Component testing for x-ray spectroscopy and polarimetry

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ABSTRACT

We present the performance and recent results of the MIT polarimetry beamline. Originally designed for testing Chandra HETG gratings, the beamline has been adapted to test components for soft x-ray polarimetry applications. Since then, its monochromator capabilities have also been used to test gratings. We present results on the measured absolute efficiencies of the Arcus Phase A gratings using the B-K, O-K, and C-K emission lines. The beamline has also been used to develop tools and techniques to measure the linear polarization of soft X-rays (0.2-0.8 keV), which form the basis for a sounding rocket mission REDSoX (Rocket Experiment Demonstration of a Soft X-ray Polarimeter) and a possible orbital mission. We present our tests to align the REDSoX gratings, as well as our idea to use thin twisted crystals as a possible alternative to laterally-graded multilayer mirrors. Support for this work was provided in part by the NASA grant NNX15AL14G and a grant from the MIT Kavli Institute.

Keywords: soft x-ray, x-ray, polarimetry, beamline, REDSoX, CAT grating, curved grating, twisted crystal

1. INTRODUCTION

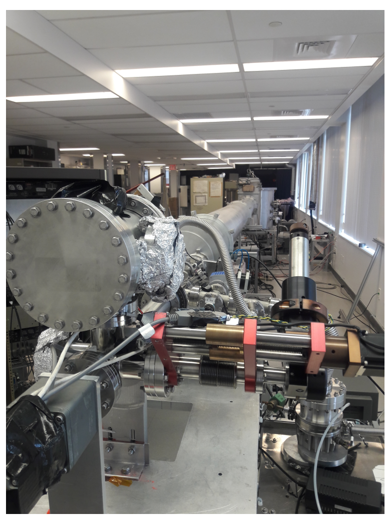

Figure 1. A photograph of the MIT X-ray Polarimetry Beamline. This is taken from the source-end, looking down the beamline toward the grating chamber.

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Figure 2. A photograph of the MIT X-ray Polarimetry Beamline. This is taken from the side and shows the two testing chambers. The right chamber is the 1.3m-diameter grating chamber, while the left chamber is the 1m-diameter detector chamber. Each chamber can be isolated from the rest of the beamline with pneumatic gate valves.

2. LAB BACKGROUND AND CAPABILITIES

The MIT X-ray Polarimetry beamline[1] is an 11m long x-ray beamline (extendable to 17m) which was built to test the Chandra HETG gratings. It has two large cylindrical vacuum chambers one of which is 1.3m in diameter and 1m deep, the other being 1m in diameter and 1m deep. These two chambers provide ample room to install optics for testing and measure high diffraction orders during the same test without changing configurations. They are also large enough to test small missions such as CubeSats directly in the beamline.

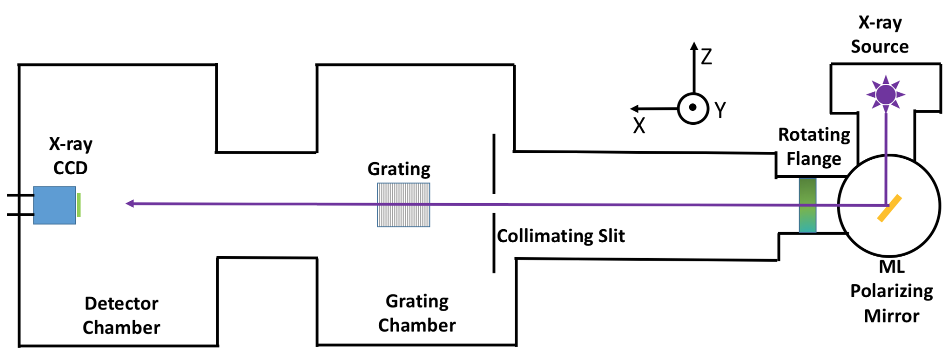

Figure 3. A cartoon diagram of the beamline's current configuration. The laterally-graded multilayer mirror, 1mm collimating slit, and sheer length of the beamline serve to create what is essentially a monochromatic collimated beam at the slit. The multilayer, operated at Brewster's angle, results in a linearly polarized reflected beam and the rotating flange allows us to rotate the angle of polarization while under vacuum.

While the x-ray source can be mounted straight onto the end of the beamline as it originally was when the beamline was created, we currently have it mounted at 90 degrees to the rest of the beamline (Figure 3). The x-ray source illuminates a laterally-graded multilayer mirror which can be translated along the beam so that only the particular energy x-rays that we choose are reflected at 45 degrees down the beamline. At the entrance of the first chamber (the "grating chamber") we have an aperture stage. Our most commonly used aperture is a 1mm slit which, given the length of the beamline and the reflection off of the laterally-graded multilayer mirror, results in a 1mm wide beam that is not only more or less collimated but also monochromatic. We typically place the grating or other optic that we would like to test after the aperture stage, while in the second chamber there is a cooled x-ray CCD. The x-ray CCD is also able to measure the energy of the x-ray events independent of any gratings.

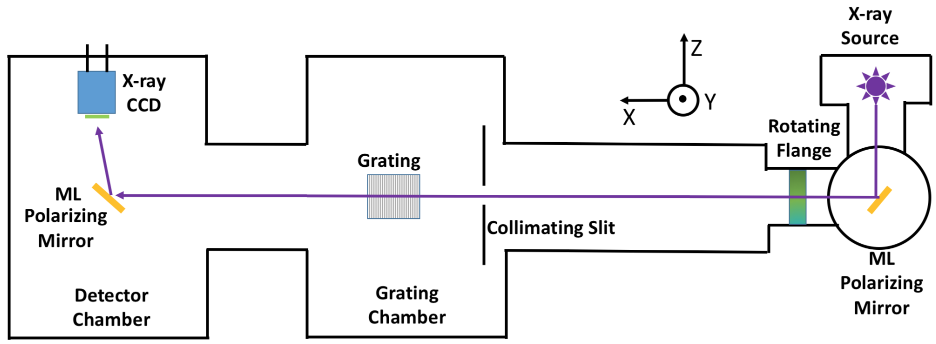

Figure 4.
A cartoon diagram of the beamline's polarimetry configuration. The laterally-graded multilayer at the source and the single-period multilayer at the camera are both operated at Brewster's angle. This allows only s-polarized x-rays to reflect off of the multilayers.[2] If the angle of reflection of both mirrors is in the same plane (i.e., if the mirrors are parallel) then the s-polarized light reflects off of both multilayers and the camera will see a maximum signal. However, if the rotating flange is used to rotate the source multilayer by 90 degrees, then the s-polarized x-rays reflecting off of the source multilayer will appear p-polarized by the second multilayer. In such a case the x-rays would be fully absorbed by the second multilayer, resulting in no reflection off of it and a minimum signal on the detector. This setup allows us to test and measure the polarization of components in the beamline in support of the REDSoX polarimeter.[3]

A second configuration we are capable of is what we call our polarimetry configuration (Figure 4). This leverages the fact that the laterally-graded multilayer at the source is operating at Brewster's angle, so even though our x-ray source is unpolarized the light being reflected off the mirror is s-polarized (linearly polarized perpendicular to the plane of reflection). In the polarimetry configuration we rotate the camera 90 degrees and install another multilayer at the detector-end of the beamline that also operates at Brewster's angle. If the angle of reflection of both mirrors is in the same plane (i.e., if the mirrors are parallel) then the s-polarized light reflects off of both multilayers and the camera will see a maximum signal. However, if the vacuum-safe rotating flange is used to rotate the source multilayer by 90 degrees, then the s-polarized x-rays reflecting off of the source multilayer will appear p-polarized by the second multilayer. In such a case the x-rays would be fully absorbed by the second multilayer, resulting in no reflection off of it and a minimum signal on the detector. Our polarimetry configuration allows us to test the polarization of components using the beamline in support of the REDSoX polarimeter mission.[3]

3. CRITICAL-ANGLE TRANSMISSION GRATING TESTING

Critical-angle transmission (CAT) gratings are etched silicon wafers that use long parallel sheets of grating bars which operate at the critical angle to disperse the x-rays. They have a very high aspect ratio (Figure 5), so it is critical to ensure the blaze angle is correct in order to maximize their diffraction efficiencies.

3.1 Arcus Prototype CAT Grating Testing

We tested the Arcus[4] prototype CAT gratings[5] in the beamline to measure their efficiencies at a range of blaze angles. The angle where the peak efficiency was reached for a given order is referred to as the "blaze peak" for that order - in other words, the transmission and diffraction efficiency for a given order is maximized at the blaze peak. As part of the test the Arcus prototype gratings were mounted in the grating chamber on a stage that is capable of translating the gratings across the beam so the slit can illuminate different parts of the grating. The stage is also capable of rotating the grating to change the angle of incidence of the x-rays (we define an angle of 0 as being normal to the surface), which allows us to adjust the blaze angle and find the blaze peak for each order. The camera can also be translated to measure the lines of higher diffraction orders, as opposed to just 0th order.

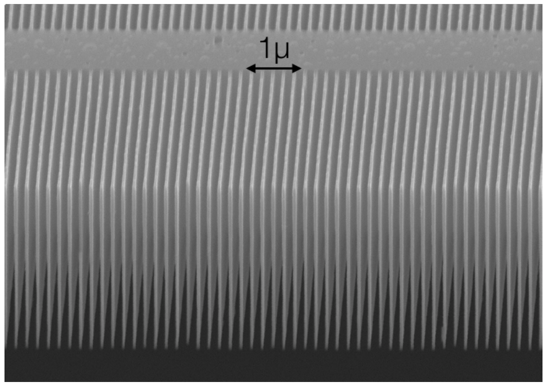

Figure 5.
A side view of etched CAT grating bars. Incoming x-rays from above would reflect and be diffracted off of the interior surfaces of the grating bars near the critical angle. The high aspect ratio makes proper alignment critical to allow for good transmission and diffraction efficiencies.

A blaze angle scan ("blaze scan") was performed for several orders of interest to the Arcus and REDSoX missions[6] at the O-Kα, B-Kα, and C-Kα line energies (Figures 6, 7, and 8). The transmission and diffraction efficiencies that we measure are high, and are consistent with predictions based on their design and manufacturing.

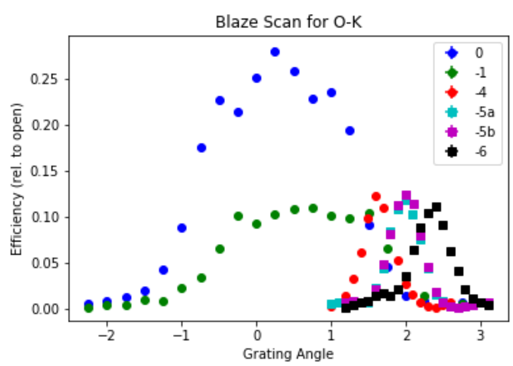

Figure 6.
A plot of the blaze scans measured for various orders at the O-Kα line energy. The different colors correspond to various orders. The efficiencies are high and consistent with predictions. Error bars are plotted but are smaller than the symbols. Errors were calculated assuming shot noise dominated.

3.2 Curved CAT Grating Testing

The REDSoX Polarimeter is a soft x-ray polarimeter that uses grazing incidence optics to focus the x-rays to a point (Figure 9). CAT gratings are placed past the mirrors to disperse those x-rays onto a matched series of laterally-graded multilayers that are operating at Brewster's angle - which allows us to measure the polarization of the light. However the converging beam that the gratings receive[7] can make it difficult for them to be blazed uniformly across their surface, due to the relatively narrow range of angles where a given grating is blazed properly with respect to the incoming x-rays (see Section 3.1).

If we leave the CAT gratings in REDSoX flat despite having a converging beam, then while the center of the grating may be blazed properly to diffract the light efficiently, at the edges it may not be diffracting efficiently at all because the x-rays are coming in at too steep or too shallow of an angle (Figure 10). To solve this, we plan to bend the CAT gratings so that all of the incoming x-rays have a consistent blaze angle across the grating.

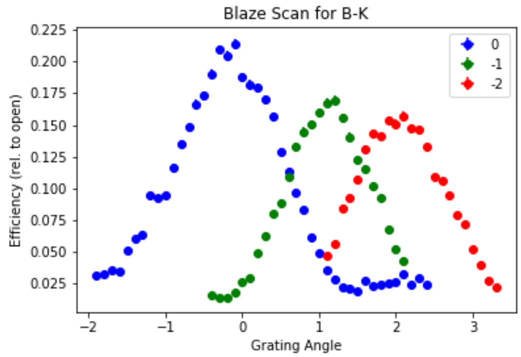

Figure 7.
A plot of the blaze scans measured for various orders at the B-Kα line energy. The different colors correspond to various orders. The efficiencies are high and consistent with predictions. Error bars are plotted but are typically smaller than the symbols. Errors were calculated assuming shot noise dominated.

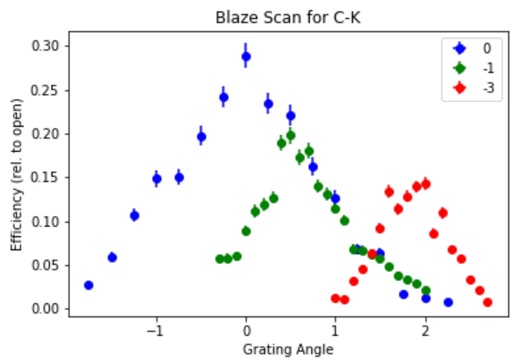

Figure 8.
A plot of the blaze scans measured for various orders at the C-Kα line energy. The different colors correspond to various orders. The efficiencies are high and consistent with predictions. Error bars are plotted. Errors were calculated assuming shot noise dominated.

However, bending CAT gratings without damage is something we needed to demonstrate as being possible. In support of this, we had a curved grating mount made. The curvature needed is actually very small - the radius of curvature is 1.5m and the gratings are only 3cm long - so the gratings don't even appear curved by eye. Next we took one of our engineering-grade gratings, transferred it onto the curved mount, used flexures to press against it to have it match the mount's curvature, and finally installed it in the beamline. We do not have a converging beam in our beamline, instead we have a slit which illuminates a narrow portion of the grating with an essentially collimated beam (see Section 2). To conduct the test we first illuminated the center of the grating with the slit and did a blaze scan (as in Section 3.1). This should be identical to the situation of flat grating illumination, because locally the section of the grating that the slit is illuminating appears flat (Figure 11). Next we translated the grating and performed another blaze scan but this time with the slit illuminating the edges of the grating. At the edges the grating bars are not parallel to the incoming x-rays when the grating is at 0 degrees. Instead the blaze peak should be offset by about 0.3 degrees compared to the center.

This process was done first with the curved grating (center of grating, left edge of grating, right edge of grating) in 0th order and 1st order of C-Kα. Then the grating was removed from the curved mount, flattened and returned to a normal flat mount, and the entire process was repeated on the flattened grating. The results of these blaze scans can be seen in Figures 12, 13, and 14. The results show that there is no loss in efficiency between the flattened and curved grating, and that the offset in the angles of the blaze peaks at the edges of

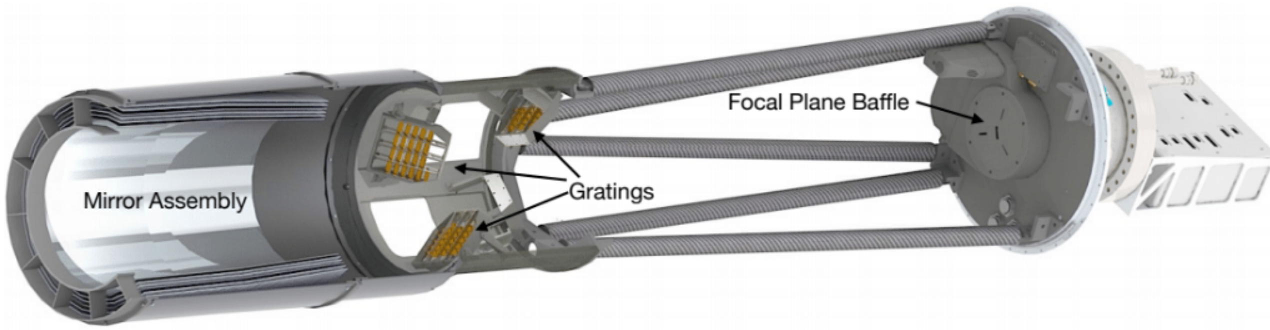

Figure 9.
A rendering of REDSoX[8] with some components hidden for clarity. X-rays enter from the left and are focused by the grazing-incidence optics. The gratings, which disperse light onto a matched series of multilayer mirrors near the detector, see a converging beam due to the focusing mirrors.

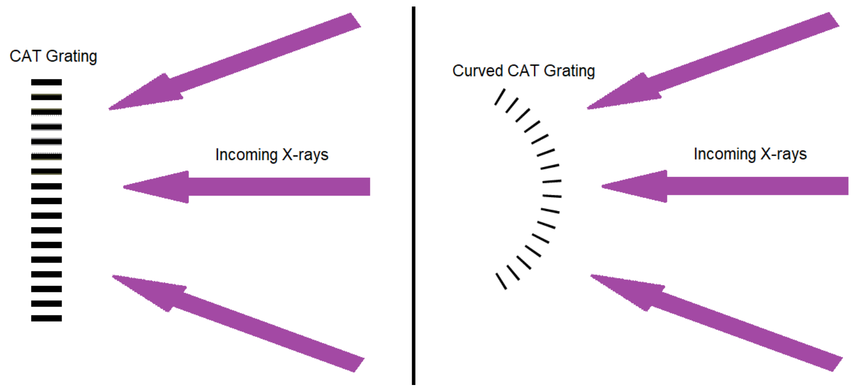

Figure 10.
In a converging beam, various sections of the CAT grating will see different angles of incidence for incoming x-rays (left). Since the efficiency of the grating is strongly dependent on the blaze angle (Figure 6) this could be a problem for REDSoX. By curving the CAT gratings for REDSoX, we aim to match the profile of the converging beam (right). This should result in a consistent blaze angle for all x-rays across the surface of the grating.

the curved grating (as opposed to the edges of the flat grating) is consistent with the prediction of 0.3 degrees. Furthermore, the fact that the curved data was taken first and then the grating was flattened back before taking the flat data demonstrates that we are not damaging these gratings by unbending them, at least with the level of curvature that is needed for REDSoX. This verifies that our plan to curve the gratings in REDSoX is sound and poses little to no risk for the gratings.

4. REDSOX GRATING ALIGNMENT

The REDSoX polarimeter incorporates over 100 CAT gratings in its design (Figure 15). Since the gratings need to disperse the light accurately onto a matched series of laterally-graded multilayer mirrors, it is critical that the gratings are aligned properly. The grating tolerances, highlighted in Table 1, are generally loose for transmission gratings except for two dimensions: the grating tip and tilt. These dimensions require that the gratings be aligned to within 6 arcmin of one another in both their tip and tilt. We have secured internal Kavli grant funding to measure the alignment of the REDSoX gratings and develop methods to adjust that alignment.

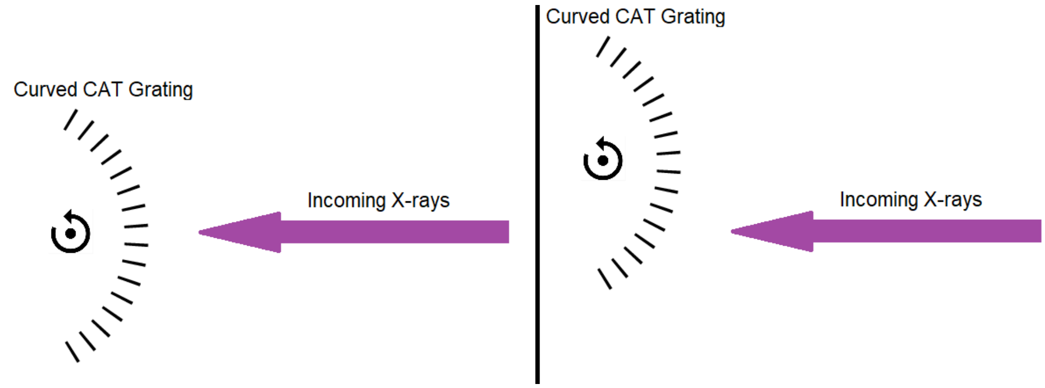

Figure 11.
To test the curved gratings in our beamline, we used the collimated beam provided by the slit to illuminate a narrow section of the grating at a time. When the center of the curved grating is illuminated (left) it is no different than a flat grating (in both cases the incoming x-rays are parallel to the grating bars locally). However when the edge of the grating is illuminated (right) the peak of the blaze curve will be offset by approximately 0.3 degrees in the curved versus the flat state.

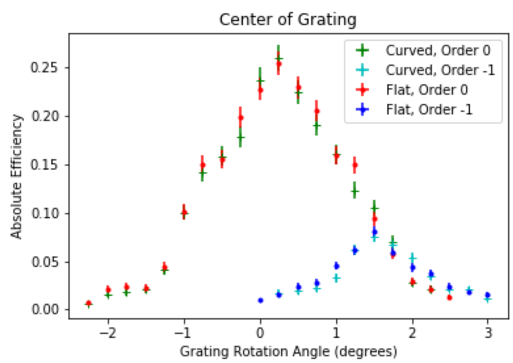

Figure 12.
Test results showing blaze scans of the center of the curved and flat configurations of the grating in 0th and 1st order. Notice that, as predicted, there is no offset in angle between the curved and flat states. Also, the efficiency is identical between the two cases.

4.1 Measuring Grating Alignment

Fortunately, a method for measuring the alignment of CAT gratings relative to one another has already been developed. Using said method, Song et al. (2017)[9] were able to align the Arcus prototype CAT gratings within 4 arcmin of one another in tip and tilt (in fact, typically better than 2 arcmin) and measure the alignment to an even higher level of precision. The alignment was measured using a "scanning laser reflection tool" (SLRT, Figure 15), which we are adapting to measure the alignment of the REDSoX prototype gratings. The REDSoX prototype gratings, which were purchased and have been verified in the beamline, are functionally identical to the Arcus prototype gratings for the purpose of alignment testing.

4.2 Grating Mount

While the SLRT enables us to measure the alignment of CAT gratings relative to one another, we also need to be able to actually align the gratings in order to have accomplished anything meaningful. To that end we've designed grating mounts that are able to adjust the tip and tilt of the gratings. The grating mounts, shown in Figure 16, are machined from a single piece of titanium. The top surface of the mount is slightly curved to match the curvature of the gratings that we want in REDSoX (see Section 3.2), and the grating is epoxied in place along its edges directly onto the curved surface. Internal flexures are machined into the part using wire

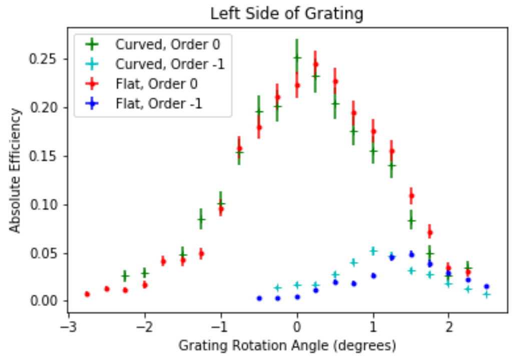

Figure 13.
Test results showing blaze scans of the left edge of the curved and flat configurations of the grating in 0th and 1st order. Notice that, as predicted, there is a small offset in angle between the curved and flat states. Also, the efficiency is identical between the two cases.

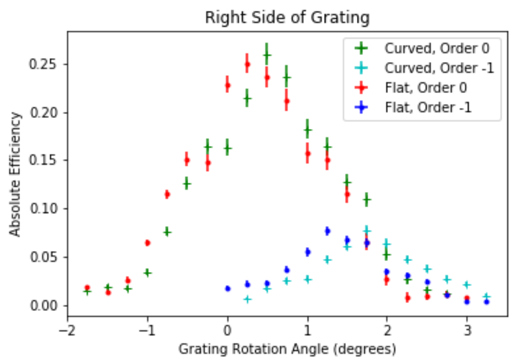

Figure 14.
Test results showing blaze scans of the right edge of the curved and flat configurations of the grating in 0th and 1st order. Notice that, as predicted, there is a small offset in angle between the curved and flat states. Also, the efficiency is identical between the two cases.

EDM machining. These flexures, in conjunction with two fine-threaded adjustment screws, allow us to adjust the tip and tilt of the grating with an angular resolution slightly better than 2 arcmin (corresponding to a quarter turns of the screws). These mounts have been designed, quoted, and are currently being fabricated. We expect delivery by the end of August 2019.

4.3 Alignment Test Status

All necessary equipment to replicate the design used in Song et al. (2017)[9] has been acquired and the test setup is assembled (Figure 4.3). The REDSoX prototype gratings have been purchased, are in-hand, and have been verified in the beamline. The grating mounts are currently being fabricated, and we expect alignment testing to begin in September 2019.

5. TWISTED CRYSTALS

Laterally-graded multilayers use a smooth change in the spacing between layers to adjust which wavelength of light satisfies the Bragg condition across the surface of the mirror. However, they suffer from relatively poor reflection efficiencies when used at steep angles as well as a broad wavelength response function at any given location. Additionally, they are typically expensive to manufacture. In contrast, the regular spacing provided by nature in crystals offers excellent diffraction efficiencies and a very tight response, all in a relatively cheap

Table 1. REDSoX Polarimeter System Tolerances

	x	y	z	tip	tilt	yaw
Subsystem	mm	mm	mm	’	’	’
Optics	2.0	2.0	2.0	60	60	-
Grating petal to structure	1.0	1.0	1.0	6.0	6.0	60
CAT grating to petal	0.5	0.5	0.5	6.0	6.0	60
ML mirror	0.1	2.	1.0	15.0	15.0	60.0
CCDs	2.0	2.0	2.0	120	120	120

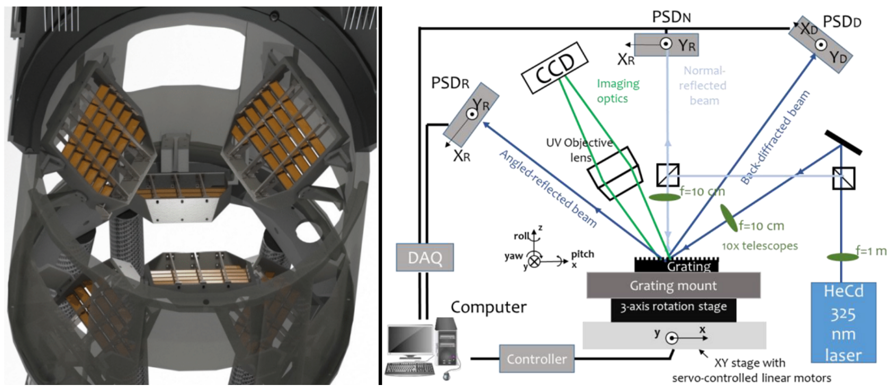

Figure 15.
A rendering of the REDSoX design (left) which shows just a portion of the many CAT gratings used in the design. The presence of so many gratings as well as their important purpose makes being able to align them well with respect to one another a top priority. Fortunately, an alignment system (right) has been developed by another group[9] that allows the alignment of two or more gratings to be measured with respect to one another.

package. However, the biggest strength of crystals as Bragg reflectors - their very regular lattice spacing across the surface, as opposed to a varying spacing across their surface - makes them unsuitable as replacements for laterally-graded multilayers.

We propose to change this by adjusting the macroscopic geometry of an otherwise flat crystal through the introduction of a simple twist - forming what we refer to as a ”twisted crystal.” Our idea starts with a flat rectangular crystal that has been twisted about its long axis by 30 degrees or so. Along the center line of that twist, the angle that is normal to the surface changes along its length. As long as the spacing of the lattice structure locally remains constant, then the Bragg condition would be satisfied for different angles along the twist (as opposed to a change in the spacing of the lattice structure). Essentially, instead of changing the spacing and keeping the angle of incidence constant, as is done with laterally-graded multilayers, we are trying to make twisted crystals where the spacing between the layers stays constant while the angle of incidence changes across the crystal (Figure 18).

We have attempted to twist crystalline silicon wafers in the lab and while they do not break easily, they also seem to crinkle rather than twisting smoothly (Figure 19). However, we have been in discussion with partners in industry who believe that the twist that we desire is possible using more advanced techniques. For example, one idea is to grow the crystal directly onto a twisted base (ensuring the that lattice structure is always parallel to the surface of the base locally). Yet the most promising avenue involves using a torsion/tension machine to keep the crystal under tension while it’s twisted to the desired shape (to prevent crinkling) all while the crystal is being heated near its melting point (to encourage a uniform twist). We are moving forward with these ideas and hope that twisted crystals will soon become a reality and find a place in future x-ray missions.

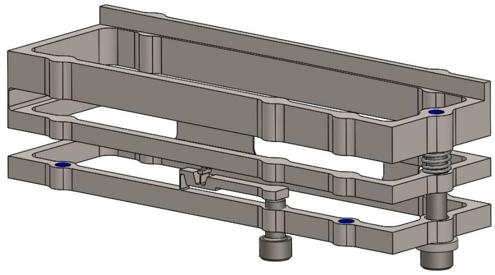

Figure 16.
The grating mount design for the REDSoX prototype gratings. Made from a single piece of titanium, its top surface is curved as in the design (see Section 3.2). The flexures are built into the piece, with fine-threaded screws to adjust the tip and tilt of the grating to a resolution of better than 2 arcmin.

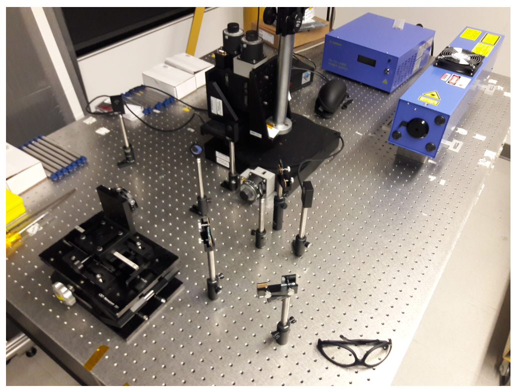

Figure 17.
Our alignment setup that, once the grating mounts arrive, will be used to demonstrate our capability of aligning the gratings relative to one another. The test setup uses three position-sensitive detectors to characterize the orientation of the grating bars.

6. FUTURE WORK

Our facility is capable of producing monochromatic soft x-rays, with large chambers capable of testing not only CAT gratings but larger optics and even small missions as well. We are open to collaboration with groups who need such a space for their own testing purposes. We have used the beamline to measure the efficiencies of the Arcus prototype gratings and found them to match predictions. We anticipate that the beamline will be used to test additional CAT gratings in the future, perhaps at different energies than previously measured. We have also used the beamline to demonstrate that CAT gratings can be curved without damage and that their performance matches prediction with transmission and diffraction efficiencies identical to those of uncurved gratings. This test may be repeated in the near future, as we soon plan to convert the beamline back to its polarimetry configuration. One of the most exciting prospects in the near future is the development of twisted crystals as a possible alternative to laterally-graded multilayer mirrors. There are several manufacturing avenues available that may be able to fabricate these twisted crystals to the desired specification, and if successful could be used in future missions to provide much higher efficiencies at a broader range of energies than current mirror technology allows.

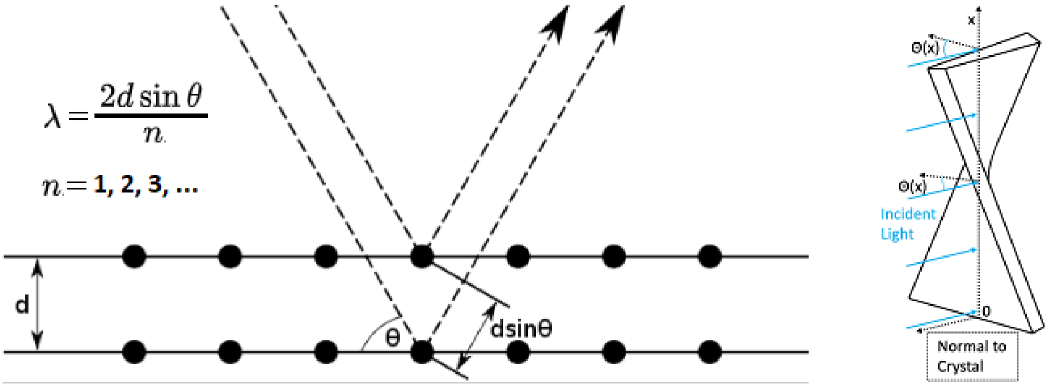

Figure 18.
Crystals have been used as Bragg reflectors for decades. By twisting them, we aim to satisfy the Bragg condition for a given wavelength by changing the angle of incidence of the light while keeping the regular lattice spacing of the crystals constant. This is in contrast to laterally-graded multilayer mirrors which satisfy the Bragg condition by changing the spacing of the layers across its surface.

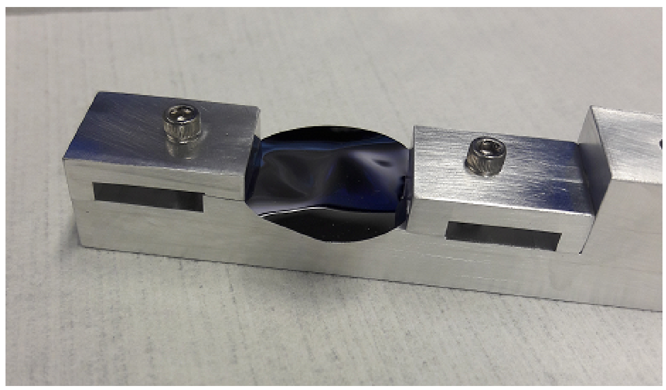

Figure 19.
Shown is an early exploratory effort to create a twisted crystal. We created a jig that pressed a crystalline silicon wafer onto an aluminum substrate that matched the twist profile that we desired. While the crystal did twist without breaking, it did not twist smoothly. Note the apparent crinkling of the crystal near its center - this is unsuitable for our intended purposes. We are currently exploring other techniques for twisting crystals that show much more promise.

ACKNOWLEDGMENTS

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