Potential Applications of a Dual-Sweep Streak Camera System for Characterizing Particle and Photon Beams of VUV, XUV, and X-Ray FELs*

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Abstract

Initial tests of a dual-sweep streak system whose vacuum interface and Au photocathode would allow time-resolved measurements from the visible to the x-ray photon regime are presented. Although selected to support the diagnostics of the Advanced Photon Source (APS), this type of system could also address the micropulse phenomena of the next generation of FELs whose lasing wavelengths are projected in the VUV, XUV, and even the x-ray regime. First results at 248 nm on the photoelectric drive laser at the Argonne Wakefield Accelerator (AWA) are presented, and the scaling on time resolution into the x-ray regime is addressed. The system has capabilities that could support benchmark experiments in the path to UV/x-ray FELs.

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1. Introduction

The projected adaptation to short wavelength FELs of successful time-resolved imaging techniques based on streak principles [1] appears to be at hand. The characterization of particle and photon beams of the recent generation of L-band linac-driven or storage ring FELs in the infrared, visible, and ultraviolet wavelength regimes is well-established [1-4]. Although the same UV-visible streak camera system can still be used with the UV-visible portion of the Cherenkov, optical transition radiation (OTR), or optical synchrotron radiation (OSR) techniques for particle beam characterization, the transition to the VUV and shorter lasing wavelengths requires a change to a "windowless" streak tube. Tests and initial data have recently been obtained with a Hamamatsu C5680 dual-sweep streak system which includes a demountable photocathode (thin Au) assembly and a flange arrangement that allows "windowless" operation with the transport vacuum system. This type of system can be employed at wavelengths shorter than 1000 Å (100 nm) and even down to 1 Å and beyond. Such a capability directly addresses diagnostics issues for the UV/x-ray free electron lasers proposed through high-gain single-pass amplifiers using the self-amplified-spontaneous emission (SASE) scheme or the high-gain harmonic generation (HGHG) scheme [5,6]. The dual sweep feature would potentially enable the tracking of the individual micropulses in the experiments and various dynamic issues.

Characterization tests on such a system at 248 nm have been performed at Argonne National Laboratory using the Argonne Wakefield Accelerator (AWA) drive laser source [7-9]. The synchroscan and dual-sweep plug-ins have been tested with a UV-visible tube on the Advanced Photon Source (APS) positron accumulator ring (PAR), injector synchrotron (IS), and 7-GeV storage ring (SR) whose single-turn circulation times are 102 ns, 1.2 μs, and 3.68 μs, respectively. The system's limiting resolution of $\sigma \approx 1$ to 1.2 ps at 248 nm would increase with higher incoming photon energies to the photocathode. This effect is fundamentally related to the increased spread in energies of the photoelectrons released from the photocathode with the incident higher energy photons. Possible uses of the synchrotron radiation sources at the APS and emerging short wavelength FELs to demonstrate the techniques will be presented.

2. Experimental Background

The wide range of pulse spacing and bunch lengths expected in the APS facility's S-band linac, injector rings, and main storage ring resulted in the selection of a dual-sweep streak system (Hamamatsu C5680) for diagnostic purposes. The additional need to address directly the x-ray beams from the SR bending magnet or undulator sources led to the need for the additional capability in the x-ray regime. Early tests with the streak system were reported previously [9]. Since a photoelectric drive laser was used in the evaluation, and the tests of turn-by-turn phenomena on the APS rings have analogs in the resonators, bunch trains, or storage ring FELs, it is appropriate to identify the possible applications to FEL diagnostics.

The AWA project in its early phase includes an L-band, 20-MeV drive linac with a high-brightness photoelectric injector (PEI) capable of delivering 2-MeV, 100-nC, 20-ps (FWHM) bunches to the linac. The drive laser for this source is a pulsed laser system constructed jointly by Coherent-Lambda Physics which is described in [8]. A harmonic tripled mode-locked Nd:YAG laser is used to pump the dye laser. For these test purposes, the laser was adjusted to provide 1- to 2-ps (FWHM) pulses at 496 nm. Amplification of the subsequent short UV pulses at 248 nm was done in a single-stage KrF excimer laser whose observed output pulse length was 4 to 5 ps (FWHM).

In our initial setup, as shown in Fig. 1, we used the amplified 248-nm component from the drive laser system to evaluate the streak camera tubes' resolutions. An autocorrelator that was on-line, but sampling the green component, served as an independent bunch length monitor. The Hamamatsu C5680 with a single-shot fast sweep plug-in unit was aligned to the laser beam. A beam splitter was used to segment the beam into two parts. One portion provided a signal to a photodiode whose output generated an electrical trigger for the camera sweep. The second portion of the beam continued to the entrance slit of the streak tube after it was appropriately delayed by increasing its transport distance.

In a second mode, shown in Fig. 2, we split off part of the dye laser component at 496 nm which was also being monitored by the autocorrelator. The autocorrelator monitor nominally indicated bunch lengths of 1 to 2 ps (FWHM) in the baseline operating mode.

Both the UV-visible (S20) photocathode (PC) tube and the Au photocathode tube were evaluated. In the latter case, a quartz window on the front flange allowed UV photons to hit the PC. We also used a front flange with a Be window for a planned test with x-rays. A portable pumping station was used to take the tube pressure to $2x10^{-7}$ Torr. For both these tests, the camera was positioned off-axis near the end of the linac. Part of the drive laser beam for the PEI was directed to the streak camera.

The streak camera's information was readable by a charge-coupled device (CCD) camera, and the video digitized with a Hamamatsu MAC temporal analyzer (TA). The U5568 software program was designed for use with the Macintosh computer and the IQ-V50 frame grabber board. The system also provided remote control of most streak camera functions through a GPIB interface. The image analysis program was used to provide initial evaluation of streak image position and profiles.

3. Preliminary Results

Initial reference measurements were performed using a UV-visible (S20 photocathode) tube. In Fig. 3 a sample temporal profile from a streak image of the green component is shown. The amplified UV was observed to have a larger FWHM (4 to 6 ps) bunch length than the green (~1.9 ps). The green component was measured at 1 to 2 ps generally when monitored by the auto correlator.

In Fig. 4 test data from the Au photocathode are shown. The focus mode reflects the physical extent of the active surface which is 80 µm tall by 6 mm wide. The 5.9 channels (ch) (FWHM) with a streak rate of 0.31 ps/ch would imply a limiting resolution of about 2 ps. Due to the penetrating nature of x-rays, defining slits in front of the PC are not a practical way to control the static spread function of the tube. The limited vertical size of the PC addresses this issue. The observed streak profile of the UV component when combined with the independent information of the S20 tube was used to determine the 2 to 3 ps (FWHM) resolution at 248 nm. In Fig. 4B, a laser retuning resulted in a 5.8-ps (FWHM) measurement result using the MAC-TA algorithm, while the Gaussian fit to this indicated 6.1 ps (FWHM). Initial x-ray tests using the Au PC with the Be window mounted were unsuccessful due to the limited intensity of x-rays that could be generated in a 5-ps pulse and also interact with the streak camera PC in the available geometry. A brighter, pulsed x-ray source would be useful as well for characterization purposes.

Subsequently, the synchroscan unit (tuned at 117.3 MHz) and dual-sweep plug-ins have been tested with the UV-visible tube with the optical synchrotron radiation (OSR) generated in a dipole magnet in the main 7-GeV storage ring at APS. The "fast-time axis" was set at 1000 ps to cover the 20- to 50-ps rms bunch length, and the slow sweep axis was operated at 10 μs and 20 μs to see single-bunch, turn-by-turn effects and 100 ms to see slower transients. One example is a fast vertical head-to-tail instability which is observed at single-bunch average beam currents of 1 to 5 mA (3.6 to 18 nC per bunch) depending on the settings of the sextupoles (and hence, chromaticity). Fig. 5 shows a case of the fast head-to-tail instability with the y-projection changing in only three turns. Such an effect causes an increase of the y-profile size when averaged over the bunch time.

4. Discussion

As described by Kim [6], in the regime from λ = 1000 Å to 100 Å both SASE and HGHG methods could be employed for the FEL. Multifaceted mirrors could be the basis of an oscillator configuration for part of this regime [10]. With the MgF_2 window transmission cutoff at 1150 Å, this first regime is where "windowless" operation is appropriate. Additionally, an adjustment to this particular x-ray photocathode fabrication would be needed since its parylene film substrate has very strong absorption in the 1000 to 200 Å regime. An alternative substrate would have to be identified. Relatively speaking, the PC as it is could support the 200 Å to 100 Å portion. In the 100 Å to few Å wavelength regime, Kim suggests only SASE appears feasible with very stringent electron-beam requirements. However, the present photocathode is directly applicable from the wavelength point of view.

In terms of bunch length, the particle beam characterization through conversion mechanisms into the visible regime allows use of a visible streak camera with rms resolution of less than 150 fs. The lasing output through the deep UV (DUV) proposal at Brookhaven (λ = 3000 to 750 Å) suggests bunch lengths from 5 to 0.2 ps. In regard to the x-ray tube under discussion, the temporal resolution could address the longer bunch lengths envisioned. At even shorter lasing wavelengths, the temporal resolution blurs due to the fundamental limit of photoelectron energy spread for the high-energy incident photons. The streak tube can be modeled to a reasonable extent to have three contributions to its limiting resolution [11] so that

$$\Delta t_{res} = [(\Delta t_1)^2+(\Delta t_2)^2+(\Delta t_3)^2]^{\frac{1}{2}},$$

where Δt_1 is due to the energy distribution of secondary electrons and the photocathode uniformity,

Δt_2 is due to non-uniform electric potential at the deflection plates, and

Δt_3 is due to the line spread function and the deflection speed.

The first term is estimated at ~1/2 ps in the UV regime but increases to about 2 ps (FWHM) in the few angstrom regime for the geometry of this tube. It still appears that the rms resolution would be 1 to 2 ps throughout this regime. While this does not satisfy the endpoint target bunch length in the final x-ray SASE, it should be able to address a critical part of the demonstrations along the way to that objective.

Further experiments at APS will involve x-ray synchrotron radiation (XSR) as well as OSR from the bending magnets and also x-rays from a λ_w = 1.8 cm, N = 198 period diagnostics undulator whose fundamental is at 0.6 Å. The undulator test line initiative at APS using a 650-MeV linac and an rf gun as injector is another possible test case for using the system [12,13]. Since the slow sweep coverage can be selected in steps from 10 ns to 100 ms, a number of pulse time structures can be addressed. The "super-pulse" phenomenon described for the Duke storage ring UV FEL at 80 nm [14] could be another dynamic case where such techniques would be instrumental in understanding the phenomena.

5. Summary

In summary, the extension of dual-sweep streak techniques to the short wavelength outputs of proposed UV/x-ray FELs now seems feasible. The initial temporal resolution tests in the AWA drive laser have shown the UV capability at 248 nm. This resolution, when extrapolated into the VUV to x-ray regime should be able to address key features of the milestone experiments as discussed. Further demonstration experiments of the diagnostics are planned at APS and other sources as appropriate and practical.

Acknowledgements

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Figure Captions.

Fig. 1. Initial setup for measurements on the amplified UV component (248 nm) of the PEI drive laser.

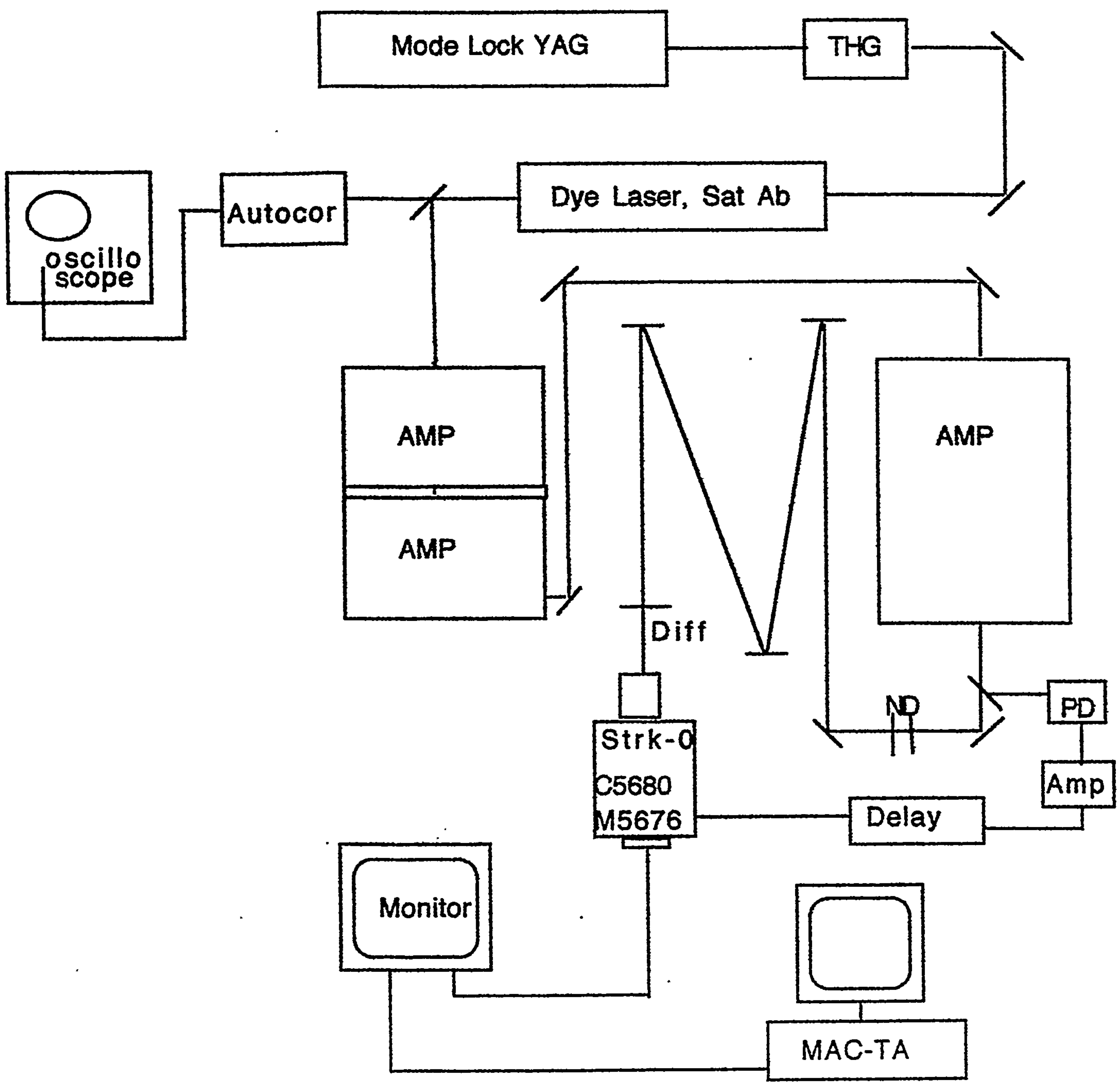
Fig. 2 Setup for measurements on the 496-nm wavelength component in the drive laser. This component is also monitored by the autocorrelator .

Fig. 3 Profile from the streak image of the green component at a bunch length of 1.9 ps (FWHM). This includes the 1.5-ps (FWHM) contribution from the camera resolution indicating a laser pulse of about 1.5 ps.

Fig. 4 Profiles from the Au-PC tube using the 248-nm irradiation: (a) focus mode with 5.9 channels (FWHM) and (b) streak mode with a 6.1-ps (FWHM) result for the total observed bunch length.

Fig. 5 Dual-sweep streak image of a single-bunch head-to-tail instability in the APS storage ring. The bunch length is about 120 ps (FWHM) and the y-profile is initially about 200 μm (FWHM). In this case, the UV-visible tube was used with the synchroscan and dual-sweep plug-in units.

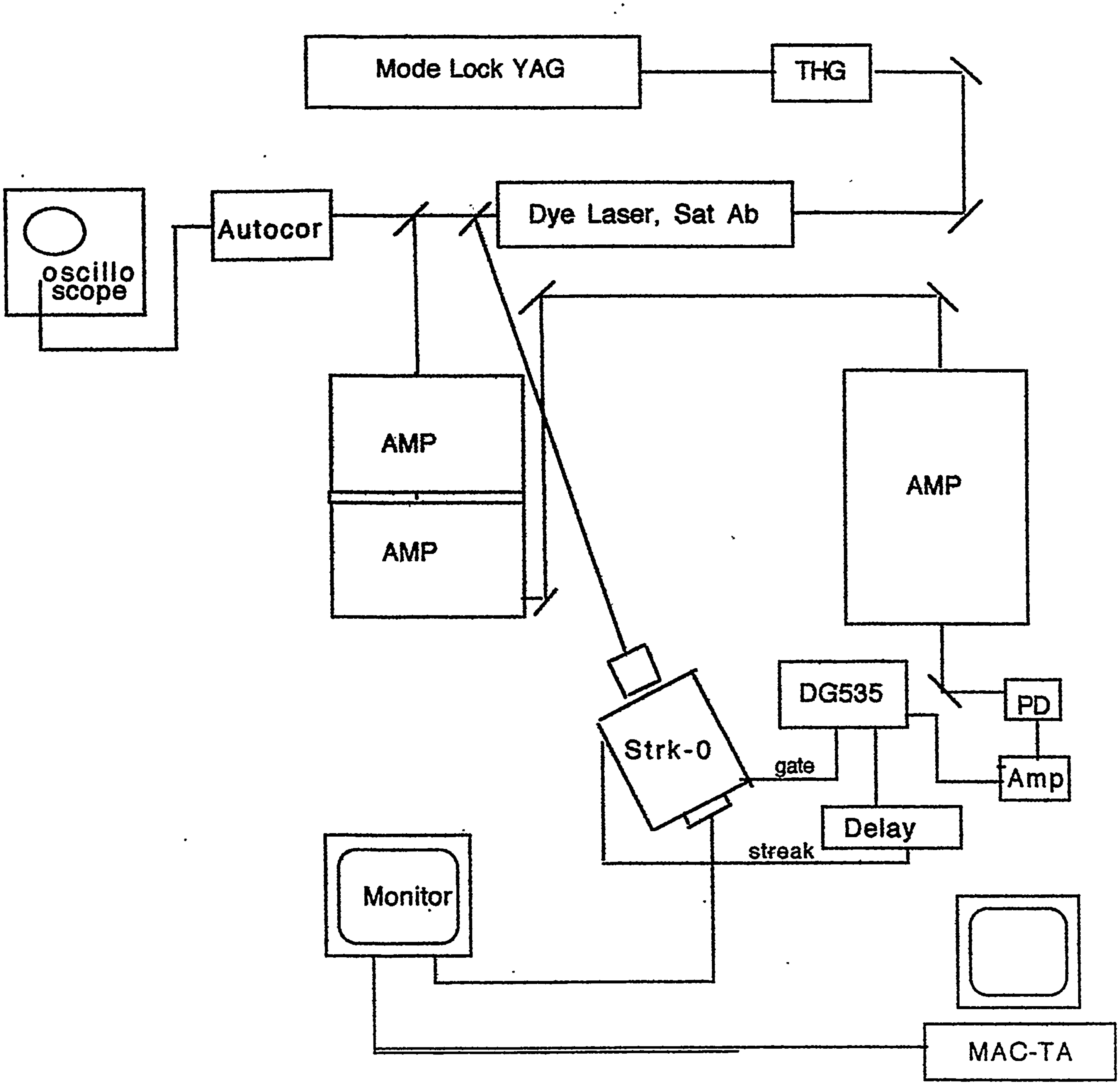
SET-UP A



Mode Lock YAG
THG
Dye Laser, Sat Ab
Autocor
oscillo scope
AMP
AMP
AMP
Diff
Strk-0
C5680
M5676
ND
PD
Amp
Delay
Monitor
MAC-TA

Fig. 1

SET-UP B



Mode Lock YAG
THG
Autocor
Dye Laser, Sat Ab
oscillo scope
AMP
AMP
AMP
Strk-0
DG535
PD
gate
Amp
Delay
streak
Monitor
MAC-TA

Fig. 2

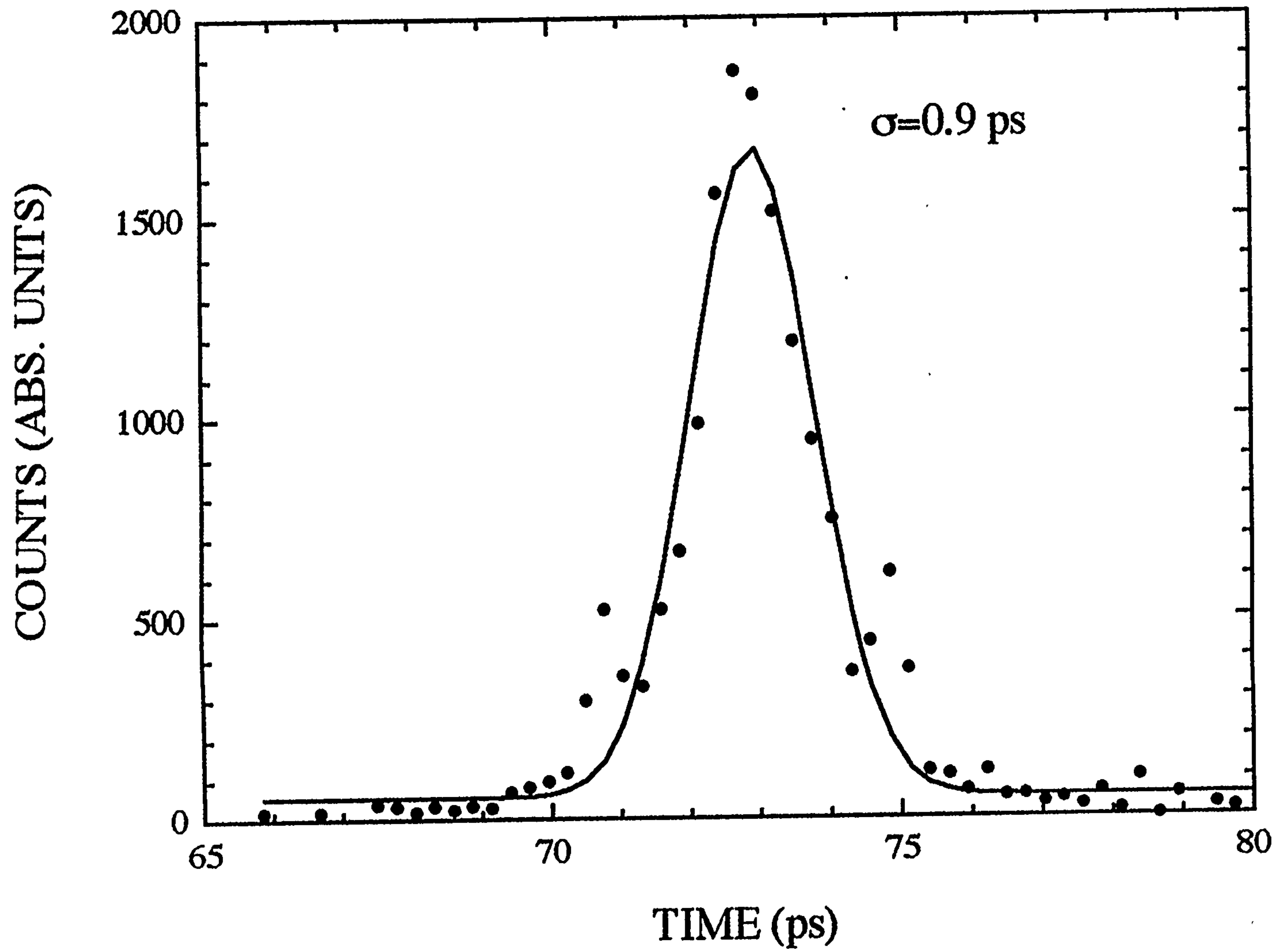


Fig. 3

x-ray slit image

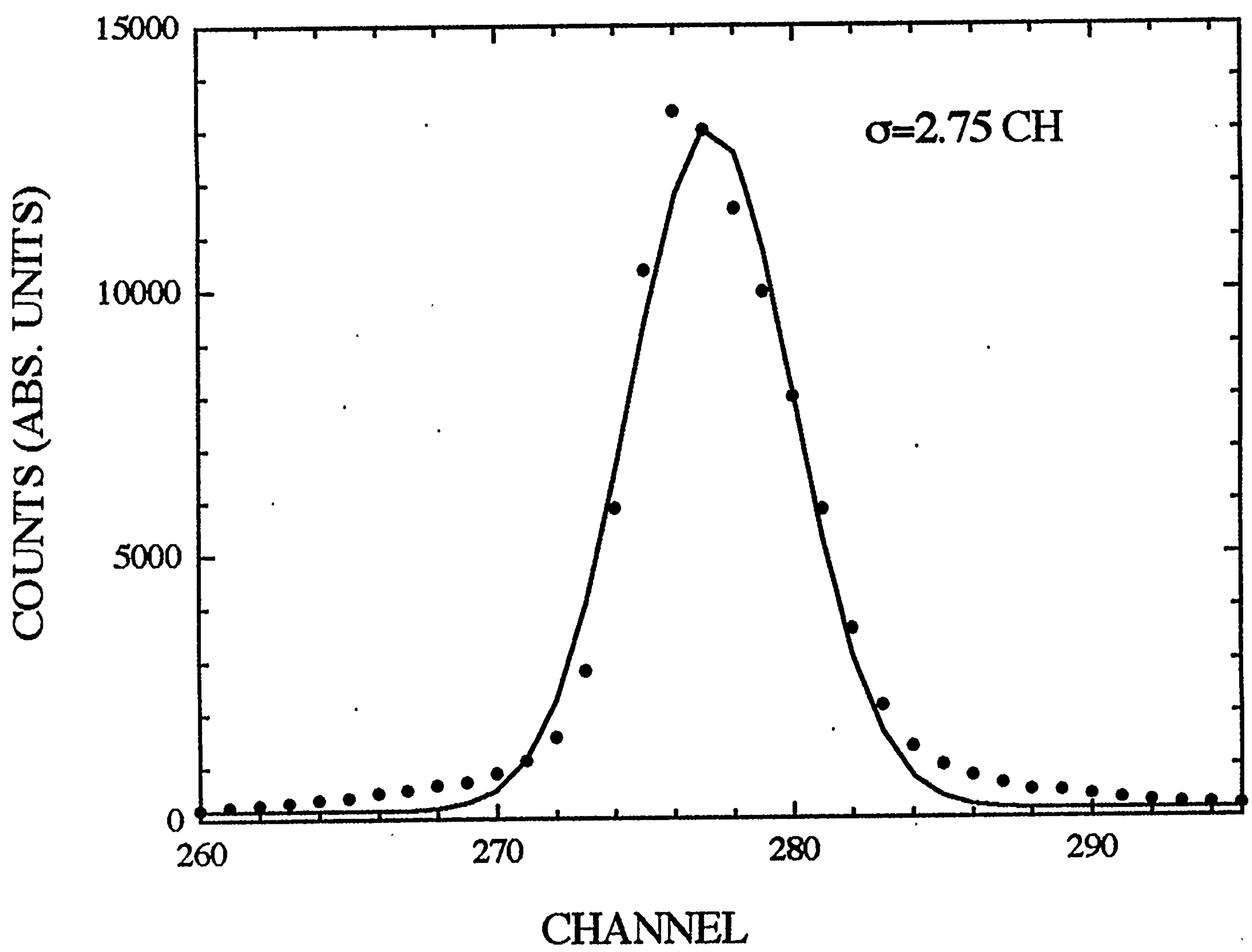


Fig. 4a

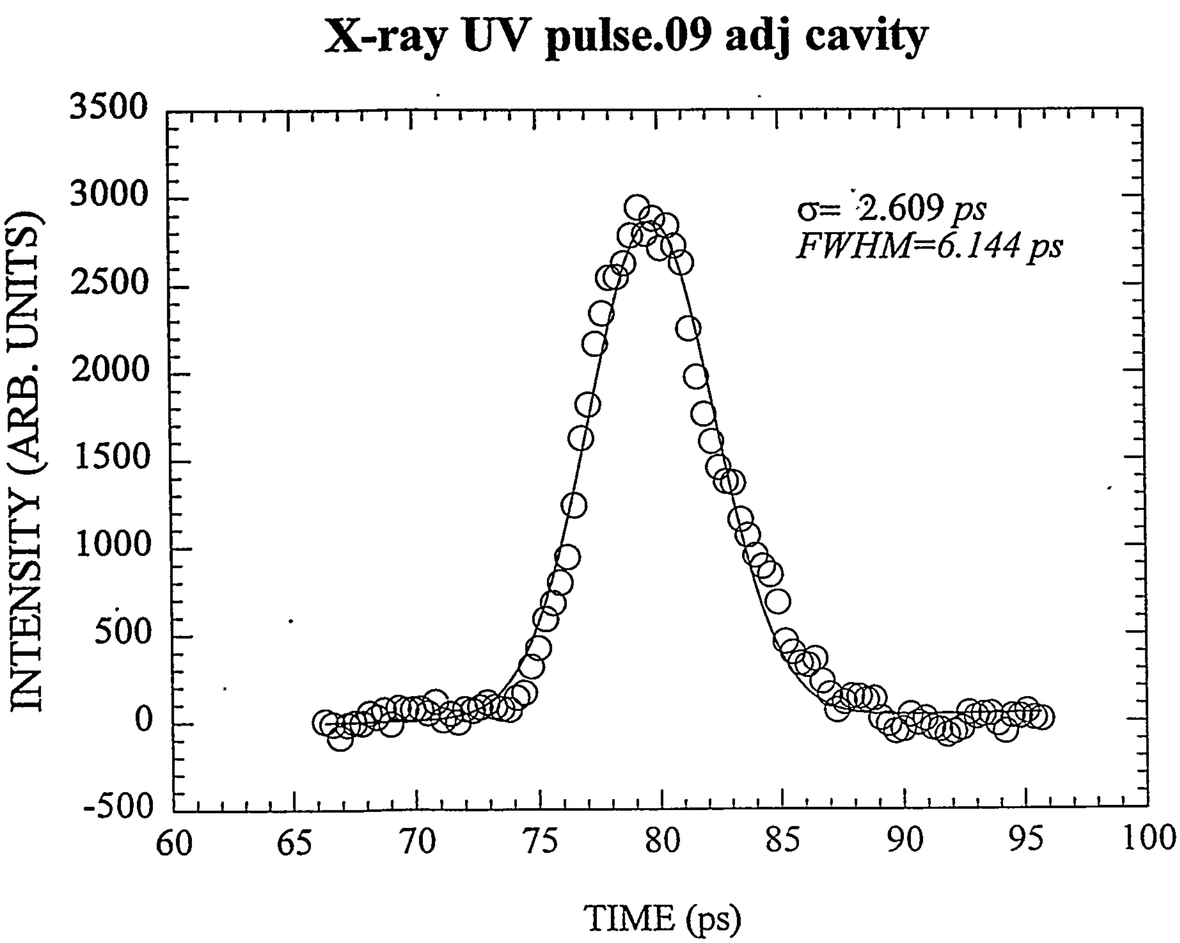

X-ray UV pulse.09 adj cavity
σ= 2.609 ps
FWHM=6.144 ps
INTENSITY (ARB. UNITS)
3500
3000
2500
2000
1500
1000
500
0
-500
60
65
70
75
80
85
90
95
100
TIME (ps)

Fig. 4b

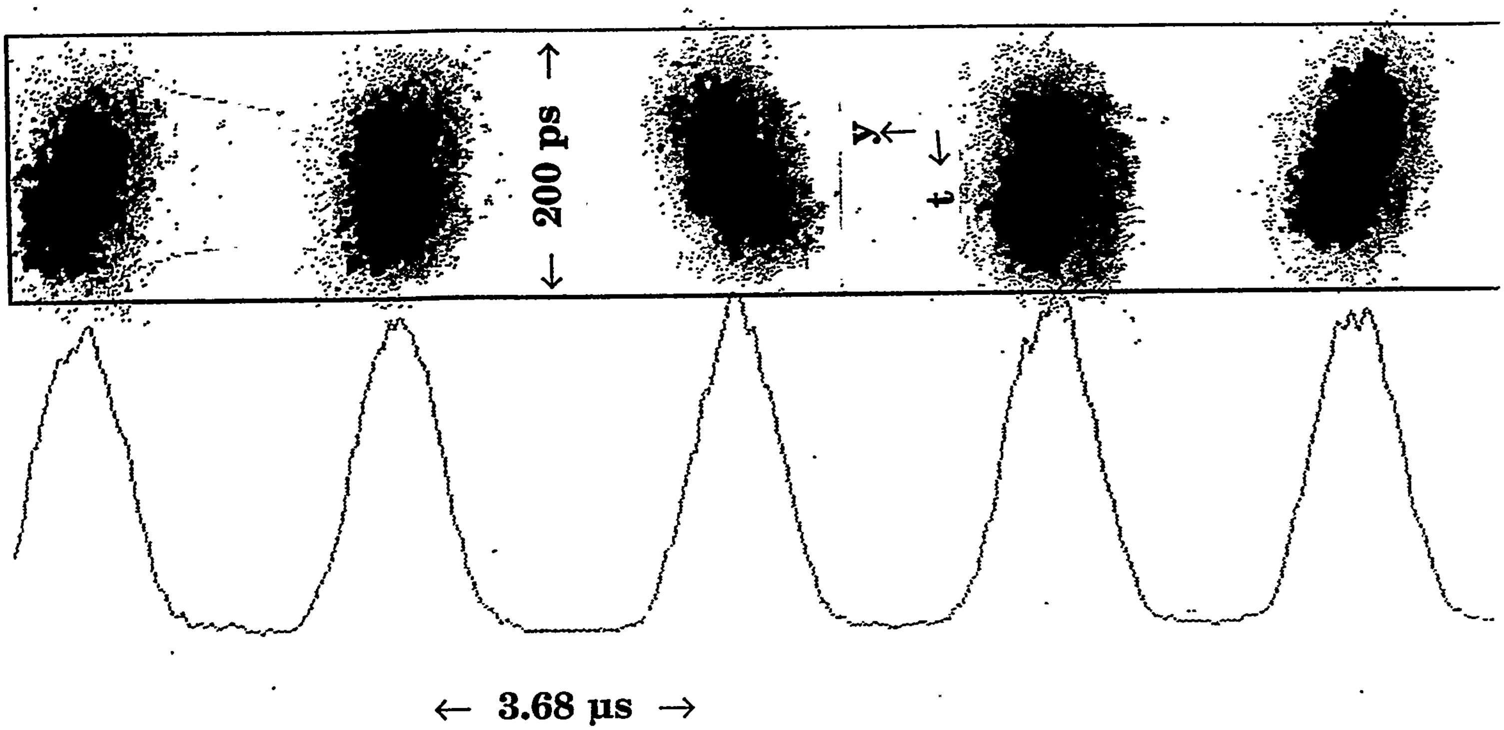


Fig. 5