Development of high sensitivity X-ray multiple-times-diffraction enhanced imaging (M-DEI) optics

Yanlin Wu1, Kazuyuki Hyodo1,2, Naoki Sunaguchi2, Tetsuya Yuasa3 and Masami Ando4
1 The Graduate University for Advanced Studies, Tsukuba, Japan
2 High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
3 Yamagata University, Yonezawa, Japan
4 Tokyo University of Science, Noda, Japan

E-mail: anlin.woo@gmail.com

Abstract. X-ray phase contrast imaging is now a powerful tool to identify tiny electronic-density difference in a subject. We propose a novel diffraction enhanced imaging (DEI) optics sensitive to the electronic-density difference smaller than 2%. This is named multiple-times-diffraction enhanced imaging (M-DEI) by use of multiple diffractions in a channel-cut groove. Ordinary DEI, which is widely utilized in many research fields, is sensitive to electronic-density difference greater than 2%. That the M-DEI adopts the multiple-times-diffraction in the Bragg case analyzer is a key point to obtain a sharp rise at the rocking curve which leads to the high electronic-density resolution. The X-ray energy was 17.5 keV, the diffraction index used was silicon (4, 4, 0), and the number of diffraction was 7. This gives 68.75% higher sensitivity of electronic-density difference compared to a single-times-diffraction. Here, we will report all recent results of the M-DEI system.

1. Introduction
X-ray phase contrast imaging is now a powerful tool to identify tiny electronic-density difference in a subject. We propose a novel diffraction enhanced imaging (DEI) optics [1] more sensitive to the electronic-density difference smaller than 2% [2]. This optic is named multiple-times-diffraction enhanced imaging (M-DEI) by use of multiple-times-diffractions [3] in a channel-cut groove. To date, no experimental evidence of the advantages of this optics has been reported. However, using the multiple-times-diffraction technique for analyzer of optics is very constructive, since the multiple-times-diffraction technique is commonly used as high angular monochromator [4]. DEI based method has relatively higher angular dynamic range than interferometer based method. For low-Z elements material, M-DEI is more sensitive to the electronic-density compared to ordinary DEI method. In this study, we compared the DEI and the M-DEI quantitatively; the latter shows 68.75% more sensitive than the former.

2. Methods
X-ray multiple-times-diffraction means the phenomenon where the incident beam undergoes multiple-times-diffraction between symmetric parallel channel-cut surfaces. Here, the intensity of a single diffracted beam is defined as R(η), so after the n times diffractions, the intensity becomes [R(η)]n [5].
Here, \( \chi_{hkl} \) is Fourier component of the crystal polarizability for reflection \( hkl \), \( r_e \) is the classical electron radius, \( F_{hkl} \) the structure factor and \( V \) the unit cell volume. The asymmetry factor \( b = \frac{\sin(\theta_B - \alpha)}{\sin(\theta_B + \alpha)} = -1 \) for a symmetric reflection and the polarization factor \( C = 1 \) for the \( \sigma \)-polarized radiation and \( C = \cos^2 \theta_B \) for the \( \pi \)-polarized radiation. Angular deviation \( \Delta \theta \) expresses the difference of crystal orientation from the exact Bragg angle \( \theta_B \). We simulated the rocking curve under the situation of 17.5keV energy and Si (4, 4, 0) (shown in Figure 1). When the refraction angle \( \Delta \theta \) is fixed, the slope \( \Delta I/\Delta \theta \) becomes bigger when \( n \) is growing. As Figure 1(B) shows, when \( \Delta I \) is fixed, \( \Delta \theta \) becomes small inversely proportional to \( n \). In that way, we can obtain better contrast resolution by using the feature of multiple-times-diffraction.

3. Experiment and Results
For certifying the above point, we have used comparative trial at the unique vertical-wiggler beamline PF BL-14C. The X-ray energy was 17.5 keV. DEI and improved method, M-DEI have been adopted as an optics system. The experimental setup is shown in Figure 2. Both of DEI and the M-DEI have used the same asymmetric collimator. About the analyser crystal, DEI has used single-times-diffraction Bragg type symmetric crystal; in the meantime, M-DEI has used 7-times-diffraction Bragg type channel-cut symmetric crystal. Sample in a water tank (see sample in Figure 2) locates between the collimator and the analyser. We collected data by using CCD camera with pixel number 4872 × 3248 and pixel size of 7.4\( \mu \)m × 7.4\( \mu \)m. In order to analyze electronic-density resolution, Refraction angle of X-rays, referring to the gradient \( \partial \delta / \partial x \) of the electronic-density \( \rho_e \), is converted to black and white contrast of image through a rocking curve of crystal, a refraction phantom was made from gelatin solution that was embedded in a certain
concentration of agarose gel with density $\rho$ of 0.9977g/cm$^3$ and $\delta$ of 7.5071E-07. Feature of refraction phantom is shown in Table 1 and Figure 3.

**Table 1.** Refraction phantom of mass concentration of gelatin, density $\rho$ and $\delta$.

| MC (%) | $\rho$ (g/cm$^3$) | $\delta$          |
|--------|-------------------|-------------------|
| 1.50   | 0.9981            | 7.5093E-07        |
| 0.91   | 0.9993            | 7.5197E-07        |
| 0.83   | 0.9993            | 7.5204E-07        |
| 0.71   | 0.9994            | 7.5215E-07        |
| 0.00   | 1.0000            | 7.5283E-07        |

* MC means the mass concentration of gelatin solution with water as solvate.

Figure 4 showed a series of phase contrast image a phantom with under different electron density under the same exposure time, 12.8sec. Suddenly we observed the edge between agarose gel and gelatin solution, in projection image. MC of 0.91% of gelatin solution is the limitation of the electronic-density solution. However, the MC of 1.50% of gelatin solution is the designed limitation for refraction phantom in this study, M-DEI can observed structure of refraction phantom.

**Figure 4.** Refraction phantom of DEI (a-e) image and M-DEI (f, g) image.

a. gelatin (1.50%, mass-concentration (MC)); b. gelatin (0.91%, MC); c. gelatin (0.83%, MC); d. gelatin (0.71%, MC); e. water (100.00%, MC); f. gelatin (1.50%, MC); g. water (100.00%, MC).

4. Discussion
The only one measurement done on the electronic-density resolution, $\Delta \rho(\%) = \left(\frac{\rho - \rho_{\text{agarose}}}{\rho_{\text{agarose}}}\right) \times 100\%$, in case of DEI gave the number 2%. We have achieved 0.16% (DEI-CT (a)) and 0.05% (M-DEI-CT (b)) by use of DEI and M-DEI, respectively. However, the M-DEI may cause the deterioration of the spatial resolution. The only adjusted effector in this study is the analyser crystal; spatial resolution is changed as analyzer crystal change. Compare the spatial resolution between DEI and M-DEI; just compare the blurriness of analyser crystal. Blurriness of analyser crystal $l_B$ according to the theory,

$$l_B = (2Z_{\text{inf}} \cos \theta_B)_1 \times (2Z_{\text{inf}} \cos \theta_B)_2 \times \cdots \times (2Z_{\text{inf}} \cos \theta_B)_n \quad (2)$$

where $l_B$ is the blurriness of analyser crystal, $Z_{\text{inf}}$ is the information depth [6] and $\theta_B$ is the Bragg angle and $n$ is the diffraction times, respectively.

In this paper, the spatial resolution is defined as the blurriness of the image. We measured the blurriness of image from back projection image. The spatial resolution of DEI is better the M-DEI around 4 times on value.
5. Conclusion
Great improvement of contrast was achieved by introducing M-DEI by a factor of 68.75% by introduction of M-DEI compared to DEI. The spatial resolution \( l_B \) of M-DEI is deteriorated compared to DEI, around 4 times on value. Furthermore we plan to introduce asymmetric M-DEI to improve the spatial resolution. Blurriness of asymmetric analyser crystal \( l_B \) according to the following equation,

\[
l_B = (Z_{\text{inf}} \cos(\theta_{\text{in}} + b \cos(\theta_{\text{out}}))) \times (Z_{\text{inf}} \cos(\theta_{\text{in}} + b \cos(\theta_{\text{out}}))) \times \cdots \times (Z_{\text{inf}} \cos(\theta_{\text{in}} + b \cos(\theta_{\text{out}})))_n
\]

(3)

where \( \theta_{\text{in}} \) and \( \theta_{\text{out}} \) are the incoming and outgoing angles of the X-ray beam measured from the surface, respectively and \( b \) is asymmetry factor. \( l_B \) is blurriness of image, \( Z_{\text{inf}} \) is information depth, \( n \) is the diffraction times, respectively.

6. Acknowledgments
This work was performed under the approval of the Program Advisory Committee of the Photon Factory (2011PF14 and 2011PF19). Use of gelatin was suggested by Dr Y. Funakoshi, and technique supported by Dr X. Zhang, to whom the authors would like to express their thanks.

7. References
[1] D. Chapman, W. Thomlinson, R. E. Johnston, D. Washburn, E. Pisano, N. Gmüir, Z. Zhong, R. Menk, F. Arfelli and D. Sayer 1997 Phys. Med. Biol. 42 2015–25.
[2] E. Hashimoto 2007 Thesis or Dissertation of The Graduate University for Advanced Studies.
[3] U. Bonse and M. Hart 1965 Appl. Phys. Lett. 7, 238.
[4] Tetsuya Ishikawa, Seishi Kikuta and Kazutaka Kohra 1985 Jpn. J. Appl. Phys. 24 559-562.
[5] Seishi Kikuta 2011 X-ray scattering and synchrotron radiation science-Fundamentals, University of Tokyo Press.
[6] D. Korytár, C. Ferrari, P. Mikulík, F. Germini, P. Vagovic and T. Baumbach 2008 Springer Series in Optical Sciences, 137.