

γ -Beam Options for Positron Production at IP2

Abstract

I examine the merits of producing the γ -beam at IP1 via Compton scattering or bremsstrahlung. This γ -beam is then collided with the laser at IP2 to produce positrons. Serious backgrounds arise from the tails of the angular distribution of the γ -beam which hit material (collimators) producing GeV electrons that can be detected by the pair spectrometer. The calculations presented below indicate that the signal to noise will be slightly greater for a γ -beam produced via Compton scattering. I recommend that we prepare both Compton and bremsstrahlung options for future runs. For the Compton backscattered beam at IP1, IR laser photons are slightly preferred over green. Green is much preferred over IR at IP2 for positron production.

1 Introduction

C. Bamber and A. Melissinos have recently advocated use of a foil at IP1 to produce the γ -beam for positron production at IP2. This has the advantage that large numbers of γ 's are readily produced, and that the spectrum extends up to the electron-beam energy at which the pair-production rate (per γ) is higher. However, a bremsstrahlung beam has more, and higher-energy, γ 's at large angles than does a Compton backscattered beam, so backgrounds are potentially higher.

Recall that the strategy of the IP2 pair-production experiment is to collect the invariant-mass spectrum of pairs. This requires low backgrounds in the pair spectrometer so that the electron in one arm can be correctly correlated with the positron in the other. Backgrounds of tracks from GeV electrons and positrons are extremely serious – are were given insufficient consideration in the E-144 proposal. Further, these backgrounds are not readily avoided by a change of detector technology (unlike the case of synchrotron radiation where different detectors may have different sensitivities to this as compared to minimum-ionizing tracks).

Recall also that much of the effort on the design of the E-144 γ -beam was spent in minimizing backgrounds from synchrotron radiation. In this we have been quite successful. Fig. 1a shows hits in one of the CCD's when it intercepts the γ -beam with the laser off, the IP1 foil out, CCM1 out, but the 1-mil-Al γ -convertor foil in. We see a faint vertical stripe of synchrotron radiation from the very soft bend magnets, and the beginnings of the more intense radiation from the soft bend magnets. The aperture shown in Fig. 1 is defined by Collimator 1, 23.4 m downstream of IP1 and which subtends $\pm 77 \mu\text{rad}$ vertically and $\pm 62 \mu\text{rad}$ horizontally (if aligned properly). The γ -convertor foil scatters most of the soft synchrotron-radiation x-rays so the foil-out rates are considerably higher. Nonetheless, when

the CCD's are in normal data-taking position they cannot view Collimator 1 directly and the rate of synchrotron radiation in the CCD's is essentially zero.

Fig. 1b shows the same CCD intercepting the γ -beam when the 2-mil-Al foil is inserted at IP1. The bulk of the hits in the CCD are now due to high-energy electrons from conversion of the bremsstrahlung γ 's in the CCD. The figure shows that the tails of the bremsstrahlung beam clip the collimator, leading to showers that leave tracks in the CCD's even when they are in normal data-taking position and no longer view the collimator directly. A qualitative estimate is that 1000 tracks hit the CCD's due to bremsstrahlung γ 's under 'normal' conditions.

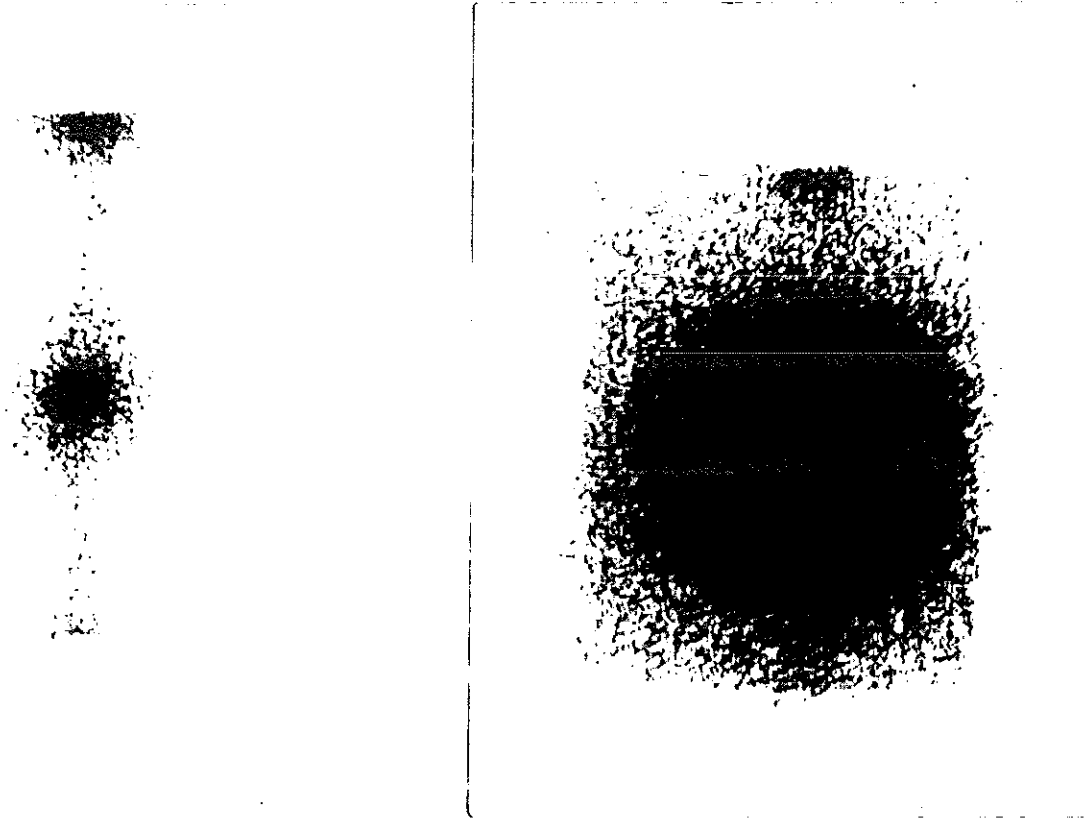


Figure 1: γ -beam profiles when a CCD intercepts the beam. Collimator 1 is the defining aperture: $\theta_x = \pm 62 \mu\text{rad}$, $\theta_y = \pm 70 \mu\text{rad}$ (nominal); (a) Synchrotron radiation observed when the laser is off, the IP1 foil is out, CCM1 is out, but the 1-mil-Al γ -converter foil is in; (b) Bremsstrahlung γ 's observed by conversion in the CCD when the 2-mil-Al IP1 foil is in. The observed aspect ratio of the collimator shadow suggests that Col 1 was cocked vertically.

Likewise, when the laser produces a Compton backscattered beam at IP1 we also have large numbers of tracks in the CCD's. The hi-lo running was developed to reduce this background, and in the March '95 run we found the background track rate was ~ 1 per pulse for an electron beam of $\sim 10^7$ and green laser pulses of ~ 50 mJ.

2 Some Basic Facts

2.1 Pair Creation

In E-144 we are well below threshold for pair creation by a single laser photon (green or infrared) colliding with γ 's of energies less than 46.6 GeV, the electron beam energy. The rate for pair creation by multiple laser photons is strongly dependent on the γ energy, the laser-photon energy and the laser intensity. It is advantageous to have high photon energies, and high laser intensities.

In this note we assume there is agreement that the laser beam at IP2 should be green, although we review the reasons for this at the end of this subsection. We will address the option of either green or infrared laser photons at IP1 to produce a Compton backscattered beam (as well as the bremsstrahlung option).

Fig. 8 of the E-144 proposal presented the pair-production cross section *vs.* γ energy, but for blue laser photons. I have recalculated this cross section for green laser photons and for several values of $\eta = eE_{\text{rms}}/m\omega_0c$ (note that $\eta \propto \sqrt{I}$). For γ 's in the energy range 25-50 GeV the pair rate varies with the γ energy ω as

$$\text{rate} \propto \omega^a, \quad \text{where} \quad a = 3.6\eta^{-2/3},$$

for a fixed value of η . For example, if $\eta = 0.5$ then the pair rate varies as ω^6 , which I will use as a representative case below. At higher values of η the pair rate has a slower dependence on the γ energy.

Recall that for a fixed γ energy near 30 GeV, the pair rate varies with (green) laser intensity I as I^4 (and hence as η^8) since four laser photons are required to produce a pair.

Table 1: Pair-production cross sections for green and IR laser photons.

| ω (GeV) | λ (μm) | η | σ_{pair} (cm^2) |
|-------------------|--------------------------------|--------|---|
| 46 | 0.53 | 0.5 | 2.1×10^{-27} |
| 46 | 1.06 | 1.0 | 4.9×10^{-28} |
| 29 | 0.53 | 0.5 | 9.1×10^{-29} |
| 21 | 1.06 | 1.0 | 3.5×10^{-31} |

We close this subsection with a sketch of why it is advantageous to produce positrons with green laser light. Recall that for the same laser pulse energy, pulse length and focal quality (square of the effective f/D ratio) an IR and green laser pulse would have the same value of η (since $\eta^2 \propto I\lambda^2$). In practice we estimate that a green laser pulse will have only half the energy of the IR pulse, and that the product of pulse length and focal quality is a

factor of two worse for IR than for green. Then the η of the green pulse is 1/2 that of the IR pulse. Table 1 lists the pair-production cross section for some representative parameters corresponding to the γ -beam being produced by bremsstrahlung ($\omega = 46$ GeV) or by green and IR laser photons, ($\omega = 29$ and 21 GeV, respectively, which are the endpoints of the corresponding Compton backscattering spectra). We see that there is an advantage for green over IR no matter how the γ -beam is produced. The table also illustrates how it might be advantageous to have a bremsstrahlung γ -beam with its higher endpoint energy.

2.2 Compton Backscattering

We suppose that γ 's are produced at IP1 by a laser beam with η low enough that mass-shift effect can be ignored. Then the backscattered photons have energy ω related to the scattering angle θ relative to the electron given by

$$\omega \approx \frac{\omega_{\max}}{1 + b\gamma^2\theta^2},$$

where $\gamma = U_e/m = 9.1 \times 10^4$ for $U_e = 46.6$ GeV, $\omega_{\max} = 29.1$ GeV and $b = 1/(1 + 4\gamma\omega_0/m) = 0.38$ for green laser photons, and $\omega_{\max} = 21.1$ GeV and $b = 0.55$ for IR. The above expression ignores the 17° crossing angle used in E-144.

The Compton scattering rate is roughly constant in γ energy:

$$dN \approx \chi_C \frac{d\omega}{\omega_{\max}},$$

where for later comparisons we introduce χ_C as the probability of Compton scattering per electron. In this approximation we readily deduce the angular distribution to be

$$\frac{dN}{N} = \frac{2b\gamma^2\theta d\theta}{(1 + b\gamma^2\theta^2)^2},$$

now normalized to one. For angles large compared to $1/\gamma = 11 \mu\text{rad}$ the angular distribution is

$$\frac{dN}{N} \approx \frac{2d\theta}{b\gamma^2\theta^3}, \quad (\theta \gg 1/\gamma),$$

and the fraction of scatters that occur at angles larger than some angle θ_0 is

$$\frac{N(\theta > \theta_0)}{N} = \frac{2}{b\gamma^2\theta_0^2}.$$

2.3 Bremsstrahlung

If a thin foil of χ_B radiation lengths is inserted into the electron beam the resulting spectrum of bremsstrahlung γ 's per electron is

$$dN = \chi_B \frac{d\omega}{\omega}, \quad (\omega < U_e).$$

In contrast to Compton scattering, a bremsstrahlung γ beam has no correlation between energy and scattering angle (or very little correlation, see eq. (93.16) of Landau & Lifshitz,

Vol. 4, 2nd ed.). The angular distribution for any bremsstrahlung photon, normalized to one, is

$$\frac{dN}{N} = \frac{2\gamma^2\theta d\theta}{(1 + \gamma^2\theta^2)^2}.$$

For angles large compared to $1/\gamma = 11 \mu\text{rad}$ the angular distribution is

$$\frac{dN}{N} \approx \frac{2d\theta}{\gamma^2\theta^3}, \quad (\theta \gg 1/\gamma),$$

and the fraction of scatters that occur at angles larger than some angle θ_0 is

$$\frac{N(\theta > \theta_0)}{N} = \frac{2}{\gamma^2\theta_0^2}.$$

The difficulty for the E-144 pair-production experiment is that both Compton backscatters and bremsstrahlung produce γ -beams with several percent outside $100 \mu\text{rad}$.

2.4 FFTB Emittance

Recall that the nominal emittance of the FFTB is $\epsilon_x = 3 \times 10^{-10}$ m-rad and $\epsilon_y = 3 \times 10^{-11}$ m-rad. Thus if we produce an electron-beam spot of, say, $10 \times 10 \mu\text{m}^2$ the angular divergence will be $\theta_x = 30 \mu\text{rad}$ and $\theta_y = 3 \mu\text{rad}$. In particular, small spots in x will aggravate the problem of tails of the angular distribution of the γ -beam.

3 Comparison of Pair Rates

For a comparison of pair-production rates with bremsstrahlung and Compton γ -beams we assume green laser photons at IP2 with $\eta = 0.5$. For this η the pair-production cross section varies with γ energy as ω^6 .

3.1 Comparison Ignoring Angular Effects

We begin the comparison by supposing that all γ 's created at IP1 interact with green laser photons at IP2.

3.1.1 Bremsstrahlung

Then the rate of pair production per electron due to bremsstrahlung γ 's would be

$$R_B \propto \int_0^{\omega_B} \omega^6 \chi_B \frac{d\omega}{\omega} = \chi_B \frac{\omega_B^6}{6},$$

using the notation of sec. 2.3 with $\omega_B = 46.6$ GeV, the electron beam energy.

3.1.2 Compton Scattering

Similarly, the rate of pair production per electron from a Compton backscatter beam would be

$$R_C \propto \int_0^{\omega_C} \omega^6 \chi_C \frac{d\omega}{\omega_C} = \chi_C \frac{\omega_B^6}{7},$$

where ω_C is the endpoint energy of the Compton spectrum. There are two options: IR at IP1 for which $\omega_{C,IR} = 21.1$ GeV, and green at IP1 for which $\omega_{C,gr} = 29.1$ GeV. If the fraction of electrons, χ_C , that are Compton scattered were the same for IR and green we would have $R_{C,IR}/R_{C,gr} = (21.1/29.1)^6 = 0.15$.

However, the situation is more favorable for use of IR at IP1 for two related reasons. If green is used at both IP1 and IP2 the available green energy must be split between them. While the rate of Compton scatters at IP1 varies as $I_1 =$ laser intensity at IP1, the rate of pair creation at IP2 varies as I_2^4 , so the combined rate varies as $I_1 I_2^4$. Since $I_1 + I_2 = I$ is fixed it is optimal to choose $I_1 = 0.2I$ and $I_2 = 0.8I$. The 20% reduction in I_2 costs about a factor of two in rate according to the cross-section calculation mentioned in sec 2.1.

Furthermore, if IR is used at IP1, the pulse energy there would be about the same as for the green pulse at IP2. For a given pulse energy, there are twice as many IR photons as green photons. Hence the IR pulse at IP1 would contain about 10 times as many photons as the 20% of the green pulse that would be used there. Hence we would have $\chi_{C,IR} = 10\chi_{C,gr}$. Thus our revised estimate is that

$$\frac{R_{C,IR}}{R_{C,gr}} = \frac{10}{0.5} \left(\frac{21.1}{29.1} \right)^6 = 3.$$

That is, we have a small advantage in using the unconverted IR photons to produce Compton scatters at IP1, compared to the use of green there.

In further comparisons involving Compton scattering at IP1 we will assume the use of IR light there.

In particular, the ratio of pair production using bremsstrahlung γ 's to that with Compton γ 's would be

$$\frac{R_B}{R_C} = \frac{\chi_B 7\omega_B^6}{\chi_C 6\omega_C^6} = 1.17 \frac{\chi_B}{\chi_C} \left(\frac{46.6}{21.1} \right)^6 = 136 \frac{\chi_B}{\chi_C}.$$

That is, we could achieve the same pair production rate with a weaker bremsstrahlung γ -beam, which appears advantageous from the point of view of backgrounds.

But we have neglected angular effects.

3.2 Comparison Including Angular Effects

I will assume the green laser spot at IP2 has an area of about $30 \mu\text{m}^2$, corresponding to a radius of about $3 \mu\text{m}$. Only a small fraction of the γ -beams discussed above overlap the laser spot. Two effects must be considered:

1. The size of the (virtual) electron beam spot at IP2. [That is, the size of the spot if the electron beam were not deflected in the dump magnets.]

2. The spread of γ 's produced at IP1 relative to the (virtual) position of the unscattered electrons.

In the rest of this note we will consider the (virtual) electron spot at IP2 to have $\sigma_x = \sigma_y = 10 \mu\text{m}$. If the γ 's were all produced at $\theta = 0$, then the pair rates would be reduced by $(3/10)^2$.

3.2.1 Bremsstrahlung

All bremsstrahlung γ 's are produced with an angular distribution with a characteristic angle $1/\gamma = 11 \mu\text{rad}$. Thus over the 11.4-m drift from IP1 to IP2 the bremsstrahlung γ 's will have spread to cover a spot of characteristic radius $125 \mu\text{m}$. In view of this, details of the (virtual) electron spot at IP2 are not relevant. However, the rate of pair production by bremsstrahlung γ 's is reduced by a factor

$$\epsilon_B = \left(\frac{3}{125}\right)^2 = 5.8 \times 10^{-4},$$

since only a small fraction of the γ overlap the laser spot at IP2. [This estimate is not changed to first order by the fact that the laser beam crosses IP2 at an angle.]

The rate of pair production from bremsstrahlung γ 's is then

$$R_B \propto \epsilon_B \chi_B \frac{\omega_B^6}{6}.$$

3.2.2 Compton Backscatters

Compton γ 's are produced with an energy-angle correlation, given in sec. 2.2. If the electron spot at IP2 has a radius of $10 \mu\text{m}$ this corresponds to an angle of $0.9 \mu\text{rad}$ as viewed from IP1. Hence a Compton γ produced at IP1 with an angle of greater than $0.9 \mu\text{rad}$ would miss the laser spot and could not produce any pairs.

For Compton γ 's produced by IR photons at IP1, a production angle of $0.9 \mu\text{rad}$ corresponds to an energy only 0.5 GeV below the endpoint energy of 21.1 GeV . For Compton γ 's in this interval we make the simplified estimate that the probability of overlapping the laser beam is just the ratio of areas of the laser spot to the (virtual) electron spot:

$$\epsilon_C = \left(\frac{3}{10}\right)^2 = 0.09.$$

The rate of pair production from Compton γ 's is then

$$R_C \propto \epsilon_C \chi_C \omega_C^6 \frac{\Delta\omega}{\omega_C},$$

where $\Delta\omega = 0.5 \text{ GeV}$.

The ratio of pair production rates is now

$$\frac{R_B}{R_C} = \frac{\epsilon_B \chi_B \omega_C \omega_B^6}{\epsilon_C \chi_C 7 \Delta\omega \omega_C^6} = \frac{(5.8 \times 10^{-4})(\chi_B)(21.1)}{(0.09)(\chi_C)(7)(0.5)} \left(\frac{46.6}{21.1}\right)^6 = 4.4 \frac{\chi_B}{\chi_C}.$$

That is, the apparent advantage of bremsstrahlung γ 's over Compton γ 's discussed in sec. 3.1 is much reduced once angular effects are taken into account.

4 Wide-Angle Backgrounds

Section 2 concerned only the signal for pair creation. We now consider the problem of conversion of wide angle γ 's. Recall that the difficulty is that such γ 's shower when they hit material, *i.e.*, Collimator 1. The resulting lower-energy electrons, positrons and γ 's have some probability of passing through Collimator 2 and leaving tracks in the CCD's.

The 5D36 magnet gives us some protection against low energy electrons and positrons. We typically run with a 0.5 T-m field, corresponding to a 150 MeV/ c kick. Charged particles of momenta below about 100 MeV are bent too far to be much of a problem. Higher-energy particles are bent into the beam pipe at small enough angles that the resulting showers can be dangerous.

I will use 100 MeV as the low-energy cutoff for dangerous γ 's, based on the previous paragraph.

4.1 Bremsstrahlung

Each 46.6-GeV electron passing through a foil of χ_B radiation lengths produces

$$\chi_B \int_{0.1}^{46.6} \frac{d\omega}{\omega} = \chi_B \ln 466 = 6\chi_B$$

bremsstrahlung γ 's of energy greater than 0.1 GeV.

If Collimator 1 has an opening angle of $\theta_1 = 70 \mu\text{rad}$ the fraction of these γ 's that hit the collimator is $2/(\gamma^2\theta_1^2) = 0.05$, according to a result in sec. 2.3. That is, the number D_B of dangerous bremsstrahlung γ 's per electron is

$$D_B = 0.3\chi_B.$$

The average energy of these dangerous γ 's is

$$U_B = \int_{0.1}^{46.6} \omega \frac{d\omega}{\omega} / \int_{0.1}^{46.6} \frac{d\omega}{\omega} \approx 8 \text{ GeV}.$$

4.2 Compton Scatters

In Compton scattering of IR photons off 46.6-GeV electrons only γ 's of less the 1 GeV have angles larger than $70 \mu\text{rad}$. Hence the fraction of dangerous Compton γ 's is only $1/21.1 = 0.05$, and the number D_C of dangerous Compton γ 's per electron is

$$D_C = 0.05\chi_C.$$

The characteristic of these dangerous γ 's is at most

$$U_C = 1 \text{ GeV}.$$

Because the typical energy of the dangerous bremsstrahlung γ 's is higher than that of Compton γ 's they will cause greater showering, at least in the ratio $\ln(U_B/U_C) = 2$. Therefore, I increase the effective number of dangerous bremsstrahlung γ 's by 2 to be

$$D_B = 0.6\chi_B \quad (\text{revised}).$$

4.3 Signal to Noise

The signal to noise for pair production detected in the CCD spectrometer is proportional to the ratio R/D of pair-production rate to the number of dangerous wide-angle γ 's. The ratio of signal to noise from bremsstrahlung to that from Compton γ 's is thus

$$\frac{R_B/D_B}{R_C/D_C} = 4.4 \frac{\chi_B}{\chi_C} \frac{0.05\chi_C}{0.6\chi_B} = 0.4.$$

Thus, to the accuracy of the present estimate, the signal to noise for pair creation at IP2 is about the same whether γ 's are produced at IP1 by bremsstrahlung or by Compton scattering.

4.4 Possible Improvements in Signal to Noise

If the apertures of the collimators were increased fewer wide-angle γ 's would cause problems. However, these apertures cannot be increased so much that wide-angle γ 's hit the CCD's, or so much that synchrotron radiation becomes a problem.

I estimate that we could increase the collimator apertures to about $100 \mu\text{rad}$ without too much consequence. It would be important to increase the field in the very soft bend magnets around IP1 by $10/7$ to keep synchrotron radiation from the soft bends out of the apertures. D. Walz confirms that we have the option to double the strength of the very soft bend magnets relative to its present value

This change would reduce the number of dangerous bremsstrahlung γ 's by $(7/10)^2 = 0.5$. At $100 \mu\text{rad}$, Compton γ 's have energy only 0.5 GeV so the number of dangerous Comptons would also be reduced by a factor 0.5 . (There is a $\ln 2$ advantage for the Compton in that their typical energy is lower now).

In sum, there is only a small advantage in small enlargements of the collimators. [A policy to do away with the collimators and let the wide-angle γ 's and synchrotron x-rays hit wherever would be very unwise.]

5 Strategy

I think we should prepare to search for pair at IP2 with both bremsstrahlung and Compton γ 's. The use of Compton γ 's is potentially slightly cleaner, but we may have insufficient laser photons. On the other hand, a foil may create too many bremsstrahlung γ 's, swamping us with background. We should prepare several foils and/or wires of differing effective thicknesses, and also be prepared to use 'hi-lo' operation of the linac when using these foils.