Experiments with relativistic electrons producing tunable X-rays from Cu crystals

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INTRODUCTION

Energy tunable Parametric X-rays (PXR) in the range of a few KeV to tens of KeV have been experimentally realized at the Rensselaer LINAC [1, 2]. PXR makes use of the interaction of relativistic electrons with periodic structures like those found in crystal. This phenomenon can be modeled as the diffraction of the "virtual photon" field associated with the relativistic electron as it traverses the crystal target [3]. Practical engineering applications of PXR have been challenged by crystal heating at higher electron beam current of greater than a few μA. Two LINAC facilities have demonstrated PXR imaging [4, 5]. In both of these studies, electron beam currents were increased to μA-levels, and both the Si and LiF crystal targets cracked under thermal stress. As an alternative, metallic crystals have been considered as PXR targets because of their thermal characteristics and their relatively high electric susceptibility, χ which is a factor in determining PXR production [6].

In previous experiments at the Rensselaer LINAC, 60 MeV electrons produced 12.0 keV and 13.6 keV PXR, respectively, from the 1-mm thick Cu222 and the W222 crystallographic planes in a Bragg geometry [7]. These experiments were proof of principle only and failed to minimize target crystal thickness for maximum PXR production. The excess crystal thickness produced excessive Bremsstrahlung, target florescence, and electron scattering. This work reports experimental PXR results using an optimized Cu thickness and makes qualitative comparison's of these results with earlier experiments.

THEORY

Parametric X-rays are smoothly energy tunable with the rotation of the target crystal with respects to the incident electron beam direction. The PXR energy is determined by Equation 1 [8].

$$E_{PXR} = \hbar\omega_{PXR} = \hbar c \frac{\tau \sin\phi}{1 - \cos\Omega} \qquad (1)$$

τ is the magnitude of the reciprocal lattice vector of the target crystallographic planes, ϕ is the electron incident angle measured with respect to the crystal planes, and Ω is the PXR emission angle measured with respect to the electron velocity.

PXR production per unit length competes with PXR absorption in the crystal allowing for crystal thickness to be optimized when PXR yield saturates [8, 9]. Details on this optimization process and electron scattering effects of the optimized crystal thickness are available in earlier works [6, 7, 10]. This analysis acknowledged that the 1-mm thick W and Cu crystals were excessively thick for the experiments conducted at RPI. New experiments reported in this paper sought to create PXR with thin metallic crystals.

EXPERIMENTAL STEP-UP

Typical PXR experiments using the RPI LINAC are conducted in air using a 10 mil (250 μm) Be output window, a 3-axis Huber goniometer for crystal rotation, a Bergoz beam charge monitor to measure beam current, a video camera to align the electron beam onto the target crystal by means of optical transition radiation (OTR), and a well collimated Amptek Si detector. Further details are available in earlier works [1, 4].

This experiment used a 0.1 mm thick, 25 mm diameter Cu target crystal provided by Matek and polished to the Cu111 face. A special crystal mount was milled from aluminum. The detector location was 3.7 m from the target crystal and lead shielded using 35 cm lead collimation with a 3 x 3 mm^2 aperture.

RESULTS

Figure 1 shows two PXR spectra for Cu crystals aligned in the Bragg geometry with the Cu111 face: the early experiment (top graph) with the 1-mm thick Cu crystal and the more recent experiment (bottom graph) with the 0.1 mm Cu crystal. The data are not easily scaled because of differences in electron beam current and detector angles. However, two important observations are made from the 1-mm Cu spectrum. First, the first order PXR, Cu111, is not observable and this is because of absorption in the air path to the detector. Second, the Cu florescence is more dominant than the second order PXR, Cu222. By contrast, the 0.1-mm spectrum demonstrates the existence of the first order, Cu111, PXR and its dominance over the florescence.

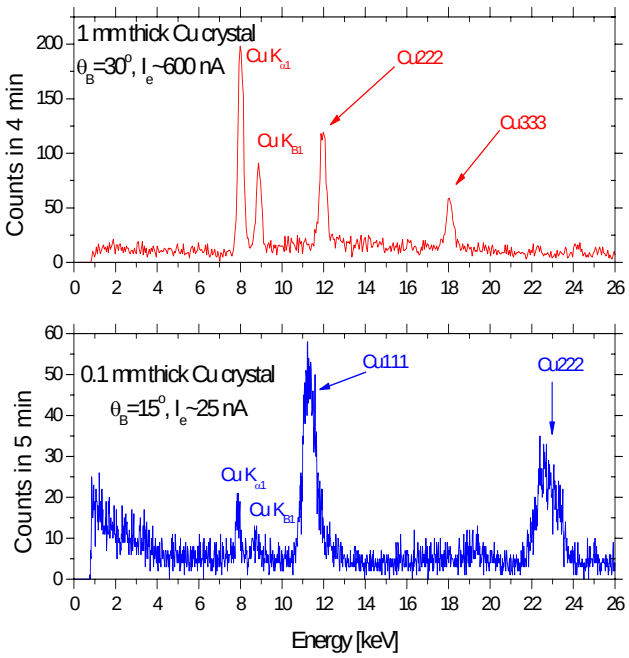

Fig. 1. Comparison of Cu PXR spectra. Top graph shows 1-mm thick crystal with dominating Cu florescence. Bottom graph shows 0.1- mm crystal with minimal Cu florescence.

Table I shows data collected from the spectra in Figure 1. θ_B is ϕ in Equation 1. The ratio, net counts is the Kα florescence peak divided by the net counts in the PXR peak, is intended to create a scalable comparison of results from the two crystal thicknesses. For the Cu222 PXR, the optimized crystal thickness of 0.1 mm reduces the K_α/PXR ratio by a factor of more than 16.

Table I. Comparison of Experiments

Thickness [mm]	θ_B [deg]	Ω [deg]	Plane	Energy [keV]	Ratio K_α/PXR
1	30	60	Cu222	11.96	1.52
0.1	15	30	Cu222	22.50	0.09
0.1	15	30	Cu111	11.24	0.07

CONCLUSIONS

This paper reports the first experimental observation of Cu111 PXR. More importantly, this experiment demonstrated that with optimized metallic crystal thicknesses, the unwanted florescence may be held relatively small to the energy tunable Parametric X-rays. This offers further motivation to continue analysis of thin metallic crystals for PXR applications with currents greater than μA levels.

FUTURE WORK

This work demands two immediate efforts to continue towards a practical imaging application with high electron beam current. First, engineering designs are necessary for crystal cooling. Second, PXR experiments at small detection angles from the electron beam are necessary to model with Monte Carlo simulations and analytical models to evaluate their feasibility for energy tunability at higher PXR energies.

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