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CAT grating alignment and testing for soft x-ray polarimetry

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ABSTRACT

We present an update on our work measuring the performance and alignment of the critical-angle transmission gratings for the proposed sounding Rocket Experiment Demonstration of a Soft X-ray Polarimeter (REDSoX) mission, as well as a possible orbital version. We built and verified a grating alignment system that could be used for REDSoX Polarimeter fabrication. The performances of the gratings were measured using the MIT polarimetry beamline. The beamline is a monochromator and has been used to measure the absolute efficiencies of not only the REDSoX prototype gratings but also the Arcus Phase A gratings. It is also capable of producing and measuring polarized soft X-rays to aid in the development and testing of future missions. Lastly, we present an update on our effort applying twisted crystals to X-ray polarimetry.

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

1. LAB BACKGROUND AND CAPABILITIES

The MIT X-ray Polarimetry beamline[1] is an 11m long x-ray vacuum system (extendable to 17m) which was built originally to test the Chandra HETG gratings (Figure 1). It has two large cylindrical vacuum chambers. The central chamber is 1.3m in diameter and 1m deep and typically holds gratings or other optics, while the second chamber (which is at the end furthest from the x-ray source) is 1m in diameter and 1m deep and hosts the CCD detector. 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.

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° to the rest of the beamline (Figure 2). The x-ray source illuminates a laterally graded multilayer mirror (LGML) which can be translated along the beam so that only the particular energy x-rays that we choose are reflected at 45° 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 beam that is not only more or less collimated (though of course, still slightly diverging) but also monochromatic ($dE/E \approx 0.01$). 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 (FWHM $\approx$ 80 eV).

A second configuration we are capable of is what we call our polarimetry configuration (Figure 3). 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° relative to the beam 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 and multilayer by 90°, then the s-polarized x-rays reflecting off of

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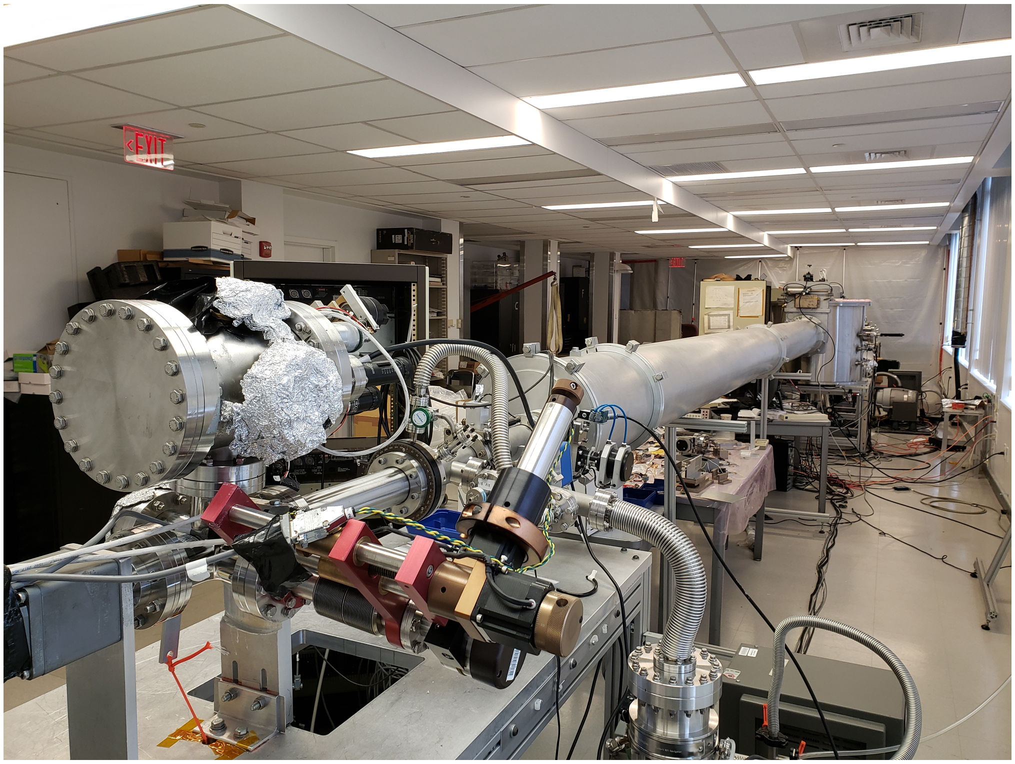

Figure 1. A photograph of the MIT X-ray Polarimetry Beamline. This is taken from the source end, looking down the beamline toward the grating chamber. The large chamber visible towards the apparent "end" of the beamline is the 1.3m-diameter grating chamber, while the chamber further downstream (not visible because it is hidden by the grating chamber) is the 1m-diameter detector chamber. Each chamber can be isolated from the rest of the beamline with pneumatic gate valves.

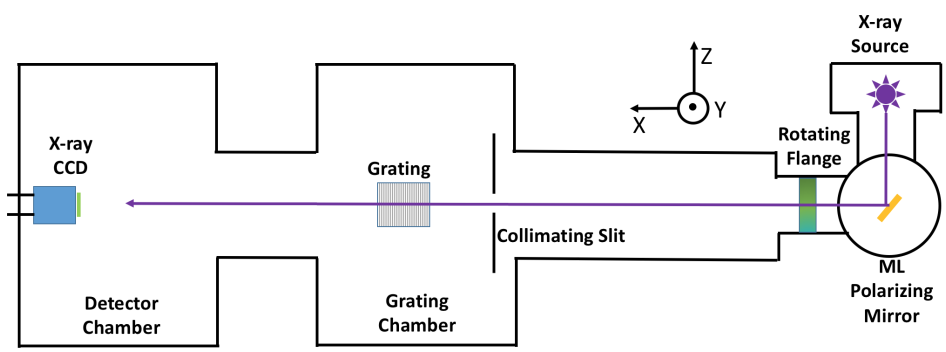

Figure 2. A cartoon diagram of the beamline's current configuration. The laterally-graded multilayer mirror, 1mm collimating slit, and sheer length of the beamline serve to create what is essentially a monochromatic beam (dE/E $\approx$ 0.01). The multilayer, operated at Brewster's angle, results in a linearly polarized reflected beam and the rotating flange allows us to rotate the angle of polarization while under vacuum.

the source multilayer will appear p-polarized at 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] as well as other polarimetry missions.

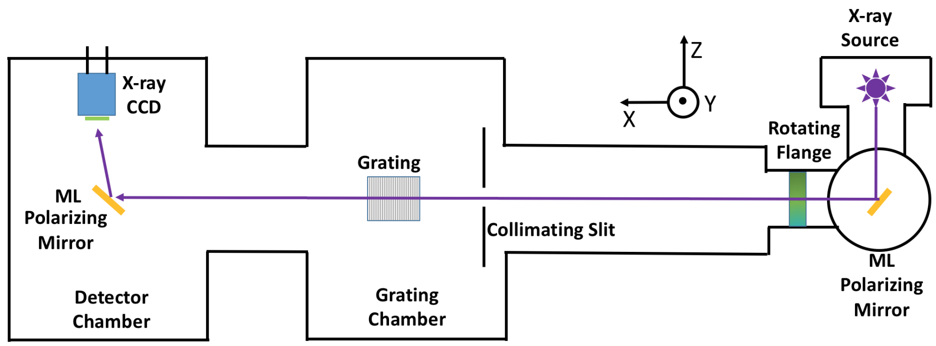

Figure 3.
A cartoon diagram of the beamline's polarimetry configuration. The laterally-graded multilayer at the source and the single-period multilayer at the camera are both operated at Brewster's angle. This allows only s-polarized x-rays to reflect off of the multilayers.[2] If the angle of reflection 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 and multilayer by 90 degrees, then the s-polarized x-rays reflecting off of the source multilayer will appear p-polarized at 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]

2. THE REDSOX POLARIMETER

The REDSoX Polarimeter (Figure 4) is a proposed sounding rocket experiment that will be the first instrument to measure linear polarizations in the 0.2-0.8 keV soft X-ray band. While soft x-ray polarimetry has the capability to shed light on many scientific questions including the nature of the surfaces of isolated neutron stars,[4] we believe that the scientific question best suited to the relatively short duration of a sounding rocket mission is probing the the relativistic jets of blazars. In particular, several BL Lac objects such as Mk 421 and Mk 501 show extremely rapid variability in their high energy emission (including soft x-rays).[5] However, the source of this emission is poorly understood. Soft x-ray polarimetry is uniquely suited to complement optical observations to distinguish between competing models on where in the AGN the variability is arising.

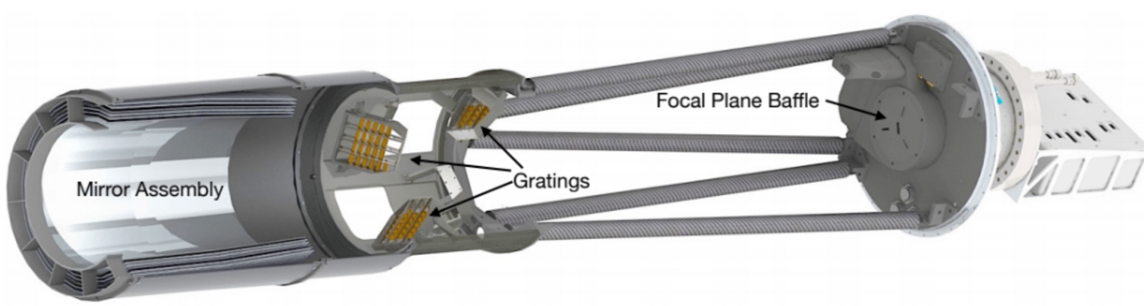

Figure 4.
REDSoX will have focusing grazing-incidence optics, critical-angle transmission (CAT) gratings, laterally-graded multi-layers mirrors, and CCDs to pioneer the new field of soft x-ray polarimetry. In order for this to be possible, the alignment and orientation of the various optical components must be assured. In particular, the large number of CAT gratings means it is critical that we are capable of aligning them.

To achieve this, REDSoX uses focusing optics that pass through CAT gratings. These gratings diffract X-rays to laterally graded multilayer mirrors, and the system is tuned such that the wavelengths dispersed by the CAT gratings onto the multilayers matches the LGMLs' own wavelength gradient.[3,6] Each LGML then reflects light onto a CCD, and polarization sensitivity is achieved due to the fact that the multilayer mirrors operate near Brewster's angle. Therefore, only light that is linearly polarized in the direction parallel to the LGML is reflected onto their CCD.

REDSoX will use three LGML-CCD pairs and operate them at 120° rotations relative to one another. This allows us to measure the three Stokes parameters needed to measure linear polarization fraction and direction all at once, which significantly loosens the rotation requirements of the instrument.

3. CRITICAL ANGLE TRANSMISSION (CAT) GRATINGS

Critical-angle transmission gratings are etched silicon wafers that use long parallel sheets of grating bars which operate at the critical angle to disperse the x-rays.[7] Due to their very large aspect ratio, it is critical to ensure the blaze angle is correct in order to maximize their diffraction efficiencies. Thankfully, our polarimetry beamline (Section 1) provides us an excellent environment to check the sensitivity of the CAT grating efficiencies as a function of their blaze angle. To this end, we've conducted numerous tests of prototype CAT gratings and measured their "blaze curves" in support of a soft x-ray polarimeter (Figure 5).

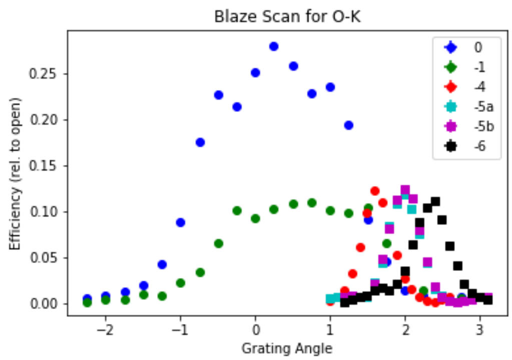

Figure 5.
A plot of the blaze scans measured for various orders at the O-Kα line energy (Garner et al., in prep). The different colors correspond to various orders. The efficiencies are high and consistent with predictions. Error bars are plotted but are smaller than the symbols. Errors were calculated assuming that photon counting statistics are shot noise dominated.

One important aspect of the REDSoX design is its use of over 100 CAT gratings (Figure 6). Since the gratings must disperse the light accurately onto a matched series of LGMLs, it is critical that the CAT gratings are aligned properly. Fortunately, the grating tolerances, highlighted in Table 1, are generally loose for the transmission gratings except for two dimensions: the grating tip and tilt. These two dimensions require that the gratings be aligned to within 6 arcmin of one another in both their tip and tilt. Given the large number of gratings used in the system, it is particularly important that we have a method of aligning (and verifying the alignment) of the CAT gratings in these dimensions.

4. GRATING ALIGNMENT

Fortunately, a method for measuring the alignment of CAT gratings relative to one another has already been developed. This method, outlined in Song et al. (2017),[8] was used to align the Arcus prototype CAT gratings within $4'$ of one another in tip and tilt (in fact, typically better than $2'$) and measure the alignment to an even higher level of precision. The alignment was measured using a "scanning laser reflection tool" (SLRT, Figure 6), which we have adapted to measure the alignment of the REDSoX prototype gratings. The REDSoX prototype gratings, which were purchased and have had their efficiencies verified in the beamline, are functionally identical to the Arcus prototype gratings for the purpose of alignment testing.

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

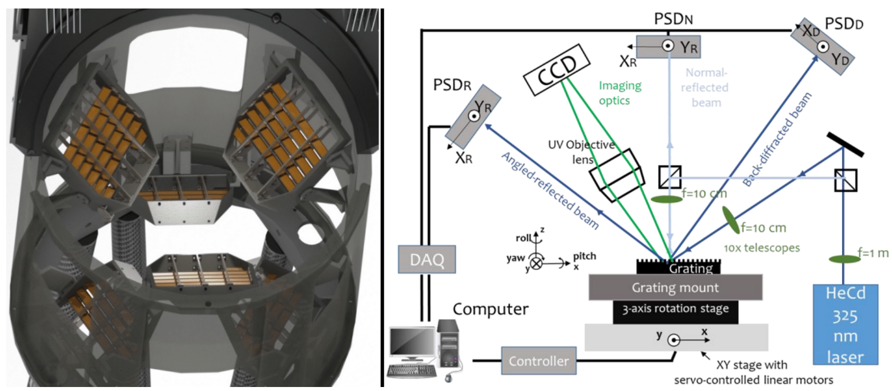

Figure 6.
A rendering of the REDSoX design (left) which shows just a portion of the many CAT gratings used in the design. The presence of so many gratings as well as their important purpose makes being able to align them well with respect to one another a top priority. Fortunately, an alignment system (right) has been developed at MIT[8] that allows the alignment of two or more gratings to be measured with respect to one another.

4.1 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 7, 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, and the grating is epoxied in place along its edges directly onto the curved surface. Internal flexures are machined into the part using wire 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 $2'$ (corresponding to a quarter turn of the screws). We've obtained a sample of five of these mounts, and have successfully epoxied test gratings onto them (Figure 8).

4.2 Alignment Test Status

As of the end of 2019, all necessary equipment to replicate the design used in Song et al. (2017)[8] had been acquired and the test setup had been mechanically assembled (Figure 9). While we originally anticipated performing the bulk of the testing in the spring and summer of 2020, unfortunately the impact of the pandemic prevented this from happening. Nonetheless, we do have progress to report.

One major step forward is we now have received five of the grating mounts mentioned in Section 4.1. Since these mounts currently serve as our working prototype for the REDSoX grating mounts, this gives us a very realistic test on our ability to align the REDSoX gratings. This is important, as the relatively large number of gratings in the REDSoX design will benefit from an "at-atmosphere" alignment tool, negating the need to use

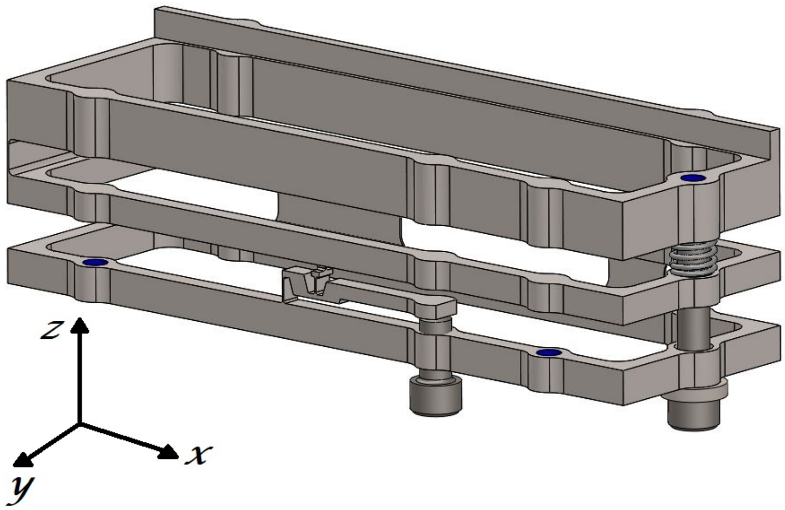

Figure 7.
The grating mount for the REDSoX prototype gratings. Made from a single piece of titanium, the flexures are built into the piece, with fine-threaded screws to adjust the tip and tilt of the grating (rotation about the x and y axes, respectively) to a resolution of better than 2 arcmin.

continuous vacuum cycles to adjust the alignment of the gratings. Instead, we can use the laser alignment tool to do the alignment, and when finished use the x-rays to verify the alignment and test the final performance.

Another area of progress is that the electronics of the test setup have been assembled and tested even during our reduced schedule. We've exercised the position-sensitive detectors (PSDs) and have verified their functionality. The PSDs are critical as they allow us to get continuous instant feedback on the alignment of the grating that we are measuring at the time. In other words, as we adjust the alignment screws in the grating mount the PSDs give us instant feedback on the alignment of the grating, which makes the process much easier.

This alignment testing is the current focus in our lab. Our most recent tests have verified the functionality of the system. We expect that in the coming months we will complete the bulk collection of data and grating alignment testing.

5. TWISTED CRYSTALS

While we have a clear path forward using laterally-graded multilayer mirrors in a soft x-ray polarimetry mission, we are – in parallel – investigating other technologies that on a longer time-horizon may one day prove even more effective.

LGMLs use a change in the spacing between adjacent layers to adjust which energy of light satisfies the Bragg condition across its surface. While they are an amazing technology, one downside is that they suffer from relatively poor reflection efficiencies for the 0.5-1 keV range due to the interfacial roughness being comparable to the X-ray wavelength. What's more, 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 package. Unfortunately, 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 direct replacements for laterally-graded multilayers.

We are investigating ways 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

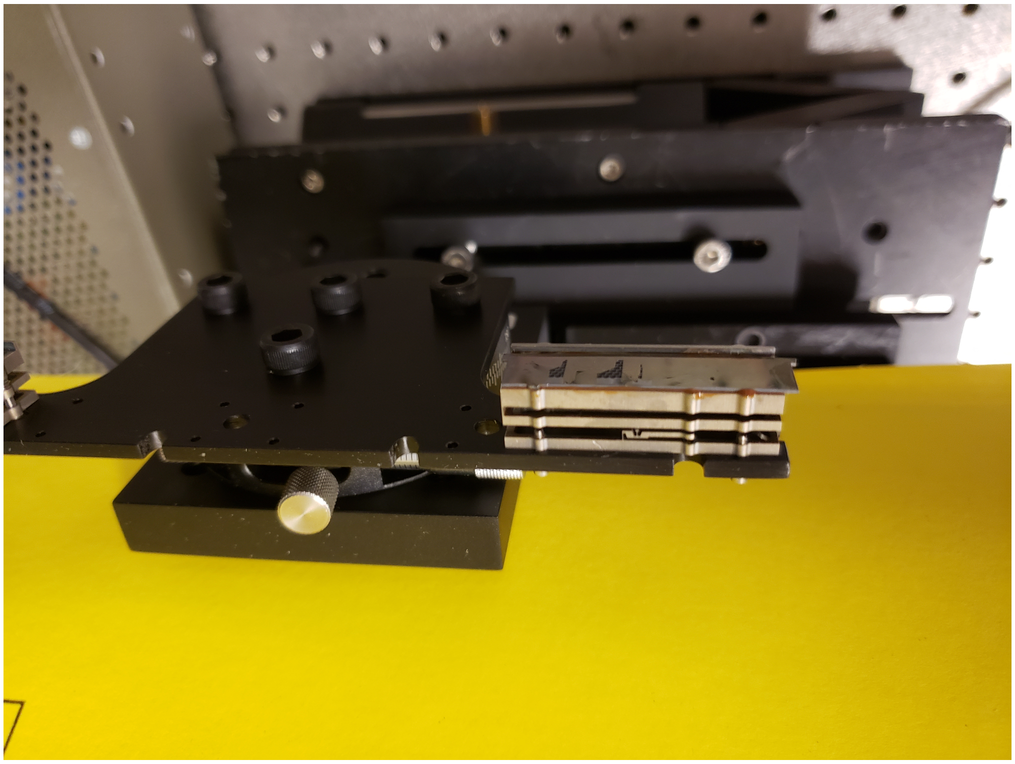

Figure 8.
A fabricated REDSoX prototype grating mount. A grating with cosmetic defects was used to test epoxies. In this picture, we've successfully epoxied the grating to the grating mount, and it is integrated into the laser reflection tool and ready for testing.

of that twist, the angle that is normal to the surface changes smoothly 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 would employ twisted crystals where the spacing between the layers stays constant while the angle of incidence changes across the crystal (Figure 10).

We have attempted to twist thin crystalline silicon wafers in the lab and while they do not break easily, they also seem to crinkle rather than twisting smoothly (Figure 11). This degree of crinkling appears to be dependent on the material of the crystal. One promising material we are pursuing is mica, which we expect to try twisting, now that we have a suitable sample. An alternative technique that we are investigating to create a twisted crystal is to start with a twisted substrate and grow the crystal on it to form a twist. If the crystal lattice grows in such a way that, locally, the planes of the lattice are at a consistent angle to the plane of the substrate, then the product will be equivalent to a twisted crystal. 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.

6. FUTURE WORK

Our facility is capable of producing polarized, 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.

Now having all materials in-hand, our immediate goal in the lab is to complete validation of the grating alignment method with the eventual goal of assembling an end-to-end prototype of our polarimeter design. To

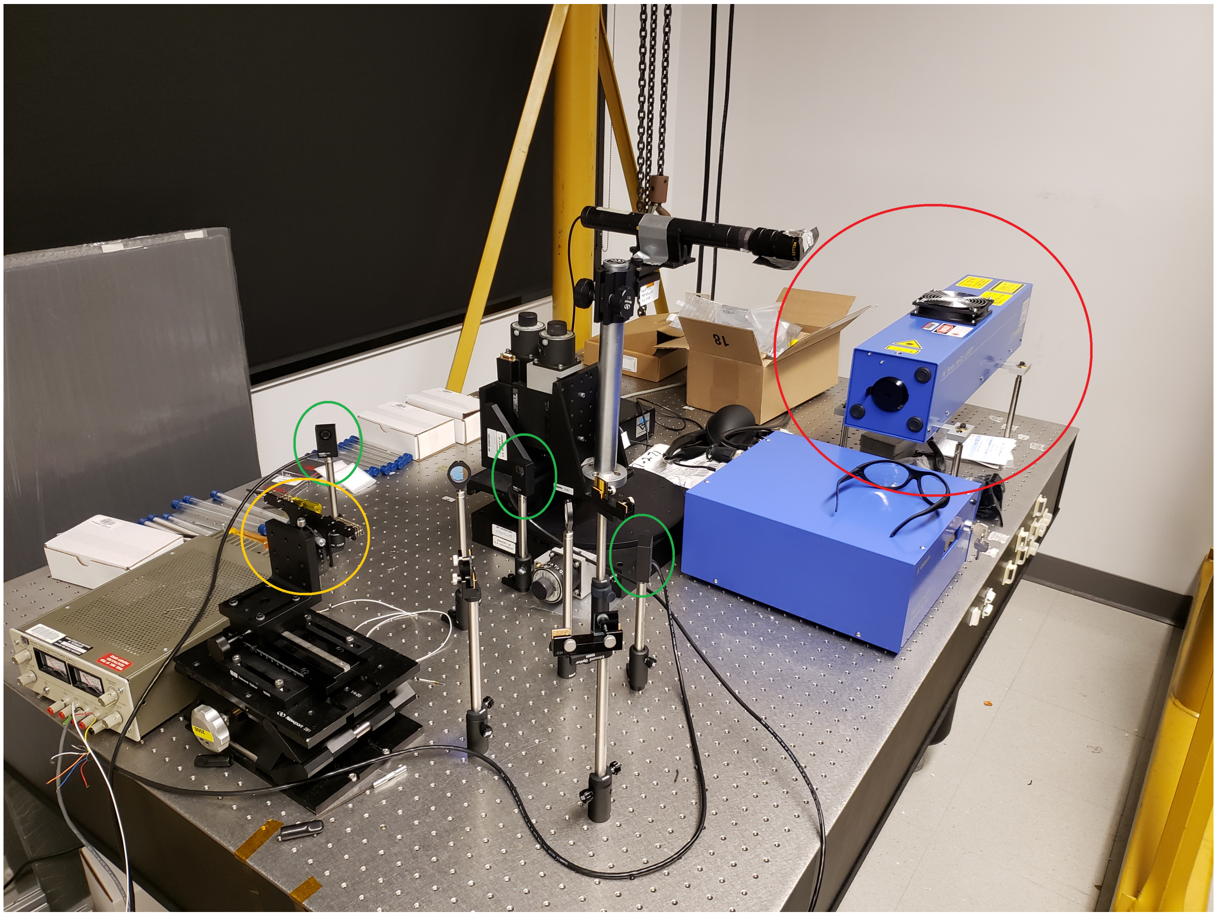

Figure 9.
Our laser alignment tool setup that we use to align the CAT gratings relative to one another. The alignment laser (circled in red) operates at 325nm. The test setup uses three position-sensitive detectors (circled in green) to characterize the orientation of the grating bars. It provides continuous feedback, which allows us to adjust the grating (circled in yellow) orientations using the capabilities built into the grating mount and get real-time feedback on its alignment status.

that end, we have acquired five of the adjustable grating mounts and appropriate prototype CAT gratings for subsystem alignment and we will be obtaining focusing optics for the prototype polarimeter.

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 in order to extend the bandpass up to 1 keV. 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 multilayer technology allows.

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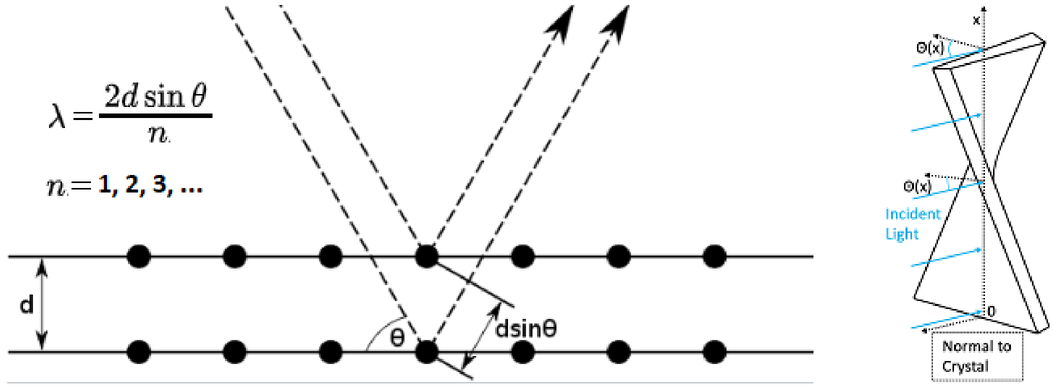

Figure 10.
Crystals have been used as Bragg reflectors for decades. By twisting them, we aim to satisfy the Bragg condition for a given wavelength by changing the angle of incidence of the light while keeping the regular lattice spacing of the crystals constant. This is in contrast to laterally-graded multilayer mirrors which satisfy the Bragg condition by changing the spacing of the layers across its surface.

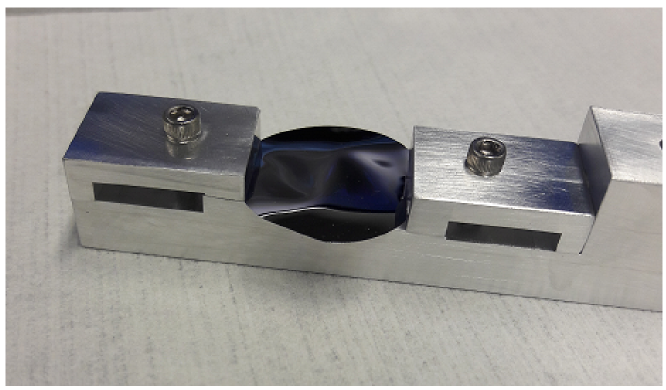

Figure 11.
Shown is an early exploratory effort to create a twisted crystal. We created a jig that pressed a thin crystalline silicon wafer onto an aluminum substrate that matched the twist profile that we desired. While the crystal did twist without breaking, it did not twist smoothly. Note the apparent 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.

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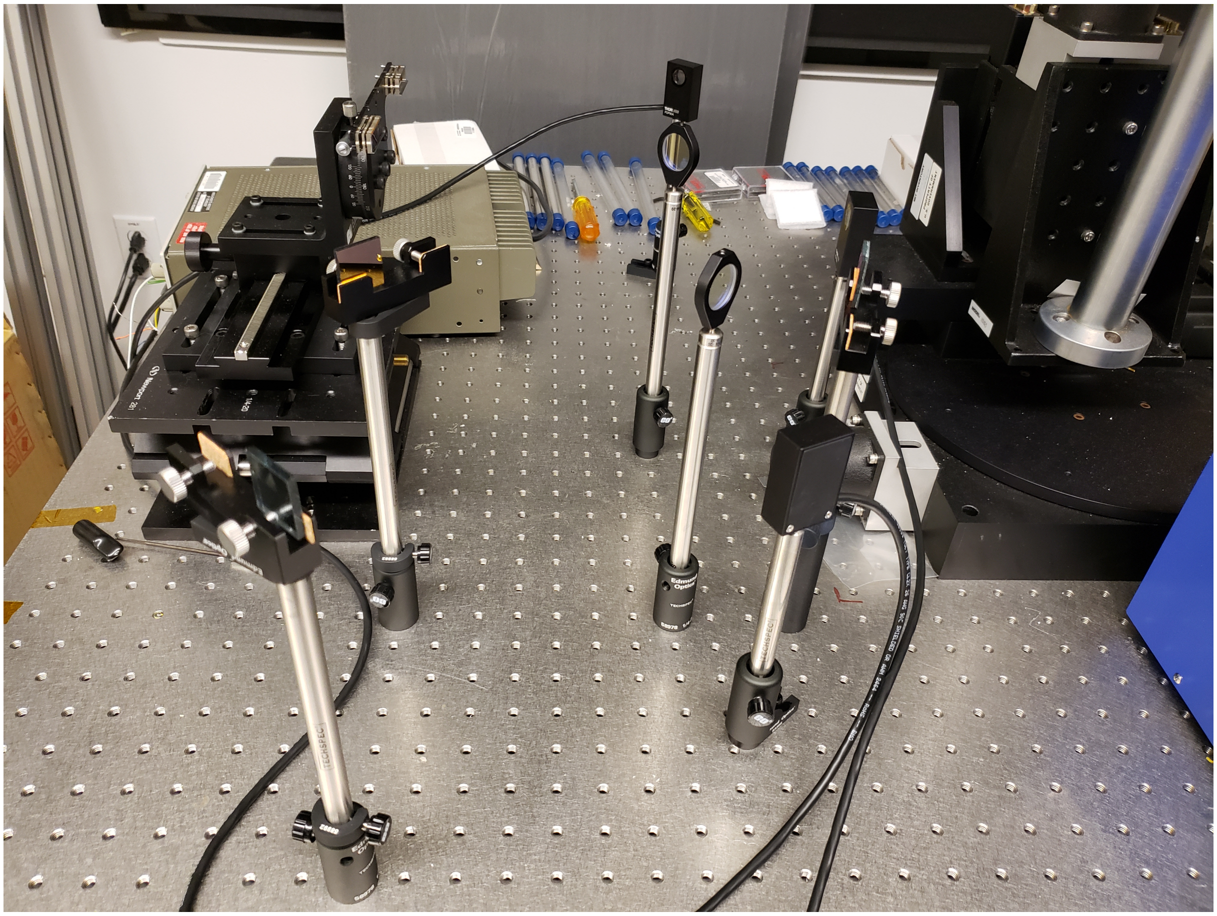

Figure 12.
Another view of our laser alignment tool setup that we use to align the CAT gratings relative to one another.

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