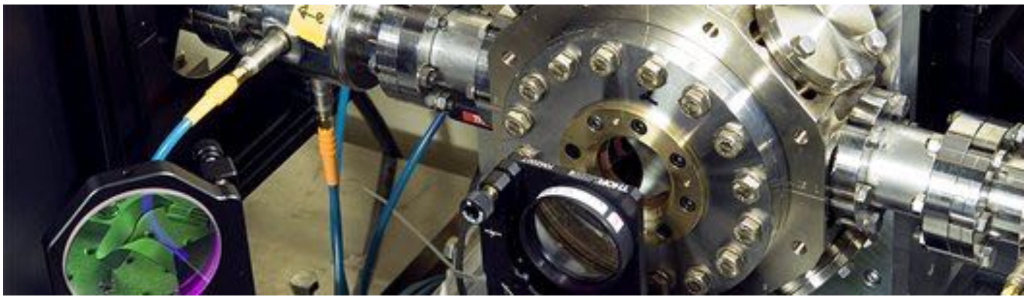
CERN Accelerator School
Advanced Accelerator Physics

3–15 September 2017

Beam Instrumentation and Diagnostics: Lab Instructions



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Contents

Lab 1: Knife-Edge Scraper for Beam Profile and Halo Measurement

1.1 Aims and Objectives

This experiment aims to demonstrate the principle of a particle beam scraper for fast measurement of transverse beam parameters, by making an analogous transverse profile measurements of a laser beam with a knife-edge scanner. The measurement of a transverse beam profile is important for several methods to determine the emittance, namely the three-screen method, the quadrupole scan, and the pepperpot technique, which are explored further in the other laboratory experiments. The knife-edge scanner is also useful for beam halo measurement. The main objectives are:

- To set up the optics equipment to measure the transverse beam profile of a laser beam.
- To autonomously translate a knife-edge across a laser beam and record the transmitted intensity at a photodiode.
- To analyze the data by filtering, then differentiating the photodiode signal to generate the measured beam profile and determine the laser beam width via a Gaussian fit.
- To appreciate the dynamic range necessary to measure beam halo distributions, through measurements of the Fraunhofer diffraction pattern from a single slit.

1.2 Beam Profile Measurement Theory

Scanning a knife-edge scanning across a particle beam allows the transverse beam profile to be measured from the differential of the transmitted intensity. See for example: J. A. Arnaud et al, *Technique for Fast Measurement of Gaussian Laser Beam Parameters*.

1.2.1 Beam Halo

The core profile of a particle beam may be measured using for example, a wire scanner that records the current resulting from secondary emission due to impacting particles. In addition, however, a particle beam normally has a halo distribution, which arises from various processes including: beam gas elastic and inelastic scattering, incoherent and coherent synchrotron radiation, scattering off thermal photons, intrabeam and Touschek scattering and ion or electron-cloud effects; beam optics, and collective effects. In synchrotrons, the beam halo is an important background source for the experimental detectors, and is also critical for radiation sensitive components in the accelerator. Beam losses at the level of $< 0.1\%$ lost particles per bunch can be harmful, therefore we require a beam monitor capable of measuring the transverse beam halo better than this. The required dynamic range is therefore of the order of 10^5 or better. To achieve this dynamic range, a combination of wirescanners and knife-edge scrapers is sometimes necessary to capture profile data from the intense core and the halo distributions respectively.

1.3 Experimental Setup

The equipment is in the dark room in section-C (far corner) of the RHUL Tolansky teaching laboratory.

Warning: the He-Ne laser in this experiment is a class IIIa laser. Avoid direct eye exposure to laser radiation. Do not stare into the beam and remove any reflective jewellery before operating the laser.

A HeNe $\lambda = 632.8$ nm laser is aligned on an optical rail such that light passes through a series of focusing lenses to converge on distant photodiode, as shown in Fig 1.1.

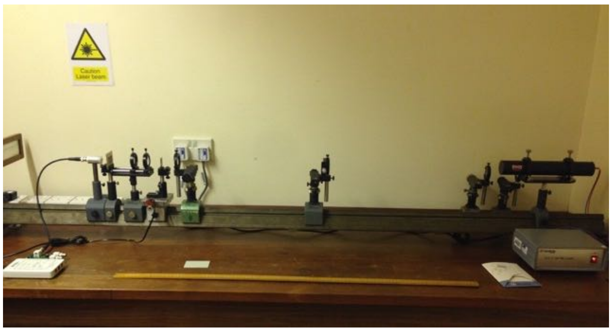


Figure 1.1: Overview of setup for knife-edge laser beam scraper

The photodiode signal is recorded via an National Instruments MyDAQ data acquisition card, as in Fig 1.2, connected to a laptop computer. The laptop also controls a New Focus pico-motor, that drives a knife-edge on a translation stage transversely across the laser beam. The laptop has LabView control software to automate the scan, that can be accessed from the desktop.

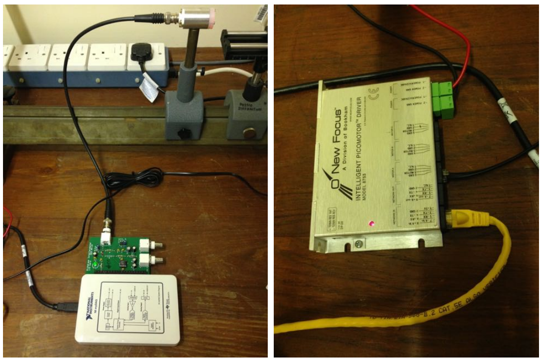


Figure 1.2: NI MyDAQ data acquisition card to record photodiode voltage and New Focus Pico Motor Controller connected via ethernet cable/USB adapter to laptop.

The New Focus pico motor can be incremented in precise 30 nm steps. To minimize the time required for a scan, the laser beam is focused to a tight laser waist, just after which the knife-edge is scanned, as in Fig. 1.3

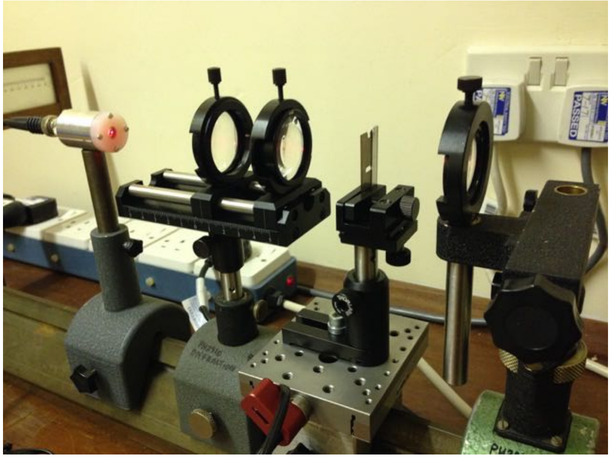


Figure 1.3: Knife-edge between focusing lenses, with the photodiode illuminated by a HeNe laser.

1.4 Measurements

1.4.1 *Knife-edge Scans*

After familiarizing yourself with the equipment, turn on the laser and observe the beam shape using the white-screen as in Fig 1.4 to image the laser beam spot at various locations through the setup, noting the focal lengths of the lenses used. The light should pass through all lens apertures to avoid clipping of the beam profile.

When the knife-edge is positioned half-way through the laser-beam, the pattern on the card appears as in Fig 1.4. You may notice there is a distortion of the geometric shadow on the card as the knife-edge passes through the laser-beam - why is this? Is this effect expected at a particle accelerator? Under what circumstances does this effect not matter for this experiment?

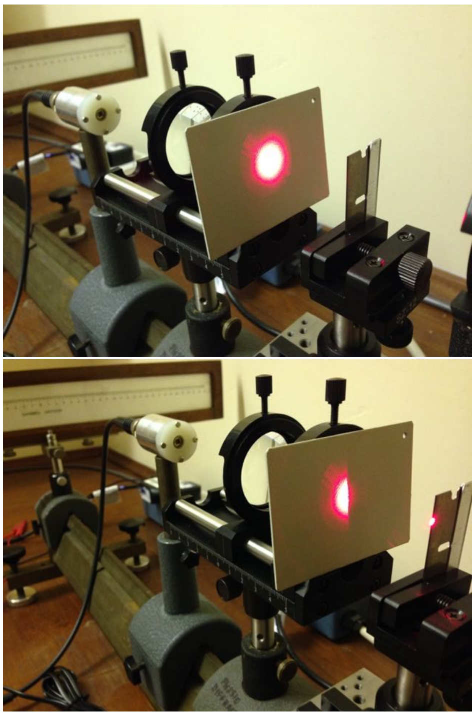


Figure 1.4: Beam imaged on white screen, without and with knife-edge in beam

The active area of the photodiode is small, therefore the light transmitted beyond the knife-edge must be refocused to be collected entirely by the photodiode, as in Fig 1.5.

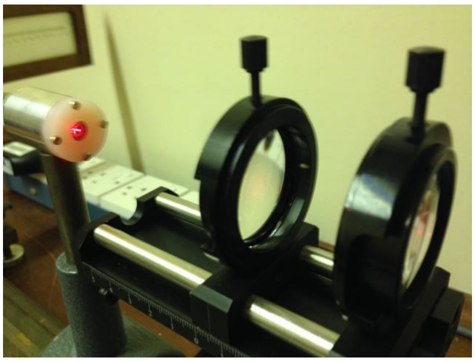
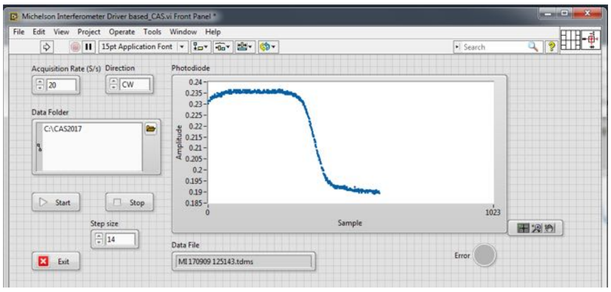


Figure 1.5: Laser spot focused onto photodiode



Michelson Interferometer Driver based_CAS.vi Front Panel *

Acquisition Rate (S/s): 20

Direction: CW

Data Folder: C:\CAS2017

Step size: 14

Data File: MI 170909 125143.tdms

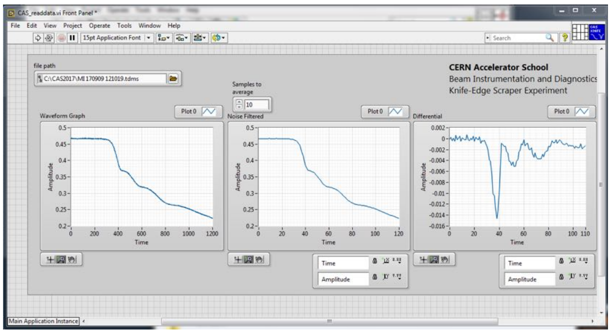
Figure 1.6: LabView software to control the stage and read out the photodiode during a scan of the knife-edge.

Performing a scan:

- Open the LabView software in Fig. 1.6 and use it to record a scan, by running the program, then pressing the start and stop buttons. Select COM3 when prompted.
- The voltage signal at each sampling point is recorded to a timestamped data file in the C:/CAS2017/ folder.
- Check that the scan records the full beam profile as an error function; you may wish to adjust the step size and sampling time for a more rapid scan, within the limits of the driver.

1.4.2 Beam profile extraction

The recorded data file may be analyzed by the CAS_readata.vi LabView software shown in Fig. 1.7. The raw data are filtered by averaging over a certain number of samples, then the signal is differentiated to obtain a plot of the beam profile versus knife-edge position.



CAS_readdata.vi Front Panel *

file path: C:\CAS2017\MI 170909 121019.tdms

Samples to average: 10

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Beam Instrumentation and Diagnostics
Knife-Edge Scraper Experiment

Figure 1.7: Analysis software to read the photodiode data, filter for noise and differentiate to obtain the profile.

1.4.3 Gaussian beam profile

Fit a Gaussian (or otherwise) to the beam profile to extract the width. Compare this with the width of the Gaussian waist you would expect at the focus of the lenses. How would you improve / calibrate the setup?

If there is sufficient time, replace the knife-edge with the adjustable slit and repeat the scan. Can you optimize the slit size to obtain the best beam profile?

1.4.4 Beam Halo measuring a single-slit diffraction pattern

When the first lens in the setup is replaced with an adjustable single slit, a diffraction pattern is produced in the far field with the intensity: $I(x) = \frac{\sin^2(x)}{x^2}$, as in Fig. 1.8. Thus the distribution has a central *"core"* and an interesting side patterns that can be considered as the *"beam halo"*.

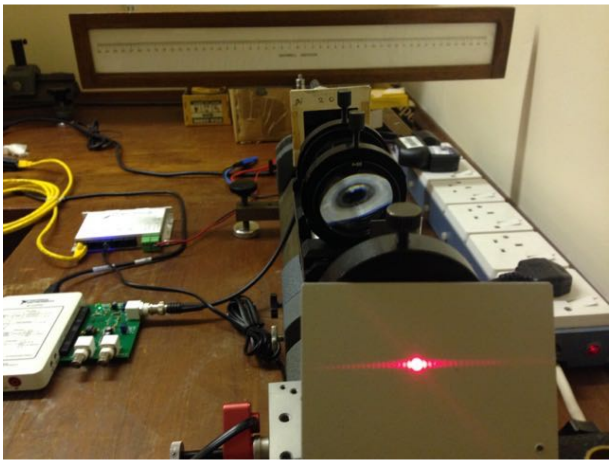


Figure 1.8: Single slit diffraction pattern.

Use the apparatus to obtain beam profiles showing clear features of the core and halo. Consider whether the photodiode will saturate when exposed to the full laser beam. Place different optical filters (ND > 2.0) in front of the photodiode, as in Fig 1.9 to obtain profiles with the necessary dynamic range. How could the setup be modified to obtain both sides of the halo distribution?

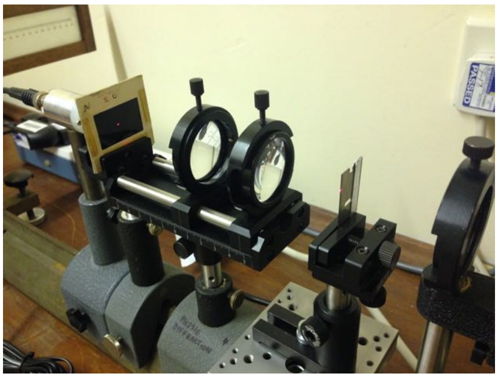


Figure 1.9: Filter inserted in front of photodiode.

Lab 2: Beam Emittance by the Three Screen Method

2.1 Aims and Objectives

The experimental aim is to measure the emittance of a laser beam. The main objectives are to:

- understand the theory of emittance measurement by the three screen method.
- calibrate a CCD camera and use it to record multiple beam profiles of a laser beam.
- calculate the beam widths using a Gaussian fit to the recorded profiles.
- apply the three-screen method matrix formalism to determine the horizontal emittance of the laser beam.

2.2 Emittance Measurement Theory

If β is known unambiguously as in a circular machine, then a single profile measurement determines ϵ by

$$\sigma_y^2 = \epsilon\beta_y.$$

But it is not easy to be sure in a transfer line which β to use, or rather, whether the beam that has been measured is matched to the β-values used for the line. This problem can be resolved by using ***three monitors (see Fig. 2.1), i.e. the three width measurement determines the three unknown α, β and ϵ of the incoming beam.***

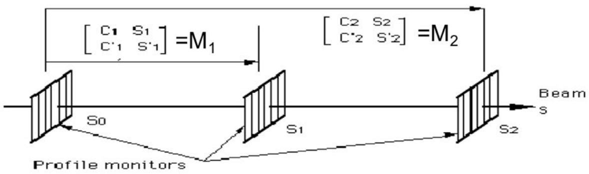


Figure 2.1: Overview of three screen profile measurement technique for emittance measurement.

Introducing the σ-matrix (see for example, K. Wille; Physik der Teilchenbeschleuniger, Teubner):

$$\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{y'y} & \sigma_{y'}^2 \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}$$

where $\beta\gamma - \alpha^2 = 1$, then the rms emittance is given by

$$\epsilon_{rms} = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}$$

The rms beam width of the measured profile is

$$\sigma_y = \sqrt{\sigma_{11}} = \sqrt{\beta(s) \cdot \epsilon}\,.$$

Transformation of σ-matrix through the elements of an accelerator:

$$\sigma_{s1} = M \cdot \sigma_{s0} \cdot M^T$$

where $M = \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix}$, $M^T = \begin{pmatrix} M_{11} & M_{21} \\ M_{12} & M_{22} \end{pmatrix}$.

$L_1,\ L_2$ = distances between screens or from Quadrupole to screen and Quadrupole field strength are given, therefore the transport matrix M is known.

Applying the transport matrix gives (now time for exercise):

$$\begin{aligned}
\sigma_{s1} &= M \cdot \sigma_{s0} \cdot M^T \\
&= \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} \cdot \begin{pmatrix} M_{11} & M_{21} \\ M_{12} & M_{22} \end{pmatrix} \\
&= \sigma^{meas} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{y'y} & \sigma_{y'}^2 \end{pmatrix}_{s1}^{meas} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix} \\
&= \begin{pmatrix} M_{11} & M_{12} \\ M_{21} & M_{22} \end{pmatrix} \cdot \begin{pmatrix} \sigma_{11}M_{11} + \sigma_{12}M_{12} & \sigma_{11}M_{21} + \sigma_{12}M_{22} \\ \sigma_{21}M_{11} + \sigma_{22}M_{12} & \sigma_{12}M_{21} + \sigma_{22}M_{22} \end{pmatrix} \\
&= \begin{pmatrix} M_{11}(\sigma_{11}M_{11} + \sigma_{12}M_{12}) + M_{12}(\sigma_{21}M_{11} + \sigma_{22}M_{12}) & \dots \\ \dots & \dots \end{pmatrix}
\end{aligned}$$

therefore

$$\begin{aligned}
\sigma(s_1)_{11}^{meas} &= \sigma^2(s_1)_y^{meas} \\
&= M_{11}^2\sigma(s_0)_{11} + 2M_{11}M_{12}\sigma(s_0)_{12} + M_{12}^2\sigma(s_0)_{22}
\end{aligned}$$

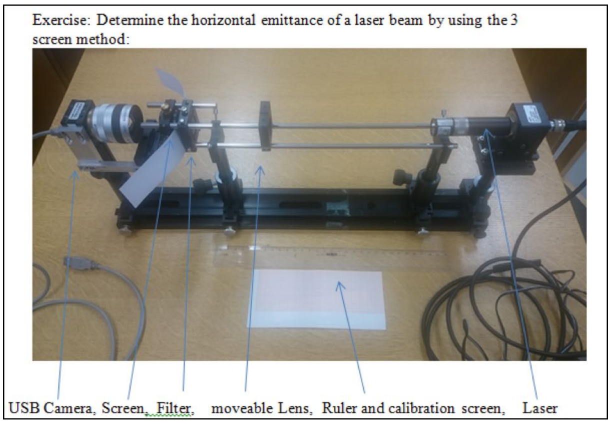
where $\sigma_{12} = \sigma_{21}$). Solving $\sigma(s_0)_{11}$, $\sigma(s_0)_{12}$ and $\sigma(s_0)_{22}$ while the matrix elements are known ***needs minimum of three different measurements, either three screens or three different quadrupole settings with different field strength***.

$$\boxed{\epsilon_{rms} = \sqrt{\det \sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}}$$

2.3 Experimental Setup

2.3.1 Overview

By moving the lens one can take pictures from the camera in the focus (not preferred due to limited resolution of the optic system) and on other positions. The distance of the lens to various screen positions can be measured by a simple ruler[1]. The camera is connected to a Computer where the readout software is installed. The pictures (.jpg) can be saved and can be loaded into a free software called ImageJ where a profile of an area can be displayed and the curser position and the value is displayed (8 bit). The σ of the profile have to be found for each screen (camera) position and the emittance have to be calculated.



Exercise: Determine the horizontal emittance of a laser beam by using the 3 screen method:

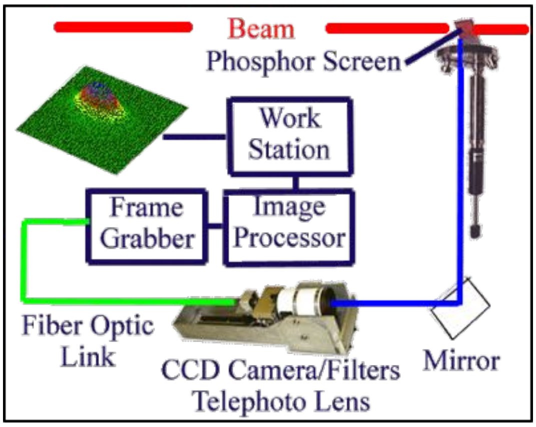


Figure 2.2: Experimental setup for three screen emittance measurement

2.3.2 *Hardware parameters*

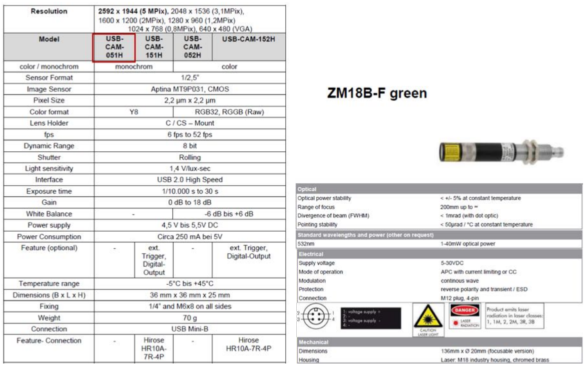
Parameters for the hardware are provided below and in Fig. 2.3.

CCD Phytec USB-CAM 051H

screen material: white paper

grid target spacing 1mm

laser Z-Lasers



Resolution	2592 x 1944 (5 MPix), 2048 x 1536 (3,1MPix), 1600 x 1200 (2MPix), 1280 x 960 (1,2MPix) 1024 x 768 (0,8MPix), 640 x 480 (VGA)			
Model	**USB-CAM-051H**	**USB-CAM-151H**	**USB-CAM-052H**	**USB-CAM-152H**
color / monochrom	monochrom		color	
Sensor Format	1/2,5"			
Image Sensor	Aptina MT9P031, CMOS			
Pixel Size	2,2 µm x 2,2 µm			
Color format	Y8		RGB32, RGGB (Raw)	
Lens Holder	C / CS – Mount			
fps	6 fps to 52 fps			
Dynamic Range	8 bit			
Shutter	Rolling			
Light sensitivity	1,4 V/lux-sec			
Interface	USB 2.0 High Speed			
Exposure time	1/10.000 s to 30 s			
Gain	0 dB to 18 dB			
White Balance	-		-6 dB bis +6 dB	
Power supply	4,5 V bis 5,5V DC			
Power Consumption	Circa 250 mA bei 5V			
Feature (optional)	-	ext. Trigger, Digital-Output	-	ext. Trigger, Digital-Output
Temperature range	-5°C bis +45°C			
Dimensions (B x L x H)	36 mm x 36 mm x 25 mm			
Fixing	1/4" and M6x8 on all sides			
Weight	70 g			
Connection	USB Mini-B			
Feature- Connection	-	Hirose HR10A-7R-4P	-	Hirose HR10A-7R-4P

ZM18B-F green

Optical	
Optical power stability	< +/- 5% at constant temperature
Range of focus	200mm up to ∞
Divergence of beam (FWHM)	< 1mrad (with dot optic)
Pointing stability	< 50µrad / °C at constant temperature
Standard wavelengths and power (other on request)	
532nm	1-40mW optical power
Electrical	
Supply voltage	5-30VDC
Mode of operation	APC with current limiting or CC
Modulation	continous wave
Protection	reverse polarity and transient / ESD
Connection	M12 plug, 4-pin
Mechanical	
Dimensions	136mm x Ø 20mm (focusable version)
Housing	Laser: M18 industry housing, chromed brass

1: voltage supply +
2: -
3: voltage supply -
4: -

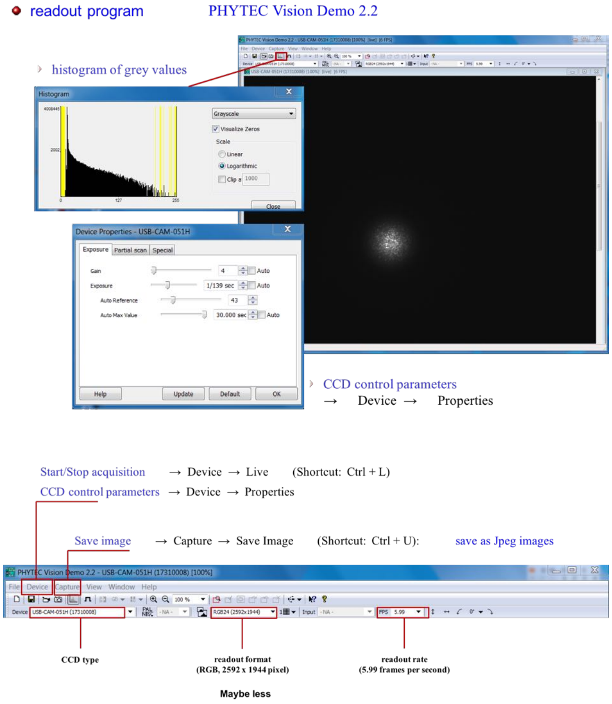
Product emits laser radiation in laser classes: 1, 1M, 2, 2M, 3R, 3B

Figure 2.3: Parameters for CCD and laser

2.4 Measurements

2.4.1 *CCD control*

Start by becoming familiar with how to acquire data from the CCD, which is readout by the program PHYTEC Vision Demo 2.2, as in Fig. 2.4.



- readout program PHYTEC Vision Demo 2.2

histogram of grey values

Device Properties - USB-CAM-051H

Gain 4 ☐ Auto
Exposure 1/139 sec ☐ Auto
Auto Reference 43
Auto Max Value 30.000 sec ☐ Auto

CCD control parameters → Device → Properties

Start/Stop acquisition → Device → Live (Shortcut: Ctrl + L)
CCD control parameters → Device → Properties

Save image → Capture → Save Image (Shortcut: Ctrl + U): save as Jpeg images

PHYTEC Vision Demo 2.2 - USB-CAM-051H (17310008) [100%]

CCD type
readout format (RGB, 2592 x 1944 pixel)
readout rate (5.99 frames per second)

Maybe less

Figure 2.4: CCD control and readout.

2.4.2 *Data analysis with ImageJ*

After acquiring a CCD image, use the software ImageJ to select a region of interest and plot the horizontal projection, as in Fig 2.5. Save the data in Excel format for profile fitting.

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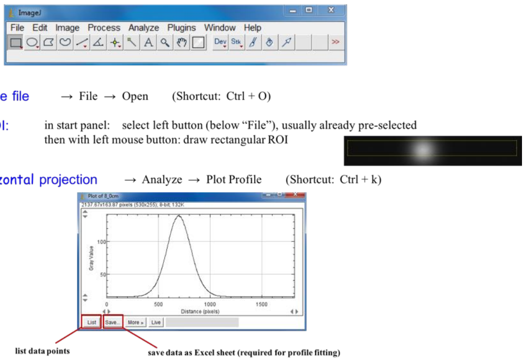
[1] Move the lens to simulate different screen positions



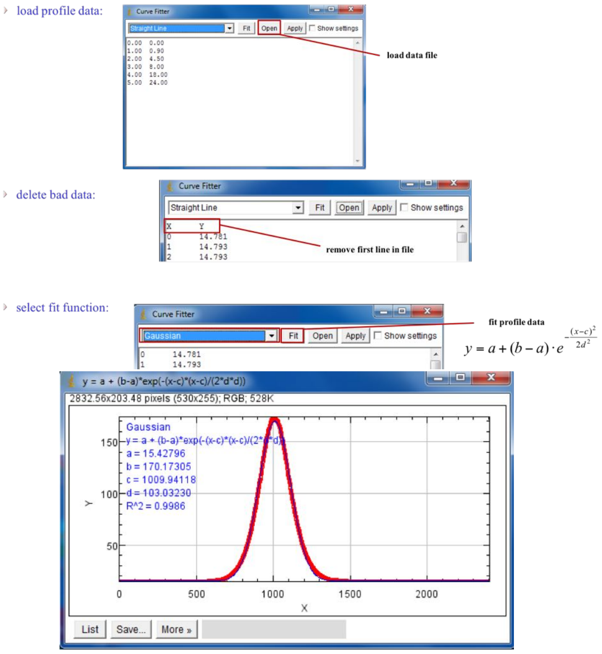
- load image file → File → Open (Shortcut: Ctrl + O)
- select ROI: in start panel: select left button (below "File"), usually already pre-selected
  then with left mouse button: draw rectangular ROI
- plot horizontal projection → Analyze → Plot Profile (Shortcut: Ctrl + k)

list data points

save data as Excel sheet (required for profile fitting)

Figure 2.5: Selection of beam profile data for fitting.

Load the recorded profile data and fit a Gaussian as in Fig. 2.6.


- load profile data: load data file
- delete bad data: remove first line in file
- select fit function: fit profile data

$$y = a + (b-a)\cdot e^{-\frac{(x-c)^2}{2d^2}}$$

```
0.00  0.00
1.00  0.90
2.00  4.50
3.00  8.00
4.00  18.00
5.00  24.00
```

```
X    Y
0    14.781
1    14.793
2    14.793
```

```
Gaussian
y = a + (b-a)*exp(-(x-c)*(x-c)/(2*d*d))
a = 15.42796
b = 170.17305
c = 1009.94118
d = 103.03230
R^2 = 0.9986
```

Figure 2.6: Gaussian fit to profile data.

2.4.3 *Calibration*

Square grid paper can be used to calibrate the distance to pixel size of the camera, as in Fig. 2.7.

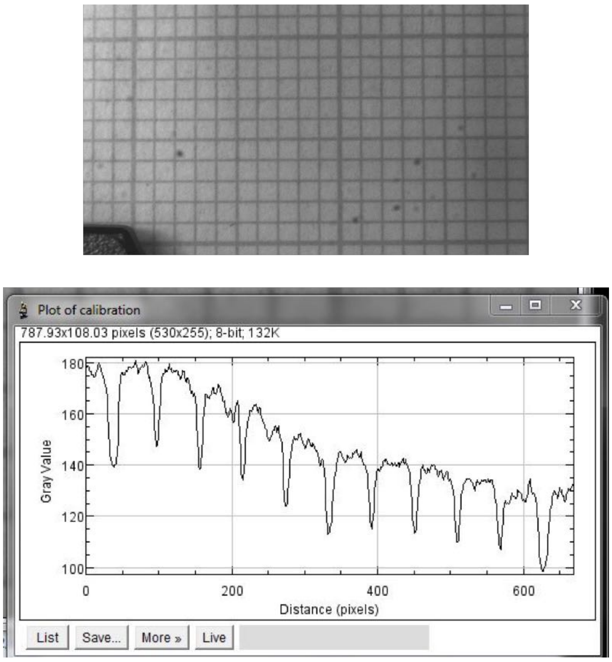


Figure 2.7: Calibration of readout setup using a mm-grid

2.5 Calculation of emittance

Take profiles at three different distances between the lens-screen, using the formula from the theory section and below to calculate to the emittance.

- *Hint 1: Make the distances equal, set $s_1 = 0$, $s_2 = -s_0$*
- *Hint 2: Avoid position at waist (why?)*

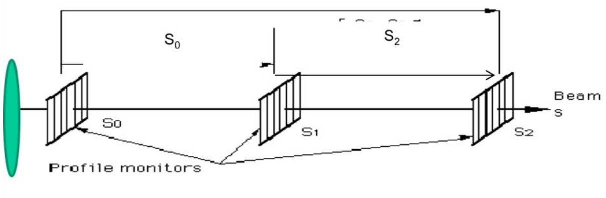


Figure 2.8: Three profiles

Recall from above that:

$$\sigma^2_{y,meas} = M_{11}^2\sigma(s_0)_{11} + 2M_{11}M_{12}\sigma(s_0)_{12} + M_{12}^2\sigma(s_0)_{22}$$

The drift matrix for no optical elements is simply $M = \begin{pmatrix} 1 & s \\ 0 & 1 \end{pmatrix}$

Note that:

$$\begin{aligned}
\sigma^2(s1)_{meas} &= \sigma_{11} + 2s1\sigma_{12} + s_1^2\sigma_{22} \\
\sigma^2(s0)_{meas} &= \sigma_{11} + 2s0\sigma_{12} + s_0^2\sigma_{22} \\
\sigma^2(s2)_{meas} &= \sigma_{11} + 2s2\sigma_{12} + s_2^2\sigma_{22}
\end{aligned}$$

with

$$\begin{aligned}
\sigma_{11} &= \sigma_y^2(0) \\
\sigma_{12} &= \frac{\sigma_y^2(+s) - \sigma_y^2(0)}{4s} \\
\sigma_{22} &= \frac{\sigma_y^2(+s) - 2\cdot\sigma^2(0) + \sigma_y^2(-s)}{2\cdot s^2}
\end{aligned}$$

$$\boxed{\sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{21} & \sigma_{22} \end{pmatrix} = \begin{pmatrix} \sigma_y^2 & \sigma_{yy'} \\ \sigma_{y'y} & \sigma_{y'}^2 \end{pmatrix} = \epsilon \begin{pmatrix} \beta & -\alpha \\ -\alpha & \gamma \end{pmatrix}}$$

$$\boxed{\epsilon_{rms} = \sqrt{\det\sigma} = \sqrt{\sigma_{11}\sigma_{22} - \sigma_{12}^2}}$$

For reference, some preliminary measurements of the beam sigma versus lens distance is given in Fig. 2.9.

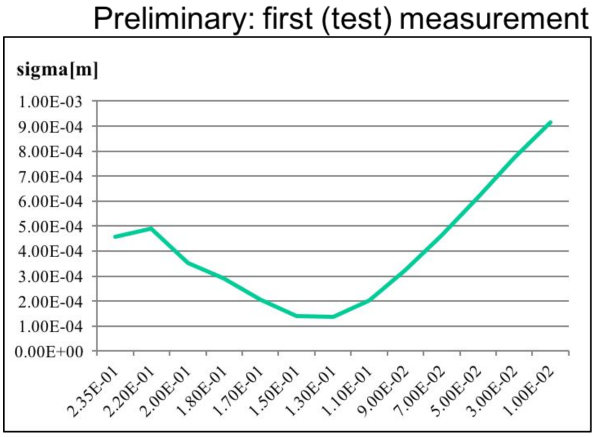


Figure 2.9: Preliminary test measurements of laser beam in this setup.

Lab 3: Pepperpot Emittance Measurement

3.1 Aims and Objectives

These hands on exercises aim to introduce emittance measurements by the pepperpot technique. An optical bench with a light source, a pepperpot plate, several lenses and a GigaBit Ethernet camera is provided.

3.2 Experimental Setup

3.2.1 The Optical Bench

The optical bench shown in Fig. 3.1 consists of the following parts:

- a particle source (powerful red LED)
- a collimator producing a point like source
- the lenses with the following focal length: 24, 30, 43, 54, 76 and 100 mm.
- a pepperpot plate with 9x9 holes (200 m) of 2 mm distance
- a screen
- a Prosilica-GC750 GigaBit Ethernet camera

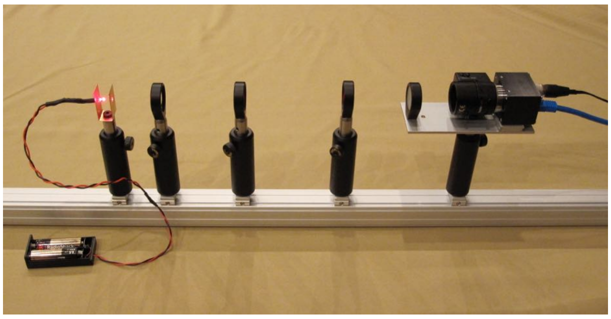


Figure 3.1: Optical bench pepperpot setup.

3.2.2 Software

The following software is part of the system:

GigEViewer This 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

3.3 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* [1] , as in Fig. reffig:PepperPotRayTrace. 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.

---

[1] http://arachnoid.com/OpticalRayTracer/index.html

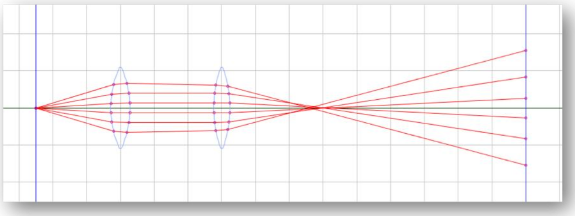


Figure 3.2: Optical ray trace of the lenses in the setup.

3.4 Emittance Measurements from a Pepperpot Image

3.4.1 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.

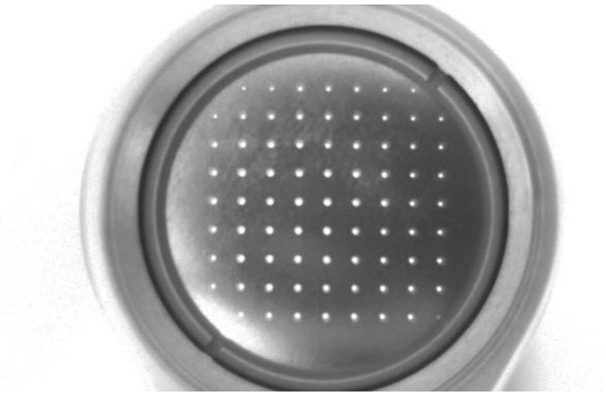
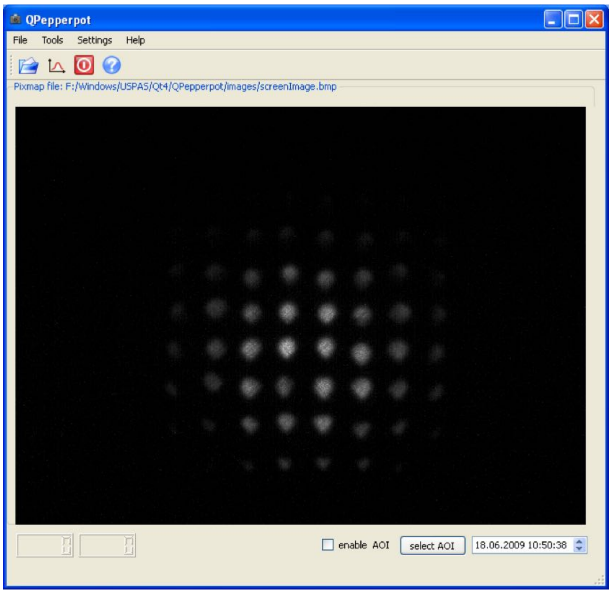


Figure 3.3: The pepperpot plate.

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.

3.4.2 Evaluating a 'good' measurement

The image in Fig. 3.4 shows a typical good measurement. The image of each pepperpot hole is clearly visible, the signal to noise ration is good.



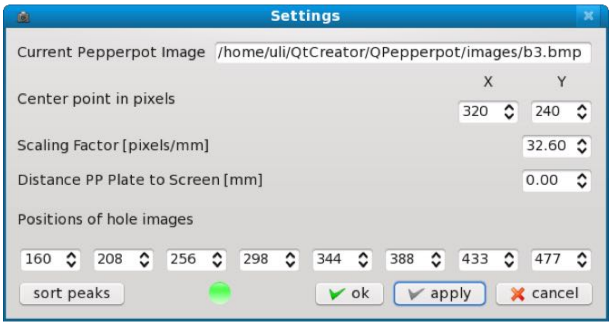
Pixmap file: F:/Windows/USPAS/Qt4/QPepperpot/images/screenImage.bmp

☐ enable AOI

18.06.2009 10:50:38

Figure 3.4: OPepperpot evaluation program.

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 Fig. 3.5) 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.



Current Pepperpot Image /home/uli/QtCreator/QPepperpot/images/b3.bmp

Center point in pixels X 320 Y 240

Scaling Factor [pixels/mm] 32.60

Distance PP Plate to Screen [mm] 0.00

Positions of hole images

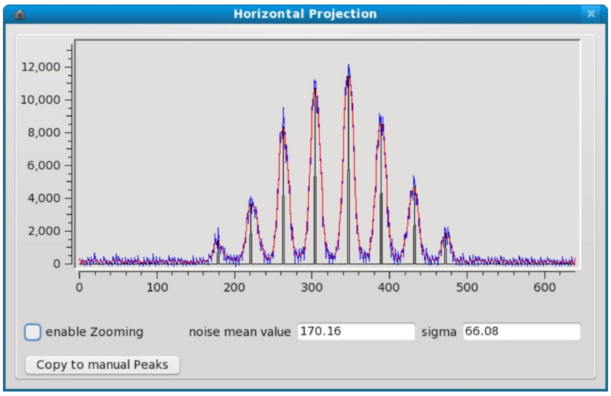
160 208 256 298 344 388 433 477

Figure 3.5: OPepperpot settings diaglog 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)

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.



☐ enable Zooming

noise mean value 170.16

sigma 66.08

Figure 3.6: Projection of pepperpot image.

In Fig. 3.6 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. Fig. 3.7 shows a typical emittance plot for a converging beam.

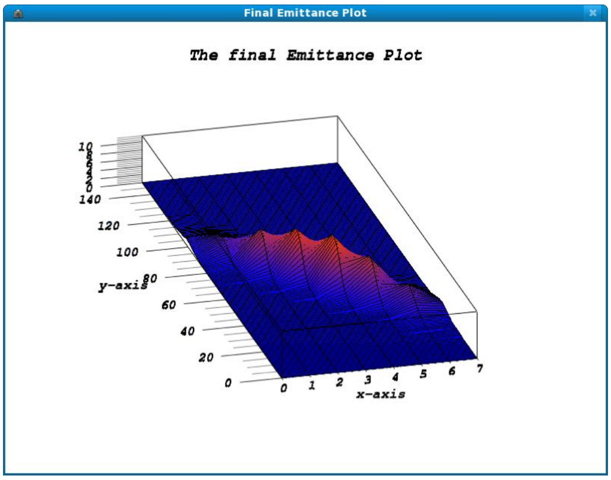
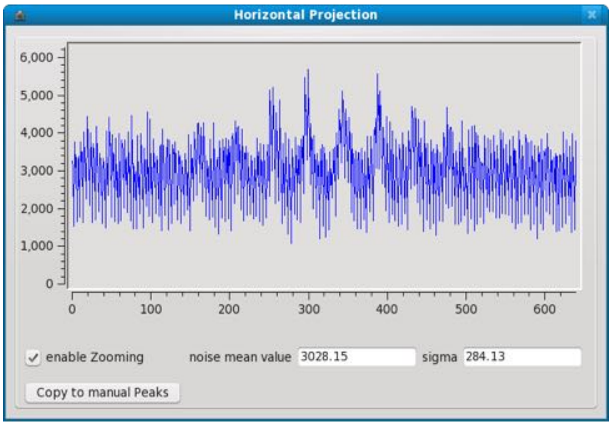


Figure 3.7: Emittance plot derived from pepperpot image.

3.4.3 *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 as not perfect e.g. the aperture is not opened enough, if the contrast settings are not perfect we may end up trying to analyse an image whos projection looks like the one shown in Fig. 3.8. 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.



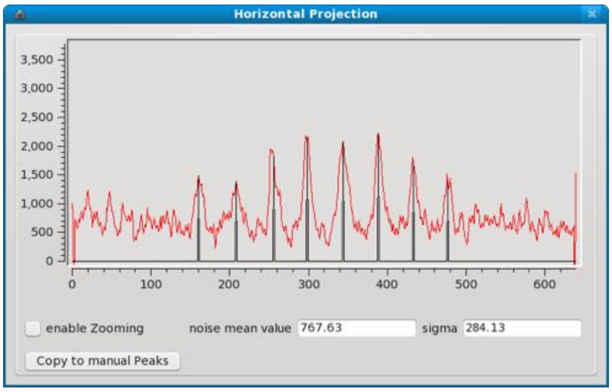
☑ enable Zooming

noise mean value 3028.15

sigma 284.13

Figure 3.8: Projection of a pepperpot image with excess noise.

The pepperpot evaluation programs help through low pass filtering and offset suppression (Tools → Show filtered and Tools → Subtract Offset).



☐ enable Zooming

noise mean value 767.63

sigma 284.13

Figure 3.9: Projection of a pepperpot image cleaned of noise.

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 the 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.

3.5 Acknowledgements

This experiment was initially developed for the USPAS (the US particle accelerator school) in Albuquerque 2009 that had a session that is dedicated to accelerator and beam diagnostics.

In the preparation of the lectures on emittance measurements I had help from several people. In particular I would like to thank:

Dr. Peter Forck, GSI Darmstadt, Germany, whose lecture notes (http://www-bd.gsi.de/conf/juas/juas.html) were used as a basis for the lectures. Dr. H. Braun PSI Villigen Switzerland, who gave me his transparencies on emittance measurements for the CERN School of Accelerators (CAS) on beam diagnostics, Gif-sur-Yvette 28.May - 7.June 2008 Dr. Brennan Goddard, CERN, Geneva, Switzerland who prepared the slides on filamentation Dr. Tom Shea, ORNL, who assembled the experimental setups for the laboratory session several collegues at CERN who gave me photographs or slides, used during the lecture.

U. Raich, CERN, 22. July 2009

Lab 4: Electro-Optic Crystals for Beam Diagnostics

4.1 Aims and Objectives

This experiment aims to introduce the properties of electro-optical effects that are typically used in beam instrumentation to rapidly monitor the longitudinal bunch shape and is recently being developed to monitor the transverse position of particles within one bunch, using an Electro-Optic BPM. The objectives are:

- To become familiar with the electro-optical setup.
- To perform scans to determine the polarization state of the light after the crystal.
- To use these scans to confirm the birefringence of the crystal.
- To see the effect that an electric field across the crystal has on the polarization state of the light.
- To observe how a Babinet compensator may be used to correct the natural birefringence of the crystal.

4.2 Motivation for Electro-Optic Beam Position Monitors

The Large Hadron Collider (LHC) will undergo an upgrade to increase the luminosity of the machine. The High Luminosity (HL) LHC will use a new type of superconducting cavity known as a 'crab cavity' to rotate the particle bunches. This will enable bunches to collide head on at certain interaction points, thus increasing the luminosity. A diagram of the principle can be seen in Fig. 4.1.

Beam position monitors (BPMs) are used to measure the position of a particle bunch inside accelerators, however a traditional BPM will not work for the HL-LHC in regions where the bunch orientation needs to be known. An alternative technique is required that is capable of performing intra-bunch measurements of the transverse position of particles within a 1 ns bunch.

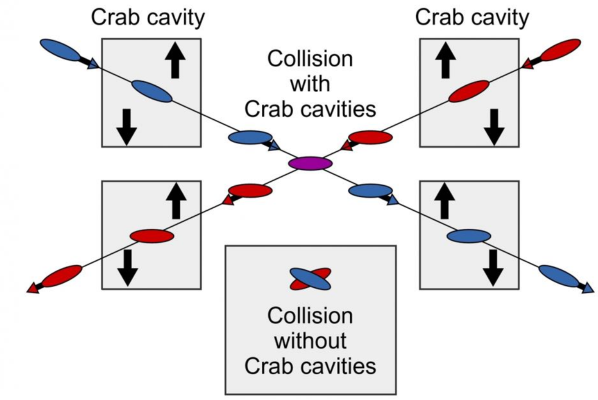


Figure 4.1: The principle behind crab cavities.

An electro-optic (EO) BPM is the proposed solution for the HL-LHC; the setup can be seen in Fig. 4.2. In this figure the two vertical pickups can be seen; there would be another two installed in the horizontal plane. Linearly polarized light at an angle of 45° is passed through an EO crystal, the chosen crystal is Lithium Niobate. The crystal is birefringent, thus the output polarization state will be typically different to the input polarization. When the electric field from a passing bunch is applied across the crystal the effective refractive indices of the crystal, due to the electro-optic Pockels effect. This results in a further change in the output polarization which can be measured and used to determine the transverse position of the particles in a bunch.

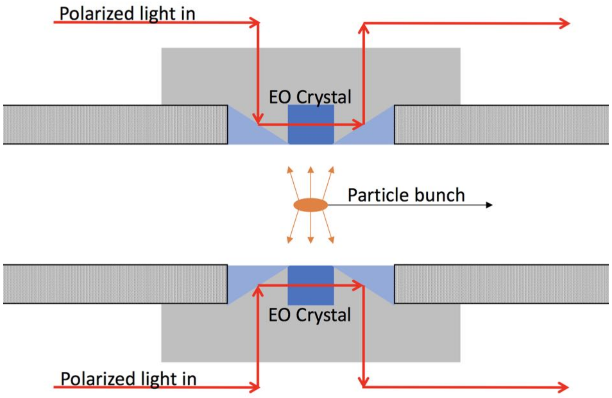


Figure 4.2: The proposed setup of an EO-BPM.

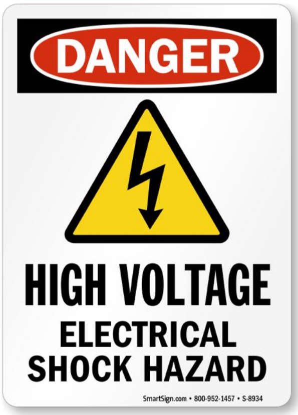
This technique promises to have faster response times than a traditional BPM, and will be able to perform intra-bunch measurements, aiming at a bandwidth of 6 - 12 GHz. The development of a prototype has been developed by Royal Holloway and the Beam Instrumentation group at CERN. It was installed on the SPS at CERN in 2016 and initial results have demonstrated the signal obtained from the electro-optic crystal responds as expected to the passing proton bunch.

4.3 Experimental Setup

The experimental setup for this lab can be found in the physics laboratory, in the dark room labeled T236. The equipment has been setup as seen in Fig. 4.3. The optical elements have been aligned for you, so please do not touch them.

Warning: the He-Ne laser in this experiment is a class IIIa laser. Avoid direct eye exposure to laser radiation. Do not stare into the beam and remove any reflective jewellery before operating the laser.

Warning: the High Voltage (up to 500V) power supply is to be used in this experiments only under the supervision of the laboratory demonstrator for your safety. Ensure all terminals are connected and well insulated before the power is turned on, and do not touch the terminals to avoid electric shock!



The optical arrangement can be seen in Fig. 4.4. The light emitted from the HeNe laser has a wavelength of 632.8 nm and is linearly polarized. It passes through a half wave plate (HWP) to rotate this polarization by 45 degrees. It is then reflected into the pickup, which contains two prisms to reflect the light into and out of the EO crystal contained inside. The crystal is connected to an electrode in order to apply an electric field across the crystal for this lab. Once the light has passed through the pickup it is reflected off a mirror through an analyzer and then a power meter.

Figure 4.3: The experimental setup

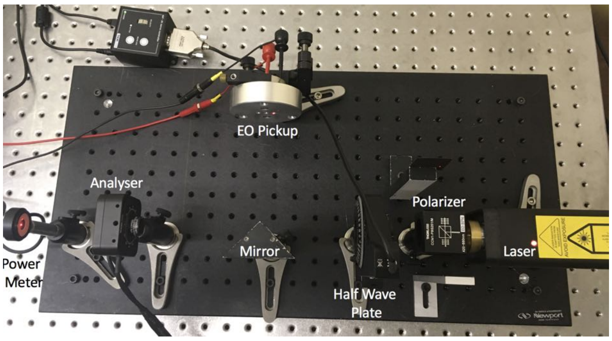


Figure 4.4: The optical setup.

The HWP and analyzer are connected to rotation stages that can be controlled by the software on the PC. Upon commencing the lab, Thorlabs APT User and Thorlabs Optical Power Utility software should be opened. They should appear as seen in Fig. 4.5.

Thorlabs APT User contains the controls for the two rotation stages: the top control is for the HWP and the bottom control is for the analyzer. In settings you can select a jog size to easily rotate the stages around in step sizes that you prefer, and in the 'Move Sequencer' tab you should find a pre-installed sequence that rotates the analyzer 360° over 6 minutes. If the software is closed for any reason, home the rotation stages before moving them.

Thorlabs Optical Power Utility displays the output of the power meter. By clicking 'Start Log' the power will be recorded for six minutes so that a full scan of the analyzer can be recorded. Please create a folder inside the CAS folder on the desktop to save your data.

There is also a DC voltage supply on the optical table, which is already connected to the crystal.

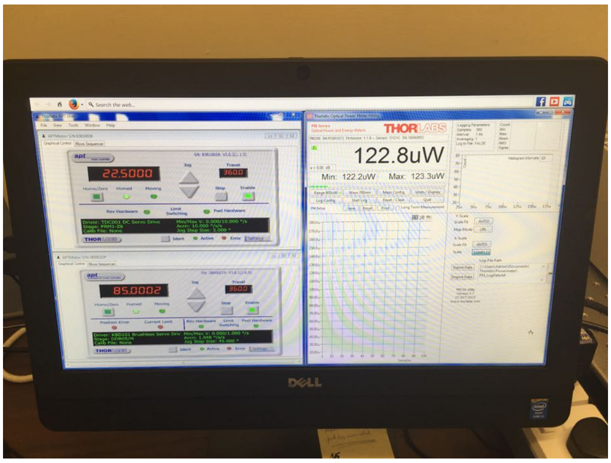


Figure 4.5: The software for data collection.

4.4 Measurements

4.4.1 *Polarization Scans*

By varying the input polarization it is possible to test whether the crystal is birefringent. The crystal has been placed in the pick up such that linearly polarized light will travel along one of the refractive index axes in the crystal. An input angle of 45° means the light will have a component traveling along both of the refractive index axes.

Linearly Polarized Light

Set the HWP to vertical (angle of 47° in the software) and set the analyzer to vertical as well (angle of 85° in the software). Using the Thorlabs APT User software set the analyzer to perform a full 360° scan and set the Thorlabs Optical Power Utility to record the corresponding power output during the scan.

For linearly polarized light the intensity should vary considerably over the scan, with some angles recording almost zero optical power.

Demonstrating the Birefringence

Set the HWP to 45° (angle of 24.5° in the software) and set the analyzer to vertical (angle of 85° in the software). Repeat the above procedure, performing a full 360° scan and set the Thorlabs Optical Power Utility to record the corresponding power output during the scan.

You should notice that the minima occur at the same angles as before, but now have a higher value than before and the maxima have a lower value than before; the contrast has reduced. Circularly polarized light would result in a constant power across all angles, therefore the compression of the contrast between maxima and mimima demonstrates the change from linearly polarized light to elliptically polarized light.

The reason for the variation in the polarization of the light output is due to the change in input polarization. With an input angle of 45°, the difference in refractive indices along the two axes results in a change in polarization.

4.4.2 *Effect of Fixed Electric Field on the Polarization*

Set the HWP to 45° (angle of 24.5° in the software) and set the analyzer to vertical (angle of 85° in the software). Now turn on the DC voltage supply and apply 100 V across the crystal. Repeat the polarization scan procedure. You should notice that the application of an electric field across the crystal has had an effect on the output polarization. Apply up to 500 V in steps of 100 V and do a polarization scan for each case. N.B. A good way to evaluate the change in polarization is to calculate the contrast between maxima and minima for each scan. The smaller the contrast, the more circularly polarized is the output light.

4.4.3 *Babinet compensator*

Even when there is not bias voltage across the crystal, the polarisation state will be altered by the natural birefringence of the crystal. This is corrected by a Babinet compensator inserted just after the crystal and before the analyzer. This device enables the polarization state emerging from the crystal to be converted an arbitrary elliptical state to the desired fully circularized, which provides conditions for the maximum signal. Observe this effect, with the assistance of the demonstrator.

4.5 Current Research

The work being carried out at Royal Holloway uses the principles demonstrated in this lab. The real challenges include developing a detector system that can pick up fast pulses of electric field across the crystal, as this is the scenario on the SPS. To more closely simulate that scenario a coaxial line has been produced, which can be seen in your lab. The pickup is installed on the side of the coaxial setup and nanosecond voltage pulses are sent along the cable running wthe axis of the tube. In order to detect such a fast signal, a power meter such as the one used in your lab is insufficient. Instead high bandwidth photodiodes are used to record the power output.

A challenge is that the beam signal resulting from a change in polarization in the initial prototype was typically small compared to background noise, so several modifications are being applied to improve the signal strength. Electrodes (like the one you can see on the pickup in the lab) have been installed to enhance the size of the electric field applied across the crystal. The dimensions of the crystal have also been optimized to enhance sensitivity to the electric field. A future proposal is to include a secondary crystal into the setup with a DC voltage applied across it. A prototype can be seen in the lab. The motivation for such a device is that it can be used to change the polarization before the analyser, similar to the Babinet compensator. Circular light polarization has a greater sensitivity to small fluctuations in optical power, so the aim is to shift the polarization to circular before detection. By applying a constant field across a secondary crystal this can be achieved.

Lab 5: Electro-Optic Modulator

5.1 Aims and Objectives

Measurements of longitudinal bunch length over short timescales requires fast detector responses with high bandwidth (many GHz). This experiment aims to demonstrate the use of electro-optic modulators in sampling ns fast pulses. The main objectives are:

- Apply a fast ns voltage pulse across an electro-optic modulator (EOM).
- Observe the modulation of light passing through the EOM recorded by a photodiode and determine the spectral components of the pulse.
- Apply fixed frequency RF signals and measure the bandwidth of the setup.
- Observe the effect of modifying the EOM bias on the RF signal.

5.2 Electro-Optic Modulator

Electro-Optic Modulators (EOMs) are commonly used in telecommunications for rapidly modulating optical intensity to transmits high bandwidth signals over optical fibre. An EOM relies on the electro-optic Pockels effect in a lithium niobate crystal, which modifies the polarization state of the light, when a transverse electric field is applied.

5.3 Experimental setup

Warning: the laser enclosed in this experiment is a class IV laser. DO NOT OPEN THE SAFETY BOX. Avoid eye exposure to laser radiation.

The present system is an optical fibre based system. It uses a DC fiber laser connected to a commercial electro-optical modulator. The RFin voltage signals, provided by a pulsed generator, are encoded onto the laser beam and measured by a fast photodiode, which provides an output signal denominated RFout. The latter is finally acquired by an oscilloscope. The EO modulator crystal can also be biased by an external DC voltage to tune and keep the system performance optimal.

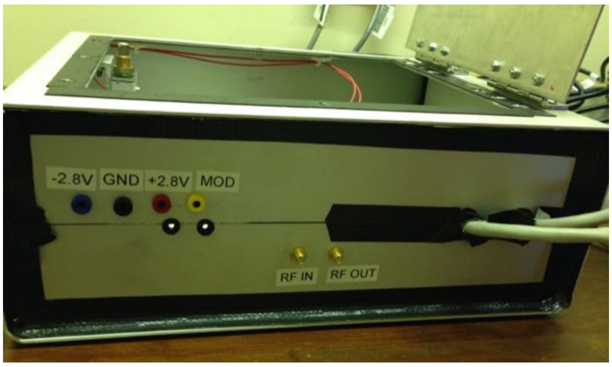


Figure 5.1: Safety housing containing laser, electro-optic modulator and photodiode.

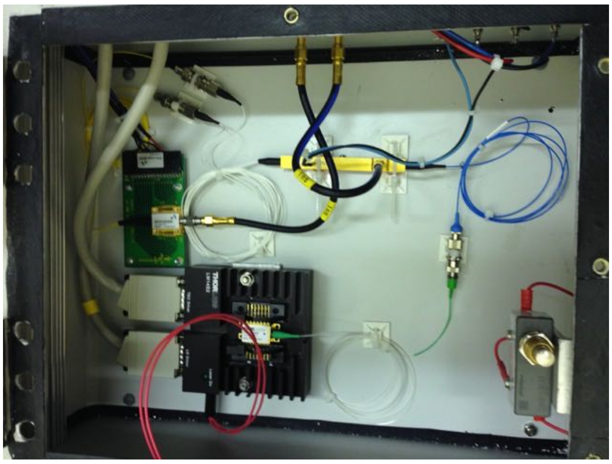


Figure 5.2: DO NOT OPEN the safety housing. Inside is a laser, electro-optic modulator, and photodiode.

5.4 Measurements

5.4.1 *Detecting Fast Pulses*

- Apply pulse (RFin) across the pickup, can you see it on the scope?

- Set the oscilloscope to measure both the input RFin and output RFout voltages simultaneously.
- Reduce the pulse length to the minimum length you can measure

5.4.2 Bias scans

- Turn on the bias voltage
- Scan the bias voltage by small step (i.e. 0.5volts) and measure the amplitude of the RFout signal. Find the best DC bias voltage that provide the highest output voltage RFout.
- Change the pulse length of RFin and redo the bias voltage scan. Do you find the same optimum as before ?

Lab 6: Bunch Length Measurement

6.1 Aims and Objectives

The aim of this exercise is to estimate the bunch length by measuring a few specific frequencies in the bunch spectrum. The bunch length is obtained by fitting the results with the assumed frequency spectrum of the beam and then transforming the result back to time domain.

This demonstrates the interplay between time and frequency measurements:

- Short in time means large in frequency.
- Measuring very short bunch length, i.e. picosecond to femtosecond range, corresponds to measuring a spectrum in the GHz to THz range.

6.2 Theory

In particle accelerators, the bunch length is encoded in the coherent power spectrum radiated by the beams. The coherence comes from the fact that all particles within a bunch will emit radiations in phase for wavelength (and corresponding frequencies) which are equivalent or longer than the bunch length.

The bunch spectrum can be generated through different ways:

- EM devices (RF antenna, RF waveguide transition)
- Radiation processes like synchrotron transition or diffraction radiation

6.3 Experimental Setup

In this experiment, a Vector Network Analyzer (VNA), shown in Fig. 6.1, is used to generate a voltage pulse, analogous to the bunch, with different durations and measuring the corresponding power spectrum.

6.4 Creating a Beam

Recall set-up *"Beam final"* using the *RECALL* button under *'System"* on the front panel.

The VNA should be set-up to measure S21 & display the frequency spectrum with a log scale (*FORMAT* → dB Mag).

First we create a *"Beam"* by using the 1 GHz low pass filter, as in Fig. 6.2:

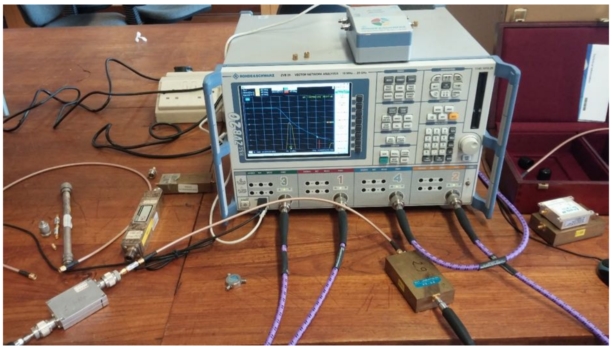


Figure 6.1: Vector Network Analyzer.

- Connect Port 2 to the attenuator side of the filter
- Connect Port 1 to the other side of the filter
- Store the Trace to memory:
  - *TRACE FUNCT ⇒ MORE MEM ⇒ DATA → MEM ⇒ DATA → NEW MEM*

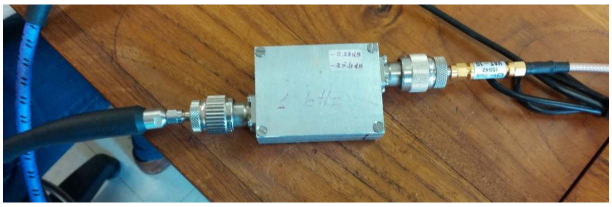


Figure 6.2: 1 GHz Low pass filter.

6.5 Sampling at Specific Frequencies

- Leave Port 1 connected to the 1 GHz low pass filter - the *"Beam"*.
- Connect the 1.5 GHz Bandpass filter shown in Fig. 6.3 after the *"Beam"* on the attenuator side
- Connect Port 2 to the other side of the bandpass filter
- Store the Trace to memory
  - *TRACE FUNCT ⇒ MORE MEM ⇒ DATA → MEM ⇒ DATA → NEW MEM*

- Repeat the same procedure for the 2.5 GHz Filter in Fig. 6.4.

Figure 6.3: 1.5 GHz band pass filter.

Figure 6.4: 2.5 GHz band pass filter.

You should now have a frequency domain picture showing the full beam spectrum and the two specific frequencies that you've probed. If time permits, you can also insert the 2.9 GHz filter to have a third reference line.

6.6 Estimating the Bunch Length

If we now make an assumption about the bunch shape we can use these discrete measurement points to estimate the bunch length.

Let's assume that the bunch has a Gaussian longitudinal profile. For our two measurement frequencies, we therefore have:

$$A_1 = Ie^{-\frac{1}{2}\frac{f_1^2}{\sigma_{\mathrm{freq}}^2}} \quad A_2 = Ie^{-\frac{1}{2}\frac{f_2^2}{\sigma_{\mathrm{freq}}^2}}$$

where σ_{freq} is the sigma of the ***frequency domain*** Gaussian profile, and f_1, A_1 and f_2, A_2 are the frequency and amplitude respectively of the discretely measured response. Solving these simultaneous equations gives:

$$\begin{aligned}\sigma_{\mathrm{freq}} &= \sqrt{\frac{f_2^2 - f_1^2}{2 \times (\ln A_1 - \ln A_2)}} \\ &= \sqrt{\frac{f_2^2 - f_1^2}{2 \times (\frac{\log_{10} A_1 - \log_{10} A_2}{\log_{10} e})}} \\ &= \sqrt{\frac{f_2^2 - f_1^2}{4.6 \times (\log_{10} A_1 - \log_{10} A_2)}}\end{aligned}$$

$$\boxed{\sigma_{\mathrm{freq}} = 0.466\sqrt{\frac{f_2^2 - f_1^2}{\log_{10} A_1 - \log_{10} A_2}}} \tag{6.1}$$

As we measured in dB, the amplitudes are already logarithmic and can therefore be directly inserted into the denominator of equation 6.1.

The conversion to the ***time domain***, σtime is then achieved through the following equation:

$$\sigma_{\mathrm{time}} = \frac{1}{2\pi\sigma_{\mathrm{freq}}},$$

where the standard deviations are expressed in their physical units, i.e. in the case of time and frequency in seconds and Hertz.

6.7 Verifying the Bunch Length

- Reconnect the VNA as in section 6.4 to give the frequency response of the *"Beam"*
- Now lets move to time domain
  - Select *"Trace"* from the menu bar
  - Choose *"Trace Funct"* from the drop down menu
  - Select *"Time Domain"*
- From the VNA Buttons select *"FORMAT ⇒ Real"* (on Menu 2/2)
- Select *"STOP SPAN"* & ensure that the timescale goes from 0-5 ns
- Select *"SCALE ⇒ Autoscale"*

You should now see the *"Bunch"* from which you can verify the bunch length.