Analysis of Cornell Electron-Positron Storage Ring Test Accelerator's Double Slit Visual Beam Size Monitor

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Abstract

In the past year, a double slit interferometer was installed to measure the horizontal beam size in the Cornell Electron-Positron Storage Ring Test Accelerator (CesrTA) at Cornell University in Ithaca, NY. To better understand the systematics of this device, a replica of the CesrTA instrument was assembled at California Polytechnic State University San Luis Obispo. From the prototype, it was found that the device will produce a calculated beam size that agrees with measurements as long as it is optimized with the proper double slits for a small range of beam sizes.

Introduction

Double slit interference patters are commonly characterized for a "point source" such as a laser. The resulting interference pattern is easily explained using the path length difference for the light traveling from one slit to the imaging plane and from the other slit to the imaging plane. This theory can be extrapolated to an extended source. In this case, it is being applied to the visible light from the synchrotron radiation in the Cornell Electron-Positron Storage Ring Test Accelerator (CesrTA). There is currently a double slit interferometer in use for CesrTA to measure the average horizontal beam size of the electron and positron bunches in the accelerator. However, some of the systematics and the accuracy of the interferometer are not fully understood. To gain a deeper understanding of this device, a similar setup was constructed on an optics table at California Polytechnic State University San Luis Obispo (Cal Poly). Several properties studied include differences between the simulated source at Cal Poly and visible synchrotron radiation from CesrTA, the optical transport system (focusing of the light), light intensity effects, and comparison of the calculated beam size from using this instrument with the measured. Through analyzing each of these properties, the characteristics observed at Cal Poly will give a better understanding to operational aspects of the device for CesrTA.

Theory

The theory behind the monochromatic double slit interference pattern is based off path length difference. The distance between one of the slits to a location on the screen (where the interference pattern is observed) will be denoted r_1, and for the other slit it will be denoted r_2. If the light traveling from each of the slits travels a distance that is an integer multiple of half-wavelengths then they will cancel each other out through destructive interference. Meaning if the difference between r_1 and r_2 is ½ λ, then a peak on one light wave aligns with the valley of another resulting in a cancellation and hence destructive interference. Alternatively, if the r_1 and r_2 are a whole integer wavelength different then they will superimpose on top of each other constructively; the peak of one light wave aligns with the peak of the other. The expression used to locate the maxima in the interference pattern, where the light is interfering constructively, is

$$d \sin\theta = n\lambda \tag{1}$$

where d is the width between the two slits, θ is the angle from the normal of the slits to the location of interest on the imaging screen, λ is the wavelength of light incident on the double slits, and *n* is an integer greater than or equal to 0. From Eq. 1, the maximums in the interference pattern on the imaging screen can be located. Fig. 1 is a visual showing the geometry of the light ray's interaction where r_1 and r_2 are the two different paths from each slit to the imaging plane.

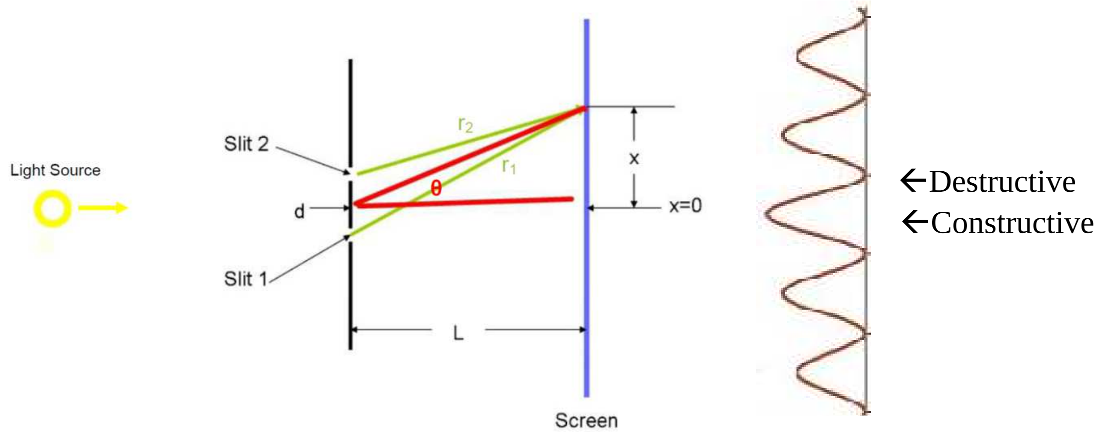

Figure 1: Double slit interference pattern drawing. The waveform on the right shows the resulting light intensity on the screen due to constructive and destructive interference.

An extension of the basic double slit experiment has been utilized to measure the horizontal beam size for CesrTA. Having the visible synchrotron radiation incident on double slits has been theorized to be a better way of measuring the beam size in some accelerators over direct imaging where determining the magnification can be difficult [1]. There are two important differences between the double slit experiment already outlined and those at CesrTA. First, synchrotron radiation produced by the electron and positron bunches is not monochromatic. The distribution of wavelengths spans the visible spectrum as well as extending into x-rays. Therefore, a minimum intensity of zero is not possible when destructive interference occurs since different wavelengths interfere differently. Second, a circulating bunch in CesrTA has a size making it an extended source, not a point source. Currently the dimensions of the bunch in the horizontal and vertical dimensions in CesrTA are $\sigma_h \sim 200\mu m$ and $\sigma_v \sim 20\mu m$ respectively. Taking into account these two differences, the interference pattern will have an intensity distribution similar to that in Fig. 2.

Several interesting features are evident in Fig. 2. Mainly, the minima in the interference pattern of the central peak do not go all the way down to the base line (background) in this case

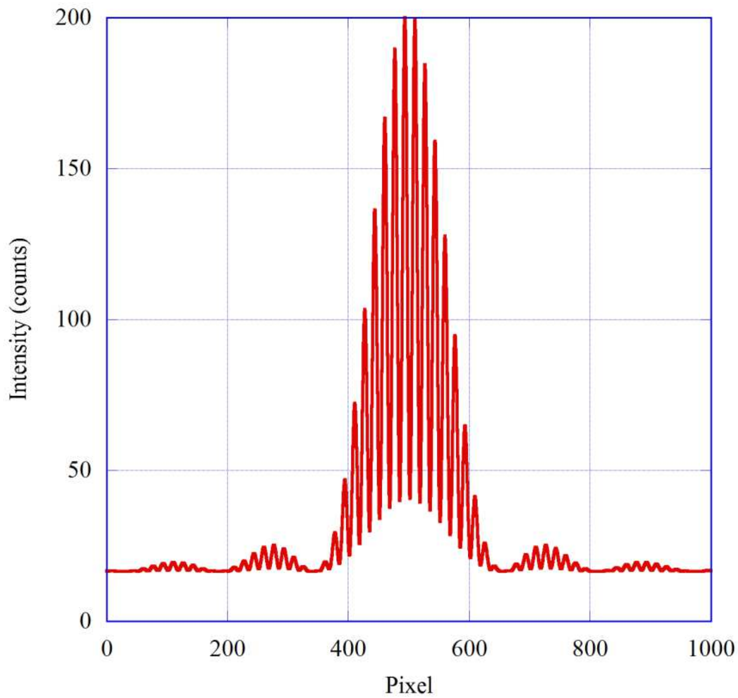

Figure 2: Example of interference pattern observed when measuring source size. This profile was created using Eq. 3 with the following values for the constants: a_0 = 105, a_1 = 500, a_2 = 0.02, a_3 = 16, a_4 = 0.75, a_5 = 0.06, and a_6 = 40.

of about 23 counts. This is due to both of the differences between the traditional double slit experiment and the modified double slit experiment utilized for the instrument: The lack of monochromatic light and having an extended source. To quantify how close the minima get to the background a quantity called the visibility is attributed to the interference pattern. The visibility is used in calculations to determine the source size and can be calculated using

$$V = \frac{I_{max} - I_{min}}{I_{max} + I_{\min}} \tag{2}$$

where the visibility is denoted by V, I_{max} is the value of the central maximum, and I_{min} is the value of a central minimum [2]. Eq. 2 is one approach to calculating the visibility, however due to shot-to-shot noise from the CCD and difficulty in programming a computer to calculate the visibility this way, an alternate method is to fit the interference pattern to a function where visibility is one of the parameters. The fit function for the interference pattern is

$$y = a_0 * (sinc((x - a_1) * a_2)^2 (1 + a_4 cos(2\pi x a_5 + a_6)) + a_3 \tag{3}$$

and is fit using LabView. a_0, a_1, …, a_6 are fitting parameters to the interference pattern, x corresponds to a distance on the imaging screen (CCD pixels) and y is the intensity of the interference pattern. a_0, a_2, a_3, and a_5 are intensity and frequency fitting variable dependent on the source and a_1 and a_6 are phase offsets which are dependent on how the light is incident on the double slits [3]. Most importantly is a_4, the parameter corresponding to visibility.

A calculation using the visibility and constants related to the experimental setup is used to determine the size of the source. When the source is a Gaussian distribution, such as the synchrotron light from the particle bunches in CesrTA, the beam size can be calculated using

$$\sigma = \frac{\lambda L}{\pi d}\sqrt{\frac{1}{2} ln\left(\frac{1}{V}\right)} \quad (4)$$

where σ is the parameter of a Gaussian distribution corresponding to the width, λ is the central wavelength of light, L is the distance from the source to the double slits, d is the slit separation, and V is the visibility. This relation is derived by taking the Fourier Transform over the source distribution by using the van Cittert-Zernicke theorem [4]. Please notice the inverse relationship between the visibility and the beam size, source width, in Eq. 4.

Eq. 4 is used to extrapolate the beam size from the visibility for CesrTA, at Cal Poly there is not a Gaussian source. Instead, the adjustable slit creates a square source. The visibility from the interference pattern generated by a square source allows one to calculate the half width. Taking the Fourier Transform of the square source distribution, gives the relation between the visibility (V) and half-width (a), where λ still represents the central wavelength, L the distance from the source to the slits, and d is separation between the double slits:

$$V = \frac{sin\left(\frac{2\pi da}{\lambda L}\right)}{\left(\frac{2\pi da}{\lambda L}\right)} \quad (5).$$

Even though the end result of interest is the source size, the initial analysis will be kept in terms of the visibility since this is what is determined from fitting the interference pattern. For example, when a parameter is changed such as the light intensity what we are interested in is how the visibility changes, since this is really what is being observed, and used to calculate the beam size.

Experimental Setup

Fig. 3 shows a diagram of the instrument at Cal Poly, a replica of the CesrTA instrument. The light source chosen was a white LED flashlight. Since the flashlight had its own focusing mechanisms the first optic was an iris to override the flashlight's focus. The light is directed towards the adjustable single slit by a mirror; this slit is the metering device for the size of the "source" (i.e. beam size). After the single slit the light is incident upon the double slits. Two different slit separations were used: 4 and 5mm, both were constructed in the CLASSE (Cornell Laboratory for Accelerator baSed Sciences and Education) machine shop at Cornell University. After the double slits the light passes through a lens (f=50cm) to focus the interference pattern to an imaging plane where the Point Grey Flea 3 color CCD camera is placed. In front of the CCD camera is a bandpass filter (500±10nm) so there is an interference pattern, without the bandpass filter the different wavelengths of light would interfere on top of each other, each slightly differently, washing out the interference pattern. A neutral density filter is used to prevent saturating the CCD camera. These optics could be constructed in one straight line chain, however, the use of the mirrors allowed for control over stray light. With this arrangement, the flashlight directs its light in the opposite direction of the CCD allowing for a lower background.

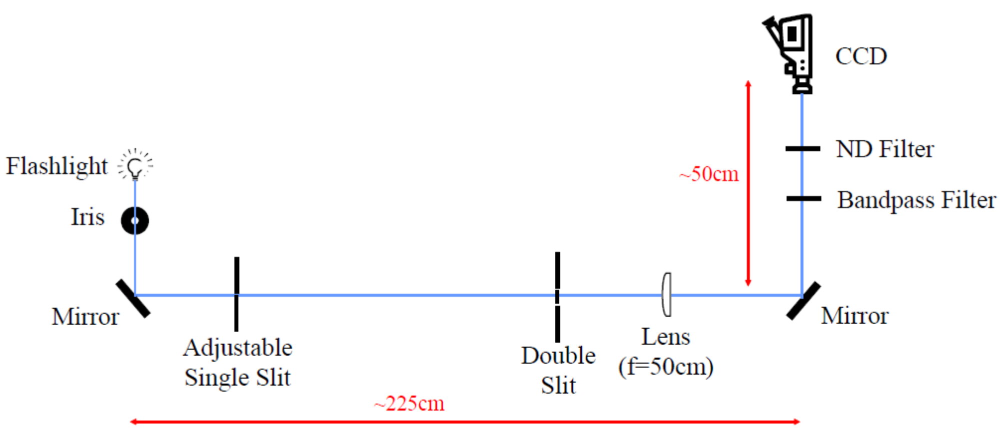

Figure 3: Experimental setup at Cal Poly showing optical layout and approximate dimensions. Blue line shows light path from flashlight to the CCD camera.

Analysis

Through measuring the beam size at CesrTA there were systematics deemed necessary of further analysis; the optics, light intensity, and comparing calculated beam size from the instrument to the source size. The main goal of the Cal Poly experiment is to better understand the setup at CesrTA and to calibrate the instrument over various interferometer parameters. However, before looking at the three things of interest for CesrTA a deeper understanding of how the simulated source in the setup at Cal Poly compares with the synchrotron radiation from CesrTA needs to be gained. Combined, there are four things of interest in the analysis: I.) The simulated source, II.) Instrument Focus, III.) Light intensity, and IV.) Comparing calculated and measured beam size.

I. The Simulated Source

Since the iris is the first and only optical element before the single slit the only other parameter that can be changed in the Cal Poly setup that affect the source is placement. Therefore, the things to analyze to optimize the Cal Poly simulated source are the iris, the distances between the flashlight, iris, and single slit, and the source distribution.

The iris cuts down the light from the source and can be an unintentional metering device, setting the size of the source; the measurement could be of the size of the iris instead of the slit. After analysis through adjusting the iris size and the slit size independently the following was found: For iris sizes that were smaller than the single slit, the beam size calculation reflected a source size equal to that of the iris instead of the slit. Alternatively, if the iris was set much bigger than the single slit (about a factor of 10) then the iris had no effect on the beam size calculation. Having the iris set to the large size allowed the single slit to be fully and evenly illuminated from the back while blocking all extra and stray light.

The placement of the light source at Cal Poly (the flashlight) was studied. Moving the flashlight in relation to the iris will change the divergence of the light. Moving the flashlight short distances away from the slit left the visibility unchanged. For large distances the visibility changed due to a decrease in light intensity causing the interference pattern to be just above the noise floor. In addition, the single slit was not longer fully and evenly illuminated.

One of the challenges of simulating the interferometer instrument at CesrTA is the producing a light source similar to circulating bunches in an accelerator. Bunches in CesrTA have a Gaussian distribution with a sigma corresponding to each of the three dimensions: horizontal, vertical, and longitudinal. Again, the main dimension of interest with this instrument is the horizontal beam size. Since in CesrTA the source is Gaussian and light sources are traditionally not Gaussian, understanding what the source looks like at Cal Poly is important.

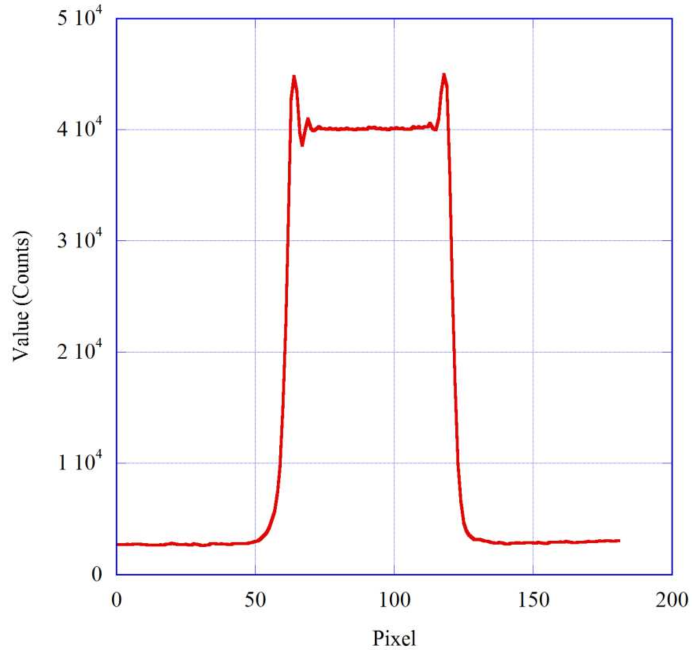

Figure 4: Source profile with the single slit micrometer set to 245 µm. Profile generated by directly imaging the single slit.

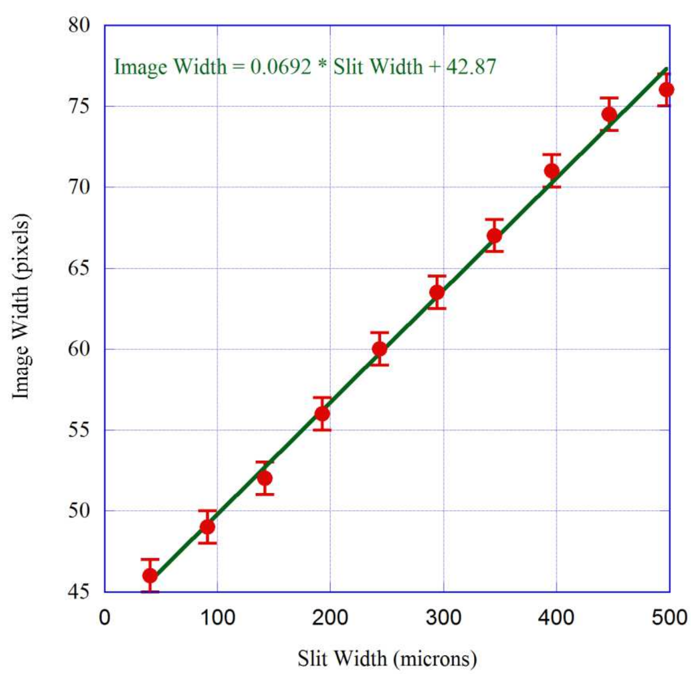

Figure 5: Relationship between micrometer set slit width and calculated source width (in pixels). This shows a linear relationship between the set slit size and the actual source size.

To see what the source looked like, direct imaging was done by removing the slits and moving the CCD camera slightly to the new focus location. The profile of the Cal Poly verifies its square distribution and that it is not a Gaussian distribution (see Fig. 4).

To verify the micrometer on the adjustable slit corresponds to the size of the "source" a sweep of images was taken, and the average full-width half-max was recorded for a range from 40µm to 500µm. The result was a linear relationship, as seen from the data in Fig. 5 which was fit to a line for reference.

II. Instrument Focus

To be sure of proper imaging, the location of the CCD relative to the interference pattern was analyzed. Properly imaging the interference pattern provides an accurate extrapolation of the visibility and beam size of CesrTA bunches. Changing the image plane location of the CCD camera was done by moving the CCD ±5cm from the focus lens. The results of moving the camera can be seen in Fig. 6.

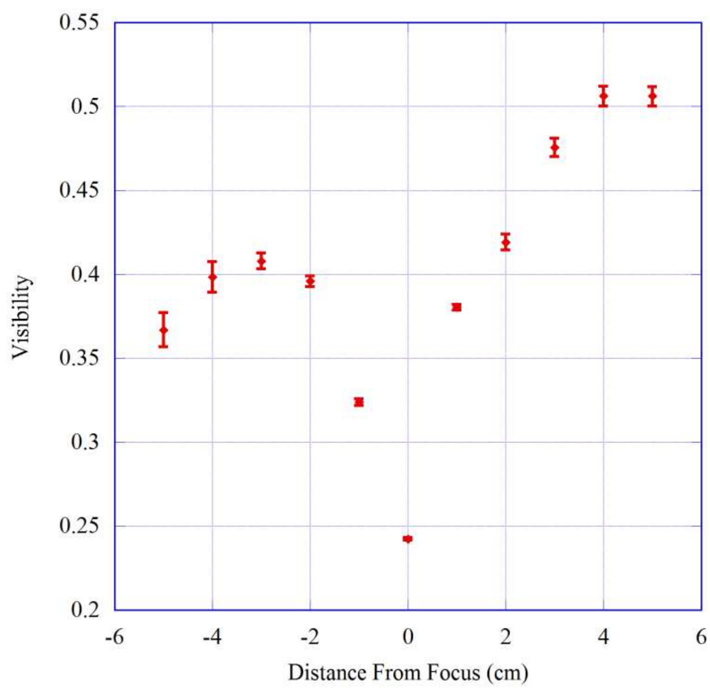

Figure 6: Visibility versus camera location for moving the CCD camera over a range of 10cm. 0cm corresponds to initially arbitrarily set "best focus".

It is evident in Fig. 6 that a minimum visibility occurs at 0cm, and this is what will be called the optimal setting. However, the minimum in the visibility corresponds to a maximum in the calculated beam size. Moving the camera away from the 0cm mark would result in a smaller calculated beam size. As a result, we have an upper limit on the beam size in CesrTA if the same method of placing the camera is used.

III. Light Intensity

While operating the Flea camera and LabView analysis code for CesrTA an auto scaling effect was noticed. The camera or LabView was changing the gain and/or the exposure time. As a result, further analysis was done to determine if this feature interferes with the ability of the analysis code to accurately determine the visibility from the interference pattern. The analysis code needs to be able to analyze images with varying intensity because the varying number of particles in CesrTA changes the amount of synchrotron radiation. The light intensity experiment was conducted at two different slit sizes, 115 and 245μm using the following method: 1.) Measure the visibility at the highest light intensity without saturating the CCD camera, 2.) Decrease light intensity by adding ND filters and measure the visibility, 3.) At each intensity take ten visibility measurements to average, and 4.) Repeat back to step 2 until the interference pattern is indistinguishable from the background. Fig. 7 shows the data for the 115μm source and Fig. 8 for the 245μm.

From these measurements it can be concluded that the visibility *is* dependent on intensity and near saturation there is a lower correlation between intensity and visibility. A note about this data is that the interference pattern started to become indistinguishable from the noise at 1 Optical Density (OD) for the 115μm slit and 1.5 OD for the 245μm slit. These measurements allow for awareness that the intensity should be maintained at a maximum via neutral density filters. Keeping the intensity at a maximum keeps the measurement in the region where there is a lower correlation between intensity and visibility as well as that a lower visibility, again, gives an upper limit on beam size for the bunches in CesrTA.

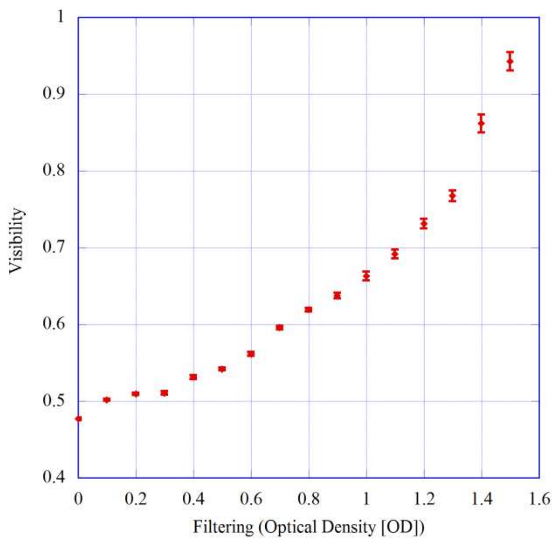

Figure 7: Effects of changing intensity via neutral density filters on the visibility for an 115μm source.

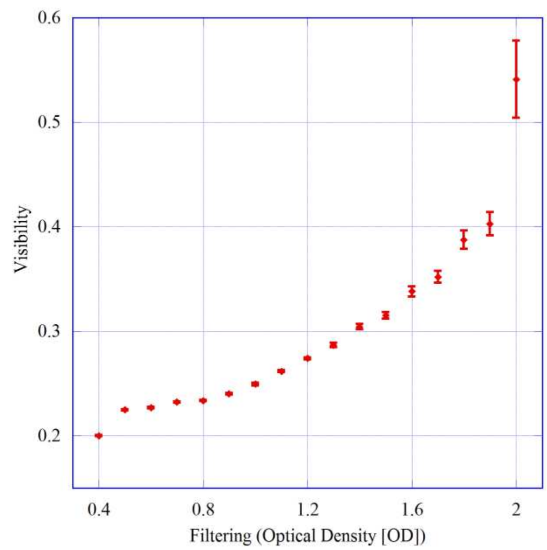

Figure 8: Effect of changing intensity via neutral density filters on the visibility for a 245μm source.

IV. Comparing Calculated and Measured Beam Size

Since the operational aspects of the experimental setup are understood, now a detailed comparison between the calculated via visibility and measured beam sizes can be conducted. This was done by using the micrometer on the single slit for what will be called the measured beam size and comparing that to the measurement that the code outputted which will be called the calculated beam size. The plots that allow for this comparison are generated by fitting the interference pattern to determine the visibility then using Eqs. 4 or 5 to determine the beam size. For the data sets the constants will follow the following convention for calculating the beam size using the equations; λ is 500nm set by the 500±10nm bandpass filter, then for each separate run d and L will be indicated along with any filtering that was used to avoid saturation. The outlined (not filled) data points correspond to the measured beam size, set and measured via the micrometer on the single slit, and the filled points correspond to using the visibility from the double slit interference pattern to calculate the beam size. This data was taken by leaving all of the optics fixed besides the single slit, then for each setting of the single slit its value was recorded as well as ten values of the visibility from the interference pattern.

In the slit width region of 50 - 250μm of Fig. 9 the measured and calculated half-width agree within 20μm at the extremes of that range. However, for the large slit widths the calculated strays away from the measured. A reason for this difference is a theoretical effect causing the visibility to decrease until it hits a lower limit, then it will rise again, and process repeat; it will look like the path a bouncing ball takes. This theoretical effect has been previously experimentally verified [5] and can be seen in the slit width range of 280 - 600µm. In addition to having the half-width in Fig. 9, there are also the sigma measurements to use as reference, where sigma corresponds to a Gaussian source like CesrTA. The calculated sigma does not correspond to the measured values further reinforcing the previous finding that the source distribution of the Cal Poly instrument is square and not Gaussian.

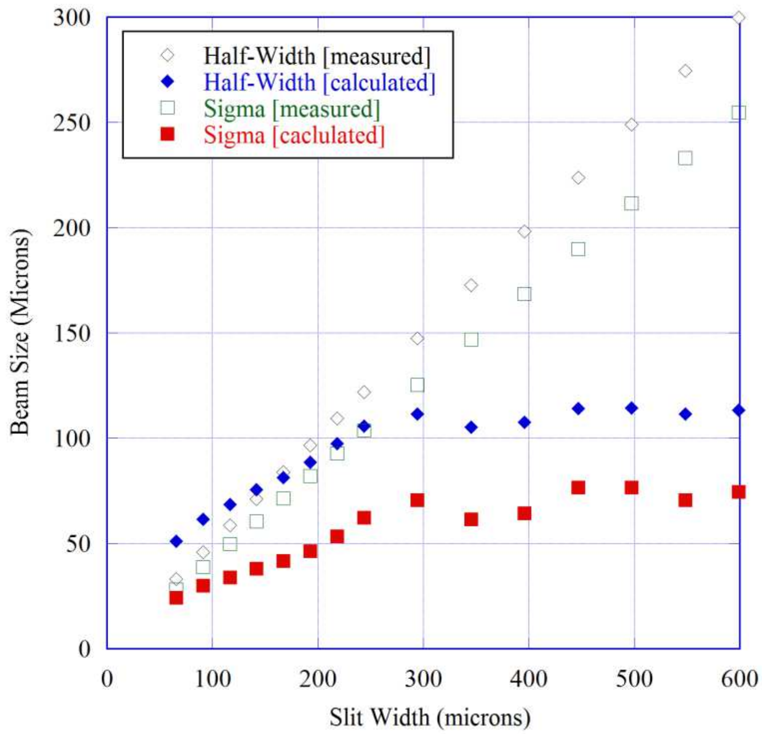

Figure 9: For various source widths, shows calculated and measured values for 5mm spaced double slits, a source to slits distance of 1.9m, and a 0.6 OD filter.

In order to extend the results from the Cal Poly setup to the CesrTA experiment, a further understanding of the other variables in Eqs. 4 and 5 needed to be obtained. The subsequent studies will reflect changing the following variables: *L*, the source to slits distance, and *d*, the slit separation. CesrTA's setup has a source to slits distance of 5.92m and a double slit separation of 2.5mm which is significantly different from the 1.9m distance and 5mm spacing used to generate the data in Fig. 9 at Cal Poly. To reconcile these differences and to determine how these parameters affect the data, *L* and *d* will be changed. Three different combinations were used: *L* = 1.9m with *d* = 5mm, *L* = 1.9m with *d* = 4mm, and *L* = 1.6m with *d* = 4mm.

With the 4mm space double slits the calculated data follows the same trend as the measured values (see Fig. 10). One reason for the Fig. 10 data agreeing better than the Fig. 9 data is that data was not taken for large slit widths that were outside the sensitive range of the interferometer. With 4mm slits it is evident that the calculated value has greater sensitivity to larger beam sizes because unlike the calculated values in Fig. 9, Fig. 10's calculated values do not bounce or asymptotically reach a maximum value.

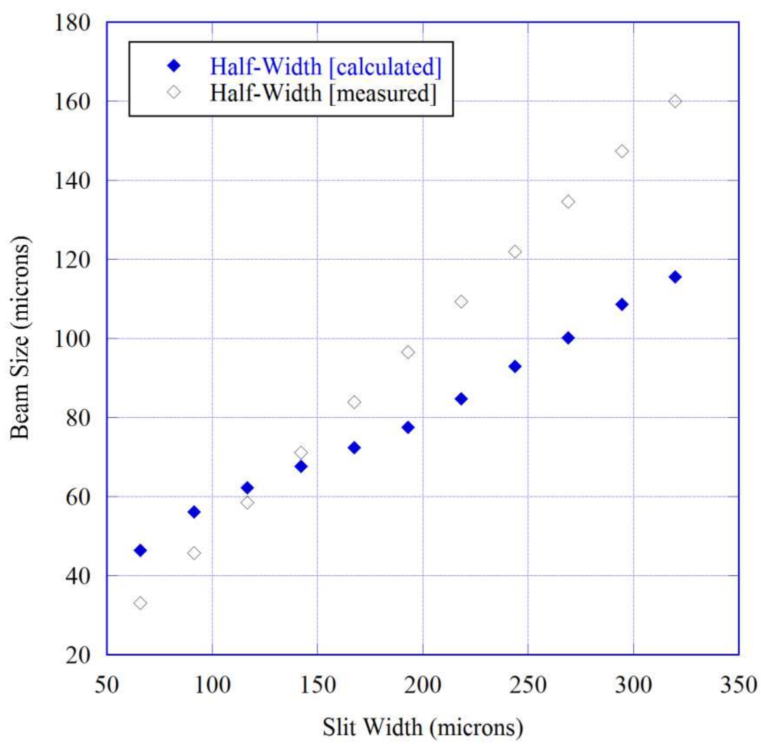

Figure 10: For various source widths, shows calculated and measured values for 4mm spaced double slits, a source to slits distance of 1.9m, and a 1.0 OD filter.

When the source to slits distance (*L*) was changed to 1.6m instead of 1.9m the data in Figs. 11 and 12 resulted. Fig. 11 data was taken with a neutral density filter of 0.6 OD and as the single slit was opened up the CCD camera saturated, clipping the signal. Fig. 12 continues to larger beam sizes avoiding saturation with a 1.0 OD filter. Since the CCD saturated the calculation from fitting the interference pattern was failing, so the sweep was ended and restarted with a higher filtering covering some of the data points twice near where the clipping was observed. For the calculated values at the overlapping slit widths, which would be the last three calculated values in Fig. 11 and the first three calculated values in Fig. 12, a slight discrepancy can be noted. However, the drop in value of calculated beam size moving from the data in Fig. 11 to Fig. 12 can be attributed to the intensity effect already analyzed. The data does reinforce the trend already noted that the higher intensity in Fig. 11 will correspond to a higher calculated beam size than the lower intensity data points in Fig. 12.

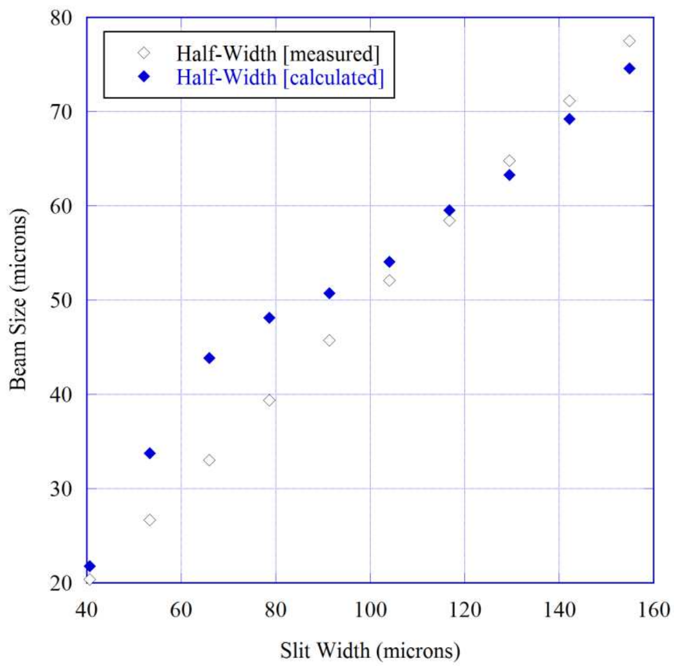

Figure 11: For various source widths, shows calculated and measured values for 4mm spaced double slits, a source to slits distance of 1.6m and a 0.6OD filter. This was the first set taken with these parameters until the CCD saturated at larger beam sizes. The data was continued in Fig. 12 with higher filtering.

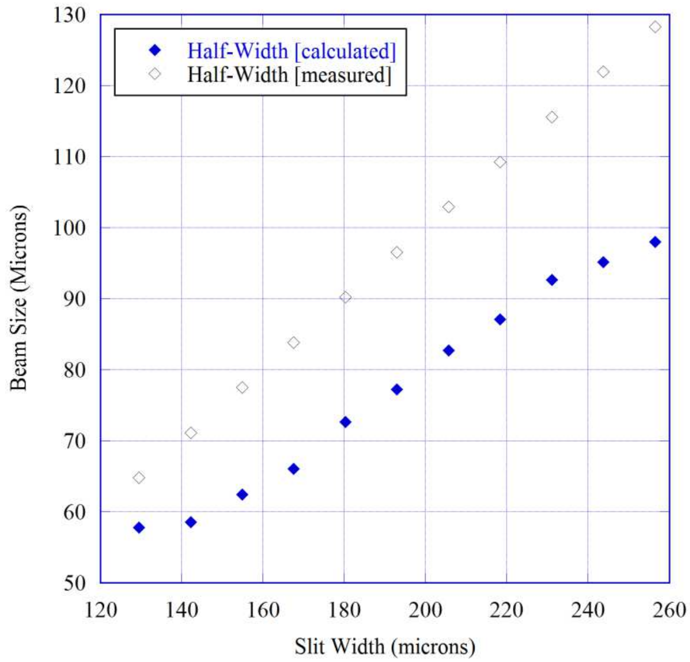

Figure 12: For various source widths, shows calculated and measured values for 4mm spaced double slits, a source to slits distance of 1.6m, and 1.0OD filter. This is a continuation of the sweep started in Fig. 11.

In Figs. 9, 10, and 11 the calculated always starts out above the measured and then falls below the measured. Based off this, if the interferometer is operated in an optimal arrangement near where the calculated crosses over the measured, then the calculated beam size using the interference pattern for a beam in CesrTA could be within a few microns. However, if the interferometer is not operated in this optimal regime that correspond to large visibilities (>0.25) and near saturation of the CCD then the measurement can be as inaccurate as 40μm which is ~15% error. In Figs. 10 through 12 the calculated follows a linear relationship just with the wrong slope to directly correspond with the measured. It appears possible that with calibration this method of using a double slit interferometer could be used to get the horizontal beam size of bunches in CesrTA with an error much less that 15%.

Conclusion

Even though the Cal Poly light source was verified to be a square distribution, compared to the Gaussian source distribution provided by bunches in CesrTA, it provided a reasonable simulation of a source needed to benchmark the double slit interferometer instrument. After verifying the differences between the CesrTA and Cal Poly setup, depending on what beam size the instrument is optimized for will change the accuracy of the measurement. For some of the measurements taken at Cal Poly at small slit sizes and hence high visibility the calculated beam size from the visibility differs with the measured by up to 30μm, and is within 50μm for the larger beam sizes and lower visibility. However, if only expecting to look at a small range of beam sizes and if properly optimized for that range then the calculated beam size can be within a few microns of the actual source size. From the data collected there is a correlation between the beam size and the visibility giving the option of using it as a relative measurement, however until the interferometer is properly calibrated for CesrTA the calculated beam size may only be 5% accurate. After the interferometer is calibrated it is reasonable that the calculated beam size may be well within 1%, if used in its calibrated and optimized range.

Special Thanks To:

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