Using Coherent Bremsstrahlung for high energy photons at HERA and ELFE

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Coherent bremsstrahlung has been a tool for producing linearly polarised photons already for a long time. But only in the last few years this process has been investigated to a few–percent level of precision. The upcoming of high duty factor accelerators with excellent beam quality allowed a more systematic study of the properties of coherent bremsstrahlung.
The results of these studies and the level of precision reached allow predictions for the use of coherent bremsstrahlung at beam energies up to 30 GeV.
In this paper the use of coherent bremsstrahlung to produce linearly polarised photons at moderate energies and quasi–monochromatic bremsstrahlung near the endpoint of the photon spectrum is investigated for the existing HERA ring as well as for the ELFE @ HERA option.

1 Introduction

Since the advent of high duty cycle electron accelerators with high beam quality the coherent bremsstrahlung (CBS) has been used to produce linearly polarised photons. The thorough investigations of this process during various experiments have shown that this process can be understood and calculated to a few percent level. The calculations were checked by measuring coherent π° photo production on ^{4}He, which has a very high analysing power for the polarimetry of linear polarised photons [1,2]. These measurements show a very good agreement between the data and theoretical predictions.

This good understanding of coherent bremsstrahlung now allows the detailed and quantitative investigation of other properties and uses of coherent bremsstrahlung.

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The scope of this paper is to give a short introduction into the phenomenology of CBS and to investigate its uses for a high energy real photon facility. Several aspects concerning the existing HERA ring and the future ELFE @ DESY option will be discussed.

It can be shown, that there are two main properties which can be exploited, either a high degree of linear polarisation at low and moderate photon energies or a high flux near the endpoint of the photon spectrum. Here the photon energy is always compared to the maximum energy achievable by the machine.

This paper concludes with an outlook on further investigation to make CBS a very useful tool for high energy physics with real photons.

2 Properties of Coherent BremsStrahlung

Using a crystal as radiator for bremsstrahlung production yields two sizeable effects. Due to the regular structure an enhancement of the bremsstrahlung yield in certain photon energy regions depending on the crystal orientation occurs and this additional contribution is polarised.

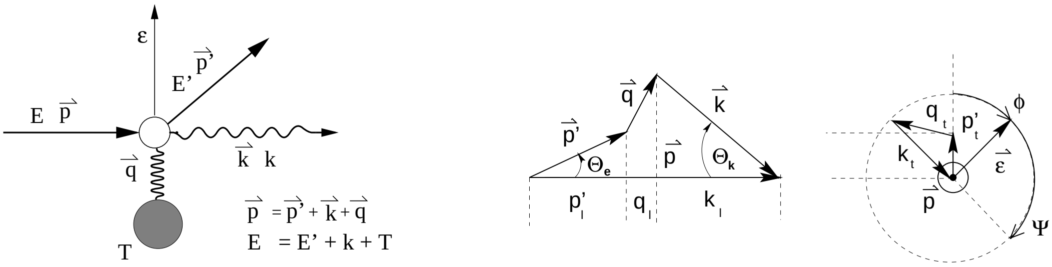

Fig. 1. *Left: kinematics of the bremsstrahlungs process and the notation of energies and momenta involved. Right: Longitudinal and transversal momentum decomposition (not to scale).*

Neglecting the recoil energy T in energy and momentum conservation (see Fig. 1) and employing an ansatz for decomposing the momenta in longitudinal and transversal components leads to constraints on the recoil momentum $\vec{q}$. The longitudinal momentum is much smaller than the transverse one allowing only a very shallow region with respect to the incident electron momentum $\vec{p}$, which is called pancake: its limits depend only on the relative photon energy $x = k/E$. This means that the recoil momentum vector must lie inside the pancake and holds for every single bremsstrahlungs process, but making use of a crystal lattice as radiator introduces additional constraints (Fig. 2). Coherent scattering with corresponding bremsstrahlung is only possible if the so called Bragg condition is satisfied and $\vec{q}$ is not transfered to a single atom but to the lattice. This requires that $\vec{q}$ coincides with a reciprocal lattice vector $\vec{g}$. The lattice basis vectors $\vec{b}_i$ form the reference frame for $\vec{g}$ and define the orientation of the crystal in space through θ and α being the polar and azimuthal angles respectively of the electron momentum.

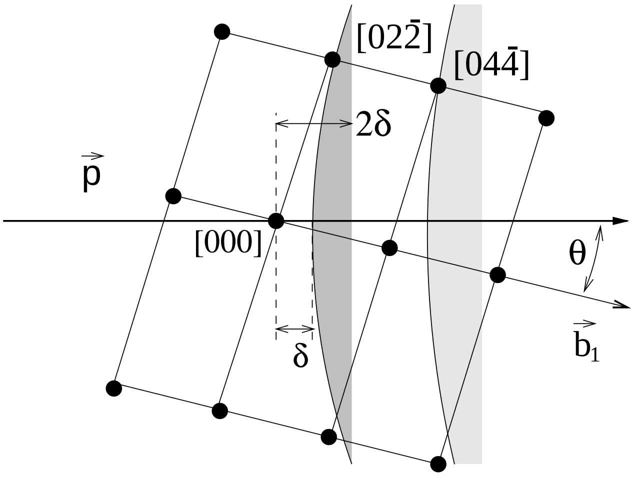

Fig. 2. *Pancakes in reciprocal lattice space of diamond for two different photon energies.* $\delta = \frac{m_e^2}{2E}\frac{1}{1-x}$ *denotes the minimum longitudinal momentum transfer and* θ *the crystal angle between the incident electron momentum and the basis vector* $\vec{b}_1$.

This has important consequences for the emitted photon (see e.g. [3]). If the recoil momentum is fixed, most of the photons have the same polarisation vector yielding a polarised beam. The degree of polarisation is only diminished by the amount of incoherent bremsstrahlung, which occurs at the same time on the nuclei inside the radiator. The coherent cross section is a sum over all lattice vectors inside the pancake. Each contribution increases with photon energy x up to a discontinuity x_d, which is determined by the minimal longitudinal momentum transfer $q_l(x)$, giving rise to a peak-like structure in the spectrum.

In addition experimental and apparative influences like a finite beam spot size, electron beam divergence and multiple scattering in the radiator have to be considered. The most important one is the electron divergence, the fraction of transversal electron momentum with respect to the crystal orientation, which is due to the latter two. Different orientations of the incident electrons with respect to the lattice lead to a variation of the lattice angles θ, α superimposing bremsstrahlungs yields with varying discontinuities $x_d(\theta, \alpha)$, which smears out sharp structures and depletes the polarisation.

In principle collimation of the photon beam enhances the degree of polarisation and counteracts the effect of divergence. For a significant influence the collimation angle should be smaller than m_e/E, which would also reduce the photon yield for high beam energy. Whether collimation is advisable depends strongly on the given electron beam parameter (like emittance and energy spread) and the desired photon beam specifications and has to be carefully studied first.

Energy range	From 15 to 25 GeV
Maximum current	30 μA
Macroscopic duty factor	88 %
Bunch spacing (433.33 MHz)	2.3 ns
Minimum horizontal emittance (90 % of particles)	4 mm $\cdot\mu$rad @ 1= 5 GeV 12 mm $\cdot\mu$rad @ 25 GeV
Associated Energy spread (FWHM)	1.2×10^{-3} @ 15 GeV 2.2×10^{-3} @ 25 GeV

Table 1
Expected performance of ELFE @ DESY [4]

The calculations shown here (Fig. 3,4) are based on [1,2,10] and described elsewhere in more detail [9,11].The primary lepton energy is taken to be 27.52 GeV, which is the current energy used in the HERA lepton ring. A diamond radiator with 0.135 mm thickness was considered, which is oriented at different angles in order to get the desired beam properties. Furthermore multiple scattering in the diamond, beam divergence of 0.14 mrad and beam energy spread of 60 MeV was taken into account.

3 CBS for ELFE @ DESY

Since 1995 the option of using the HERA ring as a pulse stretcher and the first section of the TESLA linear collider as injector has been investigated [4]. If this project would be realised, a dedicated electron beam with high current and high duty cycle would be available for nuclear physics experiments. The projected properties of such a machine are summarised in table 1.

The investigation cited deals also with the production of real photons considering laser back scattering (LBS) to produce the photon beam. If the machine is running dedicated to a real photon experiment, a total photon flux of $10^9\gamma$/s could be reached. This would correspond to a useful flux of $10^8\gamma$/s in the interesting high energy range of the spectrum and would require a refill of the storage ring every 30 minutes due to the loss of electrons in the back scattering process. The limiting factor of this solution is the maximum photon energy available. If a conventional laser at a wavelength of 266 nm would be used the highest photon energy with 25 GeV electrons would be about 16 GeV. Using the current HERA lepton energy of 27.5 GeV, this value increases to 18 GeV. The expected photon flux is high enough for a large number of experiments.

The properties of the electron beam and the length of the interaction region between the laser beam and the electron beam lead to a certain energy spread of the photons, thus requiring the installation of a tagging system in order to get the desired photon energy resolution. In this case, existing dipoles of the ring would be used to deflect the scattered electrons. A simple detector system of about 100 channels would detect the scattered electrons, measure their energy and thus in coincidence with the experimental trigger tag the photon. Such a device gives a limit to the photon rate. With the flux given above, count rates of 10 MHz per channel are expected, which is about a tolerable level. Higher rates would induce ambiguities for electron photon coincidences. Therefore this rate gives a practical upper limit to the flux of any tagged photon beam.

Such a device with similar restrictions would be needed for a coherent bremsstrahlungs beam as well.

Two running modes are possible for a CBS beam, depending on the aim of the experiment:

- Using CBS to get a fair degree of linear polarisation at moderate photon energies. The corresponding spectra are shown in Fig. 3
- Using CBS to get an enhanced photon flux near the endpoint of the photon spectrum. Unfortunately, these photons are neither unpolarised nor highly polarised, but deliver a significantly higher flux compared to a conventional radiator and at higher energies than can be obtained with the LBS technique. The spectra are shown in Fig. 4

A dedicated polarimeter should not be needed after a pilot experiment with a polarimeter reaction is done. This experiment is needed in order to study the properties of the radiator and the tagging system. After this experiment has been performed, the tagger pattern should be sufficient to monitor and calculate the degree of polarisation. Thus, the technical realisation of such a project should not give any difficulties and should be much simpler than a LBS apparatus.

4 CBS at the existing HERA Ring

The original idea [5] was to use coherent bremsstrahlung in a thin diamond target to produce an intense photon beam with a spectral enhancement near 90% of the electron beam energy, thus emulating the SLAC E156 proposal [6]. It might be possible to place such a thin diamond "stylus" or point into the halo of the HERA lepton ring to intercept approximately 10^{-7} of the circulating beam, somewhat in analogy to the HERA-B experiment [7]. One would make most efficient use of the HERA lepton beam by making the target crys-

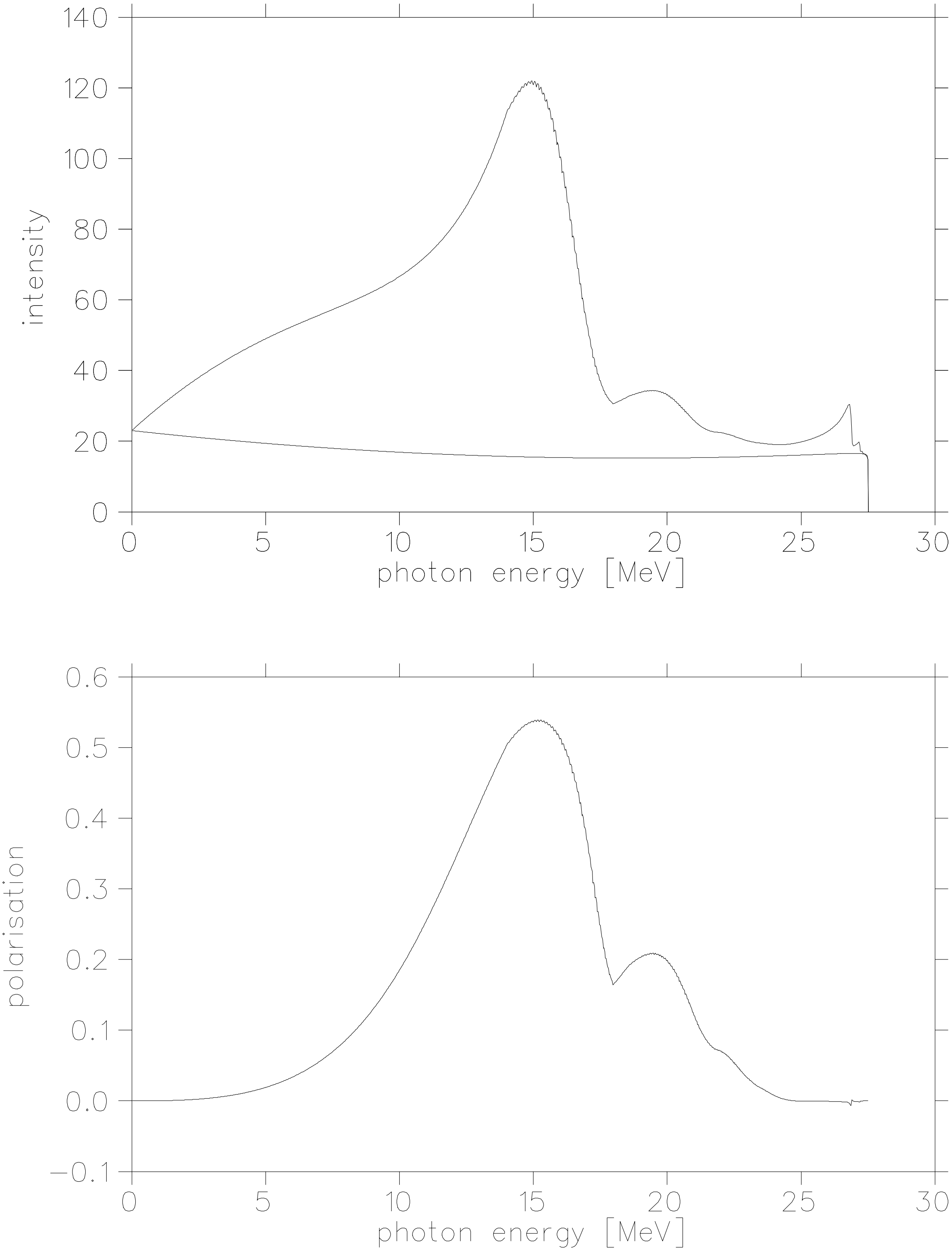

Fig. 3. Intensity $I \propto x\frac{d\sigma}{dx}$ and degree of polarisation for the high polarisation setting for a desired photon energy of 15 GeV

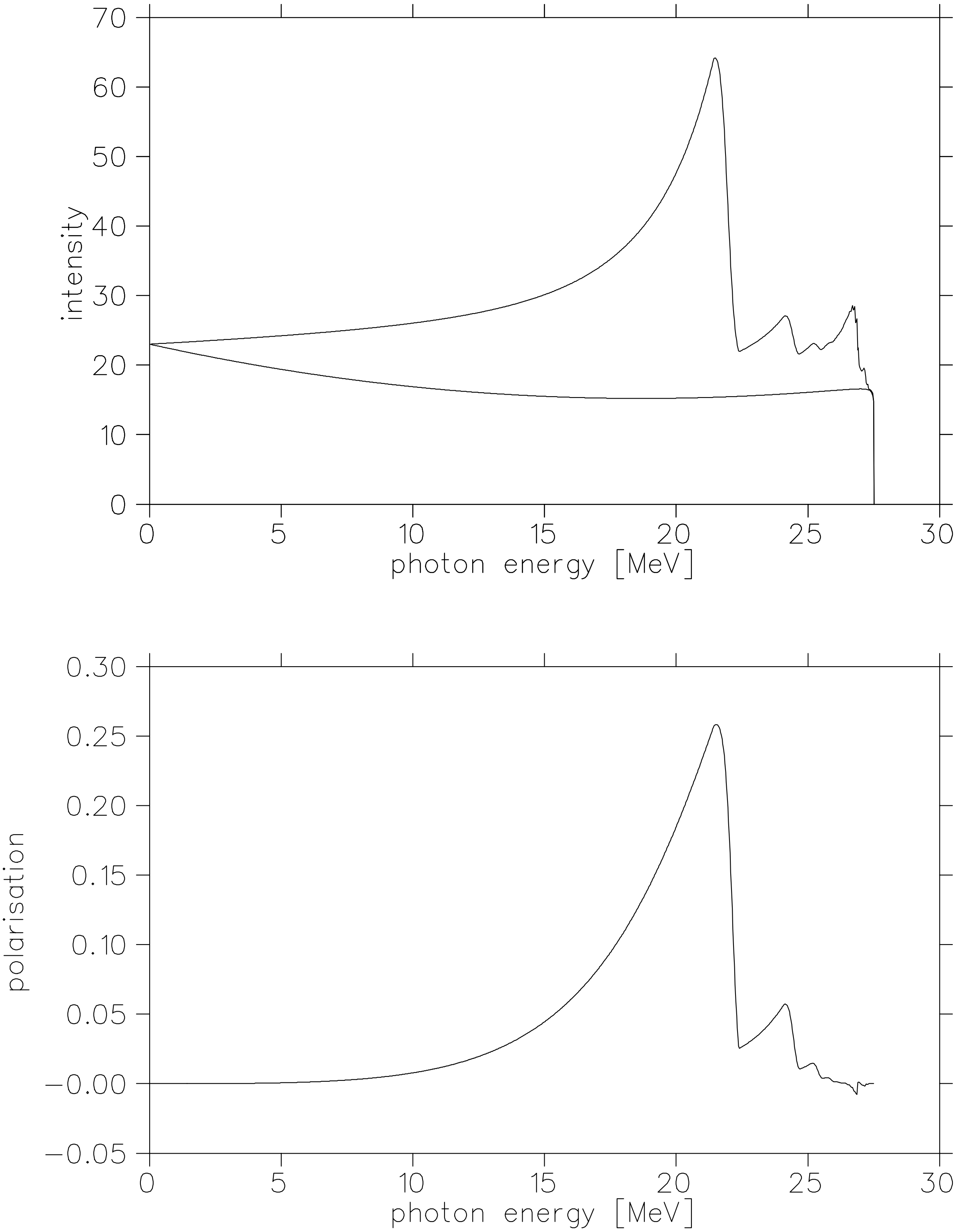

Fig. 4. Intensity $I \propto x\frac{d\sigma}{dx}$ and degree of polarisation for a high flux setting at 22 GeV photon energy

tal thin enough so that bremsstrahlung is still the dominant mechanism for beam particle loss. This seems possible since the proposed SLAC target thickness of $7 \cdot 10^{-7}$radiation lengths (0.1 mm) would produce a multiple scattering divergence comparable with the HERA lepton beam divergence at the target location envisaged by APOLLON. The settings chosen for our calculations take these effects into account.

Then CBS as photon source would be competitive with the more conventional LBS if the target 'efficiency' were of the order of 20%. This efficiency is the ratio of rate of useful high energy CBS photons to the total including incoherent bremsstrahlung (IB) photons above the effective beam loss threshold, which can be estimate to be 175 MeV based on the standard formula for beam lifetime from rest gas. It requires much more study, but the bremsstrahlung spectra computed for E156 [8] and in this report suggest that such an efficiency may not be outrageous. The *effective* target thickness averaged over the beam area would then be $5\dot{1}0^{14}$nucleons/cm^2, which results in a beam lifetime contribution of about 58 hours. The probability of loss of a beam lepton for each pass through the diamond target would be of order 1/1000.

The use of CBS would have the advantage of a higher beam energy than LBS. However, the circular polarisation of the photon beam would be essentially that of the leptons inside HERA, rather than the 100% of the LBS laser. This technique may have a unique advantage in a storage ring for creating photon beams with negligible divergence contribution from the electron beam.

This technique is interesting both for running in parallel with collider mode, as well as possibly slowly "dumping" the beam remnant with the crystal target at the end of the fill period. In the former case, the rates would presumably still be low enough to tag the photons using the associated lepton, as with LBS. One could then use the tag energy spectrum to tune the crystal orientation like it is done at low energy experiments [2,9].

5 Using CBS for circular polarised photons

Experiments aiming at nucleon spin physics require a circular polarised photon beam [13,12]. Although this is not a feature inherent to CBS, it can be exploited as well. For every bremsstrahlung process, a helicity transfer from the lepton to the photon produced occurs. This behaviour only depends on the relative photon energy $x = k/E$ (Fig. 5) [14].

$$\frac{P_\gamma}{P_{lepton}} = \frac{4x - x^2}{4 - 4x + 3x^2}$$

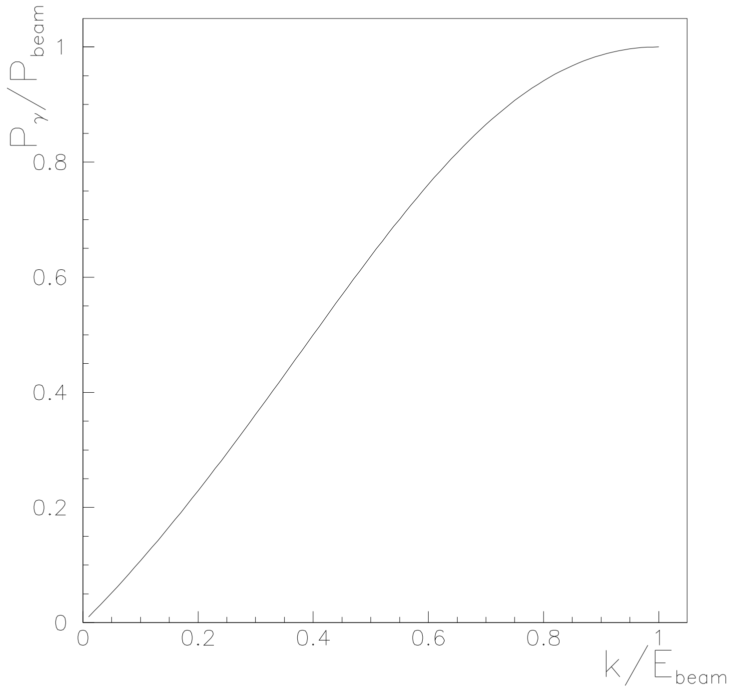

Fig. 5. Helicity transfer to the photon depending on the relative photon energy $x = k/E$

It is clearly visible, that only the upper half of the spectrum yields a sizeable polarisation, i.e. experiments are limited to a certain range of photon energies. If a high degree of circular polarisation is desired at lower energies, the energy of the primary lepton beam has to be changed. This poses no problem for a dedicated machine like ELFE @ DESY, but is certainly a limit for the parasitic mode envisaged for the existing HERA ring.

The absolute value of the polarisation depends on the polarisation of the lepton beam, which is to be expected in the order of 0.7 for both options. Fig. 6 shows the degree of circular polarisation achievable for the existing HERA lepton beam. A lepton polarisation of 0.7 is assumed.

Since the photon polarisation is directly linked to the lepton polarisation and the energy of the photon, no photon polarimeter is need. The tagging device and the existing beam polarimeters are sufficient for this purpose. Any asymmetry due to linear polarised photons cancels out, if the polarisation plane is changed regularly during the experiment.

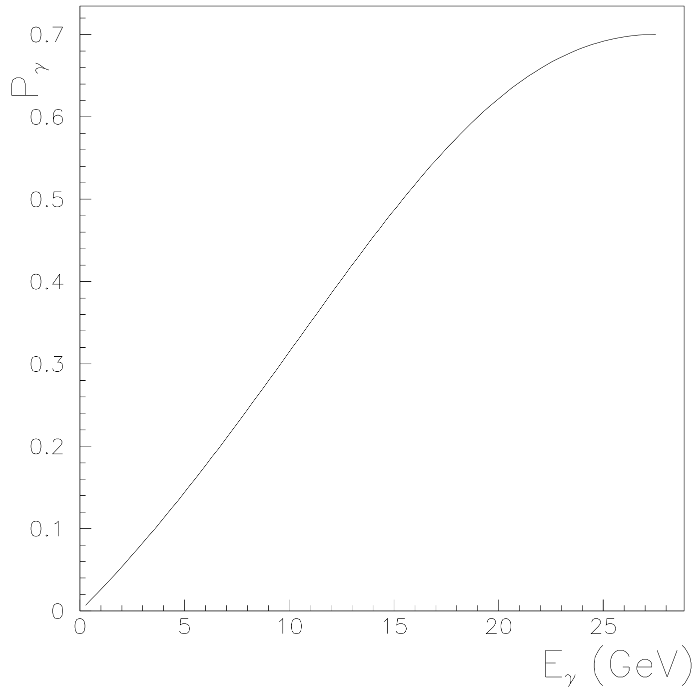

Fig. 6. Circular polarisation at HERA with $P_{lepton} = 0.7$ and $E_{lepton} = 27.5$ GeV

6 Discussion and Conclusion

The use of a diamond crystal to produce high energy real photons via the coherent bremsstrahlung process has been investigated. Experiments at lower energies at MAMI (e.g. [1,2,9]) have shown, that existing theories are able to describe this process to a few percent level, which allows to use the same method to make predictions at higher energies.

For a high energy real photon facility at DESY several options are available. The first and probably most realistic solution would be to use the existing HERA ring and run real photon experiments in parasitic mode during normal collider operation. This could be possible with minor changes to the existing accelerator and has already been investigated for the case of a LBS beam [12].

A small diamond crystal which can be put into the electron beam could be used as a slow beam dump whenever collider operation calls for it. This would produce a very intense photon beam, but only for up to one hour for every dump of the lepton beam. Another option is provided by putting the crystal into the beam halo making use of these electrons for CBS. This running mode provides a lower flux, but during the whole running time, which makes it a more favourable solution keeping other parameters like detection ambiguities and tagger rates in mind.

The other option has been discussed as ELFE @ DESY. Here HERA would act as a pulse stretcher using the TESLA linac as injector. The feasibility of this option has been shown [4]. The installation of the radiator would be similar to the HERA beam dump option. Since ELFE @ DESY would be a dedicated machine for nuclear physics experiments a wide range of intensities and energies is possible. The design current is high enough so that the factors limiting the photon flux are determined by experiment and not by the beam. The upper limit of the photon energy will be about 90% of the electron energy. Essentially, there is no lower limit, if the primary electron energy can be modified.

All these possibilities require the installation of a tagging device in order to get the photon energy as precise as possible. The electrons which emitted a bremsstrahlung photon lost energy and therefore follow a different path in the ring dipoles, i.e. they are deflected out of the primary electron beam. Since the paths of the electrons are known, one can easily construct a small detector either inside or outside of the electron ring, which measures the electron energy. Since only a very thin radiator is used, the energy resolution is expected to be quite high, provided the beam divergence is not too big.

In all cases the crystal can be oriented in two modes, one aiming at high polarisation at moderate energies, the other at a high flux near the end point of the photon spectrum.

The present calculations show that for the present HERA energy polarisation degrees of up to 60% at a photon energy of 15 GeV are possible. At higher photon energies, the degree of polarisation would be about 25%, but the photon flux would be higher by a factor of 5 compared to ordinary radiators.

The technical design of such a device is still subject to further studies. Furthermore, detailed studies of the influence of the electron beam divergence and size and the possible use of collimation to enhance the properties of the photon beam have to be studied. These calculations are possible with the existing theories and software.

In conclusion it can be said, that the use of CBS is a promising and interesting alternative to the LBS process discussed in most of the papers dealing with high energy real photons. The linear degree of polarisation can be quite high at photon energies comparable to those achievable by LBS. Circular polarised photons can be produced with a degree of polarisation given by the polarisation of the electron beam. In most reactions the effect from linear polarised photons drops out if the direction of the polarisation is switched regularly.

In addition, CBS extends the photon energy range for a fixed electron energy to 90% of the electron energy with a high flux. This is the most striking advantage of this technique. Unfortunately, due to the shape of the bremsstrahlung spectra a higher background at low photon energies is to be expected.

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