Collimation Tests on a Coherent Photon Beam from a Silicon Target

L. Criegee, M. Garrell,* H. Sadrozinski

U. Timm and W. Zimmermann

Abstract

We have looked at the narrow coherent spikes produced in strongly collimated bremsstrahlung spectra from thin silicon crystals. Dependence of the spectra on crystal thickness and collimation has been confirmed. The quality of the spectra obtained from internal synchrotron targets is seen to be limited because of the primary divergence of the electron beam.

*Volkswagen Foundation Fellow

Thin crystalline targets inserted into an electron beam and properly oriented are a source of useful bremsstrahlung spectra for photoproduction experiments.¹⁻³ These spectra have two features of particular interest: 1) coherent spikes in the photon energy distributions which dominate the lower half of the spectrum and rise above a background of incoherent radiation, and 2) high polarization of the photons at these spikes.

Several authors^{4, 5} have pointed out the possibility of improving the monochromaticity and polarization at the spikes in the crystal spectra by strongly collimating the incident electron beam and the outgoing photon beam, and by using targets whose thicknesses are 10^{-3} radiation lengths or less. We have therefore studied strongly collimated spectra from silicon crystals of various thicknesses which were inserted into the internal beam of the DESY synchrotron at primary energies of about 2 GeV.

The experimental results show that, although the dependence of the spectra on crystal thickness and collimation can be seen, primary electron divergence in the synchrotron limits the improvement of the spectra. Our studies confirm the theoretically expected effect of collimation on coherent bremsstrahlung and lead us to the conclusion that real improvement of the coherent beam can only be achieved with an external electron beam where the divergence of electrons striking the crystal radiator can be controlled.

Collimation has two effects on a crystal spectrum. First, it narrows the width of the spikes without reducing their peak intensity. Second, it reduces the incoherent part of the spectrum. The incoherent part is reduced by a factor f' which depends on the collimation angle as well as the primary angular distribution of electrons producing bremsstrahlung. We estimate f' from the following two limiting cases: a) In the idealized situation in which the crystal is infinitely thin and the primary divergence of electrons is zero, the intensity of the incoherent part of

the bremsstrahlung is proportional to a factor f which depends on the relative collimation angle $\mathcal{V}_c = \theta_c/\theta_0$ where θ_c is the collimation angle, $\theta_0 = mc^2/E_0$ is the mean photon emission angle, m is the electron mass, and E_0 the primary electron energy. This factor f is found from integrating the bremsstrahlung distribution over the photon emission angle up to θ_c .

$$f(x) = x^2/(1 + x^2) , \quad x = \mathcal{V}_c \quad (1)$$

b) On the other hand, for the case of infinitely sharp collimation ($\theta_c = 0$) but finite electron divergence, the intensity of the incoherent bremsstrahlung is proportional to a factor of the same form which now depends on the size of the relative angle of divergence $\mathcal{V}_e = \theta_e/\theta_0$, where θ_e is the mean angle of the electron angular distribution.

In the actual experimental situation, we assume that the proportionality factor f' will depend to a first approximation on both $\mathcal{V}_c$ and $\mathcal{V}_e$ in the following way:

$$f'(\mathcal{V}_c, \mathcal{V}_e) = f(\mathcal{V}_c) + f(\mathcal{V}_e) - f(\mathcal{V}_c) \cdot f(\mathcal{V}_e) \quad (2)$$

f' approaches unity whenever one of the two variables becomes large, and it depends only on $\mathcal{V}_c$ when $\mathcal{V}_e$ is extremely small and vice versa. The reduction of the incoherent part of the spectrum is significant for collimated spectra because the coherent part, to a good approximation, is not reduced by collimation. Hence the ratio of coherent to incoherent intensities displays the experimental effect of collimation.

The effect of collimation on the coherent spikes is seen principally in their widths. The low energy tail of a spike is cut off at an energy $(x_s - \Delta x)$, where x_s is the peak energy of the spike measured in units of E_0 , and the width of the spike,

$$\Delta x = x_s \cdot \mathcal{J}_c^2 \cdot (1 - x_s) / (1 + \mathcal{J}_c^2(1 - x_s)) \quad (3)$$

is a function of the relative angle of collimation $\mathcal{J}_c$. There is a slight intensity reduction from the electron angular spread which tends to smear out the exact experimental definition of crystal orientation. Therefore we have averaged the spectrum over the orientation angles in the range of the electron spread Θ_e or over the collimation angle Θ_c whichever is smaller (in the same way as described in Ref.2). We find that this averaging has an effect of only a few per cent on the peak height of the spikes for the synchrotron energies at which data were taken.

We have measured spectra from silicon monocrystals which were mounted in a goniometer in the DESY internal beam. Silicon was used because it has a rather high Debye temperature and can be obtained in thin samples. The crystals had thicknesses of 1000, 200, and 40 microns ($1\mu = 10^{-3}$ mm). They were usually oriented to give the most prominent coherent radiation from nuclei in the $\bar{2}20$ or 220 crystalline planes. The 2 GeV energy region was chosen because the electron beam occupies the smallest phase space in the synchrotron near this energy, and we thus expect the smallest possible primary divergence of electrons striking the target. In addition the relative collimation angle is reduced by using small energy values.

Bremsstrahlung spectra for the 1000 and 40 micron crystals are shown in Figures I and II respectively. The curves drawn on the figures represent theoretical spectra obtained from the bremsstrahlung cross section formulae. These plots follow the bremsstrahlung convention of References 2 and 3:

$$\begin{aligned} I &\equiv (x/\sigma_o \cdot N) \cdot d\sigma/dx \\ x &= k/E_o \\ \sigma_o &= 5.78 Z^2 \cdot 10^{-28} \text{ cm}^2 \\ N &= \text{number of target atoms} \\ d\sigma/dx &= \text{differential cross section} \end{aligned}$$

The fitting procedure is essentially three steps. First the collimation angle Θ_c is calculated from the collimator size and position and corrected for finite target spot. Secondly, the angle of divergence is taken to be:

$$\Theta_e = (\Theta_{ms}^2 + \Theta_d^2)^{1/2} \quad (4)$$

Θ_{ms} is the multiple scattering angle given by the Molière formula and Θ_d is the electron divergence of the synchrotron beam. Finally the free parameter Θ_d is used to fit the observed relative intensity of the incoherent part of the spectrum to its coherent part. The experimental points are normalized to the theoretical curve at the high energy end of the spectrum. A more expanded discussion can be found in the Diplom Thesis of H. Sadrozinski. (DESY Report soon to be issued).

The thick crystal spectrum and the thin crystal spectrum gave experimental values of $f' = 0.94$ and 0.50 respectively. The collimation angles used to fit the data in these two cases were $\Theta_c = 0.18 \pm 0.01$ and 0.16 ± 0.01 mrad. Although actual collimator size and position gave 0.10 mrad, the target spot extension due to multiple scattering or multiple traversals increases the effective collimation angle. For the thick crystal spectrum the electron beam divergence is much smaller than the multiple scattering angle $\Theta_{ms} = 0.75$ mrad, so the fit is obtained with $\Theta_d \ll \Theta_{ms}$. For the thin crystal spectrum we have $\Theta_{ms} = 0.14$ mrad, and the fit requires $\Theta_e = 0.17$ mrad which determines the electron beam divergence to be $\Theta_d = 0.10 \pm 0.02$ mrad. This electron beam divergence is due to the multiple traversals of the beam through the thin target as well as to the primary divergence of the synchrotron beam itself.

Although we tried to obtain better spectra by using movable tantalum blocks ahead of the crystalline target, these attempts failed. Scraper blocks do cut the number of multiple traversals (by two orders to magnitude for a target 10^{-4} radiation lengths thick)⁶ but the electron beam divergence remains approximately the same, and the spectra are no better. However to reduce the target spot extension, it was found most practical to use a target whose horizontal dimension in the synchrotron was small, i.e. about 2 mm. Such a target was used in the case of Fig.II.

For our thin crystal spectrum we can calculate the proportionality factor for the actual collimation $\Theta_c = 0.10$ mrad, assuming no target spot extension, and for $\Theta_d \ll \Theta_{ms}$, assuming no sources of divergence except multiple scattering. In this case $f' = 0.35$. (See Fig. IIb). We note that, while such large reductions of incoherent background in thin crystal bremsstrahlung spectra are probably not possible for an internal target arrangement like ours at DESY, such reductions appear feasible for experiments carried out in an external beam.

Acknowledgement

We gratefully acknowledge the assistance of Mr. Kumpfert and the members of the DESY machine group as well as Miss W. Kuffner, and Mr. W. Marxen. We also thank Dr. Harstorff from the Institut für Angewandte Physik Hamburg for his help in preparing thin silicon crystals. One of us (M.H.G.) wants to acknowledge support obtained from the Stiftung Volkswagen for his work.

References

1. G. Barbiellini, G. Bologna, G. Diambrini, G. P. Murtas,
Phys. Rev. Letters 8, 454 (1962).
2. G. Bologna, G. Lutz, H. D. Schulz, U. Timm and W. Zimmermann,
Nuovo Cimento A42, 844 (1966).
3. L. Criegee, G. Lutz, H. D. Schultz, U. Timm, and W. Zimmermann,
Phys. Rev. Letters 16, 1031 (1966).
4. R. F. Mozley and J. DeWire, Nuovo Cimento 27, 1281 (1963).
5. G. Bologna, Nuovo Cimento A49, 756 (1967).
6. E. Raquet and U. Timm, DESY Report No. 68/24.

Figure Captions

Fig.I: Bremsstrahlung spectrum from 1000 micron Si crystal. The curve represents the theoretical spectrum obtained from the bremsstrahlung cross section formula, following the convention of Refs. 2 and 3. For this case, $f' = 0.94$, $\theta_c = 0.18 \pm 0.01$ mrad, $\theta_{ms} = 0.75$ mrad, and $\theta_{ms} \gg \theta_d$.

Fig.IIa: Bremsstrahlung spectrum from 40 micron Si crystal, target width: 2 mm. This spectrum gives $f' = 0.50$, and the theoretical spectrum is fit by $\theta_c = 0.16 \pm 0.01$ mrad, $\theta_{ms} = 0.14$ mrad, and $\theta_d = 0.08 \pm 0.03$ mrad. Electron beam divergence is due to multiple traversals as well as the primary divergence of the synchrotron beam.

Fig.IIb: Theoretical spectrum for 40 micron Si crystal for the case $\theta_c = 0.10$, $\theta_{ms} = 0.14$ mrad, and $\theta_d \ll \theta_{ms}$. This spectrum gives $f' = 0.35$. Such a spectrum appears feasible in an external electron beam.

Fig. I

Fig. II