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The Stonehenge technique. A method for aligning coherent bremsstrahlung radiators

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ABSTRACT

This paper describes a technique for the alignment of crystal radiators used to produce high energy, linearly polarized photons via coherent bremsstrahlung scattering at electron beam facilities. In these experiments the crystal is mounted on a goniometer which is used to adjust its orientation relative to the electron beam. The angles and equations which relate the crystal lattice, goniometer and electron beam direction are presented here, and the method of alignment is illustrated with data taken at MAMI (the Mainz microtron). A practical guide to setting up a coherent bremsstrahlung facility and installing new crystals using this technique is also included.

1. Introduction

In the coherent bremsstrahlung technique a thin crystal oriented correctly in an electron beam can produce photons with a high degree of linear polarization [1]. A typical photon energy spectrum is shown in Fig. 1, where the region of high polarization is under the peak to the left of the *coherent edge* whose position depends on the orientation of the crystal relative to the electron beam. The crystal is mounted on a goniometer to control its orientation, but in order to be able to set up coherent bremsstrahlung it is first necessary to measure an appropriate set of angular offsets between the crystal axes and electron beam direction. A method for measuring offsets and aligning the crystal was developed by Lohman et al., and has been used successfully in Mainz [2]. This method is effective when the orientation of the crystal in the lab frame is already known to within a few degrees, and the crystal lattice is *adequately aligned* with the electron beam to begin with. The definition of *adequately aligned* here depends strongly on the electron beam energy. For example, at an energy of 855 MeV an initial alignment to within about 1.0° is adequate, and is achievable by laser measurement and careful mounting of the crystal in the goniometer. Moving up in energy to ~5 GeV, an initial alignment within ~0.2° would be required and this is, in practical terms, very difficult to achieve. Also, alignment with a laser has to be made relative to the cut face of the crystal, and experience has shown that this is not necessarily parallel to the lattice planes. This paper describes an alignment technique which overcomes these limitations. The technique is now used as standard at MAMI in Mainz, CB-ELSA in Bonn, MAXLab in Lund, and CLAS at Jefferson Laboratory. In all cases it allows a much faster alignment that with the previous method, and in the case of the higher energy facilities alignment would have been difficult or impossible without this method.

Wherever possible, specific examples are given to illustrate the technique, and Section 7 outlines some general methods for installing new crystals and measuring the angular offsets of the electron beam in the goniometer reference frame.

2. Coherent bremsstrahlung—a simplified view

To provide a linearly polarized photon beam for an experiment we need to be able to adjust the orientation of the polarization plane and the shape of the photon intensity distribution which determines the degree of linear polarization in the photon energy range of interest. The main coherent peak is produced by scattering from one specific set of crystal planes, represented by reciprocal lattice vector $\boldsymbol{g} = [g_x g_y g_z]$. In practice a thin diamond crystal cut in the 100 orientation is used and the main peak is produced by scattering from the set of planes represented by the [0 2 2] or [0 2 $\bar{2}$] reciprocal lattice vector, since this produces the highest polarization. For simplicity, formulae and examples will be presented for these conditions with some remarks on how to generalize to other crystals in different orientations, and different lattice vectors. The parameters of interest are illustrated in Fig. 2,

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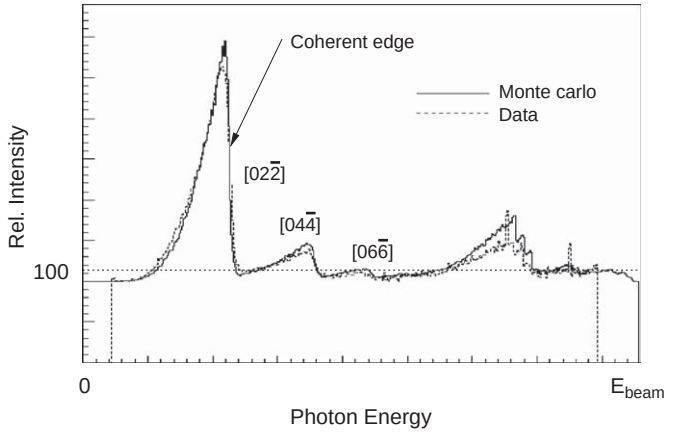

Fig. 1. Typical coherent bremsstrahlung enhancement spectrum. The spectrum obtained from the crystal is divided though by a reference spectrum from an amorphous radiator and normalized to be 100 in regions where there is only a small coherent contribution.

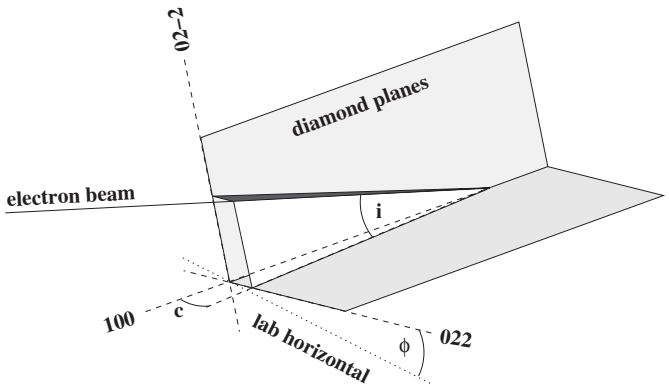

Fig. 2. Illustration of the scattering angles for coherent bremsstrahlung from a diamond in the 100 orientation. The sets of planes defined by the [0 2 2] and [0 2 $\overline{2}$] lattice vectors are represented by two single orthogonal planes.

where the sets of crystal planes defined by the [0 2 2] and [0 2 $\overline{2}$] lattice vectors are represented by two orthogonal surfaces.

The angle of the polarization plane is fixed by ϕ, the azimuthal orientation of the 022 axis relative to the lab horizontal, and the position of the main coherent edge (specifically, its fractional energy $x = E_{edge}/E_{beam}$) is controlled by the angle c between the electron beam and the [0 2 $\overline{2}$] planes. In practice then c must be adjusted to position the main coherent peak at the region of interest. This will also set the position of subsequent *harmonics*. For example, in Fig. 1 the main peak is produced by scattering from the [0 2 $\overline{2}$] planes and subsequent lower strength peaks from [0 4 $\overline{4}$] and [0 6 $\overline{6}$] are also clearly visible; all of these move *in-concert* as the angle c between the beam and the [0 2 $\overline{2}$] planes is adjusted. To control the remaining components of the distribution, whilst keeping the main coherent peak (and harmonics) fixed, requires adjustment of the angle i between the electron beam and the direction orthogonal to c. This angle will generally be set higher than c by a factor of about 4, to position the coherent contributions from the orthogonal planes at a high photon energy beyond the peak of interest.

Referring to Fig. 2, we choose the values of ϕ, c, i as follows:

(1) ϕ—the angle between the 022 axis and the horizontal.
This is simply selected by deciding which orientation of the polarization plane is best for the detector geometry of the experiment. Often, for systematics, experiments are run with two orthogonal settings of the polarization plane, ϕ and $\phi + \pi/2$. For practical reasons this is most easily achieved by swapping the values of c and i, rather than adjusting ϕ. With c, i as show in Fig. 2, the polarization plane is ϕ. Swapping them makes the polarization plane $\phi + \pi/2$. A further common simplification is to use PARA/PERP polarizations, where the polarization plane is parallel or perpendicular to the lab horizontal.

(2) c—the small angle between the beam and the [0 2 $\overline{2}$] planes which fixes the position of the coherent edge.
For a diamond in the 100 orientation, if we restrict our interest to the position of the coherent edge from $\boldsymbol{g} = [0\,2\,2]$, [0 2 $\overline{2}$], [0 4 4], [0 4 $\overline{4}$], etc. then c (in radians) can be calculated as follows:

$$c \simeq \frac{k}{gE_0^2\left[\frac{1}{E} - \frac{1}{E_0}\right]} \tag{1}$$

where $g = \pm 2, \pm 4, \pm 6, \ldots$, E is the required position of coherent edge (MeV), E_0 = electron beam energy (MeV), $k = m_e a/4\sqrt{2}\pi = 26.5601$ MeV, m_e is the mass of electron = 0.511 MeV and a is the diamond lattice constant = 923.7 (dimensionless units).
In practice, the coherent edge position E should be reasonably close to the calculated value, but this depends on how accurately the initial angular offsets are measured during the setup (see Section 7). The position of the coherent edge is tuned by looking at enhancement spectra and making small adjustments to c.

(3) i—the angle between the beam and the orthogonal planes.
This is set to be larger than c by about a factor of 4 and then tuned using feedback from the enhancement spectra. It needs to be adjusted to ensure that the main coherent peak is as *clean* as possible and that there are no interfering contributions from any higher order lattice vectors.

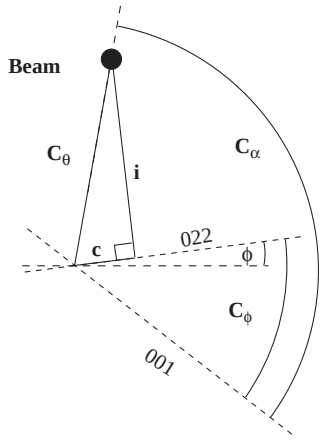

Fig. 3. Diagram showing the relationship between $c, i.\phi$ and crystal angles $C_\theta, C_\alpha, C_\phi$.

For the purposes of comparing with bremsstrahlung calculations it is necessary to describe the orientation in terms of the crystal angles[1] $C_\theta, C_\alpha, C_\phi$, where C_θ, C_α are the polar and azimuthal angles of the electron beam in the reference frame of the crystal (defined by the 100, 010, 001 axes) and C_ϕ is the azimuth of $\boldsymbol{g}$ in the same reference frame. This is represented in Fig. 3, which is effectively a

[1] In Lohman's paper [2] the crystal angles are simple defined as θ, α, ϕ, but to make it clear that they relate to the crystal coordinate system, as opposed to the goniometer system they are labeled here as $C_\theta, C_\alpha, C_\phi$.