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Chapter 3

Choice of technique

Two basic methods have been considered for producing photons of the highest possible energy, flux and polarization from electrons of 12 GeV. The methods are bremsstrahlung and Compton scattering of light. Both are well-established methods of producing photon beams, and both are actually described by the same set of Feynman diagrams, shown in Fig. 3.1. In the case of Compton scattering the incoming photon is real, whereas it is virtual for the case of bremsstrahlung.

Each of these techniques has its own limitations and advantages. In order to be suitable for GlueX, the photon source must be capable of producing photons of 80% E_0 with a significant degree of linear polarization. The energy resolution for individual photons in the beam should be better than 0.5%, ideally on the same order of magnitude as the energy spread of the electron beam itself. It should be capable of producing intensities up to 10^8/s in the range 8-9 GeV, with the flux outside the desired energy band as low as possible.

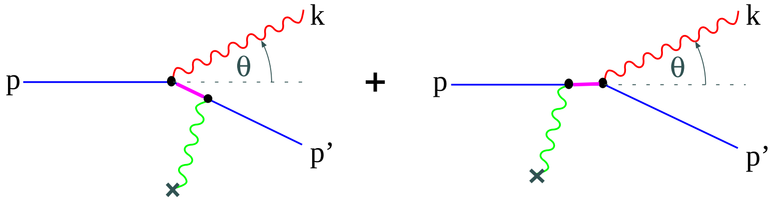

Figure 3.1: Generic diagrams for hard photon production from a high energy electron beam. The symbol × represents either a static charge distribution, in the case of virtual photons in the initial state (i.e. bremsstrahlung), or an optical cavity, in the case of real photons in the initial state (i.e. Compton scattering).

It is also important that the source be reliable and require a minimum of downtime for maintenance. The suitability of each approach is discussed below in the light of these criteria.

3.1 Compton back-scatter

A Compton source begins with a beam of visible or ultraviolet light, typically from a laser, that is aligned to intersect the incident electron beam at close to 180°. Some of the photons undergo Compton scattering with the beam electrons. In the lab frame, the scattered photons emerge in a narrow cone about the incident electron direction and carry a significant fraction of the electron energy.

The basic design of the Compton back-scatter source for this study was put forward by C. Keppel and R. Ent [1]. The design entails the use of a four-mirror high-gain cavity pumped by a 10 kW argon-ion laser putting out 2 ps pulses at a frequency of 100 MHz. The pulses in the cavity are synchronized so that the light pulses intercept an electron bucket each time they pass through the beam. The total length of the cavity is 2 m with a crossing angle of 1°. Both cavity and electron beam are focused to a tiny spot of 10 microns r.m.s. radius at the crossing point. A small spot size is necessary in order to get as high a scattering rate as possible. The gain of the cavity is 10^4, which is achievable using high-reflectivity dielectric mirrors. The wavelength of the light is 514 nm. The rate spectrum of the back-scattered beam from this source is shown in Fig 3.2a for a 1 μA electron beam at 12 GeV.

From the point of view of flux, this source is marginal. With a few μA of beam and mirror improvements, it might produce 10^8 photons/s in the upper $\frac{1}{3}$ of its energy spectrum. However, its maximum photon energy of 3.7 GeV is far below the 9 GeV needed for GlueX. To remedy this, a shorter wavelength light source is required. This can be achieved by the use of a frequency-doubling crystal that absorbs 514 nm light from a green laser and produces ultraviolet light at 257 nm. Storing this light in a cavity of similar design to that described above yields the back-scatter rate spectrum shown in Fig. 3.2b. The major reason for the drop in rate is the decrease in the cavity gain from 10000 to 250 imposed by the diminished reflectivity of mirrors in the UV. Other loss factors are the inefficiency of the doubling crystal, the factor two in rate from the doubling itself, and the decreasing Compton cross section with increasing energy. The maximum photon energy is still under 6 GeV and the flux is three orders of magnitude below the desired rate.

In order to reach photon energies of 9 GeV, a source of 20 eV light is

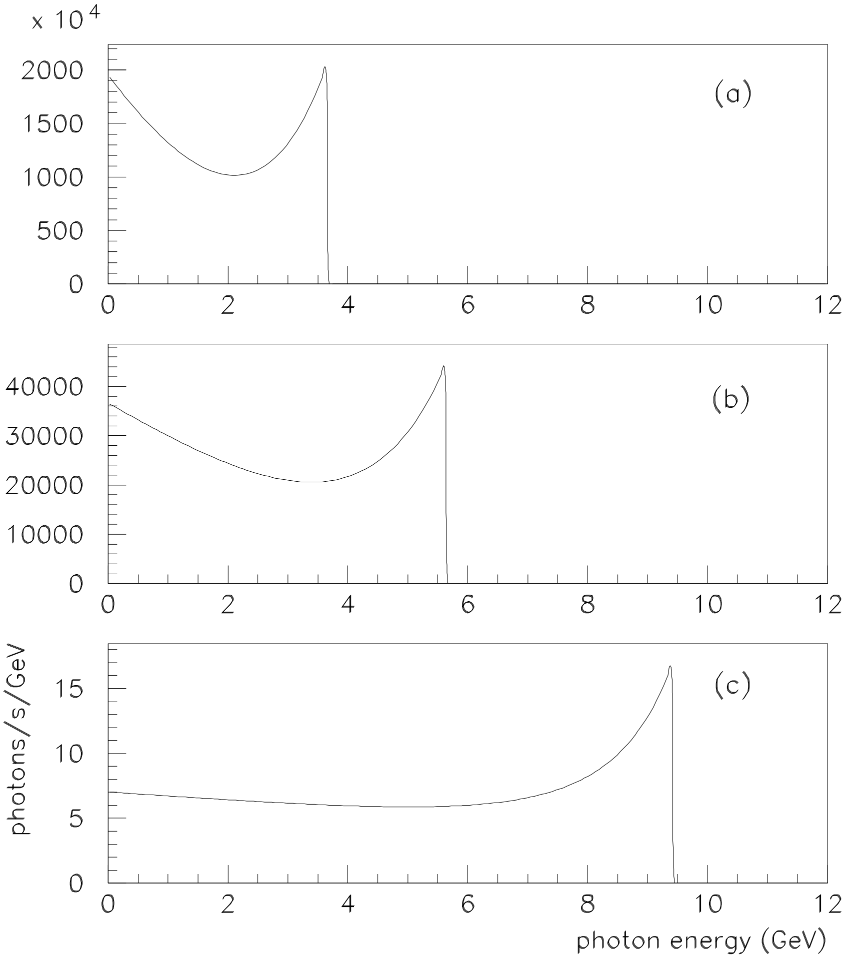

Figure 3.2: Photon energy spectrum from the Compton back-scatter source described in the text and a 12 GeV electron beam at $1\,\mu A$: (a) cavity of gain 10000 driven by a 10 kW Argon-ion laser (514 nm) at 100 MHz, (b) cavity of gain 250 driven by 3 kW frequency-doubler (257 nm) pulsed at 100 MHz, and (c) cavity of gain 1 driven by a hypothetical FEL source operating at 20 eV with the same time structure as CEBAF beam, peak power 1 kW.

needed. The brightest source of 20 eV photons would be synchrotron radiation. Mirrors that operate at these wavelengths typically have reflectivities around 70%. With these one could conceive of a scheme that uses a wiggler to extract energy from the 12 GeV beam before it enters the dump. This light would have the same time structure as the incident beam, and so it could be reflected back and made to cross the incident beam at a small angle for a Compton back-scatter source. An indication of the level of flux that could be achieved with such a source can be obtained by using the laser cavity model described above, setting the gain of the cavity to 1, the wavelength to 62 nm, and assuming 1 kW peak (1 W average) of synchrotron light within the peak. The back-scatter rate for this source is shown in Fig 3.2c. This plot shows that even if the full power of 1 μA in the 12 GeV electron beam were converted into 20 eV photons and back-scattered from the incident beam, the rate of 9 GeV photons produced would still be less than 100 Hz, six orders of magnitude below the design intensity for GlueX.

From the point of view of polarization, the Compton back-scatter source would be ideal. The polarization of the back-scattered beam is controlled by that of the laser, and can be essentially 100%. This source is also virtually background-free because the spectrum below any desired cutoff can be eliminated by collimation. The energy of the remaining beam can be measured to within the resolution of the electron beam by tagging. However the the combination of sufficient energy and sufficient flux for the purposes of the GlueX experiment in Hall D cannot be achieved using this source.

3.2 Tagged bremsstrahlung

A bremsstrahlung source consists of a thin piece of material (the radiator) that is placed in the electron beam and converts part of the energy of the beam into bremsstrahlung radiation. Bremsstrahlung offers the only practical way, starting with an electron beam at CEBAF energies, to produce a photon beam with a significant flux in the vicinity of the end point. It produces a naturally collimated photon beam with a characteristic angular spread of m/E_0. This allows the low emittance of the CEBAF beam to be effectively transferred into the secondary photon beam.

Bremsstrahlung does not suffer from the kind of flux limitations that were encountered in the examination of Compton back-scatter sources. The radiator thickness must be kept below 1% of a radiation length in order to maintain good energy resolution in the tagger. Keeping the thickness below 10^{-3} radiation lengths ensures that multiple scattering in the radiator does not significantly broaden the divergence angle of the photon beam. A 10^{-3} radiator and 1 μA of electrons would produce much more than sufficient flux for GlueX.

A bremsstrahlung source is, however, deficient in some other respects. Averaged over the bremsstrahlung cone, the photon beam has zero linear polarization. Circular polarization can be achieved by polarization transfer from a circularly polarized electron beam, but for the purposes of GlueX, linear polarization is essential. A bremsstrahlung source also suffers from a large low-energy flux in the beam. The power spectrum of a bremsstrahlung beam is approximately uniform from zero up to the energy of the incident electrons. This means that an experiment that uses the high-energy part of the beam must operate in a background of low-energy photons that are many times more frequent. Photon tagging is helpful in eliminating many of the false triggers in the detector that are produced by background beam photons, but this technique is only effective during offline analysis at rates above a few 10^7 tagged photons/s. For the typical large-acceptance experiment using tagged bremsstrahlung, background from low-energy beam particles limits the rate at which the experiment can run to less than $5 \cdot 10^7$ tagged photons/s. The GlueX tagged photon beam design pushes that limit up to 10^8/s by taking advantage of *coherent* bremsstrahlung with collimation.

3.3 Coherent bremsstrahlung

The source described in the previous section meets most of the requirements for GlueX, but is deficient in the areas of polarization and backgrounds. Both of these deficiencies can be remedied by replacing the conventional amorphous or polycrystalline radiator with a thin mono-crystalline wafer. At special settings for the orientation of the crystal, the atoms in the radiator can be made to recoil together from the radiating electron. When they do this they produce a coherent enhancement at particular energies in the radiation spectrum, which correspond to the reciprocal lattice vectors of the crystal. The kinematics are such that a randomly oriented lattice vector would make a tiny peak located up at the end point of the energy spectrum, where the coherent gain factor is negligible. By careful orientation of the crystal, however, one of the lattice vectors can be aligned with the favored kinematics for bremsstrahlung, at which point its coherent peak appears well below the end point, and its coherent gain can be large enough that it contributes a large fraction of the total radiated power.

This is illustrated in Fig. 3.3. This plot shows the intensity (dP/dE) or

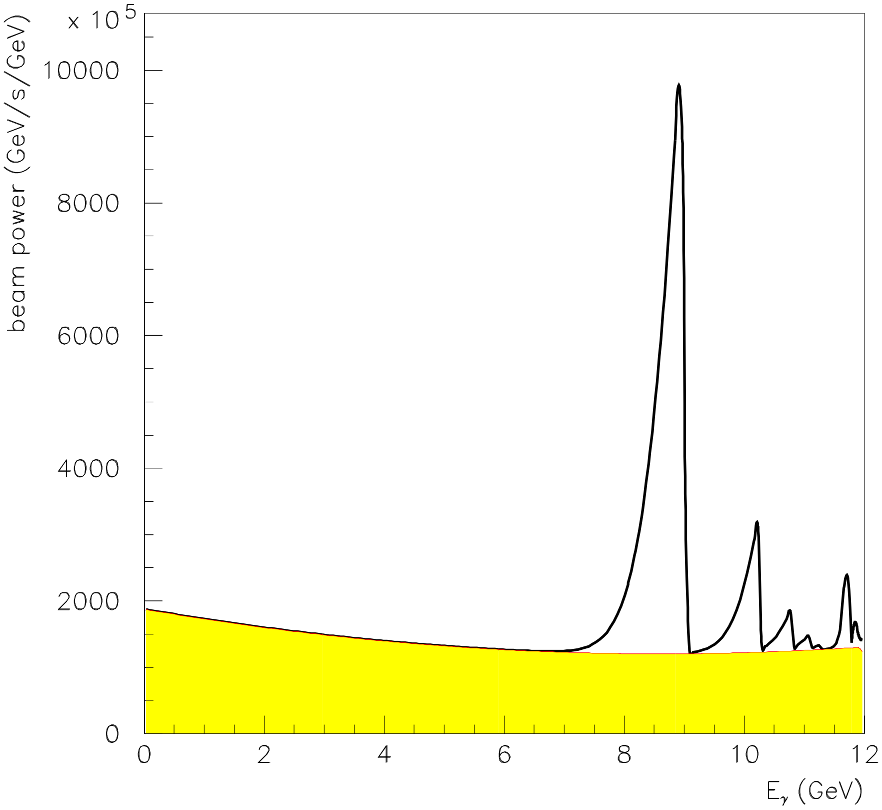

Figure 3.3: Photon power spectrum from an oriented diamond radiator. The y axis is dP/dE with power P expressed in GeV/s and E in GeV. The radiator thickness is 20 microns and the electron beam current is 1 μA. Shown is what emerges after the photon beam passes through a collimator 3.4 mm in diameter located 75 m downstream from the radiator.

power spectrum of the coherent bremsstrahlung beam after collimation. The sequence of secondary peaks above the primary correspond to integral multiples of the fundamental reciprocal lattice vector and so they are always present. By careful choice of orientation angles it is possible to suppress all other vectors and isolate just one primary peak in the energy band of interest, as shown in the figure. By a small rotation of the crystal, the position of the peak can be moved from one end of the spectrum to the other. Note that the coherent peaks appear as enhancements on top of the incoherent bremsstrahlung continuum.

Unlike those from the incoherent process, coherent bremsstrahlung photons have significant net linear polarization in the plane given by the beam direction and the crystal lattice vector. This polarization is enhanced by collimating the photon beam below its intrinsic angular spread, as discussed in the next section. The loss in flux from collimation can be recovered by increasing the electron beam current. As will be shown in the following section, even in the case of very thin crystals and severe collimation, quite modest electron beam currents are needed to produce the required photon flux.

The use of coherent bremsstrahlung improves the background conditions of the beam by enhancing the spectral intensity in the desired energy band relative to the incoherent continuum. For measurements that do not require polarization, a crystal radiator can be used without collimation to reduce the low-energy beam background for a given rate of tagged photons. Where polarization is required, coherent bremsstrahlung is indispensable.

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Bibliography

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