WHITE PAPER

Inrad optics

Quality Improvements Enable Emerging X-Ray Imaging Applications

Custom x-ray monochromator.

New things are happening at Inrad Optics in the area of x-ray imaging optics and x-ray monochromators. The fast pace of novel applications coincide with an overall improvement in the precision and quality of monochromator manufacturing, as well as, broadened applications.

Examples of recent activity include a theoretical design[1] for stigmatic x-ray imaging with magnification and the fabrication of prototype parts to verify the soundness of the concept. Also, several log-spiral monochromators were manufactured using Bragg reflection and transmission geometries. The backings for these monochromators were single-point-diamond-turned (SPDT) before attaching quartz crystals to them. Additionally, a new monochromator was produced with the crystal in the shape of an off-axis asphere with the expectation of improving spatial resolution in imaging exploding laser-fusion targets. As an example of our push for continual improvement, the absolute orientations of each element in an array of crystals were verified to be accurate to within a few arc-seconds of normal to the crystal face via direct measurements, with sub-arc-second accuracy.

All of these efforts have been directed toward producing higher quality imaging with monochromatic x-rays. Applications to-date include analytical micro-probes, spectroscopy of plasmas, back-light imaging of exploding fusion targets, and ultra-fast probing of structural changes in materials.

The basis of these monochromators is a two-element optical assembly that consists of a precisely-shaped backing and a high-quality relatively-thin crystal. The Parts List for the entire assembly consists of just two

TECHNOLOGY OVERVIEW

Features

- Interferometrically Verified Surface Profiles
- Quality Verification of Thinned Crystals
- Wide Availability of Crystals and Orientations
- Precise Crystal Orientations
- High Quality Crystal Thinning Techniques
- Assemblies Composed of Non-Outgassing Materials

Benefits

- Small X-Ray Spot Sizes
- Uniform Intensity Diffraction Profiles
- Optimization for a Specific Application
- Optimized Diffraction Efficiency
- Low Damage to Crystal Planes
- Vacuum Compatible

parts! The backing can have various shapes, depending on the application, such as spherical, cylindrical, toroidal or ellipsoidal to name a few. The thin crystal material and orientation are selected based on the 2d-spacing of the crystallographic planes. These thin crystals have the amazing property of being able to conform to the shape of the backing with high fidelity — for example, a fine scratch on the surface of the backing shows up in the reflection properties of the affixed crystal!

Construction of all Inrad Optics x-ray monochromators relies on an intimate interplay between metrology and optical manufacturing. That interplay is the basis of our reputation for delivering a product with consistent quality. The need for highly precise surface shapes arises from the short x-ray wavelength — less than one thousand times smaller than optical wavelengths. Additionally, crystals have to be of the highest perfection, and that perfection needs to be maintained throughout the manufacturing steps that end up with the crystal mimicking the shape of the backing.

APPLICATION EXAMPLES

1) Analytical Chemistry Micro-Probes

Spatially resolved chemical analysis of surfaces is made possible by imaging a small x-ray target onto an analytical sample and then analyzing either electron energies (ESCA) or x-ray fluorescence (XRF) to identify chemical elements. The result is a high-resolution spatial map of chemical impurities with <100µm resolution — and in some cases < 10µm resolution.

2) Plasma Diagnostics

Curved x-ray crystal optics are a valuable tool for measuring properties of hot plasmas in nuclear fusion research by high resolution x-ray spectroscopy[2].

Figure 1 shows spectra recorded from tokamak plasmas with an Inrad Optics spherically bent quartz crystal at the National Spherical Torus Experiment (NSTX) in Princeton, NJ and at the ALCATOR C-Mod tokamak at MIT.

3) Backlight Imaging

Target pellets from Z-pinch and laser-driven fusion experiments have been backlight-imaged using Inrad Optics monochromators. A point x-ray source, synchronized to coincide with initiation of the target burn, is used to image the dynamics of the exploding (or imploding) pellet, in a backlighter configuration. Imaging is best done with x-rays and gives information crucial to the design of both the target and excitation source. Monochromators capable of providing the highest resolution possible are of key importance.

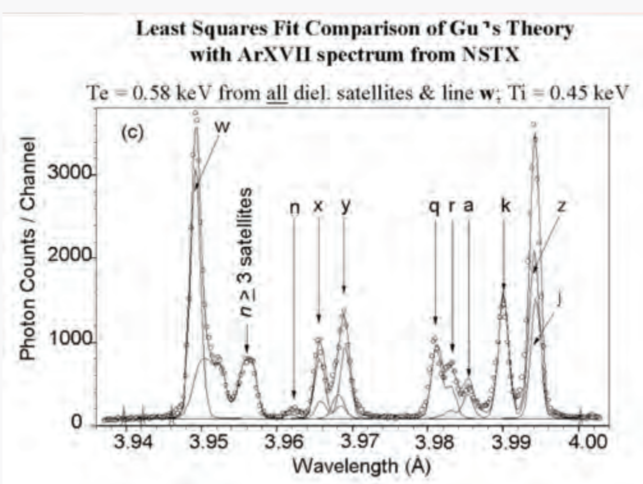


Figure 1a. Spectrum of helium-like argon from an NSTX tokamak plasma with line identification and least squares fit of theoretical predictions. The spectrum was obtained with a 100mm diameter quartz (1120) crystal with a radius of curvature of 3888 mm, manufactured at Inrad Optics, and a one-dimensional position-sensitive multi-wire detector.

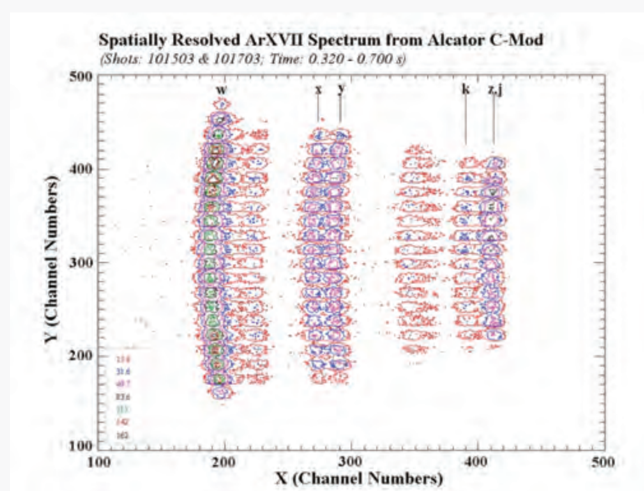
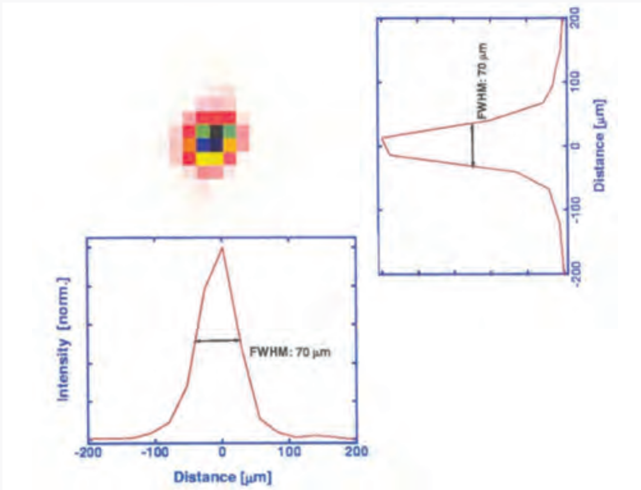


Figure 1b. Spatially resolved spectra of Helium-Like Argon from an ALCATOR C-MOD tokamak plasma. The spectra were observed with the same spherically bent Inrad Optics crystal of Figure 4a, in combination with a 2D position-sensitive multi-wire detector.



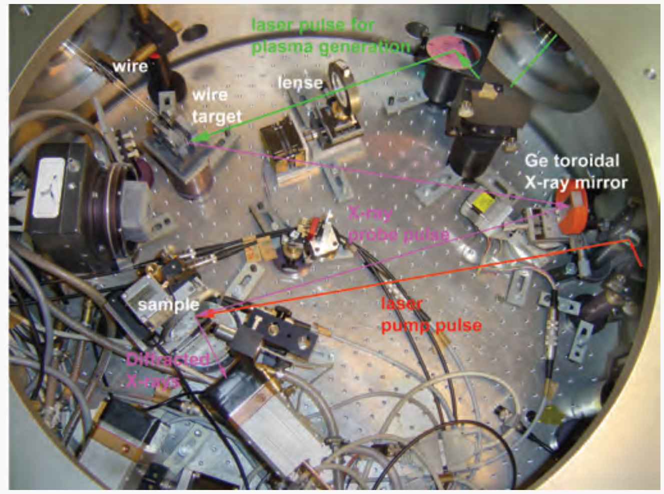


Figure 2A / 2B. Spot size of an imaged Ti Kα1 (2.749 Å) ultrafast source, and pump/probe setup.

Spot size data courtesy of Professor D. von der Linde, Institute for Laser and Plasma Physics, University of Essen, Essen, and Professor T. Elsaesser, Max-Born Institute for Non-Linear Ultra-Fast Spectroscopy, Berlin, Germany.

Picture of an optical pump / x-ray probe scheme for time-resolved x-ray diffraction experiments. Photograph is courtesy of Professor D. von der Linde of the University of Essen.

4) Ultrafast Laser Excited X-Ray Sources

An emerging application uses a focused ultrafast (< 100 fsec) laser to excite x-ray production from a metal[3]. An ellipsoidal optic can image the small x-ray spot formed at the focus of the laser onto a sample of interest. Figure 2A shows an 80µm x 60µm measurement of such an imaged spot.

A vacuum compatible experimental arrangement for generation and use of x-rays is shown in Figure 2B. In this arrangement, the laser, shown by a green arrow, is focused onto a thin titanium wire. Purple arrows trace the path of the Ti Kα1, 2.75 Å, x-rays that are captured by the x-ray toroid and re-focused onto the sample under test. Diffraction efficiency of the sample is captured by an x-ray CCD camera, and is used as a probe of the state of the test sample. An optical pump beam, indicated by the red line, is optically delayed with respect to the x-ray probe, allowing observation of structural changes to the sample on an unprecedented short time scale.

CRYSTAL AND BACKING

Crystals need to be highly perfect, which means that we typically use silicon, germanium, or quartz. By choosing crystal type, orientation, and diffraction order, often a suitable Bragg angle can be found to fit an application. The attached table is a good place to start a search for an appropriate crystal.

High-quality crystals, typically thinned to less than 100µm, are readily bent, and when affixed to a sturdy backing, accurately conform to that shape. The quality of the curved surface of the backing, as well as, the affixed crystal are determined to high accuracy by optical methods.

Large-area elements can be prepared using a mosaic of individual crystals. Since a large-area single crystal undergoes excessive deformation when bent to a tight radius, a better design replaces the single, large crystal with an array of several smaller crystals. Special processing techniques maintain the orientation of the individual crystals to high accuracy.

ORDERING INFORMATION AND SPECIFICATIONS

All toroidal and spherical x-ray crystals are manufactured at Inrad Optics according to a customer-supplied print or detailed specification. Many different sizes are possible and specifications can vary.

Please refer to our Design Guideline on our website, and consult with Inrad Optics directly for help in determining specifications.

As a crystal grower and manufacturer of fine optics, Inrad Optics has unparalleled experience in the manufacture of these high quality x-ray optical assemblies.

DESIGN GUIDELINES

We currently manufacture monochromator crystals from quartz, silicon, and germanium.

There are many possible orientations for quartz and fewer for silicon and germanium. Examples of quartz orientations are (2023), (1011), and (1010). Silicon and germanium orientations include (220), (111), and (400). A fairly complete listing of useful orientations for these three crystals is given in Table 1 along with 2d spacings.

All monochromators that we manufacture are done on a custom basis. If you can give us an orientation and dimensions for a flat crystal, we can begin the quoting process. Please, also include the quantity that you need.

Crystal surfaces either can be ground or polished, depending on your specific requirements. Our polished surfaces of quartz produce rocking curves on the order of about 10 arc-seconds for quartz and about 20 arc-seconds for either silicon or germanium when used with Cu K-alpha radiation. Some crystal orientations naturally produce wider rocking curves. Unless specified, we assume the crystals will be polished.

Here are general guidelines for choosing dimensions, based on our present capabilities: If toroidally bent, radii should be in the range of 0.2 meters to 1.0 meters. If spherically bent, then the radius can be up to 2.0 meters and longer.

Finished crystal size is dependent on 1) the availability of large, high quality raw crystals, and 2) the ability of the crystal to bend to the required radius or radii. A convenient strip for bending is 50 mm x 15 mm. Such rectangular crystal strips, which are in the ratio of 1.0:0.3, can be manufactured with a maximum size of about 100 mm x 30 mm. For ease of manufacture, the maximum circular crystal is about 50 mm. These circular crystals can be used when the backing radius is in the several meter range.

The above dimensional comments are meant as rough guidelines only. We always are pleased to consider the specifics of your application, even though they may not be an exact match to these guidelines.

Large-area elements can be assembled from single crystals if the bend radius is large, or from a mosaic of smaller crystals.

TABLE 1: SELECTED X-RAY DATA

Inter-Planar Spacing of Quartz, Silicon, and Germanium.

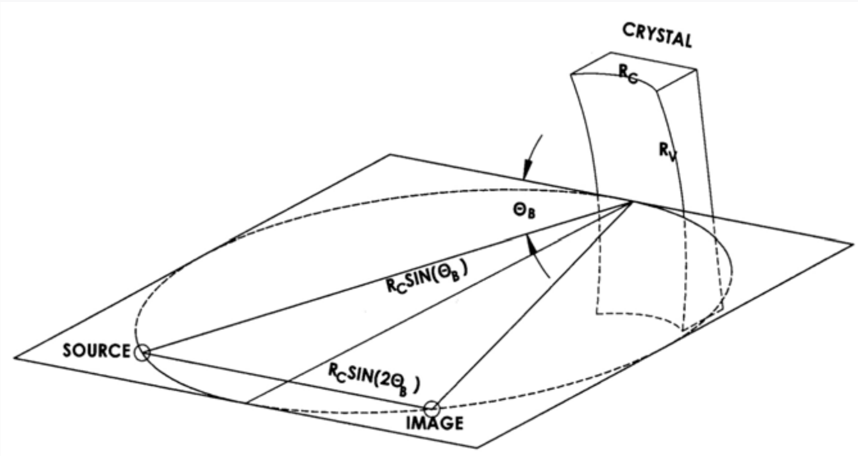
Inter-planar Spacing for High Quality Crystals		
Crystal	Miller Indices	2d (Å)
α-Quartz SiO_2	(5052)	1.624
	(2243)	2.024
	(3140)	2.3604
	(2240)	2.451
	(2023)	2.749
	(2131)	3.082
	(1122)	3.636
	(2020)	4.246
	(1012)	4.564
	(1120)	4.912
	(1011)	6.687
	(1010)	8.5096
Ge Germanium	(400)	2.828
	(220)	4.00
	(111)	6.532
Si Silicon	(220)	3.8403117
	(111)	6.2712

X-ray crystal data was extracted from Table 4-1 of the "X-Ray Data Booklet", second edition, January 2001, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720. Note, we have added the Ge(400) entry to this table.

THE ELLIPSOIDAL GEOMETRY OF X-RAY MONOCHROMATORS

A popular geometry for imaging a point source of x-rays onto another point is that of an ellipsoidal surface. Based on geometry, the ellipsoid has two foci such that light emanating from one focus is imaged onto the other focus. The concept is shown in Figure 1 where the crystal diffracts x-rays that satisfy the Bragg condition, $n \lambda = 2d \sin(\theta_B)$. In this equation, n is an integer, λ is the wavelength, d is the spacing between adjacent crystal lattice planes, and θ_B is the Bragg angle referenced to the plane of the crystal.

These x-ray monochromators often are used when large flux is required at a given point. Inrad Optics has made monochromators with active areas as large as 178 cm^2 based on an array of over 20 individual crystal elements.



Configuration showing the focusing geometry of an elliptically bent crystal. The radius of curvature in the horizontal plane is R_c and in the vertical direction the radius of curvature is R_V. The Bragg angle for the reflection, θ_B, is shown.

REFERENCES

1. M. Bitter, et al., Rev. Sci. Instrumen. 83, 10E527 (2012).
2. M. Bitter et al., Rev. Sci. Instrumen. 70, 292 (1999); ibid. 74, 1977 (2003).
3. D. von der Linde, et al.., Zeitschrift fur Physikalische Chemie 215, 12, 1527-1541 (2001)