A COMPACT TUNABLE X-RAY SOURCE BASED ON PARAMETRIC X-RAY GENERATION BY MODERATE ENERGY LINACS*

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Abstract

Parametric x-radiation can be described as the diffraction of virtual photons associated with the electric field of a relativistic charged particle passing through a crystal. In analogy with Bragg reflection of x-rays, these diffracted photons appear as real photons, with an energy which satisfies Bragg's law for the reflecting crystal planes. We describe the results of experiments performed on the Naval Postgraduate School linac which were designed to explore the basic properties of PXR in order to assess its potential application as a compact tunable x-ray source. Experiments using a mosaic graphite radiator show that this radiator produced multiple order, narrow bandwidth reflections from 5 - 45 keV. The measured production efficiency is found to exceed that predicted for spectral orders n > 1. We demonstrated the tunability of PXR by rotating the crystal in order to change the Bragg angle relative to the incident 90 MeV electron beam.

I. INTRODUCTION

Parametric x-radiation (PXR) is generated when a charged particle passes through a crystalline structure. The real x-rays produced by this mechanism are quasi-monochromatic and therefore spectrally intense[1]. Through the proper selection of the crystal, Bragg angle, angular aperture and electron beam parameters, the photon energy and the bandwidth can be specified. In contrast to other mechanisms for the production of x-rays, to produce 10 keV photons, PXR requires less than a 50 MeV electron beam whereas synchrotron radiation (SR) requires 3 GeV and transition radiation (TR) 300 MeV. Furthermore, the spectral brightness exceeds that of SR, TR and channeling radiation (CR) on a per electron basis.

Experiments done in the former Soviet Union have studied the intensity, angular distribution, bandwidth and polarization of PXR from beams with energies from 25 to 900 MeV[1].

II. THEORY

The spectral distribution over the solid angle subtended by the detector, $d\Omega = \Delta\theta_x \Delta\theta_y$ can be approximated by

$$\partial N / \partial\omega = \Psi J_2(\alpha_y, u) S(\alpha_x - |u|),$$

where the function J_2 describes the main features of each spectral line[2] and the step function S, which is unity when the argument is positive and is zero otherwise, describes the effect of $\Delta\theta_X$.

$$\alpha_{x,y} = \Delta\theta_{x,y} / 2\theta_p,$$

$$u = [(\omega - \omega_B)/\omega_B] \cdot \tan\theta_B / \theta_p = \theta_x / \theta_p$$

where, $\theta_p = (\gamma^{-2} + \chi_o + \theta_s^2)^{1/2}$, with γ and χ_o, respectively, the Lorentz factor and the mean dielectric susceptibility. $\theta^2{}_s = \theta^2{}_d + \theta^2{}_{scat} + \theta^2{}_{mos}$ is included, ad hoc, to approximate the effects of beam divergence, multiple scattering of electrons and crystal mosaicity. The factor,

$$\Psi = \frac{e^2}{\hbar c} \frac{|\chi_{10}|^2}{(4\sin\theta_B \cos\theta_B)} \frac{L_a(1 - e^{-L/L_a})}{\pi c \theta_p},$$

describes the roles of absorption length, L_a, the interaction length, L, θ_B and χ_{10}, the structure factor.

Fig. 1 illustrates the spectral function, $J_2(u)$, and the portion of the spectrum observed by our fixed detector when the crystal is oriented at $\theta_B = 22.5°$ and $\theta_B = 23.5°$. At a distance of 1 meter $\Delta\theta_{x,y}$ = 16 mrad and $\Delta\theta_X$ prescribed the observed bandwidth (4%).

III. MEASUREMENTS

We have recently measured higher order spectra of parametric x-radiation from thick graphite and silicon crystals. The production is

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determined by the interaction length, L, rather than by absorption lengths, L_a , for higher energy x-rays. For these conditions, the intensity of the higher harmonics is considerably enhanced and the n=2 intensity is comparable to the fundamental[2]. The measurements presented here show that PXR is a promising compact source of spectrally bright hard x-rays, and demonstrates that PXR production is directional, quasi-monochromatic and tunable.

The absolute PXR yield (photons/electron) has been obtained by simultaneously monitoring the x-ray fluorescence from a tin foil placed directly behind the PXR target[3] The crystal was a 1.39 mm thick mosaic compression annealed pyrolytic graphite (CAPG), a form of highly oriented pyrolytic graphite (HOPG), which is reported to have the highest x-ray reflectivity of any known crystal[4]. Fig. 2 illustrates the experimental arrangement. Optical transition radiation was used to align the beam and crystal[5,6]. The <002> reflection planes are parallel to the face of the crystal so that the PXR is produced in the Bragg geometry. Since graphite is not a good optical reflector, a small mirror mounted coplanar to the surface was used to align the crystal.

The Bragg condition, $2d\sin\theta_B = n\lambda$, defines the resonance condition for the production of PXR. Figure 2 illustrates the experimental arrangement for silicon in a Laue geometry for which the Bragg angle, $\theta_B = 22.5°$. Figure 3 shows a series of spectra for mosaic graphite in a Bragg geometry for Bragg angles varying from 19.1° to 25.6° and a fixed detector angle θ_B=45°. The fall off of intensity of the high order spectra as θ_B departs from 22.5° is due to the fact that the spectral line falls off the fixed detector aperture as shown in Fig. 1.

IV. DISCUSSION

Table 1 presents the measured PXR yields for a Bragg scattering angle of 22.5°. The electron energy in this case was 90 MeV. The important observation to be made here is that the measured yields for the higher order peaks are many times larger than predicted by theory. We are theoretically investigating several possible mechanisms to explain our observations, but our present understanding of the phenomenon is incomplete[2]. Our experiments involving PXR from the $\langle 111\rangle$ and $\langle 022\rangle$ planes of silicon have definitely shown that the yield for the higher orders increases with thickness[2]. There is also some evidence that the enhancement over theory observed in graphite may not exist for silicon. We are planning further experiments to investigate the role of the mosaic structure of the graphite target.

order n	Energy (keV)	PXR Yield (N/e) 10^{-9}	Theory Yield (N/e) 10^{-9}	$\frac{\text{Data}}{\text{Theory}}$
1	4.88	1670	5230	0.3
2	9.53	1720	990	1.7
3	14.29	850	240	3.6
4	19.08	420	80	5.3
5	23.88	230	34	6.9
6	28.68	130	16	8.3
7	33.56	68	8	8.8
8	38.44	34	4	8.8

Table 1. Measured and Theoretical PXR yields in graphite.

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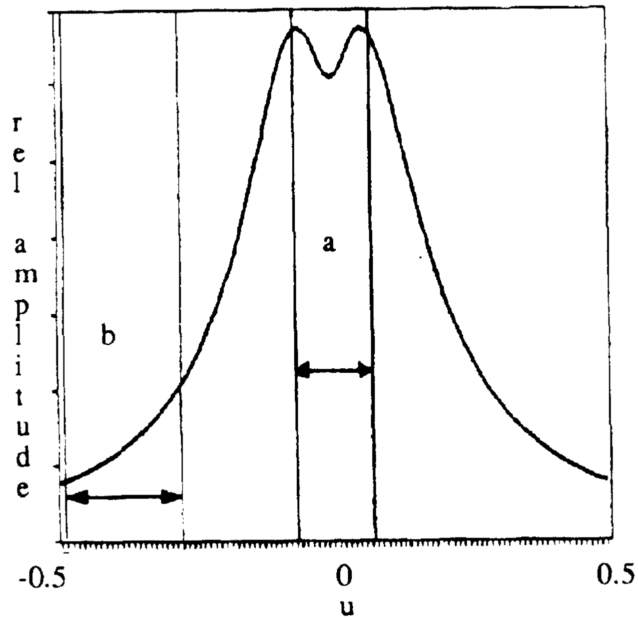

Figure 1. The spectral function $J_2(u)$. The regions between the vertical lines represent the bandwidths Δu corresponding to the detector aperture $\Delta\theta_X$ for crystal orientation a) $\theta_B = 22.5°$ and b) $\theta_B = 23.5°$

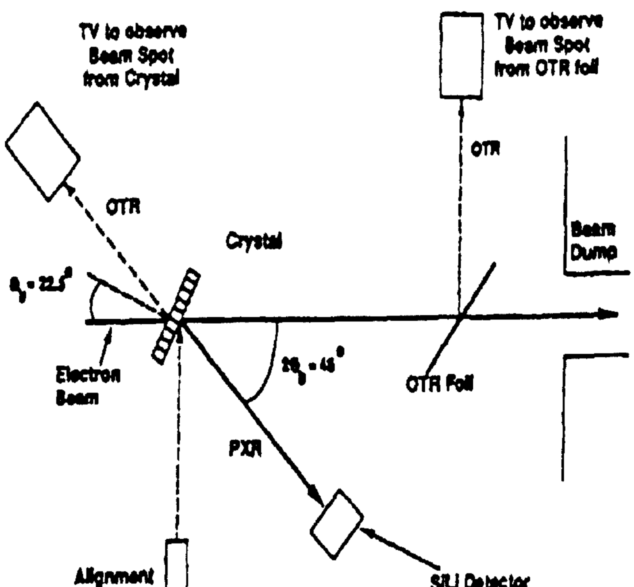

Figure 2. Experimental setup for observing parametric x-ray in the Laue geometry with $\theta_B = 22.5°$. In the Bragg geometry, the photons exit from the same side as the incoming electron beam.

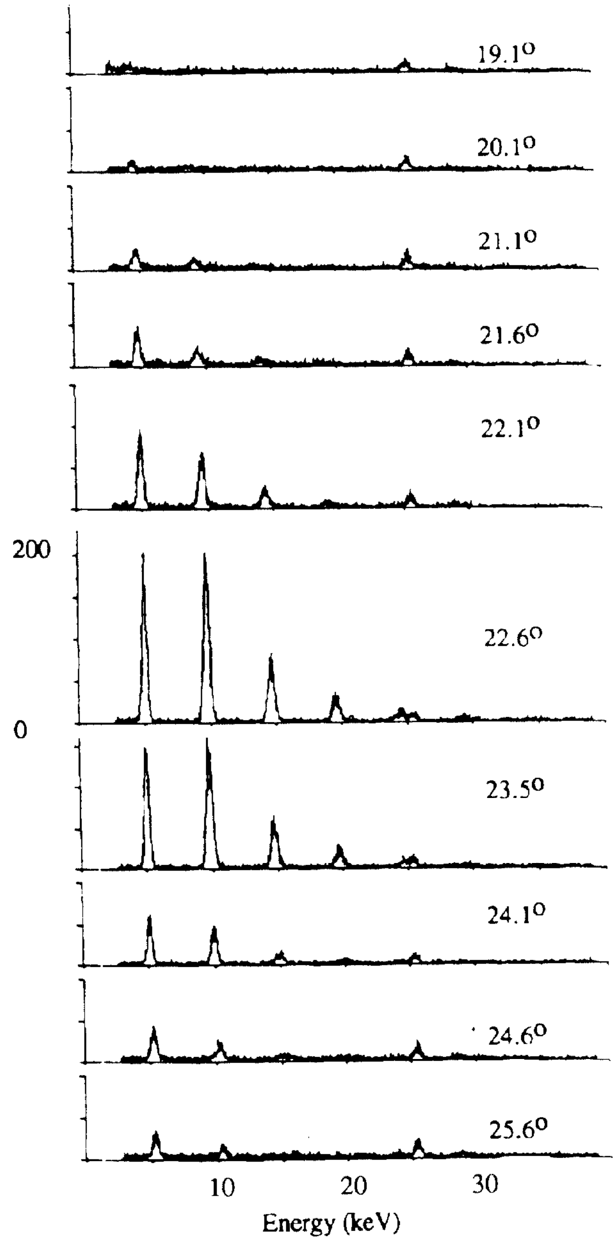

Figure 3. PXR spectra from the ⟨002⟩ plane of mosaic graphite, observed with the detector fixed at 45° and the crystal oriented at the indicated Bragg angles. The tin fluorescence line at 25.2 keV serves as an energy and beam intensity calibration peak.