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Experimental Techniques for the CESR Streak Camera*

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1. Introduction

The goal of this paper is to point out some of the operating techniques established for the Hamamatsu streak camera. We begin with a general description of the streak camera, followed by a description of the experimental techniques used to reduce, or eliminate, the systematic errors associated with the streak camera. A more detailed description of the streak camera operation may be found elsewhere [1,2].

2. Brief Description of the Streak Camera

In this section is a brief description of the streak camera used to measure the longitudinal bunch distribution in the Cornell Electron-Positron Storage Ring (CESR).

The streak camera was made by Hamamatsu (model C1587) and is located in the L3 annex. The streak camera is a device to measure ultra-fast pulsed light intensity versus time. The basic components of the streak camera are shown in figure 1, and they are the variable input slit, input optics, photo cathode, accelerating mesh, deflection plate, micro-channel plate, phosphor screen, output optics, CCD camera, and analog to digital read-out system.

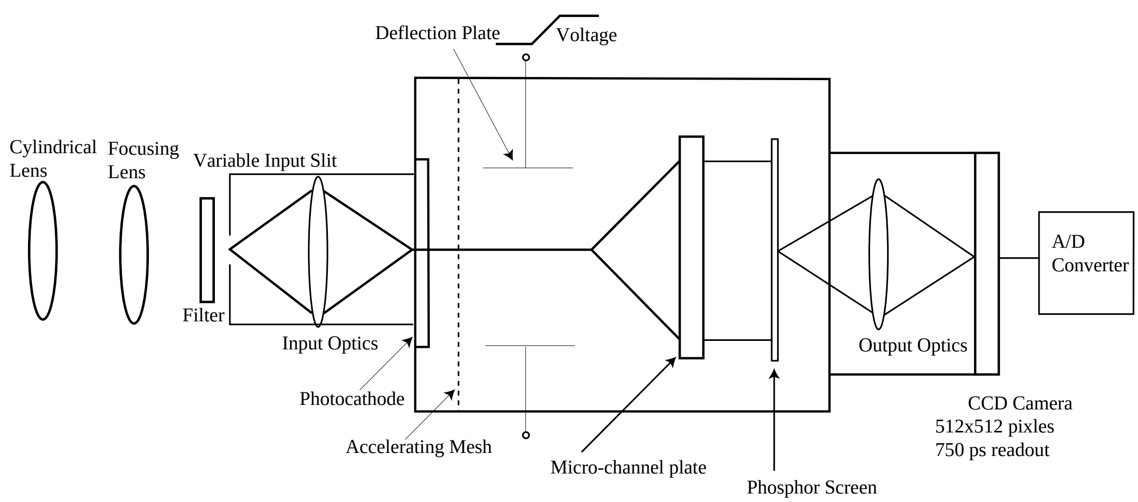

Figure 1. The layout of the various components of the Hamamatsu streak camera.

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The streak camera uses synchrotron radiation produced by the soft bend magnet located near L3 to measure the longitudinal bunch distribution in CESR. The synchrotron light is transported from the source out of the vacuum chamber to a safe location shielded from ionizing radiation where the streak camera measurements can be performed. The primary mirror used to extract the synchrotron radiation from the tunnel is made from copper that has been diamond turned. The set-up for transporting the synchrotron light from its source is described elsewhere[3].

The additional optics located before the main sweep unit consist of: 1) A focusing and cylindrical lens combination to focus and spread the light over the camera's horizontal slit 2) a neutral density filter to eliminate space charge effects. The need for the additional input optics elements is described in the following sections. The streak camera takes images of the bunch distribution, which are 512 by 512 pixels in size. A selected area is chosen such that the horizontal columns in that area are projected on the vertical axis. This creates a profile that is fit to a function that characterizes the distribution of the bunch. The function used to characterize the bunch shape is an asymmetric Gaussian function. The longitudinal profiles of the beam distribution are fit to an asymmetric Gaussian function with a constant background given by

$$I(z) = I_0 + I_1 \exp\left\{-\frac{1}{2}\left(\frac{(z-\bar{z})}{(1+\operatorname{sgn}(z-\bar{z})A)\sigma}\right)^2\right\} \qquad (1)$$

where I_0=pedestal, I_1=peak of the asymmetric Gaussian. The term $\operatorname{sgn}(z-\bar{z})A$ is the asymmetry factor that parameterized the shape of the asymmetric Gaussian.

The streak camera's deflection plate voltage is adjustable to allow different length light pulses to be measured. Adjusting the sweep voltage changes the output window width. The optimum speed for measuring the CESR bunch distribution has a 750ps window.

In the next sections, I will describe a series of experiments performed on CESR, which point out the systematic errors and the resolution of the streak camera. These experiments were made during high-energy physics collisions, which means the bunch current was not constant.

3. Space Charge and Intensity Effects in the Streak Camera

Space charge effects can occur when the intensity of the synchrotron light incident on the photo cathode is too high. This causes the photoelectrons to interact and leads to a systematic error in the bunch length measurement. The measured length is larger than the actual length. To eliminate the space charge effects, the multichannel plate gain was set to its maximum setting and the incident light was filtered until the bunch length measurement was stable over a range of light intensities. The height of the distribution is also measured to illustrate the signal for saturation of the CCD camera. A measurement of intensity and space charge effects was made with the steak camera during high-energy physics running. The bunch length was measured as a function of neutral density filters to determine acceptable intensity levels. The transmittance, given by

$$T = 10^{-OD} = \frac{I_{out}}{I_{in}}$$

where OD is the filter's optical density, is the ratio of the input intensity to the output intensity. The bunch length was measured five times at each light intensity (filter level) and the bunch length was determined by fitting the bunch distribution to an asymmetric Gaussian distribution (equation 1). The bunch length is plotted as a function of transmittance and Gaussian peak (I_1 in equation 1) in figure 2 (a-b). The mean bunch length and peak of the asymmetric Gaussian function is determined from the fit to the function. These parameters can be used to determine the filtering of the light intensity necessary to eliminate bunch lengthening. In this example, at a bunch current of 5mA, the light intensity is filtered by 50% to eliminate this effect in subsequent measurements.

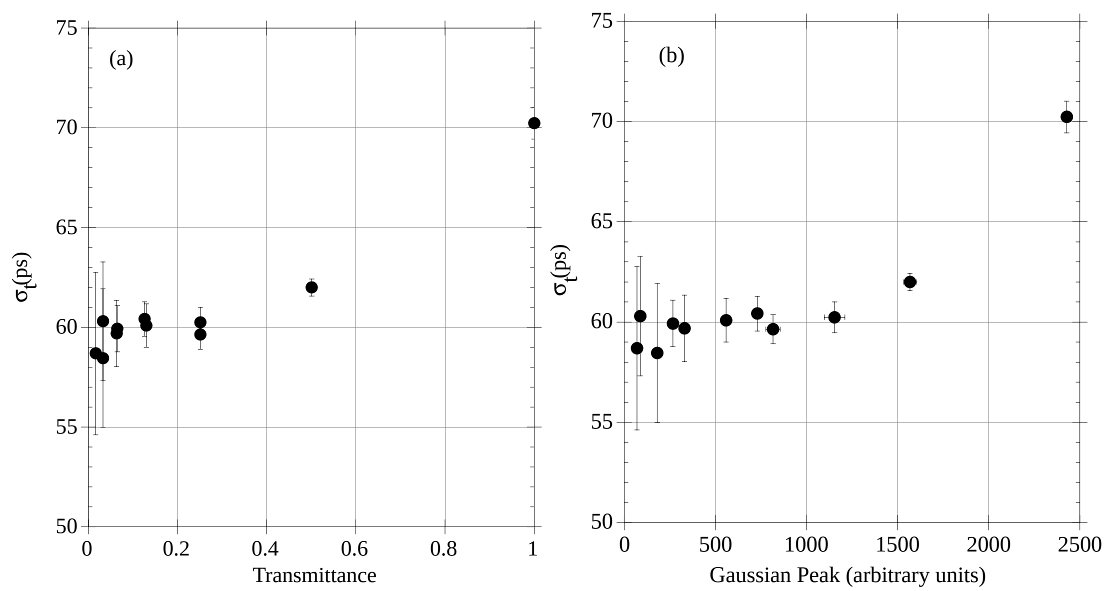


Figure 2. (a) The measured bunch length dependence on light intensity. (b) The measured bunch length dependence on the peak of the asymmetric Gaussian distribution. The measurement consists of taking five streak camera profiles at each density filter setting. The mean and rms error of each density filter setting is plotted.

The bunch distribution at three different transmittance values is shown in figures 3 a-c. The bunch distribution without filtering has a flat top which is characteristic of intensity saturation. It should be noted that saturation can be determined by two methods, 1) when the image readout is red, the camera is in saturation, 2) when the Gaussian peak is less than 1200 units the image is not in saturation. The Gaussian peak does depend on the profile window width. For these measurement the profile window width was 203 pixels.

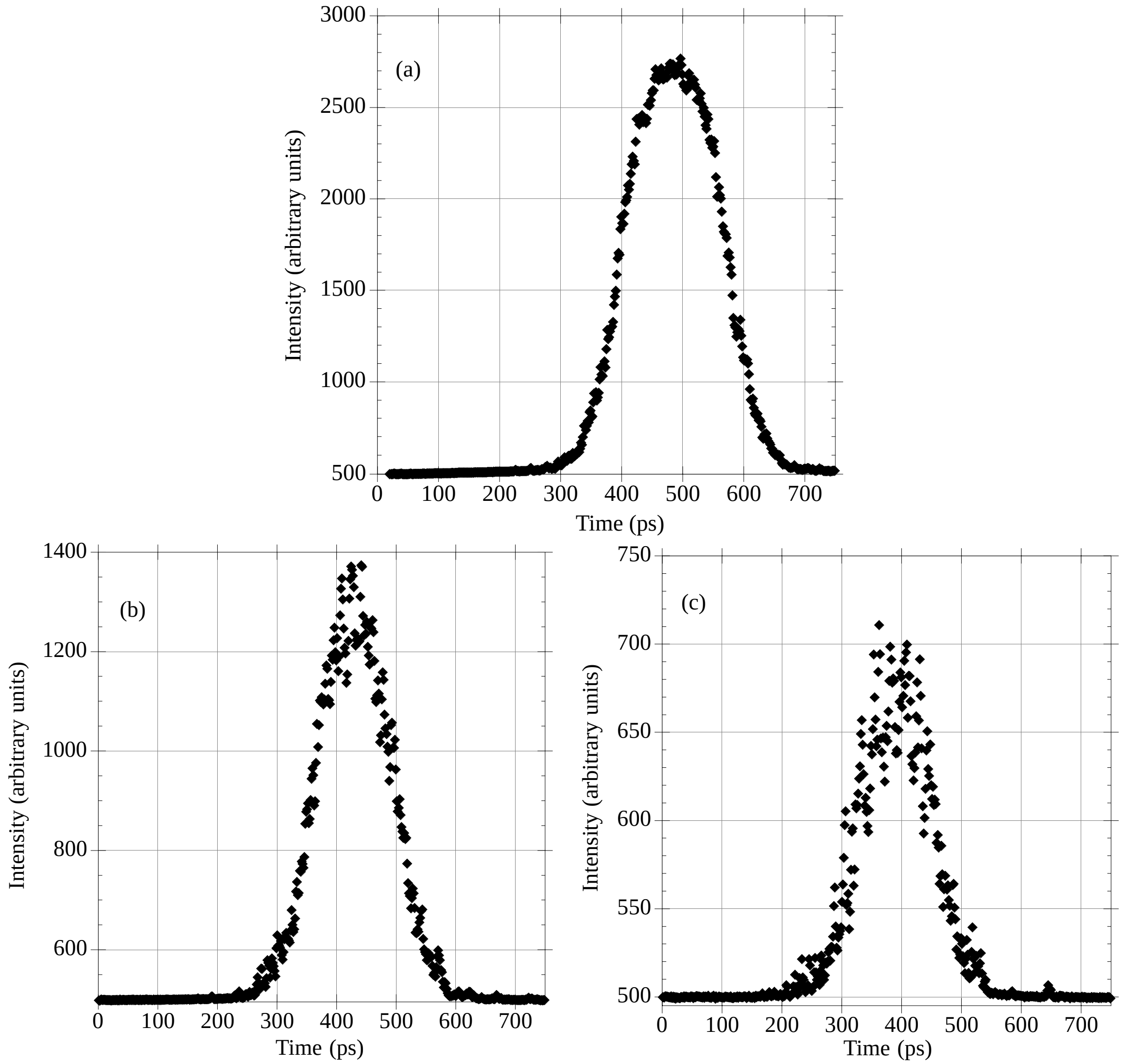


Figure 3. A typical bunch distribution during high-energy physics collisions with: (a) no neutral density filter, (b) neutral density filters that have total optical density value of 0.6, (c) neutral density filters that have a total optical density value of 1.486.

4. Linearity of the Streak Camera Voltage Sweep

The Hamamatsu Corporation provided the measurement of the linearity of the streak voltage. The calibration data was fit to a polynomial curve and the fit to the data is used in the streak camera image analysis.

The steak camera's read out monitor has a 750ps window to observe the bunch distribution. This 750ps window allowed the time calibration of the camera to be confirmed by measuring the beam location on the streak camera and varying the trigger signal. The trigger signal for the streak camera had a fine delay of 82ps and adjusting the trigger in 82ps steps, for a total of six trigger settings, allowed the linearity of the streak sweep to be measured. The measurement consisted of taking ten streak camera pictures at each trigger time, for a total of 60 pictures, when the streak image was visible in the 750ps window. The 60 pictures were taken during high-energy physics colliding beams so the current was not constant but it did not vary during the measurement by more than five percent. Each image was fit to an asymmetric Gaussian distribution (equation 1). The bunch length and mean position of the distribution was determined from the fit. Figure 5a is the uncalibrated bunch length as a function of the mean position and figure 5b is the calibrated bunch length as a function of the mean position of the readout monitor. The calibration curve provided results in a linear bunch length with a negligible slope.

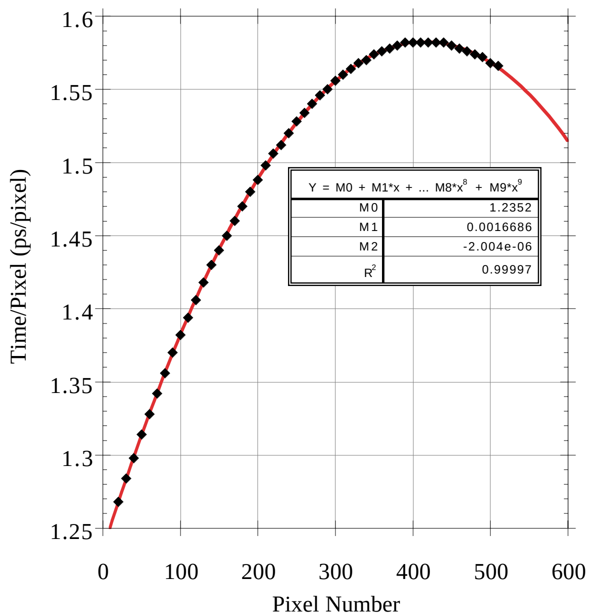


Figure 4 (color). The calibration curve for the streak camera for the streak speeds of 1 nsec/15 mm which has an output window of 750ps.

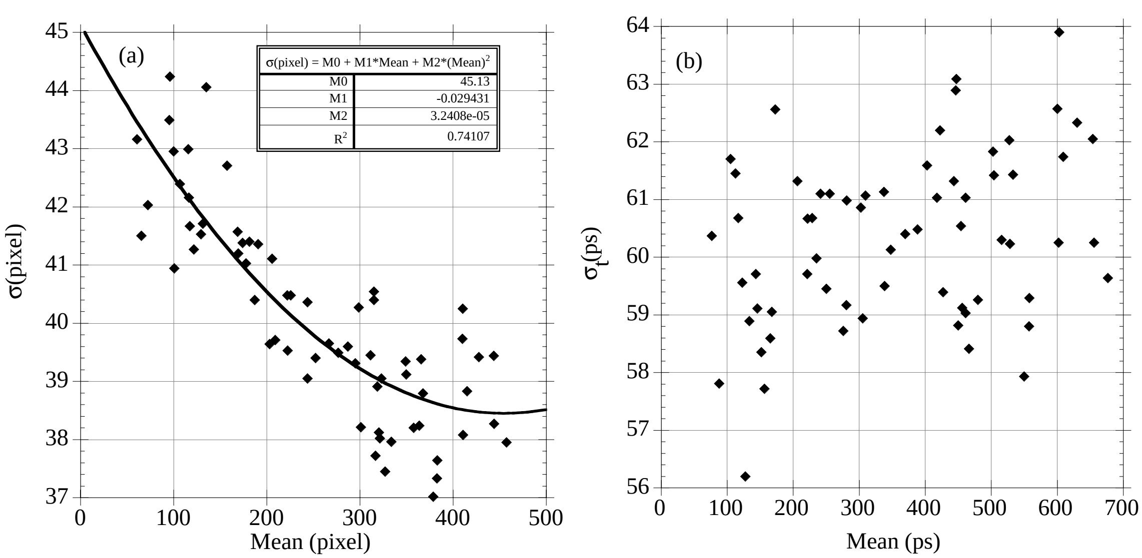


Figure 5. The bunch length as a function of the mean location on the CCD camera window. The raw data fit to an asymmetric Gaussian distribution without the calibration curve is plotted in figure (a) and the data fit to an asymmetric Gaussian distribution with the calibration curve is in figure (b).

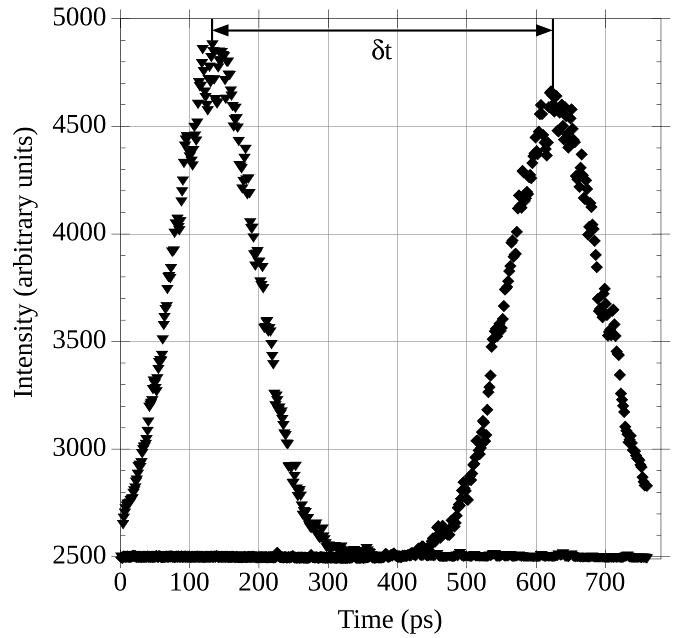


Figure 6. The sum of ten streak camera pictures separated by a trigger setting of 492ps. The measured difference between the two peaks is within a percent of the expected value.

The images at each trigger setting can also be used to test the time calibration of the streak camera sweep. The ten images from each trigger setting were fit to an asymmetric Gaussian function and the average of the 10 mean positions were calculated to determine the mean location of the bunch relative subsequent trigger settings. The time difference on the camera was then determined from the calibration curve (figure 4) and compared with the trigger delay. Two of the data sets, which are separated by six 82ps (for a total of 492ps) trigger settings, are plotted in figure 6. The mean difference measured by the streak camera between the two trigger settings is $\delta t = T_2 - T_1 = 494.1 \pm 11.4\text{ps}$ which is in agreement with the expected value.

5. Streak Camera Resolution

The resolution of the streak camera was measured, using a pulsed femto-laser, by Hamamatsu to be 1.6ps at the fastest sweep speed (300ns window) and with a slit width of 10 µm. This apparatus is not available so an estimate of the resolution due to our mode of operation will have to suffice.

The two factors not already mentioned that limit the resolution of the streak camera are:

1) Dispersion in the streak camera and transport system glass optics t_1.

2) The slit image at the photo cathode gives a temporal width t_2.

Each limitation will be discussed separately. The time resolution including all of these factors is given by adding these in quadrature

$$t_{res} = \sqrt{t_1^2 + t_2^2}\,.$$

The actual bunch length can be written in terms of the camera resolution and the measured bunch length as

$$t_{actual} = \sqrt{t^2_{measured} - t^2_{res}}\,.$$

1) Using narrow band interference filters minimizes the effect of dispersion in the glass optics. Bunch lengthening due to dispersion has been measured on the Stanford Linear Accelerator Center (SLAC) Linac (where σ_z~1mm) but not on the SLAC damping rings (where σ_z~5mm)[1]. The effect of dispersion was measured at three different interference filter values. The peak spectral response of the streak camera is 500nm. The interference filters used have a peak response at 500 nm with 10, 40, and 80nm full width half-maximum acceptance. The bunch length without interference filter is $59.44 \pm 2.1\text{ps}$. The results of the measurement are displayed in figure 8. The results from SLAC and CESR show that bunch lengthening due to dispersion is not significant unless σ_z is less than 5mm.

2) The contribution of the bunch length on slit size can be determined by measuring the slit size with the streak camera in focus mode. In focus mode, the streak camera is not streaked and the image projected by the camera is the slit width. Figure 7 is a plot of the dependence of measured effective image width on the slit width in focus mode. The upper plot shows the corrected bunch length with the slit width measurement subtracted in quadrature. Therefore, the resolution degradation due to the slit width is 3.6ps at a width of 50µm. The measurement also serves as a calibration of the slit width degradation for future experiments.

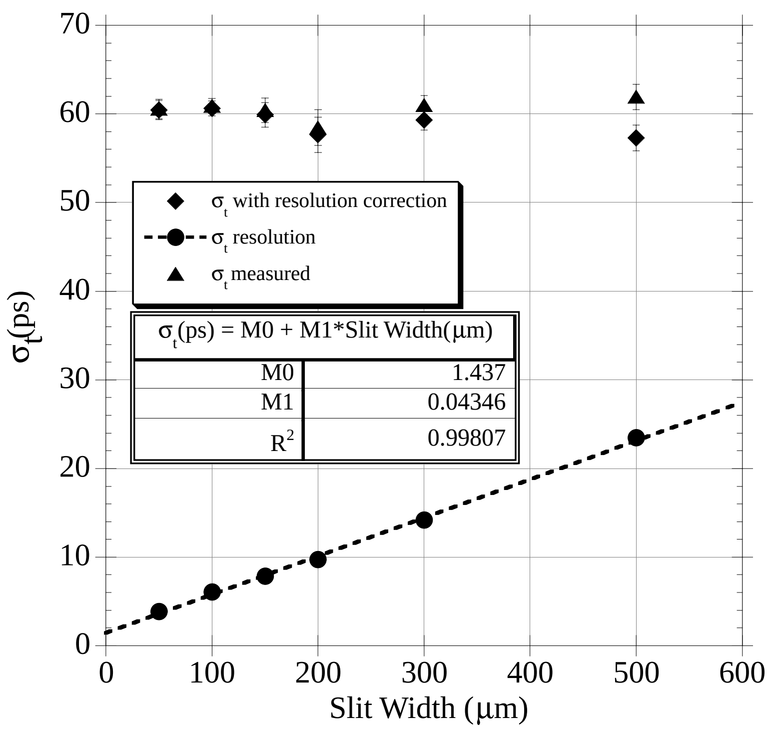
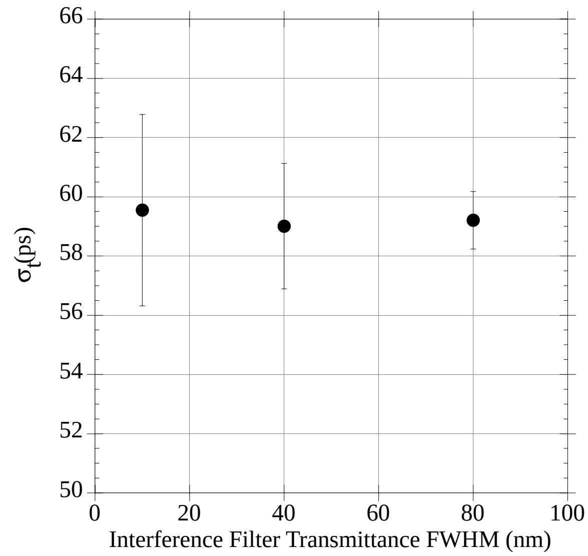


Figure 7. The bunch length, with and without the slit width resolution correction, as a function of slit width. The slit width resolution correction is also plotted in the figure.



Figures 8. The measured electron bunch length for the three different interference filter acceptance values. The measurement consists of taking 10 streak camera profiles and plotting the mean and rms error for each filter acceptance. The light intensity was appropriately set to avoid intensity bunch lengthening.

6. Conclusions

This paper presents the experimental techniques necessary to eliminate systematic errors associated with streak camera measurements. The results of the measurements are:

(1) When operating the streak camera, set the multichannel plate to its highest setting and use neutral density filters to eliminate space charge and light intensity bunch lengthening. The CCD camera image read-out is a good indicator for intensity saturation. If the image has many red pixels, more filtering is needed.

(2) Dispersion in the glass optics does not produce bunch lengthening at nominal CESR bunch lengths (~18mm). At shorter bunch lengths, especially for high tune measurements, this measurement should be repeated.

(3) Bunch lengthening due to the slit width is present but it is negligible at nominal CESR bunch lengths. It is recommended that a slit width of 200μm or less should be used to reduce this affect.

(4) The linearity of the voltage sweep of the streak camera was verified by taking data at several different trigger settings. The time calibration was measured to be within a percent of the advertised value.

(5) The resolution correction determined from these experiments are due to the slit width and resolution correction can be determined from the fit to the data in figure 7.

The data taking techniques discussed in this note should provide the user a guideline to stable and reproducible results with the Hamamatsu streak camera.

7. References

[1] Holtzapple, R.L.,"Longitudinal Dynamics at the Stanford Linear Collider", SLAC, SLAC-Report-487, June 1996. 180pp.

[2] The Hamamatsu Streak Camera Instruction Manual.

[3] Holtzapple, R.L., et al., "Single Bunch Longitudinal Measurements at the Cornell Electron-Positron Storage Ring", Phys. Rev. ST Accel Beams 3, 034401, 2000.