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°. 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° is 16.8 keV with a tunable energy resolution of 0.69 eV per goniometer step and a calculated 4.2 x10⁵ photon yield per electron. Measured photon yields were 3.0 x 10⁵ 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 10⁻⁵ 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° [19], whereas the 60 MeV PXR is concentrated in about a 9 mrad cone (~ 0.5°). In applications where directionality and energy dependent 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 dependent 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

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).


