Thin metallic crystals for Parametric X-ray (PXR) production

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INTRODUCTION

Parametric X-rays (PXR) are produced from relativistic electrons interacting with targets with periodic structures [1]. The rotation of a crystal target in an electron beam smoothly varies the PXR energy. PXR is energy tunable, quasi-monochromatic, and directionally intense [2] making it an attractive novel x-ray source for medical imaging applications. Two LINAC facilities have demonstrated PXR imaging [3, 4]. 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. For imaging applications, low Z target crystals such as Si, LiF, and HOPG (graphite) have advantages over high Z targets because they produce less unwanted Bremsstrahlung, electron energy deposition, and electron scattering [5]. PXR production is a function of the square of the target crystal electric susceptibility, χ [6]. High Z metallic targets such as W and Cu have higher electric susceptibility, better thermal characteristics, and much smaller optimum thicknesses. At the Rensselaer LINAC, 60 MeV electrons produced 12.0 keV and 13.6 keV PXR, respectively, from the 1-mm thick Cu111 and the W222 crystallographic planes in a Bragg geometry, i.e., the planes were parallel to the target surface [7]. In those experiments, the target crystals thickness was much thicker than the optimum. This work seeks to parametrically study electron scattering, and its effect on broadening the PXR photon distribution from thin crystals of these two metallic crystals.

THEORY

There are two crystals geometries used in PXR production. One is the Bragg geometry mentioned above, and the other is the Laue geometry which makes use of diffraction planes perpendicular to the crystal surface. Optimized PXR target thickness is x-ray energy dependent, and the PXR production approaches a saturation level for greater thicknesses [1]. For 15 keV PXR from W222, in the Bragg geometry, a target thickness of one absorption length, L_a, reaches 99.9% of the saturation production level and in the Laue case, a target thickness of 3 L_a, reaches 96.5% of saturation. Low Z PXR targets are typically a few hundred microns thick, but optimized metallic crystals may be just a few microns.

An analytical expression for the electron multiple scattering standard deviation, σ_{ms}, for electrons with energy E_e traversing a distance d across a material with radiation length X_0 is shown below [6].

$$\sigma_{ms} = \frac{13.6}{E_e}\sqrt{\frac{d}{X_o}}\left(1+0.038\ln(\frac{d}{X_o})\right) \tag{1}$$

Mean medical x-ray energies range from about 15 keV for certain mammography applications to about 60 keV for a chest x-ray [8]. In Table I, 15, 30, and 60 keV PXR are compared for optimized production from W222 and Cu111 in the Bragg and the Laue geometries. For 15, 30, and 60 keV, x-rays, the W absorption lengths, L_a, are 3.7 µm, 22.8 µm, and 139.8 µm, respectively. For Cu, the absorption lengths are 15.0 µm, 102.2 µm, and 723.0 µm, respectively [9]. An effective crystal thickness, d, is calculated by setting the crystal thickness to either 1 L_a (for Bragg) or 3 L_a (for Laue) and calculating the electron's pencil beam path across the crystal when rotated to produce the particular PXR energy. The Bragg angle, θ_B, is measured between the electron beam direction and the crystal planes, and the PXR emission angle for the Bragg Condition is $2\theta_B$ from the electron beam direction. Equation 2 is used to calculate σ_{ms} for the 60 MeV electrons, and the 1-mm W and Cu crystals are presented for comparison.

Table I. Electron Multiple Scattering

Crystal Plane	E_{PXR} [keV]	θ_B [deg]	d (µm)	σ_{ms} [rad]
W222 Bragg	15	26.9	8.3	5.58E-03
	30	13.1	101.0	2.20E-02
	60	6.5	1239.8	8.60E-02
(1 mm thick)	*15*	*26.9*	*2212.4*	*1.17E-01*
W222 Laue	15	26.9	12.6	7.02E-03
	30	13.1	70.3	1.80E-02
	60	6.5	422.1	4.80E-02
Cu111 Bragg	15	11.4	76.0	8.38E-03
	30	5.7	1033.9	3.50E-02
	60	2.9	14465.9	1.46E-01
(1 mm thick)	*15*	*11.4*	*5058.4*	*8.30E-02*
Cu111 Laue	15	11.4	46.0	6.36E-03
	30	5.7	308.1	1.80E-02
	60	2.9	2171.7	5.20E-02

Without consideration of electron beam divergence and scattering, the PXR photon distribution is described by N(θ_x,θ_y) around the emission that satisfies Bragg's condition [10].

$$N(\theta_x, \theta_y) = \frac{\theta_x{}^2 \cos^2 2\theta_B + \theta_y{}^2}{(\theta_x{}^2 + \theta_y{}^2 + \theta_{ph}{}^2)^2} \quad (2)$$

where θ_x and θ_y are angular positions measured from the Bragg condition, and θ_{ph} is approximately the Lorentz factor. θ_x is measured in the diffraction plane and θ_y is perpendicular to the diffraction plane. Refer to previous work for more details about PXR theory and the photon distribution [11-15]. Techniques for broadening the photon distribution generally involve convoluting the PXR photon distribution with a Gaussian distribution that includes effects from electron scattering [16-17]. For these calculations, the effect of electron scattering is considered, and each calculation is normalized to the unbroadened distribution in Equation 2.

RESULTS

Figure 1 shows a cross section of the PXR photon distribution centered on the Bragg condition and varied angularly in the diffraction plane, θ_x. Photon distribution broadening resulting from electron multiple scattering is observed. Instead of a relatively directional PXR beam characterized by an emission cone confined to a little more than θ_{ph} (~ 8.5 mrad for 60 MeV electrons), the photon distributions flatten and spread to larger solid angles. Relative to the experiments with 1-mm thick target crystals, the optimized thin crystals demonstrate gains in photon intensity. For small solid angles of $1\text{x}10^{-6}$ steradian, an improvement of a factor of 10 and 2 is expected for 15 keV PXR from W222 and Cu111, respectively in the Bragg geometry. For larger solid angles of 100 mStr, which would illuminate a 10 cm x 10 cm target at 1 m, factors of 11 and 8 are expected, respectively.

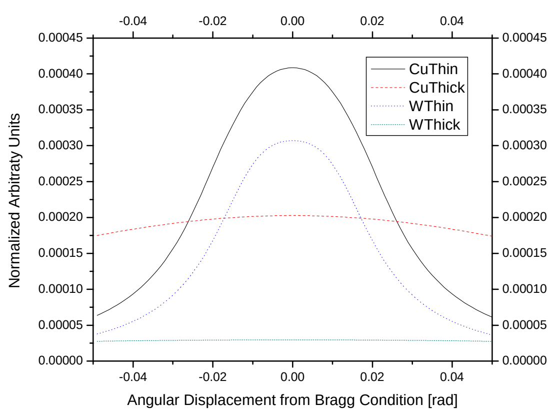

Fig. 1. W222 and Cu111 crystal theoretical PXR photon distribution broadening for 1-mm thick crystals compared to thin crystals optimized for 15 KeV PXR.

CONCLUSIONS

This work demonstrated that there are some advantages to using thin metallic target crystals in the production in PXR when high electron beam currents are needed. PXR from relatively thick W and Cu crystals was produced at the Rensselaer 60-MeV LINAC, and this work studied the potential gains in PXR intensity by optimizing the PXR target crystal thickness. In some cases, an order of magnitude gain in intensity can be achieved. Metallic crystals optimized for thickness may be the best suited target for PXR imaging applications. Despite their density, these thin metallic crystals also heat less that the low Z targets. For example the heating of the W222 crystal for 15 KeV PXR would be approximately 22 mW per μA of electron beam current. By contrast, a typical 500 μm thick Si target heats at about 220 mW per μA.

FUTURE WORK

The way forward for this work takes two paths. First, there are engineering designs for crystal cooling that consider force convection methods. Second, Monte Carlo simulations need to be done to examine the production of Bremsstrahlung from the metallic crystals.

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