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AN ENERGY DISPERSIVE BENT LAUE MONOCHROMATOR FOR K-EDGE SUBTRACTION IMAGING

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INTRODUCTION

K-Edge Subtraction (KES) is a powerful synchrotron imaging method that allows the quantifiable determination of a contrast element (i.e. iodine) and matrix material (usually represented as water) in both projection imaging and computed tomography[1-5]. With living systems, a bent Laue monochromator is typically employed to prepare imaging beams above and below the contrast element K-edge which focus at the subject location and subsequently diverge onto a detector[6]. Conventional KES prepares the two beams by utilizing a splitter that blocks approximately 1/3 of the vertical beam size to prevent “edge crossing” energies beyond the monochromator[7]. The two beams then are identified as one being above the K-edge and the other as below the K-edge. Though this monochromator behaves as an angular energy dispersive optic, the energy resolution, i.e. the ability to angularly disperse energies, is quite poor and leads to the need to block 1/3 of the vertical beamsize.

For research on the biomedical beamlines [8, 9] at the Canadian Light Source we required a small focus of the bent Laue monochromator beam for high resolution imaging of small animals, specifically the vasculature using iodated contrast agents. A small focus is possible when the diffraction conditions are properly chosen [10, 11]. To better understand the conditions that lead to a small focal size, some background information about Laue type diffraction is needed.

BENT LAUE DIFFRACTION

The Laue case of diffraction refers to a crystal geometry in which the X-ray beam is diffracted through the crystal in transmission. The angle between either the incident or diffracted beam and the lattice planes is called the Bragg angle or θ. The geometric plane containing the incident and diffracted beams is called the diffraction plane with the angle between the beams is 2θ. If the crystal is a parallel sided plate and the lattice planes used for diffraction are perpendicular to the plate, this is referred to as the symmetric case of diffraction, or symmetric Laue case. An inclination of the lattice planes by an angle, χ, is referred to as the asymmetric case or asymmetric Laue case. In order to have good diffraction efficiency or bandwidth the asymmetric Laue case is often used. One aspect of the Laue case is that a single ray incident on a crystal will produce a fan beam on the exit surface – the Borrmann fan[12]. When a Laue type crystal is bent around an axis perpendicular to the diffraction plane, parallel X-rays incident on the convex side of the crystal will be focused on the downstream or concave side of the crystal. This effect is similar to that produced by a lens or mirror but with a modified focal equation given by,

$$\frac{\cos(\chi \mp \theta)}{f_2} - \frac{\cos(\chi \pm \theta)}{f_1} = \frac{2}{\rho}, \tag{1}$$

where χ and θ are as defined earlier, f_1 and f_2 are the distances from the crystal to the source and focus, respectively, and ρ is the bending radius. The signs are set by the location of the lattice or Bragg planes in relation to the source and focus locations. If the Bragg planes are between the source and focus the upper sign is used, otherwise, the lower sign is used. Equation 1 describes what we call the geometric focus.

A single polychromatic ray incident upon a bent asymmetric Laue crystal results in a fan of X-rays on the exit surface as described earlier. These rays will then form a real or virtual focus called the single-ray or polychromatic focus given by,

$$L = \frac{\rho \sin 2\theta}{-2\sin(\theta-\chi)+(1+\nu)\sin 2\chi \cos(\theta-\chi)} \qquad (2)$$

where ν is the Poisson ratio for the crystal and orientation and all other variables are as defined earlier.

To achieve a small focus at the geometric focus we then require that the two foci, the geometric, f_2, and polychromatic, L, match. This leads to a transcendental equation that is easily numerically solved. Figure 1b shows schematically the effect of matching these two foci as well as the unmatched conditions.

planes made a 3.33^o asymmetry angle with respect to the wafer surface was chosen. This closely matches the geometric and polychromatic foci at 33.17keV which is the iodine K-edge energy. The crystal thickness was 0.6mm and was bent to a radius, ρ, of approximately 3.13m with f_1 = 20.5m and f_2 = 1.61m. At this energy for the (3,1,1) type reflection the Bragg angle, θ=6.55^o. The bending was accomplished with an adjustable four bar bender.

<u>Focal Properties</u>

The bent crystal focused to a line with a measured vertical size of 0.088mm which was sufficient for many of the experiments planned on this beamline. The source size focal limit is below 10 microns. The difference between the measured and limiting focal size is easily accounted for by deviations of the asymmetry angle from the value that causes the foci to match.

<u>Energy Dispersive Properties</u>

In addition to the small focus achieved, the angular energy dispersive properties of the crystal system described was also very good. The vertical size of the beam involved in “edge crossing” was approximately 5% as opposed to the 33% typically found. An example showing the vertical dispersion of the beam with an iodine filter is shown in Figure 2. The energy measurement was made 1.04m downstream of the focus or 2.65m from the monochromator crystal. At this location, the focused beam is inverted, placing the high energies (above K-

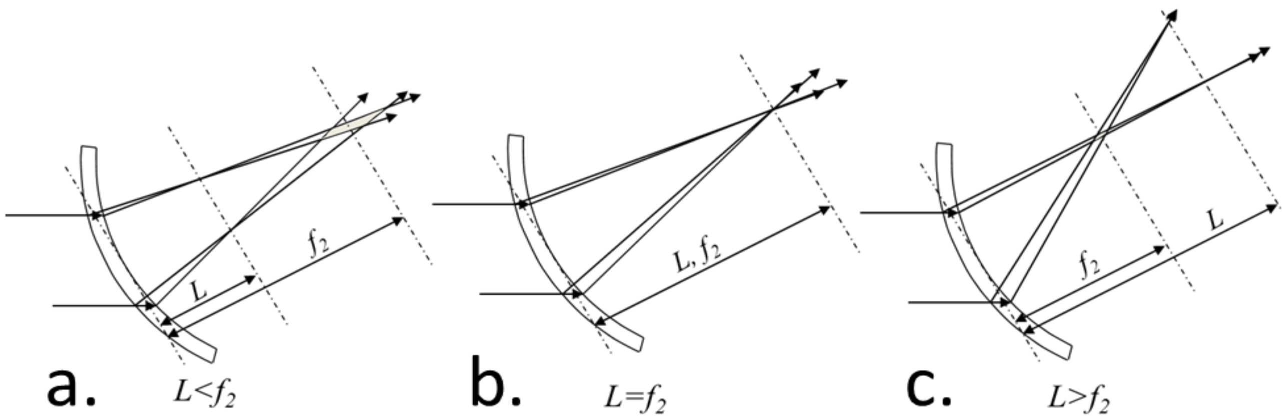

Figure 1: Examples of geometric, f_2, and polychromatic, L, foci. Figure a shows L < f_2, figure b where they match, L = f_2, and figure c where L > f_2.

RESULTS AND DISCUSSION

The experiments were performed at the bend magnet beamline, 05B1-1, of the Biomedical Imaging and Therapy facility at the Canadian Light Source. Commercially available silicon wafers were used as the monochromator crystal element. A 125mm (5 inch) silicon wafer with (5,1,1) orientation was used for this setup. The (3,1,1) type reflection whose lattice edge) at the bottom and the low energies (below K-edge) at the top. It should be noted that a splitter to remove edge

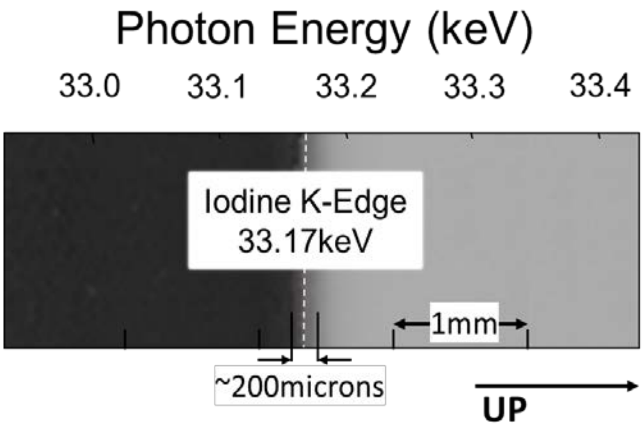

Figure 2: Image of a section of the beam with an iodine filter at the detector location. The iodine K-Edge indicated near the middle of the image. Approximately 200 microns of vertical beam size correspond to the edge crossing energies indicating very good energy resolving capabilities of this monochromator. The full beam was approximately 4mm high by 50mm wide.

crossing energies just before or after the monochromator would be approximately 0.2mm in vertical height and would be impractical; thus no splitter was used in our imaging system. The detector used was a Hamamatsu beam monitor AA-60 with C9300-124 camera effective pixel size of 8.75 x 8.75 microns (Hamamatsu Photonics, Hamamatsu City, Shizuoka Pref., Japan). Figure 2 shows a negative logarithm of the transmission image through a NaI solution iodine filter (30mg iodine/cm^3, 21mm thick) normalized by a flat field image or blank image. The dark region on the left represents the relatively low absorption of the energies below the K-edge and the bright region the much higher absorption above the K-edge. It is this spectral difference that the imaging system depends on for contrast.

The imaging procedure is to scan the object through the focused beam while rapidly acquiring transmission images. The resulting data set is a three dimensional data cube with two dimensions representing the spatial information (or one dimension could be rotation and the data set represents a sinogram for CT reconstruction) and the third dimension is energy about the K-edge energy.

The data analysis method relies on a multiple energy least squares fit to the measured transmission data through the sample[13]. A full description is beyond the scope of this paper and will be published elsewhere. For each pixel, this analysis results in a projected contrast density value and at least one other projected density value which is typically chosen to be water.

An example of computed tomography of an iodated test object is shown in Figure 3.

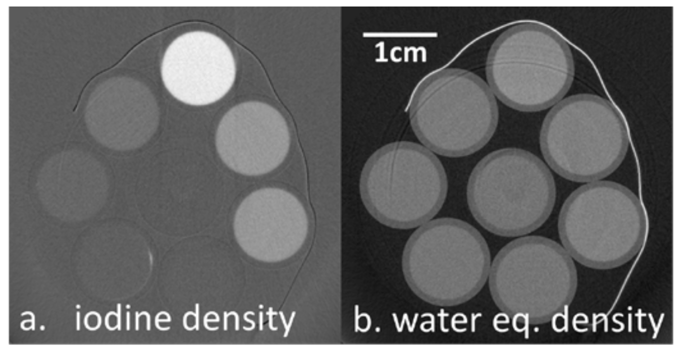

Figure 3: Computed tomography reconstruction of an iodine tube test object. Figure a is an iodine density image showing various concentrations of iodine in solution; figure b shows the water equivalent image.

CONCLUSION

A high spatial resolution, high energy dispersion monochromator has been developed for KES imaging using a spectral analysis method. The high energy dispersion of the monochromator makes very efficient use of the incident beam from the synchrotron source. The high energy dispersion, together with the elimination of a splitter to remove unnecessary edge crossing energies, has led to a spectral approach to imaging with great success.

Future work with this type of imaging will include more efficient choices of monochromator reflections and methods to deal with some small but important artifact due to subtle differences that the focused beam takes through the object (crossover artifacts).

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REFERENCES

[1] E. Rubenstein, Medical Imaging with Synchrotron Radiation, Nucl Instr Meth Phys Res A, 222 (1983) 302-307.
[2] P. Suortti, W. Thomlinson, Medical applications of synchrotron radiation, Phys Med Biol, 48 (2003) R1-35.
[3] D.M.L. Cooper, L.D. Chapman, Y. Carter, Y. Wu, A. Panahifar, H.M. Britz, B. Bewer, W. Zhouping, M.J.M. Duke, M. Doschak, Three dimensional mapping of strontium in bone by dual energy K-edge subtraction imaging, Phys Med Biol, 57 (2012) 5777-5786.
[4] S. Bayat, L. Porra, H. Suhonen, T. Janosi, S. Strengell, W. Habre, F. Petak, Z. Hantos, P. Suortti, A. Sovijarvi, Imaging of lung function using synchrotron radiation computed tomography: What's new?, Eur J Radiol, 68 (2008) 78-83.
[5] E. Schultke, S. Fiedler, C. Nemoz, L. Ogieglo, M.E. Kelly, P. Crawford, F. Esteve, T. Brochard, M. Renier, H. Requardt, G. Le Duc, B. Juurlink, K. Meguro, Synchrotron-based intra-venous K-edge digital subtraction angiography in a pig model: A feasibility study, Eur J Radiol, 73 (2010) 677-681.
[6] P. Suortti, W. Thomlinson, A bent Laue crystal monochromator for angiography at the NSLS, Nucl Instr Meth Phys Res A, A269 (1988) 639-648.
[7] P. Suortti, W. Thomlinson, D. Chapman, N. Gmur, D.P. Siddons, C. Schulze, A Single-Crystal Bent Laue Monochromator for Coronary Angiography, Nucl Instr Meth Phys Res A, 336 (1993) 304-309.
[8] T.W. Wysokinski, D. Chapman, G. Adams, M. Renier, P. Suortti, W. Thomlinson, Beamlines of the biomedical imaging and therapy facility at the Canadian light source - Part I, Nucl Instr Meth Phys Res A, 582 (2007) 73-76.
[9] T.W. Wysokinski, D. Chapman, G. Adams, M. Renier, P. Suortti, W. Thomlinson, Beamlines of the biomedical imaging and therapy facility at the Canadian Light Source - Part 2, 11th International Conference on Synchrotron Radiation Instrumentation, SRI 2012, July 9, 2012 - July 13, 2012, Institute of Physics Publishing, Lyon, France, 2013.
[10] C. Schulze, U. Lienert, M. Hanfland, M. Lorenzen, F. Zontone, Microfocusing of hard X-rays with cylindrically bent crystal monochromators, J Synchrotron Radiat, 5 (1998) 77-81.
[11] U. Lienert, S. Keitel, W. Caliebe, C. Schulze-Briese, H.F. Poulsen, Source size conserving broad band monochromators of fixed exit geometry for high energy synchrotron radiation, Nucl Instr Meth Phys Res A, 467-468 (2001) 659-662.
[12] B.W. Batterman, H. Cole, Dynamical Diffraction of X-rays by Perfect Crystals, Reviews of Modern Physics, 36 (1964) 681-717.
[13] N. Kozul, G.R. Davis, P. Anderson, J.C. Elliott, Elemental quantification using multiple-energy X-ray absorptiometry, Measurement Science & Technology, 10 (1999) 252-259.