

X-Ray Toroids

The high quality of many synthetic crystals, coupled with state-of-the-art optical manufacturing and optical test methods, has made applications involving toroidally shaped crystals practical.

Curved x-ray crystal optics have been known and used for many years for focusing and analyzing x-ray emissions¹. Current applications of technological importance include the use of curved X-ray crystal optics in analytical chemistry micro-probes, for diagnosis via monochromatic imaging of hot plasmas,²⁻⁴ and in ultra-fast probing of structural changes in materials.⁵

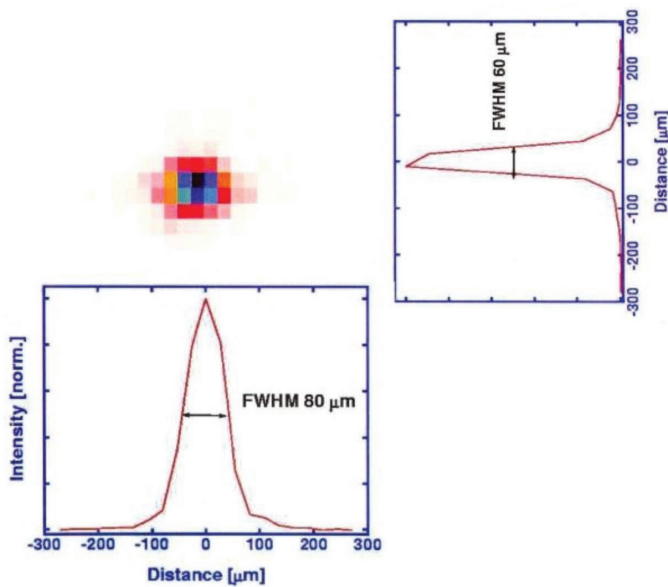


Figure 1. Spot size of an imaged Ti K α 1 (2.749 Å) ultrafast source using an Inrad Optics Ge(400) toroid.

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, Germany⁶

These crystal optics work by diffracting x-rays that satisfy the Bragg condition,

$$n \lambda = 2 d \sin (\theta_B)$$

where 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.

By curving the crystal planes in two directions, to form a toroidal surface, focusing is possible (see Figure 2).

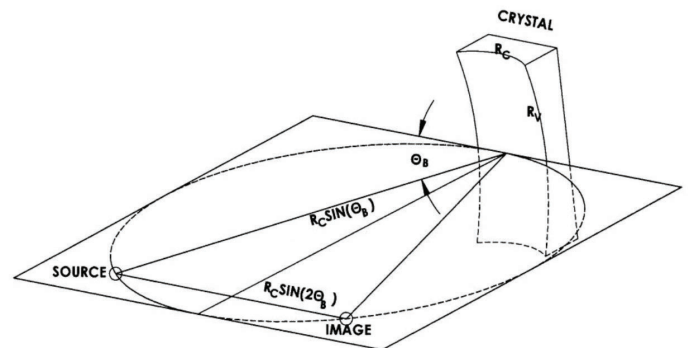


Figure 2. Configuration showing the focusing geometry of a toroidally bent crystal. The radius of curvature in the horizontal plane is R_C and in the vertical direction the radius of curvature is R_V .

APPLICATIONS

The ability to focus, or image, an x-ray source from one point to another enables several unique applications. Some of these applications are described below.

Analytical Chemistry Micro-Probes

Spatially resolved chemical analysis can be done on surfaces by imaging a small x-ray target onto the analytical sample of interest and analyzing either electron

energies (ESCA) or x-ray fluorescence (XRF) to identify the element. Because the focussed spot size can be small, < 100 μm or in some cases < 10μm, a high-resolution spatial map of chemical impurities can be made.

Over the years, Inrad Optics has manufactured hundreds of quartz toroidal x-ray optics for microprobe applications. A variety of assemblies with a mosaic crystal pattern have been made with from two to thirty-six individual crystals per assembly.

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 spectroscopy².

A calibration setup for an Inrad Optics 10 cm diameter quartz crystal is shown at the National Spherical Torus Experiment (NSTX) in Princeton, New Jersey in Figure 3.



Figure 3. In situ calibration of the X-ray imaging crystal spectrometer at the National Spherical Torus Experiment (NSTX) in Princeton, NJ with use of an X-ray tube. The 10 cm diameter spherical crystal is housed at the point shown.

Figures 4 show spectra of helium-like argon, ArXVII, from tokamak plasmas that have been imaged by a spherically bent crystal.

Data for Figure 4a were recorded from a deuterium plasma with a central electron temperature of 600 eV at NSTX. The crystal used was a spherically bent (1120) quartz crystal, manufactured by Inrad Optics; detection

FEATURES

1. Interferometrically Verified Surface Profiles
2. Quality Verification of Thinned Crystals
3. Wide Availability of Crystals and Orientations Precise
4. Crystal Orientations
5. High Quality Crystal Thinning Techniques
6. Assemblies Composed of Non-Outgassing Materials

BENEFITS

1. Small X-Ray Spot Sizes
2. Uniform Intensity Diffraction Profiles
3. Optimization for a Specific Application
4. Optimized Diffraction Efficiency
5. Low Damage to Crystal Planes
6. Vacuum Compatible

was by a conventional one- dimensional position-sensitive multi-wire proportional counter. Argon, when added to the deuterium plasma as a trace element, allows non-perturbing measurements of the central ion and electron temperatures to be made.³

Figure 4b shows spatially resolved spectra of ArXVII obtained with a new type of X-ray imaging crystal spectrometer from an ALCATOR C-Mod tokamak plasma at MIT. The spectra were recorded using the same spherically bent quartz crystal in combination with a two-dimensional multi-wire proportional counter.⁴ Such data make it possible to measure spatial profiles of ion and the electron temperatures, plasma rotation, and ionization equilibrium with a spatial resolution of less than one centimeter.

This new X-ray imaging spectrometer is likely to play a major role in diagnosis of future large tokamak and stellerator plasmas.

**Least Squares Fit Comparison of Gu 's Theory
with ArXVII spectrum from NSTX**

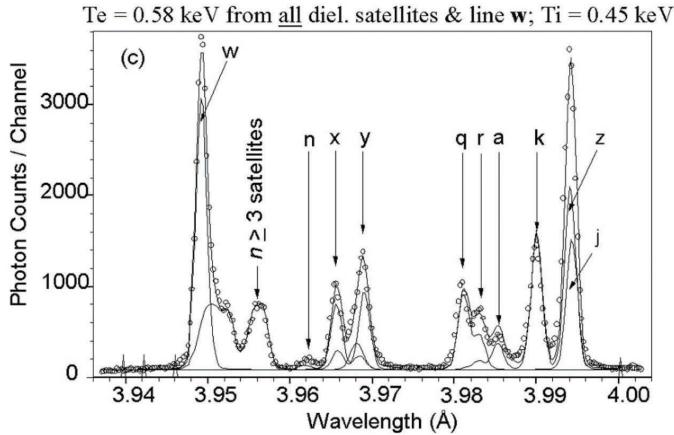


Figure 4a. Spectrum of helium-like argon from an NSTX tokamak plasma with line identification and least squares fit of theoretical predictions. The spectrum was obtained with a 100 mm diameter quartz (1120) crystal with a radius of curvature of 3888 mm, manufactured at Inrad Optics, and a one-dimensional position-sensitive multi-wire detector.

Ultrafast laser excited x-ray sources.

An emerging area of importance uses a focused ultrafast (< 100 fsec) laser to excite an x-ray source. A toroidal optic can image the small x-ray spot that is formed at the focus of the laser onto a sample of interest. Figure 1 shows the small size of the imaged spot. The experimental arrangement for generation and detection of the x-rays is shown in Figure 5.⁶ In this arrangement, the laser is focused onto a thin titanium wire, which is shown near the left side of the picture. A toroidal mirror is at the right side of the picture; a CCD camera is used to image the x-rays. The entire chamber is capable of being placed under vacuum. By translating the detector to the focus position, one obtains a measure of the spot size. By translating the detector out of the focal plane, an image of the uniformity of the x-ray reflection efficiency across the toroidal optic can be recorded.

The experimental arrangement for an optical pump / X-ray probe, using a toroidal x-ray optic, is shown in Figure 6. The green arrow shows the path of the ultrafast Ti:sapphire laser that impinges on the titanium wire to generate x-rays. Purple arrows trace the path of the Ti K α 1, 2.75 Å, x-rays that are captured by the x-ray toroid and focussed onto the sample under test. Diffraction efficiency of these x-rays, which are captured by the

Spatially Resolved ArXVII Spectrum from Alcator C-Mod
(Shots: 101503 & 101703; Time: 0.320 - 0.700 s)

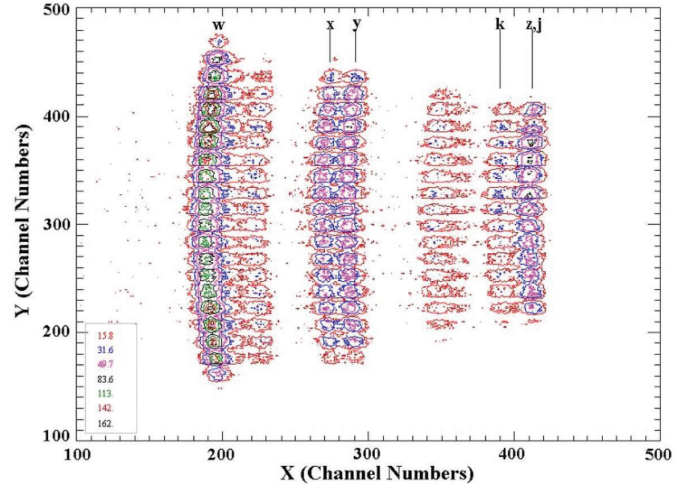


Figure 4b. Spatially resolved spectra of Helium-Like Argon from an ALCATOR C-MOD tokamak plasma. The spectra were observed with a new X-ray imaging crystal spectrometer, which used the same spherically bent crystal of Figure 3a, in combination with a 2D position-sensitive multi-wire detector.

x-ray CCD camera, 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.

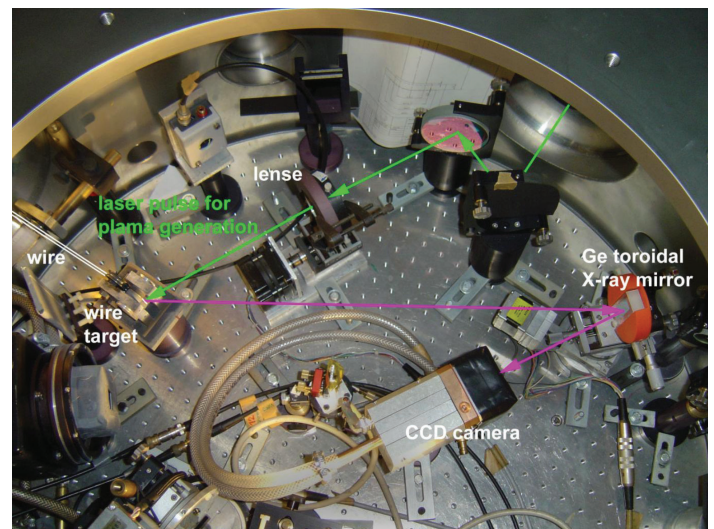


Figure 5. Basic layout for measuring the X-ray topography of the toroid, showing the wire target at the focus position of the laser, a toroidal mirror, and a ccd camera located out of the X-ray focal plane. Photograph is courtesy of Professor D. von der Linde of the University of Essen.⁶

The two images below show the reflected wavefront of the backing support and of the crystal after affixing it to the backing support. The scale at the right in Figure 7 is in waves at 633 nm. The picture at the left is an interferogram taken in reflection from the backing; the picture to the right of that is an interferogram taken in reflection from the germanium crystal after being affixed to the backing.

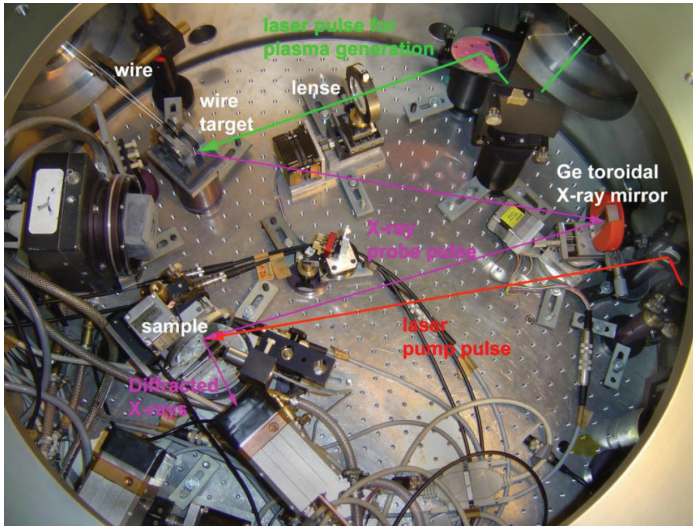


Figure 6. Picture of an optical pump / x-ray probe scheme for time-resolved x-ray diffraction experiments. Photograph is courtesy of Professor D. von der Linde of the University of Essen.⁶

CRYSTAL SELECTION

Crystals of particularly high perfection are grown from silicon, germanium, and quartz. By changing the orientation of a crystal or the diffraction order, a range of 2d spacings can be attained; often a crystal spacing can be found to fit an application.

Data for the table in the reference section 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 SiO₂(0001), Ge(400), and Ge(100) entries to this table.

High-quality crystals, typically thinned to 100 μm, are readily bent and affixed to the shape of a sturdy backing support. Both the quality of the curved surfaces of the support, as well as, the affixed crystals can be determined to high accuracy by optical methods.

Large-area elements can be prepared using a mosaic of individual crystals. A large area single crystal undergoes excessive deformation when bent to a tight radius. In this case, a better design replaces a single, large crystal

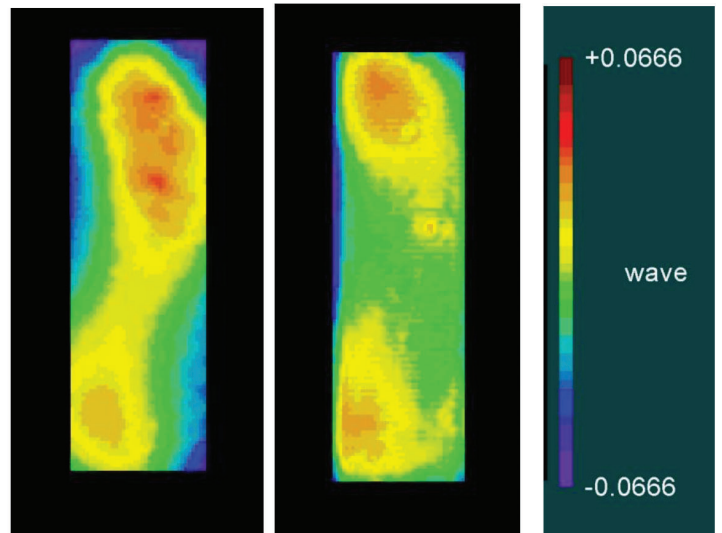


Figure 7. Deviation of optical figure from perfect focusing condition for the backing and the affixed crystal, using 633 nm light. Scale at right is in waves at 633 nm. Picture at left is interferogram taken in reflection from the backing substrate. The picture to the right of that is the germanium crystal after it was affixed to the backing. The entire 12.5 mm x 40 mm crystal face is shown here.

with an array of several smaller crystals. By using special processing techniques, one can maintain the orientation of the individual elements to high accuracy.

OPTICAL FABRICATION

When appropriately thinned, crystals can become quite flexible and readily conform to the curvature of a backing support. The focusing ability of curved surfaces can be measured through an interferometric setup whereby visible light is used. In this test setup, the toroidal optic images visible light.

The crystal conforms to the toroidal shape very well with deviations from a perfect focusing element being similar to the figure of the backing – on the order of $\lambda/10$ at 633 nm. Additional local high spots appear due to microscopic deformations that perturb the crystal surface away from the underlying surface of the backing support. These imperfections arise both during crystal fabrication and thinning, as well as, during the affixing process.

PERFORMANCE

X-ray performance of a Ge(400) toroid used to image x-rays produced at the focus of an ultrafast laser pulse is shown in Figure 8 below. The focal spot size is less than 100 microns in diameter. Note that the image really is a spot and not a line as would be produced by a crystal bent in one direction only. Uniformity of the x-ray intensity across the toroid is quite good as shown by the image on

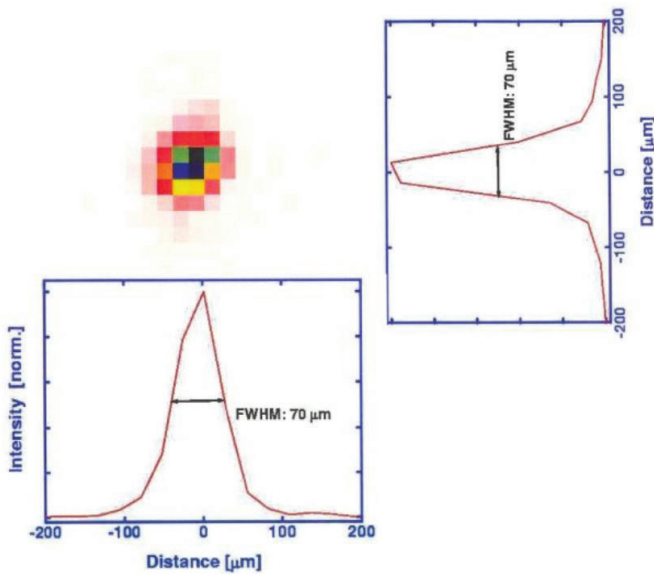


Figure 8a. Focal spot of Ti K α 1 imaged by a toroidal Ge(400) crystal.

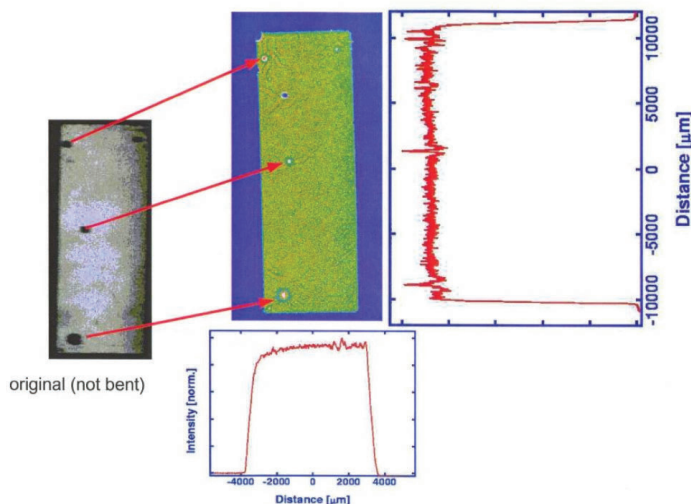


Figure 8b. Comparison of reflection topograph taken on the thin, flat crystal before affixing to the backing with the observed diffraction uniformity from a toroidally shaped Ge(400) crystal. Imperfections induced during manufacturing and affixing the crystal to the backing result in reduced efficiency.

the right that was produced by moving the ccd detector out of the image plane. Local intensity variations are due to deformations in the crystal planes induced during fabrication and assembly.

ORDERING INFORMATION AND SPECIFICATIONS

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

Manufacturing tolerance for the crystal plane orientation generally is 0.1 degrees with twenty arc-seconds being possible in some situations. The rocking curve width (FWHM) of the finished crystal, measured before bending, is less than 20 arcseconds. Tolerance for the radii of curvature of the crystal is 0.5% of the radii, and the ratio of R_v/R_c is accurate to between two and three decimal places. Reflected wavefront of the toroidal assembly is better than $\lambda/4$ per inch, measured at 633 nm.

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

An example of a custom optic is the germanium toroid referred to in this note. A picture of that specific optic is shown below.

GERMANIUM TOROID

A photograph of a germanium toroid is shown in the figure below.



Figure 9. Photograph of an Inrad Optics Germanium Toroid. Crystal cross-section is 12.5 mm x 40 mm.

SELECTED X-RAY DATA

Data for the table below 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 Ge(400) to this table.

Selected Data for 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
Ge	(1010)	8.512
	(400)	2.828
	(220)	4.00
Si	(111)	6.532
	(220)	3.8403117
	(111)	6.2712

References:

1. H. H. Johann, *Z. Phys.* 69 (1931) 185.
2. M. Bitter et al., *Rev. Sci. Instrum.* 70, 292 (1999); *ibid.* 74, 1977 (2003).
3. "New Benchmarks from Tokamak Experiments for Theoretical Calculations of the Dielectronic Satellite Spectra of Helium-like Ions," M. Bitter, M. F. Gu, L. A. Vainshtein, P. Beiersdorfer, G. Bertschinger, O. Marchuk, R. Bell, B. LeBlanc, K. W. Hill, D. Johnson, and L. Roquemore, *Phys. Rev. Lett.* 91, 265001 (2003).
4. "A New Instrument for Simultaneous Measurements of Profiles of the Toroidal and Poloidal Plasma Rotation Velocities," M. Bitter, K.W.Hill, L.Roquemore, and B.Stratton (Princeton University), S.G.Lee (Korea Basic Science Institute), and J.E.Rice (MIT), 45th Annual Meeting of the Division of Plasma Physics, Oct, 2003, Albuquerque, NM -- poster 1.007.
5. "Ultrafast Extended to X-Rays: Femtosecond Time-Resolved X-Ray Diffraction," D. von der Linde, K. Sokolowski-Tinten, Ch. Blome, C. Dietrich, A. Tarasevitch, A. Cavalleri, and J.A. Squier, *Zeitschrift fur Physikalische Chemie* 215, 12, 1527- 1541 (2001).
6. Professor D. von der Linde, Institut fur Laser-und PlasmaPhysik, University of Essen, Essen, and Professor T. Elsaesser, Max-Born Institut fur Nichtlineare Optik und Kurzzeitspektroskopie, Berlin, Germany.