3.6 A High-Energy, High-intensity and Highly Polarized Photon Beam for ELFE@CERN using Coherent Bremsstrahlung

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Coherent Bremsstrahlung is investigated with the aim to produce a high-energy, high-intensity and highly polarized photon beam from a quasi-continuous 25 GeV electron beam. All presented numerical results are based upon the electron beam parameters as they are known for ELFE at CERN. Such photon beam could be used in high-energy photoproduction experiments such as GDH, Apollon, Real Compton Scattering (RCS) and Vector Meson production.

3.6.1 Photon Beam Requirements

Table 3.6.1 gathers the photon beam requirements for the 4 main experiments which are proposed and have been studied so far (*cfr.* Chapter 1, Theoretical Motivation).

	GDH	Apollon	RCS	Meson prod.
E_γ [GeV]	3 - 20	> 18	8 - 12	3 - 20
$\Delta E/E$ [%]	< 3	< 0.5	< 0.1	< 0.1
Tagged photons intensity [s^{-1}]	$\sim 10^6$	$> 4 \cdot 10^6$	10^8/GeV	10^7
Circular polarization [%]	> 50	> 50	> 50	> 50
Linear polarization [%]	-	-	-	30 - 80

Table 3.6.1: *Photon beam requirements for GDH, Apollon, Real Compton Scattering (RCS) and Vector-Meson photoproduction in terms of energy, energy spread, tagged photons intensity (flux) and percentage of circular and linear polarization.*

From table 3.6.1, it can be deduced that, in terms of flux, the most demanding experiment is the real Compton scattering experiment. In particular, such a high flux strongly constrains the tagging system performances which are discussed in Section 3.7. Another constraint which has to be emphasized is the requirement to have a high degree of linear polarization available for the vector-meson production measurement at high energy.

In the following, we will investigate the Coherent Bremsstrahlung (CBS) process in order to meet as many requirements as possible.

3.6.2 Properties of coherent bremsstrahlung

It has been known for a long time (for details, see ref. [1] - [7]) that replacing the conventional amorphous or polycrystalline radiator used in bremsstrahlung by a thin, oriented, mono-crystalline wafer reduces the background by increasing the ratio of hard to soft photons and, in addition, gives rise to a supplementary contribution, which is linearly polarized. Amorphous and Coherent Bremsstrahlung are both based on electron scattering : in the latter process the scattering occurs off the whole crystal whereas in the former it occurs off single atoms. The adjective 'coherent' refers to the effect of multiple atoms in a crystal lattice (Bragg scattering) absorbing the recoil momentum from a high-energy electron coherently when it radiates a photon. Due to the regular structure of a crystal an enhancement of the bremsstrahlung yield occurs for specific photon energies, which depends on the crystal orientation with respect to the incident electron momentum. The photon spectrum off a crystal radiator consists of two contributions (see Fig. 3.6.1) :

- an incoherent, unpolarized part which is invariant under crystal rotation and independent of crystal structure (the ordinary $1/k$ Bremsstrahlung spectrum, the continuum). Nevertheless, the intensity of this incoherent Bremsstrahlung is less than what one would obtain using an amorphous radiator.
- a coherent part, appearing as a set of peak structures of which the intensities and positions are very sensitive to the crystal orientation. Only the 'coherent' photons are linearly polarized and their degree of polarization is only decreased by the amount of incoherent bremsstrahlung which occurs at the same time.

The coherent cross section is a sum over all lattice vectors (see [6]). Each contribution increases with the relative photon energy x ($x = k/E$, k and E being the final photon and the incident electron energy, respectively) up to a discontinuity x_d giving rise to a peak-like structure in the spectrum. Experimentally, due to the finite electron beam spot size, multiple scattering in the radiator and mainly electron divergence, the electrons have different directions which leads to a variation in the orientation of the electron beam with respect to the lattice. This results in superimposing bremsstrahlung yields with varying discontinuities, which smears out sharp structures and depletes the polarization. Collimating the photon beam enhances the degree of linear polarization and counteracts the effect of the electron divergence.

From the literature, it is well-known that there exist two main features which can be exploited using coherent bremsstrahlung. One can either obtain :

- a high degree of linear polarization [5] at low and moderate energy (for k_d about one third of the incident electron energy),

- a high flux near the end point [6].

To benefit from these Coherent Bremsstrahlung properties, it will be shown in the next section that one can vary the crystal orientation in order to improve the ratio of coherent to incoherent bremsstrahlung for the photon energies required in the proposed experiments.

3.6.3 Calculations and Results

Since the advent of high duty cycle electron accelerators with a high quality beam, the Coherent Bremsstrahlung process (CBS) has been experimentally investigated. All studies have lead to a good understanding of CBS and it can now be calculated to the 2% level (for more details, see [8]).

The code ANB (ANalytical Bremsstrahlung) that was used for the calculations has been developped by F.A. Natter [9]. First predictions for a linearly polarized photon beam of 8 GeV for ELFE@CERN have been presented in [10].

The beam parameters used for all calculations are listed in Table 3.6.2. Further information on the ELFE beam properties can be found in [12].

Beam characteristics	Values	Units
Horizontal & Vertical beam spot size at radiator	1.0	mm
Horizontal & Vertical beam divergence	0.01	mrad
Energy spread	0.017	GeV
Energy gain per pass	3.5	GeV
Maximum Energy	24.6	GeV

Table 3.6.2: *ELFE Beam characteristics.*

In the ELFE design, the maximum electrom beam energy is reached after 7 passes. We have also assumed that it will be possible to extract the beam after 4 passes to obtain a 14.7 GeV electron beam.

Before using the code ANB [9], one has to determine the optimized orientation of the crystal lattice for each electron beam energy and each desired photon energy; for further details, see ref. [8]. For all sets of electron (E_e) and desired photon energies (k_d), we have listed in Table 3.6.3, the azimuthal (α) and the polar (θ) angles of the crystal lattice with respect to the electron momentum. For all calculations, to maximize the degree of polarization, we have chosen $\phi = 45°$.

Beam Energy (GeV)	Discontinuity k_d (GeV)	α (rad)	θ (rad)
24.6	20.0	0.737	0.049
24.6	16.0	0.754	0.032
24.6	12.0	0.763	0.023
24.6	10.0	0.766	0.019
24.6	8.0	0.769	0.016
14.672	12.0	0.722	0.064
14.672	10.0	0.742	0.044
14.672	8.0	0.752	0.033

Table 3.6.3: *Combination of crystal angles, corresponding to different sets of electron and desired photon energies. (For the electron energies, energy losses due to synchrotron radiation have been taken into account).*

All the desired discontinuities listed in Table 3.6.3 can be obtained by only a few combinations of crystal angles. The values of θ and α have been chosen to facilitate the crystal alignment. As a matter of fact, due to the high electron energy, the discontinuity is very sensitive to the crystal angles (θ,α); these would have to be adjusted to an accuracy less than half a milliradian. A method for accurate crystal alignment is being investigated and could be implemented [13].

Out of a set of 9261 contributing lattice vectors (Miller indices $|h_i| \leq 10$) the 100 strongest contributing vectors were used in this calculation. Each other vector contributes less than 10^{-4} to the cross section with respect to the strongest one, which justifies the limitation of this calculation to only 100 vectors.

All parameters related to the radiator and which were used in the calculation are listed in Table 3.6.4.

Radiator thickness	0.05 mm
Radiator temperature	293.17 K
Z of Diamond Radiator	6
Z of Nickel	30 (used as amorphous radiator)
Incident beam current	1 μA

Table 3.6.4: *Radiator parameters used in the calculation.*

Using these parameters for a 24.6 GeV electron beam and a discontinuity at 12 GeV, one obtains a typical uncollimated coherent bremsstrahlung spectrum which is represented in Fig. 3.6.1 (top plot). The top part of this figure also shows the incoherent part (dashed line) which has been calculated for an amorphous Nickel radiator. In the calculation only Nickel has been implemented as the amorphous radiator so far. The bottom part in Fig. 3.6.1 represents the relative flux which corresponds to the total flux (solid line of top plot) divided by the 'incoherent' part (dashed line of top plot). In the following, one of our goals will be to vary the available parameters in order to maximize this relative flux at the required photon energy (discontinuity).

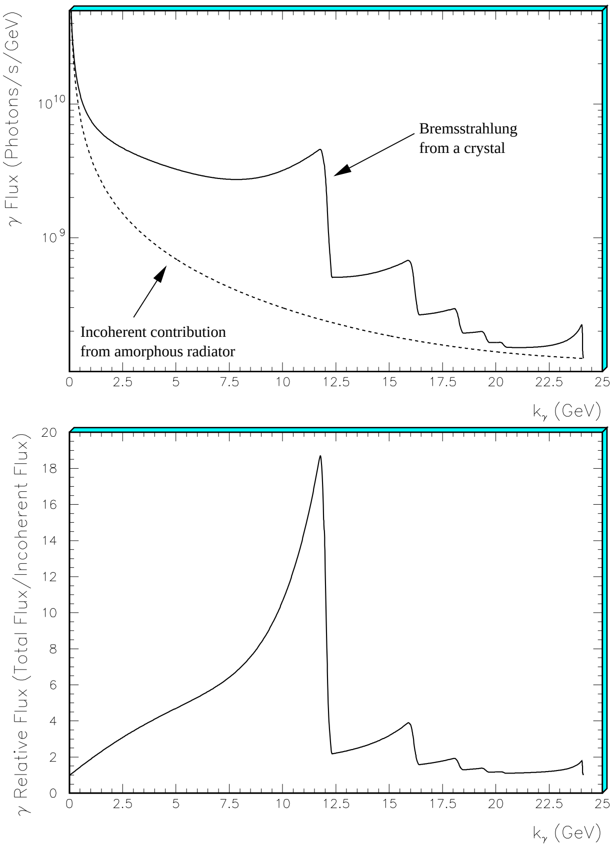

Figure 3.6.1: *The top plot represents the typical uncollimated coherent (solid line) and incoherent (dashed) bremsstrahlung spectra corresponding respectively to a 50μm thick diamond crystal radiator and an amorphous radiator. The calculation assumes a 1μA electron beam of 24.6 GeV and the discontinuity has been fixed at 12 GeV. The bottom plot represents the relative flux corresponding to the ratio of 'total' to 'incoherent' bremsstrahlung.*

To reduce the rate of 'incoherent' photons and maximize the relative flux, it will shown that one can collimate the photon beam. Maximizing the relative flux means also increasing the degree of linear polarization as only the coherent part is linearly polarized.

Collimation of the photon beam

Collimating the photon beam in order to increase the relative flux requires the adjustment of the collimator radius and of the distance between the radiator and the collimator. From the current layout of ELFE@CERN and within the context of this report, it has been decided to fix the distance from radiator to collimator at 75m. Moreover, as it has been observed from the calculation that the length of the collimator was not a sensitive parameter, we have used a collimator with a length of 16 cm. In order to determine the optimized collimator radius we have plot the total flux, the relative flux and the degree of linear polarization versus a set of collimator radii as shown in Figs. 3.6.2 (k_d=12 GeV) and 3.6.3 (k_d=20 GeV) for a 24.6 GeV electron beam.

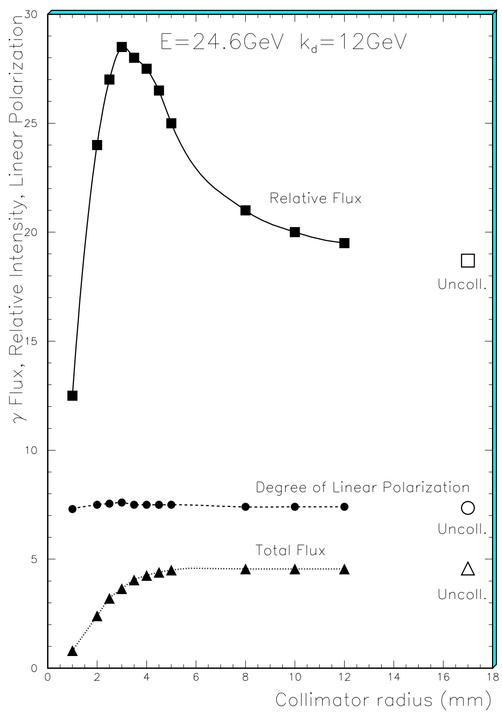

Figure 3.6.2: *Total flux in units of 10^9 photons/s/GeV, relative flux and degree of linear polarization (scaled up by a factor 10) versus collimator radius. All the points refer to an electron beam of 24.6 GeV and 1μA. The calculation has been performed for a discontinuity k_d of 12 GeV. The distance from radiator to collimator is 75 m. The 3 empty symbols plotted at a collimator radius of 17 mm correspond to an uncollimated photon beam.*

From Figs. 3.6.2 (k_d=12GeV) and 3.6.3 (k_d=20GeV), one notices that the relative flux reaches a maximum for a collimator radius of about 3 mm and then decreases. The behaviour of the total and relative fluxes is related to the ratio

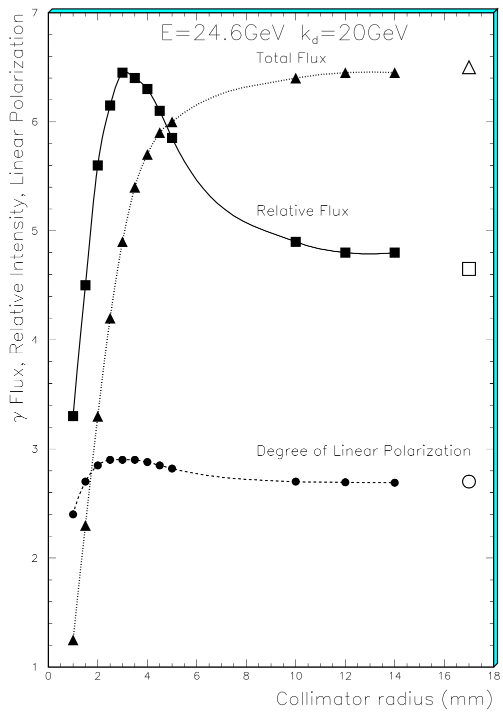

Figure 3.6.3: *Total flux in units of 10^8 photons/s/GeV, relative flux and degree of linear polarization (scaled up by a factor 10) versus collimator radius. All the points refer to an electron beam of 24.6 GeV and 1μA. The calculation has been performed for a discontinuity k_d of 20 GeV. The distance from radiator to collimator is 75 m. The 3 empty symbols plotted at a collimator radius of 17 mm correspond to an uncollimated photon beam.*

of the coherent/incoherent part of the spectrum that one is cutting away by the collimator. As a matter of fact, if the collimator radius is too small then one is cutting away both coherent and incoherent photons. Due to a finite beam spot size, as the collimator radius increases one is favouring the coherent part due to its more forward angular distribution, until a maximum in the relative flux is reached. Beyond this maximum, increasing the collimator radius does no longer enhance the relative flux but is increasing the total flux as one is cutting less and less from both spectra.

In Fig. 3.6.4, representing the total and the relative fluxes for an electron beam of 24.6 GeV and 1μA, one can see the effect of collimating the photon beam (k_d=12 GeV), with a collimator (the radius of which equals 3 mm), situated at 75 m from the radiator.

It has to be emphasized that collimation is very sensitive to the electron beam properties such as beam spot size and emittance (see references [10] [7]). As an example, with a electron beam diameter of 500μm instead of 1 mm one can obtain the same result as the one represented in Fig. 3.6.4 (for the collimated photon beam) by placing a 1.5 mm radius collimator at 40 m. Further simulations taking into account 'real' electron beam parameters, will have to be performed to reach a final design (i.e. the precise diameter and distance of the collimator).

Table 3.6.5 summarizes all the collimator parameters used to obtain the results presented on page 154.

Collimator length	160 mm
Distance from radiator to collimator	75 m
Collimator radius	3 mm

Table 3.6.5: *Collimator parameters used in the calculation.*

Crystal thickness

The range of permissible thicknesses for a crystal radiator is restricted on both sides. It is limited at the higher thickness because of multiple scattering of the electron beam as it passes through the radiator, which causes a growth of the divergence of the incident beam, thereby enlarging the photon beam spot at the collimator and degrading the degree to which the collimator discriminates against the incoherent component in favour of the coherent part. At lower thicknesses it is governed by the fact that the crystal must have some minimum thickness in order to achieve the full coherent gain. From Reference[7], this minimum thickness can be evaluated by calculating the coherence length λ which depends upon both the electron energy and the photon energy.

$$\lambda = \frac{2e\,(1-x)}{x\,m^2} \qquad \textit{in units of } \hbar c \tag{6.1}$$

For a 24.6 GeV electron beam and a 20 GeV photon beam, the coherence length is about 30 nm. This shows that the coherence length does not impose a limit on how thin the radiator should be. Now, the determination of how thick the radiator should be is, as said above, depending upon the multiple scattering in the crystal and on the collimator radius. From our calculations, a 50μm thick diamond crystal seems to be a good compromise using a 3 mm radius collimator.

Circular Polarization

Using coherent bremsstrahlung, one will obtain linearly polarized photons but the experiments such as GDH, real Compton scattering, Apollon and the photoproduction of vector mesons require circularly polarized photons. In references [14] [6] , it has been shown that the helicity is transferred from polarized electrons to bremsstrahlung produced photons as follows :

$$\frac{P_\gamma}{P_{e^-}} = \frac{4x - x^2}{4 - 4x + x^2} \tag{6.2}$$

with $x = \frac{k_\gamma}{E_{e^-}}$

Assuming that one could use a linearly polarized electron beam, from equation 6.2 one can calculate what the degree of circular polarization would be that one could obtain from a 24.6 GeV or from a 14.7 GeV electron beam. An electron energy of 14.7 GeV could be reached extracting the beam after 4 passes. This could be interesting for our purposes as the degree of circular polarization is maximum at the end point (x=1). In Fig. 3.6.5, one observes that for a 12 GeV photon beam, the degree of circular polarization is 46% from a 24.6 GeV polarized (75%) electron beam, but reaches 71% for a 14.7 GeV polarized (75%) electron beam. This result shows that, in order to meet the polarization requirements listed in Table 3.6.1 (page 141), it would be an important advantage to have the possibility for extracting the electron beam after 4 passes.

Results

Using the parameters as quoted before (electron beam, radiator and collimator characteristics) as the input for the ANB code, one obtains the results which are summarized in Fig. 3.6.6. This figure shows the total flux, the relative flux and the degree of polarization that could be achieved for an electron beam of 24.6 GeV and 14.7GeV, respectively. For each electron energy, different discontinuity values have been considered corresponding to the specific experimental requirements. Technically, we should be able to rotate very accurately the crystal using a goniometer [13] in order to use photon beams of different energies.

3.6.4 Discussion and Conclusion

The calculations which have been performed so far show that one can produce a photon beam which meets most of the experimental requirements as formulated before.
A high degree of linear polarization (> 70 %) can be reached for photons of moderate energies (8-12 GeV) whereas only about 30 % of linear polarization is accessible for a 20 GeV photon beam.
In order to make a photon flux available with a degree of circular polarization

higher than 50 % in the energy range from 8 to 14 GeV, which is required in the Real Compton Scattering experiment, it is advisable extracting the electron beam after 4 passes. Experimentally, it should be possible to separate both polarization states (linear and circular) using their asymmetry dependence.
The results that have been obtained so far also show that a high intensity photon beam (i.e. higher than $10^8\,\gamma$/s/GeV) can be produced as determined by the experimental requirements. Moreover, our calculations have shown that the optimum radiator thickness is situated in the 10 - 50 μm range. On the other hand, the estimated tagging efficiency will only be of the order of 30 %.
Regarding the crystal radiator, it was assumed that one has a perfect single diamond crystal at ones disposal; however, even the very best crystals have some dislocations and other defects. All these imperfections will reduce the performance of the radiator and diminish its capability to withstand radiation damage. As far as the crystal lifetime is concerned, the SLAC group [7] observed that the performance of the used diamonds had considerably degraded after a total charge of about 3 Coulombs, accumulated over a surface of 6mm $\times$ 6mm in area. However, they also noticed that putting the damaged crystal through an annealing process, makes it recover from the damage. Although further studies are needed in this field, one can assume that with the proposed crystal radiator and 1μA of electron current, one could run for at least 5 weeks, which does not seem to be unreasonable taking into account the cost of the diamond radiator which is not excessive. In this respect, it should also be pointed out that the use of a cheaper material such as beryllium metal, is now under investigation but its properties remain to be experimentally proven.
All along this report, it has been emphasized that the quality of the photon beam produced in the coherent bremsstrahlung process, is strongly determined by the characteristics of the electron beam : in particular its divergence and its spot size. The relatively large values of these two quantities are at the origin of the rather low tagging efficiency. Besides, this large beam spot size foreseen in the ELFE@CERN option, necessitates the positioning of a collimator at a distance of 75 m from the radiator in order to meet the photon beam requirements. Evidently, such distance may put constraints on the lay-out of the envisaged experimental hall(s).

Bibliography

[1] G. Diambrini Palazzi : 'High-Energy Bremsstrahlung and Electron Pair Production in Thin Crystals', Reviews of Modern Physics, vol. 40, 611-631, 1968.

[2] U. Timm : 'Coherent Bremsstrahlung of Electrons in Crystals', Fortschritte der Physik 17, 765-808, 1969.

[3] H. Bilokon *et al.* : 'Coherent Bremsstrahlung in Crystals as a Tool for

producing High-Energy Photon Beams to be used in Photoproduction Experiments at CERN SPS', Nucl. Instrum. & Meth. 204, 299-310, 1983.

[4] D. Lohmann *et al.* : 'Linearly polarized photons at MAMI (Mainz)', Nucl. Instrum. & Meth. A343, 494-507, 1994.

[5] F. Rambo *et al.* : 'Enhancement of the linear polarization of coherent bremsstrahlung by collimation of the photon beam', Physical Review C, vol. 58, 489-501, 1998.

[6] B. Seitz, F.A. Natter, M. Düren, C.A. Miller : 'Using Coherent Bremsstrahlung for high energy photons at HERA and ELFE', this report : Section 3.4

[7] The Hall D collaboration : Design Report, version 2, August 1999, http://dustbunny.physics.indiana.edu/HallD/

[8] F.A. Natter : 'Production of Linearly Polarised Photons', Proceedings of the 4^{th} Workshop on 'e-m induced Two-Hadron Emission', Granada, May 26-29,1999.

[9] Code ANB (ANalytic Bremsstrahlung calculation, version 2.0, http://www.pit.physik.uni-tuebingen.de/grabmayr/

[10] F.A. Natter & P. Grabmayr : 'Prediction of Linearly Polarized Bremsstrahlung Production for ELFE at CERN' (Coherent Bremsstrahlung at ELFE energies, July 1999, to be published).

[11] F.A. Natter, P. Grabmayr, T. Hehl, R.O. Owens & S. Wunderlich, to be published in NIM.

[12] H. Burkhart *et al.* : ELFE at CERN : Conceptual Design Report', Yellow report, CERN-99-10.

[13] K. Livingston *et al.* : Stonehenge Technique : a method of crystal alignment for cherent Bremsstrahlung', report of the European Conference 'Electromagnetic Interactions with Nucleons and Nuclei', Santorini, Greece, 1999.

[14] H. Olsen, L.C. Maximon, Phys. Review 114, 887, 1959.

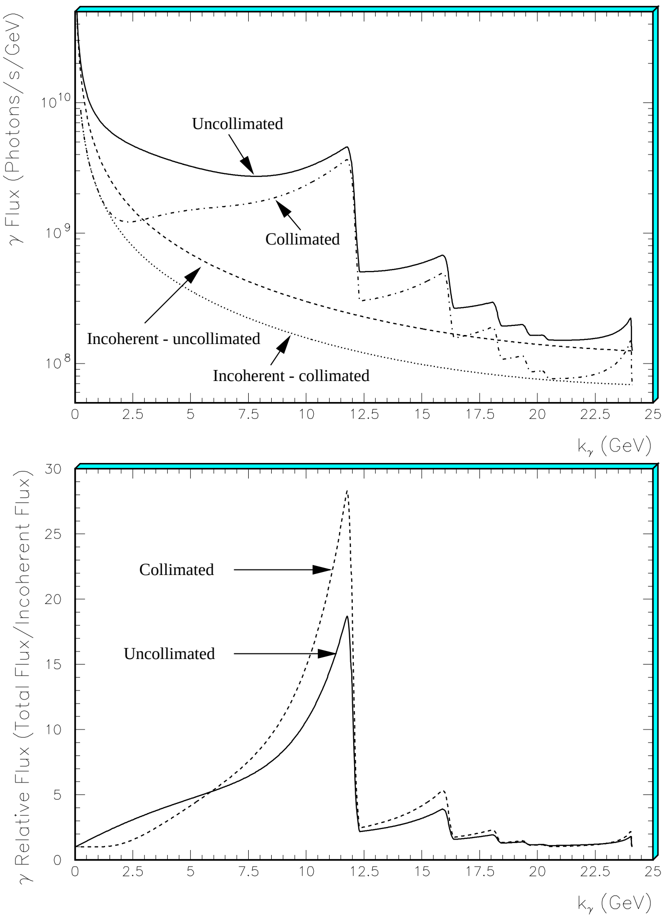

Figure 3.6.4: *Top plot : Total flux for an uncollimated (solid line) and for a collimated photon beam (dotted line), 'Incoherent' flux for an uncollimated (dashed line) and for a collimated photon beam (dot-dashed line). For a collimated beam the collimator is situated 75 m downstream the radiator and its radius is 3 mm. Bottom plot : relative flux for an uncollimated (solid line) and collimated photon beam as described in the text (dashed line). These calculatations have been performed for an incident electron beam energy of 24.6 GeV, with the primary discontinuity in the photon spectrum located at 12 GeV.*

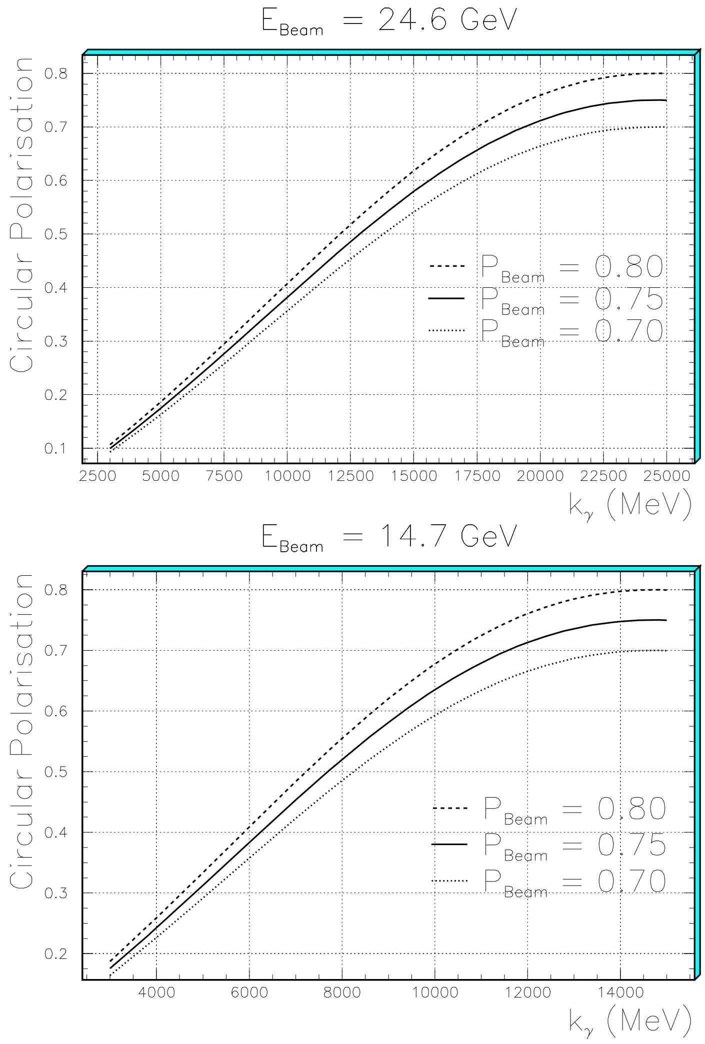

Figure 3.6.5: *Degree of circular photon polarization obtained from a 24.6 GeV (top plot) and a 14.7 GeV (bottom plot) polarized electron beam. Dashed, solid and dotted lines refer to a degree of electron beam polarization of 80%, 75% and 70%, respectively.*

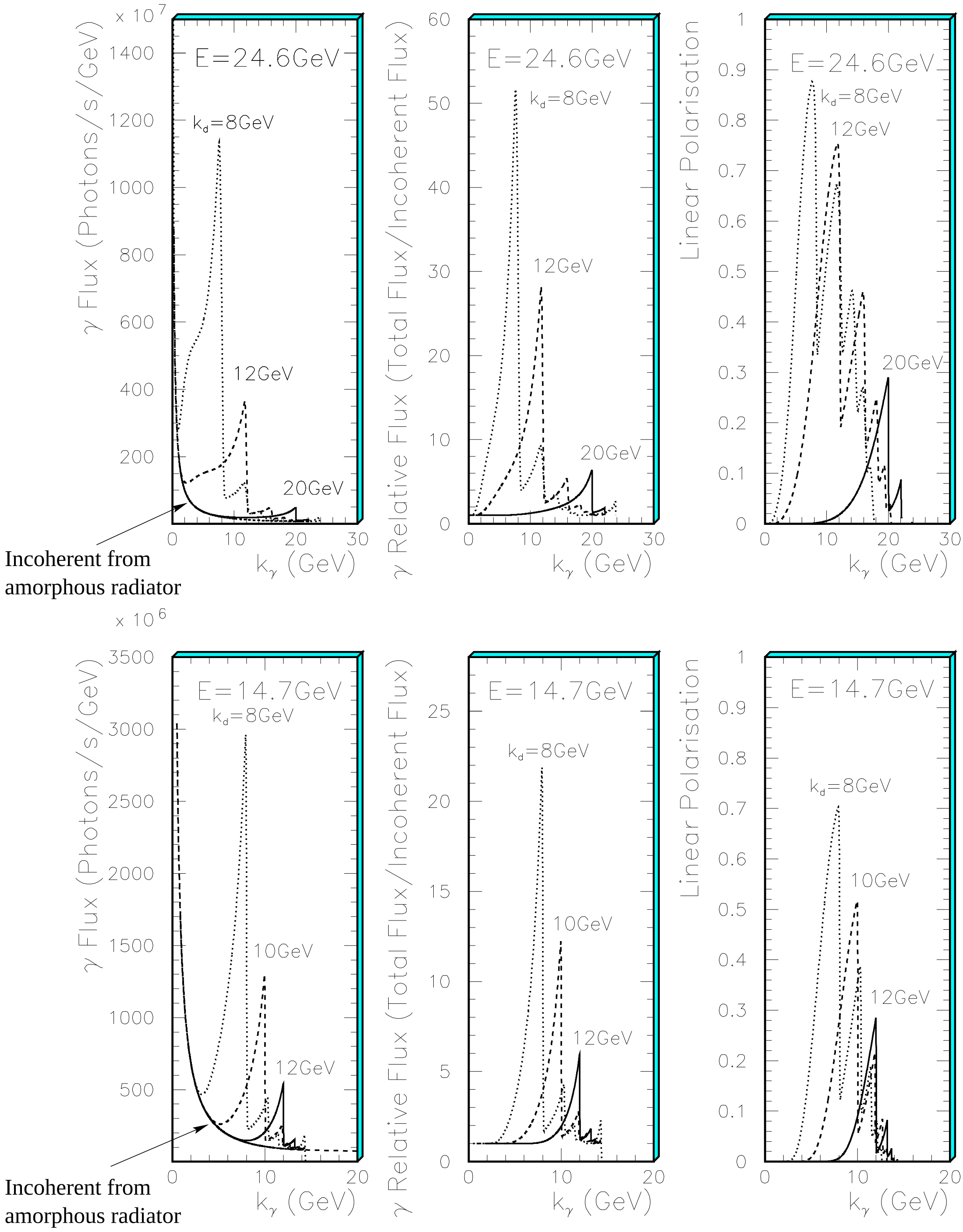

Figure 3.6.6: *The 3 top (bottom) plots represent the total flux, the relative flux and the degree of linear polarization, obtained with a 24.6 GeV (14.7 GeV) electron beam. For both electron energies, different values for the discontinuity have been considered :* k_d *= 20 GeV, 12.0 GeV and 8.0 GeV for a 24.6 GeV electron beam, and* k_d *= 12.0 GeV, 10.0 GeV and 8.0 GeV for a 14.7 GeV electron beam. All plots correspond to a 3 mm radius collimator placed at 75 m downstream of the radiator. The dashed lines on the 'total flux' figures refer to the incoherent bremsstrahlung component.*