THORLABS

Discovery

EDU-SPEBCT1
EDU-SPEBCT1/M

Spectrometer Extension Kit
Czerny-Turner Configuration

Manual

Table of Contents

Chapter 1 Warning Symbols

Below is a list of warning symbols you may encounter in this manual or on your device.

Symbol	**Description**
	Direct Current
	Alternating Current
	Both Direct and Alternating Current
	Earth Ground Terminal
	Protective Conductor Terminal
	Frame or Chassis Terminal
	Equipotentiality
	On (Supply)
	Off (Supply)
	In Position of a Bi-Stable Push Control
	Out Position of a Bi-Stable Push Control
	Caution: Risk of Electric Shock
	Caution: Hot Surface
	Caution: Risk of Danger
	Warning: Laser Radiation

Chapter 2 Brief Description

The EDU-SPEBCT1(/M) Extension kit provides all the components needed to extend the EDU-SPEB2(/M) spectrometer setup to a Czerny-Turner geometry. This configuration is used in most commercial spectrometers due to its flexibility, compactness, and relatively small aberrations. Moreover, the reflective grating is made rotatable via the PR01(/M) rotation stage and a second adjustable slit is included, which adds the functionality of a monochromator and enables absorption spectroscopy of various solid and liquid samples. Note that all functions of the original kit are retained or improved by the Czerny-Turner configuration.

With this extension kit, students can obtain a deep understanding of the working principles of modern spectrometers and monochromators by building their own scanning spectrometer and by experimentally recording the transmission spectra of various materials.

The detector of the spectrometer is designed for wavelengths between 350 nm and 1100 nm, and the white light LED emits between 430 nm and 700 nm. A filter with multiple bandpasses in the visible regime is included as a test sample.

Chapter 3 Kit Components

This kit is an extension to the EDU-SPEB2(/M) Spectrometer Kit. To build the complete Czerny-Turner setup, parts from EDU-SPEB2(/M) are required; see Chapter 5.1 for details. To only order those parts, please contact sales@thorlabs.com.

In cases where the metric and imperial kits contain parts with different item numbers, metric part numbers and measurements are indicated by parentheses unless otherwise noted.

3.1. Mechanical Components

<table>
<tr>
<td>
2 x PH2 (PH50/M)
2" (50 mm) Long Post Holder</td>
<td>

2 x TR2 (TR50/M)
2" (50 mm) Post</td>
<td>
2 x PH3 (PH75/M)
3" (75 mm) Long Post Holder</td>
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<tr>
<td>

4 x TR3 (TR75/M)
3" (75 mm) Post</td>
<td>
2 x UPH3 (UPH75/M)
3" (75 mm) Long Universal Post Holder</td>
<td>

3 x BE1(/M)
Ø1.25" (Ø31.8 mm) Pedestal Base Adapter</td>
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<tr>
<td>
2 x CF125
Clamping Fork</td>
<td>

1 x KCP05(/M)
Centering Plate</td>
<td>
1 x PR01(/M)
High-Precision Rotation Mount</td>
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	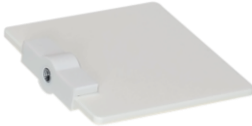	
1 x **PR01A(/M)** Solid Adapter Plate for PR01(/M)	**EDU-VS2(/M)** Small Viewing Screen	1 x **R2(/M)** Slip-On Post Collar

3.2. Optical Components

 1 x **LB1757** Bi-Convex Lens Ø1", f = 30 mm, Uncoated	 1 x **LMR1(/M)** Ø1" Lens Mount	 2 x **CM254-200-P01** Ø1" Silver-Coated Concave Mirror, f = 200 mm
 2 x **KM100** Kinematic Mirror Mount for Ø1" Optics	 2 x **KCP1(/M)** Centering Plate	 1 x **VA100(/M)** Variable Slit
 1 x **FGB67** Colored Glass Filter with Multiple Bandpasses in the Visible Range	 1 x **SM1A1** Adapter with External SM05 Threads and Internal SM1 Threads	 1 x **SM1RR** SM1 Retaining Ring

3.3. Detector

 1 x **SM05PD1A** Silicon Photodiode, 350-1100 nm	 1 x **SM05M10** SM05 Lens Tube Without External Threads, 1" Long	 1 x **SM05L05** SM05 Lens Tube, 0.5" Thread Depth
 1 x **SM05A3** Adapter with External SM05 and External SM1 Threads	 1 x **CA2812** SMA Coaxial Cable, SMA Male to BNC Male, 12" (304 mm)	 1 x **T3285** BNC T-Adapter (F-M-F)
 1 x **T4003** BNC Female to Banana Plug Adapter	 1 x **FT104** 100 kΩ Fixed Stub-Style BNC Terminator	 1 x **DVM1** 10 Function Digital Multimeter

3.4. Tools and Hardware Kit

Imperial Kit Hex Keys, Ball Driver, and Screws

<table>
<tr><th>Type</th><th>Quantity</th><td rowspan="2">Hex Keys: 3/32", 5/64", and 9/64"</td></tr>
<tr><td>8-32 x 1/4" Cap Screw</td><td>3</td></tr>
<tr><td>1/4"-20 x 3/8" Cap Screw</td><td>4</td><td rowspan="4">
1 x BD-5/64
5/64" Balldriver</td></tr>
<tr><td>1/4"-20 x 5/8" Cap Screw</td><td>2</td></tr>
<tr><td>1/4"-20 x 1/2" Setscrew</td><td>1</td></tr>
<tr><td>1/4"-20 Washer</td><td>6</td></tr>
</table>

Metric Kit Kit Hex Keys, Ball Driver, and Screws

<table>
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<tr><td>M4 x 6 mm Cap Screw</td><td>3</td></tr>
<tr><td>M6 x 10 mm Cap Screw</td><td>4</td><td rowspan="4">
1 x BD-2M
2 mm Balldriver</td></tr>
<tr><td>M6 x 16 mm Cap Screw</td><td>2</td></tr>
<tr><td>M6 x 12 mm Setscrew</td><td>1</td></tr>
<tr><td>M6 Washer</td><td>6</td></tr>
</table>

Chapter 4 Theoretical Background

The general theoretical background for spectrometry can be found in the manual of the EDU-SPEB2(/M) kit. Here we focus on the layout and properties of the Czerny-Turner configuration, the working principle of a monochromator, and on the specific setup included in this extension kit.

4.1. The Fastie-Ebert and Czerny-Turner Configurations

A simple but effective spectrometer design is the Fastie-Ebert configuration[1], depicted in Figure 1a. It consists of a planar diffraction grating and one large spherical mirror. Light coming from the entry slit is collimated by the mirror onto the grating. The intended diffraction order from the grating is then focussed by the same mirror onto a screen, detector array, or exit slit, depending on the method of operation of the spectrometer (see Chapter 4.2).

The Czerny-Turner configuration is an extension of the Fastie-Ebert design, in which the single spherical mirror is substituted by two smaller spherical mirrors, one of which is responsible for collimating and the other for focusing; see Figure 1b. This allows more freedom in the optical layout (e.g. folded beam paths, see Figure 2) and allows for correction of some aberrations at specific wavelengths[1], making the Czerny-Turner geometry the most commonly used spectrometer design.

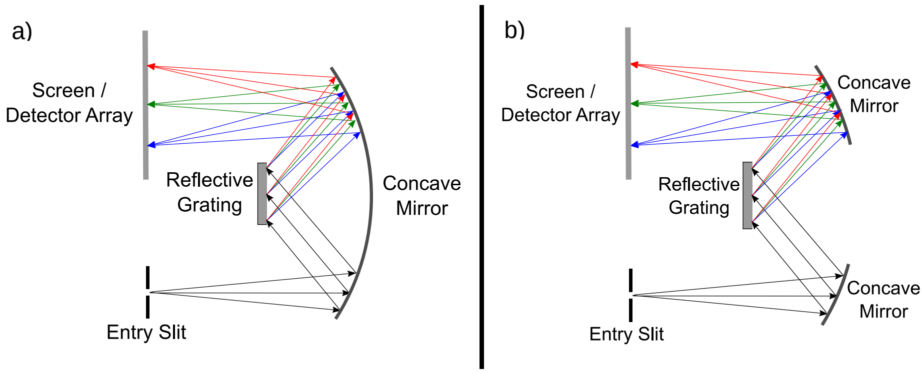

Figure 1: (a) Fastie-Ebert Configuration and (b) Czerny-Turner Configuration.

[1] Chapter 2.2. of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf

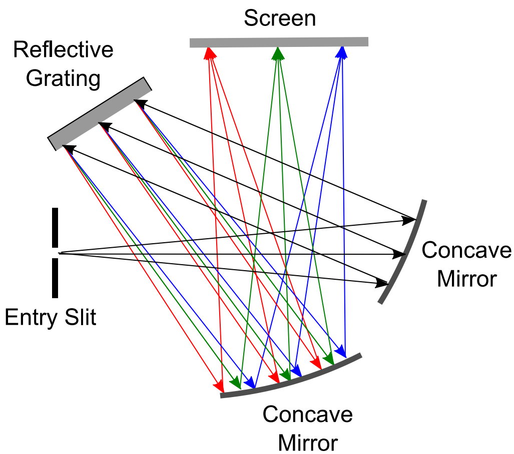

Figure 2: Czerny-Turner Design with Folded Beampath

Some aberrations, i.e. astigmatism and aspherical aberrations, cannot be corrected in the Czerny-Turner configuration due to the limitations of spherical optics. For high-precision applications, aspherical concave gratings are used, which combine all optics of the spectrometer in a single element and correct for all aberrations at one wavelength[2] (see Figure 3).

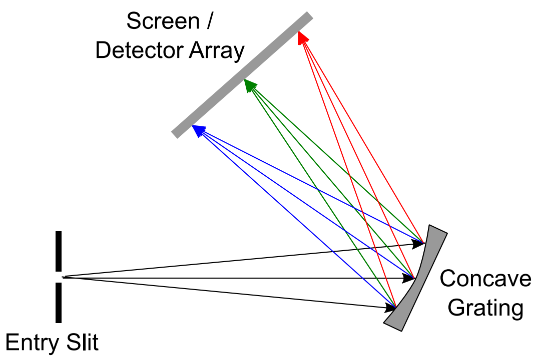

Figure 3: Spectrometer Design with Concave Grating

[2] Chapter 2.4.1 of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf

4.2. Methods of Operation for a Spectrometer

There are two main methods of operation for a spectrometer, which are described in the following, assuming a Czerny-Turner configuration:

- Spectrograph: A linear detector array is placed in the focal plane of the second concave mirror. Thus, each individual detector element (pixel) is illuminated by a narrow wavelength range, allowing for a precise measurement of the whole spectrum in a single step. If the detector array is replaced by a screen, one can observe the spectrum directly by eye.
- Scanning Spectrometer: A second slit (called exit slit from here on) is placed in the focal plane of the second concave mirror, so that only a narrow wavelength regime passes this slit. Such a setup is called a monochromator. This is the method of operation used in this kit and is described in detail in the following section.

4.3. Monochromator and Scanning Spectrometers

A monochromator is a device used to select light of a single wavelength (or, more precisely, a small wavelength range) from a polychromatic light source. Monochromators can be categorized by whether they include dispersive elements or not.

The latter group relies on absorption and/or reflection of unwanted wavelengths, e.g. in the form of the dielectric coatings of bandpass filters. However, such monochromators only work for one specific wavelength and are limited in how narrow the selected wavelength range can be.

Thus, monochromators are most often realized by the use of dispersive elements, especially gratings. The spectrometer geometries introduced in Section 4.1 can also be used for monochromators by replacing the screen with a second slit, the exit slit, as shown in Figure 4. To tune the selected wavelength, one can either move the slit and detector or rotate the grating, with the latter method being used in this kit.

A scanning spectrometer (such as in this kit) has a single photodetector behind the exit slit of the monochromator. Often, an additional lens is used to focus the light passing the exit slit onto the detector. A spectrum is obtained by varying the wavelength selected by the monochromator in small steps and recording the intensity measured by the photodetector for each step. In contrast to detector-array-based spectrographs (see Chapter 4.2), higher precision is possible, but the time required to record a spectrum is significantly longer.

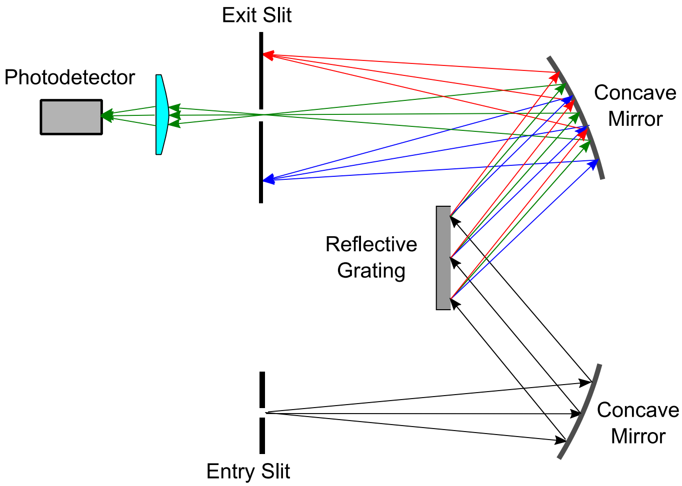

Figure 4: Scanning Spectrometer in Czerny-Turner Configuration

4.4. Grating Equation for a Rotatable Grating

In a scanning spectrometer, one controls the rotation of the grating to select which wavelength is passing the exit slit of the monochromator. This section provides the derivation of an equation that links the grating rotation angle to the wavelength.

Note: In reality, the monochromator is not able to select a single wavelength λ, but always a wavelength range centered around this wavelength. For simplicity, the following calculations are performed for the center wavelength only.

As sketched in Figure 5a, we assume light of wavelength λ, coming in from the entry slit, falls onto a grating with a line spacing d under some arbitrary angle α between the incoming light and the grating normal. The first order diffraction of the light leaves the grating under the angle β between the grating normal and the diffracted light. Please note that for the following calculation, α is defined as negative if the incoming light is counterclockwise from the grating normal. The same is true for β and the outcoming beam. This convention is shown in Figure 5b. The angle θ between the incoming and outcoming light is then defined as:

$$\theta = \beta - \alpha \qquad \textbf{\textit{(1)}}$$

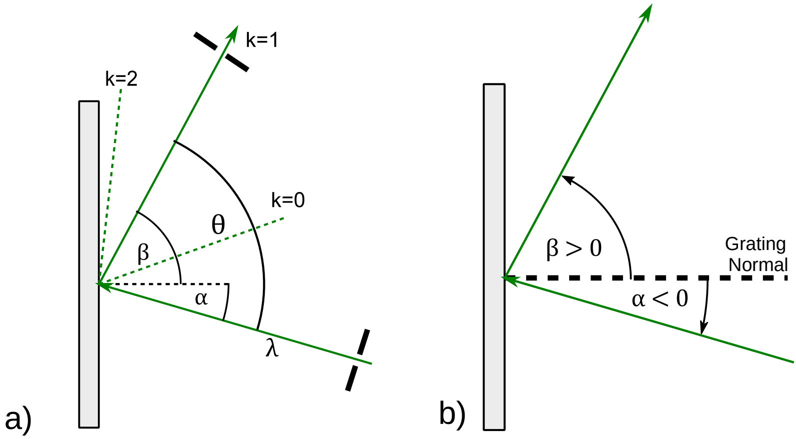

Figure 5: a) Diffraction of light on a reflective grating and b) convention for signs of angles. The black dotted line indicates the grating normal.

Under those conditions, constructive interference in the diffraction order k occurs for a wavelength λ and a grating spacing d if the optical path difference between two beams reflected from neighbouring grating lines is equal to $k \cdot \lambda$. From Figure 6, one can see that this is the case for:

$$k \cdot \lambda = \sin\beta \cdot d + \sin\alpha \cdot d \qquad \textbf{(2)}$$

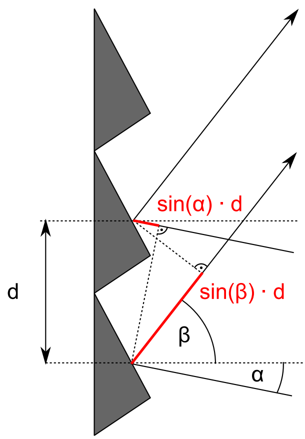

Figure 6: Constructive Interference Condition after Diffraction on Grating

Remember that α is negative in the convention used here. After rearranging Equation (2), one obtains the grating equation for arbitrary angles of incidence:

$$k \cdot \lambda \cdot g = \sin(\beta) + \sin(\alpha) \qquad \textbf{(3)}$$

Here, $g = \frac{1}{d}$ denotes the grating groove density.

Now assume a monochromator setup with a rotatable grating. In this configuration, the illumination occurs with white light. The beampath before and after the grating is fixed. Hence, upon rotating the grating, the angle θ stays constant, while the angle of incidence α changes. This results in a different wavelength λ passing the exit slit.

We now substitute $\beta = \theta + \alpha$ [see Equation (1)] in Equation (3) and yield:

$$k \cdot \lambda \cdot g = \sin(\theta + \alpha) + \sin(\alpha) \qquad \textbf{(4)}$$

For a known θ, this is the relation between the angle of incidence α (controlled by rotating the grating) and the wavelength λ hitting the exit slit. As θ is a constant of the setup, it will be called the setup angle from now on.

Determining the Setup Angle θ

One could measure θ directly or perform a measurement with light of a known wavelength and calculate it from this measurement. However, there is a more elegant way to determine θ, which is introduced in the following.

The grating is first rotated until the zero order reflection from the grating falls back into the exit slit, see Figure 7a. This defines an angle of incidence of 0°.

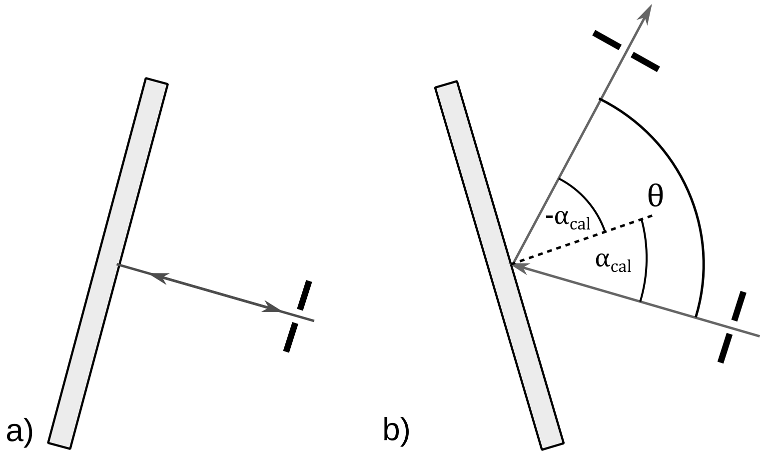

Figure 7: The two grating positions for determining the setup angle θ. Only the zero order reflection is shown hitting the (a) entry slit or (b) exit slit. The grating rotation angle α_{cal} between the two positions is used to calculate θ.

Next, the grating is rotated until the zero order reflection falls onto the exit slit, see Figure 7b. The rotation angle required to get from position (a) to (b) determines the angle of incidence α_{cal} in position (b). For the zero order, the grating acts just like a mirror, i.e. the angle of reflection β is equal to $-\alpha_{cal}$. Substituting this in Equation (1) yields:

$$\theta = -2 \cdot \alpha_{cal} \qquad \textbf{\textit{(5)}}$$

4.5. Angular and Linear Dispersion

In this section, we define the terms angular and linear dispersion for a typical Czerny-Turner spectrometer with a layout as shown in Figure 8.

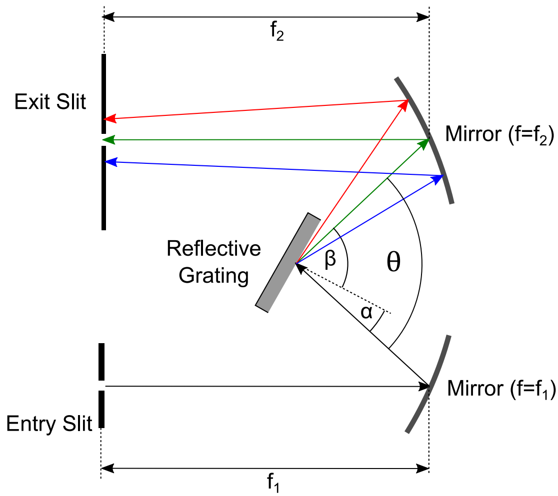

Figure 8: Beampath in the Monochromator of a Scanning Spectrometer

All wavelengths arrive at the grating under the same angle α, but leave the grating under different angles β. Rearranging Equation (3) and differentiating with respect to β results in the following equation.

$$\frac{d\lambda}{d\beta} = \frac{\cos\beta}{k \cdot g} \qquad \textbf{(6)}$$

The term $\frac{d\lambda}{d\beta}$ is called angular dispersion, k is the diffraction order and g is the grating groove density. The angular dispersion describes how strongly diffraction at the grating separates the wavelength angularly.

Often, one is interested in the spread of the wavelengths over a given distance x in the focal plane of the focusing mirror, where the exit slit (alternatively a screen or detector) is placed. The goal is then to calculate this linear dispersion $\frac{d\lambda}{dx}$.

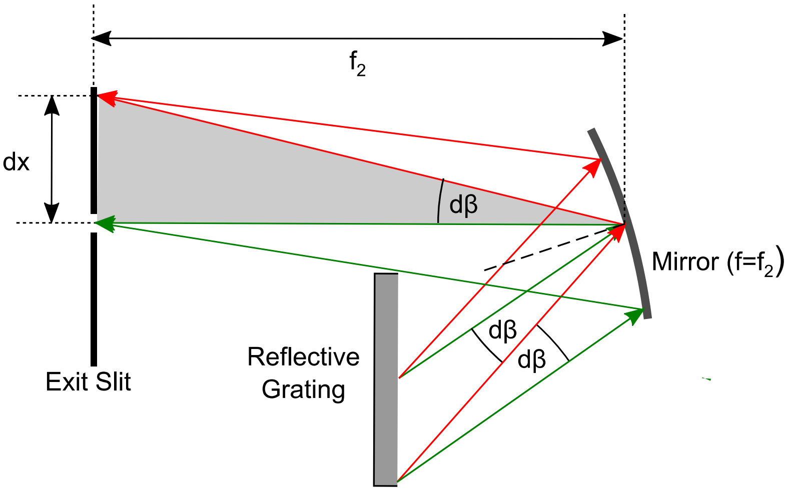

Figure 9: Sketch for Calculation of Linear Dispersion

In Figure 9, we show the rays[3] emitted from two different spots on the grating for two different wavelengths λ and $\lambda + \mathrm{d}\lambda$. They leave the grating with an angle difference of $d\beta$.The rays for each wavelength are parallel coming from the grating and are focused onto the slit by the concave mirror. They hit at different spots which are separated by a distance dx. The two rays of different wavelengths coming from the same point on the concave mirror also leave the mirror with an angle difference of $d\beta$. For understanding this fact, it helps to keep in mind that the reflection on the concave mirror at a given point is determined by the local surface normal at that point. It follows the same rules as reflection on a plane mirror with that surface normal, i.e. incident angle equals reflection angle. A look at the shaded triangle then results in:

$$\tan(d\beta) = \frac{dx}{f_2} \qquad \textbf{(7)}$$

Assuming a small $d\beta$ and rearranging the equation yields

$$dx = f_2 \cdot d\beta \qquad \textbf{(8)}$$

[3] We are aware that using the term “ray” in the context of diffraction on a grating is misleading. What is meant is not a ray in the sense of classical optics but rather the direction in which constructive interference is found. To improve readability, we still decided to use the term “ray” here in order to derive the linear dispersion from the geometrical properties of the spectrograph.

Substituting this result in Equation (6) and using the chain rule yields the following equation for the linear dispersion of the first diffraction order:

$$\frac{d\lambda}{dx} = \frac{\cos\beta}{g \cdot f_2} \qquad \textbf{(9)}$$

Please note that these calculations only hold for small angle differences.

4.6. Resolution and Bandpass

The terms resolution and bandpass are closely related. Fundamentally, they describe the ability of the spectrometer to separate adjacent spectral light. If used with a spectrally continuous light source, bandpass describes the width of the spectral range that may be isolated[4].

When analyzing an idealized monochromatic light source, the output of an ideal spectrometer would be the same monochromatic line. In reality, however, the output will always be a profile of finite spectral width, the so-called instrumental bandpass (we use $\Delta\lambda$ as a symbol for the bandpass in this manual).

When analyzing a light source with a continuous spectrum, the spectrum can be viewed as being composed of an infinite amount of monochromatic lines. The measured spectrum is then a convolution of the light source spectrum and the wavelength-dependent instrumental bandpass.

Several factors contribute to this instrumental bandpass. The most important are:

1) The width of the entry slit
2) The width of the exit slit
3) Diffraction on the grating
4) Aberrations

The contribution of each individual factor is determined by measuring the instrumental bandpass for that property while all others are assumed to be negligibly small. For example, the influence of the entry slit width on the instrumental bandpass can be determined by measuring the spectral width $\Delta\lambda$, while assuming the effects of the exit slit width, diffraction on the grating, and aberrations are negligibly small. The overall bandpass is then a convolution of all the individual contributions. In the following those contributions will be looked at one by one.

Slit Width

The instrumental bandpass caused only by the entry slit width is a rectangular profile with the width of the image of the entry slit on the exit slit plane multiplied with the linear

[4] Chapter 2.12 of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf

dispersion (see Section 4.5). Similarly, the instrumental bandpass caused by the exit slit width is the exit slit width multiplied by the linear dispersion.

This can be understood by imagining the spectrum that would be recorded when scanning a monochromatic line of finite width over an infinitely small slit or scanning an infinitely sharp line over a slit of finite width. The instrumental bandpass functions of the entry slit and exit slit are schematically shown in Figure 10 for a center wavelength λ_0. Here, we call the spectral width of the entry slit bandpass $\Delta\lambda_{en}$ and the width of the exit slit bandpass $\Delta\lambda_{ex}$.

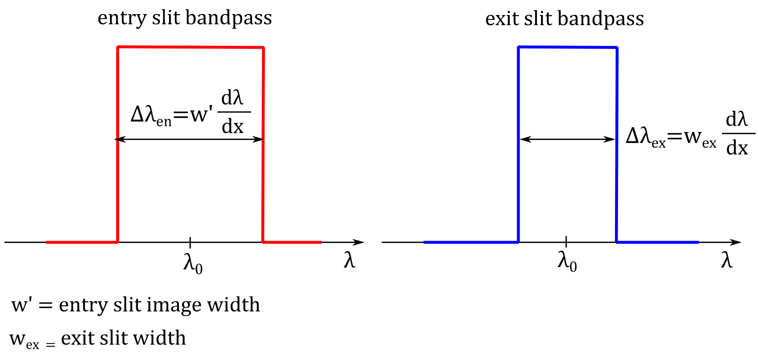

Figure 10: Instrumental Bandpass Functions of Entry and Exit Slit

For a Czerny-Turner spectrometer as depicted in Figure 8, the width w' of the entry slit image can be calculated as follows:

$$w' = w_{en} \cdot \frac{\cos\alpha}{\cos\beta} \cdot \frac{f_2}{f_1} \qquad \textbf{(10)}$$

with w_{en} being the slit width of the entrance slit; α, β the incoming and outgoing angles of the light at the grating (see Figure 8); and f_1, f_2 the focal lengths of the collimating and focusing concave mirror, respectively. The term $\frac{f_2}{f_1}$ is the magnification or demagnification of the entry slit image due to the focal lengths of the concave mirrors, while the term $\frac{\cos\alpha}{\cos\beta}$ describes the influence of the anamorphism of the optics, i.e. the difference in magnification in the planes vertical and horizontal to the grating (for a more detailed description, see literature[5]).

[5] Chapter 2.10 of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf

The overall contribution of the slit widths is the convolution of the contributions of both slits. The general mathematical expression for a convolution of two functions f and g is:

$$(f * g)(x) = \int_{-\infty}^{\infty} f(x-z) \cdot g(z) \cdot dz \tag{11}$$

Figure 11 shows schematically how the convolution of two functions works in this case[6]. The bandpass function of the exit slit (blue) is fixed and centered around some wavelength λ_0 while the bandpass function of the entry slit (red) is moved along the λ-axis. The steps 1 to 6 in Figure 11 are snapshots of that continuous movement. To calculate the value of the convolution (green) at the point λ, one positions the center of the bandpass function of the entry slit at λ and calculates the area of the overlap of the two bandpass functions.

The full width at half maximum (FWHM) of the convolution is equal to the bandpass of the entry slit or the exit slit, whichever is wider. In order to maximize throughput without increasing the width of the bandpass, the exit slit width should therefore be identical to the width of the image of the entry slit. At this point the convolution becomes a triangular profile with a FWHM of $w' \cdot \frac{d\lambda}{dx}$, , i.e.

$$\Delta\lambda = w \cdot \frac{\cos\alpha}{\cos\beta} \cdot \frac{f_2}{f_1} \cdot \frac{d\lambda}{dx} \tag{12}$$

Substituting Equation (9) yields:

$$\Delta\lambda = w \cdot \frac{\cos\alpha}{f_1 \cdot g} \tag{13}$$

The convolution function in Figure 11 describes how the spectrum behind the exit slit looks like. If you would measure the spectrum behind the exit slit with a commercial spectrometer, such as the Thorlabs CCS100, the spectrum would have the same top-hat form as the convolution function in step 6 of Figure 11 as long as the exit slit width is different from the width of the entry slit image. If both widths are equal, this form changes to triangular.

[6] Chapter 2.12.1 of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf

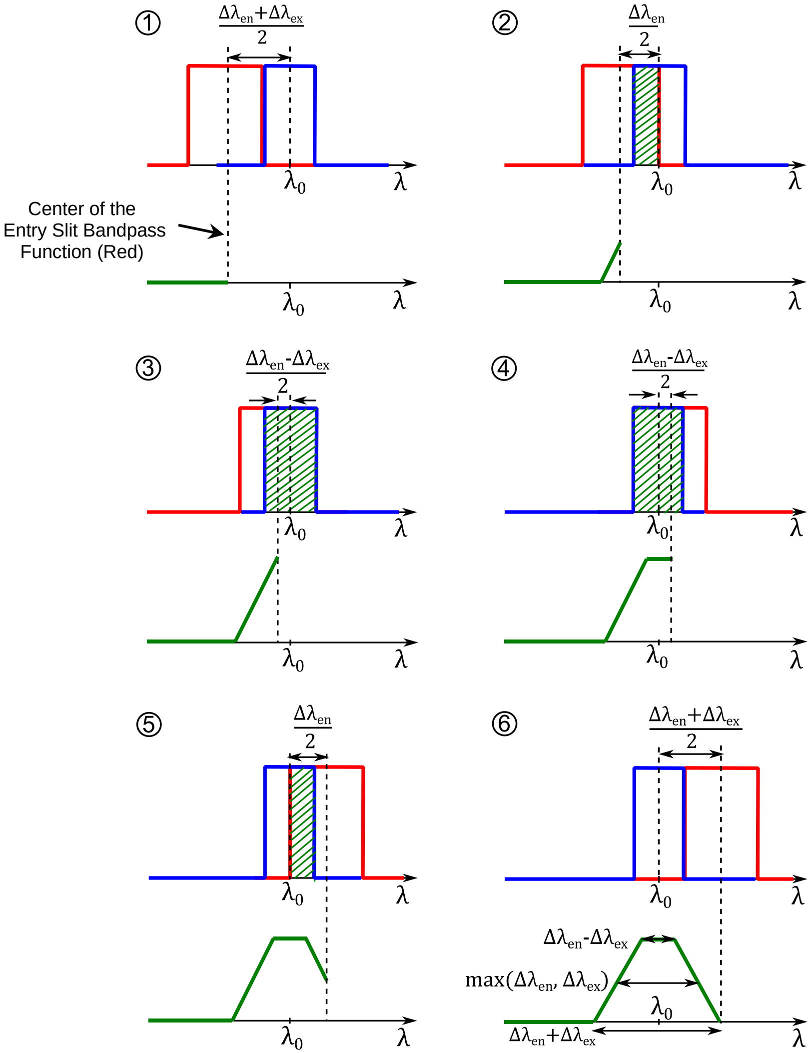

Figure 11: Convolution of Instrumental Bandpasses of Entry Slit (Red) and Exit Slit (Blue). The calculation of the convolution (green) is shown exemplarily for different values of λ in steps 1 to 6. To obtain the whole convoluted bandpass, this is done continuously for every λ.

Diffraction at the Grating

For infinitely narrow slits and without aberrations, the instrumental bandpass will be a diffraction pattern caused by the grating. The width of this pattern can be derived from the resolving power of a grating as[7]:

$$\Delta\lambda = \frac{\lambda}{k \cdot N} \qquad \textbf{(14)}$$

with k the diffraction order and N the number of illuminated grating lines.

Aberrations

In order to avoid chromatic aberrations, most spectrometers rely on mirrors as opposed to lenses. However, spherical aberrations, astigmatism, and coma are still present in most setups, although they can be minimized by optimizing the setup geometry. For example, some of the aberrations induced by the first mirror in a Czerny-Turner spectrometer are negated by the aberrations of the second mirror[6]. Aberrations generally widen the instrumental bandpass.

4.7. Etendue

For each optical system, there is a maximum beam size it may accept. This is described by the geometrical etendue G. For a cone-shaped beam, it is defined as

$$G = \pi \cdot A \cdot \sin^2 \Omega \qquad \textbf{(15)}$$

Here, A is the area of the light source or any stop in the system and Ω is the opening angle of the cone-shaped beam subtended at that stop.

The etendue is defined for each element in the optical system. For a perfect optical system, the etendue is conserved. This is a consequence of the second law of thermodynamics: Imagine a black body source with a given area. If any optical system could increase the etendue, then it would be possible to create an image of the source with a higher surface brightness by capturing all of the emitted photons in a smaller area. This image would then have a higher equilibrium temperature, which is forbidden by the second law[8].

As a consequence, the geometrical etendue of the whole system is that of the element with the **least** etendue. This means that, beginning at the light source, the etendue of the system can only be decreased but not improved with the addition of each new element.

In Figure 12, we show a simplified sketch of the beam path in a Czerny-Turner spectrometer viewed from above.

[7] Chapter 1.5 of: https://web.mit.edu/8.13/8.13d/manuals/Hydrogenic/jy-theory-optics-spectroscopy.pdf
[8] https://archive.org/details/DesignOfOpticalSpectrometers/page/n11/mode/1up

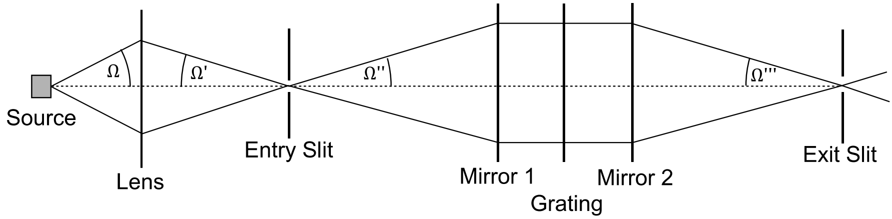

Figure 12: Simplified Beam Path in a Czerny-Turner Spectrometer

For a perfectly optimized spectrometer, the following equation would hold:

$$G = \pi \cdot A_s \cdot \sin^2 \Omega = \pi \cdot A_l \cdot \sin^2 \Omega' = \pi \cdot A_{entr} \cdot \sin^2 \Omega'' = \pi \cdot A_{m2} \cdot \sin^2 \Omega''' \quad \textbf{(16)}$$

Here, A_s is the area of the light source, A_l is the area of the illuminated part of the lens, A_{entry} is the illuminated area of the entry slit, and A_{m2} is the area of the illuminated part of the second concave mirror (identical to the illuminated area of the the first concave mirror and the grating, because the light is collimated between the mirrors).

In reality, however, it is often the case that either the spectrometer part or the light source are the limiting factor and a perfect matching of the etendue values might not be realistic. There are generally two cases:

- If the source area is very small, for example a fiber output, then the first term of Equation (16) will also be very small, even for large opening angle. The system etendue is then limited by the source etendue.
- If the source is rather large, such as the LED chip in this kit or a typical mercury lamp, then the source etendue will also be large for typical opening angles. In this case it may not be feasible to match this etendue with all other parts of the spectrometer, as this will require optics with either very short focal lengths, severely increasing aberration problems, or with very large diameters, increasing cost and size of the spectrometer.

In the second case, the spectrometer geometry is typically chosen in a way that the light coming from the entry slit will be fully collected by the mirrors and the grating. This means that the factor $A_{entr} \cdot \Omega''$ is the limiting factor of the system etendue, hence $G = A_{entr} \cdot \Omega''$. The entry slit is a rectangle with the height h and the width w_{en}. Hence, the following equation describes the system etendue:

$$G = h \cdot w_{en} \cdot \Omega'' \quad \textbf{(17)}$$

If the spectrometer bandpass is limited by the slit width, i.e. for bandpasses larger than the limit induced by the grating and for negligible aberration effects (see Chapter 4.6), then the bandpass is [as given in Equation (13)]:

$$\Delta\lambda = w_{en} \cdot \frac{\cos\alpha}{f_1 \cdot g} \tag{18}$$

Here, f_1 is the focal length of the collimating mirror and g is the groove density of the grating.

Once the setup geometry is fixed, the only adjustable factor in both Equations (17) and (18) is the entry slit width w_{en}, as all of h, Ω'', α, f_1, and g are constant in a given setup.

As a result, one can only improve the resolution (decrease the bandpass) of a given setup by narrowing the slit widths, but this will always decrease the etendue and therefore the signal intensity. Vice versa, the signal intensity can only be increased at the cost of an increasing bandpass, i.e. a worsened resolution. All relations are linear, hence for improving the resolution by a factor of 2 (halfing the width of the smallest observable spectral feature), one needs to reduce both slit widths by a factor of 2, which will reduce the intensity at the detector by a factor of 2. Please note that by narrowing the slits, the bandpass can only be decreased down to a lower limit given either by aberrations in the optical system or by the resolving power of the grating (see Chapter 4.6).

Chapter 5 Setup and Adjustment

5.1. Assembly of the Components

5.1.1. Components of EDU-SPEB2(/M) Kit

If not already done, assemble the following components of the EDU-SPEB2(/M) kit according to the descriptions in this section:

- Lens Component (f = 50 mm)
- Adjustable Slit Component
- LED Component
- Bandpass Filter

Lens

Assemble the lens as follows:

- Attach a BE1(/M) base to a PH3 (PH75/M) post holder.
- Connect an LMR1(/M) lens mount to a TR3 (TR75/M) post and place the post into the prepared post holder. Remove the retaining ring from the LMR1(/M), insert the LB1471 lens, and secure it with the retaining ring. The complete component is shown in Figure 13.

Figure 13: Lens Component on Ø1/2" Post

Slit and LED Mount

Next, mount the VA100(/M) slit and the LED component to posts in a similar fashion:

- Attach BA1(/M) bases to two PH3 (PH75/M) post holders using 1/4"-20 x 3/8" (M6 x 10 mm) cap screws.
- Mount the VA100(/M) adjustable slit on a TR3 (TR75/M) post and place the post into one of the prepared post holders; see Figure 14a.
- Mount the SMR05 lens mount on a TR3 (TR75/M) post. Screw the LEDMT1F LED mount into the SMR05 from one side and screw the SM05L03 lens tube into the SMR05 from the other side.Then place the component into the second prepared post holder; see Figure 14b.

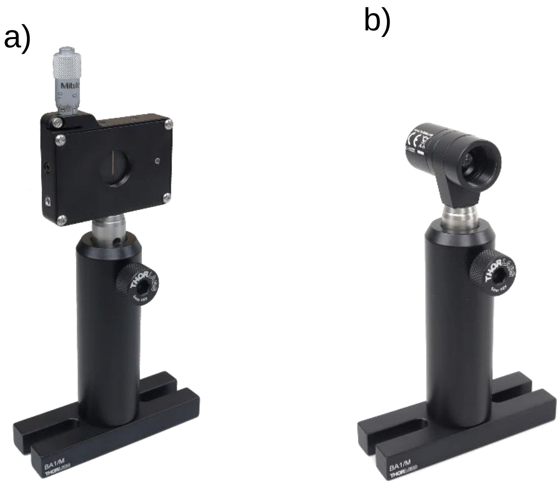

Figure 14: VA100(/M) Adjustable Slit (a) and LEDMT1F LED Mount (b) Both on Ø1/2" Posts

Bandpass Filter

Unscrew the retaining ring from an SM05L03 lens tube, place the bandpass filter in the lens tube, and fix it with the retaining ring. The side of the filter that appears green should face towards the retaining ring; see Figure 15.

Figure 15: Bandpass Filter Component From the Front (Left) and Back (Right)

5.1.2. Grating Holder on Rotation Stage

- Use the four 4-40 cap screws that are included with the PR01A(/M) adapter plate and a 3/32" hex key to fix the adapter plate to the PR01(/M) rotation stage.
- Then use a 1/4"-20 x 1/2" (M6 x 12 mm) setscrew to mount a PH2 (PH50/M) post holder on the center of the stage. Make sure to screw about half of the setscrew into the stage. That way, you cannot accidentally connect a post to the setscrew inside the postholder later on.
- If the grating component of the EDU-SPEB2(/M) kit is already assembled, remove the grating and the TR3 (TR75/M) post from the KMSR(/M) grating mount. ***Never touch the grating surface! It will scratch easily and is therefore not cleanable.***
- Now mount the grating mount to the KCP05(/M) spacer[9] by using the counterbore hole and an 8-32 x 1/4" (M4 x 6 mm) cap screw; see Figure 16a.
- Mount the spacer on a TR2 (TR50/M) post via the threaded hole and ensure that the front plane of the grating is roughly centered over the post. Place the component into the post holder on the rotation stage. The complete assembly is shown in Figure 16b.
- Mount the GR25-1205 grating (1200 lines/mm) in the KMSR(/M). The arrow on the grating substrate should point to the right when facing the grating from the front; see Figure 16c. This is the opposite orientation when compared to the EDU-SPEB2(/M) kit.

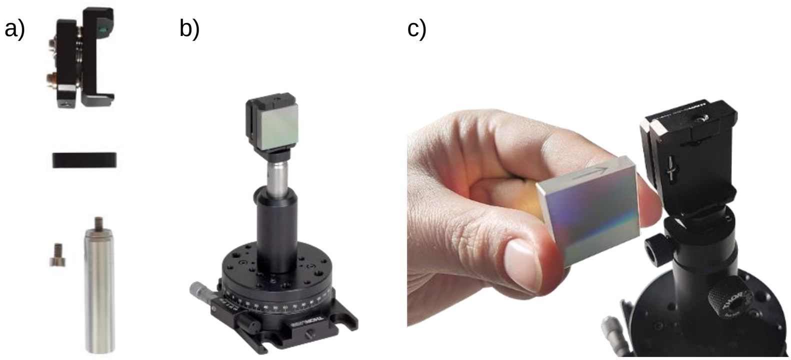

Figure 16: a) Assembly of Grating Holder Component, b) Complete Grating Holder on Rotation Stage, and c) Correct Orientation of the Grating in the Grating Mount (Note the Arrow on the Top Grating Face)

[9] The older revision of the main spectrometer kit [Item # EDU-SPEB1(/M)] includes a CH1A grating holder instead of the KSMR(/M). In this case, you need a KCP2(/M) spacer plate (not included in the extension kit) to center the grating surface over the post.

5.1.3. Concave Mirrors

- Connect two PH3 (PH75/M) post holders to BE1(/M) bases.
- Connect a KCP1(/M) centering plate to a TR3 (TR75/M) post. Then connect the KM100 kinematic mirror mount to the centering plate with an 8-32 x 1/4" (M4 x 6 mm) cap screw so that the mirror face will be centered over the post. Place the post in one of the prepared post holders.
- Loosen the nylon-tipped setscrew of a KM100, place a CM254-200-P01 silver-coated concave mirror in the mount, and secure it by tightening the nylon-tipped setscrew.
- Repeat the same steps for the second mirror but choose the other counterbored hole of the KM100(/M), so that the component is mirrored compared to the first one; see Figure 17.

Figure 17: Concave Mirror Components

5.1.4. Second Adjustable Slit

- Connect the VA100(/M) adjustable slit of the extension kit to a TR3 (TR75/M) post and place it into a UPH3 (UPH75/M) universal post holder; see Figure 18a.

The VA100(/M) slit is calibrated, i.e. the slit width can be precisely controlled by the micrometer screw. To set a specific slit width, first turn the micrometer screw clockwise slowly until no light passes the slit and the scale shows “0”. ***Be very careful not to overturn the micrometer screw as this destroys the calibration and may damage the slit.*** Then turn the micrometer screw counterclockwise slowly while observing the scale. A full turn of the screw corresponds to an increase of the slit width by 500 µm and one division corresponds to 10 µm.

5.1.5. Detector Lens

- Connect an LMR1(/M) lens mount to a TR3 (TR75/M) post and place it in an UPH3 (UPH75/M) universal post holder.
- Unscrew the retaining ring from the LMR1(/M) by using the SPW606 spanner wrench and place the LB1757 lens in the lens holder.
- Secure the lens with the help of the retaining ring. The complete component is shown in Figure 18b.

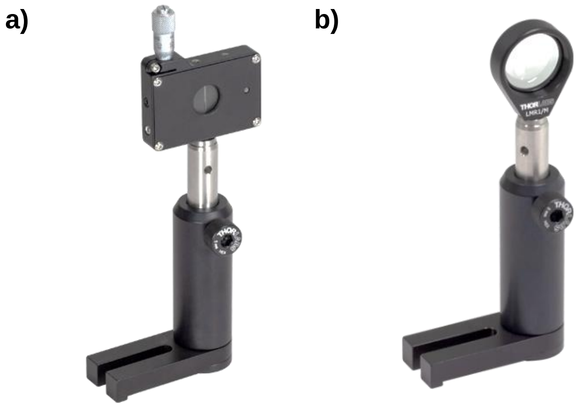

Figure 18: a) Adjustable Slit and b) Detector Lens Components

5.1.6. Photodetector Assembly

- Remove one retaining from the SM05M10 lens tube. Screw the other ring to about the middle of the lens tube.
- Then screw the SM05PD1A photodiode into the SM05M10 lens tube from the opposite site, until it is stopped by the retaining ring.
- Screw a SM05L05 lens tube on that end of the SM05M10 from which the retaining ring was screwed in, remove the retaining ring from the lens tube, and add the SM05A3 lens tube adapter.
- Attach the CA2812 SMA to BNC adapter cable to the photodiode. Connect the cable and the FT104 BNC terminator to either end of the crossbar at the top of the T3285 BNC T-adapter. Attach the T4003 BNC to banana plug adapter to the base of the T-adapter. The complete assembly is shown in Figure 19.

Figure 19: Photodetector Component with BNC Cable, Adapters, and Resistor

5.1.7. Blocking Screen

Connect the EDU-VS2(/M) screen to a TR2 (TR50/M) post and place it in a PH2 (PH50/M) post holder with a BE1(/M) base (see Figure 20a).

5.1.8. Test Sample

Insert the FGB67 colored glass filter into the SM1A1 adapter and fix it with an SM1RR retaining ring. The finished component is shown in Figure 20b.

a) b)

Figure 20: a) Blocking Screen Component and b) Bandpass Filter in SM1A1 Adapter from Front (Top) and Back (Bottom)

5.1.9. Multimeter

Before using the DVM1 multimeter for the first time, a battery has to be inserted. A charged battery is included with the multimeter and stored in one of the side pockets of the multimeter bag. Please refer to the multimeter manual for a detailed description of the battery change procedure. The manual is included with the multimeter and also available digitally on the Thorlabs DVM1 product webpage.

5.2. Setup and Adjustment of the Experiment

This section describes how the Czerny-Turner Spectrometer is set up. In addition to the parts included in the extension kit, you need the following components from the EDU-SPEB2(/M) kit:

- LED Component
- Lens Component (f = 50 mm)
- Adjustable Slit Component
- Grating (1200 lines/mm) + Grating Holder

All other parts of the EDU-SPEB2(/M) kit are not required for the Czerny-Turner spectrometer and can be put aside.

The setup described in this section is optimized for the LEDW7E included in the main EDU-SPEB2(/M) kit. For other light sources, some optical elements will have to be moved slightly in order to optimize performance, as described in Chapter 8.1.

For the Czerny-Turner configuration, the goal is to maximize the intensity of the light after the exit slit for given slit widths. On the one hand, the amount of light passing the entry slit has to be high and, on the other hand, loss of light after the entry slit (e.g. by passing by mirrors or the grating) has to be minimized (see Chapter 4.7). In the following, we describe how these goals can be reached.

5.2.1. Illumination of the Entry slit

Please note: The components used in this subsection are part of the EDU-SPEB2(/M) kit and are not included in this extension kit.

- As a first step, position the LED source at the left end of the breadboard and close to the front of the breadboard.
- Set the beam height to about 13 cm above breadboard level by adjusting the LED post in its post holder. The acceptable range is 12 cm – 13.8 cm. For lower or higher values, you will not be able to achieve a constant beam height later on.
- Place the entry slit very close to the LED mount and vary its height until the slit aperture matches the height of the LED.
- Then place the slit 24 cm to the right of the light source (measured between the front of the LED holder and the center of the slit element). It is helpful for later adjustment to have both post holders centered on a breadboard hole.
- Match the height of the f = 50 mm lens to the LED source by placing it at a position where the diameter of the beam is a bit larger than the lens. This way you can see light on the lens holder and adjust the height of the lens until the light spot is centered on the lens.
- Place the f = 50 mm lens about halfway between the light source and the slit. Do not fix it with a clamp yet.

- Slowly move the 50 mm lens closer to the light source, until you can see an image of the LED chip on the entry slit, see Figure 21. When moving the lens, you will at first see two black lines. These are the contacting wires of the LED chip. After moving the lens a few millimeters closer to the light source, you should see two black dots on a bright rectangle. This is the image of the LED chip with the contacts. Once you found the right position for the lens, fix it with a CF125 clamp and a 1/4"-20 x 1/2" (M6 x 12 mm) cap screw plus washer.

Figure 21: Beampath from light source to entry slit (left) and the image of the LED chip on the slit (right).

Tip: To make sure that all components are on the optical axis, we advise using the breadboard holes as a guide.

5.2.2. Adjusting Post Heights

The next step is to adjust the remaining elements to the same height. To do this, place the elements one by one between the 50 mm lens and the slit and vary the post height for each element until the light spot is centered on the element. Do this for:

- Grating on Rotation Stage
- Both Concave Mirrors
- Exit Slit
- Detector Lens (f = 30 mm)

Afterwards, use an R2(/M) slip-on post collar to mark the post height of the grating.

5.2.3. Concave Mirrors and Grating

- Place the first concave mirror 20 cm (measured between post centers) behind the entry slit. Of the two mirror components, choose the one that has its upper thumbscrew closer to you than its lower one when being placed in the setup. Adjust the position until the light is centered on the mirror. You may use a piece of paper to better see the light. Do not fix the component with a clamp yet.
- Next, ensure a constant beam height after the mirror. Rotate the mirror component until the reflected light hits the backside of the entry slit and adjust

the upper thumbscrew of the kinematic mirror mount until the beam is centered on the slit aperture.

- Place the PR01(/M) rotation stage on the breadboard between the entry slit and the first concave mirror as shown in Figure 22. In relation to the breadboard hole the entry slit post is centered on, the lower left mounting slot of the stage should be two breadboard holes to the right and one breadboard hole in the orthogonal direction towards the center of the board. The micrometer screw and Vernier scale should be facing your direction (see Figure 22). Fix the stage with two 1/4"-20 x 1/2" (M6 x 12 mm) cap screws.
- Loosen the locking screw of the PR01(/M) rotation stage and rotate the stage until the grating faces roughly in the direction of the concave mirror (do not loosen the grating post); see Figure 22.
- Open the entry slit a few millimeters and turn the concave mirror component until the light spot is centered on the grating.
- Now close the entry slit to about 1 mm and watch the backside of the entry slit (the side facing the concave mirror). There you should see an image of the slit (see Figure 23). If you don't see an image, rotate the grating stage until an image appears on the slit. Rotate further until this image is close to the slit but still observable.

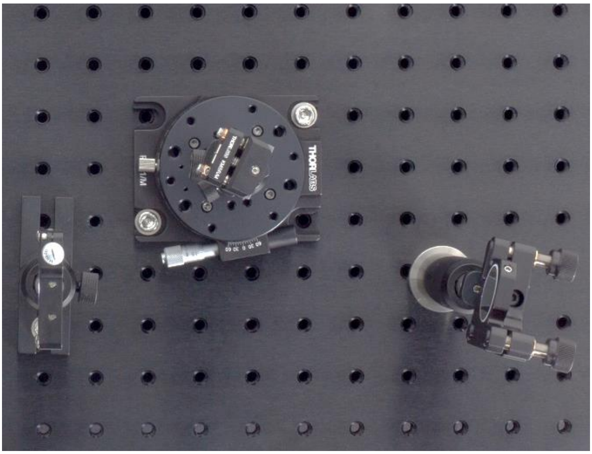

Figure 22: Positions of Entry Slit, First Concave Mirror, and Grating Stage

- If the light between the mirror and the grating is collimated, the image of the slit should be sharp. To ensure collimation, slightly change the distance between the entry slit and the concave mirror by moving the mirror until the image is as sharp as possible and still close to the slit. Make sure that the light is still centered on the mirror.

- Depending on how far you moved the mirror, the light will not be centered on the grating anymore. Rotate the mirror component until that is the case again, then rotate the rotation stage until the image of the entry slit is close to the entry slit again. The image should still be sharp. After making sure of that, fix the position of the concave mirror with a CF125 clamp and a 1/4"-20 x 5/8" (M6 x 12 mm) cap screw.
- If the image of the entry slit on its backside does not have the same height as the entry slit aperture, use a BD-5/64 (BD-2M) ball driver to adjust the lower setscrew of the kinematic grating holder until the height of the image matches that of the slit. This ensures a constant beam height after the grating.

Figure 23: Zero order reflection from the grating on the back of the entry slit.

- Place the second concave mirror at a 10 cm distance from the first one (measured between post centers), in the direction perpendicular to the light path from the light source to the first mirror (see Figure 24).

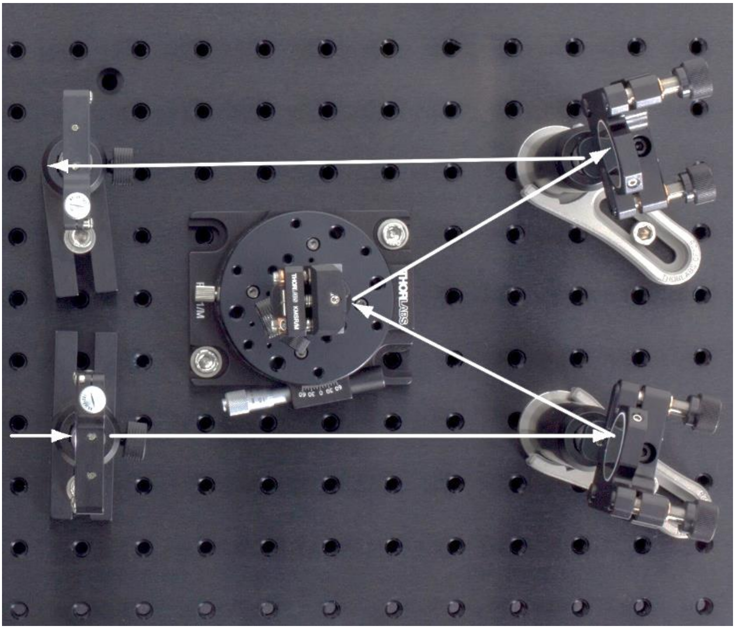

Figure 24: Positions of the slits, mirrors and grating. The light path is marked by white arrows.

- Open the entry slit a few millimeters. Then rotate the stage until the zero order reflected light is centered on the second concave mirror.
- Rotate the second concave mirror (the whole component, do not loosen the post) until the light is reflected parallel to the horizontal hole line on the breadboard. It is helpful to use the second slit as a target for the intended beam direction. After roughly adjusting, fix the mirror position with a CF125 clamp and a 1/4"-20 x 5/8" (M6 x 12 mm) cap screw. The lower thumbscrew of the mirror holder can then be used for fine adjustment.
- To ensure a constant beam height, place the second VA100(/M) adjustable slit far away from the second concave mirror and adjust the upper thumbscrew of the kinematic mirror mount until the light is centered on the slit aperture.

5.2.4. Exit Slit and Photodetector

- Set the entry slit width to about 500 µm. An introduction into setting the slit width of the calibrated slits is given in Chapter 5.1.4. Then close the second VA100(/M) adjustable slit (exit slit) almost completely and position it in such a way that a sharp image of the entry slit is centered on the exit slit. Because the focal lengths of both concave mirrors are identical, the distance of both slits to the mirrors should be similar (see Figure 24). A slight offset is to be expected due to the not perfectly symmetric beampath. Fix the position of the exit slit with a 1/4"-20 x 5/8" (M6 x 16 mm) cap screw.

- Open the exit slit until its width is identical to that of the image of the entry slit.
- Place the detector lens (f = 30 mm) closely behind the exit slit, and make sure that the light from the exit slit is centered on the lens. The back side of the lens holder (where the retaining ring is visible) should point away from the exit slit. You should see a small spot of light about 3 cm behind the lens (see Figure 25). Fix the position of the lens with a 1/4"-20 x 5/8" (M6 x 16 mm) cap screw.
- Screw the detector assembly into the back side of the lens holder. The length of the lens tubes is chosen in such a way that the detector is now positioned right where you previously observed the light spot.
- Connect the photodetector to the DVM1 multimeter, set the multimeter to mV_{DC} and fine-tune the lens position and height for maximum signal.

Tip: The signal of the photodiode is always a mixture of real signal coming from the monochromator and background signal from the surroundings. To make sure that you are optimizing for “real” signal, repeatedly block the light path and check the background signal (also called dark signal).

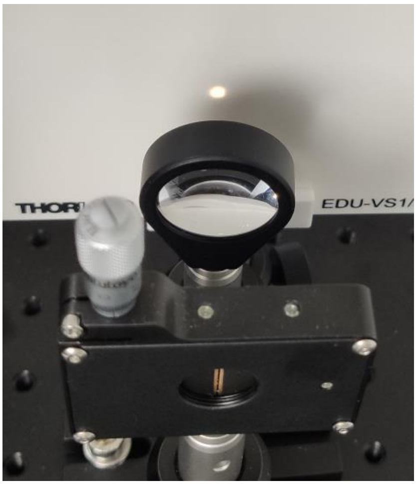

Figure 25: Light Spot Behind the Detector Lens

As a last step, position the EDU-VS2(/M) screen between the two slits to keep stray light from the light source from reaching the spectrometer part of the setup. The complete setup should now look similar to Figure 26.

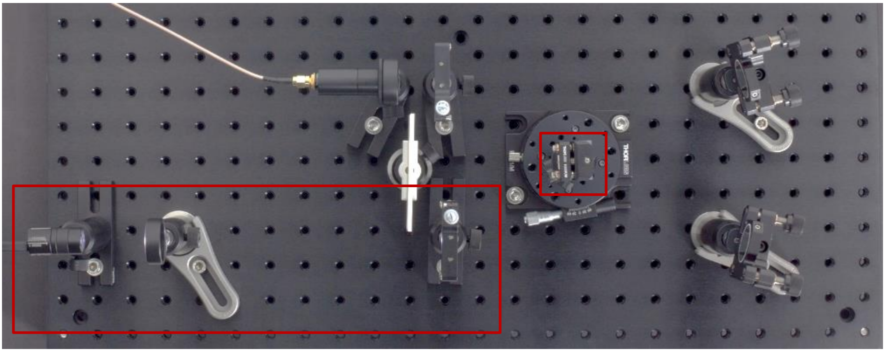

Figure 26: Complete Czerny-Turner Spectrometer Setup. The components marked by red rectangles are part of the EDU-SPEB2(/M) kit.

Hint: After completing the setup for the first time, it may be helpful to label the post holders of some components such as the lenses, mirrors, and slits. This makes it easier for students to find the right components when tasked with rebuilding the setup.

5.3. Vernier Scale Readout

For the operation of this kit, it is important to understand the functionality of the PR01(/M) rotation stage. The stage has a coarse and fine adjustment mode. For coarse adjustment, the locking screw is loosened. The stage can then be rotated by hand over the full 360° while the micrometer screw can be turned but has no influence on the stage rotation. For fine adjustment, tighten the locking screw. Now, the stage cannot be rotated by hand anymore, and instead it is rotated by turning the micrometer screw. The rotation range of the fine adjustment is about 10°.

The Vernier scale allows for an adjustment as fine as 5 arcmin $\left(\frac{5°}{60}\right)$. A Vernier scale is read the following way:

- First, check the position of the zero on the Vernier scale in relation to the main scale on the stage.
  - If the zero line precisely matches a line from the main scale, this is your readout value. An example is given in Figure 27a.
  - If the zero line is between two lines of the main scale, this determines between which two full degrees the readout value is located.
- In the latter case: There will be two lines on the Vernier scale (one each on the left and right side of the Vernier zero) that precisely match lines on the main scale as shown in Figure 27b. There are two ways to determine the final readout value:

- Take the line on the left side of the Vernier zero and substract that value (in arcmin) from the larger value of the full degree range. As an example, reading the left blue arrow in Figure 27b results in 343° -15 arcmin.
- Take the line on the right side of the Vernier zero and add that value (in arcmin) to the lower value of the full degree range. As an example, reading the left blue arrow in Figure 27b results in 342° + 45 arcmin.

- In theory, both ways yield the same result. However, due to inaccuracies of the scale or readout errors, there may be a deviation of 5 arcmin. For experiments that require more than one measurement, it is therefore recommended to start with deciding which side of the scale should be used and stick to that side throughout the whole experiment. The decision can be made on the basis of a calibration measurement, as described in Chapter 5.5.

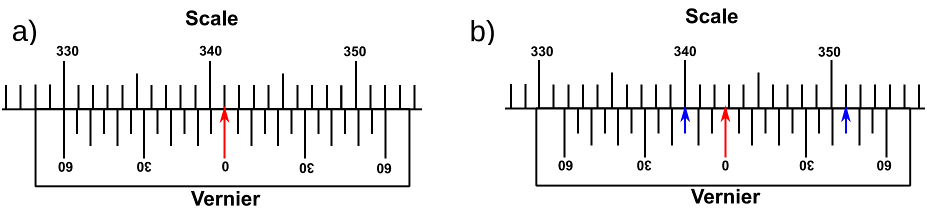

Figure 27: An example of a Vernier Scale. The red arrow indicates the pointer and the blue arrows indicate the Vernier lines that match the main scale. The scale in a) reads 341°, and the scale in b) reads 342.75° (read either as 342° + 45 arcmin or 343° - 15 arcmin)

Hint: Reading the Vernier scale at an angle may result in errors. When searching for the correct division line, make sure to move your head along the scale, so that you always look straight along the division line you are attempting to read out[10].

5.4. Setup Preparation

In order to conduct the experiments described in Chapter 6, we recommend the preparation steps described in the following subsections.

5.4.1. Zeroing the Rotation stage

It is convenient to zero the PR01(/M) rotation stage. This means that its Vernier scale shows the actual angle of incidence of light on the grating.

[10] Using a smartphone camera to zoom onto the Vernier scale can help during readout. In order to avoid errors, make sure to position the camera in such a way that it "looks" along the line you want to read out.

- As a first step, loosen the locking screw of the PR01(/M) rotation stage and rotate the stage by hand until the Vernier scale shows 0° (see Figure 28). Then re-lock the locking screw.

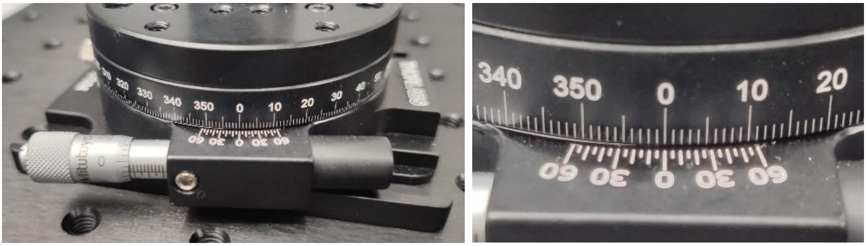

Figure 28: Zero-Position of the Rotation Stage

- Rotate the grating post in such a way that the grating surface is approximately perpendicular to the direction in which the light is coming from the first concave mirror. The R2(/M) post collar ensures that the grating height does not change while rotating the post.
- Watch the backside of the entry slit (the side facing the concave mirror). There you should see an image of the slit (see Figure 29). Fine-adjust the rotation of the grating post until this image is centered on the slit, and then fix the post in the holder.

In this position, the angle of incidence on the grating is 0°, corresponding with the Vernier scale value. Thus, the rotation stage is now zeroed and shows the angle of incidence on the grating.

Figure 29: Zero order reflection from the grating on the back of the entry slit. Note: For 0° calibration, turn the grating until the light overlays with the slit.

5.4.2. Determining the Setup Angle

As discussed in Chapter 4.4, in order to be able to relate the rotation angle of the stage to the wavelength passing the exit slit, one needs to know the setup angle θ (between the incident light and the lightpath from the grating to exit slit). From this, the wavelengths for all other angles can be calculated. To determine θ, follow the steps below.

- Loosen the locking screw on the PR01(/M) rotation stage, use the coarse rotation of the stage until the zero order reflection from the grating passes through the exit slit, then tighten the locking screw.
- You can now read the angle of incidence corresponding to the zero-order reflection hitting the exit slit from the Vernier scale of the rotation stage.
- Write down this angle α_{cal}. It should typically be in the range of 320° to 340°, or -40° to -20°, respectively.
- Calculate the setup angle $\theta = -2 \cdot \alpha_{cal}$

5.5. Calibrating the Rotation Stage

As mentioned in Chapter 5.3, there are two ways to read the angle from the Vernier scale of the PR01(/M) rotation stage, one of which is usually more accurate than the other due to manufacturing reasons. In order to determine which side of the Vernier scale should be used during the experiments described in Chapter 6, we recommend doing a one-time calibration measurement with a light source of known wavelength. A simple way to obtain this light source is using the bandpass filter of the EDU-SPEB2(/M) kit. From the measurement described below, one can decide which side of the Vernier scale to use for all future applications of the rotation stage.

- Prepare the setup as described in Chapter 5.4. Record two values for α_{cal}, as read from the left and right side of the Vernier scale, respectively.
- Screw the lenstube with the bandpass filter from the EDU-SPEB2(/M) kit onto the backside of the entry slit (the side facing the mirror). Alternatively, the bandpass filter could be put directly in front of the LED mount, however, the relatively large divergence of the light at this position might shift or widen the bandpass of the filter.
- Loosen the locking screw of the rotation stage and rotate the stage clockwise by hand until you observe a green line on the exit slit, as shown in Figure 30. A piece of paper may help to see the line more clearly.

Figure 30: Green Line of the Bandpass Filter on the Exit Slit

- Adjust the width of the entry slit until the line is narrow but still visible.
- Adjust the width of the exit slit until the slit width matches the line width.
- Tighten the locking screw and fine-tune the rotation of the grating stage via the micrometer screw until the line is centered on the exit slit.
- To precisely center the line, watch the output signal of the photodetector and fine-tune to maximum signal.
- Once the line is centered, record two values for the angle of incidence α, as read from the left and right side of the Vernier scale, respectively.
- Calculate the measured wavelength via the equations below, as derived in Chapter 4.4. Do this once for the values of α_{cal} and α that have been read from the left side of the Vernier scale and once for the values read from the right side.

$$\theta = -2 \cdot \alpha_{cal}$$

$$\lambda = \frac{\sin(\theta + \alpha) + \sin(\alpha)}{g}$$

Here, $g = 1200\ \mathrm{mm}^{-1}$ is the grating groove density of the GR25-1205 grating.

- Compare both results to the actual center wavelength of the bandpass filter (532 nm). The side of the Vernier scale that yields the result closer to 532 nm should be used for all future applications of the PR01(/M) rotation stage. Should both values be equal or nearly symmetrical around 532 nm, both sides of the Vernier scale can be used and will yield results with good accuracy.

Chapter 6 Exercises and Examples

In the following section we describe how the wavelength of spectral lines can be determined via the Czerny-Turner setup. Regarding the calibration measurement described in Chapter 5.5, there is the following choice to be made:

Either the calibration measurement is performed once by the lab course organizer and the students are told which side of the Vernier scale to use, or the students perform the calibration measurement themselves.

In the latter case it is not possible to use the same bandpass filter for the calibration and the experiment described in Chapter 6.1. Hence, a spectral line source, such as a mercury lamp, or a different filter is required.

6.1. Determining Wavelengths

After preparing the setup as described in Chapter 5.4, it can be used to determine the wavelength of spectral lines similar to the EDU-SPEB2(/M) kit. The bandpass filter that is included in the EDU-SPEB2(/M) kit creates a spectrally narrow light source. In the following, we describe how to determine the central wavelength of that source using the Czerny-Turner spectrometer.

- Screw the lens tube with the bandpass filter on the backside of the entry slit (the side facing the mirror) [11].
- Loosen the locking screw of the rotation stage and rotate the stage clockwise until you observe a green line on the exit slit, as shown in Figure 30. A piece of paper may help to see the line more clearly.
- Once you see the line, you can adjust the width of the entry slit. Opening the entry slit increases the intensity and the width of the line. The minimum width is determined by the width of the bandpass. The theoretical description of how the slit width corresponds to width and intensity of the line is given in Chapters 4.6 and 4.7.
- After setting the entry slit width, adjust the exit slit width until it matches the width of the line.

Once you have adjusted the slit widths, you can begin measuring the wavelengths of the spectral line.

- Tighten the locking screw and fine-tune the rotation of the grating stage via the micrometer screw until the line is centered on the exit slit.

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[11] Positioning the filter on the front of the LED holder would make even more sense from a didactic standpoint. However, the working principle of the filter is based on interference on multiple layers. If the light is divergent, as is the case directly behind the LED, the lengths of the light paths between the layers change, which results in different interference criteria. As a consequence, the slope on the sides of the bandpass would become less steep and the center wavelength would move about 0.6 nm towards shorter wavelengths.

- To precisely center the line, watch the output signal of the photodetector and fine-tune to maximum signal.
- Once the line is centered, record the angle of incidence via the Vernier scale of the rotation stage (use the side of the Vernier scale which has been determined to be more accurate via the one-time calibration measurement described in Chapter 5.5). From this angle α, the wavelength of the spectral line can be calculated via the following equations:

$$\theta = -2 \cdot \alpha_{cal}$$

$$\lambda = \frac{\sin(\theta + \alpha) + \sin(\alpha)}{g}$$

Here, $g = 1200\ \mathrm{mm}^{-1}$ is the grating groove density of the GR25-1205 grating. The derivation of these equations and the method to determine α_{cal} are given in Chapter 4.4.

The following table shows the results of an example measurement:

Spectral Line	**Wavelength [nm] (Literature)**	**Angle of Incidence α (Measured)**	**Wavelength [nm] (Calculated)**
Zero Order Reflection	-	- 26.333° (α_{cal})	-
Bandpass Filter	532	- 5.5°	531.2

Table 1: Example Measurement

The wavelength of the bandpass filter is calculated from the measured angles as follows:

During calibration of the setup, we measured: $\alpha_{cal} = -26.333°$

Hence: $\theta = -2 \cdot \alpha_{cal} = 52.667°$

For the green line, an angle of incidence $\alpha = -5\frac{30}{60}° = -5.5°$ was measured, hence:

$$\lambda = \frac{\sin(52.667° - 5.5°) + \sin(-5.5°)}{1200\ \frac{\mathrm{lines}}{\mathrm{mm}}} = 5312 \cdot 10^{-4}\ \mathrm{mm} = 531.2\ \mathrm{nm}$$

Hint: Of course, the same procedure can be used to determine the wavelengths of spectral lines for spectral line sources such as mercury or sodium vapor lamps. Please see Chapter 8.1 for how to slightly modify the setup in order to accommodate those light sources.

6.2. Absorption Spectroscopy

The Czerny-Turner configuration allows for absorption spectroscopy of solid or liquid samples. As a test sample, a FGB67 multi-bandpass colored glass filter is included in the extension kit. It features multiple transmission and absorption bands in the visible regime, making for a very characteristic spectrum to be measured. While a black body emitter such as an incandescent lamp would be an ideal light source for absorption spectroscopy due to the continuous spectrum, the white light LED included in the EDU-SPEB2(/M) kit is also well suited for this purpose.

In the following, all steps required for an absorption spectroscopy experiment are explained.

6.2.1. Preparation

First, prepare the spectrometer as described in Chapter 5.4.

In the visible regime, a spectral region of approximately 250 nm passes the exit slit over the fine rotation range (≈ 10°) of the PR01(/M) rotation stage. To set a spectral range, follow the steps below:

- Loosen the locking screw of the PR01(/M) rotation stage and set the micrometer screw to its zero position ***(there is a hard stop, do not overturn!)***.
- Calculate the angle corresponding to the short end of your desired wavelength range (see Chapters 4.4 or 6.1) and rotate the stage to that angle. The angle is expected to be between -20° and 0° for a wavelength of 430 nm, which is where the emission of the included LEDW7E starts.
- Tighten the locking screw.

The next steps are to define the bandpass required for your experiment and to choose the correct slit widths. To define the bandpass, follow these guidelines:

- The bandpass should be set to about the width of the smallest spectral feature that needs to be resolved. A larger bandpass reduces measurement time and increases the detector signal.

  Bandpasses below 2 nm are not useful because the detail of the Vernier scale of the PR01(/M) rotation stage limits the precision of readout to 5 arcmin, which corresponds to 2 nm. This precision is similar to the EDU-SPEB2(/M) (using a motorized stage can improve the resolution significantly, see Chapter 8.2.)

In Chapter 4.6, the relation between the bandpass and the slit widths is described in detail. Hence, you can calculate the required slit widths for the bandpass you determined.

As an example, in order to set the bandpass to about 2 nm, set the width of the entry slit to 500 µm. The width of the exit slit should be set to 700 µm. See Chapter 5.1.4 for an introduction on how to set the widths of the adjustable slits. If you don't require a bandpass as low as 2 nm and want larger signals on the photodetector, increase the slit width of both slits. For details, refer to Chapter 4.6.

6.2.2. Reference Spectrum

The spectrum of the light source and the spectral responsivity of the photodetector are not precisely known. Hence, a reference spectrum without any sample needs to be recorded first. In the following, the steps are given:

- Turn the micrometer screw of the PR01(/M) rotation stage counterclockwise very carefully until you can read a clear value on the Vernier scale of the PR01(/M). Record the rotation angle of the stage and the signal on the multimeter.
- Rotate the stage by a fixed step size via counterclockwise motion of the PR01(/M) micrometer screw and record the angle and multimeter signal for every step until the limit of the fine rotation range is reached after about 10° of total rotation (The micrometer screw will still turn, but the stage won't. Don't turn too far or you'll dislodge the micrometer screw).

  Block the light from the light source completely (or switch off the light source) and record the signal value of the multimeter. This dark signal will later be subtracted from the data.

The spectrum obtained this way is not yet an accurate spectrum of the light source. For this, the signal for each wavelength needs to be multiplied with the spectral responsivity of the detector at this wavelength (which is not available for the uncalibrated photodiode included in the kit). However, the influence of the detector responsivity cancels out when calculating the transmission spectra of samples later (see Section 6.2.4), so accurate transmission spectra can be obtained even without this knowledge.

In Figure 31, an example reference spectrum is shown, as taken with the LEDW7E light source and a step width of 10 arcmin, corresponding to about 4 nm. Note that an LED, as employed here due to cost and simplicity considerations, would not be the light source of choice for a commercial absorption spectrometer due to the large variance of the intensity over wavelength. A black body emitter such as an incandescent lamp would be preferable in such cases. Please also note that the peak positions and their relative intensity may vary slightly between different LEDs even from the same production batch, so small deviations from the spectrum shown in Figure 31 are to be expected.

Hint: Be aware that the PR01(/M) stage has significant backlash, meaning that after changing the rotation direction of the micrometer screw, there won't be an immediate response of the rotation stage. Thus, we recommend approaching the intended measurement points very carefully so that no change of the turning direction is required.

Hint: The step width should be about the same as the bandpass chosen in Chapter 6.2.1. The smallest step of the Vernier scale is 5 arcmin, corresponding to approximately 2 nm. However, steps as small as that are difficult to read on the scale and the measurement will take rather long with such fine steps. We recommend steps of 10 arcmin (4 nm) or 15 arcmin (6 nm) depending on the expected width of the spectral features of the sample.

Hint: This detector configuration has a linear intensity-voltage response up to voltages of 200 mV. If you use the LEDW7E source and typical slit widths as described above, the signal at the maximum of the peak in the blue spectral range should be 35 - 80 mV. The large variance is a result of the the LED production process. Should you want to use a very bright source, then close the entry and exit slits until the measured voltages remain under 200 mV. Should you want to use a very dim source, you can use an FT254 resistor (250 kΩ, not included in the kit) instead of the FT104 to increase the sensitivity of the detector.

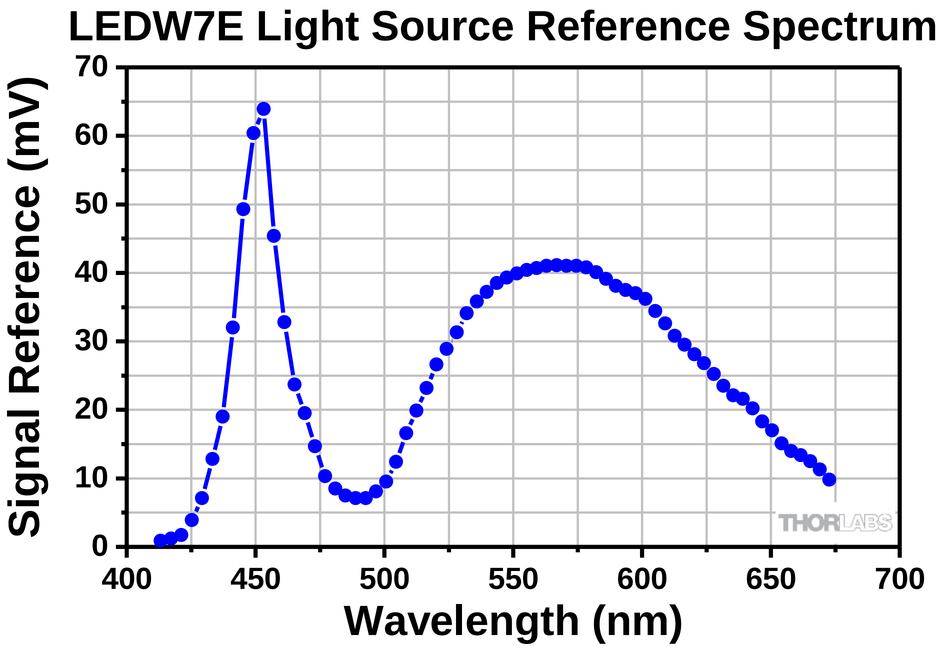


Figure 31: Example of a Reference Spectrum, taken with the LEDW7E light source and a step width of 10 arcmin or ≈ 4 nm.

6.2.3. Sample Spectrum

After the reference spectrum has been recorded, insert the sample of your choice in the light path. The FGB67 colored glass filter included in this extension kit is a good sample to start with and confirm the spectrometer performance.

Screw the lens tube with the FGB67 filter on the backside of the entry slit (see Figure 32). Now record the sample spectrum at the same measurement points of the reference spectrum.

In Figure 33, an example measurement for a sample spectrum is shown; the LEDW7E is used as the light source and the FGB67 filter is used as the sample. The step width is 10 arcmin, corresponding to about 4 nm.

Figure 32: Filter Component on the Back Side of the Entry Slit

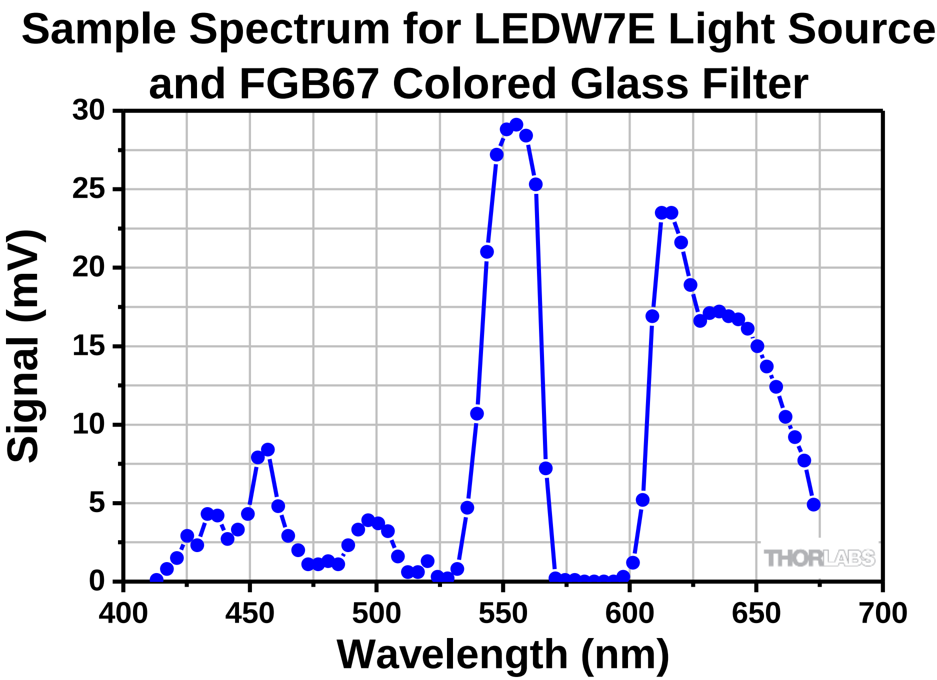


Figure 33: Example of a Sample Spectrum with the LEDW7E light source and an FGB67 filter as sample. Step width is 10 arcmin, corresponding to about 4 nm.

Of course other solid and liquid samples can be measured the same way. A suitable solid sample has to fulfill the following criteria:

a) The sample should have two planar and parallel surfaces of at least 15 mm x 10 mm size.

b) The sample should be homogeneous.

c) The sample should transmit some portions of the visible spectrum, i.e. you should be able to look through the sample when holding it against the light.

For liquid samples, we recommend using a small cuvette with plane surfaces, which can be filled with the sample liquid and then mounted in a suitable sample holder. Please note that the reference spectrum should be recorded with an empty cuvette in the beampath to account for the imperfect transmission of the cuvette itself.

The sample should be placed as close as possible behind the entry slit, as this is the point of the setup with the smallest area of the light spot.

6.2.4. Data Analysis

From the data recorded in the previous two subsections, the absorption spectrum of the sample can be calculated. As the rotation angle α of the grating and the wavelength λ hitting the exit slit are not linearly dependent on each other, we recommend making use of spreadsheet software to calculate the wavelength λ for each measured angle α automatically via equations (5) and (4) in Chapter 4.4:

$$\theta = -2 \cdot \alpha_{cal}$$

$$\lambda = \frac{\sin(\theta + \alpha) + \sin(\alpha)}{g}$$

Here, α_{cal} is the calibration angle and $g = 1200\,\mathrm{mm}^{-1}$ is the groove density for the GR25-1205 grating used.

- After the wavelengths have been calculated, subtract the dark signal from all measured values in both the sample and reference spectra. This value is assumed to be identical for all wavelengths.

- Then divide the background-corrected sample signal by the backround-corrected reference signal for each wavelength. The result is a transmission value between 0 and 1 for each wavelength. Plot these values over the wavelength to obtain the transmission spectrum of the sample. Under the assumption that the reflection is negligible, the absorption is just 1 minus the transmission.

The results of an example measurement of the FGB67 filter with the LEDW7E light source are shown in Figure 34 in comparison with the same measurement conducted with a Thorlabs CCS100/M spectrometer. A step size of 10 arcmin (≈4 nm) has been used for the measurement with the kit.

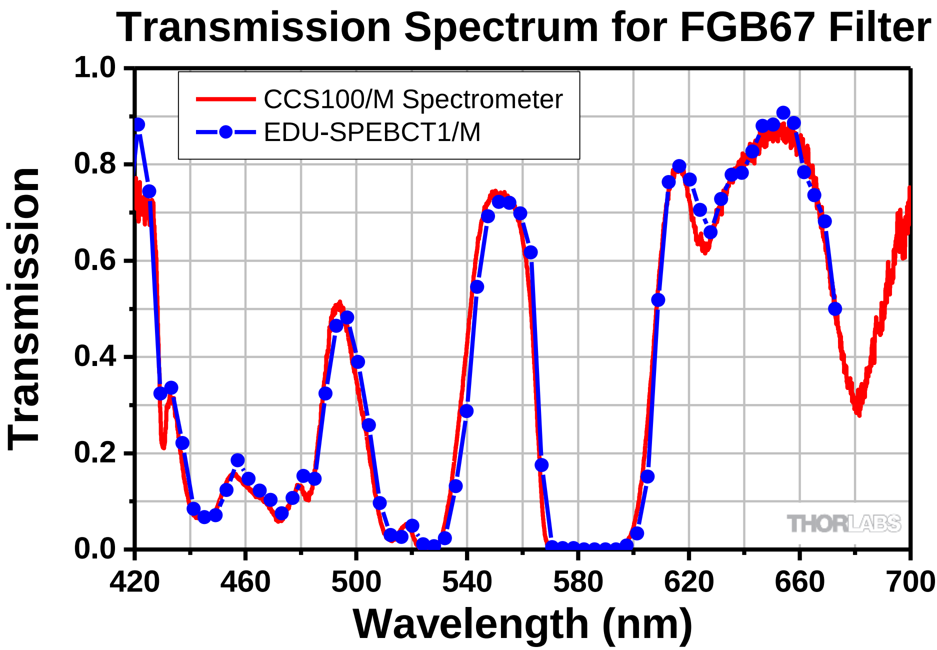


Figure 34: Example Measurement: Transmission Spectrum of FGB67 filter measured with a CCS100/M spectrometer and the EDU-SPEBCT1/M kit (step size 10 arcmin or ≈4 nm).

Chapter 7 Troubleshooting

Problem: *When zeroing the rotation stage as described in Chapter 5.4.1, the image of the entry slit is sharp on the exit slit. But when observing a spectral line source as explained in Chapter 6.1, the lines are not sharp.*

Solution: If the light is not collimated between the first concave mirror and the grating, the focal planes of the zeroth and first order diffraction are different. You can test the collimation by rotating the grating stage until the zeroth order reflection falls back on the entry slit. The image there should be sharp. If that is not the case, change the position of the first concave mirror as described in Chapter 5.2.3. and repeat all setup steps after that.

Chapter 8 Additional Experiments

8.1. Different Light Sources

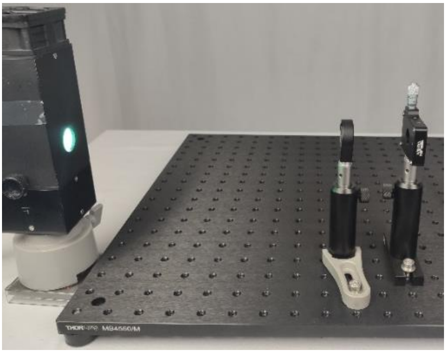
Chapter 6.1 describes how to measure the central wavelength of a bandpass filter with the Czerny-Turner spectrometer. Of course, the same procedure can be applied to spectral lines of different light sources, such as mercury or sodium vapor lamps. In the following, we describe how to modify the setup for a different light source.

- Replace the LED with the light source of your choice, e.g. a mercury or sodium lamp. Put the light source as close to the prior LED position as possible.
- Different light sources have different sizes. To account for this, move the f = 50 mm lens (between the light source and the entry slit) to get a sharp image of the light source and thus maximize the intensity passing through the slit. An example for a setup with a mercury lamp is shown in Figure 35. The entry slit should be opened by about 500 µm and the exit slit by about 700 µm. For an introduction to setting the slit widths, see Chapter 5.1.4.
- If your source features a spectral double line (e.g. orange lines of a mercury lamp or sodium D-lines), you can tune the width of the entry slit until you can see the two lines separately, see Figure 35. The exit slit should be opened as wide as the width of a single spectral line.

Figure 35: Examples of the green line and orange double line of a mercury lamp on the exit slit for wide (left) and narrow (right) entry slits.

Hint: If you use a very large light source, the optimal lens position will be close to the entry slit, resulting in a large opening angle after the entry slit. In turn, only a part of the light will be collected by the first concave mirror, reducing the overall intensity reaching the exit slit / detector and introducing stray light. For this educational kit, this is not a problem. Should you want to avoid it nevertheless, replacing the 50 mm lens with a 75 mm lens can be helpful.

Hint: Some light sources contain a significant amount of UV light, which may pass by the second concave mirror during a typical measurement. To avoid this light from leaving the setup, we recommend placing the TPS5 screen included in the EDU-SPEB2(/M) kit behind the second concave mirror.



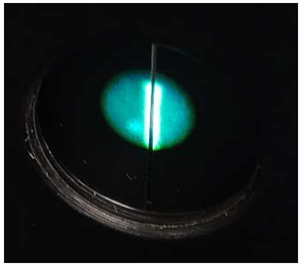


Figure 36: Setup for a mercury lamp (not included in this kit) as an example for light sources larger than the slit length (left) and resulting image of the mercury lamp on the slit (right).

After replacing the light source and setting the slit widths, the measurement and calculation proceeds as explained in Chapter 6.1. The results of an example measurement for the spectrum of a mercury lamp are shown in Table 2.

Spectral Line	Wavelength [nm] (Literature)	Angle of Incidence α (Measured)	Wavelength [nm] (Calculated)
Zero Order Reflection	-	- 29.5° (α_{cal})	-
Orange Double 1	579.1	- 6°	578.8
Orange Double 2	577.0	- 6° 5 arcmin	576.8
Green	546.1	- 7° 25 arcmin	545.4
Blue	435.8	- 12°	436.6

Table 2: Example Measurement of Mercury Lamp Spectral Lines

8.2. Liquid Samples

The absorption spectroscopy experiment described in Chapter 6.2 can of course be conducted with liquid samples as well. We recommend using a standard cuvette (not included in the kit) and filling it with the sample liquid of your choice. The cuvette can be mounted, for example, with a PCM(/M) Post Clamp Mount, a PCMP(/M) Flat Base Adapter, and a PM3SP(/M) Extension Post (not included in the kit). Figure 37 shows this assembly. Place the sample as close as possible to the entry slit; note that it does not matter if the sample is placed in front of or behind the slit.

Figure 37: Example of a Cuvette Holder Assembled from a PCM/M Mount, PCMP/M Adapter, and PM3SP/M Extension post

A very interesting liquid sample that is also easy to prepare is red cabbage juice (just cut some red cabbage into small pieces, add a small amount of warm water wait about 10 minutes, and then pour the liquid through a sieve). The dyes in the juice are pH-sensitive. At pH values close to 7, the juice will be violet. In acidic solutions the color changes to red, while in alkaline solutions it changes to blue or green depending on the exact pH value. To lower the pH-value, we recommend adding a couple of drops of vinegar to the cuvette. To increase the pH value, dissolve some baking soda in water and then add about 20 drops of the solution to the cuvette.

The results of an example measurement with the samples described above is shown in Figure 38, along with reference measurements taken with a Thorlabs CCS100/M spectrometer.

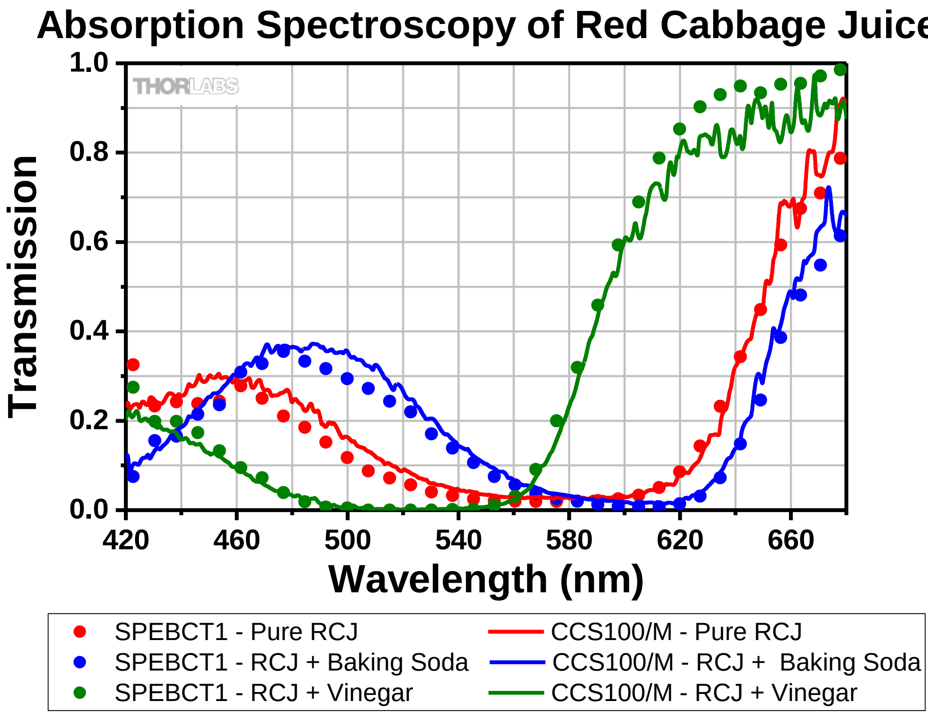


Figure 38: Results of absorption spectroscopy of red cabbage juice (RCJ) at different pH values both with the EDU-SPEB-CT1 setup and with the CCS100/M spectrometer.

8.3. Motorized Rotation Stage

The smallest possible rotation step of the PR01(/M) manual rotation stage is 0.08° degree, limited by the detail of the Vernier scale. This corresponds to about 2 nm steps in the Czerny-Turner setup. Finer steps can be achieved with a motorized rotation stage. For example, the PRM1/MZ8 Motorized Precision Rotation Stage allows for increments as small as 0.03°, corresponding to 0.7 nm. When using continuous rotation at the slowest possible speed of 0.04°/s and a suitable detector, such as the PM60-120 USB power meter, data points can be collected every 0.2 nm, which is far below the resolution limit caused by abberations in the system.

An additional advantage of such a configuration is a reduction of measurement times. At the aforementioned rotation speed, a spectrum of 300 nm width can be recorded in less than 5 minutes.

Please note that in order to obtain reliable results, you will require some kind of self-created software that synchronizes the rotation of the stage and the data collection.

Do you also have ideas for an experiment which you either have implemented already or want to implement? Please contact us at techsupport@thorlabs.com. We are happy to enter into partnerships!

Chapter 9 Regulatory

As required by the WEEE (Waste Electrical and Electronic Equipment Directive) of the European Community and the corresponding national laws, Thorlabs offers all end users in the EC the possibility to return “end of life” units without incurring disposal charges.

- This offer is valid for Thorlabs electrical and electronic equipment:
- Sold after August 13, 2005
- Marked correspondingly with the crossed out “wheelie bin” logo (see right)
- Sold to a company or institute within the EC
- Currently owned by a company or institute within the EC
- Still complete, not disassembled and not contaminated

Wheelie Bin Logo

As the WEEE directive applies to self-contained operational electrical and electronic products, this end of life take back service does not refer to other Thorlabs products, such as:

- Pure OEM products, that means assemblies to be built into a unit by the user (e.g. OEM laser driver cards)
- Components
- Mechanics and optics
- Left over parts of units disassembled by the user (PCB’s, housings etc.).

If you wish to return a Thorlabs unit for waste recovery, please contact Thorlabs or your nearest dealer for further information.

Waste Treatment is Your Own Responsibility

If you do not return an “end of life” unit to Thorlabs, you must hand it to a company specialized in waste recovery. Do not dispose of the unit in a litter bin or at a public waste disposal site.

Ecological Background

It is well known that WEEE pollutes the environment by releasing toxic products during decomposition. The aim of the European RoHS directive is to reduce the content of toxic substances in electronic products in the future.

The intent of the WEEE directive is to enforce the recycling of WEEE. A controlled recycling of end of life products will thereby avoid negative impacts on the environment.

Chapter 10 Thorlabs Worldwide Contacts

For technical support or sales inquiries, please visit us at www.thorlabs.com/contact for our most up-to-date contact information.

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