Laboratory Session on Emittance Measurements

Accelerator Beam Diagnostics

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USPAS and University of New Mexico
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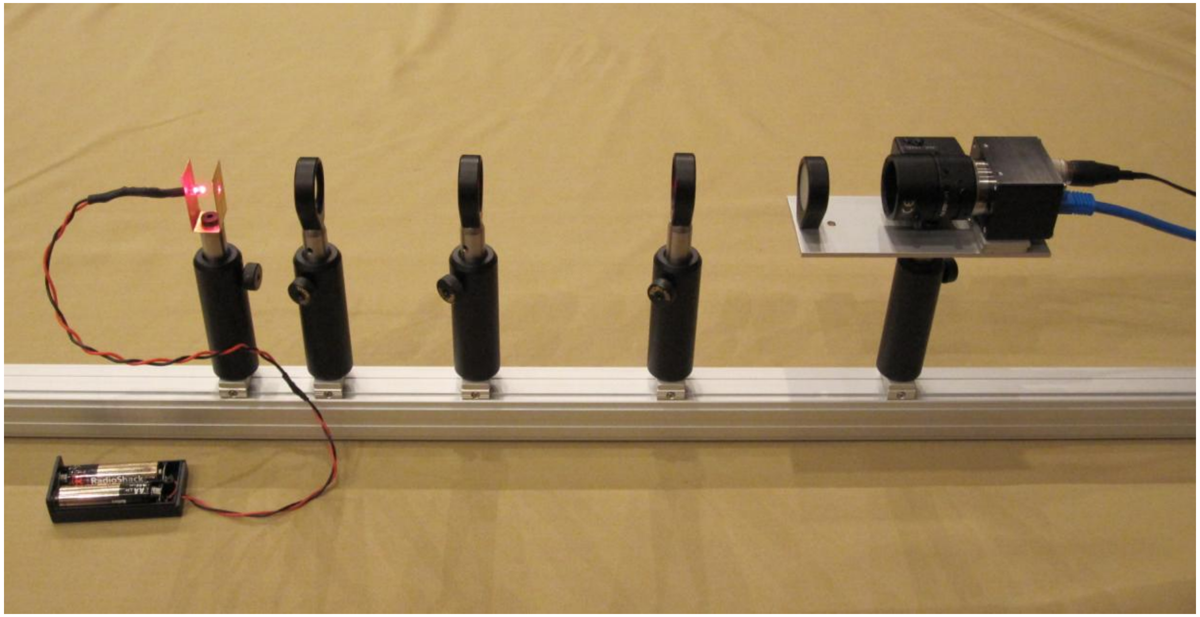
The ultimate emittance measurement

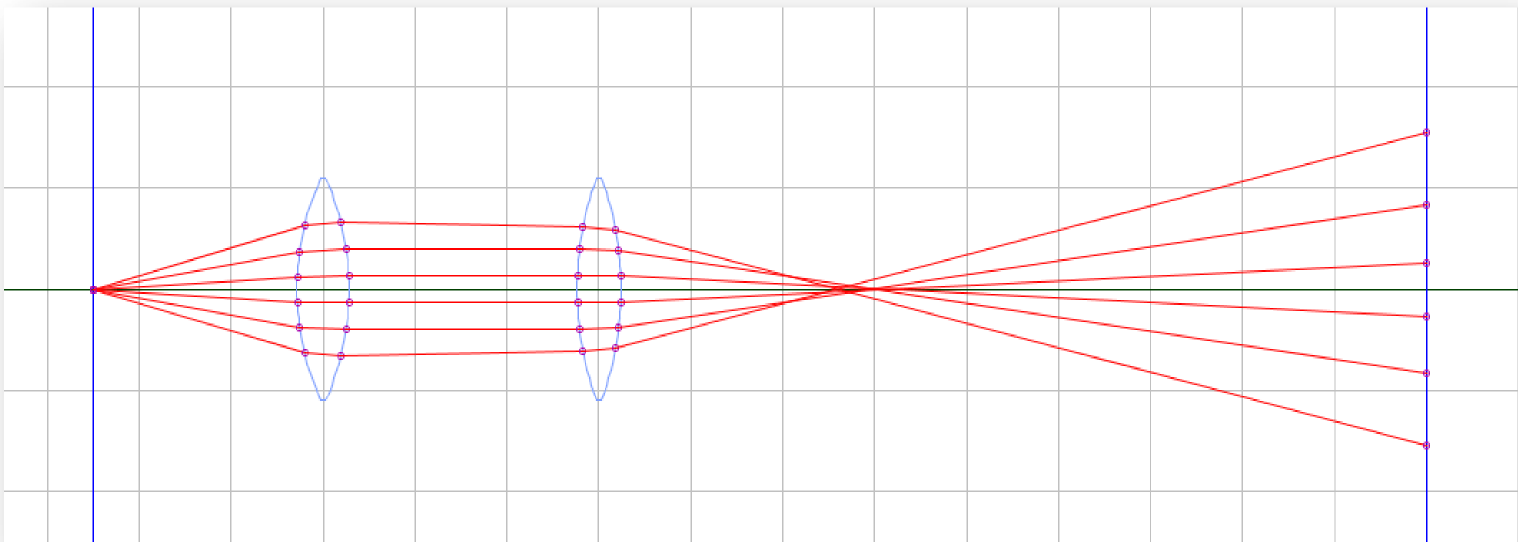


Optical bench with:

- Point light source
- Pepperpot plate
- Screen
- Lenses
- Data acquisition
- Evaluation programs

Calculating the optics

Optical Ray Tracer (http://arachnoid.com/OpticalRayTracer/index.html)



Possible measurements

These measurements can be simulated:

- Pepperpot
- 3 (or more) profiles measurement
- Quadrupole Scan

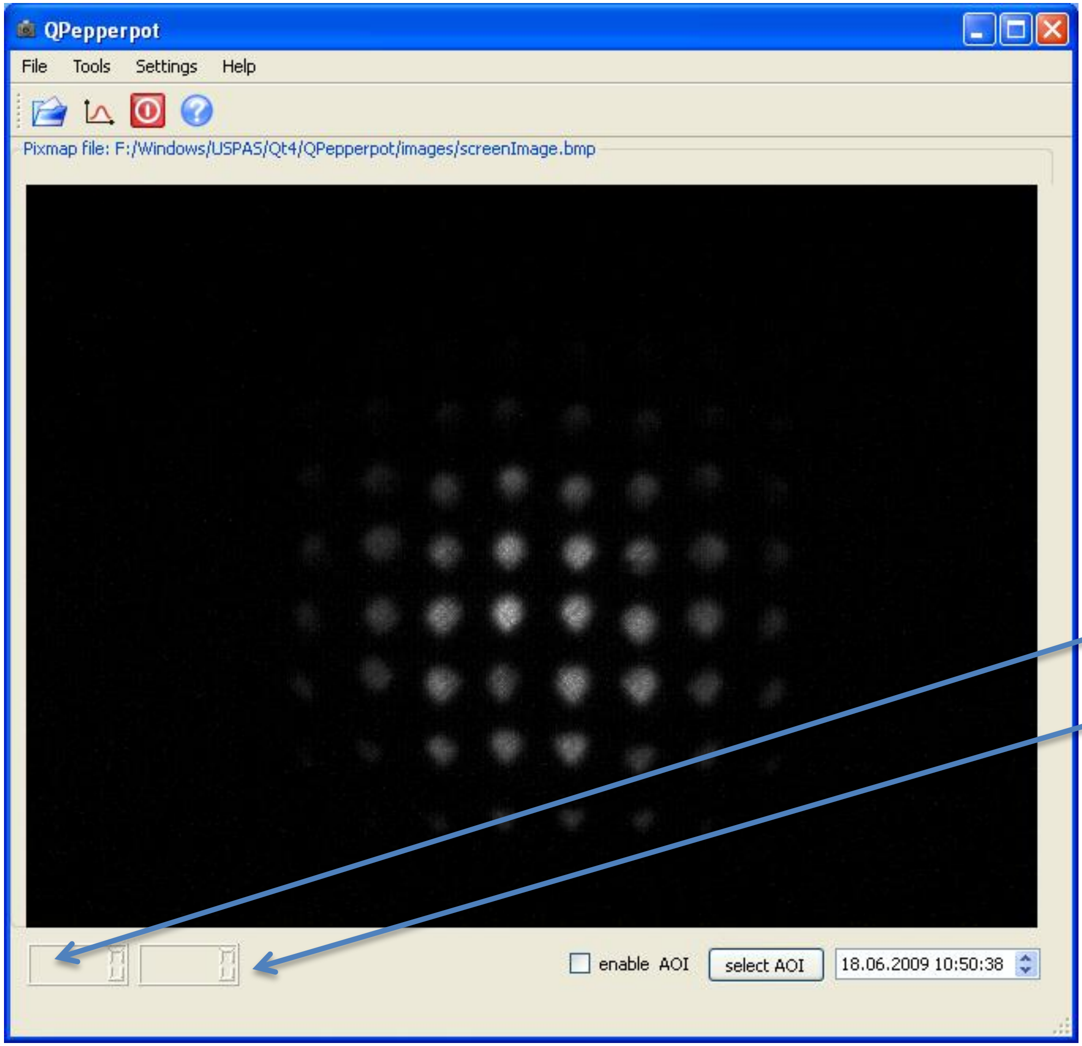
Pepperpot Measurement

Only the evaluation of the horizontal phase plane is implemented but… on an optical system horizontal and vertical phase space is symmetric.

Steps to be performed:

- We will use a series of vertical holes like a slit calculating the projection of the image to the horizontal axis. Therefore …
  Make sure the holes are perfectly aligned and are on an exactly vertical line
- Measure the distance between the holes (in pixels) and calculate the scaling factor s [pixels/mm]
  To do this: Replace the screen with the pepperpot plate. After this measurement keep the distance screen-camera constant.
  Save the image as an 640x480 .bmp file
- Take the pepperpot image on the screen (make sure the camera focuses on the screen) and save it.

Pepperpot Evaluation Program



Clicking the left mouse button on the image creates a hor/ver cursor which allows to check the alignment.

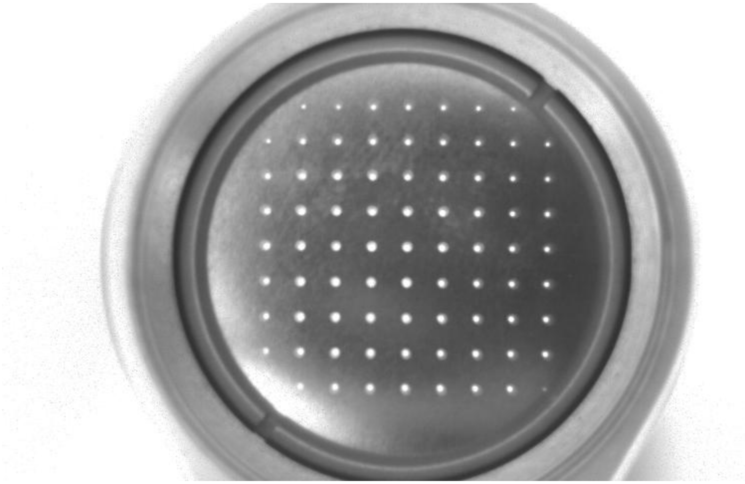
The cursor position is displayed on the LCD displays (left: x pos, right y pos)

File menu contains entries to save intermediate results

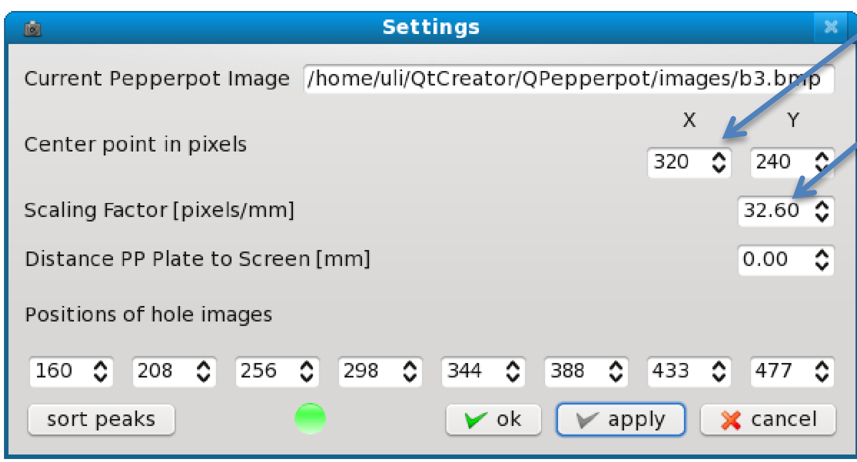
Tools menu controls projections and calculates emittance plot

Settings allows entering scaling Factors or manually defined peaks

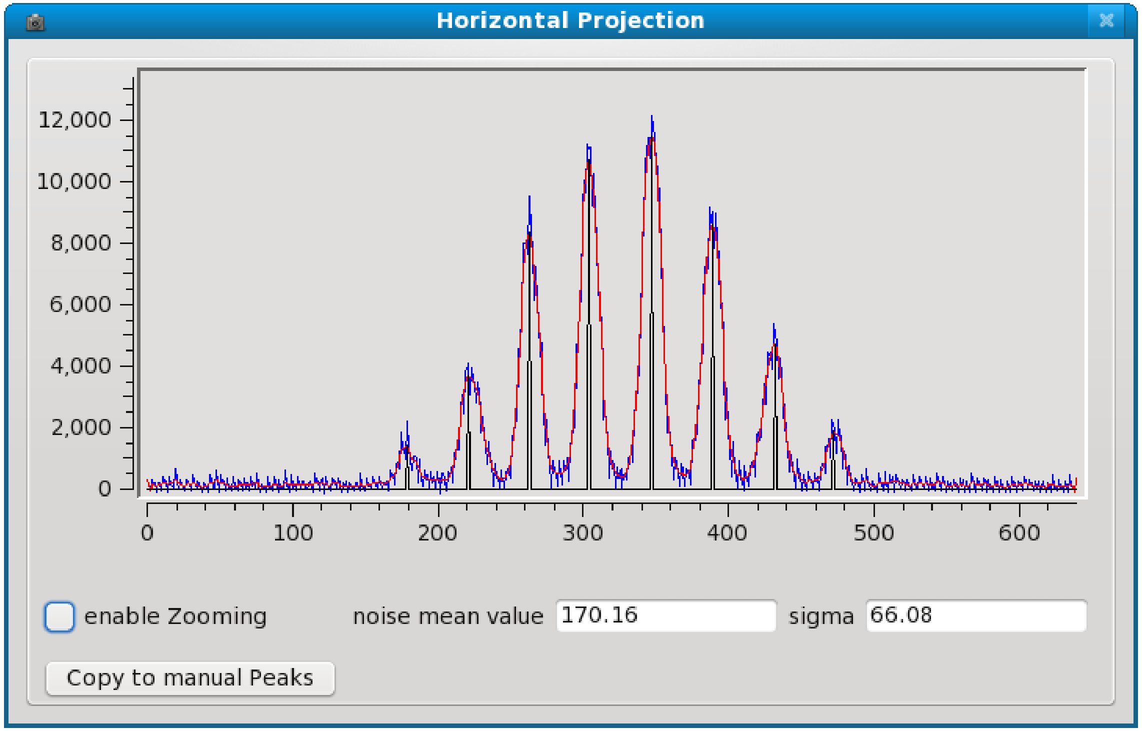
Calibration



Settings menu brings up the settings box
Enter the scaling factor (pixels/mm) and center position (mm()



Projections



Projection box comes up Through "Tools" menu or histogram button on the tool bar.

Blue curve: raw data

Red curve: low pass filtered data

Black curve: peaks (hole image)

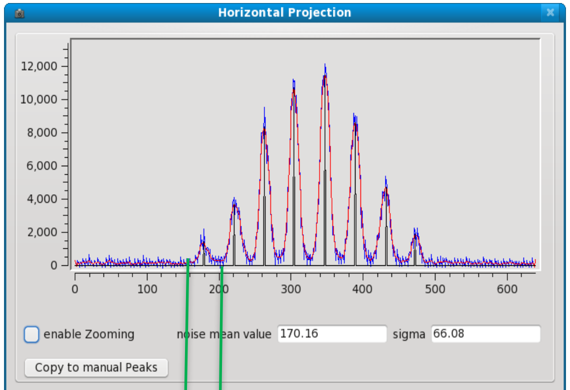
Each histogram may be switched on or off from the Tools menu

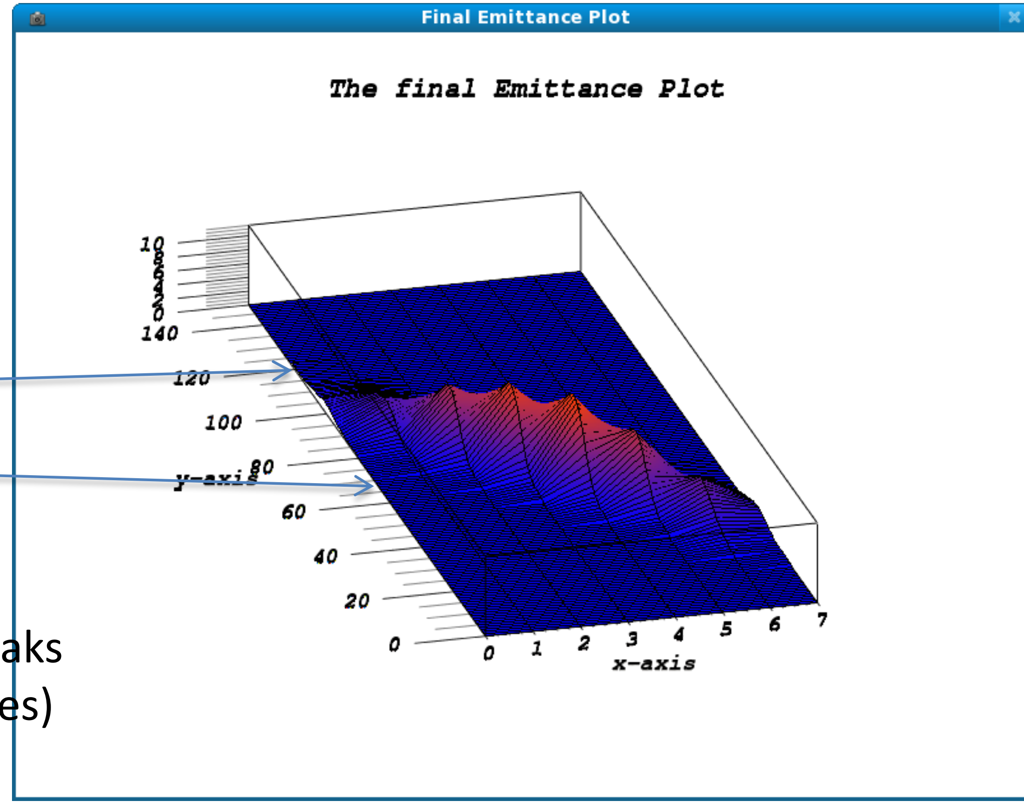
Left mouse button on plot shows cursor + cursor position

Useful to manually find peaks

When zoom is active, use the mouse to define zoom area

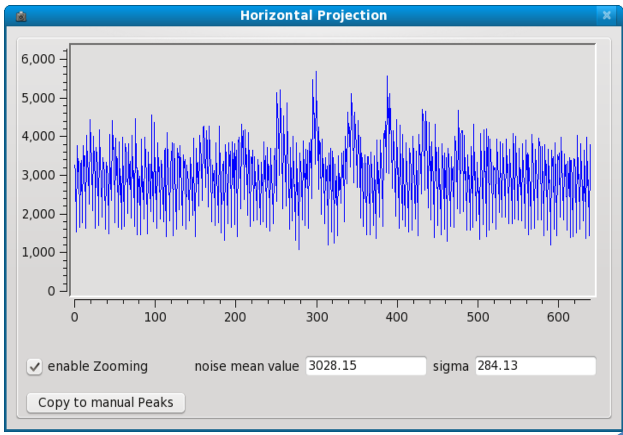
Emittance Plot

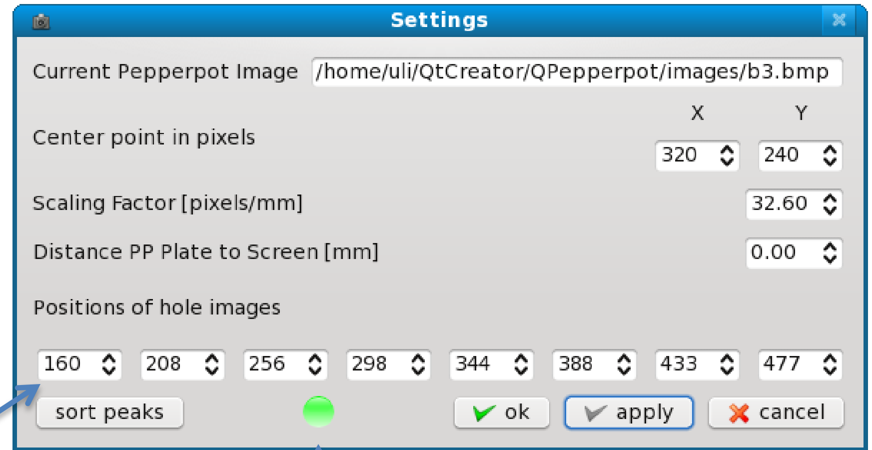


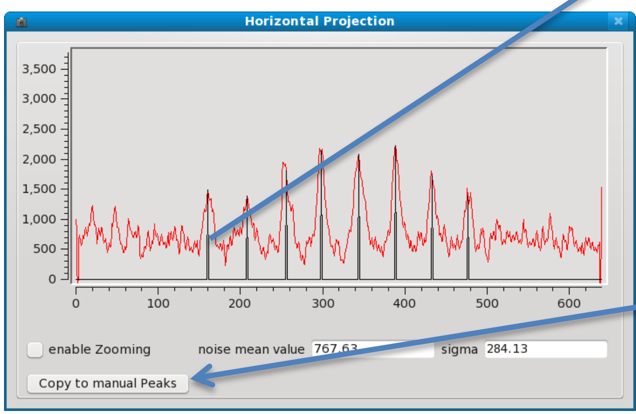


The projection is split into slices
Length of 1 slice = distance between peaks
8 such slices (eight pepperpot plate holes)
make up the emittance plot

Noisy projections







- Filter the projection
- Try to find peaks automatically (will probably fail to find all peaks)
- Copy to manual peaks copies the automatically found peaks to the settings box.
- Switch off automatic peak finding
- Correct peaks and add the missing ones, press “apply” (will be shown in the projection box)
- Displays in red in changes without “apply”
- Calculate emittance from manually defined peaks

3 Profile Measurements

Principle

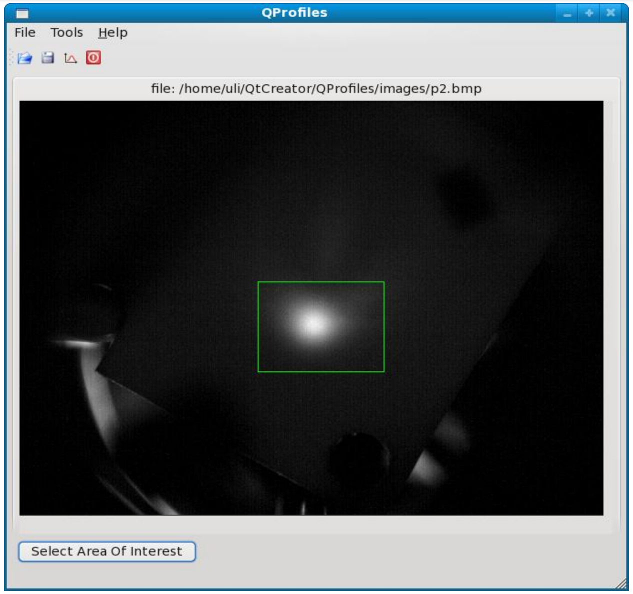
- Measure the beam profile and find the beam size at 3 (or more) different locations around a beam waist (around the focal point of the lens).
- Beam size corresponds to 2 vertical lines in phase space
- Transform these lines through transfer matrix calculations to the position of the first profile

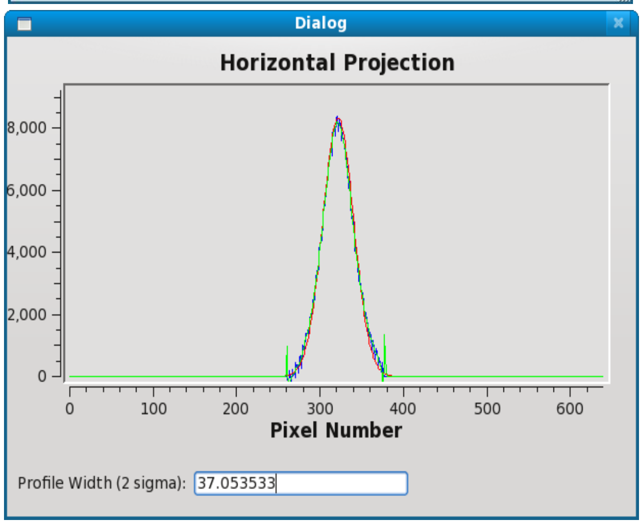
  For a drift space:

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

L: length of drift space

Determination of Beam Width

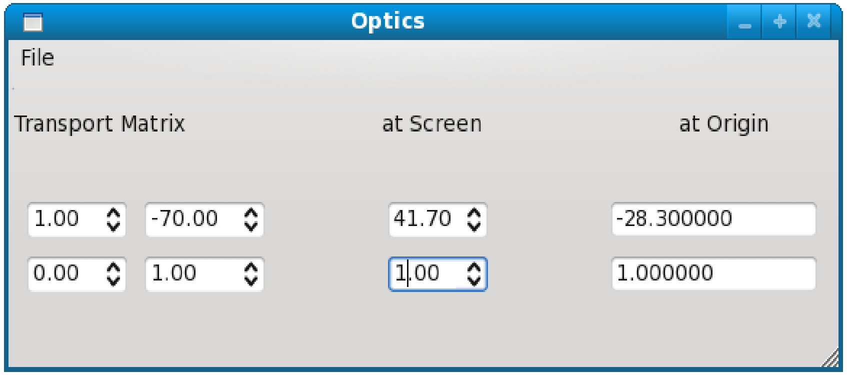


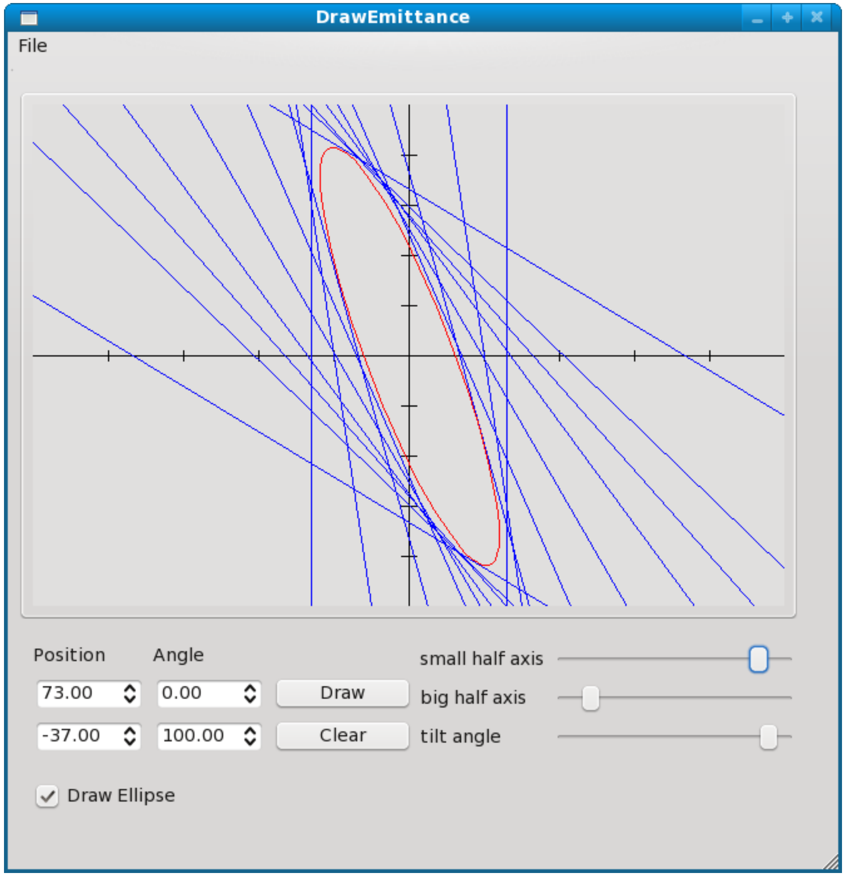


- Check that the image is not saturated at any of the 3 or more locations
- Take images of the light (beam) spot
- Read the images with the QProfiles program
- If you have background light, the area of interest function allows to get rid of it (first mouse button drag)
- Click 3rd mouse button to restore the original image
- You may low-pass filter the projection
- Offset can also be suppressed

QProfiles calculates the first and second moment of the distribution and shows a gaussian curve with the same Center position and σ.
The profile width is displayed.

Optics calculations





Enter the inverse Transfer matrix into the optics program (simple multiplication of the transport matrix with a phase space vector) and calculate the line at the position of the first profile (vertical lines)

The emittance ellipse can be fitted by hand using the control sliders for
the half axis and the tilt angle

Quadrupole scan

The emittance is determined by varying a quadrupole and measuring the beam spot size after a drift space.

The transport matrix is given by:

$$R = R_{drift} * R_{focus} = \begin{pmatrix} 1 & 0 \\ K & 1 \end{pmatrix} \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} = \begin{pmatrix} 1+KL & L \\ K & 1 \end{pmatrix} \qquad (1)$$

where K=-1/f is the quadrupole strength (f=focal length)

and L the length of the drift space.

The beam matrix is transformed through

$$\sigma(1) = R\sigma(0)R^T \qquad (2)$$

Inserting (1) into (2) allows us to calculate the beam width

Transformation of the beam matrix

$$\sigma(1) = R\sigma(0)R^T$$

$$R\sigma = \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}\begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} R_{11}\sigma_{11} + R_{12}\sigma_{12} & R_{11}\sigma_{12} + R_{12}\sigma_{22} \\ R_{21}\sigma_{11} + R_{22}\sigma_{12} & R_{21}\sigma_{12} + R_{22}\sigma_{22} \end{pmatrix}$$

$$R\sigma R^T = \begin{pmatrix} R_{11}\sigma_{11} + R_{12}\sigma_{12} & R_{11}\sigma_{12} + R_{12}\sigma_{22} \\ R_{21}\sigma_{11} + R_{22}\sigma_{12} & R_{21}\sigma_{12} + R_{22}\sigma_{22} \end{pmatrix}\begin{pmatrix} R_{11} & R_{21} \\ R_{12} & R_{22} \end{pmatrix} =$$

$$\begin{pmatrix} R_{11}(R_{11}\sigma_{11} + R_{12}\sigma_{12}) + R_{12}(R_{11}\sigma_{12} + R_{12}\sigma_{22}) & R_{21}(R_{11}\sigma_{11} + R_{12}\sigma_{12}) + R_{22}(R_{11}\sigma_{12} + R_{12}\sigma_{22}) \\ R_{11}(R_{21}\sigma_{11} + R_{22}\sigma_{12}) + R_{12}(R_{21}\sigma_{12} + R_{22}\sigma_{22}) & R_{21}(R_{21}\sigma_{11} + R_{22}\sigma_{12}) + R_{22}(R_{21}\sigma_{12} + R_{22}\sigma_{22}) \end{pmatrix}$$

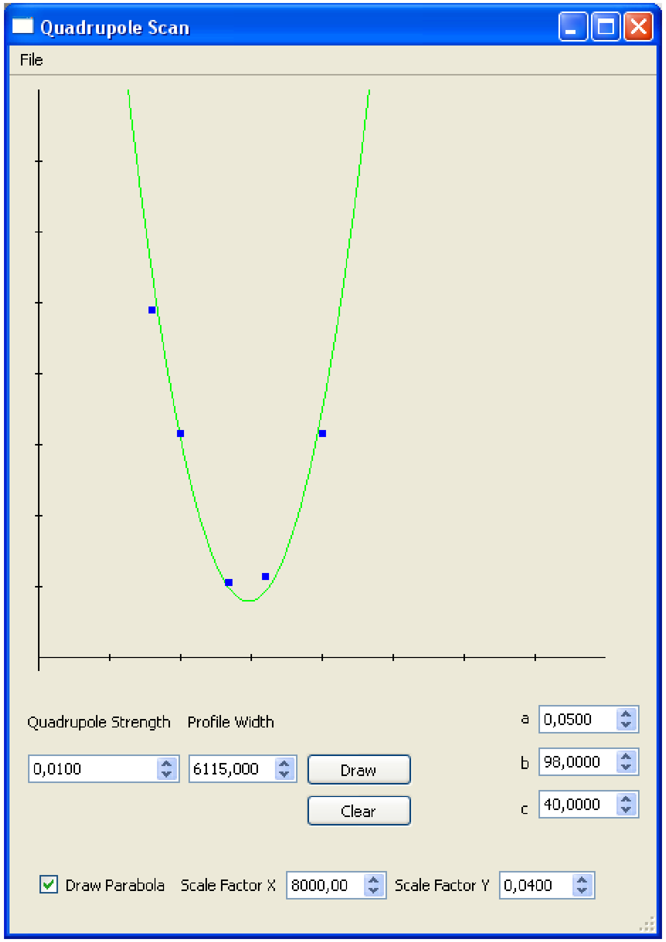
$$\sigma_{11}(1) = R_{11}^2\sigma_{11} + 2R_{11}R_{12}\sigma_{12} + R_{12}^2\sigma_{22}$$

$$R = \begin{pmatrix} 1+LK & L \\ K & 1 \end{pmatrix}$$

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

$$\sigma_{11}(K) = aK^2 - 2abK + a^2b + c$$
$$a = L^2\sigma_{11}$$
$$-ab = L\sigma_{11} + L^2\sigma_{12}$$
$$a^2b + c = \sigma_{11} + 2L\sigma_{12} + L^2\sigma_{22}$$
$$\sigma_{11} = \frac{a}{L^2}$$
$$\sigma_{12} = (-\frac{ab}{L^2} - \frac{a}{L^3}) = -\frac{a}{L^2}(b + \frac{1}{L})$$
$$a^2b + c = \frac{a}{L^2} - 2\frac{ab}{L} - 2\frac{a}{L^2} + L^2\sigma_{22}$$
$$\sigma_{22} = \frac{1}{L^2}(a^2b + c + 2\frac{ab}{L} + \frac{a}{L^2})$$

Results from a Quadrupole Scan



The square of the beam width is Plottet over the „Quadrupole Strength“ or 1/f where f is the focal length of the lens

The plot uses 400x400 pixels and a scaling Factor can be defined for both axis
Ex: 1/f = 0.01 * 8000 = 80 (pixels)