Optimal Photon Sources for CEBAF at Higher Energies

R.T. Jones
University of Connecticut, Storrs, CT
and
Jefferson Lab, Newport News, VA

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Abstract

A leading motivation for the push towards CEBAF electron beam energies beyond 8 GeV is the physics that could be done with intense polarised photon beams of these energies. Three established techniques have been considered as possible means for producing photon beams from electrons. Conventional bremsstrahlung is the most widely-used technique, generally in combination with a recoil electron tagging spectrometer to measure the photon energy associated with a given interaction. Coherent bremsstrahlung is a refinement of this technique which exploits an oriented crystal radiator to enhance the production rate in the high-energy part of the photon spectrum. Backward Compton scattering of visible photons from a laser by the electron beam is the third method considered in this study. The photon beam energy spectrum from the two latter techniques can be reduced to a narrow band in the high-energy part of the spectrum by collimating the photon beam, or they can be monochromatised by the use of tagging. In this report the performance factors for each technique are evaluated with regard to energy range, achievable intensity, and polarisation. The comparison shows that a coherent bremsstrahlung beam line would offer unique opportunities for photoproduction physics with polarised photons beyond 8 GeV, and that polarisation benefits from the very highest electron beam energies that can be made available.

One of the unique opportunities that would be presented by a CEBAF upgrade to energies of 8GeV and beyond would be the possibility of generating high-intensity c.w. photon beams for high-energy photoproduction experiments, where by "high-energy" I refer to the regime in which the photon interacts with hadrons predominantly through its own hadronic component. In this regime, photon beams present an interesting extension to the meson spectroscopy program that has been actively pursued using beams of pseudoscalar mesons at hadron accelerator laboratories: with high-energy photons one has essentially a beam of *vector* mesons. It is difficult, in fact, to conceive of any other way to obtain such a vector beam. Vector beams offer at least two advantages in the search for a more complete understanding of the hadron spectrum. From the theoretical standpoint, vectors are interesting as a possible source of hybrid mesons because the two are connected in the flux tube model by a simple operator which excites the orbital motion of the string. Thus measuring the coupling between conventional and hybrid vector mesons is a direct way to probe the structure of hybrids. From the experimental point of view, the polarisation of a vector beam offers new observables that are not available to experiments with pseudoscalar beams. These additional observables are useful to distinguish the exchange character of the production process and help to resolve contributions from different interfering waves in the spin-parity analysis of the final state.

Three major methods have been considered for producing photons of the highest possible energy, flux, and polarisation from electrons in the energy range 8-12GeV. The methods are ordinary bremsstrahlung, coherent bremsstrahlung, and Compton-backscattering of light. None of these methods is new, and the calculation of the basic cross sections that underlie them are presented in most text books on applications of QED. All three techniques are actually described by the same Feynman diagram, which is sketched in Fig. 1. Their similarity leads to a similar expression for the production amplitude in the three cases, and its dependence on the spin of the electron and the photon. The beam polarisation proper-

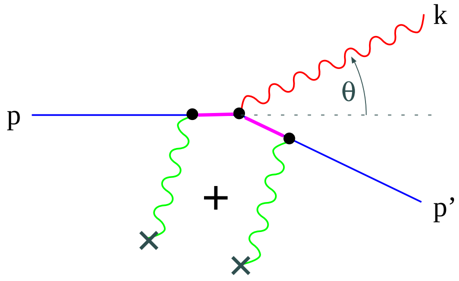

Figure 1: Generic diagrams for hard photon production from a high-energy electron beam. The symbol × represents either a static charge distribution, in the case of virtual photons in the initial state (i.e. bremsstrahlung), or an optical cavity, in the case of real photons in the initial state (i.e. Compton scattering). The + denotes the fact that this leading-order amplitude is actually the sum of two diagrams, one with the initial-state photon attached to the incoming electron leg and one with it attached to the outgoing electron.

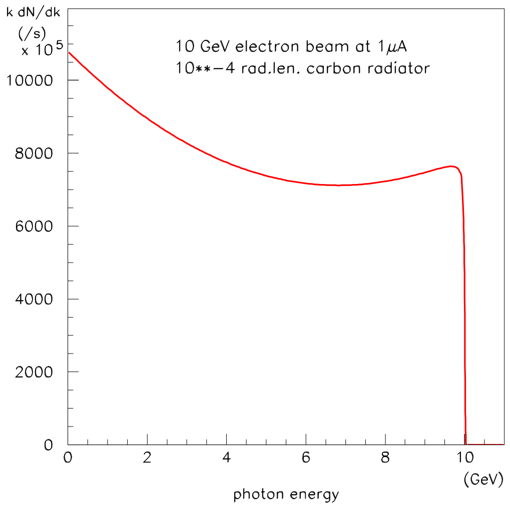

Figure 2: Intensity spectrum $k\frac{dN_\gamma}{dk}$ in photons$/s$ as a function of photon energy k for a 10GeV electron beam at $1\mu A$ and a 10^{-4} radiation-length amorphous carbon radiator.

ties I calculated myself for this study because the standard references generally report only unpolarised cross sections.

Beams of each of the three kinds are presently in use at electron machines throughout the world. So rather than describe the formalism for these calculations, which is well-established, this report concentrates on the results obtained in the particular case of a 10-12GeV beam from an upgraded CEBAF. At the end a comparison is given between the methods in terms of suitability for a prospective meson photoproduction facility at CEBAF.

The intensity spectrum of bremsstrahlung photons from a 10GeV electron beam is shown

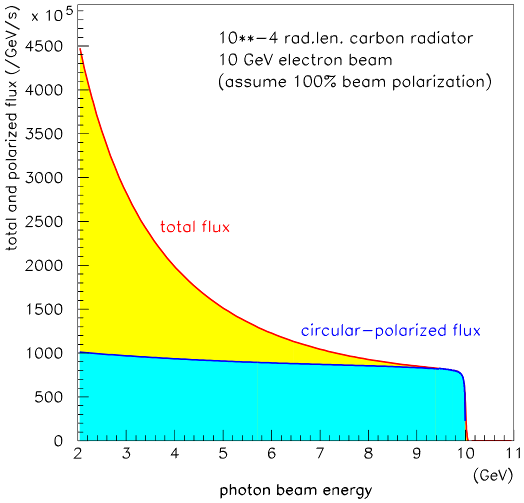

Figure 3: Photon energy spectrum in a bremsstrahlung beam (upper curve) generated from a 10GeV electron beam of $1\mu A$ incident on a carbon radiator of thickness 10^{-4} radiation lengths, and the circularly polarised component (lower curve) from pure-helicity electrons.

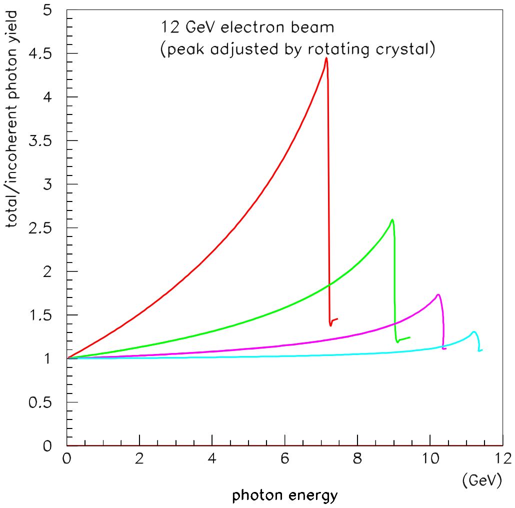

Figure 4: Coherent gain from an oriented diamond radiator as a function of photon energy, for a discrete set of crystal plane orientations with respect to the electron beam axis.

in Fig. 2. Intensity is just the photon rate per GeV weighted by the photon energy. The bremsstrahlung intensity spectrum is approximately flat up to within 50MeV of the endpoint, showing that some photons are produced with essentially the full energy of the electron beam. However the median photon energy in the beam is only about 10MeV which highlights a major drawback of this technique, the large background of low-energy photons in the beam. In the case of circularly polarised electrons, there is a significant transfer of circular polarisation to the photon beam. The lower curve in Fig. 3 is the total flux (upper curve) multiplied by the circular polarisation, assuming a 100% circularly polarised electron beam. The actual polarised flux would be the lower curve multiplied by the circular polarisation of the electron beam. Because the bremsstrahlung cross section comes from the integration of the amplitude in Fig. 1 over all azimuthal angles in $\vec{p}\,'$ there is no net plane polarisation for any polarisation state of the incident beam.

If the bremsstrahlung radiator is a single crystal and is oriented such that one of its symmetry axes is very nearly perpendicular to the beam then coherent scattering from crystal planes produces enhancements in the bremsstrahlung spectrum at discrete energies, as shown in Fig. 4. Small adjustments in the angle between the symmetry axis and the electron beam moves the peaks around in energy. The coherent gain plotted in Fig. 4 is defined as the total spectral intensity with a crystal radiator divided by that for a disoriented radiator of the same elemental composition and thickness. This figure demonstrates the general feature of coherent bremsstrahlung that the gain goes to zero in an approximately linear fashion as the energy of the primary peak is made to approach the endpoint.

Within the vicinity of the coherent peaks there is a strong correlation in the photon beam between photon energy and polar angle θ which can be exploited using collimation to make the peak narrower and more prominent. The effect of collimation is shown in Fig. 5. The series of peaks come from a sequence of collinear reciprocal lattice vectors of increasing indices. The effect of collimation is to reduce the intensity of the incoherent part and eliminate the low-energy tail of the coherent peak without affecting the coherent radiation near the high-energy edge of the peak.

In Figs. 6-7 the effects of modest and severe collimation are shown, respectively. In the former case, it is possible to obtain substantial improvement in the peak/background ratio while still maintaining a large integrated flux within the peak. An experiment requiring definition of the incident photon energy to better than 5% could obtain that information by measuring the energy of the post-bremsstrahlung electron in a tagging spectrometer. Alternatively, one might consider improving the definition of the beam by tightening the collimation. This does narrow the peak up to a point, but eventually the effects from multiple scattering in the radiator, beam emittance and crystal imperfections prevent further improvements. For details on how these effects can be taken into account analytically, see references [1]-[2]. The situation in Fig. 7 represents a practical limit for CEBAF at 12GeV. The width of the peak has been reduced to less than 1% r.m.s. albeit at a cost of a factor of more than 30 in flux.

It is possible with coherent bremsstrahlung to obtain considerable photon beam polarisation, both in planar and circular modes. Plane polarisation is always produced in the plane containing the electron beam and the crystal axis, and is non-zero only within the energy window around a coherent peak, reaching a maximum at the high-energy edge of the peak. The maximum value depends on the energy of the peak as shown in Fig. 8. Plane polarisation is going linearly to zero as one approaches the endpoint, in the same way as the intensity, so that polarised flux goes to zero as $(k - E)^2$. The total and plane-polarised flux of a coherent bremsstrahlung beam for a fixed crystal orientation is shown in Fig. 9. Collimation improves the polarisation of the beam by preferentially reducing the incoherent component, which is unpolarised.

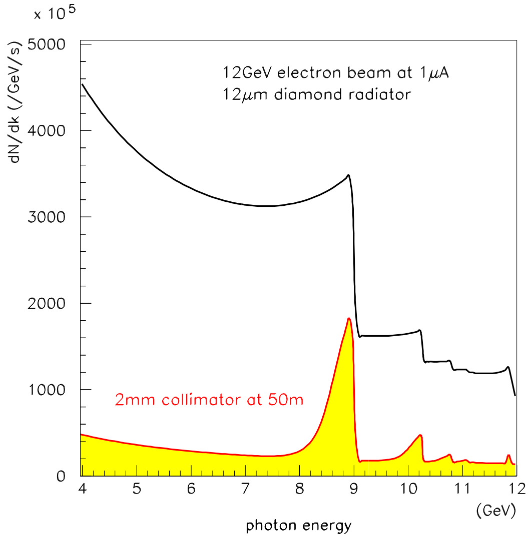

Figure 5: Photon energy spectrum from an oriented diamond radiator of thickness 10^{-4} radiation lengths without (upper curve) and with (lower curve) photon beam collimation.

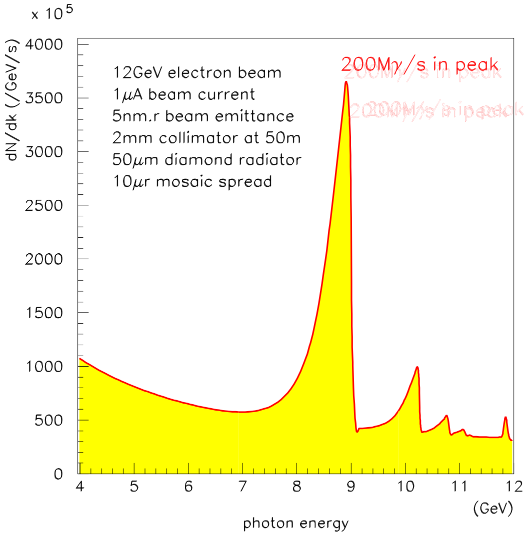

Figure 6: Photon energy spectrum from an oriented diamond radiator collimated down to 1/2 bremsstrahlung characteristic angle m/E. The total flux inside the peak is $2 \cdot 10^8 \gamma/s$. The full width at half maximum is about 500MeV.

If the electron beam is circularly polarised then the same transfer from electron to photon polarisation takes place in the coherent case as shown in Fig. 3 for incoherent bremsstrahlung. The event of circular polarisation does not contradict or reduce the plane polarisation in Figs. 8-9: the resulting photon beam carries elliptical polarisation. Note that the plane polarisation of the photon beam goes linearly to zero at the endpoint where the circular polarisation transfer coefficient approaches 100% quadratically, as should be the case if the sum of squares is constant.

The basic design of the Compton-backscatter source for this study was taken from C. Keppel and R. Ent [3]. The design entails the use of a four-mirror high-gain cavity pumped

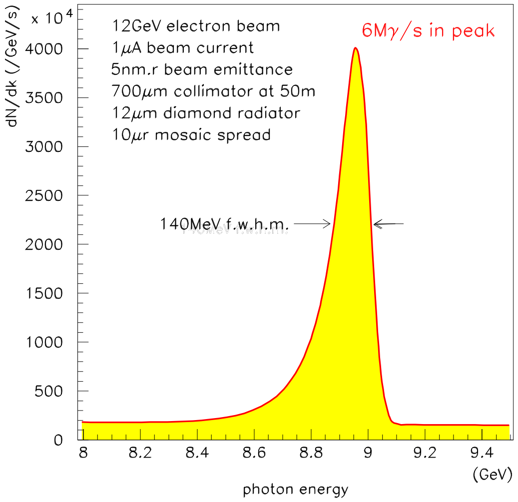

Figure 7: Same as Fig. 7 except collimation has been narrowed to 0.15 m/E.

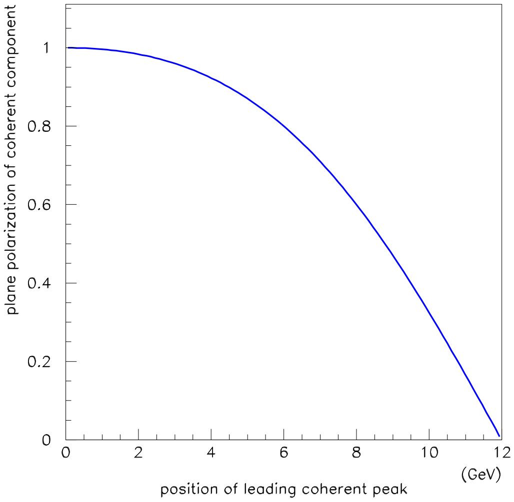

Figure 8: Plane polarisation at the coherent peak as a function of the peak energy for a constant endpoint of 12GeV.

by a 10kW argon-ion laser putting out 2ps pulses at a frequency of 100MHz. The pulses in the cavity are synchronised so that light pulses in each of the arms crossing the electron beam intercepts an electron bucket on each pass through the beam. The total length of the cavity is 2m, with a crossing angle of 1^0. Both cavity and electron beams are focused down to $10\mu m$ r.m.s. radius at the crossing point, and ideal alignment is assumed, making this a technically challenging device to implement. Even so, and using the best dielectric mirrors currently available, the source suffers from flux limitations. Fig. 10 shows the photon energy spectrum

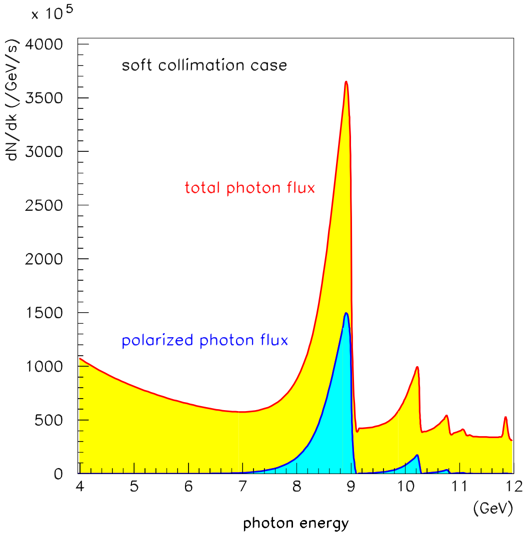

Figure 9: Total flux (upper curve) and plane-polarised flux (lower curve) of the coherent bremsstrahlung beam, resulting from orientation of the crystal planes in the diamond radiator, as a function of photon energy. Plane polarisation of the incoherent component in the spectrum is zero.

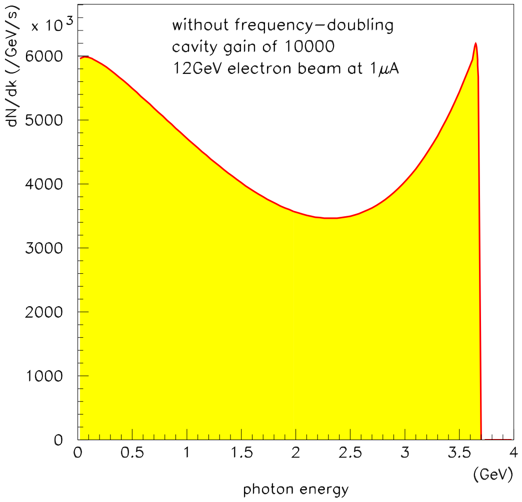

Figure 10: Photon energy spectrum in a laser-backscatter photon beam for a resonant optical cavity driven by a state-of-the-art pulsed Argon-ion laser operating at 514nm that is synchronised with the pulse cycle of the accelerator.

in photons/GeV/s for a $1\mu A$ electron beam. The highest energy photons in this beam are only 30% of the endpoint energy. Higher energies can be obtained by frequency-doubling the laser before injection into the cavity. The spectrum and flux under these conditions is shown in Fig. 11. The observed losses in intensity arise from poorer mirror reflectivity at shorter wavelengths, inefficiency of the frequency-doubling apparatus, and the dropping Compton cross section with increasing photon energy. The polarisation of the photon beam from such a source is shown in Figs. 12-13.

The Compton-backscatter source considered above fails to meet the criteria for a high-energy photon source at CEBAF on two counts: energy range and flux. Figs. 10-11 show

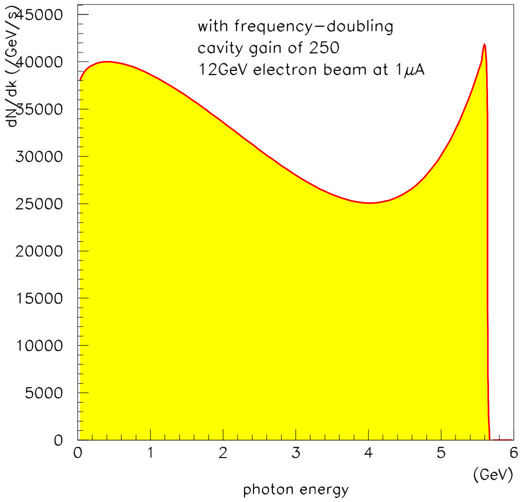

Figure 11: Same as Fig. 10 but using a frequency-doubler and a cavity tuned to 257nm.

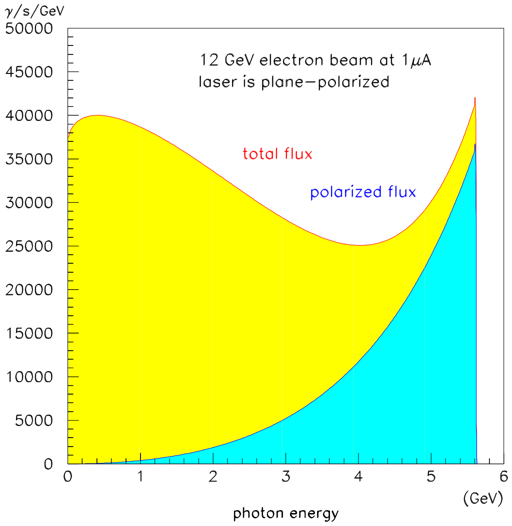

Figure 12: Total flux (upper curve) and plane-polarised flux (lower curve) from a frequency-doubled laser-backscatter source as a function of photon energy. The light in the cavity is assumed to be 100% plane polarised.

that energy and flux are complementary demands for such a source, and the combination of the two is doubly difficult to achieve. This is unfortunate, because from the point of view of polarisation and low-energy background flux, this source is without peer. Two orders of magnitude of flux can be regained by locating the source below ground, where beam currents up to $100 \mu A$ may be achievable, but the cost increment would be considerable and

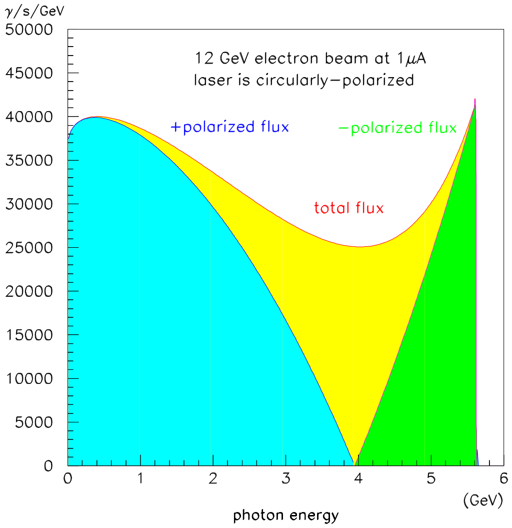

Figure 13: Total flux (upper curve) and circularly-polarised flux (lower curve) from a frequency-doubled laser-backscatter source as a function of photon energy. The light in the cavity is assumed to be 100% circularly polarised. The helicity of the photon beam is the same as [opposite to] the helicity of the cavity light for forward [backward] Compton scattering.

the energy would still be limited to 50% of the endpoint. One interesting possibility would be to pump the cavity using the electron beam itself and a free-electron laser apparatus. The stored beam inside the cavity would serve both to stimulate coherent photon production on the forward pass and as a source of back-scatter photons on the backward pass. Both power and frequency range of the trapped light would be tunable far beyond the range of a conventional laser, and might make a close-to-ideal photon source. This would involve considerable development, however, and is not a realistic choice for the near future.

A coherent bremsstrahlung source provides photon beams of significant coherent gain up to about 85% of the endpoint energy. Significant coherent gain is important because only the coherent part of the beam carries the plane polarisation which is desired for meson photoproduction studies. Using modest collimation the coherent part of the photon beam can be enhanced, providing improved polarisation and flux over the energy range of interest and still provide a flux well above $10^8\gamma/s$. The photon beam energy resolution of a fraction of 1% that is desired for meson photoproduction experiments can only be practically achieved by tagging the post-bremsstrahlung electrons in a spectrometer. Such a tagging spectrometer would only need to measure electron momenta over a range of a few GeV because it is the high-energy photons that are of interest. The tagging system would operate the same way with any radiator material, which would allow one to run a conventional bremsstrahlung beam to reach the very highest energies available from CEBAF for experiments for which polarisation is not required.

While in the future Compton-backscatter has the greatest promise as a nearly-ideal photon source, at the present, flux and energy considerations make bremsstrahlung the only practical way of generating high-energy photons from a 10-12GeV CEBAF. A collimated coherent bremsstrahlung source is presently envisioned for the new meson photoproduction facility being considered as a part of the upgrade plan for the laboratory.

References

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