Extreme Ultraviolet Radiation Spectrometer Design and Optimization

Shaun Pacheco
Mentors: Dr. Guillaume Laurent & Wei Cao

Project Description

This summer project was dedicated to spectrally resolving the high harmonic generation spectrum that was generated in the COLTRIMS set-up in the James R. Macdonald Laboratory at Kansas State University. High harmonic generation is a cheaper way to generate wavelengths in the soft x-ray and extreme ultraviolet region of the electromagnetic spectrum. The goal of my project was to improve the resolution of the spectrometer that was already installed and to calibrate the spectrometer in order to quantitatively resolve the high harmonics that are being generated.

Spectrometer Design

The spectrometer consists of a focusing mirror, diffraction grating, a microchannel plate (MCP), and a phosphor plate. A diagram of the set-up can be seen in Fig. 1.

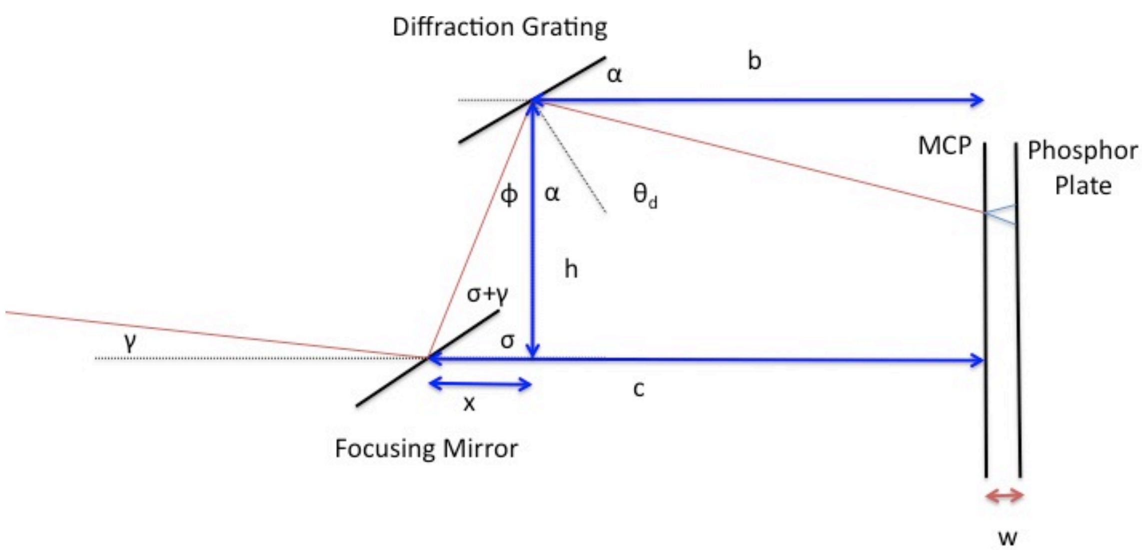


Figure 1: The spectrometer consists of a focusing mirror, diffraction grating, MCP, and phosphor plate. All important angles and distances are indicated on the diagram.

When a beam of light hits the focusing mirror at an angle γ, the beam is reflected at an angle equal to the incidence angle. If the focusing mirror is tilted by an angle σ from the horizontal, the beam of light will be reflected by an angle $2\sigma+\gamma$ relative to the horizontal.

If the beam of light hits the diffraction grating in the center, it will make an angle ϕ with the vertical. This angle can be determined in one of two ways:

$$\phi = \tan^{-1}\left(\tfrac{c-b}{h}\right)$$

$$\phi = \tfrac{\pi}{2} - (2\sigma + \gamma)$$

If the distances between the centers of the diffraction grating and the focusing mirror are known, or if the angle of the focusing mirror is known along with the angle at which the beam of light hits the focusing mirror, then ϕ can be determined.

Different wavelengths are diffracted from a diffraction grating by the equation:

$$d(\sin\theta_i - \sin\theta_d) = m\lambda$$

where d is the separation of each slit, m is the diffraction order, which is an integer, θ_i is the angle incident to the diffraction grating normal, θ_d is the angle at which wavelength of light is diffracted from the normal, and λ is a wavelength of light. Note: θ_d is taken to be positive if it makes an angle to the right of the diffraction grating normal.

If the beam of light hits the center of the diffraction grating, the incident angle is $\phi+\alpha$, where α is the angle at which the diffraction grating is tilted. Since the diffracted angle can't be measured directly, the diffracted angle for each wavelength of light is determined by the position of the mark on the phosphor plate. The center of the spectral line visible on the phosphor plate is taken to be the point at which a photon hits the MCP. The position of a point on the MCP will be denoted as the variable y. Theoretically, the diffracted angle can be determined by

$$\theta_d = \tan^{-1}\left(\tfrac{b}{h-y}\right) - \alpha$$

However, it is extremely difficult to measure h, b, and α accurately enough to obtain a value for θ_d. So another method must be used.

Since diffraction grating acts like a mirror for the zeroth diffraction order, the angular displacement from the zero order spectral line can be used to determine the diffracted angle.

For positive diffraction orders, the diffracted angle can be determined by

$$\theta_d = \theta_i - \tfrac{\Delta y}{b}$$

where Δy is the distance away from the zero order peak. Note that this is an approximation for the angular displacement.

For negative diffraction orders, the diffracted angle can be determined by

$$\theta_d = \theta_i + \tfrac{\Delta y}{b}$$

where Δy is the distance away from the zero order peak. This method for calculating the diffracted angle will be used for the rest of this paper.

The length of the focusing mirror and diffraction grating are roughly 2.54 cm. Thus, the beam of light can hit up to 1.27 cm from the center of the diffraction grating and focusing mirror. If the beam of light doesn't hit the diffraction grating in the center, then the measured distance from the diffraction grating to the MCP will result in an error. An error of 5 mm in the measurement of the distance between the diffraction grating and the MCP can result in an error of .8 in the harmonic order for the 27th harmonic. So, a small displacement from the center of the diffraction grating can have a large error in the reading of the spectrometer.

The measured distances between each component can be seen in the table below.

Distance (variable as seen on Fig 1)	Measurement	Error Bar
Center of diffraction grating to MCP (b)	19.05 cm	.32 cm
Center of focusing mirror to center of diffraction grating (h)	3.96 cm	.08 cm
Center of focusing mirror to center of diffraction grating (x)	6.75 cm	.08 cm
Center of focusing mirror to MCP (c)	25.8 cm	.33 cm
Separation between MCP and Phosphor Plate (w)	5 mm	1 mm
Distance between focused light in target chamber and focusing mirror	38.75 cm	.5 cm
Diameter of MCP	4 cm	

Table 1: Measurements of components in spectrometer

Effects of Moving Each component

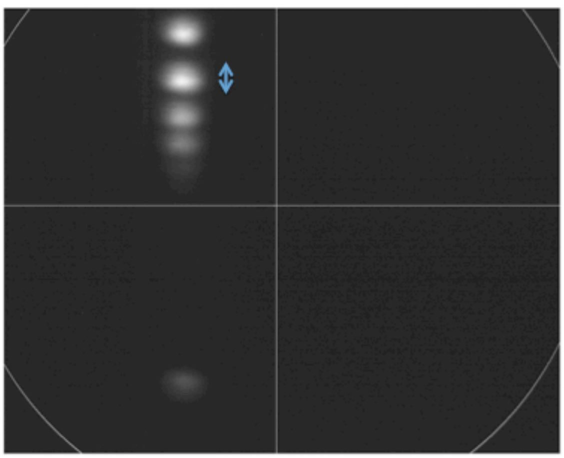
Assuming the zero order spectral line hits the same spot on the MCP in all these cases, the effect of moving each component can be seen in the table below.

Component	Effect
Moving diffraction grating closer to the MCP	Separation between spectral lines decreases Average width of the peaks decreases Distance between zero order and 11th harmonic stays relatively constant
Moving diffraction grating away from the focusing mirror	Separation between spectral lines decreases Average width of the peaks decreases Distance between zero order and 11th harmonic decreases
Moving MCP horizontally away from the focusing mirror and diffraction grating	Separation between spectral lines increases Average width increases Distance between zero order and 11th harmonic increases
Moving MCP vertically away from diffraction	Separation between spectral lines decreases Average width decreases Distance between zero order and 11th harmonic decreases

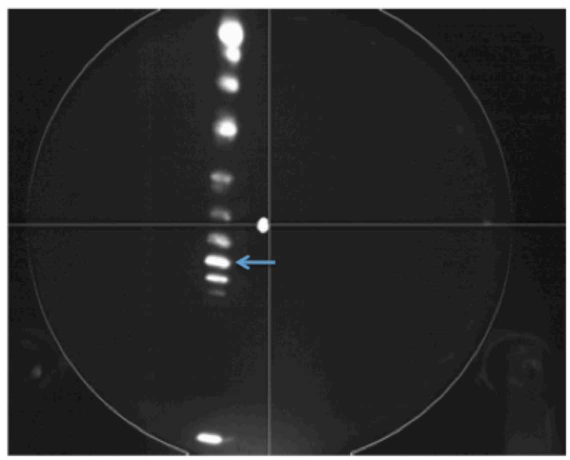
Fixing the Resolution

Since extreme ultraviolet radiation is undetectable to the human eye, another method to see the extreme ultraviolet radiation must be used. When a photon hits the MCP, the MCP acts like an electron multiplier and showers electrons through the back of the MCP. These electrons then hit the phosphor plate, which causes fluorescence. These marks on the phosphor plate are used to indicate where the photons hit the MCP. At the start of this REU program, the spectral lines on the phosphor plate were too large and they appeared out of focus. One of my goals was to discover why the resolution of the spectral lines was so poor, and then fix the problem.

The cause of the poor resolution was due to the phosphor plate being positioned too far away from the MCP. When the electrons exit the MCP, they leave in a shower. The farther away the electrons travel, the wider the spread of the electron shower. Originally, the phosphor plate was positioned about 10 mm away from the MCP. We moved the phosphor plate about 5 mm away from the MCP, and the resolution improved tremendously. The results can be seen below.



Old Resolution



New Resolution

When moving the phosphor plate, we discovered that the phosphor plate that is currently being used was burned in the center. The results can be seen in the picture on the right. The intensity of the spectral lines near the center of the phosphor plate decreases. Therefore, it was determined that a new phosphor plate was needed.t

Calibrating the Spectrometer

When placing the camera, make sure that the entire phosphor plate is visible on picture of the phosphor plate. The area containing the phosphor plate on the picture should be slightly grayer than the surrounding area. Being able to see the outline of the phosphor plate is very important in determining the distance covered by each pixel. A good photo of a set-up can be seen in Fig. 2.

To find the distance covered by each pixel, a circle should be fit to the circular phosphor plate. A simple way of doing this is to draw a circle by changing the pixel values that lies on the circle to a different color. The equation that describes a circle is

$$(x - x_0)^2 + (y - y_0)^2 = r^2$$

Once, the correct x_0, y_0, and r are obtained in terms of pixels. Then the distance covered by each pixel is just the value obtained for r divided by the measured radius of the phosphor plate.

The next step is to find the area of the picture that should be considered in the spectrometer. The spectrum may appear tilted on the phosphor plate. This is most likely due to the fact that the rod that holds the diffraction grating is bent. If the spectrum is tilted, a slope relative to the horizontal of the picture should be determined. The conversion from a pixel coordinate to a distance is

$$\sqrt{\left((zeropos - i) * pixelsize\right)^2 + \left(\lfloor \alpha * i \rfloor * pixelsize\right)^2}$$

where zeropos is the y-component of the pixel coordinate, pixelsize is the distance covered by each pixel, α is the slope that ensures the tilt is taken into account, and i is the ith pixel coordinate in the y-direction.

All the pixels that are equidistant away from the zero order spectral line should be taken into account, so the pixel values should be summed up horizontally. Some lines that were used to sum up the pixel values horizontally can be seen in Fig. 2. Now an integrated pixel value can be paired with a corresponding distance away from the zero order.

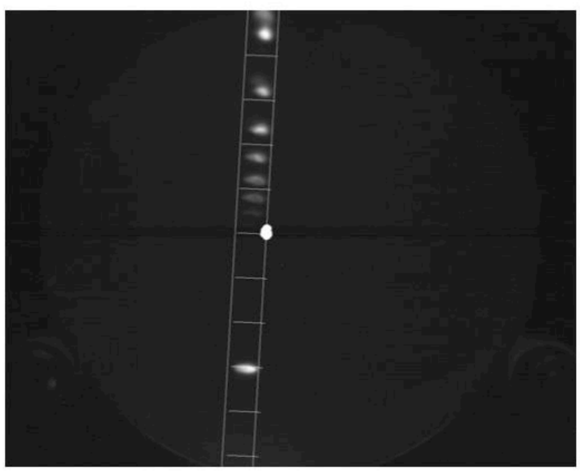


Figure 2: Photograph of spectrum with area of integration outlined. All pixel values between the two vertical lines were summed up in lines similar to the ones shown horizontally.

The wavelengths can be determined by the equation

$$\lambda = \tfrac{d}{m}\left(\sin\theta_i - \sin\left(\theta_i + \tfrac{\Delta y}{b}\right)\right)$$

Using this equation by plugging values for the incident angle and b, the following spectrum using this method can be seen below in Fig 3.

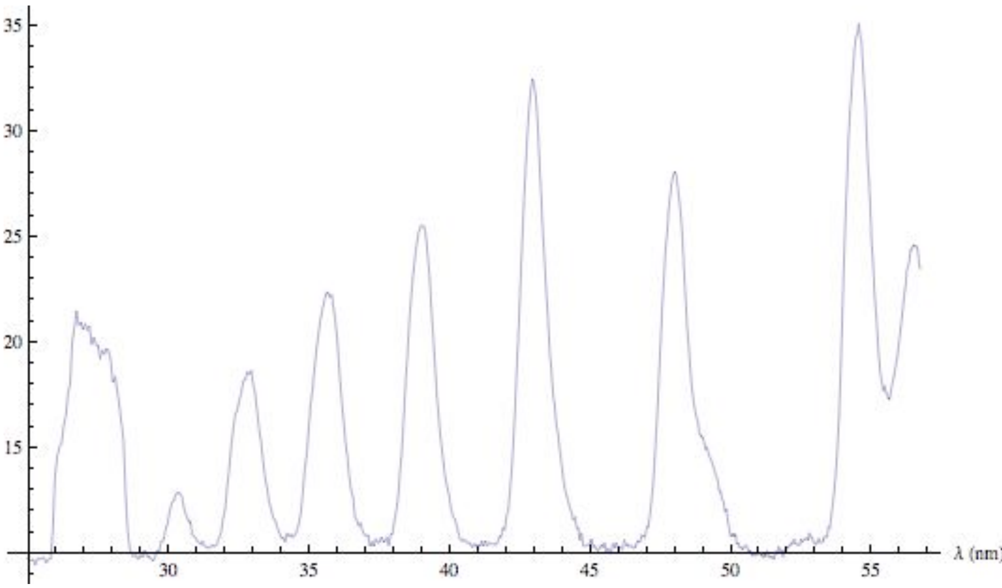


Figure 3 A spectrum generated by High Harmonics Generation. Note the peak smaller than 29 nm is due to a burn mark on the camera that can be seen in the center of Fig 2, this peak does not describe a photon.

If the incident angle and *b* cannot be directly measured accurately enough, then these values can be obtained if an electron energy spectrum is calibrated to find the photon energies. Since the distances from the zero order are known and the photon energies can be determined from the electron spectrum, the energies can be plotted against the distance to the center of each spectral peak. Then the equation

$$E = \frac{hc}{\frac{d}{m}\left(\sin\theta_i - \sin\left(\theta_i + \frac{\Delta y}{b}\right)\right)}$$

can be fit to the plot. Values for the incident angle and *b* can be obtained from the fitting. As long as the diffraction grating and the mirror aren't moved or tilted, these values should remain relatively constant. Thus, these values can be used in future experiments. As long as all components remain fixed, then using the electron energy spectrum can be used to find the necessary incident angle and *b* value.

Improvements

Replace the phosphor plate. The current size of the phosphor plate is adequate to fit all harmonics greater than or equal to the 11^{th} harmonic. Therefore, another phosphor plate equal in diameter will be adequate. However, most of the phosphor plate and MCP aren't used. The widths of each peak horizontally on the phosphor plate are less than 4 mm in length. A phosphor plate that is 55 mm x 8 mm can be purchased from Hamamatsu. This size should be more than adequate to fit all the harmonics on the MCP.

The rod that holds the diffraction grating should be replaced, so that the diffraction grating isn't tilted. This should result in a spectrum that is vertical on the phosphor plate. The rotator for the diffraction grating should be fixed so that the diffraction grating always moves when it's rotated. Currently, the diffraction grating will get stuck when someone tries to rotate it. If changes in the angle of the diffraction grating could be measured with this rotator, then calibrating the spectrometer would be much simpler, since a more accurate way of determining the distance from the diffraction grating. If changes in the angle can be measured, then a small change in the angle can be correlated with a small change in the position of light on the phosphor plate. From this relationship, the angle at which the diffraction grating is tilted can be determined. This will give greater flexibility in the experiment, since the spectrometer doesn't have to remain fixed.

Conclusion

When the spectrometer is calibrated the resolution is comparable to a photoelectron spectrum. The spectrometer is good enough to observe small changes in the harmonic wavelength. One interesting phenomenon that can be seen with this calibrated spectrometer is the blue shift of the harmonic spectrum when the laser intensity is extremely high.