

# The Pepperpot measurement bench

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## Abstract

The USPAS (the US particle accelerator school) in Albuquerque 2009 had a session that was dedicated to *accelerator and beam diagnostics*. In addition to lectures, hands on exercises were provided in the laboratory. This paper explains the exercises on emittance measurements for which an optical bench with a light source, a pepperpot plate, several lenses and a GigaBit Ethernet camera was provided. The goal of this exercise is to understand the different types of emittance measurements, namely the pepperpot, the 3 profile measurement and the quadrupole scan.

The exercises have been recuperated and updated for the African School of Fundamental Physics (Dakar 2014) where unfortunately the optical bench could not be provided for logistical reasons. We therefore evaluate measurements that are provided as images using the same evaluation programs.

## 1. THE OPTICAL BENCH

The optical bench consists of the following parts:

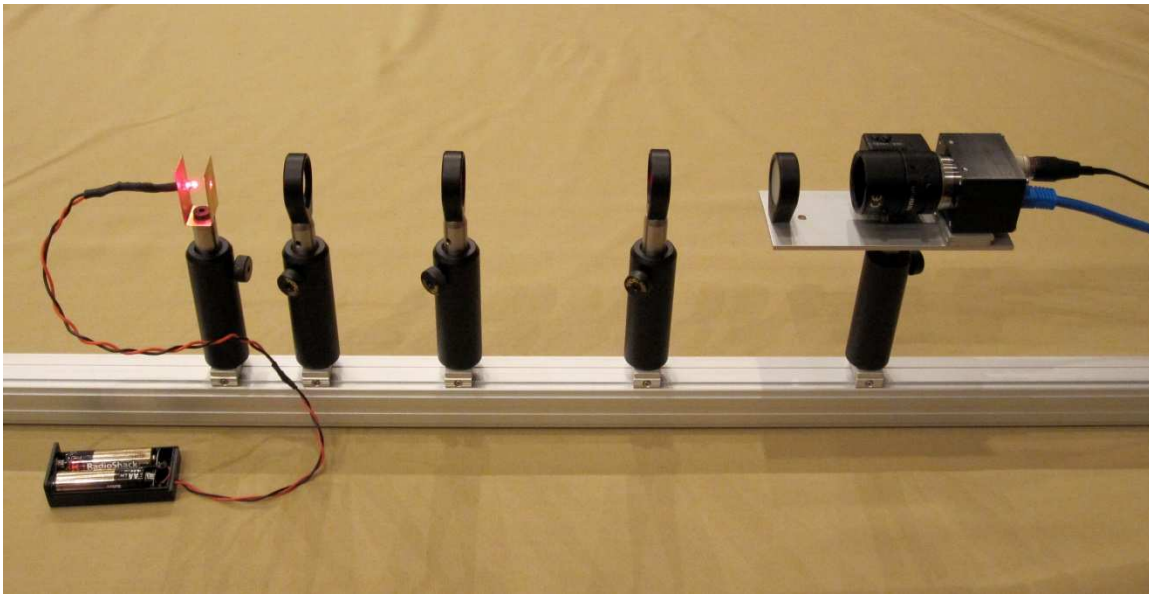
- a particle source (powerfull red LED)
- a collimator producing a point like source
- the lenses with the following focal length:
  - 24 mm
  - 30 mm
  - 43 mm
  - 54 mm
  - 76 mm
  - 100 mm
- a pepperpot plate with
  - 8x8 holes (200  $\mu\text{m}$ ) of 2 mm distance
- a screen
- a Prosilica-GC750 GigaBit Ethernet camera

The following software is part of the system:

- The *GigEViewer* program as well as a LabView equivalent is delivered by the supplier of the camera. It allows modifying the settings of the camera (exposure time, gain ...) and

can display the camera image in real-time. Snapshots can also be taken. The program allows saving the camera image in Microsoft tif (.tif) format, the LabView program also permits .png, which is the preferred format.

- OpticalRayTrace is a simulation program for optical benches. This program is used to understand the optical properties of the pepperpot bench.
- *QPepperpot* is a program that allows evaluation of the bitmap file. You can:
  - load an image
  - find x and y coordinates of a point within the image
  - find and plot a single row or column to find the pixel intensities
  - define an area of interest (AOI)
  - calculate and plot projections to the x or y axis
  - save the image in ASCII format for evaluation with standard tools like excel, MatLab etc.
  - save the projections (in ASCII)
  - enter the center position of the image
  - enter the scaling factor (number of pixels / mm)
  - calculate and plot the emittance mountain
  - save the emittance data (in ASCII) for further evaluation or plotting with an external program

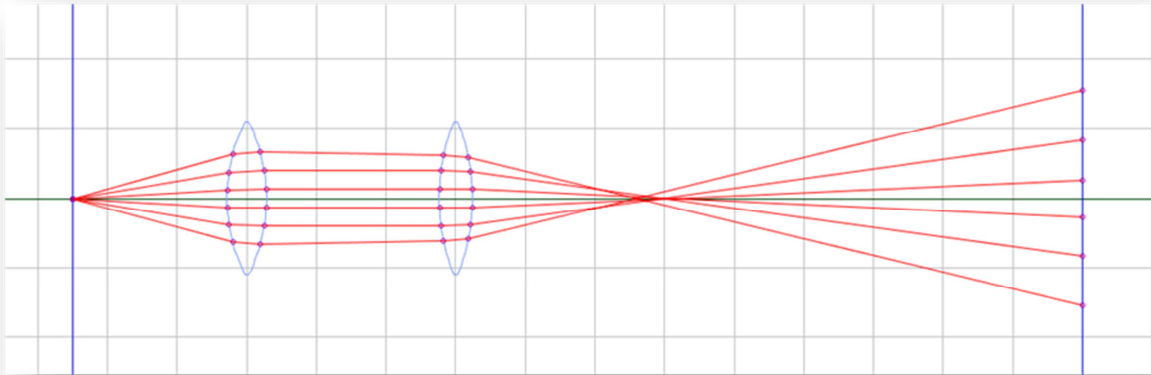


## 2. CALCULATION OF THE OPTICS

Measure the distances between the light source, the lenses and the screen and simulate the optical properties of your line with OpticalRayTracer. The physics background used by this

program can be found in the document “*OpticalRayTracer Technical Discussion*” of which you have a printed copy. Details on how to use the program you find in its help file.

For ASP 2014 we will skip this part for lack of time.

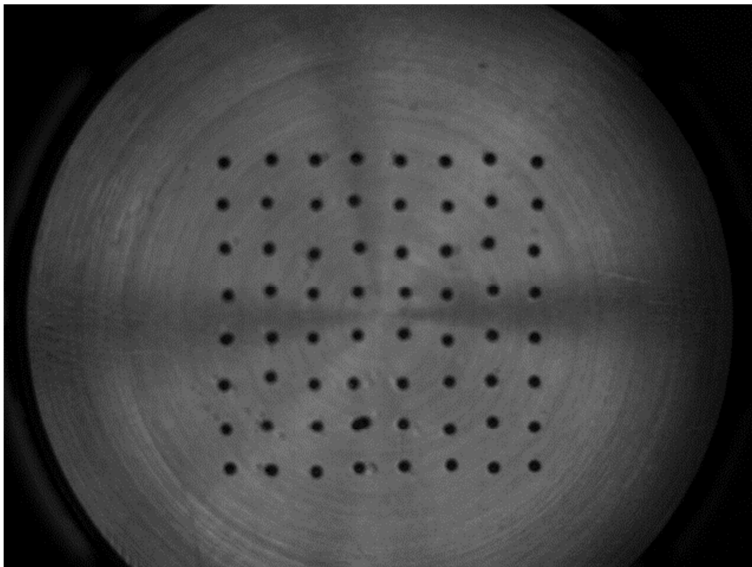


**Figure 1: Simulating the optical bench**

### **3. THE EMITTANCE FROM A PEPPERPOT IMAGE**

#### *3.1.1 Calibration*

Before starting to take any measurements the device needs to be calibrated. We need to know the relationship between the distance of 2 points on an image in pixels and this same distance in reality, in mm. In order to do this calibration the screen is replaced by the pepperpot plate and an image is taken. The center of the image in pixels must also be determined.



**Figure 2: The pepperpot plate**

The pepperpot evaluation program brings up a cursor if you press the first mouse button on the pepperpot image and the current cursor position is shown on the LCD display (bottom left in Figure 3). The screen is then put back and the distance between camera and screen stays fixed from then on.

### 3.1.2 Evaluating a “good” measurement

The image on the right of figure 2 shows a typical “good” measurement. The image of each pepperpot hole is clearly visible, the signal to noise ratio is good.

In order to extract the emittance from this image first start the pepperpot evaluation program *QPepperpot* and read in an image from a measurement file (File -> Open image). The image file must be a valid pixmap file e.g. “screenimage.bmp”. Then enter the calibration values, scaling factor in pixels/mm (32.6 in Figure 4) and the center of the pepperpot plate in pixels (320,240).. Only the horizontal value will be used. The *settings dialog box* (*Settings -> Configure Pepperpot*) is foreseen for this purpose.

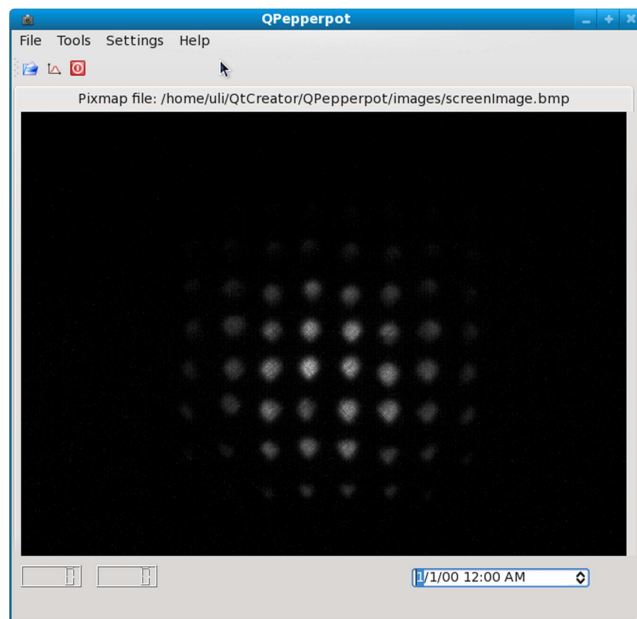


Figure 3: QPepperpot evaluation program

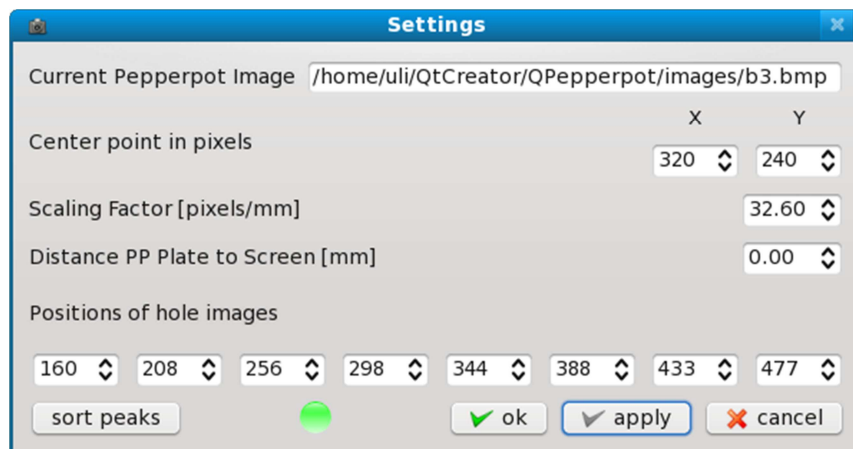
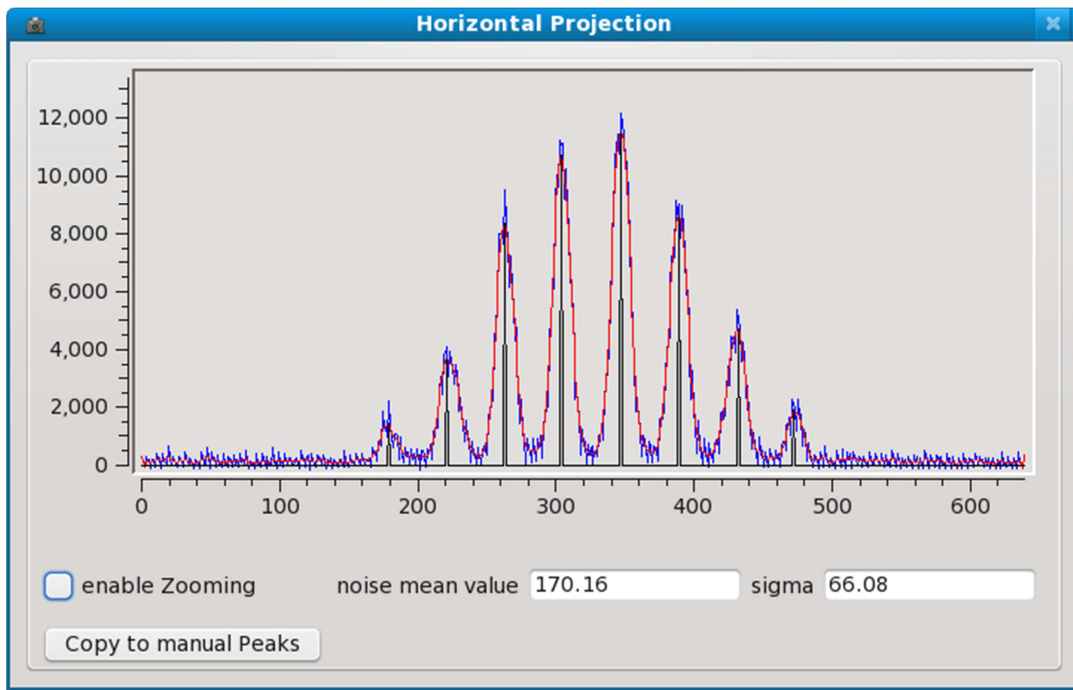


Figure 4: The settings dialog box

The next step is to calculate the projection of the image to the horizontal axis (*Tools->Projections* or the Toolbar button showing the histogram)



**Figure 5: Projection**

The Tools menu in the menu bar allows selection of options for display of the projection. You may

- Display only the raw data. Display of raw data may be switched of if low-pass filtering is enabled.
- Low-pass filter the data and show the filtered data
- Automatically find the 8 peaks in the histogram that correspond to the image of the 8 pepperpot holes.
- Switch display of the peak positions on or off.

In Figure 5 all curves are shown on a single plot: The blue curve shows the raw data. On the red curve the projection is filtered and the black curve shows the peaks found. The mean noise value and its variance, calculated over the first 50 points is also displayed. You may also read the peak positions by pushing the first mouse button

Now that the positions of the image of all 8 pepperpot holes is known and the calibration has been entered the emittance ellipse can be determined. Tools -> Emittance will display the results.

Figure 6 shows a typical emittance plot for a converging beam.

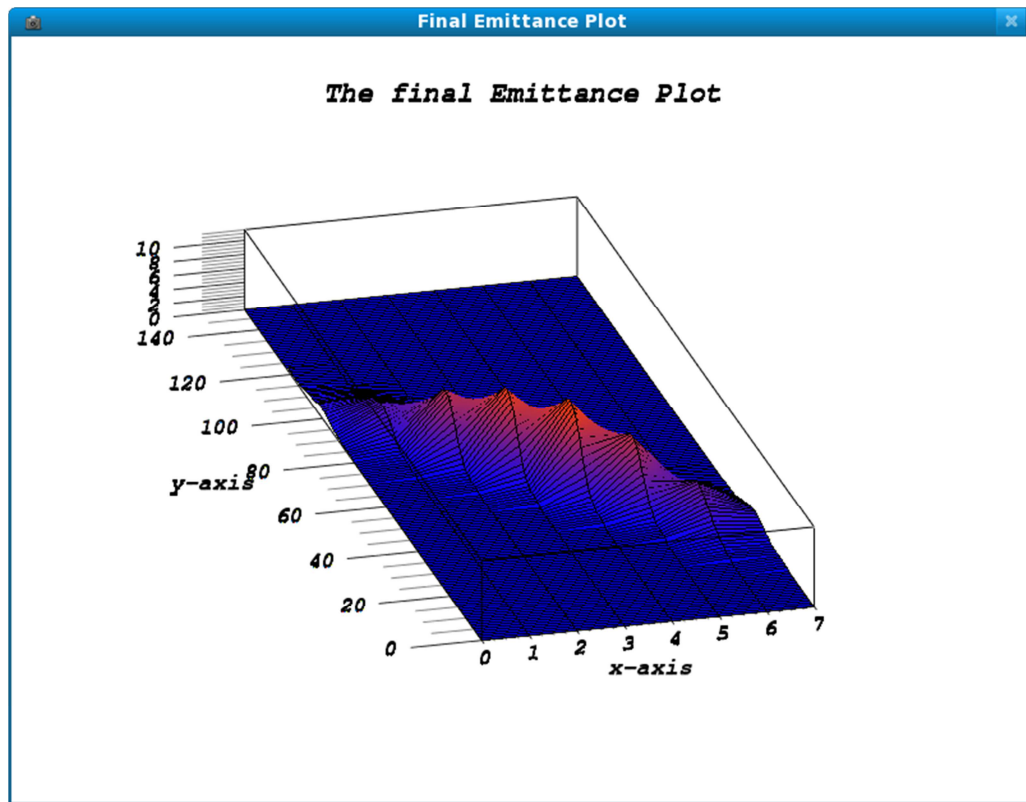


Figure 6: Emittance Plot

### 3.1.3 Evaluating a measurement that is less clean

Unfortunately not all measurements are as clean as the one shown in the previous section. If the camera settings are not perfect e.g. the aperture is not opened enough, if the contrast settings are not perfect ... we may end up trying to analyze an image whose projection looks like the one shown in Figure 7. Since even a human has a hard time to see the hole-images, it is even more difficult for a program to automatically evaluate such an image.

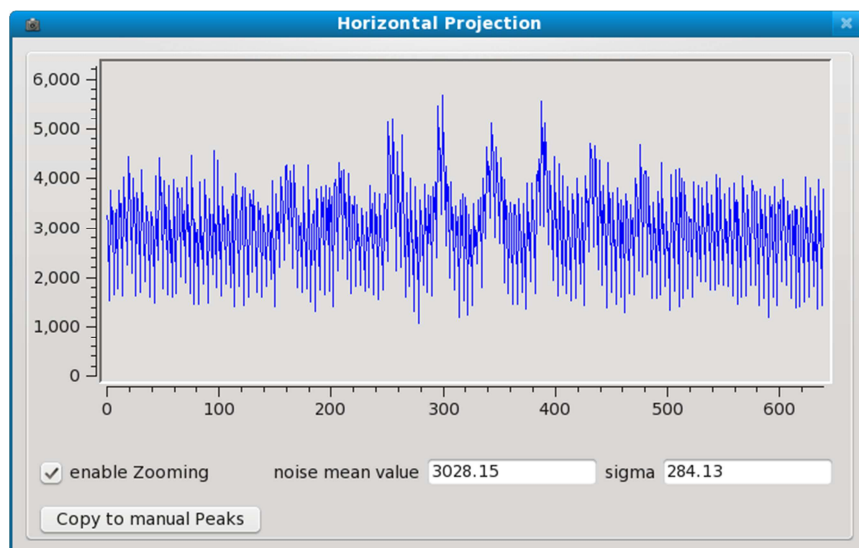
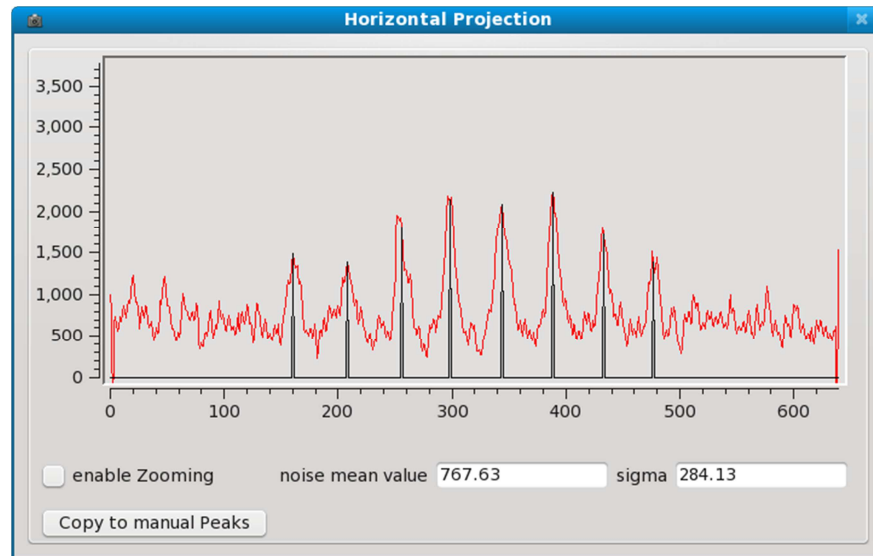


Figure 7 Noisy projection

The pepperpot evaluation program helps through low pass filtering and offset suppression (*Tools->Show filtered* and *Tools -> Subtract Offset*).



**Figure 8: Cleaned projection**

If you try to automatically find the peaks however, the program will only find four out of the eight peaks. These peaks can be copied to the *settings dialog box* with the “copy to manual peaks” button. After having copied the peaks, switch off automatic peak finding (*Tool->Automatically find peaks* must be switched off). You may now define the peaks by hand in the *settings dialog box*. The plot will show you how you placed them. All 8 peaks must be defined. Clicking the left mouse button on the projection plot brings up a cursor whose current position is shown. This may help you when finding the peaks. You may also have a closer look at the background in order to see if there are any systematic errors by switching on the zooming. Click and drag to zoom into the picture.

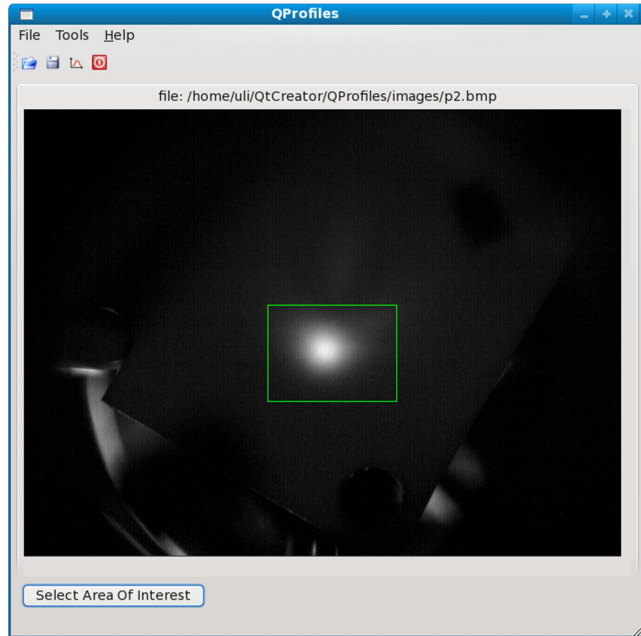
Once you finished defining the peaks by hand you may again try to plot the emittance. The emittance plot will use the manually defined peaks instead of the automatically found ones.

#### 4. EMITTANCE MEASUREMENT USING 3 PROFILES

Another method for determination of the emittance is the so-called *3 profile method*. Three profiles are measured in a drift space, if possible at a phase advance of 60 degrees between each profile. Measuring the beam width defines 2 vertical lines (the beam “edges”) in phase space. Knowing the optics (which is particularly simple in a drift space) and in the absence of non-linear forces like e.g. space charge effects, these vertical lines can be transformed to the position of one of the other measurements using the optical transfer matrix. The lines then enclose the emittance ellipse.

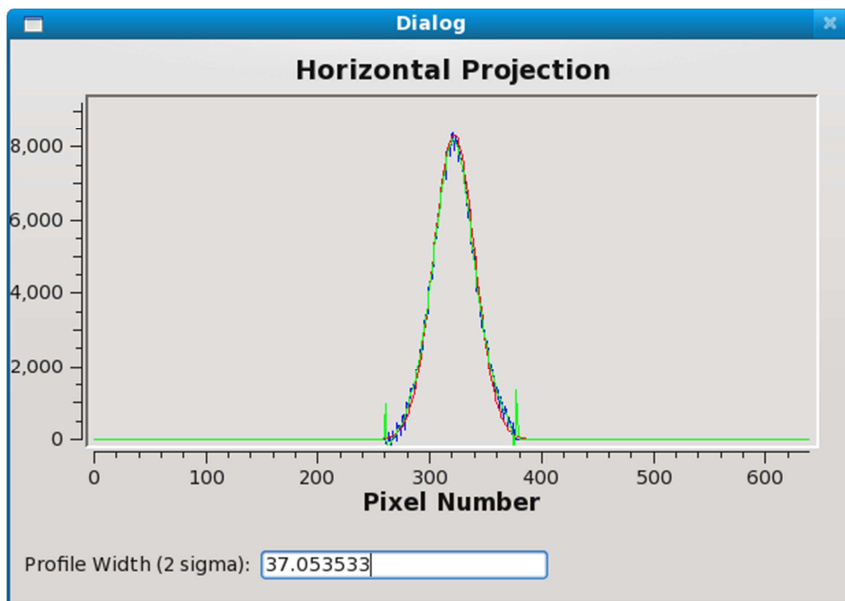
First we create a converging beam which becomes diverging after a waist (focal point). We measure beam profiles at several positions along the optical bench and note the distance to the lens. From the beam spots the beam width must be extracted. Unfortunately it is difficult to avoid stray light coming into the system such that a typical image does not only show the beam stop but also some background coming from the frames etc. This background must be eliminated. An

evaluation program for the profiles (qprofile) allows the selection of an area of interest (click the first mouse button and drag, push *Select Area of Interest* to eliminate background. Click the right mouse button to restore the original image).



**Figure 9: A raw beam spot**

Once the Image has been cleaned the projections can be calculated (*Tools -> Hor Projection* or the histogram button). The projection may be noisy and can be low-pass filtered with *Tools -> Filter Data*. A possible offset can also be corrected (*Tools -> Subtract Offset*). When the *subtract offset* option is switched off, the calculated offset is shown (curve in magenta).



**Figure 10: Projection of light spot**



The variance is calculated from the corrected curve and a gauss curve with the same sigma is shown (in red).

Knowing the beam width at several positions we can now proceed with the optics calculations. The transfer matrix T for a drift space is given by

$$T = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix}$$

where L is the length of the drift.

If calculating back to the first profile position, its inverse is needed.

With  $T = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$  we get:  $T^{-1} = \frac{1}{\det T} \begin{pmatrix} d & -b \\ -c & a \end{pmatrix}$  and  $\det T = ad - bc$ .

which results in  $T^{-1} = \begin{pmatrix} 1 & -L \\ 0 & 1 \end{pmatrix}$

(L is replaced by -L). Another small program (optics) does the simple multiplication of the vector with the inverse Matrix. As you can see, the angle is set arbitrarily to 1.

The vertical line at position 41.7 (beam width) transforms to a line going through (x,0) and (x-Lx',x'), in the example below (41.7,0) to (-28.3,1).

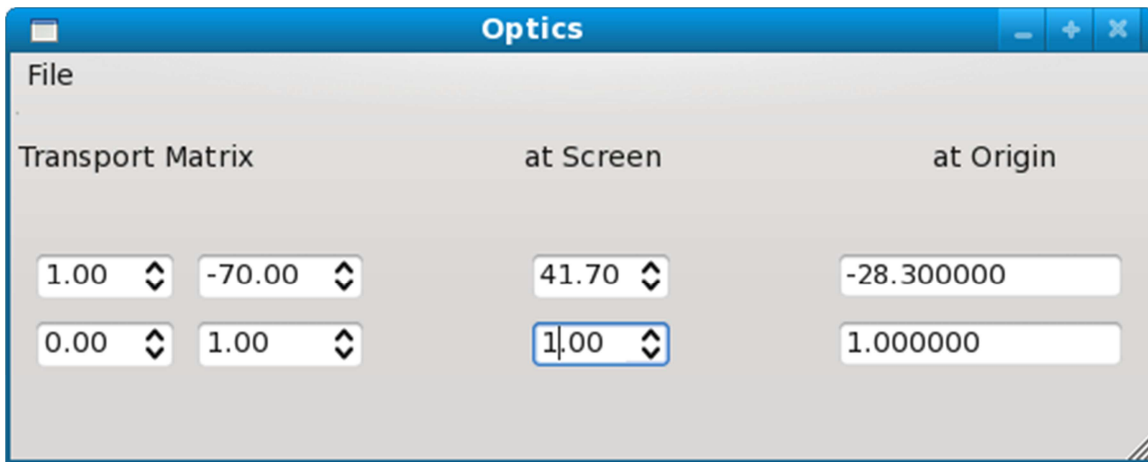


Figure 11: Program to calculate the optics

Finally these lines must be drawn and an emittance fitted to it, which is done with a third program (drawEmittance). Simply enter the end points of the lines and fit the ellipse manually.

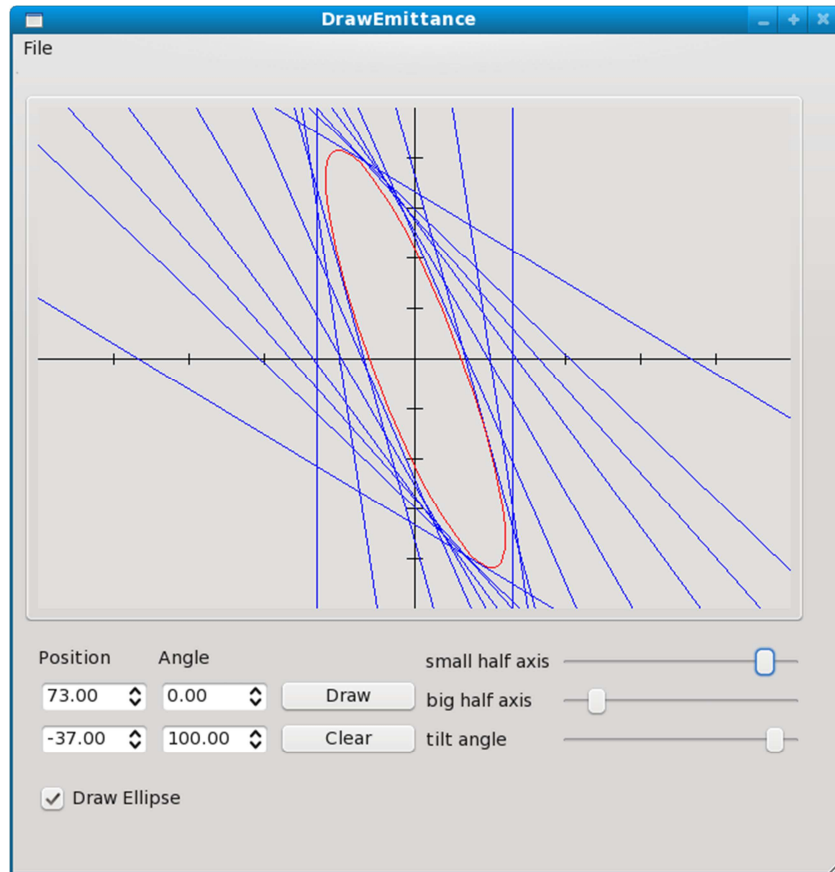


Figure 12: 3 Profiles measurement

## 5. THE QUADRUPOLE SCAN

The beam at a certain position in the transfer line can be described by the symmetric beam matrix, which is transformed by transfer matrices corresponding to the magnetic elements as the beam follows its trajectory.

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix}$$

Frequently the Twiss parameters are used, which are the beam matrix elements normalized by the emittance:

$$\alpha = -\sigma_{12}/\epsilon \quad \beta = \sigma_{11}/\epsilon \quad \gamma = \sigma_{22}/\epsilon$$

Using the Twiss parameters, the beam matrix becomes:

$$\sigma = \varepsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

The equation of the beam ellipse can be written as

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = \varepsilon \quad \text{with normalization} \quad \beta\gamma - \alpha^2 = 1$$

The width of the position and angular profiles are given by

$$x_\sigma = \sqrt{\sigma_{11}} = \sqrt{\varepsilon\beta} \quad \text{and} \quad x'_\sigma = \sqrt{\sigma_{22}} = \sqrt{\varepsilon\gamma}$$

In the quadrupole scan the beam size is measured always at the same position but now the field strength of a quadrupole is changed. While a drift space results in a shearing of the emittance ellipse along the x axis, the effect of a quadrupole is a shearing along the x' axis.

The transfer matrix in this case is

$$T_{quad} = \begin{pmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{pmatrix}$$

where f is the focal length of the lens, which simulates the quadrupole.

The transfer matrix through quadrupole (in thin lens approximation) and drift space is

$$T = T_{drift} * T_{quad} = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix} = \begin{pmatrix} 1+LK & L \\ K & 1 \end{pmatrix} \quad (1)$$

where the focussing strength-1/f has been replaced by the quadrupole strength K

The beam matrix  $\sigma$  is transformed by this transfer matrix when moving from position 0 to position 1:

$$\sigma(\mathbf{1}) = R\sigma(\mathbf{0})R^T$$

Looking only at the first matrix element  $\sigma_{11}(1)$ , describing the beam width we get:

$$\sigma_{11}(\mathbf{1}) = R_{11}^2 \sigma_{11} + 2 * R_{11} R_{12} \sigma_{12} + R_{12}^2 \sigma_{22} \quad (2)$$

and inserting (1) in (2):

$$\sigma_{11}(\mathbf{1}) = L^2 \sigma_{11}(\mathbf{0}) K^2 + 2K(L\sigma_{11}(\mathbf{0}) + L^2 \sigma_{12}(\mathbf{0})) + L^2 \sigma_{22}(\mathbf{0}) + \sigma_{11}(\mathbf{0})$$

This is a quadratic function in K:

$$\sigma_{11}(\mathbf{1}) = a(K - b)^2 + c = aK^2 - 2abK + ab^2 + c$$

where  $\sigma_{11}$  is the square of the beam width at the measurement point.

Plotting  $\sigma_{11}$  over the quadrupole strength  $1/f$  results in the following plot which has been produced with the program *QuadScan* once the spot width has been determined with *QProfiles*.

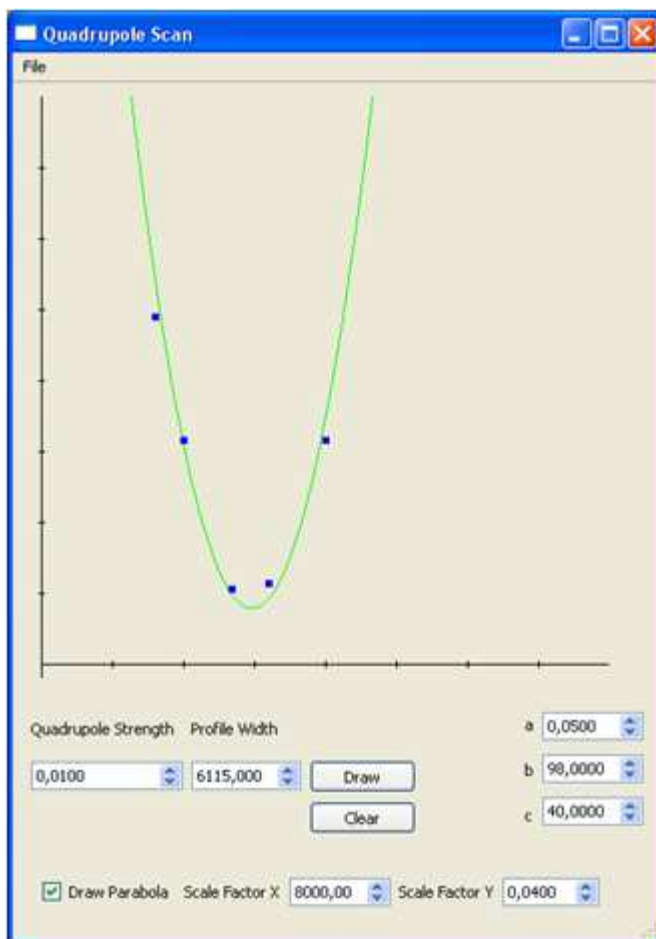


Figure 13: Quad Scan