X-ray Imaging Beamline User Manual

Andrew Ames

April 26, 2018

Contents

Chapter 1

Introduction

here is the introduction

Chapter 2

X-ray Source

This chapter discusses the operation of the Jupiter 5000 X-ray tube sources. Section 2.1 covers the procedure for starting up the source under normal conditions. If the source is new, or hasn't been used in more than three months, then it must be started up using the conditioning procedure outlined in Section 2.2. Finally, Section 2.3 discusses how to safely shut down the X-ray source.

2.1 Normal startup procedure

1. Mount the x-ray tube to the aluminum stand with the copper collimator. Affix the thermocouple wire to the outside of the x-ray tube, near the center, with tape. Start up cooling fans by plugging the 12V power supply into the power strip.

2. Ensure that the on/off switch on the x-ray power supply is in the off position. Connect the blue filament cable to the BNC input on the x-ray tube. Insert the high voltage cable into the x-ray tube and screw down the connector. Connect the ground wire to the screw next to the high-voltage input and screw down snugly.

3. Double check that all shielding is in place, including copper pipes, brass optic housing, and leaded glass at the detector end of the beam. Use brass foil to cover any gaps in the shielding. Also make sure everyone in the room is wearing proper dosimetry.

4. Turn on the power supply by moving the switch to the on position. The front panel should read **0.0 mA, 0.0 kV**, and the HV OFF button should light up.

5. Press and hold the HV OFF button to display the preset current and voltage. When the HV is enabled, it will power up to this preset value. The value can be adjusted by turning the mA and kV knobs while holding down the HV OFF button. Set the preset current to 0.0 mA and the preset voltage to 10.0 kV. This is the minimum voltage rating for the Jupiter 5000 x-ray tubes. Note that no actual output is being produced at this stage.

6. Press the HV ON button to power up the supply to the preset voltage. The HV ON button should illuminate and the front panel should read 0.0 mA, 10.0 kV. Using the Geiger counter, check the beamline area for radiation leakage, especially in places where two pieces of shielding come together (such as the holes in the brass optic housing). If any radiation leakage is detected, or any warning lights illuminate on the front panel of the power supply, turn off the output by pressing HV OFF. Record the time and tube temperature reading in the logbook.

7. Increase the output voltage to **20.0 kV**. Sweep the beamline area again using the Geiger counter. Record the time and tube temperature.

8. Increase the output current to **0.025 mA**. Sweep the beamline area again using the Geiger counter. Record the time and tube temperature. Wait 30 seconds after increasing the current before proceeding to the next step.

9. Increase to the desired voltage in increments of 10 kV, checking for radiation leakage, recording the time and temperature, and waiting 30 seconds between each increase. Do NOT exceed 50 kV. Lower the voltage and/or the current if the temperature nears 45C. Do NOT allow the temperature to exceed 49.5C.

10. Once the desired voltage is reached, test the flux by taking a 30 second test spectrum with the detector. If more flux is needed, the current may be increased in increments of 0.025 mA. Check for radiation leakage, record the time and tube temperature, and wait 30 seconds between each increase. If the detector dead time reaches 5% or higher or the

temperature rises too much, decrease the current. Do NOT exceed 1 mA. You should generally not need to exceed 0.1 mA to obtain sufficient flux.

11. The x-ray source is now powered up and ready for the alignment process to begin. While the source is powered on, do not reach onto or over the benchtop. Every 15 minutes or so, record the temperature of the tube, make sure the current and voltage is stable, check for error messages on the front panel of the power supply, and sweep the beamline area for radiation leakage.

2.2 Tube conditioning procedure

This procedure must be used when starting up a new tube or a tube that has been in storage for longer than three months. During a period of storage, residual gasses can accumulate in the x-ray tube vacuum, and applying a high voltage without first conditioning the tube can cause arcing, which can lead to permanent damage to the tube.

1. Follow steps from Section 2.1 up to step 6 to start up the tube at **0.0 mA, 10.0 kV** and check for radiation leakage.

2. If any instability is noted on the mA meter, allow it to stabilize to display 0 mA. Operate at this condition for at least 15 minutes.

3. Increase the beam current to **0.2 mA** and sweep the beamline area for radiation leakage with the Geiger counter. Note the tube temperature and any instability in the mA meter. Maintain this setting for 5 minutes or longer, until no instability is noted on the mA meter.

4. Increase high voltage in 5 kV steps at 5 minute intervals until **25 kV** is reached. After each increase, note the tube temperature and check for radiation leakage. Hold 5 minutes at these conditions.

   Note: if any instability (especially loud popping) is observed, lower the kV setting to the previous step. Allow mA to stabilize at least 5 minutes before increasing settings again.

5. Increase beam current to maximum current rating, **1.0 mA**. Note the temperature, current stability and radiation leakage. Hold for 5 minutes.

6. Continue to increase high voltage as in step 4, in 5 kV steps every 5 minutes until the maximum rated voltage, **50 kV**, is reached. Note the tube temperature and check for radiation leakage and instability after each increase. Do not allow the tube temperature to exceed 49.5C. Allow at least 5 minutes at full power to insure that the tube is operating correctly.

7. Slowly reduce the current to 0.025 mA, then slowly reduce the voltage to the desired operating voltage. Note the tube temperature and check for radiation leakage. Proceed with step 10 onward from Section 2.1.

2.3 Shutdown procedure

1. Slowly dial current down to **0.0 mA**. Wait 10 seconds.

2. Slowly dial voltage down to **10.0 kV**. Wait 10 seconds.

3. Press the HV OFF button. Wait until the current and voltage readings are stable at **0.0 mA, 0.0 kV**.

4. Once current and voltage are stable at zero, turn the power switch on the power supply to the off position.

5. Allow tube temperature to cool to room temperature, then unplug 12V power supply to disable cooling fans.

Chapter 3

Software Overview

This chapter will serve as an overview of the functionality of the BLControl software. Figure 3.1 shows the full user interface that appears when the application is started. Each panel in the window is explained in its own section below.

3.1 Scan Settings

The scan settings panel is shown in Fig. 3.2. The top half contains fields for setting a sample name and ROI (region of interest) and a drop-down menu for choosing a scan type.

The sample name field is only used to identify the sample in any saved files. You can put whatever you like here or leave it blank.

The ROI setting allows you to choose a region of the spectrum between two energy values to be analyzed in real-time along with the total spectrum. If this value is set, the ROI will be highlighted in the spectrum plot and information about the portion of the spectrum will be displayed on the plot. The counts in the ROI will also be counted separately in any scans that are run.

The dropdown menu allows you to choose what type of scan to run, with the choices being "Single Spectrum," "Linear Scan" and "Grid Scan." Each scan type is covered in more detail below. When the scan type is changed, the lower portion of the panel will change to display the settings available for that scan type. For each scan type, press the "Start" button on the bottom of the scan settings panel to begin running the scan. The "Stop" button

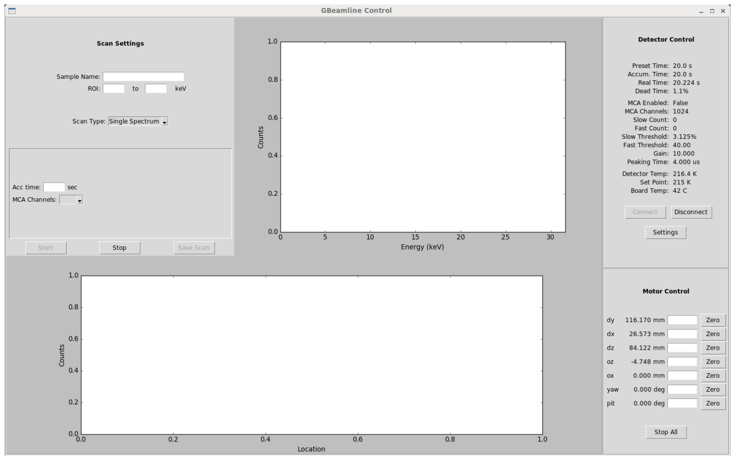

Figure 3.1: Screenshot of the full user interface on startup. The elements of the interface, clockwise from top left, are the scan settings, the single spectrum plot, the detector status readout, the motor control panel, and the scan plot.

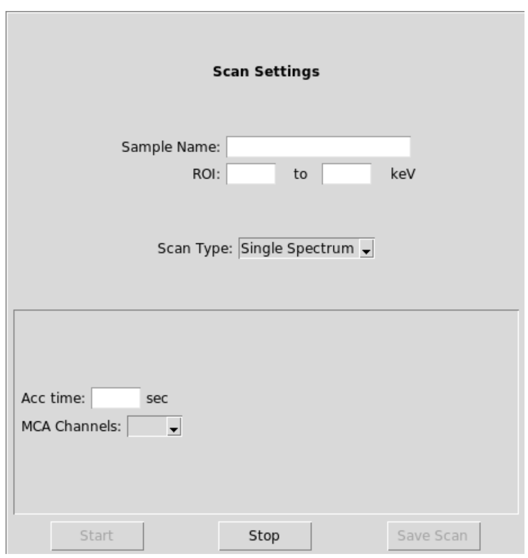

Figure 3.2: The scan settings panel, with scan type set to “Single Spectrum.”

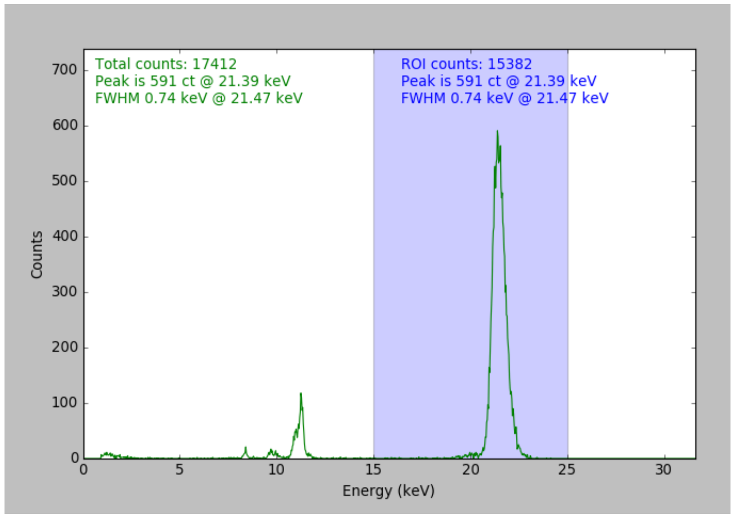

Figure 3.3: The spectrum plot display panel, during the collection of a single spectrum.

may be used to terminate the scan prematurely. Once a scan is finished or has been stopped by the user, the "Save Scan" button allows you to save the data from the most recent scan in a plaintext format.

3.1.1 Single Spectrum

Fig. 3.2 shows the layout of the scan settings panel when "Single Spectrum" is selected. For a single spectrum, there are only two scan-specific options: the accumulation time, in seconds, and the number of MCA channels to be used. The accumulation time can be any value, and the number of channels is selectable from a drop down menu. The detector allows the use of 256, 512, 1024, 2048, 4096, or 8192 channels.

When the spectrum acquisition is started, after a few seconds the spectrum will begin to display in the spectrum plot display panel, to the right of the scan settings panel. This plot will update in real time (with the update frequency depending on the number of channels) until the acquisition is complete.

An example image of the spectrum plot is shown in Fig. 3.3. In the upper left corner, the green text displays some information about the spectrum: the total number of counts, the number of counts and the location of the peak

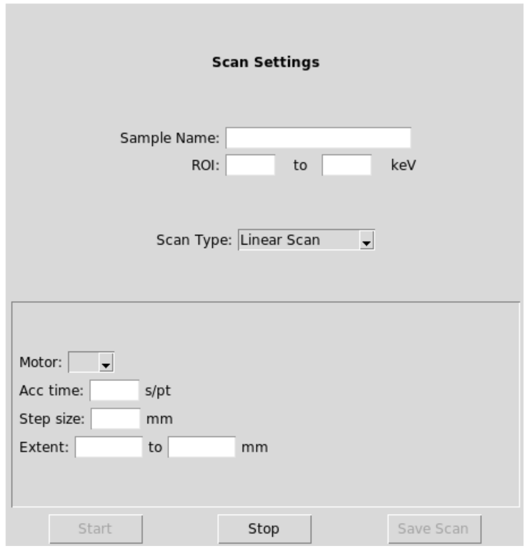

Figure 3.4: The scan settings panel when "Linear Scan" is selected.

channel, and the full width at half maximum (FWHM) and center of the highest peak in the spectrum. For this spectrum, the ROI was set to 15-25 keV, and this region is highlighted in blue. The blue text in the upper right corner gives the similar information about the portion of the spectrum that is contained in the ROI. In this example, the highest peak in the ROI is the same as the highest peak in the full spectrum.

3.1.2 Linear Scan

A linear scan consists of moving a single stage over a distance in specified increments, and taking a spectrum at each position. This is useful during the alignment process, when you want to position each stage at the location that maximizes the count rate.

Fig. 3.4 shows the layout of the scan settings panel when "Linear Scan" is selected. A dropdown menu allows you to choose a motor to scan from the motors that are connected. The accumulation time field specifies the duration of the spectrum that will be taken at each position. Step size is the distance interval between each scan position. The default units are millimeters, but will change to degrees if a rotary stage is selected from the motor dropdown menu. Finally, the extent fields specify the beginning and ending points of

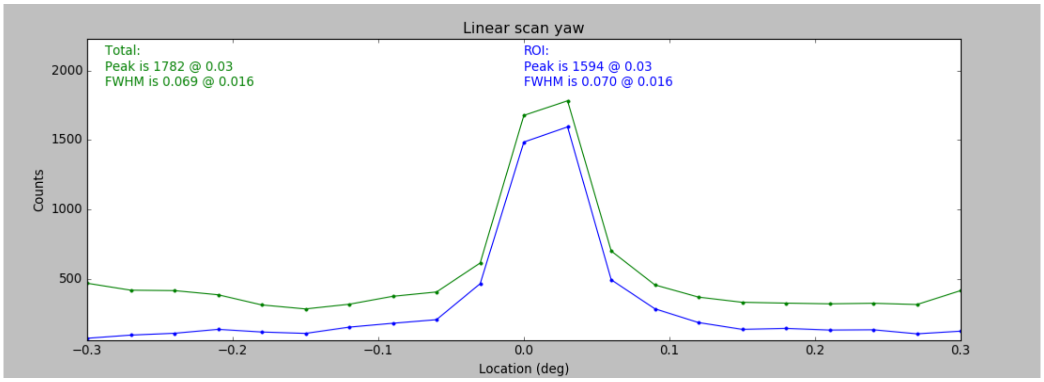

Figure 3.5: The plot displayed in the scan plot display panel, after a linear scan is run.

the scan. The extent is inclusive, meaning a spectrum will be taken at the beginning of the interval, and, if the interval is exactly divisible by the step size, a spectrum will be taken at the end of the interval as well. Together, the extent and the step size define the number of points in a linear scan. The approximate duration of the scan can be determined from the accumulation time at each point and the number of points, but note that some extra time will be needed for data transfer and stage motion.

While the scan is running, the spectra collected at each point will be displayed in the spectrum plot panel, similar to how it is displayed while collecting a single spectrum. During a scan, however, the number of MCA channels is limited to 256 to improve data transfer speed and decrease the size of the files generated from the scans. When the scan is finished, the stage will remain in the final location of the scan until moved by the user.

A plot will also be generated in the scan plot panel, as shown in Fig. 3.5. In real time during the scan, the plot will show the total number of counts collected at each location in green, and the number of counts in the ROI (if used) in blue. Information is also displayed about the highest peak for both the total count data and the ROI data.

3.1.3 Grid Scan

A grid scan is a 2D scan of the detector in the xy plane, which is useful for centering the detector on the axis of the optic. Fig. 3.6 displays the options for setting up a grid scan. The user specifies the accumulation time as in

Figure 3.6: The scan settings panel when "Grid Scan" is selected.

a linear scan. The step size is the distance between consecutive points in both the x and y directions. The grid size dropdown menu allows the user to specify the number of points to be collected, from 3×3 to 11×11 points (odd numbers only).

Unlike the linear scan, which allows the user to specify the start and end points of a scan, a grid scan is always centered around the position of the detector at the time the scan is started. When the scan is initiated, the detector will move to the first position, the lowest values of x and y, and proceed in a raster fashion until the scan is complete. First x is scanned all the way across in units of the step size, then y is incremented by one step and x is scanned in the opposite direction, and so on until the entire area has been scanned. As in the linear scan, the spectra appear in the spectrum plot panel as they are acquired.

The results of the scan are displayed in real time in the scan plot panel, shown in Fig. 3.7. Points are filled in as they are collected, and points not yet collected appear in gray. The total counts are plotted on the left, and the counts in the ROI, if used, are plotted on the right. Both plots display the calculated center of mass of the scans to aid the user in centering the detector. When the scan is finished, the detector will remain at the final point of the scan until moved by the user.

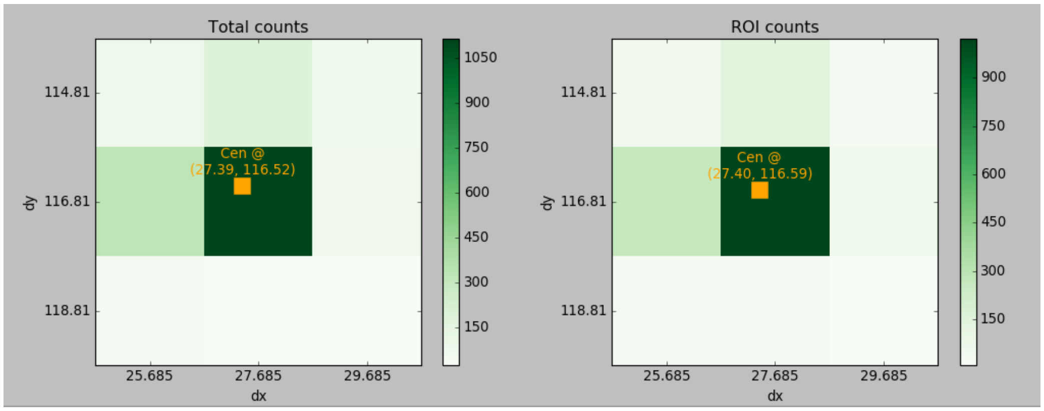

Figure 3.7: The plot displayed in the scan plot display panel, after a grid scan is run.

3.2 Motor Control

The user can move each stage independently using the motor control panel, shown in Fig. 3.8. For each connected stage, the current position is shown, followed by a new position field and a "Zero" button. To move the stage to a new position, enter the new position in the field and press Enter. The current position will update in real time as the stage moves. You can also move the stages using the hardware knobs. The zero button will set the current position of the stage to zero. The "Stop All" button, located at the bottom of the panel, can be used for an emergency stop of all stages.

3.3 Detector Control

3.4 Configuration Files

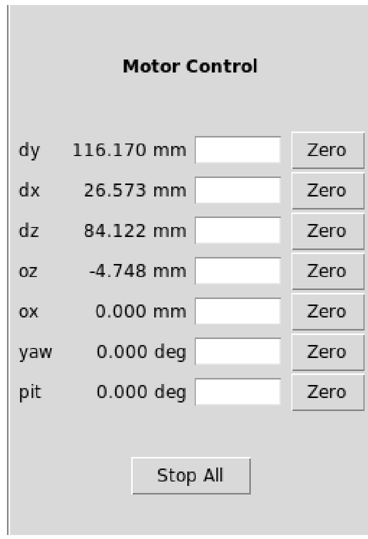

Figure 3.8: The motor control panel.

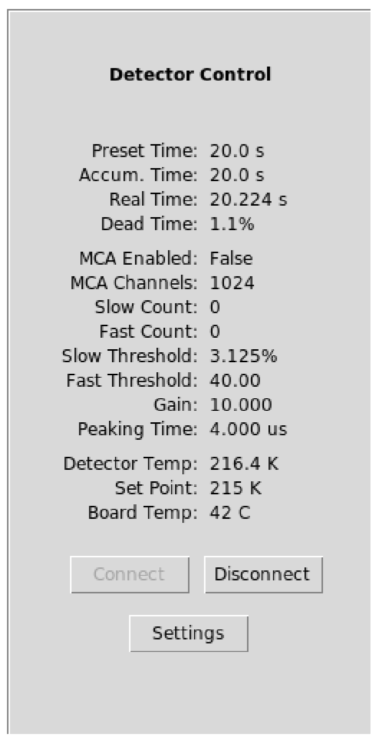

Figure 3.9: The detector status panel.

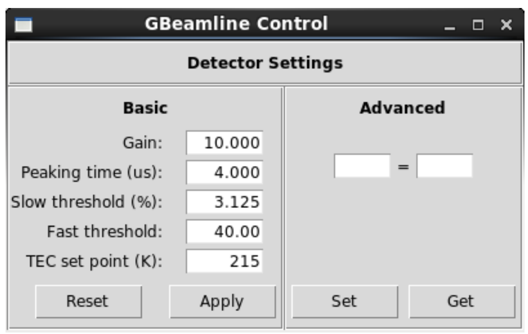

Figure 3.10: The detector settings popup window.

Chapter 4

Alignment and Data Aquisition

This chapter covers the steps for aligning a point-to-point focusing optic in the beamline, and then collecting the data which will later be analyzed to determine the optic's resolution and reflectivity with respect to energy. This procedure is valid for bare nickel/nickel-cobalt optics as well as multilayer-coated optics. A basic familiarity with the BLControl software is assumed here, so please read Chapter 3 first if you have not done so already.

During the alignment process, there are a few things that you will need to regularly check (every 15 minutes or so) and make note of in the log book:

- X-ray tube temperature: make sure it does not rise above 45°C
- Detector temperature: should be below 230K for taking data
- Radiation leakage: sweep the beamline periodically with the Geiger counter to check
- Helium (if using) pressure and flow rate—see Section 4.2 for details

In addition, while the x-ray source is on, you should always be wearing chest and ring dosimetry.

4.1 Setup and visual alignment

Before starting the alignment, mount the detector and plug it in if necessary. Make sure the detector and the motor controllers are connected to the computer. Then, start up the software as described in Section 3. During the initial alignment, leave the red cap or blank tungsten pinhole on the end of the detector to protect the beryllium window from damage.

Take note of the detector temperature and set point, displayed in the "Detector Control" panel. If the detector has just been plugged in, it may need 10-15 minutes before it cools to below 220K, at which point it can be used.

The first step in the alignment process is to roughly align the optic and detector by eye using visible light.

1. Start up the software. Make sure all motors appear in the "Motor Control" panel, and that the detector is cooling.

2. Remove all brass and copper pieces of shielding from the beamline and set them aside. Be careful not to bump any of the copper pipes into the detector.

3. Place the optic into the housing, and put the housing onto the v-block in the optic mount. If measuring in a magnifying configuration (i.e. the optic is closer to the source than to the detector), then the small end of the optic should point toward the sorce.

4. Using the optic z stage ("oz"), move the optic so that the inflection point is at the correct source-to-optic distance, as indicated in the optic design. Note that this distance is to the x-ray source spot, which is actually 1.22 inches behind the front flange of the x-ray tube. Set this oz location to zero in the software.

5. Move the detector z stage to the center of its travel. By moving the stage assembly on the table, put the front window of the detector at the correct focal length as specified in the optic design, again keeping in mind that the x-ray source should be measured 1.22 inches behind the x-ray tube flange.

6. If the x-ray tube is currently mounted on the aluminum bracket, remove it and carefully set it aside. Attach the fiber optic holder to the aluminum bracket, with the copper collimator on the front. Insert the fiber optic output into the holder and turn on the white light source.

7. Replace the brass housing around the optic. If necessary, move the source or optic mounts so that the holes in the brass housing are centered with respect to the white light. Then, using the optic x and

Figure 4.1: Setup and visible light alignment

y stages ("ox" and "oy"), adjust the optic position so that it is centered with respect to the holes in the housing. Set these "ox" and "oy" positions to zero in the software.

8. Holding a sheet of paper between the optic and the detector, locate the single-bounce focal spot. Adjust the pitch and yaw stages until the single-bounce focus appears symmetric. See Fig. 4.1 for reference images. Once pitch and yaw are aligned, set their positions to zero in the software.

9. Holding a sheet of paper in front of the detector, locate the double-bounce focal spot. Adjust the position of the detector in the x and y directions ("dx" and "dy") until the focal spot coincides with the front window of the detector. Try to keep the dx stage close to the center of its travel– you may need to move the detector stage mount around on the table to achieve this.

10. Replace the copper pipes, starting with the pipe closest to the source. After placing each pipe, use a piece of paper at the end of the pipe to locate the beam of visible light, and adjust the position of the pipe so that the beam is centered. The pipes may not end up exactly parallel to the tabletop.

11. Remove the white light source and mount the x-ray tube. Take care not to move the source mount in the process, as doing so could alter the alignment. Use brass foil to cover any remaining gaps in the shielding. Remove the protective cap from the detector window.

4.2 Helium

In this section, we will start the flow of helium through the copper shielding pipes to reduce the attenuation of the x-rays (since helium has a much longer attenuation length than air). This is only necessary if you want to measure low energies (below about 5 keV), so for most multilayer-coated optics you can skip to Section 4.3.

Note that if you are using helium, your count rate will probably be considerably higher than what you are used to in air for a given tube current. You will probably need to reduce the current accordingly so that the detector dead time remains below 5%.

1. Seal any connection points in the copper pipes to create a mostly airtight seal. Carefully wrapped duct tape many overlapping layers with few wrinkles) works fine for this.

2. Connect any tubing that runs from one pipe to another, so that helium can flow from one end of the beamline to the other.

3. Connect the helium tank to the tubing on one end of the beamline. You may want to use a needle valve between the tank and the copper pipe to give you greater control over the helium flow rate.

4. At the other end of the beamline, you should have one open section of tubing. Fill a beaker or other container with water and insert the open end into the water. When helium is flowing, it will bubble through the water and allow you to visualize the flow rate.

5. Open the helium tank. Using the tank regulator and the needle valve if present, adjust the output pressure until you see about one bubble every few seconds on the other end of the beamline. This should correspond to < 5 psi of output pressure. If the pressure is too high, then stop the helium flow and check for leaks, especially at the points where two copper pipes come together (add more duct tape if using).

6. Once you have a decent flow rate at a sufficiently low pressure, you can move on to Section 4.3. While using helium, you need to keep an eye on the flow rate, output pressure, and amount of helium remaning in the tank. Check and record these values every 15 minutes or so while the helium is flowing, and adjust the output pressure if the flow rate becomes too high or if bubbles stop appearing.

4.3 Initial X-ray alignment

In this section, we align the optic in pitch and yaw, and the detector in the x and y directions (i.e. perpendicular to the optical axis).

1. Start up the x-ray source, as detailed in Section. 2.1. The source voltage should be set so that the max energy is at least 5 keV above the energy range of interest (e.g. the location of the multilayer peak). All shielding should be in place at this time. Make sure to check periodically for radiation leaks and note the X-ray tube temperature.

2. Without setting an ROI, perform a 3×3 grid scan to find the center of the beam, and move dx and dy to this location.

3. If the optic has a multilayer, take a 30 second spectrum to find the multilayer peak. Set the ROI to encompass this peak. It should be wide enough to still encompass the entire peak, even if it shifts 1 or 2 keV in either direction during alignment, but should not encompass any "stray peaks" at lower energy.

   Note: If the optic does not have a multilayer, then no ROI needs to be set. From now on during the alignment process, if an ROI is set, then the ROI peak or center of mass from a linear or grid scan should be used, as opposed to the peak or center of mass of the total counts.

4. Perform a linear scan of *pit*, $\pm 0.3°$ (18 arcminutes) in steps of $0.03°$. 3-5 seconds of counting time per point should be sufficient. Move *pit* to the center of the peak, and set it to zero.

5. Repeat step 4 for *yaw*.

6. Scan ox ± 1 mm in steps of 0.2 mm. Move ox to the center of the peak and set it to zero.

7. Repeat step 6 for oy.

8. Repeat steps 4 and 5 for $\pm 0.2°$ in steps of $0.02°$, then repeat steps 6 and 7.

9. Repeat steps 4 and 5 for $\pm 0.1°$ in steps of $0.01°$, then repeat steps 6 and 7.

10. Using a brass sheet to block the beam and shield your hand, place the 3 mm diameter pinhole on the end of the detector. Perform a 3×3 grid scan, with the step size the same as the pinhole diameter, and move to the center of mass.

11. Scan and re-zero *pit* and *yaw* again $\pm 0.1^\circ$ in steps of 0.01°, then scan and re-zero *ox* and *oy* ± 1 mm in steps of 0.2 mm (as in step 9).

12. Repeat steps 10 and 11 with 2 mm and 1 mm diameter pinholes. Increase count time if necessary for better statistics. You may also reduce the size of the linear scans and use smaller steps to help refine the peak location, as long as the peak fits entirely within the bounds of the scan.

    Note: If the grid scan is still very symmetric with a 1 mm pinhole, you can continue to step down to a 0.5 mm or even 0.25 mm pinhole. The smallest pinhole that will be used depends on the resolution of the optic being measured, but generally you should go as small as possible while the 3×3 grid scans are still symmetric and have a well-defined beam center.

13. With the smallest pinhole in place, continue to repeat the alignments of *ox*, *oy*, *pit* and *yaw* (linear scans) and *dx* and *dy* (grid scan). Repeat this cycle until the positions are no longer changing by more than 0.001° or 0.01 mm.

This alignment may change slightly if the source is turned off, as the focal spot within the tube can be in a different position each time it is powered on. If the source is power cycled at any point, just repeat step 13 to verify the alignment.

4.4 Focus finding and HPD measurement

Now that the optic is aligned with respect to the x-ray beam, and the detector is aligned in the xy plane, we will locate the focal point in the z direction and calculate the resolution of the optic.

This section can be time-consuming, and you may want to skip it if you only care about the optic's spectral response and don't need to know the resolution (or already have good enough resolution data from a previous measurement). You are likely to be close enough to the focal distance that the spectrum data will be the same whether you find the exact focus or not. However, if you skip this step, you will have to repeat the entire alignment process to get resolution data in the future, so it's best to do it now if you think you might want it.

During this procedure, you are moving the detector back and forth along the beam direction. Therefore, you must be careful to ensure that the detector does not run into the copper shielding pipes. If you need to reposition the pipes to make room for the detector to move, turn off the x-ray source first, and make sure you don't hit the optic with the pipes while moving them.

1. Your current dz position should be at the nominal focal length of the optic (measured manually during visual alignment) and should be set to $dz = 0$. If not, set it to zero now.

2. With the smallest pinhole in place, re-center the detector using a grid scan. Then take a spectrum of about 30 seconds (you can alter this depending on your count rate) at the current position. Note in the log book how many counts are in your ROI.

3. Change the pinhole to the next size up and repeat the spectrum for the same amount of time. Again note the ROI counts in the log book. Repeat this step with progressively larger pinholes, up to 5 mm diameter.

4. Following the instructions in Section 5.1.1, calculate the HPD at the current position.

5. Move to $dz = 20$ mm. Repeat steps 2-4. If the HPD improves (i.e. decreases), continue another 20 mm in this direction. If it worsens, try the opposite direction. Continue moving in steps of 20 mm until a minimum in the HPD is found. Return dz to the position where the HPD is minimized.

   Note: If you run out of travel on the dz stage, you can return dz to the center of travel and move the entire stage assembly forward or backward on the tabletop. Your position reference will be lost, so you will need to re-center the detector in x and y and re-find the minimum HPD in z.

6. Move dz 10 mm in the direction of the next lowest HPD, and repeat steps 2-4. If the HPD is lower, stay at this dz position, otherwise return to the position of the minimum.

7. Repeat step 6 for a move of 5 mm, and then for a move of 2.5 mm.

8. Using the lowest measured value of the HPD, calculate the optic's spatial resolution as outlined in Section 5.1.2.

4.5 Spectrum data collection

1. If you performed the focus finding alingment in Section 4.4, then move dz to the location of the best measured HPD. Remove any pinhole from the detector and re-center by performing a 3×3 grid scan in 5 mm steps.

2. Collect a long spectrum (typically 10 minutes or more, depending on count rate) with no pinhole on the detector. When the acquisition is complete, make sure to save the spectrum file.

3. Turn off the x-ray source and remove the optic from the beamline. Place a 3 mm pinhole on the detector. Re-start the source to the same current and voltage as before.

4. Collect a long spectrum without the optic for the same amount of time as in step 2. If, after one minute or so, the dead time of the detector is over 5%, stop the acquisition, change the pinhole to a smaller diameter to reduce the count rate, and restart. Once the long spectrum is complete, make sure to save the spectrum file in the same directory as the file from step 2. Make sure to record which file is which (optic vs. no optic) and what size pinhole you used for the no optic spectrum.

Chapter 5

Data Analysis

5.1 Optic Resolution

5.1.1 Half-Power Diameter

5.1.2 Spatial Resolution

5.1.3 Angular Resolution

5.2 Reflectivity

Chapter 6

Detector Calibration

6.1 Collecting calibration spectra

6.2 Calibration data analysis

Chapter 7

Troubleshooting

7.1 Can't see peak in spectrum plot

7.2 Software freezes or gives a mysterious error

7.3 Ran out of travel

7.4 Detector not cooling