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FY06 LDRD Final Report "Next-generation x-ray optics: focusing hard x-rays"

Michael J. Pivovaroff, Regina Soufli (LLNL)

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Auspices Statement

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FY06 LDRD Final Report

Next-generation x-ray optics: focusing hard x-rays

LDRD Project Tracking Code: 04-ERD-032

Regina Soufli, Principal Investigator

Abstract

The original goal of our research was to open up a new class of scientific experiments by increasing the power of newly available x-ray sources by orders of magnitude. This was accomplished by developing a new generation of x-ray optics, based on hard x-ray (10–200 keV) reflective and diffractive focusing elements. The optical systems we envision begin with a core reflective optic, which has the ability to capture and concentrate x-rays across a wide range of energies and angles band, combined with diffractive optics, based on large-scale multilayer structures, that will further enhance the spatial, spectral and temporal resolving power of the system. Enabling technologies developed at LLNL such as precise mounting of thermally formed substrates, smoothing techniques and multilayer films of ultra-high reflectance and precision were crucial in the development and demonstration of our research objectives. Highlights of this phase of the project include: the design and fabrication of a concentrator optic for the Pleiades Thomson X-ray source located at LLNL, smoothing of glass substrates through application of polyimide films, and the design, fabrication and testing of novel volume multilayers structures. Part of our research into substrate smooth led to the development of a new technique (patent pending) to construct high-quality, inexpensive x-ray optics. This innovation resulted in LLNL constructing a x-ray optic for the CERN Axion Solar Telescope (CAST) and allowed LLNL to join the international experiment.

1. Introduction/Background

In recent years, a new generation of x-ray sources has become available or has been under development (Pleiades, JANUSP, NIF, LCLS), promising hard x-rays with unprecedented flux and temporal resolution and opening up new horizons for exciting science, including crucial programmatic research in high-energy, high-density physics and biological imaging. However, currently available x-ray optics are not suited to the demands placed on them by this new generation of x-ray sources. As a matter of fact, pinholes are the only readily available solution for imaging at photon energies above 10 keV. The problem with this solution is that the small aperture of the pinhole results in few photons reaching the camera. Furthermore, moving the camera closer to the exploding target corrupts the image due to the convolution of the target-pinhole image that occurs, thus diminishing the resolution. A focusing hard x-ray optic would dramatically improve diagnostic capability. It is thus proposed to demonstrate the next generation of hard x-ray diagnostics, and lead the world in this new field, by developing optical systems capable of increasing the source flux at target by at least two orders of magnitude. Furthermore, novel diffractive elements can be developed and installed in tandem with such an optic in order to further enhance its resolving power. The success of this technological achievement will allow us, for the first time, to perform scientific investigations heretofore impossible; in particular the study of the dynamics of shocked materials at the single grain level. High-resolution shock tomography and crystallography will also be enabled.

To illustrate the importance of optics, consider the laser induced, hard X-ray Kα radiation produced when a laser strikes a foil of high atomic number or a Thompson source. To achieve sufficiently high spatial resolution (≤ 10 μm) with a pinhole requires a small aperture that results in few photons reaching the camera. Although the solid angle can be increased by moving the pinhole closer the site of the X-rays, this proves infeasible for the Kα source as moving the camera closer to the exploding target corrupts the data quality due to the convolution of the target-pinhole image. In the case of a Thompson source (e.g., Pleiades) there is a minimum distance between the interaction site of the electrons and IR laser pulse where the X-rays are produced to the location where a sample can be placed. As the emerging pulse of photons is diverging, maintaining this necessary stand-off distance results in a significant loss of flux.

The usefulness and importance of the proposed hard x-ray optics extends beyond the high-energy, high-density applications discussed above. The same technology could be implemented in telescopes for hard x-ray astronomy such as NASA's *Constellation-X*, Japan's *NEXT* and the European Space Agencies' *XEUS* missions. These missions, now on the roadmaps of the respective agencies, require the development of the proposed x-ray optics technology to allow unprecedented sensitivity in studies of galaxy and black hole formation and the origins of dark matter and evolution of the early universe. Finally, these hard x-ray elements are useful in biomedical imaging applications, including small animal radionuclide imaging [2,3].

In the x-ray energy region, where the index of refraction is less than unity, the reflective ability of single-layer materials is limited by the critical angle of total reflection: Snell's law dictates that for grazing angles larger than the critical angle, reflectance falls off by several orders of magnitude. As the x-ray energy increases the critical angle decreases, thus further reducing the geometric efficiency of the reflective element. Multilayer-coated, nested-shell optics are therefore used at hard x-rays to increase the collection efficiency. In addition, by modulating the bilayer thickness across the multilayer stack ("depth-graded" multilayers), one can broaden the bandwidth and extend the operating energy of these elements beyond 100 keV.

State-of-the art advances in x-ray optical technology have been implemented at LLNL to build actual optics for applications such as hard x-ray astronomy, lithography and medical imaging.

1) X-ray substrates: A new generation of substrates, thermally formed glass, has been developed at LLNL and has now significantly advanced performance in terms of cost and surface quality compared to conventional super-polished glass [1].These optics have been used successfully in applications such as NASA's *HEFT* X-ray telescope with 72 nested shells operating at 20–70 keV, and the SARIS project for medical imaging of 27.5 keV γ-rays emitted by ^{125}I in mice [2,3]. Nevertheless, the performance of these substrates is understood to be limited by mid-spatial and figure errors, thus limiting their angular resolution to the 0.5–1 arcmin regime.

2) Substrate smoothing: It was recently demonstrated at LLNL that inexpensive diamond-turned substrates can be smoothed with polyimide and become usable as illumination elements for Extreme Ultraviolet Lithography (EUVL). It has been shown that the high spatial frequency roughness of diamond-turned metal substrates (measured in the spatial frequency range 0.02 to 5 microns by atomic force microscopy) is mitigated from 15 Å to 3 Å, by applying a polyimide treatment on the surface, thus enabling use of these elements as normal-incidence reflectors [4].

3) Multilayer coatings: Through the EUV Lithography program at LLNL, a tremendous amount of progress has been demonstrated in recent years in the areas of multilayer growth and thickness control. Among the results of this effort is establishing "clean" processes for thin film deposition, thus minimizing defects, and achieving world-record multilayer thickness control at the precision level of 0.02% rms on large-area optics through velocity modulation techniques during deposition [5,6] and world-record reflectivity [7].

LLNL has the unique advantage of the aforementioned core competencies that, as will be shown below, are immediately applicable to this new generation of hard x-ray diagnostics. At the present time, a critical juncture is occurring: demonstrating actual hard x-ray optical systems can establish LLNL as a major participant in multiple programs and promote programmatic research. In the following section, the following advances will be discussed that were achieved as part of this LDRD project: (a) a 30 keV reflective optical system capable of increasing the Pleiades (Thomson source) flux at target by at least two orders of magnitude (b) experimental results on novel diffractive elements that can be installed in tandem with an optic such as described in (a) in order to further enhance its resolving power (c) experimental results on the smoothing of thermally formed glass that could be applicable to hard x-ray optical systems for astronomical and medical applications (d) A novel x-ray optic for the 2-10 keV energy range that will be implemented in the CERN Axion Solar Telescope (CAST) project, an international collaboration aiming in the experimental search for axions as candidate particles for dark matter. The optic will increase the sensitivity to detecting high-mass axions by a factor of two. This work also demonstrates new LLNL capabilities in manufacturing high-quality, low-cost reflective optics out of novel substrates.

2. Results and technical outcome

2.1 Pleiades optic

To demonstrate the feasibility and power of this new class of optic, we designed and built a prototype collimating lens to work on Pleiades, the Thompson X-ray source operating at LLNL. After several discussions with the Pleiades research team, we decided the best use for an optic would be one that could simultaneously monochromatize the broad-band output from Pleiades and refocus the divergent beam to a small spot for pump-probe experiments. To allow direct comparison of experimental results obtained with the reflective element to those without a focusing element, we selected an operating energy of 29 keV. To understand the tremendous benefit provided by the optic, consider the diffraction simulation shown in Figure 1.

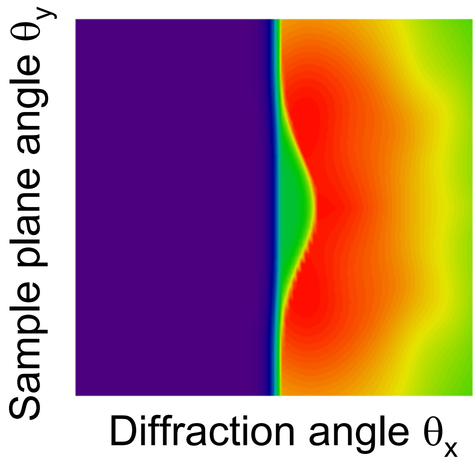

Figure 1: Theoretical calculation of Au (111) diffraction results using a Sn filter is shown, with the peak energy of the Pleiades x-ray beam tuned just below the Sn Kα edge at hν = 29.2 keV. Diffraction takes place according to the Bragg law: 2d sin(θ_x)= λ, where d=4.709 Å is the Au (111) lattice spacing, θ_x is the x-ray beam angle of incidence and λ= c/ν is its wavelength. The gaussian shape indicates lattice spacing contraction due to pump laser illumination of the Au crystal. The Sn filter cuts off the high-energy (hν > 29.2 keV) content of the Pleiades incident x-ray beam, resulting in a "clean", background free region in the left portion of the image. However, the low-energy content of the Pleiades beam remains and gets diffracted from the crystal, resulting in the diffracted background shown in the right portion of the image. By monochromatizing the beam, the reflective optic will both improve the flux at target and completely eliminate the background shown in this calculation.

After defining the experimental application, we performed a detailed study to optimize the performance. Figure 2 sketched the basic geometry and indicates the design parameters including the multilayer prescription, graze angle α, mirror length and radius R_0 and operating distance L (the distance from the location of the photon generation to the focus spot). Several competing factors had to be traded while developing the design. For example, as spot-size scales with L, shorter operating distances will lead to higher fluxes. At the same time, practical concerns like keeping the optic or sample sufficiently far from the electron-laser interaction region require larger value of L. Table 1 summarizes the properties of the optic and the design parameters. Detailed ray-trace simulations indicate the point spread function (PSF) of the optic, shown in Figure 3, would have a narrow core with a FHWM approximately 900 µm in diameter. By folding in the expected spatial distribution of the spectrum in the ray-trace simulation, our calculations reveal that the optic would increase the flux (photons per unit area) by an order of magnitude over configurations with no focusing element. This result is shown graphically in the Figure 4.

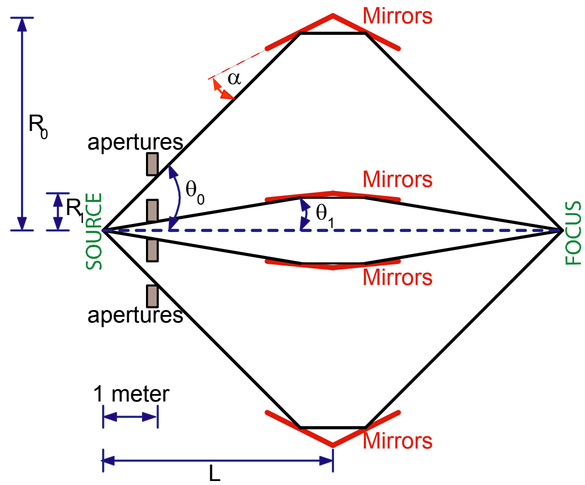

Figure 2. Schematic diagram showing a cross-section through the optic and some of the design parameters.

Table 1: Properties of the Pleiades optics

Optic Characteristics	
Number of nested shells	2
Radii, R_0	42-44 mm
Graze angles, α	0.42-0.44°
Operating distance, L	6.0 m
Spot size (FHWM)	900 µm
Flux gain	10×
Multilayer Properties	
Bilayer materials	W/Si
# of bilayers	70
Energy Properties	
Peak energy	29.2 keV
Band-width (FWHM)	1.3 keV

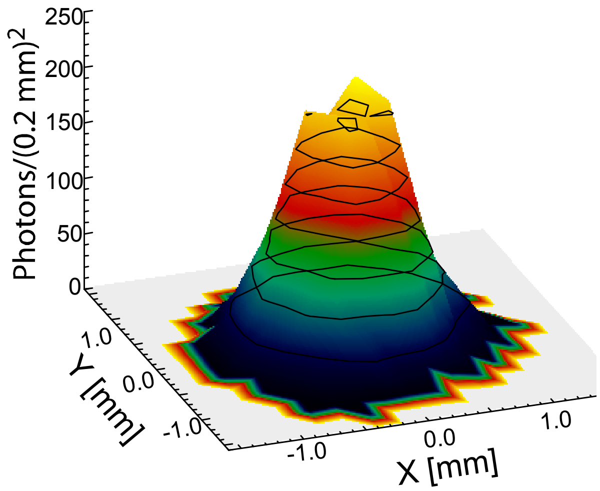

Figure 3: The simulated PSF of the focused spot.

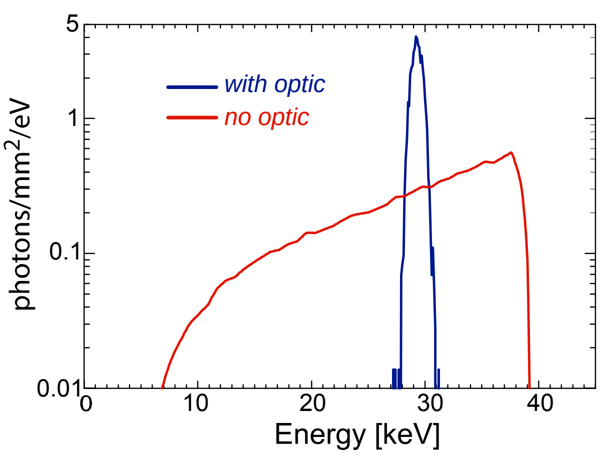

Figure 4: Spectral flux of Pleiades with and without the optic. This result is obtained via Monte Carlo simulation, which allows the spatial-spectral distribution of X-ray emitted by Pleiades (red curve) to be convolved with the reflective properties of the multilayers and the focusing properties of the optical design. The resultant gain in flux with the optic is a factor of 10.

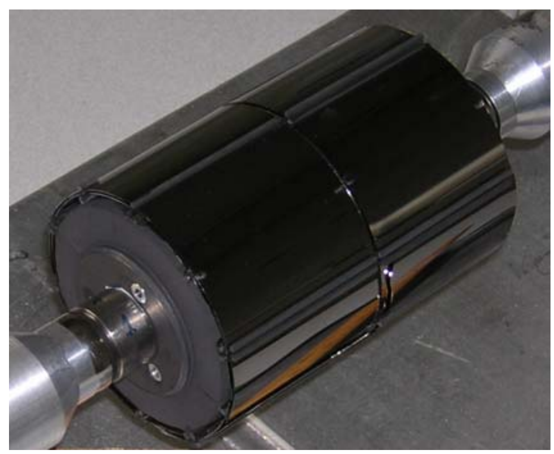

Figure 5: Photograph of the Pleiades optic in its assembly fixture. The optic operates at such low graze angles that the optic appears cylindrical, although it is actually has a triangular shape.

Figure 5 shows a photograph of the finished optic, resting in a support structure. The optic was constructed using a custom assembly machine originally designed for fabricating focusing mirrors for biomedical applications. Refer to Pivovaroff et al. for a detailed discussion of the construction methodology and the assembly machine [3]. Unfortunately, unforeseen budgetary circumstances required the Pleiades project to stop new experimental campaigns and prevented us from using the optic for the planned gold pump-probe experiments.

2.2 Multilayer-based diffractive elements

The feasibility of macro-scale (several microns thick) multilayer elements in Bragg diffraction geometry as resolution enhancing elements has also been demonstrated as part of this work. Growing multilayer structures with bilayer thickness on the order of a few nanometers, and with total thickness of several microns (or tens to hundreds of microns, for more efficient elements) is an extremely challenging task since it involves long deposition runs lasting several days or weeks, depending on the total thickness of the element. During the lengthy deposition run, it is extremely important that the bilayer thickness be maintained accurately throughout the film, and that overall roughness be controlled so that it does not become detrimental to the performance of the film. Furthermore, after deposition is completed, the film needs to be cut and polished in a variety of geometries, while maintaining the quality of the periodic structure within the film. As a demonstration of our capabilities to precisely deposit and polish these multilayer structures, we have already fabricated: (i) a 5-μm thick molybdenum/silicon multilayer, cut-and-polished into a 10-micron slice with metallography developed at LLNL, shown in Figure 6, to be used as transmission grating for studies of Ag Ka (22 keV) spectra in JanUSP experiments (ii) a 17-μm thick molybdenum/silicon multilayer, as highly efficient volume diffraction grating when operated at extreme ultraviolet wavelengths, shown in Figure 7. The results presented in Figures 6 and 7 are very promising in all aforementioned directions, and foreshadow the ability to produce Bragg diffraction multilayer elements of even greater thickness in the future, that can be used as efficient resolution (temporal, spatial, spectral) enhancing elements in a variety of high-energy applications.

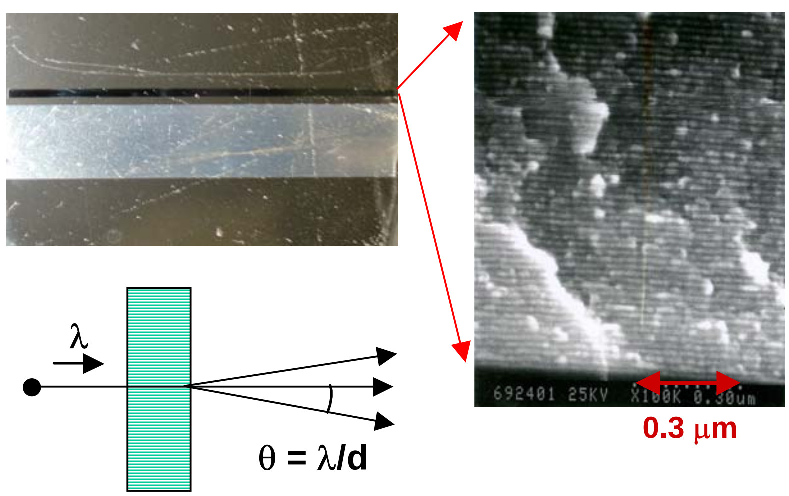

Figure 6: A 5 μm-thick Mo/Si multilayer (with bilayer period d=20 nm) was thinned and polished to a 10-μm slice. To be used as transmission grating to study Ag Kα (22 keV) spectra in JanUSP laser backlighting experiments. A cross-sectional image of the multilayer is shown on the right-hand side, obtained with a Scanning Electron Microscope (SEM).

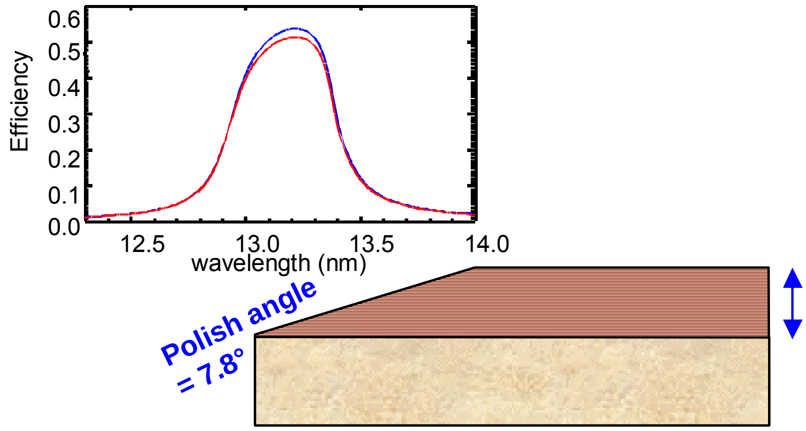

Figure 7: 17.3 mm-thick, asymmetrically cut Mo/Si multilayer (d = 7 nm) demonstrated highest efficiency (52%) ever recorded at EUV wavelengths as diffraction grating. The EUV performance was measured at beamline 6.3.2 of the Advanced Light Source (ALS) at LBNL.

2.3 Smoothing glass substrates with polyimide

Figure 8 demonstrates experimental results of polyimide smoothing (successfully implemented earlier on aluminum, diamond-turned substrates [4]) on thermally formed glass that has been developed as substrate material for hard x-ray, grazing incidence optical systems. A special facility was installed at LLNL to accommodate the cylindrical geometry of these substrates, and the smoothing process was optimized with this particular geometry in mind. The results of Figure 1 demonstrate the feasibility and compatibility of the smoothing process on glass, and could enable new generations of hard x-ray optics based on these segmented substrates. This novel technique is promising for improvement of figure (and therefore resolution) during thermal forming of glass substrates, by allowing relaxation of their high-frequency roughness requirements. It should be noted that demonstrating better than 30 arcsec angular resolution on the thermally formed substrates would represent a key milestone for the *Constellation-X* and *NuStar* missions, which require the same type of substrates for their hard x-ray telescopes. With this achievement, LLNL would be able to play a leading role in several aspects of these NASA programs.

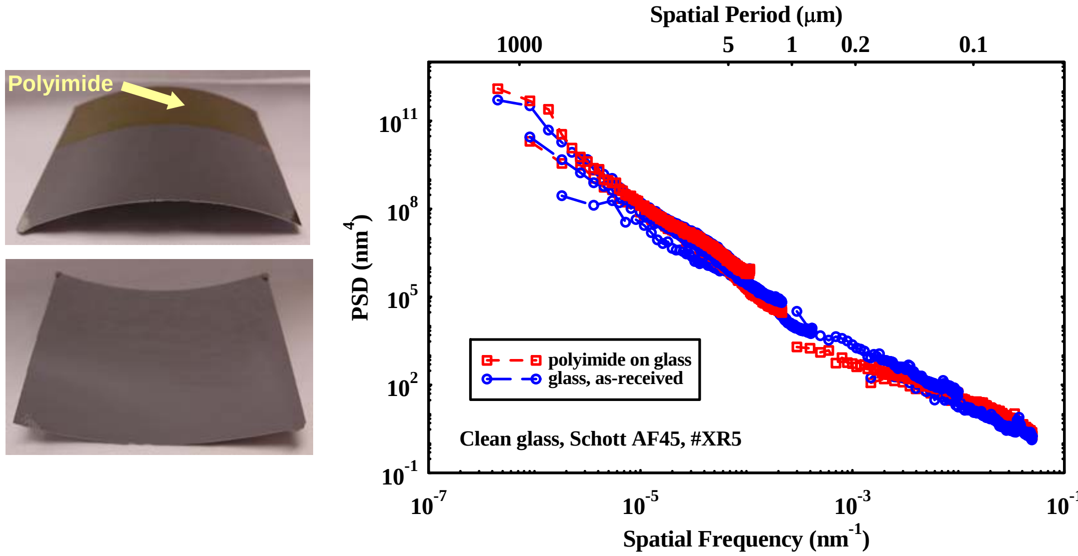

Figure 8: *Left, top*: Thermally formed glass, shown from its back side. A polyimide smoothing layer has been applied on half the area of the glass, followed by a multilayer coating on its entire area. *Left, bottom:* the front, reflective side of the glass is shown, after polyimide smoothing and multilayer-coating. *Right:* the Power Spectral Density (PSD) of the glass surface is plotted, derived from Atomic Force Microscopy (AFM) and optical profilometry measurements. The polyimide-coated side demonstrated high-spatial frequency roughness of 0.25 nm rms, and the mid-spatial frequency roughness of the glass was not degraded by the polyimide.

2.4 Plastic substrates for x-ray optics

A natural outgrowth of the smoothing effort was research into directly using a polymer as a substrate. After trying a variety of materials and techniques, our team formulated a new method based on spin-casting polycarbonate sheet into integral shells suitable for X-ray optics. This technique is described in detail in the patent application filed by LLNL in 2006 [8]. This approach has proven extremely successful, enabling exact control of the dimensions of the substrate and the production of extremely small radius integral shells, crucial for NIF imaging applications and providing even more flexibility in the design of relay optics like that constructed for Pleiades. The substrates offer additional advantages over more traditional approaches (i.e., optics made through replication from a master or ground and polished from a monolithic blank) including extremely low cost, low mass (important for space applications) and the flexibility to deposit either thick monolayers of high-Z materials or multilayers for reflective coatings. Two uncoated optics are shown in Figure 9.

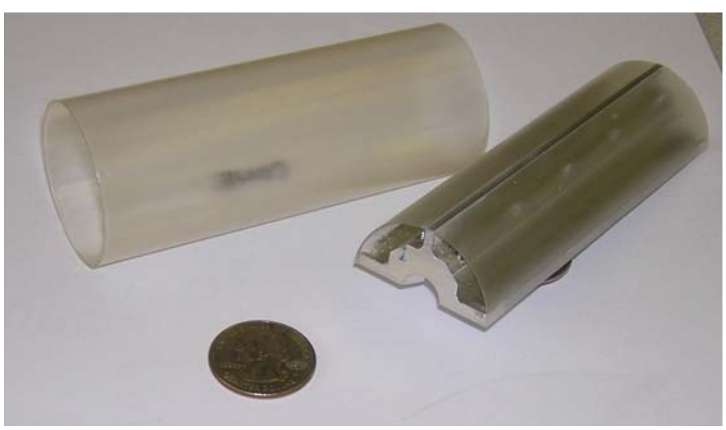

Figure 9: Polycarbonate optics constructed from 300 μm thick sheet. An integral shell is pictured to the left, a mounted half-shell to the right.

Extensive metrology of the plastic substrates revealed excellent performance of both the finish and figure of the optics. Figure 10 shows the encircled energy function (EEF) measured at 8 keV from one of the integral shells. The derived half-power diameter (HPD), a metric commonly used by the X-ray community to describe the focusing quality of an optic, is 50 arcsec, comparably to that of glass or metal foil substrates used for X-ray telescopes. Figure 11 shows the power spectral density (PSD) derived from optical profiling microscopy and AFM measurements. The computed roughness over the spatial frequency range of 10^{-3} nm^{-1} to 5×10^{-2} nm^{-1} is just 2.5 Å, approaching that commonly achieved for highly polished silicon or Zerodur.

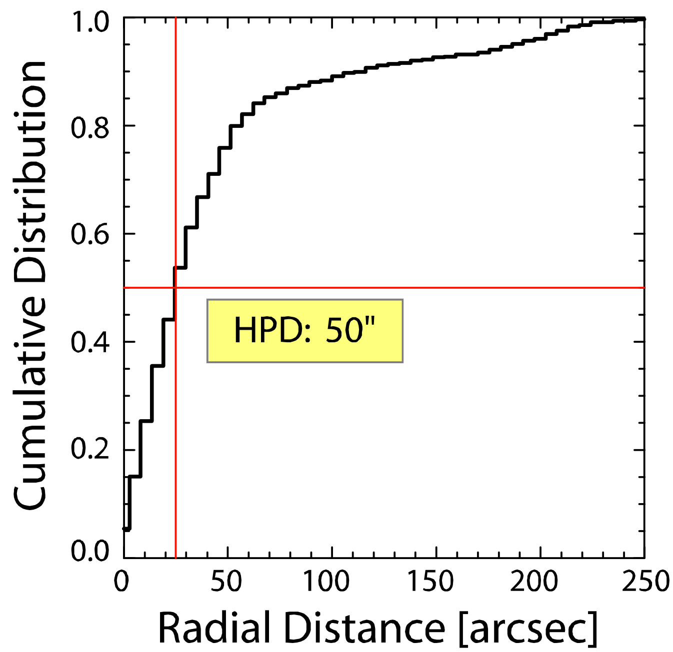

Figure 10: Encircled energy function (EEF) of a polycarbonate substrate measured at 8 keV. The distribution shows the amount of flux captured by increasingly large circles. The half power diameter (HPD), the size of a circle needed to capture half of the focused X-rays, is only 50 arcsec.

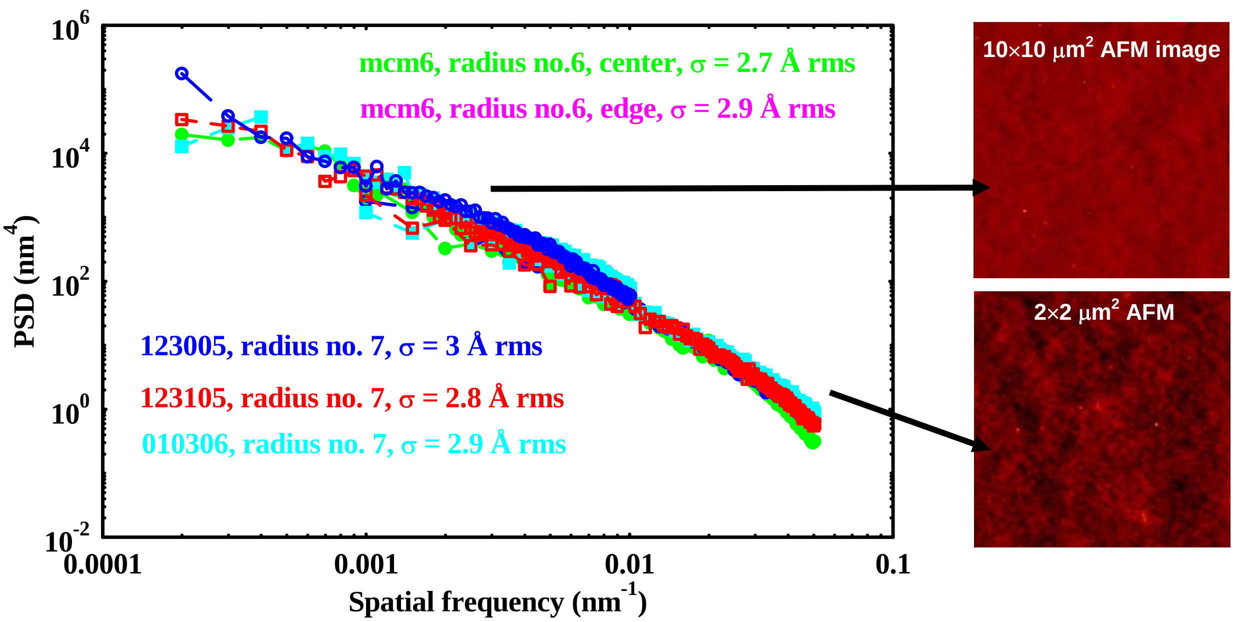

Figure 11: Power spectral density (PSD) of the polycarbonate substrate, derived from AFM and Zygo measurements. The power-law distribution is typical of high-performance X-ray optics. The AFM images shown at the right were used in the PSD analysis and reveal the high degree of homogeneity of the surface finish.

2.5 CAST: The CERN Axion Solar Telescope

2.5.1 Motivation

The breakthrough we have achieved with the fabrication of inexpensive plastic optics led to the recognition that they were perfectly suited for use in a collimator optic for the CERN Axion Solar Telescope (CAST). Before we discuss the optic we have constructed for this project, we briefly describe the scientific motivation for CAST.

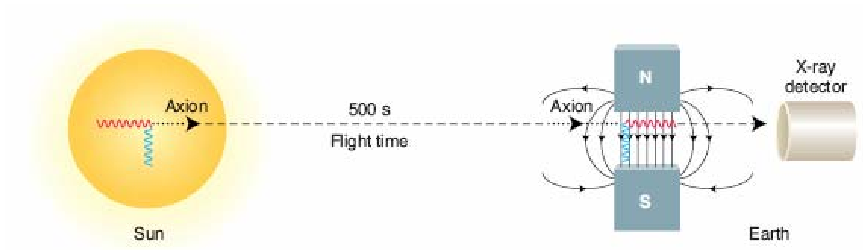

Figure 12: Schematic showing how the experiment detects an axion. First, thermal keV X-rays generated in the solar interior interact with the strong electric fields there to produce axions via the Primakoff effect. The axions stream from the sun and are reconverted to axions, again via the Primakoff effect, by interaction with a strong laboratory magnetic field. Traditional methods can then be used to detect the X-rays.

The last several years have seen an explosive resurgence in axion physics, due in large part to the solution they offer to the strong charge-parity (CP) problem*, one of the last outstanding mysteries in the Standard Model of particle physics. The interest in the field is evident by several ongoing experiments, including the CERN Axion Solar Telescope (CAST), a high-visibility experiment which has recently published its first Physics Review Letter [9]. The CAST experiment uses a decommissioned LHC magnet to search for solar axions via the Primakoff effect—an interaction between an axion and a strong magnetic field that results in an X-ray photon. The basic concept is shown in Figure 12, and actual experimental apparatus is shown in Figure 13. During the initial phase of the experiment (Phase I) from the end of 2003 to the middle of the 2005, CAST operated with the magnet bores evacuated. This provided excellent sensitivity to axion masses up to approximately $m_a \approx 10^{-2}$ eV, with the sensitivity rapidly decreasing for high axion masses. During the second phase of the experiment (Phase II) beginning in December 2005, a dispersion matching gas is pressurized in the bore to probe deeper into higher-mass phase space.

Figure 13: The CAST apparatus consists of a decommissioned LHC magnet integrated into a pointing system that moves ±8° elevation and 90° in azimuth, enabling it to track the position of the sun for 1.5 hours each day to an accuracy of 30″.

* Strong nuclear interactions appear to conserve CP symmetry, while week nuclear interactions do not. The observed behavior requires an arbitrary, fundamental parameter in Quantum Chromodynamics (QCD) to be infinitesimally small, a conundrum dubbed the "strong CP problem."

Currently, arguments from cosmology and astrophysics constrain the axion's mass from 10^{-6} to 10^{-3} eV, with another window incompletely closed around 0.1 – 3 eV. The axion is not only extremely light, it is also extraordinarily weakly coupling to matter and radiation. Very crudely the scale of axion interactions are as far below the weak interaction, as the weak interaction is itself below atomic scattering cross sections! The coherent mixing of an axion into a photon state in a strong magnetic field provides the key to all modern experiments searching for the axion, but even then the signal looked for is extremely small. In the case of the solar axion search, an axion passing through the magnet bore may convert to an x-ray of the same energy – a few keV – but the signal may be just a handful of such x-rays in a run of several weeks. The coupling of axions to photons, $g_{\alpha\gamma\gamma}$ is in general expected to be proportional to the axion's mass, m_a, as indicated schematically by the yellow band on Figure 14.

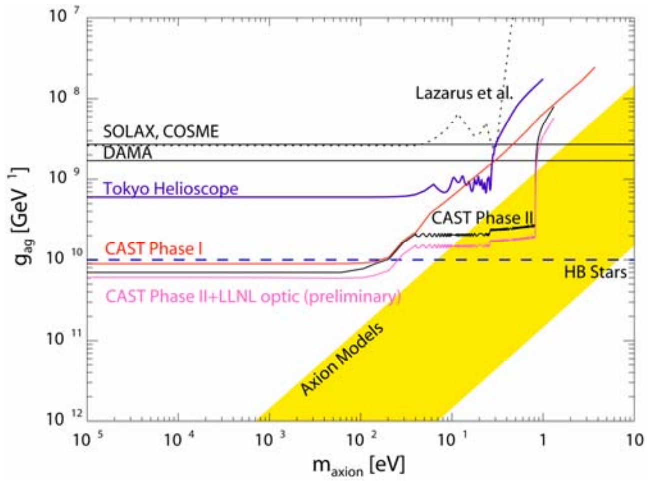

Figure 14: A phase-space diagram showing axion-photon coupling $g_{a\gamma\gamma}$ vs. axion mass m_a. The yellow band indicates the expected range of possible axion models, but in reality we do not know how strongly the axion may couple. The three generations of solar helioscope experiments are indicated: Lazarus et al. (Rochester-BNL-FNAL); Tokyo, and CAST. The dotted line indicates a limit on $g_{a\gamma\gamma}$ inferred from observations of the population of Horizontal Branch stars. It is self-evident truth that a direct observation or experiment is much more compelling than inferences based on stellar evolution; which are in any case in a not entirely satisfactory state.

2.5.2 An x-ray collimator for CAST

Based on the excellent performance of the polycarbonate substrates described above, the CAST collaboration invited LLNL to join the project as a full-member and construct a new optic for the experiment. After a detailed study, it was decided the optimum design would be that of a highly-nested concentrator consisting of 14 individual mirrors. Figure 14 shows an engineering drawing and a photograph of the optic. The basic approach was to approximate the ideal shape of a parabolic surface of revolution with a truncated cone. When placed behind the bore of the magnet, the optic will focus the x-rays to a spot 2 mm in diameter, greatly reducing size of the detector needed to sense the putative axion signal. Focusing dramatically minimizes the background and leads to a significant gain in sensitivity to the axion coupling constant, $g_{\alpha\gamma\gamma}$.

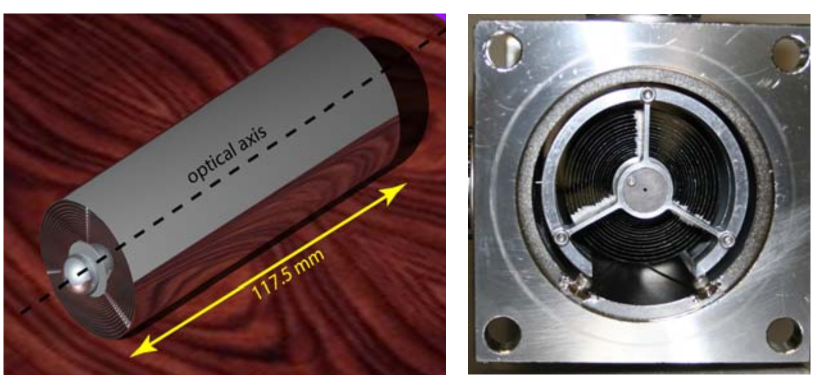

Figure 14: (Left) An engineering model of the CAST optic, consisting of 14 nested polycarbonate shells. (Right) A close-up photograph of the exit aperture of the completed optic. The symmetric three-legged structure is used to position and align individual shells to a common optical axis.

After individual shells were fabricated at LLNL, they were shipped to Germany where a vendor deposited a 350 Å thick film of iridium on the interior surface, to enhance soft X-ray reflectivity. The coated shells were then assembled into the final optic at LLNL and installed into a vacuum housing for installation into the CAST experiment.

In August 2006 we undertook a detailed calibration of the optic at the PANTER long beam x-ray calibration facility in Germany. PANTER is maintained by the Max-Planck-Institut für extraterrestrische Physik (MPE Garching) and use of the facility was arranged through fellow CAST collaboration members who are affiliated with MPE. The goal of the calibration campaign was to measure the PSF and effective area (i.e., the throughput of the optic) as a function of energy. Figure 15 shows the optic mounted in its vacuum structure (left) and installed inside the large vacuum chamber at PANTER (right).

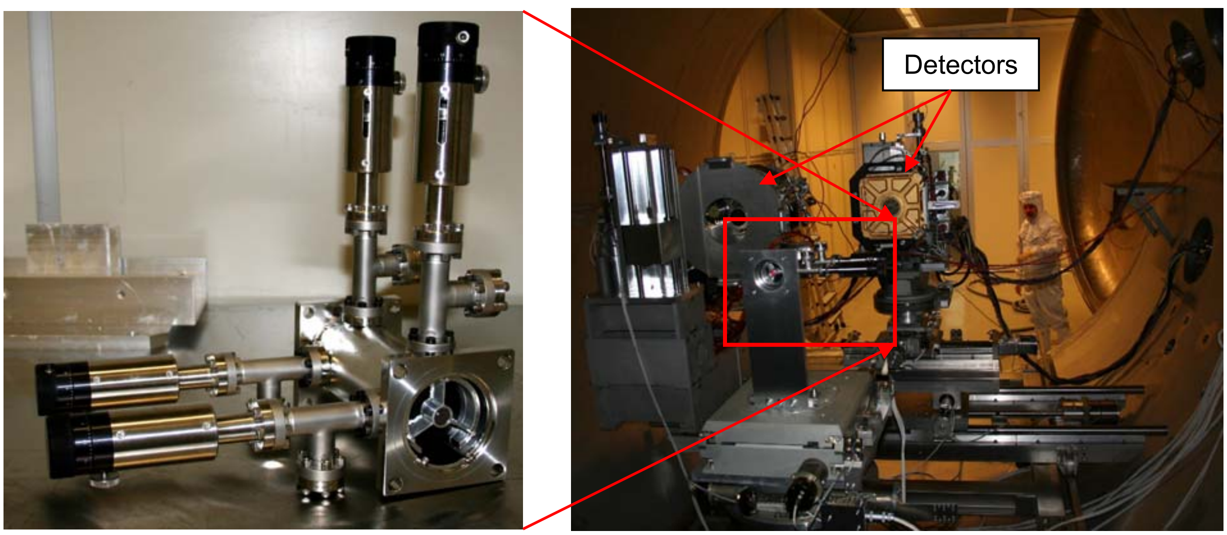

Figure 15: (Left) The cast collimator positioned inside its alignment housing. The four long extensions allow for fine pitch and yaw adjustment of the optic respect to the magnet bore, after the optic housing has been integrated into the vacuum system at CERN. (Right) A photograph of the optic inside the PANTER test chamber. The optic has been mounted on a rotation and translation stage. The optic is then moved into the X-ray axis of the facility. One of two detectors can than be translated behind the optic to determine its performance characteristics.

The at-wavelength calibration at PANTER verified the successful reflective and focusing properties of the collimator we constructed for CAST, as is shown in Figure 16. These tests were the first experimental results obtained from a complete optic, and thus served as an important demonstration for our novel substrate fabrication, coating and alignment approaches developed under this research.

Nevertheless, the testing at PANTER also revealed that the prototype x-ray optic did not meet its throughput specifications and thus precluded its installation at CAST. X-ray photoelectron analysis on pieces from the actual x-ray optic, as well as detailed simulations, indicate two types of problems: coating defects, and geometric errors: deviations in the graze angle and the length of the substrates arising during substrate manufacturing. The geometric errors led to a slightly larger core in the PSF than expected (4 mm diameter instead of the 2 mm predicted by Monte Carlo ray-tracing simulations) and a modest decrement (approximately 20–30%) in the effective area. The coating errors resulted in a high-level of scatter in the wings of the PSF and a more severe loss in effective area (approximately 50%). We now understand the origin of both types of errors and are actively pursuing funding to correct the manufacturing process of the substrates and to alleviate the issues with the coating process.

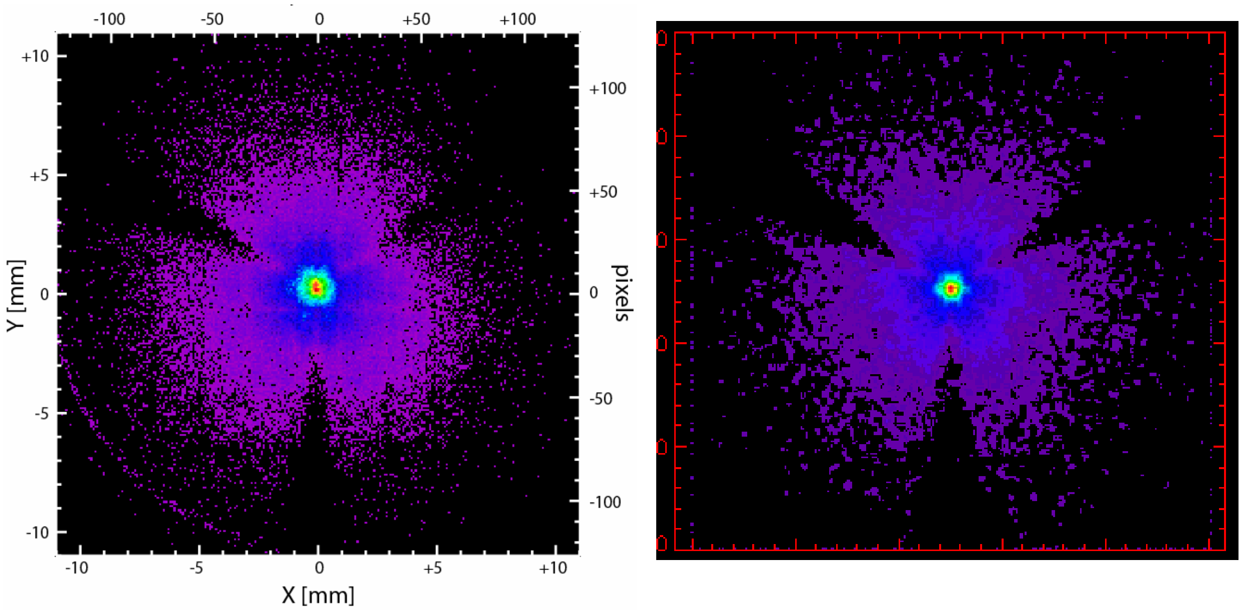

Figure 16: (Left) Measurement of the PSF of the CAST collimator made using 8.048 keV (Cu Kα) x-rays. (Right) Simulated performance of the PSF, after including geometric errors and coating imperfections. The narrow core of the PSF indicates the excellent focusing properties (i.e., good figure performance) of the plastic substrates. The extended scatter results from high-spatial frequency errors introduced by the iridium-deposition process.

3. Publications and presentations

3.1 Refereed publications and conference proceedings

1. P. Abbon, S. Andriamonje, S. Aune, D. Besin, S. Cazaux, T. Dafni, T. Decker, B. O. Dogan, N. Duportail, G. Fanourakis, E. Ferrer Ribas, J. Galan, T. Geralis, M. Gros, A. Giganon, I. Giomataris, R. Hill, I. G. Irastorza, K. Kousouris, J. Morales, T. Papaevangelou, M. Pivovaroff, M. Riallot, J. Ruz, R. Soufli, K. van Bibber, K. Zachariadou, G. Zaffanela, "Micromegas for Axion Search and Prospects", to be published in *Journal of Physics: Conference Series.*

2. Samuel Andriamonje, Stephan Aune, Berkol Dogan, George Fanourakis, Esther Ferrer Ribas, Javier Galan, Theodoros Geralis, Arnaud Giganon, Ioannis Giomataris, Igor G. Irastorza, Konstantinos Kousouris, Julio Morales, Jean Philippe Mols, Thomas Papaevangelou, Mike Pivovaroff, Marc Riallot, Jaime Ruz, Regina Soufli, Katherina Zachariadou, "A new Micromegas line for the CAST experiment", to be published in the Proceedings of the 11th Vienna Conference on Instrumentation (VCI).

3. P. Abbon, S. Andriamonje, S. Aune, D. Besin, S. Cazaux, P. Contrepois, N. Duportail, E. Ferrer Ribas, M. Gros, I. G. Irastorza, A. Giganon, I. Giomataris, M. Riallot, G. Zaffanela, G. Fanourakis, T. Geralis, K. Kousouris, K. Zachariadou, T. Dafni, T. Decker, R. Hill, M.

Pivovaroff, R. Soufli, J. Morales, "A low background Micromegas detector for the CAST experiment", *Astroparticle, Particle and Space Physics, Detectors and Medical Physics Application: Proceedings of the 9th Conference (2006).*

4. R. Soufli, S.L. Baker, S. Ratti, J. C. Robinson, S. Bajt, J. B. Alameda, E. Spiller, J. S. Taylor, E. M. Gullikson, F. J. Dollar, A. L. Aquila, R. L. Bristol, "Substrate smoothing for high-temperature condenser operation in EUVL source environments", *Proc SPIE*, **5751**, 140-145 (2005).

5. M. J. Pivovaroff, T. Funk, W. C. Barber, B. D. Ramsey, and B. H. Hasegawa, "Progress of focusing x-ray and gamma-ray optics for small animal imaging," *Proc SPIE*, **5923**, 5923B1-12 (2005).

6. R. Soufli, E. Spiller, M. A. Schmidt, J. C. Robinson , S. L. Baker , S. Ratti, M. A. Johnson , E. M. Gullikson, " Smoothing of diamond-turned substrates for extreme ultraviolet illuminators", *Opt Eng,* **43**, 3089 (2004).

7. H. C. Kang, G. B. Stephenson, C. Liu, A. Macrander, J. Maser, S. Bajt and H. Chapman, "Synchrotron X-ray studies of multilayers in Laue geometry", *Proc SPIE*, **5537**, 127 (2004).

8. D. E. Graessle, R. Soufli, A. J. Nelson, C. L. Evans, A. L. Aquila, E. M. Gullikson, R. L. Blake, A. J. Burek,"Iridium optical constants from synchrotron reflectance measurements over 0.05- to -12 keV x-ray energies", *Proc SPIE*, **5538**, 72-83 (2004).

3.2 Invited talks

1. M. J. Pivovaroff, "Multilayer X-ray optics for biomedical imaging", *8th International Conference on the Physics of X-Ray Multilayer Structures*, Sapporo, Japan, 12-16 March 2006.

2. M. J. Pivovaroff, "Progress of focusing x-ray and gamma-ray optics for small animal imaging," *Penetrating Radiation Systems and Applications VII,* San Diego, CA, 4 August 2005.

3. M. J. Pivovaroff and R. Soufli, "Multilayer Optics for Space-based Extreme Ultraviolet and Hard X-ray Telescopes," *CEA Dapnia seminar series*, Saclay, FRANCE, 24 June 2005.

4. R. Soufli, "Polymer smoothing processes for EUV and x-ray optical substrates", *2nd International Symposium on Technologies and Applications of Photoelectron Micro-Spectroscopy with Laser-Based VUV Sources*, Tsukuba, Japan, 1-3 February 2005.

3.3 Presentations

1. M. J. Pivovaroff, on behalf of the CAST collaboration, "Searching for axions with the CAST experiment," *Neutrino 2006: XXII International Conference on Neutrino Physics and Astrophysics*, Santa Fe, NM, 13-19 June 2006

2. S. Bajt, H. N. Chapman, R. Soufli, R. M. Bionta, H-C Kang, B. Stephenson, J. Maser, "Multilayers in Laue geometry", *8th International Conference on the Physics of X-Ray Multilayer Structures*, Sapporo, Japan, 12-16 March 2006.

3. R. Soufli, S. L. Baker, S. **7.** R. Soufli, S. L. Baker, S. Ratti, E. A. Spiller, J. S. Taylor, R. L. Bristol, "Optical profilometry and atomic force microscopy characterization of novel EUV and x-ray optical substrates", *SPIE 50th Annual Meeting, 2* August 2005.

3.4 Patents

1. R. M. Hill and T. A. Decker, "Thermal casting of polymers in centrifuge for producing X-ray optics," *United States Patent Application:* 20060071354, 6 April 2006.

4. Exit Plan

We have a three-pronged approach for continuing support of our research efforts. Internally, we will work with scientists within the high-energy density physics (HEDP) and NIF Programs to develop inexpensive, disposable optics for concentrating applications (e.g., an optic similar to that fabricated for Pleiades, except made from polycarbonate substrates). The high-resolution diffractive elements may also be useful to the HEDP and NIF communities. These optics also appear to be very promising for experiments planned for the Linac Coherent Light Source (LCLS), a 4^{th} generation X-ray source currently being constructed by the Department of Energy LLNL currently has an important role in the construction of the transport tunnel and development of a diagnostic suite crucial to the commissioning of the facility. Soliciting direct support from DoE Office of Science to build new instruments for LCLS represents the second part of our strategy. Finally, we will pursue funding from NASA by continuing our support and participation in on-going collaborations to build the next generation of hard X-ray observatories.

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