Novel X-Ray Imaging Opportunities for the RPI Linear Accelerator's Tunable, Quasi-monochromatic X-ray Source

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INTRODUCTION

The development of an intense, tunable, polarized, and quasi-monochromatic X-ray source has been ongoing at Rensselaer Polytechnic Institute since 2001 [1, 2, 3, 4, 5, 6]. This X-ray source, known as Parametric X-rays (PXR), is generated from the interaction of relativistic electrons from the RPI linear accelerator and the periodic structure found in crystalline materials. PXR has been extensively characterized since its first experimental realization in 1985 [7,8,9,10,11,12,13,14, 15, 16, 17]. The energy linewidth (FWHM) of PXR is limited only by the inverse of the photon lifetime in the material, ~ 0.3 eV for a 17.5 keV X-ray in silicon [18], however PXR is experimentally broadened by the quality of the electron beam (spot size and divergence) and the detection geometry (collimation and solid angle) [9].

Such nearly monochromatic, intense, and tunable x-ray sources have gotten attention for their uses in imaging applications. This paper summarizes two imaging opportunities for PXR in (1) near absorption edge imaging for material detection and (2) typical absorption contrast imaging.

PXR PRODUCTION

At RPI, the linac typically produces 60 MeV electrons that interact in air with a target crystal held by a three-axis goniometer with a resolution of 0.001^o. The PXR energy is a function of the crystal d-spacing and the geometry of the experiment [13,2]. For lithium fluoride LiF (220) d-spacing is 0.14 nm. Rotation of the target crystal changes the PXR energy. The calculated PXR energy for a 1.5 mm thick crystal LiF (220) with a Bragg angle of 15^o is 16.8 keV with a tunable energy resolution of 0.69 eV per goniometer step and a calculated 4.2 $x10^{-5}$ photon yield per electron. Measured photon yields were 3.0 x 10^{-5} photon per electron, a 40% difference from the calculated value. This difference is likely due to the experimental broadening, which was not considered in the calculated values [9]. In comparison, a bremsstrahlung X-ray tube operating at 100 kVp typically produces a photon yield of ~ 0.05% (5 x 10^{-4} photon/e), but those photon energies are spread from zero to 100 keV. Additionally, the X-ray tube directionality is a photon distribution fan of up to 30^o [19], whereas the 60 MeV PXR is concentrated in about a 9 mrad cone (~ 0.5^o). In applications where directionality and energy dependant interactions are of interest, PXR has its merits.

MATERIAL DETECTION NEAR ABSORPTION EDGES

The PXR energy can be tuned slightly below and above a material's absorption edge to enhance contrast for imaging purposes or to provide material identification from transmission changes. For example, iodine and barium are often used as contrast agents in medical imaging [20]. The iodine K-edge is at 33.2 keV at which the linear absorption coefficient changes from 25.8 to 175.1 cm^{-1}, a factor of nearly seven. Similarly, uranium has a K-edge at 116 keV and an L-edge at 17.2 keV at which the absorption coefficients change by factors of 3.7 and 2.3, respectively for the K and L edges. Such edge experiments have been done at RPI to characterize the PXR energy linewidth. The copper K-edge at 8.96 keV was probed by PXR [3]. These same principles can be used to search for materials in support of homeland defense or to enhance contrast in medical imaging applications.

ABSORPTION CONTRAST IMAGING

X-ray energy is important in optimizing image quality in traditional radiography. X-ray transmission is necessary to record the image, and contrast is necessary to observe distinctions between two absorbing materials such as bone and tissue. Both are energy dependant but inversely related; transmission increases and contrast generally decrease with increasing X-ray energy. Tunable X-rays like PXR help to make it possible to image small, slightly differing absorbing objects. In the first-ever PXR images, a small fish was imaged on a CCD camera using 16.6 keV X-rays produced from LiF (220) at an electron current of ~2.6 μA. The fish dimensions were measured at the thickest fleshy part of the fish (7.5 mm) and the largest spinal fish bone (2.0 mm). For this case a higher energy would have degraded the contrast and a lower energy would have limited the detected signal.

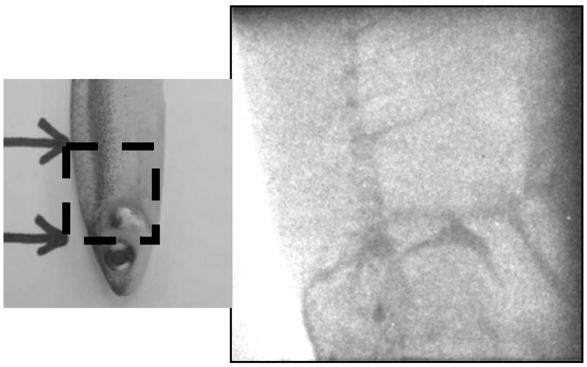

Fig. 1. PXR image of fish shown on at right using LiF (220) and 60 MeV electrons at 2.6 μA beam current.

CONCLUSIONS

An intense, tunable, quasi-monochromatic X-ray called parametric X-rays is being produced at Rensselaer Polytechnic Institute. The X-ray shows promise in two imaging modalities both demonstrated in the laboratory. The advantage of PXR over traditional X-ray tubes is in its energy tunability and nearly monochromatic X-ray beam. These novel characteristics allow PXR to be applied in nearly any X-ray application requiring a mono-energetic, energy tunable X-ray source.

REFERENCES

1. Y. Danon,, B. Sones, R. Block, *Novel X-ray Source at the RPI LINAC*, Proceedings, ANS Annual Meeting, Hollywood, Florida, June 2002.

2. B. Sones, Y. Danon, R. Block, *Optimization of Parametric X-ray (PXR) Production*, Proceedings, ANS Annual Meeting, Hollywood, Florida, June 2002.

3. B. Sones, Y. Danon, R. Block, *Advances in Parametric X-Ray Production at the RPI Linear Accelerator*, Proceedings, ANS Annual Meeting, San Diego, California, June 2003.

4. B. Sones, Y. Danon, R. Block, *Lithium Fluoride Crystal Advantages in Parametric X-Ray (PXR) Production*, Proceedings, ANS Winter Meeting, New Orleans, Louisiana, November 2003.

5. Y. Danon, B. Sones, R.C. Block, *Dead time and pileup in pulsed parametric X-rays spectroscopy,* accepted for publication Nuc. Inst. Methods B (2003).

6. B. Sones, Y. Danon, R. Block, *Lithium Fluoride Crystal for Parametric X-Ray Production*, Proceedings, Radiation from Relativistic Electrons in Periodic Structure (RREPS) 2003 Tomsk, Russia, submitted for publication Nuc. Inst. Methods B (2003).

7. M.L. Ter-Mikaelian, High Energy Electromagnetic Processes in Condensed Media (Wiley-Interscience, New York, 1972).

8. V.G. Baryshevshy, et. al., *Angular distribution of parametric X-rays*, Phys. Lett. 110A, 447 (1985).

9. K. H. Brenzinger, et. al., *How narrow is the linewidth of parametric X-ray radiation?*, Phys. Rev. Lett. 79, 2462 (1997).

10. A.V. Shchagin, V.I. Pritupa, and N. A. Khizhnyak, *A fine structure of parametric X-ray radiation from relativistic electrons in a crystal*, Phys. Let. A, 148, 485 (1990).

11. R. B. Fiorito, D. W. Rule, M. A. Piestrup, Qiang Li, A. H. Ho, and X.K. Maruyama, *Parametric X-ray generation from moderate energy electron beams*, Nuc. Inst. Methods B79, 758 (1993).

12. S. Asano, I. Endo, M. Harada, S. Ishii, T. Kobayashi, T. Nagata, M. Muto, K. Yashida, and H. Nitta, *How intense is parametric X radiation?*, Phys. Rev. Lett. 70, 3247 (1993).

13. T. Akimoto, M. Tamura, J. Ikeda, Y. Aoki, F. Fujita, K. Sato, A. Honma, T. Sawamura, M. Narita, and K. Imai, *Generation and use of parametric X-rays with an electron linear accelerator*, Nuc. Inst. Methods A459, 78 (2001).

14. I. Endo, M. Harada, T. Kobayahi, Y.S. Lee, T. Ohgaki, T. Takahashi, M. Muto, K. Yoshida, H. Nitta, A.P, Potylitsin, V.N. Zabaev, T. Ohba, *Parametric X-radiation from thick crystals*, Phys Review E51, 6305 (1995).

15. K. Yu. Amosov, B.N. Kalinin, A.P. Potylitisin, V. P. Sarychev, S.R. Uglov, V.A. Verzilov, S. A. Vorobiev, I. Endo, T. Kobayahsi, *Influence of temperature on parametric x-ray intensity*, Phys, Rev. E, Vol 47, No 3 (1993).

16. A.P. Polylitsin, *Influence of beam divergence and crystal mosaic structure upon parametric X-ray radiation characteristics*, arXiv:cond-mat/9802279 v1, 26 Feb (1998).

17. K. Brenzinger, et. al., *Investigation of the Production Mechanism of Parametric X-Ray Radiation*, Z. Phys. A 358 (1997) 107.

18. X1 Collaboration web site [online]. Available at :http://www.kph.uni-mainz.de/X1/pxr_infoprob.html. Accessed 1 January 2004.

19. A.B. Wolbarst, Physics of Radiology, (Medical Physics Publishing, Madison, Wisconsin, 2000).

20. F. Hagenbuck, et. al., *Novel Digital K-Edge Imaging System with Transition Radiation from an 855-MeV Electron Beam*, IEEE Transaction on Nuclear Science, Vol 48, No 3 (2001)