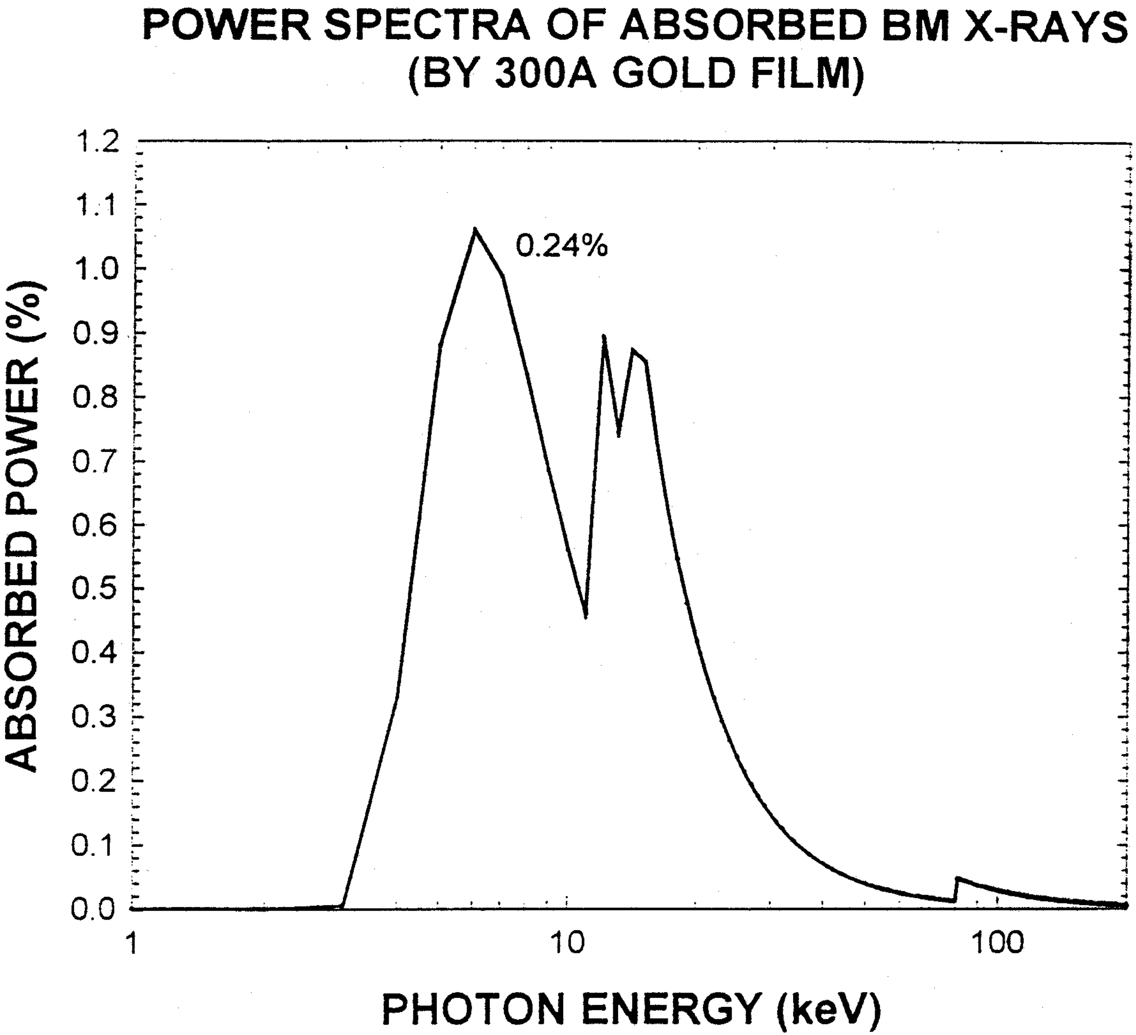
PRINCIPLE OF OPERATION OF A STREAK CAMERA



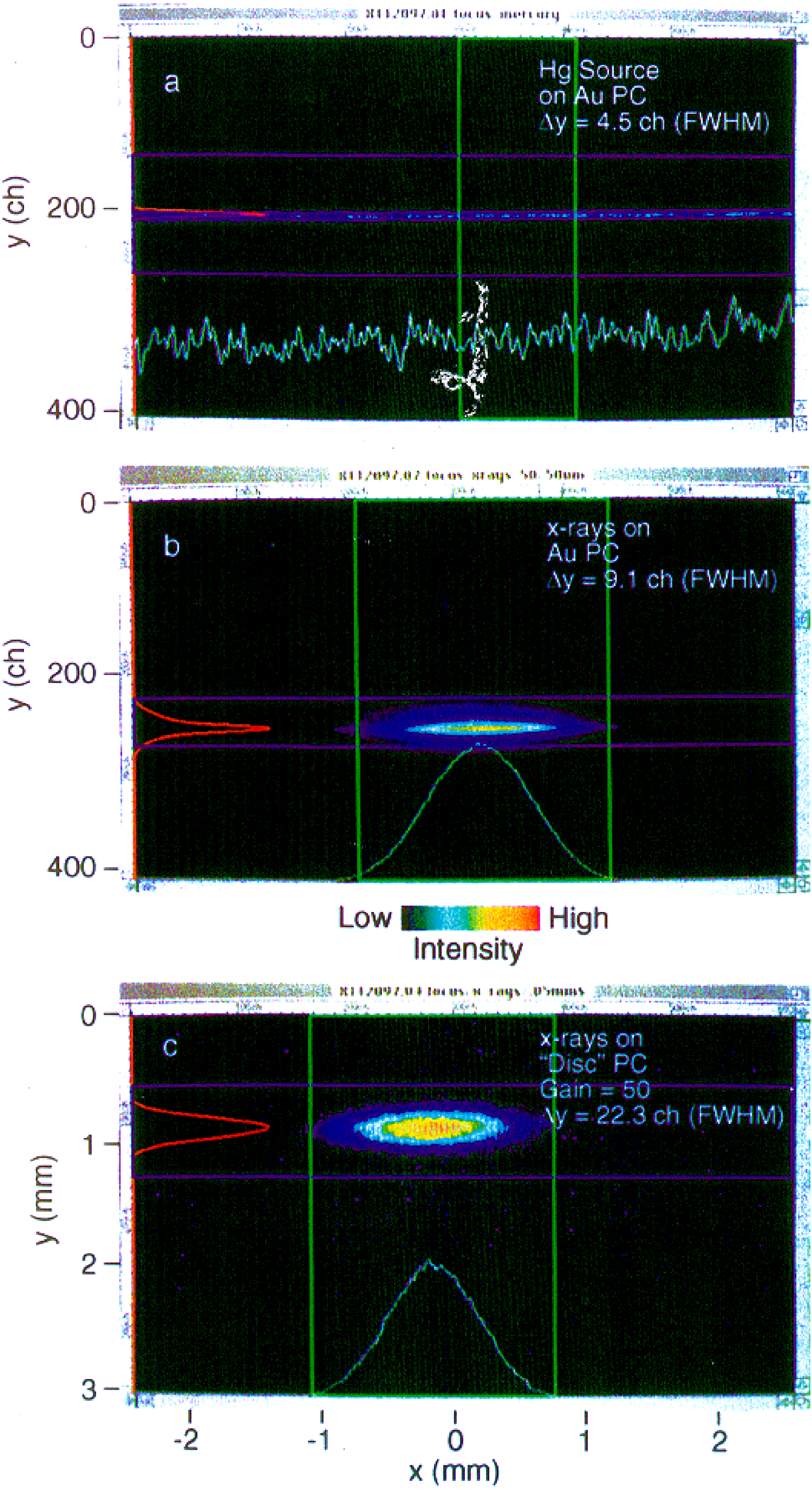




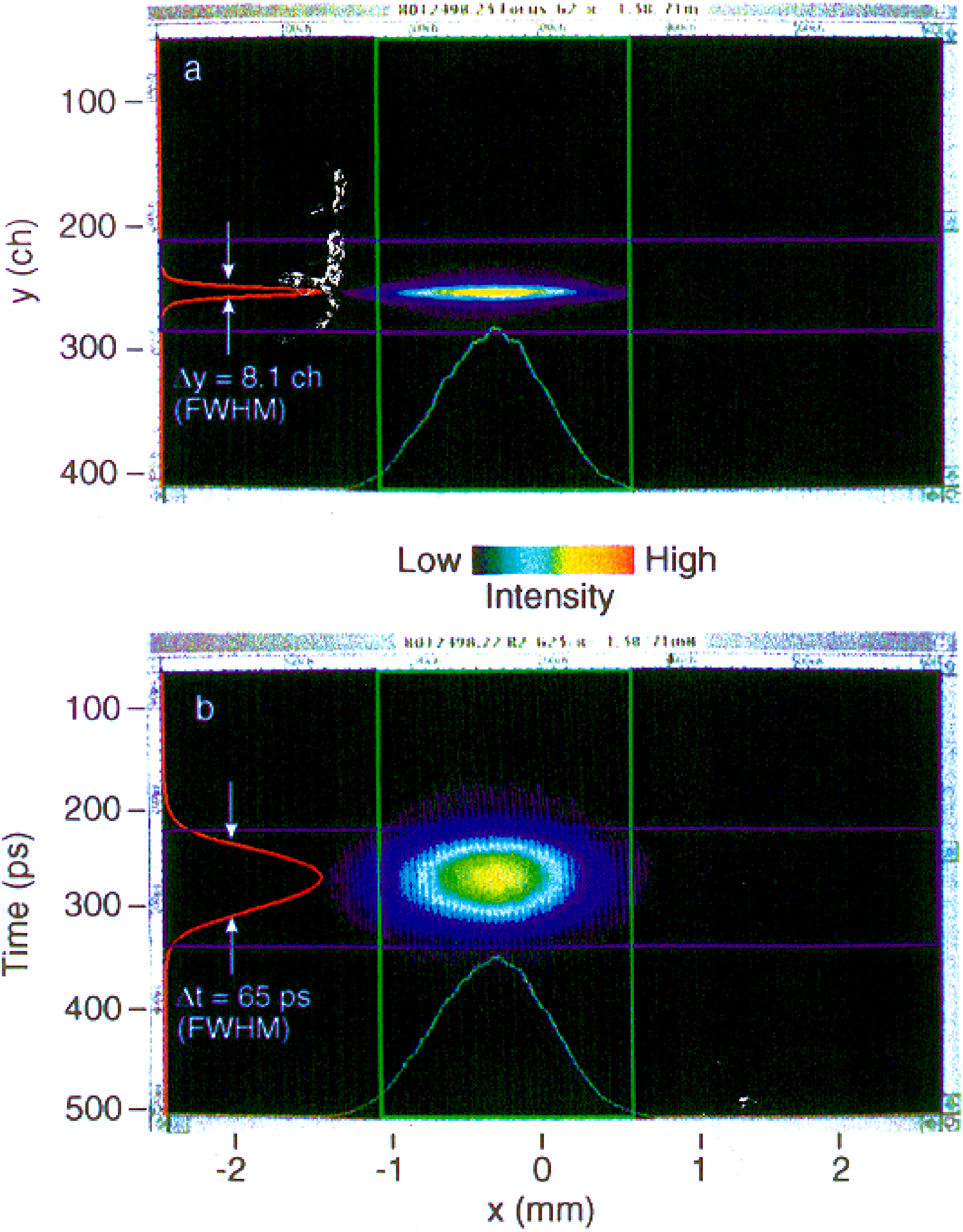
TRANSMITTED POWER SPECTRUM
TRANSMITTED POWER (ARB. UNITS)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
(0)
1
10
100
PHOTON ENERGY (keV)


POWER SPECTRA OF ABSORBED BM X-RAYS
(BY 300A GOLD FILM)
0.24%
ABSORBED POWER (%)
PHOTON ENERGY (keV)
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
1
10
100

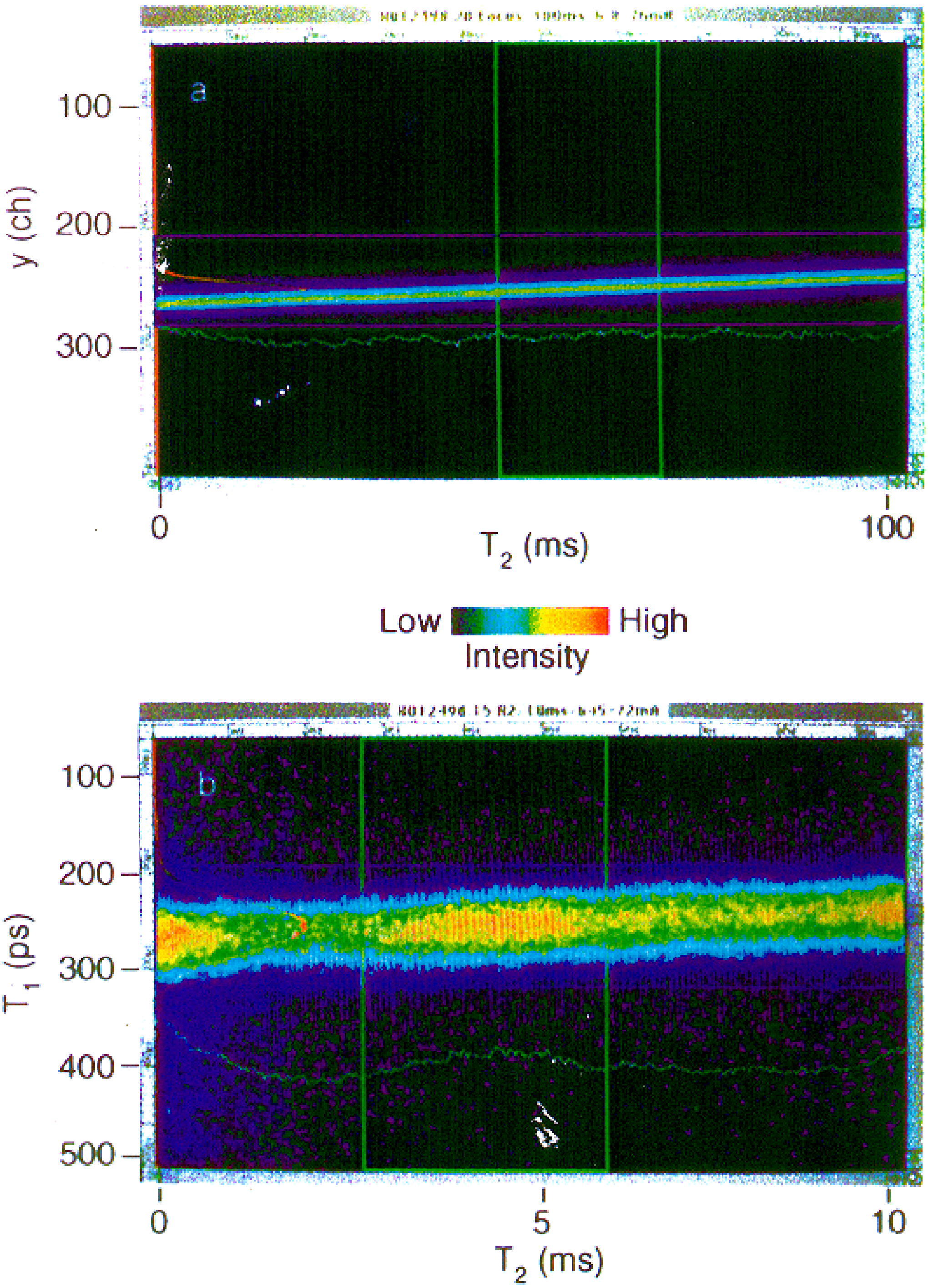
X-Ray Streak Camera Data (Focus Mode)



X-Ray Streak Camera Data
(Focus and Synchroscan Modes)



X-Ray Streak Camera Data
(Single and Double Sweep)



Scaling Factors for the X-ray Streak Camera

X-ray streak camera results on 7-GeV stored beam:

A. Longitudinal

- 28-ps bunch length measured with 4 ps resolution
- Demonstrated resolution of 0.6 ps (σ) for UV light
- Potential resolution of 1.0 to 1.5 ps (σ) for hard x-rays using fastest sweep range on this tube
- Other hard x-ray tubes pushing into sub-ps resolution for laser-triggered techniques: ALS, Univ. of Mich.

Scaling Factors for the X-ray Streak Camera

X-ray streak camera results on 7-GeV stored beam: (Continued)

B. Transverse

- Estimated effective resolution about 15-20 μm (σ) with 4-jaw aperture at 50×50 μm^2 size

- Could see 1-mA (~3nC) with averaging over many turns from bending magnet (BM)

- ID source strength greater than dipole

- CsI photocathodes are about 50 times more sensitive than Au photocathode, but not as robust. (May be area of development)

- X-ray microscope technique such as at ESRF beam-line could work

Summary

Initial characterizations of a multi-GeV particle beam have been done with a unique x-ray streak camera. Both small transverse sizes (< 50 μm) and short bunches (30 ps with 4-ps resolution) have been measured. Even better resolutions are projected.

Potential Applications:

- Studies of small beams in third-generation storage rings (low vertical coupling)
- Studies of beams in R&D for fourth-generation light sources
- ps-domain diagnostics for time-resolved user experiments in the 10-eV to 10-20-keV regime

Table 1: Comparison of Beam Spot Sizes Using the YAG and OTR Converter Screens (June '98 Data)

Converter	ND Filter	I_B (mA)	X-Size (FWHM)(μm)
OTR YAG	0.0 2.0	30 30	90 ± 7 77 ± 7
OTR YAG	0.5 2.5	60 60	68 70
OTR YAG	0.8 2.8	107 107	84 114
OTR YAG	0.8 2.8	150 150	95 125
OTR YAG	1.0 2.8	220 220	103 205

The aspect ratio $^H/_V$ was ~ $^1/_{10}$. ND = 0.3 is a factor of 2 in attenuation.

MEASURED BEAM SIZE VS. BEAM CURRENT

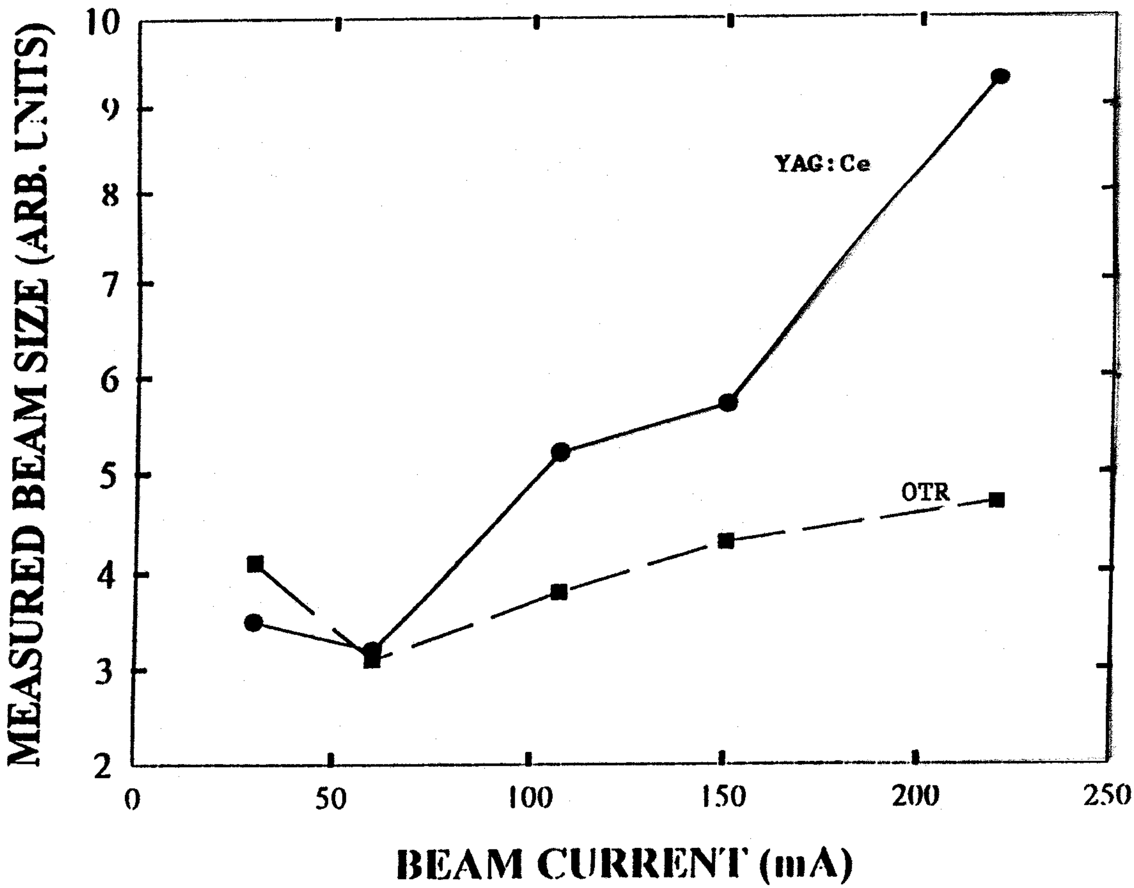
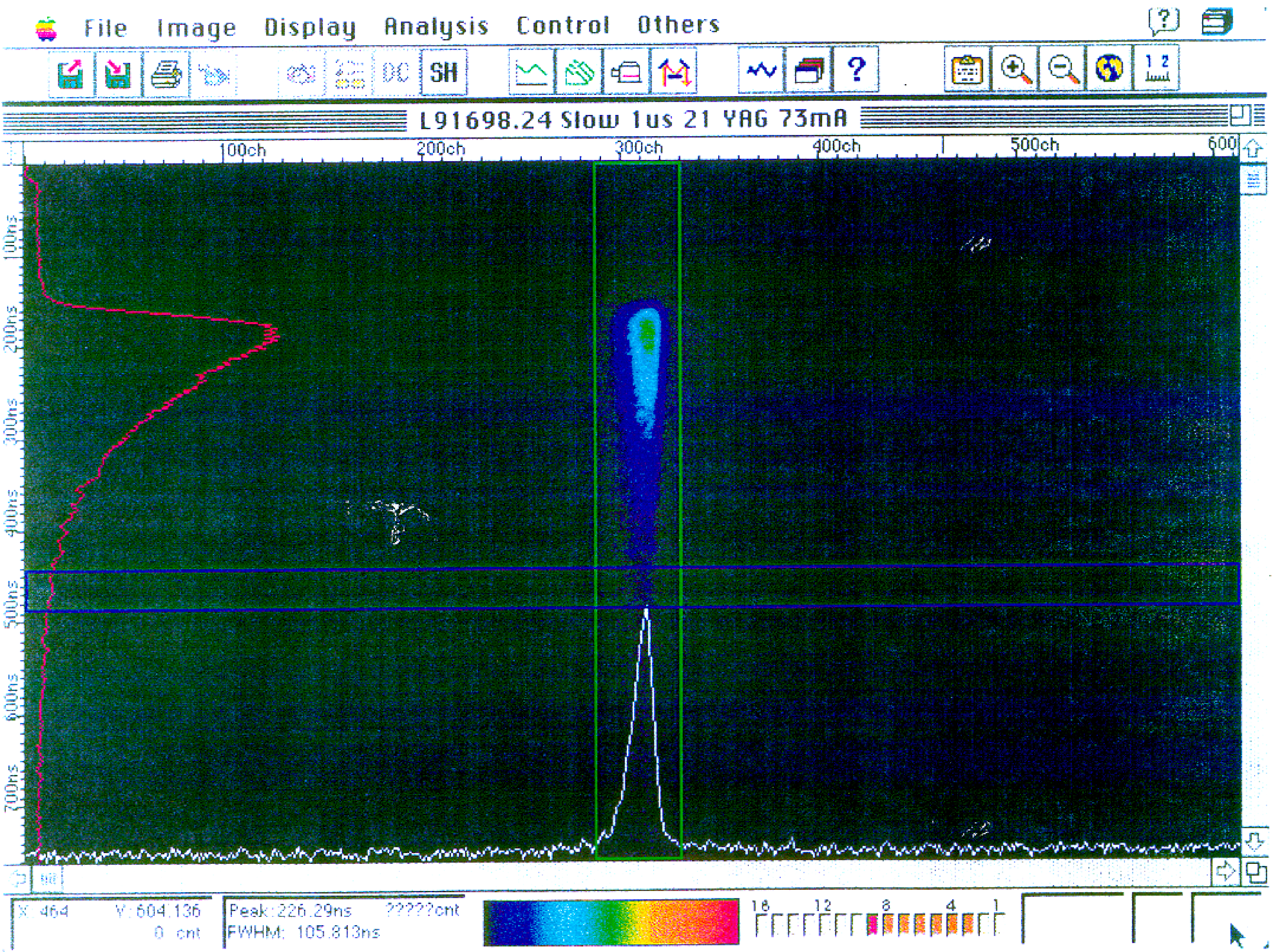
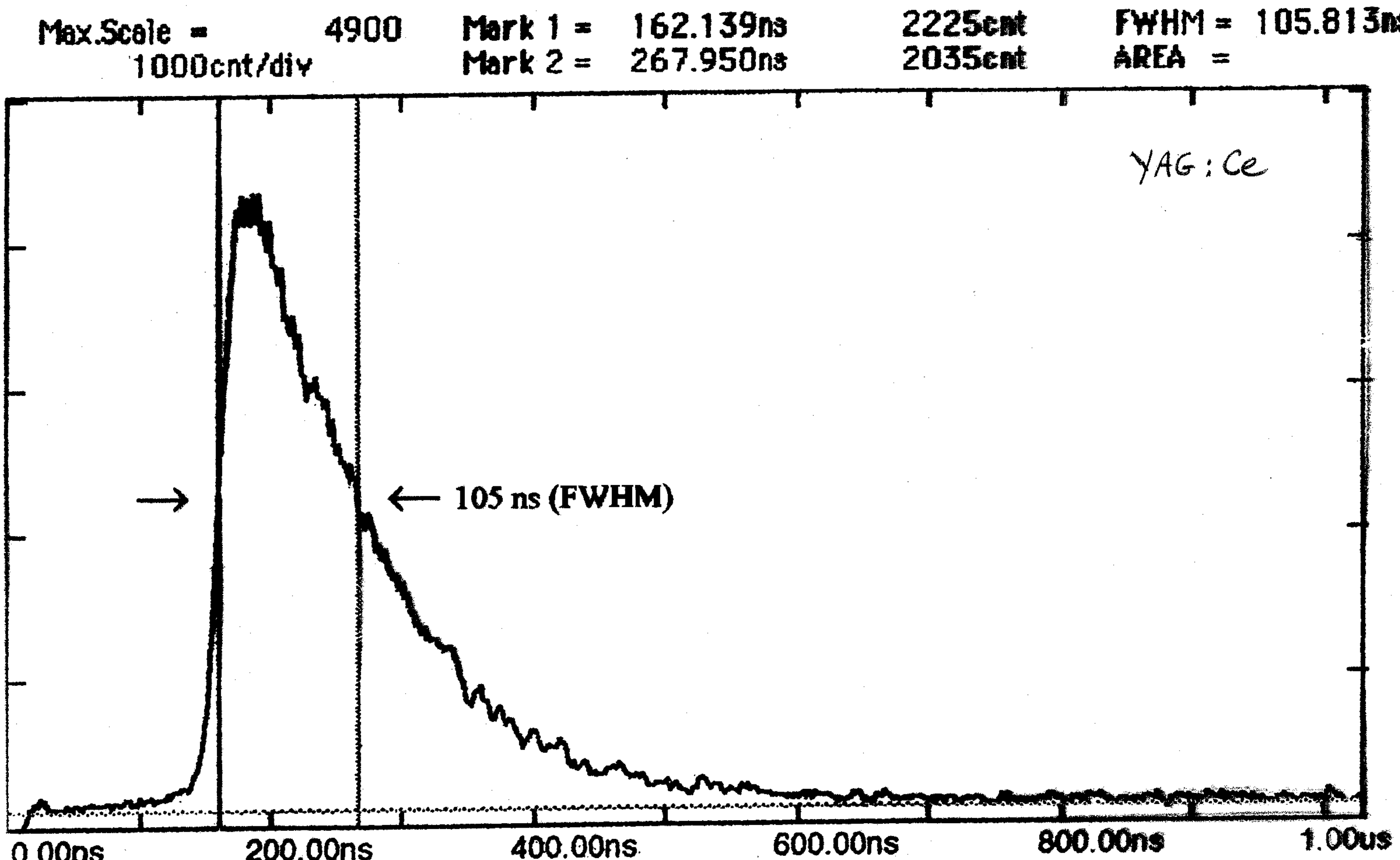


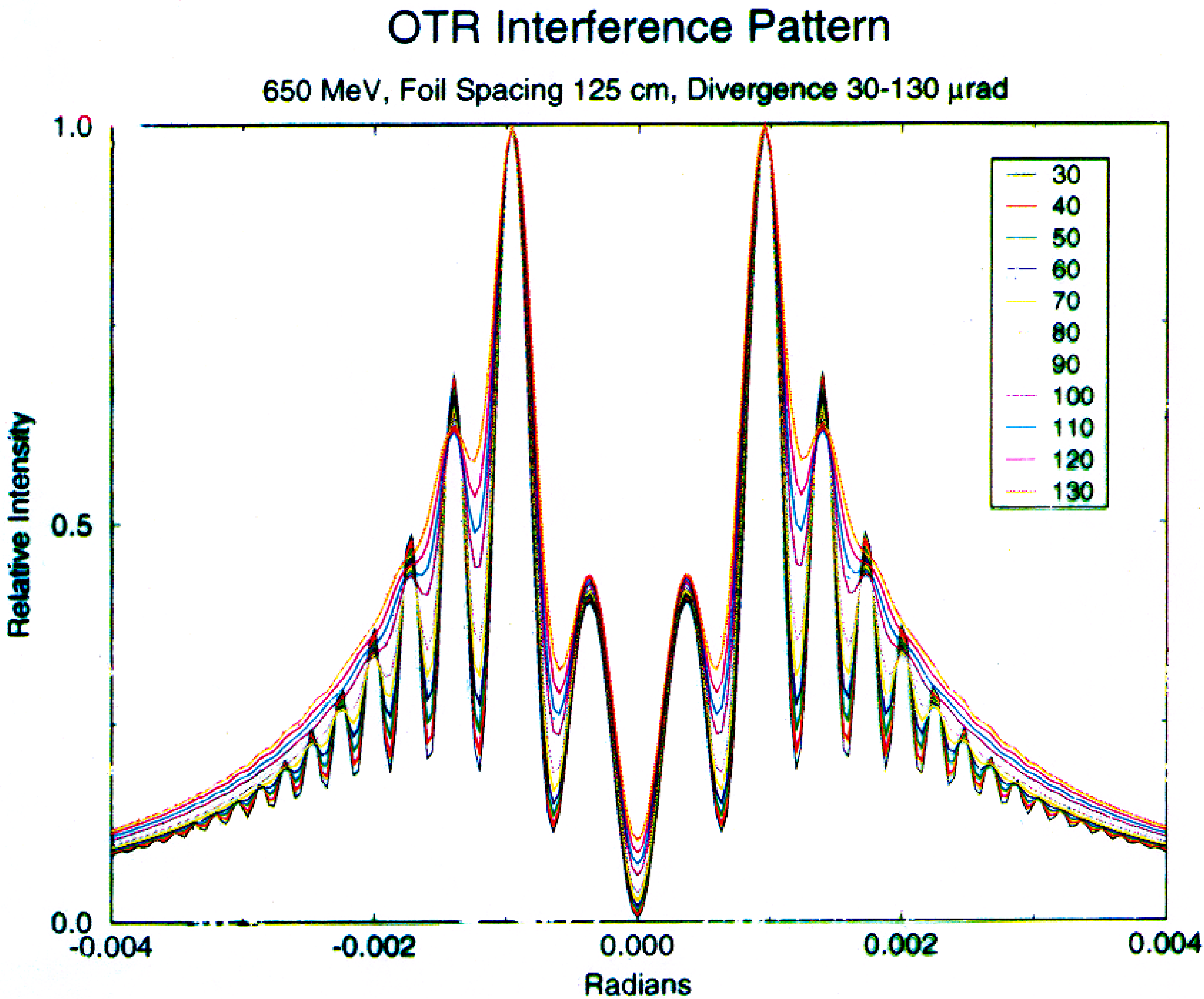
Fig. 3
A. H. Lumpkin



File Image Display Analysis Control Others
SH
L91698.24 Slow 1us 21 YAG 73mA
100ch
200ch
300ch
400ch
500ch
600
100ns
200ns
300ns
400ns
500ns
600ns
700ns
X: 464
Y: 604.136
0 cnt
Peak: 226.29ns
?????cnt
FWHM: 105.813ns
16
12
8
4
1



Max.Scale = 4900
1000cnt/div
Mark 1 = 162.139ns 2225cnt
Mark 2 = 267.950ns 2035cnt
FWHM = 105.813ns
AREA =
YAG : Ce
105 ns (FWHM)
0.00ps
200.00ns
400.00ns
600.00ns
800.00ns
1.00us



OTR Interference Pattern
650 MeV, Foil Spacing 125 cm, Divergence 30-130 µrad
1.0
0.5
0.0
Relative Intensity
-0.004
-0.002
0.000
0.002
0.004
Radians
30
40
50
60
70
80
90
100
110
120
130

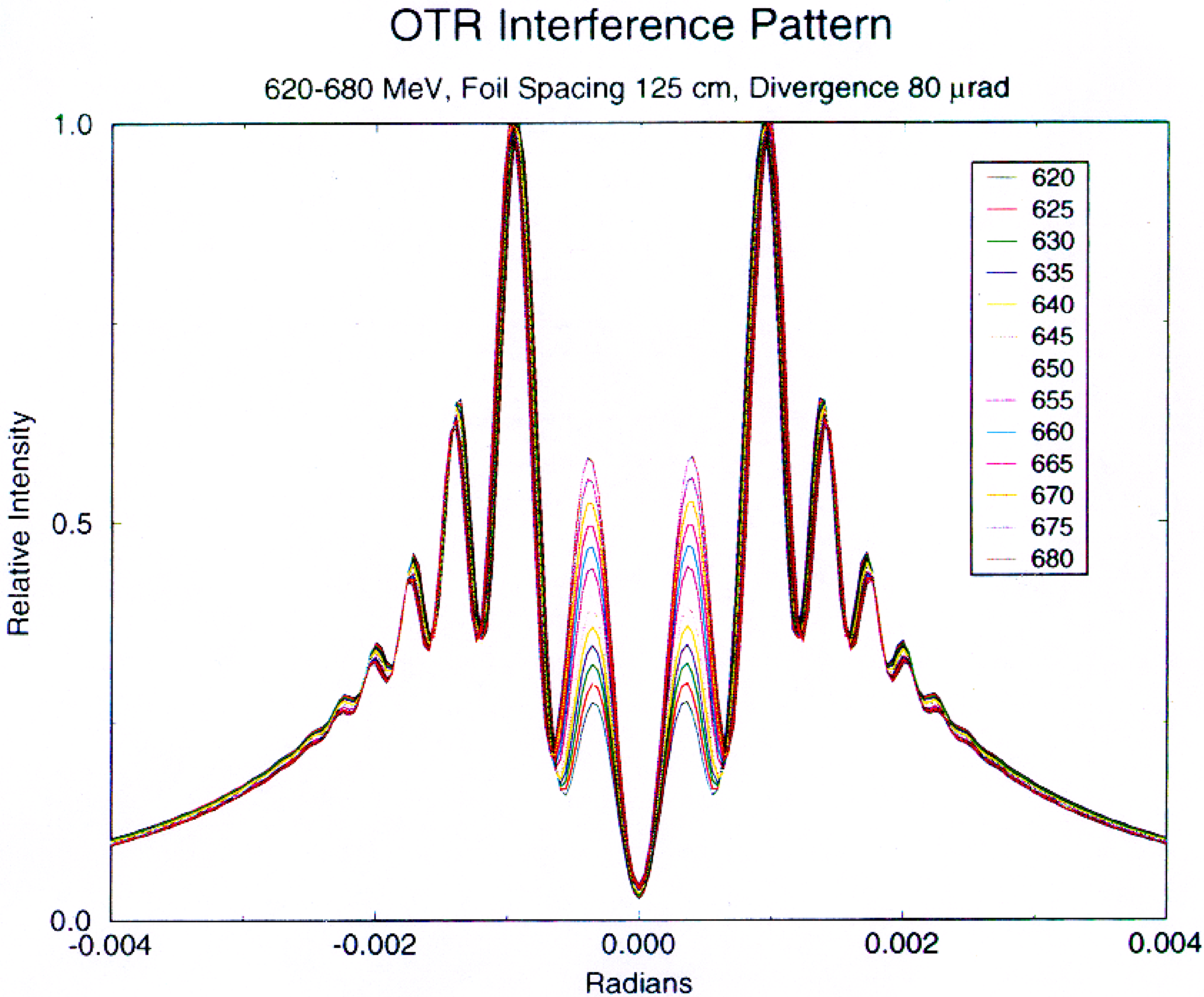
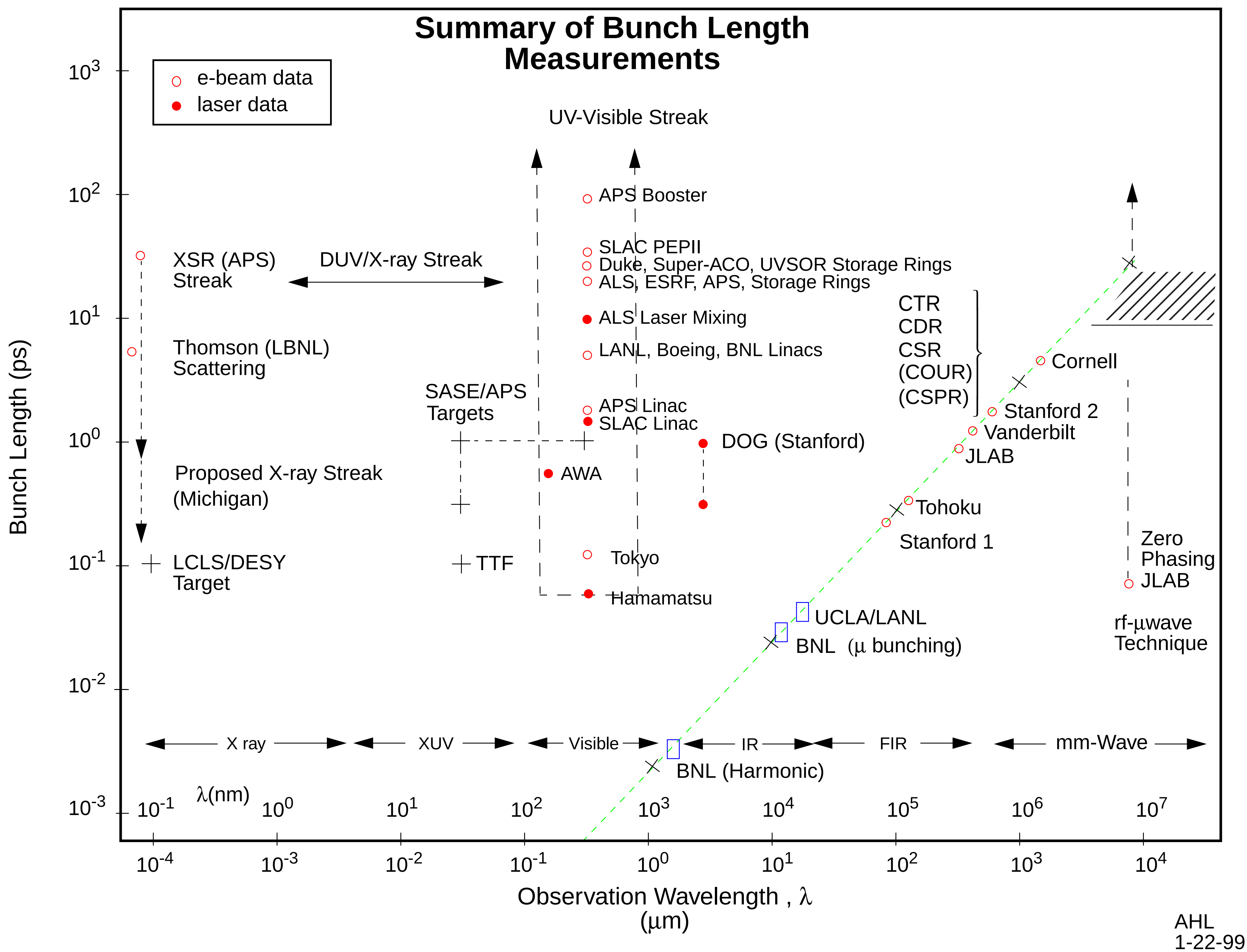

OTR Interference Pattern
620-680 MeV, Foil Spacing 125 cm, Divergence 80 μrad
Relative Intensity
Radians
1.0
0.5
0.0
-0.004
-0.002
0.000
0.002
0.004
620
625
630
635
640
645
650
655
660
665
670
675
680

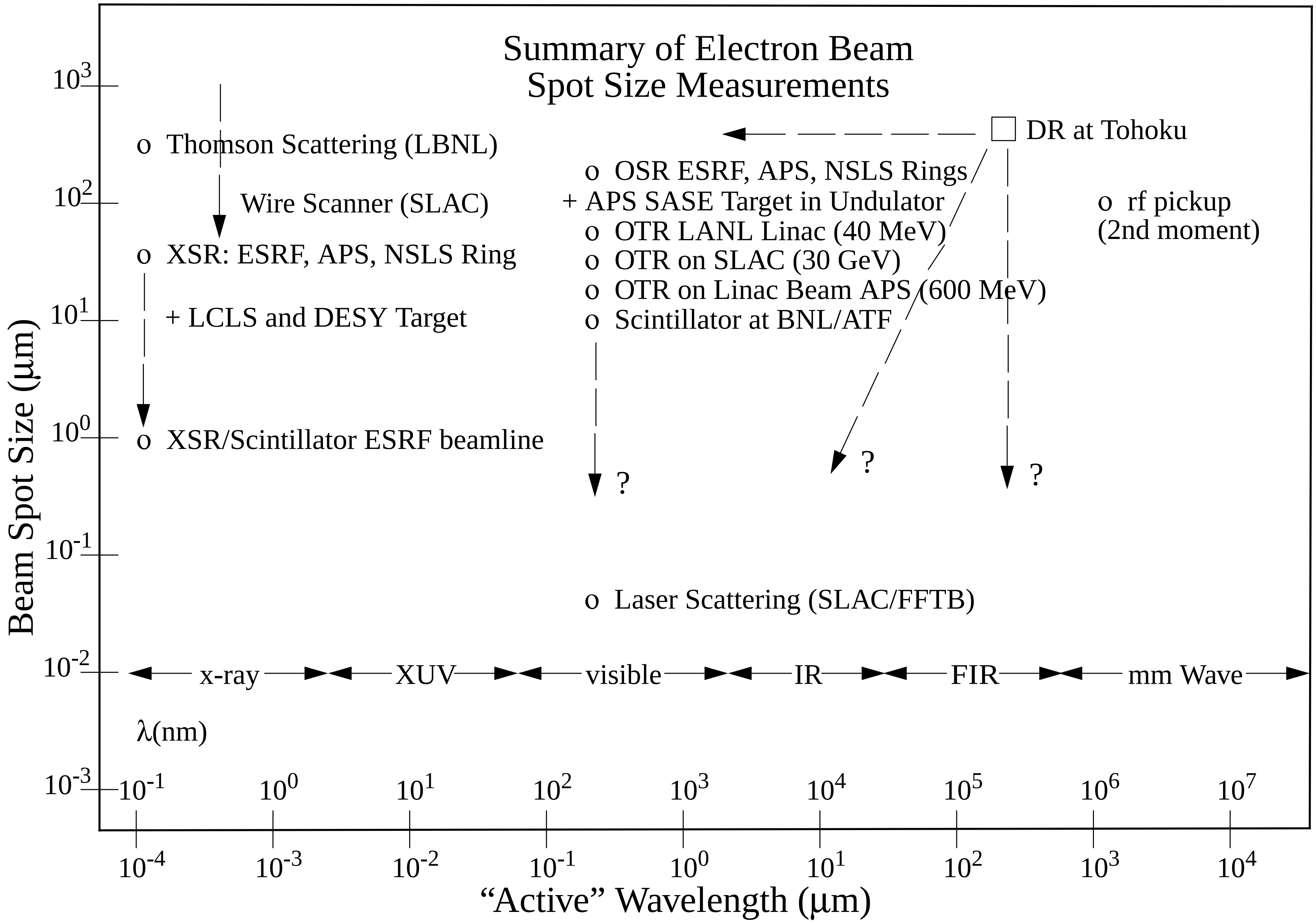
Table 1: Comparison of Diffraction Radiation (DR) Parameters for a 5 mm Radius Aperture and Various Representative Accelerators†

E (GeV)	γ	$\lambda^{(l)}$ (μm)	Linac
0.05	10^2	250	BNL/ATF
0.5	10^3	25	ANL/APS, Duke Upgrade, DESY
5.0	10^4	2.5	Jefferson Lab (CEBAF)
50	10^5	0.25	SLAC/LCLS

(1) Threshold DR wavelength for incoherent production.

†Adapted from Table 1 of Rule, Fiorito, Kimura. Presented at BIW '96, Ref. 7


Summary of Bunch Length Measurements
e-beam data
laser data
UV-Visible Streak
APS Booster
SLAC PEPII
Duke, Super-ACO, UVSOR Storage Rings
ALS, ESRF, APS, Storage Rings
ALS Laser Mixing
LANL, Boeing, BNL Linacs
APS Linac
SLAC Linac
DOG (Stanford)
AWA
Tokyo
Hamamatsu
XSR (APS) Streak
DUV/X-ray Streak
Thomson (LBNL) Scattering
SASE/APS Targets
Proposed X-ray Streak (Michigan)
LCLS/DESY Target
TTF
CTR
CDR
CSR
(COUR)
(CSPR)
Cornell
Stanford 2
Vanderbilt
JLAB
Tohoku
Stanford 1
Zero Phasing JLAB
rf-µwave Technique
UCLA/LANL
BNL (µ bunching)
BNL (Harmonic)
X ray
XUV
Visible
IR
FIR
mm-Wave
λ(nm)
Bunch Length (ps)
Observation Wavelength , λ (µm)
AHL
1-22-99



Summary of Electron Beam
Spot Size Measurements
Beam Spot Size (μm)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
o Thomson Scattering (LBNL)
Wire Scanner (SLAC)
o XSR: ESRF, APS, NSLS Ring
+ LCLS and DESY Target
o XSR/Scintillator ESRF beamline
DR at Tohoku
o OSR ESRF, APS, NSLS Rings
+ APS SASE Target in Undulator
o OTR LANL Linac (40 MeV)
o OTR on SLAC (30 GeV)
o OTR on Linac Beam APS (600 MeV)
o Scintillator at BNL/ATF
o rf pickup
(2nd moment)
?
?
?
o Laser Scattering (SLAC/FFTB)
x-ray
XUV
visible
IR
FIR
mm Wave
λ(nm)
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
"Active" Wavelength (μm)

Summary

Simplistically speaking we are on the path, but some development areas can be identified:

A. Bunch Length

- Challenge for visible or x-ray streak cameras for <100fs resolution for available signal in an e-beam micropulse. Measuring a photon beam at 1 Å is a development area that is already being addressed.

- Coherent radiation techniques need to move towards single-shot capability and the challenge to provide profile information realistically.

B. Transverse Profiles

- Provide sub-10 μm spatial resolution on a single shot (probably there)

- Provide a non-intercepting technique or sufficiently non-interfering-one. This is a development area.