DESY Summer Students Programme Report

Monte Carlo Error Analysis for Wire Scanner Measurements at FLASH

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Abstract

I studied the error contribution to measurements of the transverse electron beam profile with wire scanners. Monte Carlo simulations were made to understand the contribution of three sources of error to the measurement of the σ of the beam profile. Based on the analysis of the simulated data obtained, I have derived an equation to calculate the statistical error of σ. This expresion was later applied to measured data. As a result of this, it was seen that the most significant contribution to the error of σ comes from the the change in position between electron bunches. This report shows the work I did as part of the DESY Summer Students Programme 2007, I worked in the Accelerator Physics Group, in the field of beam instrumentation.

1 Introduction

1.1 FLASH

FLASH is a free electron laser that is currently used both as a pilot facility for the European XFEL project and as a user facility for VUV and soft X-ray coherent light experiments. A diagram of the machine is shown in figure 1 .

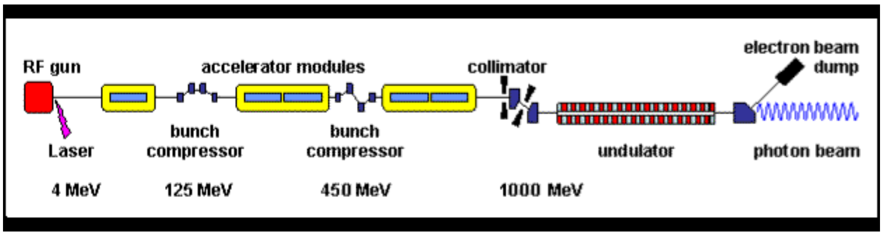
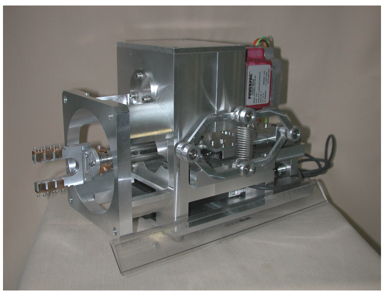


Figure 1: FLASH diagram.

Bunches of electrons are produced in a laser-driven photoinjector and accelerated up to 1 GeV by a superconducting linear accelerator. Once the electrons have been accelerated, they enter the undulator region, where the laser light is produced by means of *Self Amplified Stimulated Emision*. This process requires a very straight beam trajectory along the undulator and very high electron density inside the bunches. To achieve the second, instrumentation for transverse beam size is needed as will be explained in the next section.

1.2 Transverse beam size instrumentation

Along the FLASH facility, Wire Scanners (WS) and View Screens (VS) are used to determine the electron beam transverse profile. The WS consists of a wire mounted in a way that it can be moved perpendicularly to the electron beam, so it interrupts the motion of a certain amount of electrons that form the electron bunch passing by at that instant. In figure 2 left we can see the mechanism by which this is achieved. When electrons interact with the wire, they unleash a cascade of electromagnetic radiaton that is detected by a photomultiplier positioned downstream. The magnitude of this cascade is proportional to the number of electrons that interacted with the wire. Therefore, whenever the density of electrons increases, so too will the cascade detector response. In this way a one dimensional profile can be obtained after analysing the data taken by the photomultipliers. Each scanner has three wires of diferent material and diameter as shown in figure 2 right. The amplitude of the signal depends on the wire used as well as on the voltage applied to the photomultiplier. There are two WSs at each position, one that moves horizontally and the other vertically, to measure the horizontal and the vertical beam sizes, respectively.



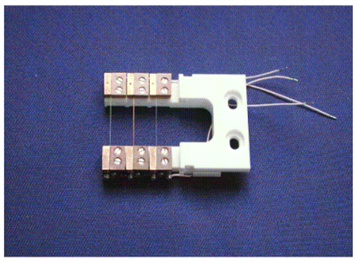


Figure 2: Each scanner has three wires mounted: $10\mu m$ Carbon, $10\mu m$ and $50\mu m$ Tungsten.

The VS consists of a screen that emits light when the electron beam goes through it, so that a camera takes a picture of it and a two dimensional profile can be seen immediatly. Unfortunately, the interaction

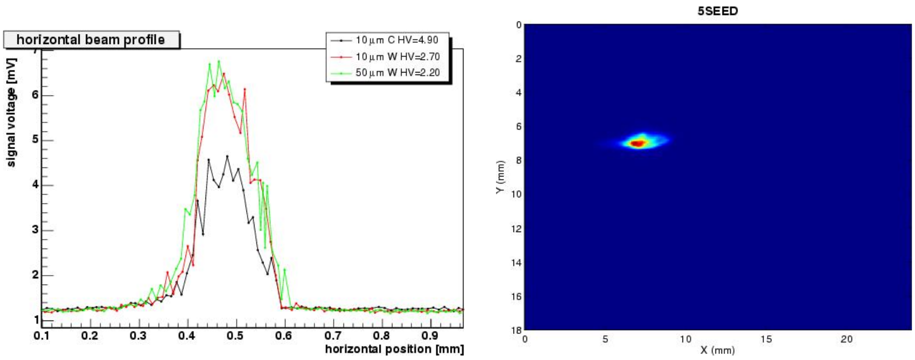


Figure 3: View screen and wire scanner example measurements.

with the screen destroys the electron beam and the radiation emitted makes it imposible to place them in the undulator region. Instead, they are placed elsewhere. Examples of both measurements are shown in figure 3 right. WSs only interupt a very small fraction of the beam and no significant amount of radiation is emitted to the surrounding so it is safe to place them along the undulator section as they will not damage them. As the WS moves along the cross section of the beam, different electron pulses interact with the wire and if the pulses are not in the same position nor have the same charge, as indeed happens, it is difficult to interpret the data taken.

2 Monte Carlo Simulation

We have made Monte Carlo simulations in order to understand the influence of the errors when measuring the electron beam profile with a WS. We have taken a Gaussian profile to represent the transverse beam profile in order to simplify the analysis, and this is, in first order, a good approximation to the measured data. So, the initial beam profile was generated from the Gaussian function:

$$f(x) = \frac{B}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}. \quad (1)$$

For simplification again, $\sigma = 1$, $\mu = 0$ and $B = \sqrt{2\pi}$ were used. The parameters used in the simulation (described below) will be expressed in terms of σ or B. To represent the measured points, we have then sampled the function:

$$f(x) = e^{-\frac{x^2}{2}}, \quad (2)$$

taking N points in the range of $[-4, 4]$, so that the pairs $\{x_i, y_i = f(x_i)\}$ were obtained. The sampling frequency, or points per sigma n_s, which is an important parameter to take into account, is obtained from N, the range of x_i and σ

$$n_s = \frac{N}{(x_{max} - x_{min})\,\sigma}. \quad (3)$$

Afterwards, errors are introduced as indicated in the following, where r_g is used to denote a pseudorandom number within a Gaussian distribution centred around zero.

ex is the error introduced by relative changes on the position of succesive bunches and it is relative to $\sigma = 1$.

$$x_i \to x_i + r_g \times ex. \quad (4)$$

ey is the error due to the detector noise and is relative to the maximum $y_{max} = 1$:

$$y_i \to y_i + r_g \times ey \quad (5)$$

ey2 is the error due to charge variations between successive electron bunches and it is relative to the signal in each point y_i:

$$y_i \to y_i + y_i \times r_g \times ey2 \quad (6)$$

An example of the profile obtained as a result of all this is shown in figure 4.

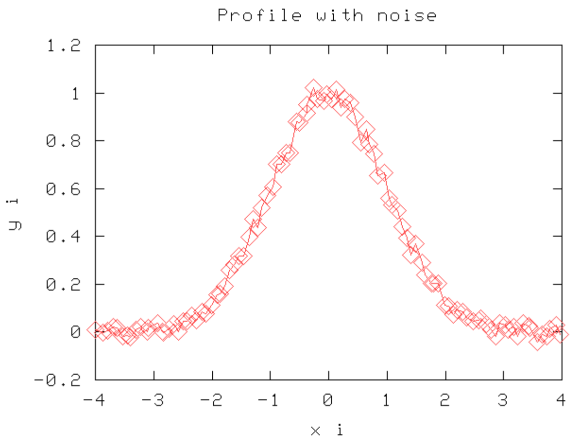


Figure 4: Profile used to simulate the measured beam profile. In this case $ex = ey = ey2 = 2\%$ and $N = 100$, $n_s = 12.5$.

After the profile with noise is obtained, a Gaussian curve is fitted to the points in it, and a parameter σ_k (the sigma of the Gaussian curve) is obtained (not equal to $\sigma = 1$, but close). This process is repeated many times, typically ten thousand ($simul = 10000$), so an array with the parameters σ_k is generated.

In figure 5 the distribution of these values is shown and, as we can see, it is close to a Gaussian one. At this point, the standard deviation of these values is calculated to get the final parameter σ_{sd}, which represents the relative statistical error of the σ of the measured beam profile.

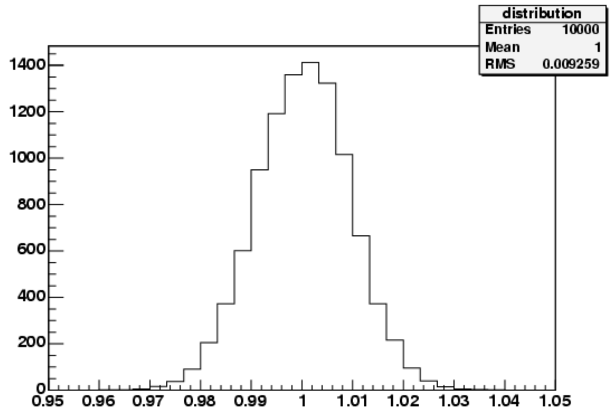


Figure 5: Histogram of the σ_k distribution and whose standar deviation will be σ_{sd}.

2.1 Analysis of simulated data

In figure 6, three graphs of the data obtained from the simulations are shown. In each graph, one error was increasing while the others were set to zero. These curves are plotted with the same scale so it is easy to compare the relevance of each source of error. For the same relative error value, the error caused by the detector noise (ey) is the largest, followed by the error due to charge variations (ey2) and finally by the error associated with the beam movement (ex).

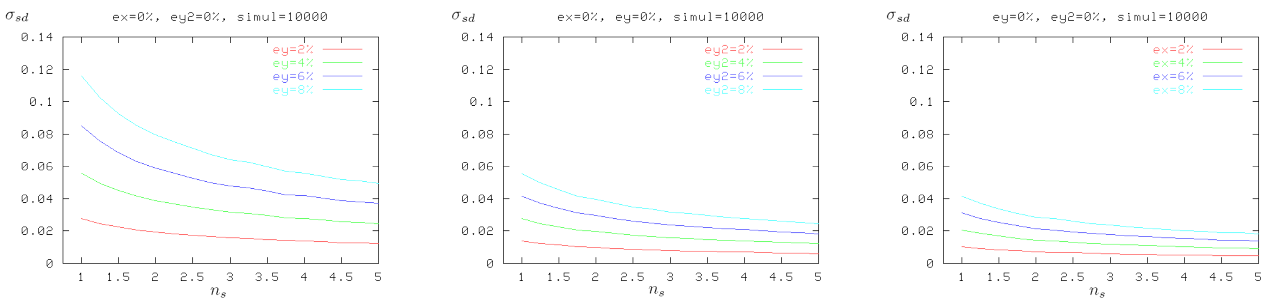


Figure 6: Error sources taken individually.

As we can see, the relative error of σ, σ_{sd}, decreases with increasing number of points n_s. As expected, the function that determines this behaviour is:

$$\sigma_{sd} = \frac{a}{\sqrt{n_s}}. \tag{7}$$

This function is fitted to the simulated data of figure 6 right as it is presented in figure 7. The parameter a of equation 7 is determined for each curve fitted. An analogous procedure was applied to the other two graphs in figure 6, and the data obtained was plotted and shown in figure 8.

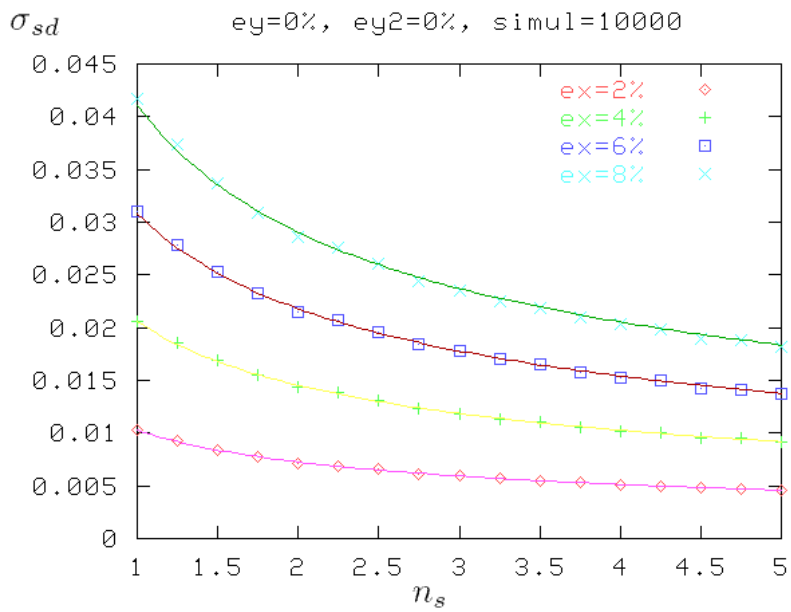


Figure 7: σ_{sd} Vs n_s for diferent values of ex while $ey = ey2 = 0$.

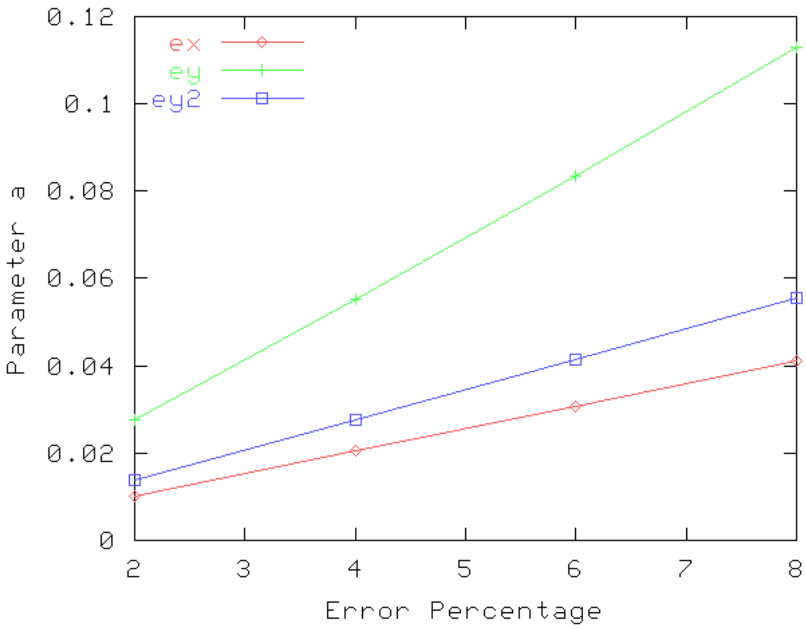


Figure 8: Relation between error values and a parameter from equation 7.

As can be easily seen, the lines of figure 8 have a constant slope given by $A = \frac{a}{error}$. The values calculated are shown in table 1. The parameter A is independent of the magnitude of the error and provides information only on the relative contribution of each source of error to σ_{sd}.

As the sources of error in the simulation are independent, the relation they must obey is:

$$\sigma_{sd} = \sqrt{\frac{(A_x\ ex)^2\ +\ (A_y\ ey)^2\ +\ (A_{y_2}\ ey_2)^2}{n_s}}. \tag{8}$$

A_x	A_y	A_{y_2}
0.51	1.38	0.69

Table 1: Value of parameters **A.**

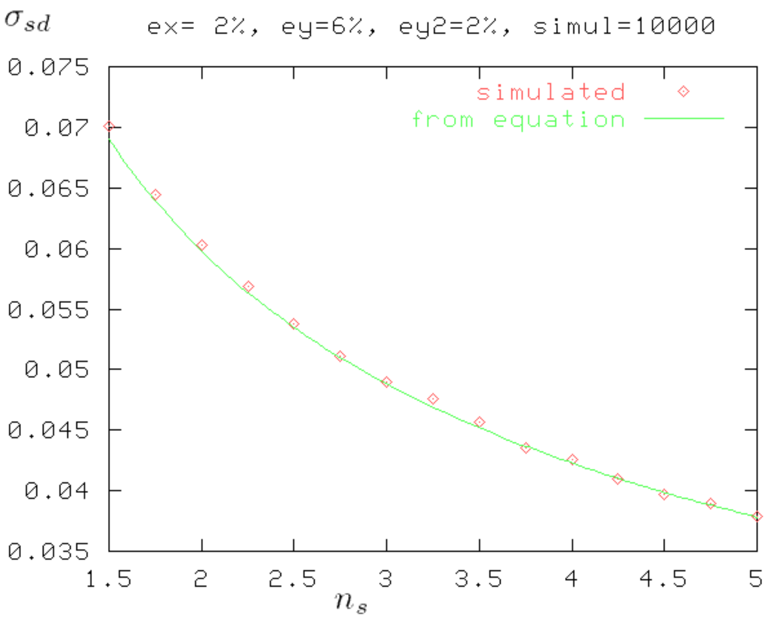


Figure 9: Comparision of data simulated and expected value from equation 8.

This is proved in figure 9 where the simulated data have the values $ex = 2\%$, $ey = 6\%$, $ey2 = 2\%$. The lines from equation 8 were obtained using the same value for the parameters and the corresponding values of A. As it is seen, there is a good correspondance between them.

3 Analysis of Measured Data

Some measured data was analysed in order to calculate the typical magnitude of the errors in our experimental setup. Data of the position of the beam from one monitor was used to calculate ex. First, the standard deviation of all the values was taken and afterwards it was divided by the σ of the profile obtained with the WS. To calculate ey2, the standard deviation of data of the charge of the beam was taken and then it was divided by the average charge. In order to find ey, the standard deviation of the data taken with the photomultiplier was divided by the height of the profile. This height was found by subtracting an average value of a region with no signal to the maximum of the profile. The results are shown in table 2. The column for σ_{sd} was obtained using equation 8 and data from previous columns.

n_s	σ [mm]	ex [%]	ey [%]	ey2 [%]	σ_x [%]	σ_y [%]	$\sigma_y 2$ [%]	σ_{sd} [%]
4.9	0.030	31	1.9	3.4	16	2.6	2.3	7.4
5.7	0.035	43	0.3	2.8	22	0.4	1.9	9.3
7.2	0.148	10	0.5	2.1	5.3	0.6	1.4	2.0
15.9	0.0978	21	2.1	2.8	11	2.8	1.9	2.8
18.3	0.113	17	0.5	3.2	8.9	0.6	2.2	2.1
20.2	0.124	12	0.6	3.1	6.3	0.8	2.1	1.4
20.3	0.125	21	1.3	3.5	11	1.7	2.4	2.5
28.8	0.176	9.6	1.4	3.7	4.8	1.9	2.5	1.0

Table 2: Parameters calculated from measured data.

Considering both the parameter A and the actual value of the error, it is seen that the error due to the movement of the beam is the one that contributes the most to the measurement of σ.

Fortunately, the position of the centre and the magnitude of the electron pulse can be measured by means of a charge monitor. One might think that these corrections could be easily introduced to make the curve of the profile more accurate. A graph in which these corrections were introduced is shown in figure 10. The black line corresponds to data taken directly by the WS, the red one shows data with position corrections and the green one shows both position and charge corrections. It can be seen there that the curve worsens when this is done.

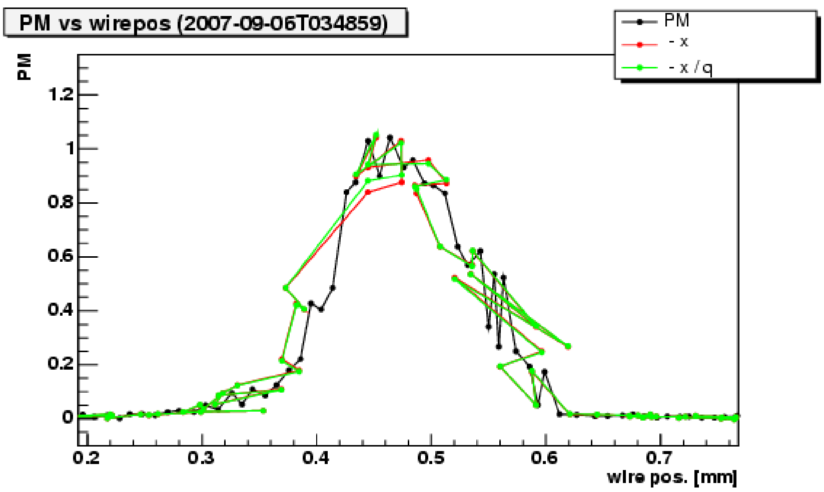


Figure 10: Corrections due to beam movement and charge variations were introduced to green data of figure 3 left.

To understand this, it is necessary to consider that the charge and position monitors have a measurement error that has not been treated in this work. Apparently, this error is bigger than the correction that is intended to be introduced, so it is worthless to do so at the moment.

4 Outlook

In order to introduce a correction to the electron beam profile due to position variations, it is necessary to lower the error of the monitor used to measure this position. This can be done by using a correlation method between several position monitors in a way that only movement seen by all of them is considered.

Acknowledgements

I would like to thank my supervisor Dr. Pedro Castro García for his continued patience and support throughout this project.