Mission Design and Development of the Rocket Experiment Demonstration of a Soft X-ray (REDSoX) Polarimeter

Sarah N. T. Heine[a], Herman L. Marshall[a], Alan Garner[a], Elio Angile[a], C. Marc Baker[a], Stephen Bongiorno[b], H. Moritz Günther[a], Ralf K. Heilmann[a], Beverly LaMarr[a], Sean McNeil[a], Jill Juneau[a], and Swati Ravi[a]

[a]MIT Kavli Institute, Cambridge, MA, USA
[b]NASA Marshall Space Flight Center, Huntsville, AL, USA

ABSTRACT

The REDSoX (Rocket Experiment Demonstration of a Soft X-Ray) polarimeter is a NASA-funded sounding rocket mission. The rocket payload will measure the polarization strength and direction as a function of energy in the 0.2-0.4 keV band, providing measurements complementary to those made by IXPE in the 2-8 keV band. The first flight, scheduled for 2027, will provide a technology demonstration of our polarimeter concept, which utilizes an aligned system of a focusing mirror module assembly, critical-angle transmission gratings, laterally graded multilayer mirrors, and charge-coupled device detectors to measure polarization. We will describe the current status of mission design and development.

Keywords: X-ray, astronomy, detectors, polarimetry

1. REDSOX MISSION OVERVIEW

The Rocket Experiment Demonstration of a Soft X-ray (REDSoX) polarimeter is a NASA-funded sounding rocket mission planned for launch in the summer of 2027.[1,2] REDSoX will measure the linear polarization of X-ray light between 200 and 400 eV with a minimum detectable polarization of roughly 20%. The first planned target is MK421, which is chosen in large part because of its brightness. By measuring polarization in the 200-400 eV band, REDSoX will complement similar measurements made by the Imaging X-ray Polarimetry Explorer (IXPE) in the 2-8 keV band. A key future application for this technology is the study of isolated neutron stars and their magnetized atmospheres, which mainly emit below 1 keV. This science is inaccessible from a sounding rocket mission because of the short exposure times available; however, this science would be well within reach of an orbital mission utilizing the same technology.

The REDSoX mission team completed a preliminary design review in March 2024 and is currently working to finalize designs before the critical design review, currently planned for sometime in the fall of 2025. The flight is scheduled for late 2027. Here we provide an update on the status of the REDSoX mission development.

1.1 Working Principle and Design Overview

REDSoX provides spectropolarimetry measurements across our bandpass by combining precisely aligned optical elements. Incoming light is incident on the 5 shells of replicated Ni-shell Wolter-I X-ray mirrors, which focus the light with a focal length of 2.5 meters. The critical angle transmission (CAT) gratings are arranged within the converging beam and disperse the light. Our laterally graded multilayer (LGML) mirrors have a layer spacing that is varied along the surface of the mirror such that the energy of the Bragg peak across the surface of the mirror varies linearly. We align the LGMLs with the CAT gratings such that the energy of the light dispersed by the CAT gratings matches the energy of the Bragg peak at each point along the surface of the LGML. The 45 degree Bragg reflection off of the LGML reflects light polarized along the surface of the multilayer, which is then measured by a CCD. There are three channels, with LGMLs oriented at 120 degrees to each other, which will allow us to measure both the strength and the direction of polarization. A diagram of a single channel is shown

Further author information: (Send correspondence to S.N.T.H.)
S.N.T.H..: saraht@mit.edu, Telephone: 1 617 258 8819

UV, X-Ray, and Gamma-Ray Space Instrumentation for Astronomy XXIV, edited by Oswald H. Siegmund, Keri Hoadley, Proc. of SPIE Vol. 13625, 1362510
2025 Published by SPIE · 0277-786X · doi: 10.1117/12.3064718

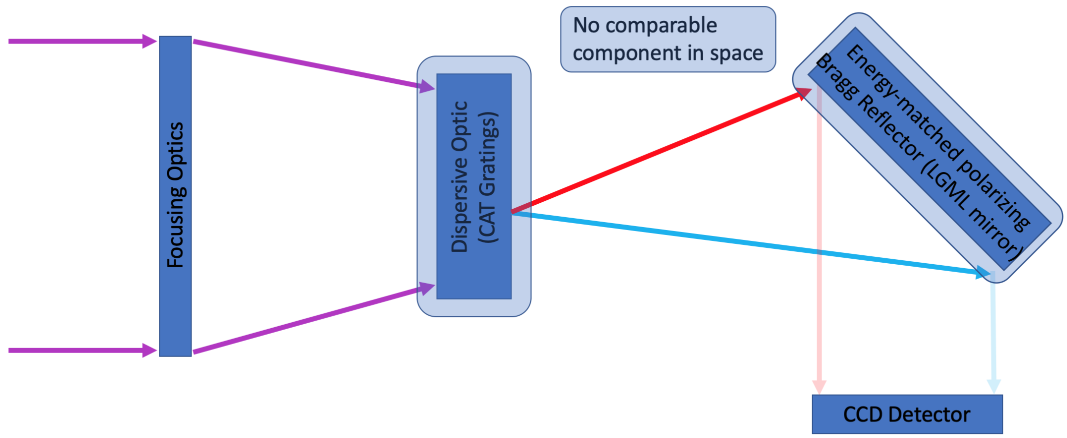

Figure 1. A diagram of the main optical elements of a single (one of three) channel of the REDSoX payload, illustrating how a spectral polarization measurement is achieved. No optical element comparable to the CAT gratings or the LGML mirrors has been flown in space, so this mission will serve to raise technology readiness levels in addition to its science and technology development goals.

in Figure 1. For REDSoX, the focusing optics will be produced by NASA Marshall Space Flight Center, the CAT gratings will be provided by Izentis LLC, and the LGMLs will be produced by Lawrence Berkeley National Laboratory. The CCD cameras will be provided by XCAM Ltd., utilizing Teledyne-e2V sensors.

CAD drawings of the rocket and the REDSoX payload are shown in Figures 2 and 3. These schematics show both a cutaway view of the payload emphasizing its structure, as well as an end view, which highlights the relative orientations of the optical elements of the payload. In both of these renderings some support and baffling elements, as well as optical blocking filters, have been suppressed to allow a clearer view of the assemblies. The star tracker, which will sit in the center of the focusing optic, has also been suppressed. The focal plane will be held at the correct distance from the optics by a structural skin, which will be nested within the outer skin of the rocket.

The central "imaging detector" is used to achieve sufficient pointing accuracy for science acquisition. We require pointing precision to within 5 arcseconds. This is achievable with the Wallops tri-level pointing system, which provides pointing to within ± 3 arcseconds at three sigma. However, data suggests that the initial pointing is far less accurate due to factors including shifting of the alignment between the optical axis of the telescope and the star tracker during launch. To correct for initial pointing errors we will spend the first 30 seconds of the flight acquiring an image of the source on the imaging detector. We will then use centroid data from this detector to guide a pointing adjustment to get the telescope within its pointing requirement for science acquisition during the remainder of the flight. We also plan for a 60° roll of the instrument halfway through the science acquisition time to allow us to remove systematic errors introduced by any efficiency differences in our channels from our final science result.

2. MIT POLARIMETRY BEAMLINE

Testing of most of the elements of REDSoX is being conducted in the MIT polarimetry beamline.[3–5] This facility has been re-purposed from its original use as a calibration facility for the Chandra HETG gratings and now serves as a testbed for REDSoX hardware and other technology development projects. A block diagram of the beamline is shown in Figure 4.

The beamline is roughly 20 meters long and has three chambers (source, grating and detector). The X-ray source is a Manson source with several interchangeable anodes to produce various line energies. The source reflects off of a W/B_4C laterally graded multilayer mirror. By selecting the anode material and the corresponding location to place the X-ray spot on the LGML (where the energy of the emission line produced by the source

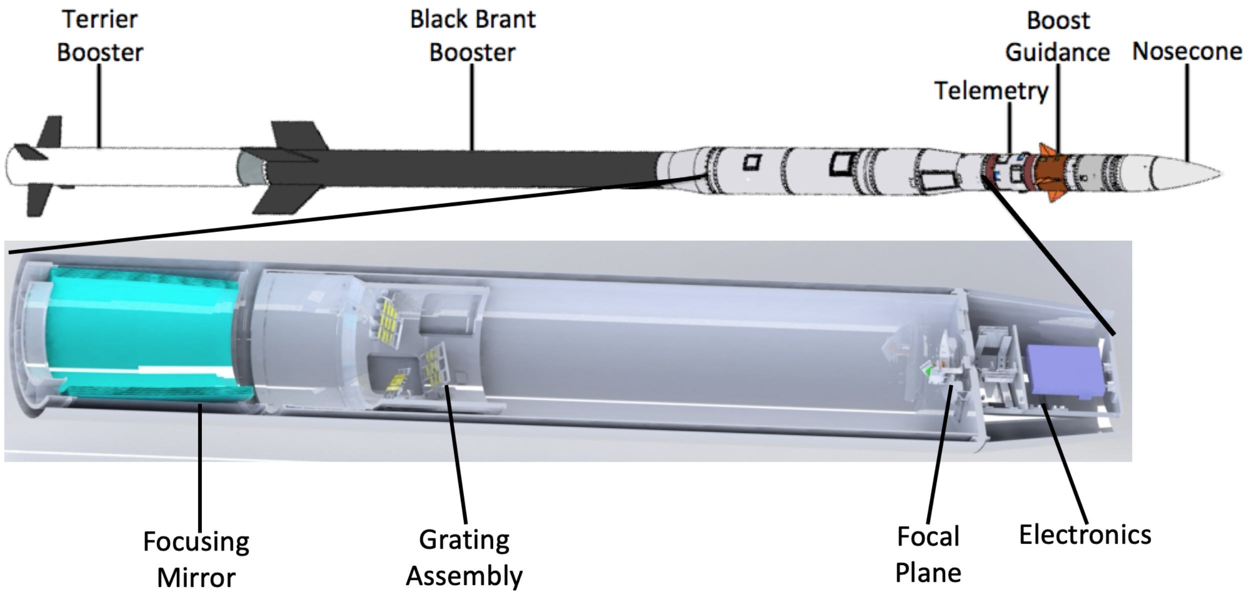

Figure 2. CAD representations of the full rocket (top) and the REDSoX payload (bottom). Major systems and components are labeled. The design is expected to be finalized by the time of the critical design review in 2025.

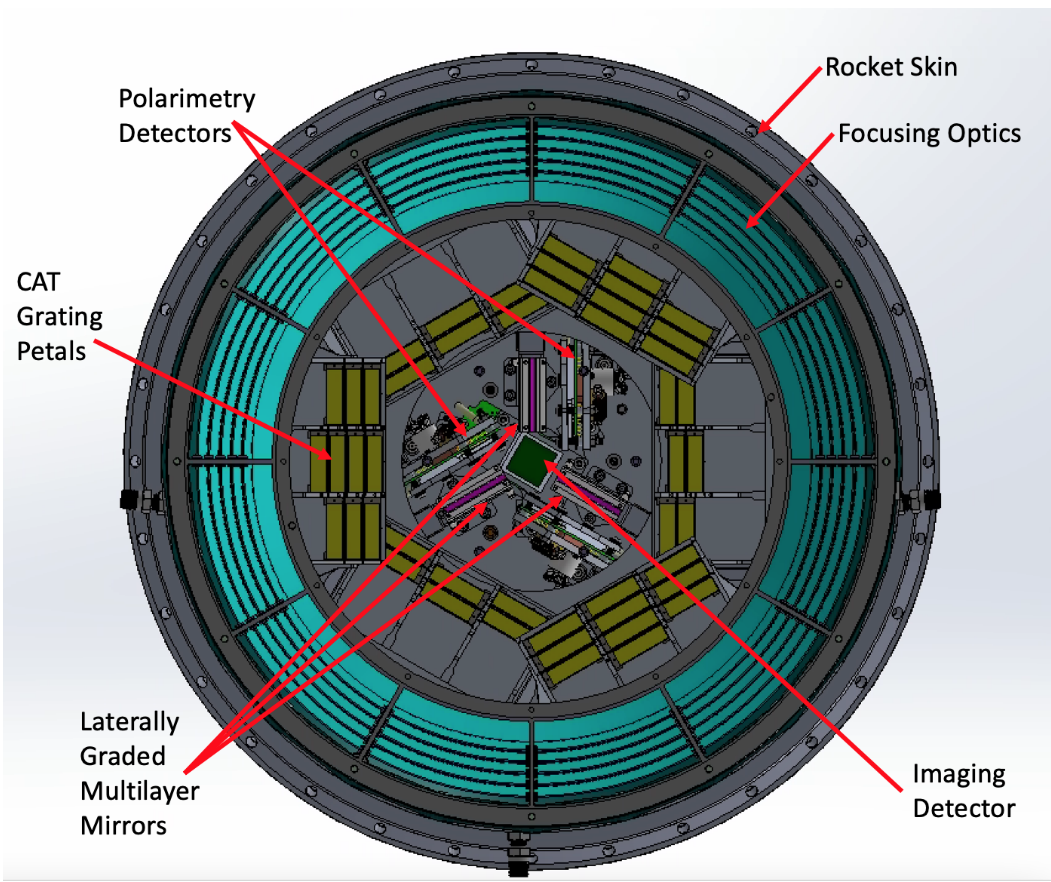

Figure 3. A CAD representation of the payload as seen from the aft end where photons enter the payload The focusing mirror is shown in blue, the gratings are shown in gold, the LGMLs are highlighted purple, and the detectors and associated boards are shown in green. Major components are labeled.

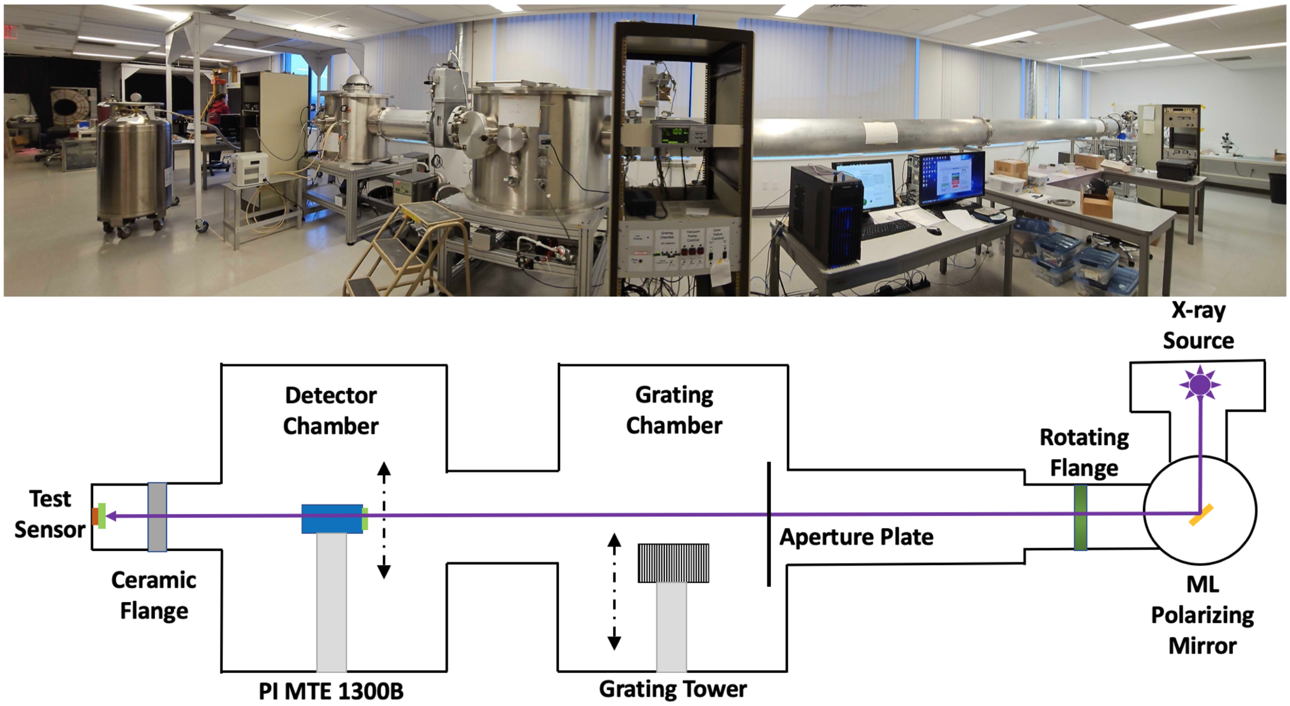

Figure 4. A panoramic image of the polarimetry beamline (upper). A block diagram of the MIT polarimetry beamline (lower). The PI MTE 1300B detector is installed on a motorized XY stage and can be inserted into the beam or moved out. It is installed with an optical blocking filter as well as a shutter, which closes during readout. There is a an electrically isolating ceramic flange on the end of the beamline, on which a flange-mounted detector or small chamber with a mounted sensor chip may be connected for testing.

matches the energy of the Bragg peak on the LGML), we reflect polarized, monochromatic light at the energy of our choice down the beamline. We are able to tune the mirror to several different emission lines between 183 eV and 700 eV without breaking vacuum. The beamline can also produce energies between emission lines of the anodes by utilizing continuum emission. This emission is not as strong as that of the emission lines, but has proven sufficient for testing given sufficient exposure time. A rotating flange between the source and the rest of the beamline allows us to rotate the source assembly via a motor to change the direction of polarization of the light traveling down the beamline while under vacuum. The grating chamber contains an aperture plate, slit plate, and grating plate, which are all mounted on motorized stages. Gratings installed on the grating plate with custom mounting handles can be inserted, manipulated, or removed from the beam using another motorized stage.

The detector chamber contains a Princeton Instruments MTE1300B CCD mounted on a motorized X-Y stage (perpendicular to the system optical axis). This allows us to move the Princeton Instruments detector in and out of the beam while under vacuum. Quick-look analysis is provided by custom Python-based code. The motors and camera are controlled by custom Labview software. There is also a flange on the end of the detector chamber allowing a test detector to be mounted in the beam path.

3. MIRROR MODULE ASSEMBLY

Details of the development of the MMA are discussed in.[6] A CAD drawing of the MMA with its major elements labeled is shown in Figure 5. The aluminum mandrels were originally produced for the Micro-X rocket payload but were never polished. The Marshall team has completed polishing of the five mandrels for the REDSoX optic to a roughness specification of 10 Angstroms. The designs for the support structures for the MMA have been completed and released for fabrication. Replication of the 1 mm thick shells will begin in the late summer of 2025 with delivery of the completed assembly expected in early 2026. Integration of the optics with the rest of the payload will be completed at MSFC in late 2026. This will also afford the team the opportunity to complete

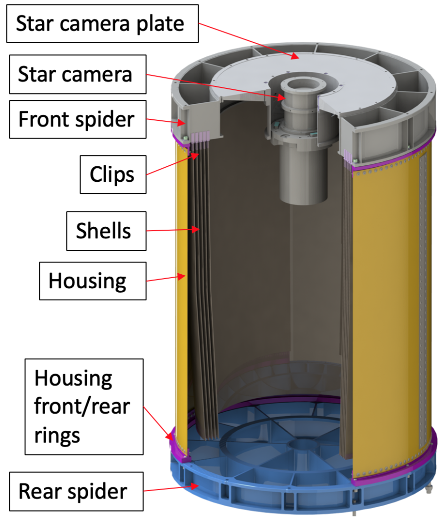

Figure 5. Labeled CAD drawing of the mirror module assembly being developed by the X-ray optics group at MSFC.

an end-to-end test of the payload utilizing the Marshall 100 meter beamline. We intend to use a single spacing multilayer tuned to 277 eV (the Carbon-K line) installed in the crystal box initially produced for testing the IXPE optics to produce a polarized source for testing REDSoX. An optical cart and access port have been manufactured and tested for previous sounding rocket missions and will be available for our use.

4. CRITICAL-ANGLE TRANSMISSION GRATINGS

The CAT gratings produced for REDSoX are 200 nm period, 4 micron deep gratings etched from silicon wafers. The grating bars are supported by an outer 1 mm thick frame, a hexagonal support structure, and linear supports within those hexagonal cells. The details of fabrication of these gratings are discussed in.[7] Each individual grating is roughly 1 cm by 3 cm and there will be 48 co-aligned gratings on the payload, as shown in Figure 3. Each grating will be epoxied on a titanium mount with two flexures, which allows for precise control of the tip and tilt of the grating. The gratings are organized into petals and placed precisely in the converging beam at locations determined by measurements of the slope of the grading of the individual multilayers. Coalignment of the gratings within the petals will be achieved via a system utilizing a UV laser bounced off of the surface of each grating and reflected into a quadcell detector to determine the angle of that surface. This system is currently under development in our lab.

We intend to evaluate the alignment of the petals to the rest of the optical elements in the payload by utilizing a portable coordinate measuring machine available at MKI, which can measure relative locations with a precision of microns.

We initially assumed that the grating bars would be aligned precisely with respect to the physical edge of the frame of each grating. In consulting with the Izentis team, we learned that the orientation of the edge is not precisely linked to the orientation of the grating bars, so our initial design plan to use an edge of the grating chip to constrain the rotation of the grating with respect to its mount is not viable. To that end we have designed a gluing mount that allows us to rigidly attach the grating mount with respect to a line underneath it A laser is mounted above the grating and shines through it, producing diffracted laser spots as the visible light diffracts off of the support structure for the grating bars. By aligning those laser spots to the line beneath the grating itself, we can assure the rotation is within the 1 degree tolerance required for REDSoX. The gluing jigs are 3D printed, allowing for quick and easy iteration of the design in addition to inexpensive large scale production of the jigs. An image of the current prototype for the gluing jig is shown in Figure 6.

The initial testing plan for REDSoX gratings involved testing a small subset of the gratings to determine if further testing was statistically necessary. Testing of initial grating samples showed variation in the efficiencies based on the details of the fabrication procedures in addition to the initial locations of each grating on the larger wafer from which they were etched, and variations that seem to be inherent to the recent history of the individual

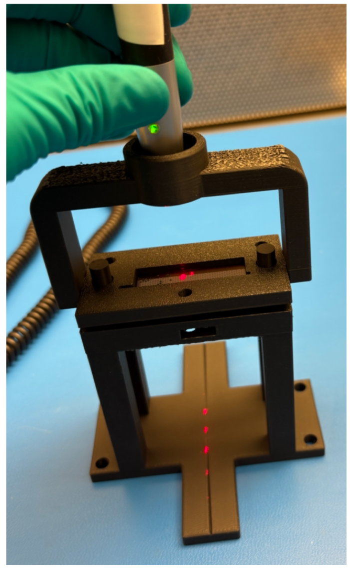

Figure 6. The 3D printed gluing jig designed to control the rotation of the grating with respect to the mount itself during gluing. A mounted grating is installed and a laser is being shined through producing diffraction spots that allow us to evaluate the rotational alignment of the grating during the gluing process.

tools used in various steps of the grating fabrication process. Realizing this, and taking into account the fact that concentrating particularly successful or particularly poor gratings in one petal could lead to biasing of the centroid on the imaging detector, we made the decision to test each and every grating. However, our initial testing procedures required roughly a week to test each grating, which is impractical on a mission requiring 48 such gratings. In order to streamline the process, we developed a testing procedure that can be completed in half a day for each grating. The gratings are only tested using C-K (277 eV) light. An initial exposure is taken with the grating out of the beam to establish the beam strength. The grating moved into the beam and a blaze scan is performed, collecting an image of the first order diffraction at each of several blaze angles of the grating with respect to the incoming light. From this test, a "best" blaze angle is determined. This test is completed in the center of the grating. We then hold the blaze angle constant while stepping horizontally across the grating to measure the first order diffraction efficiency across the surface of the grating, from which we can produce an average efficiency number for each grating. We set a rough acceptance criteria of 10% average efficiency to qualify a grating for flight. Of the 43 gratings that have been produced and delivered to the REDSoX team, 31 of them have been tested and 29 of them have met the acceptance criteria. A histogram of the measured efficiencies of these 31 gratings is shown in Figure 7. We plan to test the remaining gratings in hand during late August. We expect a final delivery of roughly 30 gratings at the end of August. The gratings in this delivery will be tested throughout the early fall in the beamline.

4.1 Grating Vibration Testing

One of our initial concerns when designing the mounts for the gratings was vibration. While the gratings had been successfully shaken to a GEVS level in the past, which was a positive sign for their ability to withstand the higher sounding rocket loads, we were concerned that resonances in the mount the grating is epoxied to could cause problems for the grating under vibration. In order to test our design we designed and fabricated a "mini-petal," which was designed to be able to install two gratings on their mounts, and was designed to mate with the LabWorks ET-140 Vibe Table, which is a small shaker maintained for use by MKI projects. With this setup we were able to shake a mounted grating on the mini-petal to full sounding rocket specifications in both random and sine sweep. A picture of the vibration setup is shown in Figure 8. While we were shaking we took video with a high-speed camera hoping to diagnose any particularly troublesome resonance frequencies. There were no frequencies in the test that we identified as a cause for concern, however we were able to diagnose a problem with a size mismatch between the grating and the mount as we observed movement in a corner of the grating that had not adhered to the mount properly. Despite this size mismatch and resulting slight movement,

Figure 7. A histogram of the measured average efficiencies 1st order diffraction efficiencies for the first 31 gratings evaluated in the beamline. Measurements are made using the C-K line at 277 eV.

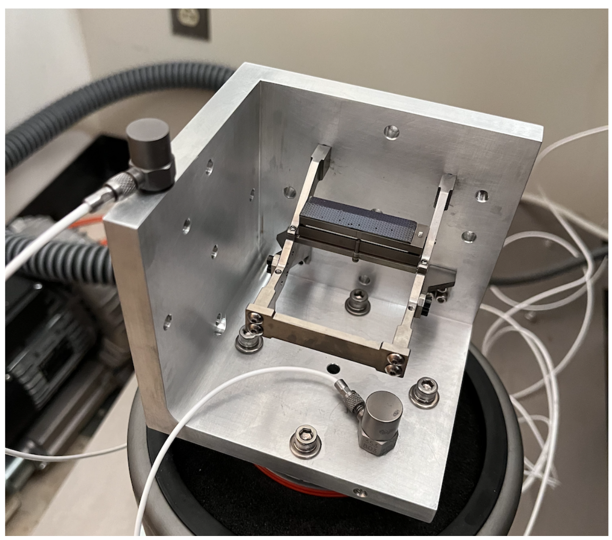

Figure 8. A single CAT grating installed on the mini petal vibration test setup on the small vibration table at MKI.

the grating performed well in the vibration test. We tested X-ray diffraction efficiency before and after the vibration test and observed no degradation in performance.

Once we have the alignment setup up and running we also plan to coalign two gratings on the mini-petal, shake it at sounding rocket loads, and check the alignment afterwards to verify that the co-aligment of the gratings is also able to survive vibration in the current design.

5. LATERALLY GRADED MULTILAYER MIRRORS

Fabrication of the flight LGMLs at LBNL is complete and they have been tested at the Advanced Light Source (ALS). The four mirrors (three flight and one spare) have been delivered to MIT along with the data from the

ALS, which will allow us to choose the precise location of the gratings with respect to each as-built multilayer in the design. To prepare for the case where we need to swap out a multilayer for a spare, we have taken care to design the grating petal mount with flexibility to change its distance from the focal plane by remachining a single part, the substitution of which will not disrupt the coalignment of the gratings on the petal. We have also designed the focal plane with the ability to move the LGMLs radially by 2-3 mm, which will allow us to adjust their positions should the distance between the 200 eV Bragg peak and the edge of the LGML prove to be different than expected.

Another concern with the multilayers is their temperature in the payload. Our current design will cool the entire focal plane, including the LGMLs, when the detectors are cooled. We calculated the coefficient of thermal expansion for the materials in the substrate and multilayer and concluded that alignment should not be a problem during cooling. Our other concern was the change in temperature causing delamination of the multilayer. To test this we placed a CrSc mirror built for lab use into a small dewar of liquid nitrogen. In order to avoid condensation when we removed it from the nitrogen, we left the dewar with the nitrogen inside the dry box and allowed the liquid nitrogen to boil off overnight. Subsequent inspection showed no detrimental effects to the tested multilayer. We are thus confident that the low temperatures will not be a problem with the multilayers.

6. DETECTORS

A great deal of progress has been made in working with our detectors. An engineering unit detector and associated readout boards was delivered by XCAM to MIT in December 2024. We designed and fabricated a test cradle for the detector allowing us to cool it with liquid nitrogen run through a cold block in contact with the back surface of the detector package. The test cradle is mounted on a vacuum flange that interfaces with the beamline. A ceramic flange isolates the detector flange from the rest of the beamline and its pumps and other instrumentation. We wrote Labview software to control a solenoid valve that turns the liquid nitrogen flow on and off based on the slope of the cooling curve of the detector. Utilizing this method we can optimize for the fastest cooling while ensuring the cooling slope will stay below 5 K/minute, the rate at which damage may occur. A picture of the EM unit detector installed on the testing flange in the process of being mated with the beamline is shown in Figure 9.

We have completed initial testing in this configuration and are in the process of writing a testing and quicklook tool to allow much faster troubleshooting while running the detector. We have also acquired our flight computer, a rugged computer from RTD Embedded Technologies Inc. that is designed to withstand sounding rocket vibration levels. One of our next tests will be to install the readout software on the flight computer and set up a communications test between the two pieces of flight hardware. We have verified the “imaging” mode of the detector meets our requirements. In this mode the detector is designed to read out more quickly and can tolerate a higher noise level than the science channels, as it will principally rely on detection of higher energy X-rays. We also were able to verify the mechanical footprint of the detectors to allow XCAM to move ahead manufacturing the flight camera units.

We are continuing to test the unit in “polarimetry mode” to achieve the required noise level for the polarimetry channels.

7. PROTOTYPE DESIGN AND FABRICATION

As our design work on the focal plane is wrapping up, we have been preparing to fabricate and test a focal plane prototype. This will allow us to test for alignment within our tolerances, assemble-ability and cooling. Working from the CAD of the REDSoX focal plane, we have designed a flange-mounted prototype of the focal plane that can be assembled on a flange similar to that used for the EM unit testing cradle. A CAD image of the prototype setup is shown in Figure 10. Parts have been ordered for this prototype and we expect to be able to begin assembly and testing in early Fall of 2025.

8. UPCOMING WORK

Much of the work described in this paper builds toward the critical design review for REDSoX, which is anticipated in the fall of 2025. As mentioned, we expect the remainder of our gratings to be delivered in the late summer and testing will run through the early fall. Detector testing is expected to continue for two or

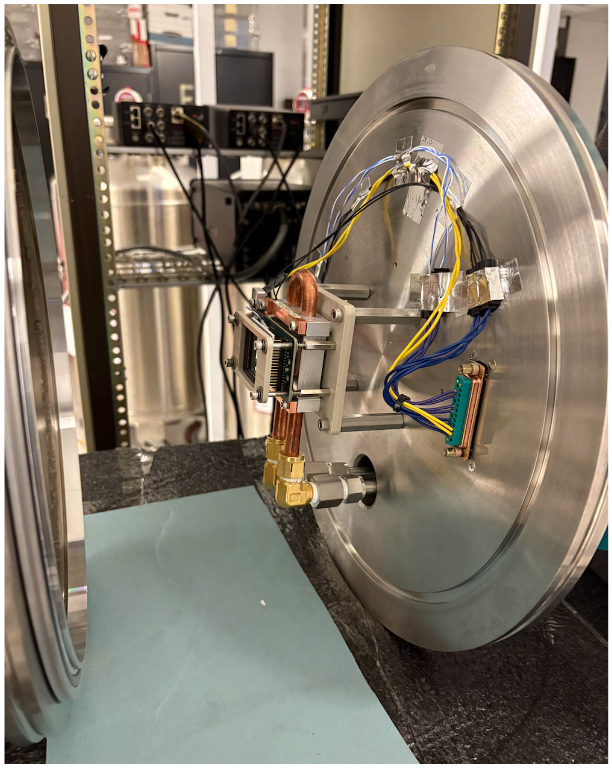

Figure 9. The engineering unit detector installed on its custom testing flange that interfaces with the beamline.

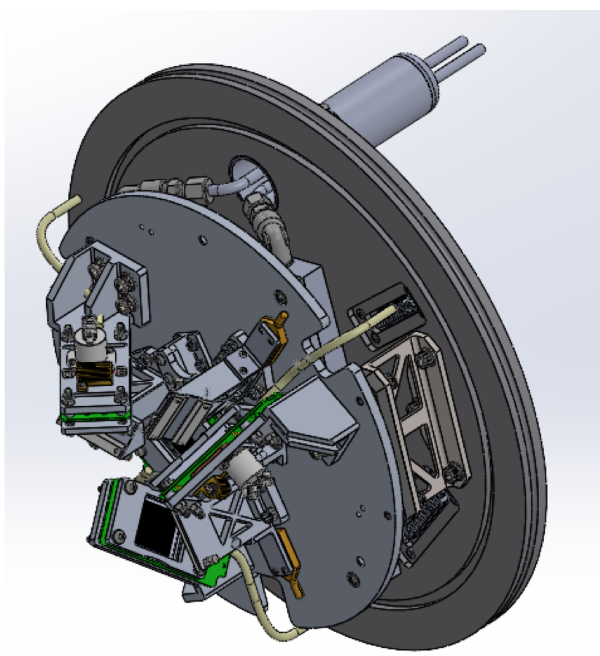

Figure 10. A CAD rendering of the focal plane prototype we will be producing. Our initial prototype will use stand-ins for all electronics and detectors and focus on testing assemble-ability and cooling. In the future we will install the flight detectors as they arrive and can be tested in the beamline.

more months, up until CDR. Cleanroom facilities are being prepared in our lab for assembly of flight parts after conclusion of CDR. Integration of the optics and end-to-end testing are expected sometime in mid-late 2026 at Marshall Space Flight Center, while integration at Wallops Flight Facility is expected to begin in early 2027 leading towards a flight in mid-2027 out of White Sands Missile Range in New Mexico. We have also submitted a Pioneer proposal for the Globe Orbiting Soft X-ray (GOSoX) Polarimeter, which is an orbital version of REDSoX. If selected, its design will draw heavily from that of REDSoX to compress our development timeline.

REFERENCES

[1] Marshall, H. L., Günther, H. M., Heilmann, R. K., Schulz, N. S., Egan, M., Hellickson, T., Heine, S. N. T., Windt, D. L., Gullikson, E. M., Ramsey, B. D., Tagliaferri, G., and Pareschi, G., "Design of a Broad-band Soft X-ray Polarimeter," *Journal of Astronomical Telescopes, Instruments, and Systems* **4**, 11004 (Mar. 2018).

[2] Garner, A., Marshall, H. L., Heine, S. N. T., Schulz, N. S., Heilmann, R. K., Gunther, H. M., Juneau, J., LaMarr, B., Metivier, A., Ravi, S., Kothnur, N. V., Bongiorno, S. D., and Gullikson, E. M., "Current status of the REDSoX sounding rocket, in prep," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **13093** (2024).

[3] Murphy, K. D., Marshall, H. L., Schulz, N. S., Jenks, K., Sommer, S. J. B., and Marshall, E. A., "Soft x-ray polarimeter laboratory tests," in [*Space Telescopes and Instrumentation 2010: Ultraviolet to Gamma Ray*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **7732**, 77322Y (July 2010).

[4] Heine, S. N. T., Marshall, H. L., Heilmann, R. K., Schulz, N. S., Beeks, K., Drake, F., Gaines, D., Levey, S., Windt, D. L., and Gullikson, E. M., "Laboratory progress in soft x-ray polarimetry," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series* **10399**, 1039916 (Aug. 2017).

[5] Garner, A., Marshall, H., Heine, S., Heilmann, R., Song, J., Schulz, N., LaMarr, B., and Egan, M., "Component testing for x-ray spectroscopy and polarimetry," in [*Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*], *SPIE Conference Series,* **11118**, 1111811–1–12 (Sept. 2019).

[6] Bongiorno, S. D., "Full-shell replicated x-ray optics modules for REDSoX and FOXSI-5," these proceedings (2025).

[7] Heilmann, R. K., Bruccoleri, A. R., Garner, A., Gullikson, E. M., Günther, H. M., Heine, S., Marshall, H. L., and Schattenburg, M. L., "Characterization of soft x-ray critical-angle transmission gratings for the REDSoX polarimetry sounding rocket," in [*Optics for EUV, X-Ray, and Gamma-Ray Astronomy XII*], **13626**, International Society for Optics and Photonics, SPIE (2025).