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Almost Monochromatic Photon Beams at the Stanford Linear Accelerator Center*

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ABSTRACT

A method of obtaining almost monochromatic photon beams from well-collimated positrons is investigated. It is found that such photon beams are naturally suitable for use with a hydrogen bubble chamber. The main background is due to electron tracks from pair production and Compton effect which limit the number of acceptable photons/pulse to about 400.

A typical case has been calculated with the result that for incoming 15 GeV positrons one obtains a 7.27 GeV photon beam with $\left|\frac{\Delta k}{k}\right|$ of 1% and a signal-to-noise ratio of 1:3.

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I. INTRODUCTION

Recent experiments at the Cambridge Electron Accelerator have shown that photoproduction of strongly interacting particles and their resonant states can be successfully studied with a hydrogen bubble chamber.[1] The photon spectrum used was a regular thin target bremsstrahlung.

A significant improvement in the rate of production and analysis of photoproduction data could come from the case of a monochromatic gamma beam. Such a beam seems feasible at SLAC because of the expected high intensity of positrons. The process considered here is e^+e^- annihilation in flight into two photons.

In this note we examine (1) a feasible way of obtaining almost monochromatic photon beams, (2) a proposed beam design, and (3) the maximum number of photons/pulse that can be admitted into a hydrogen bubble chamber.

II. PHOTON RATE CALCULATION

A. Photons from Positron Beams

The possibility of obtaining almost monochromatic photon beams from electron-positron annihilation has been examined[2] recently. In e^--e^+ annihilation into two photons, an emerging photon at a fixed angular interval θ_1 in $d\theta_1$ has a unique energy k_1 in dk_1, related by

$$\left.\begin{aligned} \frac{k_1}{\mu} &= \frac{1+\gamma}{1+\gamma(1-\beta y)} \\ \text{where, } y &= \cos\theta_1 , \; \beta = \frac{p_o}{E_o} , \text{ and } \gamma = \frac{E_o}{\mu} \end{aligned}\right\} \quad \ldots\ldots \quad (1)$$

The cross section of pair-annihilation into two photons with the electron at rest (Laboratory System), integrated over the variable of the second photon and the azimuthal angle of the first photon is given by:

$$\sigma_{pair} = Z r_o^2 \pi \frac{dy}{\beta\gamma^2(1 - \beta y)} \left\{ (\gamma + 3) - \frac{[1 + \gamma(1 - \beta y)]^2}{\gamma(1 + \gamma)(1 - \beta y)} - \frac{2\gamma(1 + \gamma)(1 - \beta y)}{[1 + \gamma(1 - \beta y)]^2} \right\} \qquad (2)$$

In the small angle and extreme relativistic approximation, $\beta \approx 1$, $\gamma \pm 1 \approx \gamma$, and $1 - \beta y \approx \theta_1^2/2$, Eqs. (1) and (2) reduce to:

$$\left.\begin{aligned} \theta_1^2 &= \frac{2\mu(E_o - k_1)}{k_1 E_o} \\ \sigma_{pair} &= Z\, 2\pi r_o^2 \frac{dx}{x} \left\{ \frac{1}{\gamma} + \frac{3}{\gamma^2} - \frac{4x^2}{[2\gamma + x^2]^2} - \frac{[2\gamma + x^2]^2}{2x^2\gamma^4} \right\} \\ \text{where, } x &= \gamma\theta_1 \,, \quad \frac{k_1}{\mu} = \frac{\gamma}{1 + \frac{x^2}{2\gamma}} \end{aligned}\right\} \qquad (3)$$

and, $dx = \frac{x}{2} \frac{E_o}{k_1} \frac{dk_1}{(E_o - k_1)}$, $r_o = 2.8178 \times 10^{-13}$ cm .

Thus, the number of photons/pulse from the pair-annihilation process, having energy k_1 and emerging at an angle θ_1 in $d\theta_1$ is:

$$N_{pair} = \frac{N_o}{A} \cdot t \cdot I \, \sigma_{pair} (\theta_1 \, , \, dk_1) \qquad (4)$$

where N_o = Avogadro's number, A = mass number, t = target thickness measured in gm-cm^{-2}, and I = number of beam positrons/pulse.

B. Direct Bremsstrahlung

A competing source of photons in such a beam is due to the direct bremsstrahlung process of positrons in the field of target nuclei and electrons, emitting photons at an angle θ in $d\theta$ having energy k in dk. The energy-angle distribution of thin target electron bremsstrahlung has been examined by Schiff,[4] who has integrated the Bethe-Heitler equation over the scattered electron angles taking screening effects into consideration.

In the relativistic limit, the direct bremsstrahlung cross-section due to electrons on target nuclei is given by:

$$\sigma^{\mathrm{dirc}}_{\mathrm{brems.}}(\theta,k) = \frac{8}{137} r_o^2 \frac{dk}{k}\frac{dx}{x^3}\left\{-[1+(1-\nu)^2]\,\ell n\, P(x,\nu) - (2-\nu)^2\right\}$$

where

$$P(x,\nu) = \frac{1}{M(x,\nu)} = \left[\frac{\mu}{2E_o}\frac{\nu}{(1-\nu)}\right]^2 + \left[\frac{1}{111x^2}\right]^2 \qquad (5)$$

$\nu = \frac{k}{E_o}$, and $x = \gamma\theta$, where we have chosen hydrogen as the target. Here, we have assumed that e^+p and e^+e^- bremsstrahlung are roughly equal because their small angle scattering cross-sections are similar.

The number of photons/pulse from the direct bremsstrahlung of positrons on hydrogen having energy k in dk and emerging at an angle θ in $d\theta$ is:

$$\delta N^{\mathrm{dirc}}_{\mathrm{brems.}}(\theta,k) = \frac{8}{137} r_o^2\, N_o t I \frac{dk}{k}\frac{dx}{x^3}\left\{\begin{matrix}\text{of}\\ \text{Eq. (5)}\end{matrix}\right\} \qquad (6)$$

whereas,

$$N_{pair}(\theta, x) = 2\pi r_o^2 N_o t I \frac{dx}{x} \left\{ \begin{matrix} \text{of} \\ \text{Eq. (3)} \end{matrix} \right\} \qquad (7)$$

Comparing Eq. (6) with Eq. (7) we note that the number of produced photons as a function of emission angle behaves as $\frac{dx}{x^3}$ from the direct bremsstrahlung process, and as $\frac{dx}{x}$ from pair-annihilation; the ratio of pair-annihilation produced photons to that of bremsstrahlung increases with x as x^2. Hence, to obtain a desirable ratio it is necessary to collimate in the range of $x = 200\text{-}300$. In cases to be considered θ is always $\lesssim 1^{\circ}$.

C. Indirect Bremsstrahlung

As a second source of background photons we consider the indirect bremsstrahlung process, where the positron suffers a single large angle scatter θ in $d\theta$ and subsequently emits into $d\theta$ a bremsstrahlung photon having energy k in dk.

From elementary considerations, the probability of scattering[5] $e^{\pm}$ at an angle θ in $d\theta$ on a proton, for the relativistic case, is given by:

$$P_{sc} = 8\pi N_o r_o^2 t \left(\frac{\mu}{E_o}\right)^2 \frac{d\theta}{\theta^3} .$$

Since $e^- - e^+$ scattering at small momentum transfers is similar to $e^+ - P$ scattering, the probability for a positron to scatter on hydrogen (e^-, P) can be approximated to be $2 \times P_{sc}(e^+ - P)$. Hence,

$$P_{sc}(e^+ - H) = 16\pi N_o r_o^2 t \frac{dx}{x^3} \qquad (8)$$

where $x = \gamma\theta$ and t is measured in $gm\text{-}cm^{-2}$.

The probability for a positron of energy E_o to emit a photon of energy k in dk, in the field of a proton is:

$$\sigma_{rad}\cdot(e^+\text{-}H) = \frac{8}{137} N_o r_o^2 t \frac{dk}{k} F(E_o,\nu) \qquad (9)$$

where, in the case of complete screening, the function $F(E_o,\nu)$ is given[6] by:

$$F(E_o,\nu) = \left[1 + (1-\nu)^2 - \frac{2}{3}(1-\nu)\right] \ln(183) + \frac{1}{9}(1-\nu), \quad \nu = \frac{k}{E_o} .$$

Here, again we have multiplied by 2 to account for both e^+,P and e^+,e^-.

Thus, the number of photons/pulse from the indirect bremsstrahlung of positrons on hydrogen is expressed as:

$$\delta N^{indir.}_{brems.}(\theta,k) = \frac{1}{2}\left(\frac{8}{137} N_o r_o^2\right)(16\pi N_o r_o^2) t^2 I \frac{dk}{k} \frac{dx}{x^3} F(E_o,\nu) \qquad (10)$$

Comparing Eqs. (6) and (7) with (10), we note that the number of photons/pulse as a function of target thickness behaves as $t(\text{gm-cm}^2)$ from pair-annihilation and direct bremsstrahlung, and as t^2 from indirect bremsstrahlung. So that, in order to suppress this competing source of indirect bremsstrahlung photons it is not only necessary to collimate at large values of x but also to use a hydrogen target of thickness $t \lesssim 0.5$ gm-cm^{-2}. This thickness has not been optimized but is a useful value in that it yields an indirect bremsstrahlung background which is about 8% of the direct bremsstrahlung.

D. Computational Results

To obtain the photons/pulse total spectrum for fixed values of x, dx and I, integration of Eqs. (6) and (10) was performed[7] over the photon energies. A lower limit of photon energy $k_{min} = 0.020$ GeV was taken, assuming that only bremsstrahlung photons of energy greater than 20 MeV would be transmitted by a one radiation length liquid hydrogen photon filter.

It turns out that the best results are achieved for the highest energy positrons. Accordingly we have chosen as two typical examples the case of 7.27 GeV and 4.86 GeV photons produced by 15 GeV positrons. The results are shown in Fig. 1(a) and (b). Results for 10 GeV positrons are shown in Fig. 2. All these cases have been calculated based on a positron intensity of 4×10^{10} e^+/pulse and a liquid hydrogen target thickness of 0.50 $gm\text{-}cm^{-2}$. We have investigated the effects of multiple scattering and found them to be negligible. For example, in the case of Fig. 1(a), the ratio $\theta_{m.s.}/\theta_{annih} \lesssim 10^{-2}$.

The total number of photons stated on the figures do not take into account the absorption of photons in the beam hardner nor any reduction due to azimuthal collimation (see Fig. 4). We estimate these effects to be on the order of a factor of 10 reduction for practical cases.

III. BEAM DESIGN

A positron source for the 25 GeV Stanford Linear Accelerator has been designed by Drs. H. C. DeStaebler, Jr., of SLAC and J. Pine of the California Institute of Technology. The source is shown schematically in Fig. 3. Electrons are accelerated to approximately 5 GeV down the first third of the accelerator. At this point they impinge on a high Z converter, producing pairs. Low energy positrons in the range of 3-30 MeV are captured in a tapered solenoid with a maximum magnetic field of 20 kilogauss, followed by a uniform field solenoid placed over the first following accelerator tube section. The accelerator is reverse phased after the converter and the captured positrons are accelerated for the remaining two-thirds of the machine. Quadrupole triplets are spaced more or less uniformly down the remaining length of the accelerator in order to maintain the phase space.

For Stage I accelerator operation this would correspond to 15 GeV positrons. For a power of 50 kW dissipated in the converter calculations indicate that a beam intensity of 4×10^{10} e^+/pulse is feasible.

Figure 4 shows the proposed beam layout. A well-collimated positron beam of $\left|\frac{\Delta p}{p}\right| = 1\%$ and $\Delta\theta \approx 10^{-4}$ rad. passes through a steering magnet H1 onto the target T. This steering magnet allows one to change the observed annihilation angle without moving the collimators. A sweeping magnet H2, placed far enough so as not to interfere with the primary beam deflects non-interacting 15 GeV positrons. The photons are hardened by a one radiation length of liquid hydrogen surrounded by a weak magnetic field. This is followed by a high Z circular slit S1. A second sweeping magnet H4 clears the defined photon channels from any created pairs at the filter or slit. A second defining circular slit S2 is placed 2/3 downstream from the target with an aperture slightly larger than required by a line through T, S1, and S2; the purpose of S2 is to absorb second generation photons from S1.

Assuming a characteristic collimation angle of $\theta = 8 \times 10^{-3}$ rad., the photon beam after a drift length of 60 m will be localized in a circular ring of $r = 48$ cm in $dr = 1.2$ cm. To accept 1/3 of this beam into the hydrogen bubble chamber requires a beam thin window of dimensions 25×70 cm. This thin window should be made of a low Z material, preferably a beryllium alloy.

IV. BACKGROUND ELECTROMAGNETIC INTERACTIONS IN THE HBC

The background electromagnetic interactions in the hydrogen bubble chamber are pair-production and Compton scattering. As such these interactions set a tolerance limit on the number of beam photons entering the chamber. The proposed beam design assures that such interactions within the chamber will take place in a spread-out fashion. This requirement is essential for easy scanning and measurement of interesting events. The probability for these reactions to occur in a 1.0 m HBC is shown in Fig. 5. In such a chamber we estimate that a total of 400 incident photons will produce a maximum tolerable background of 27 electromagnetic interactions.

LIST OF REFERENCES

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5. B. Rossi, High Energy Particles, Prentice-Hall (1952); p. 65.
6. Ibid., p. 49.
7. The integration was performed numerically, executed on the Stanford University IBM 7090 computer.

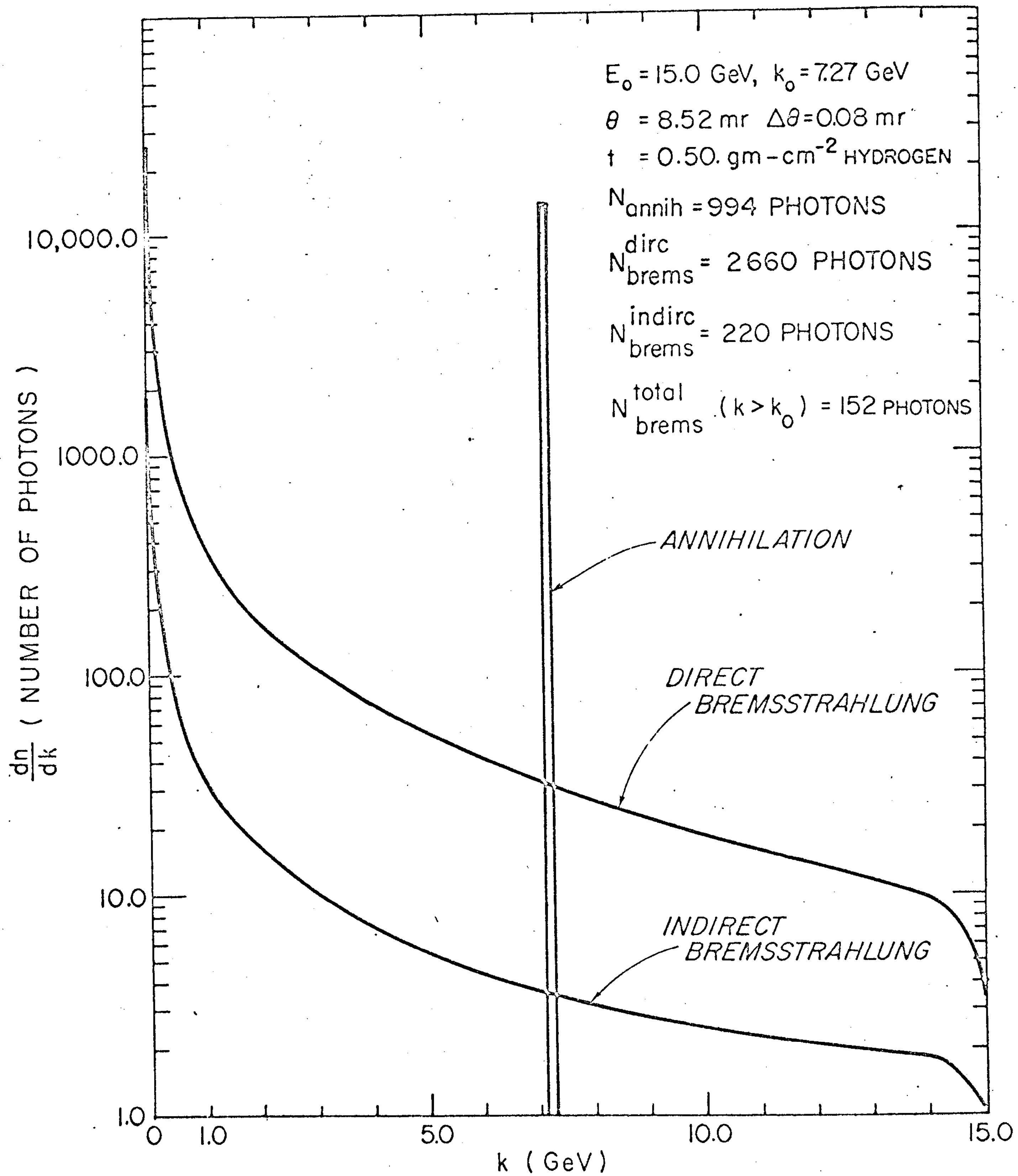


FIGURE 1a

106-5-A

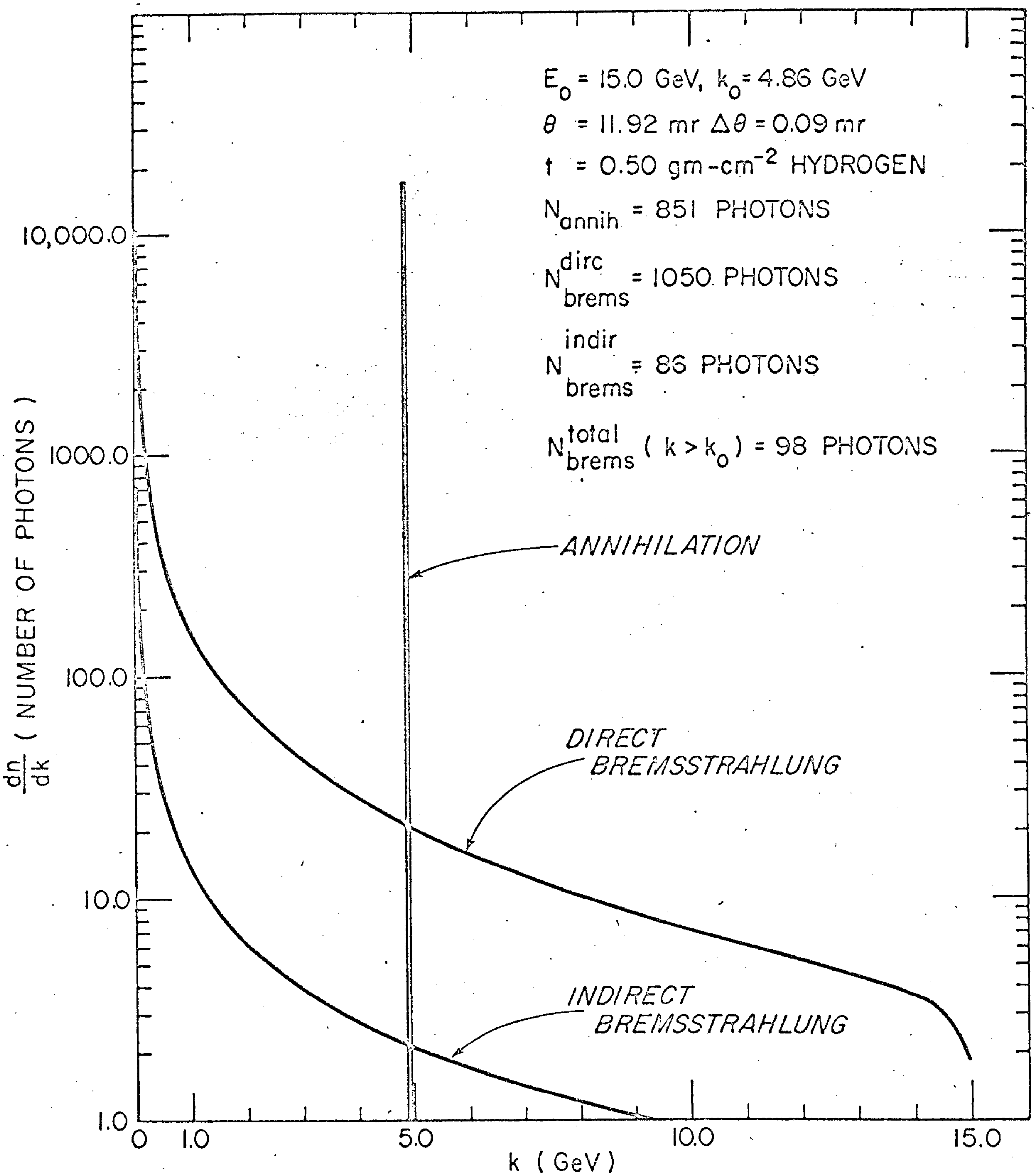


FIGURE 1b

106-6-A

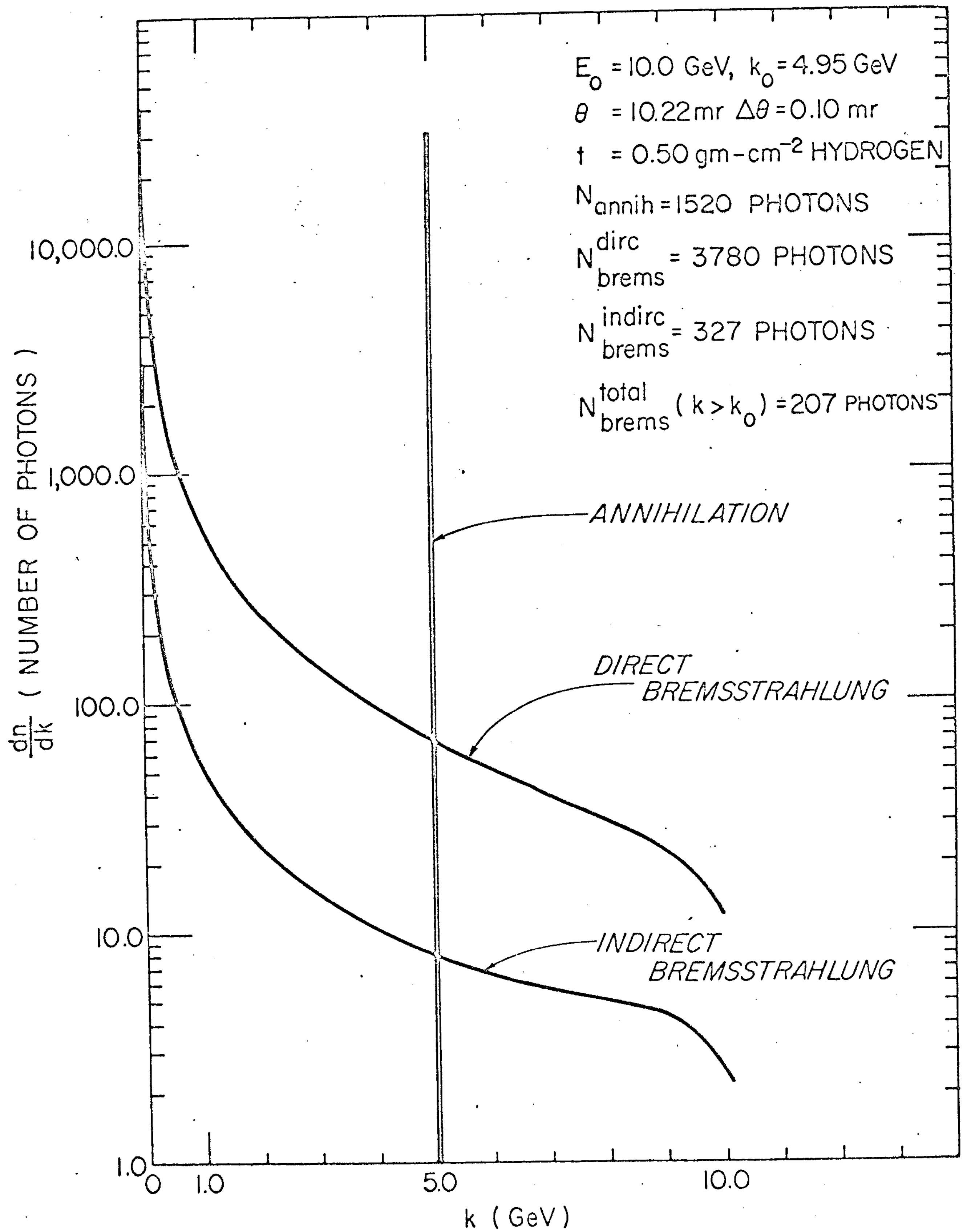
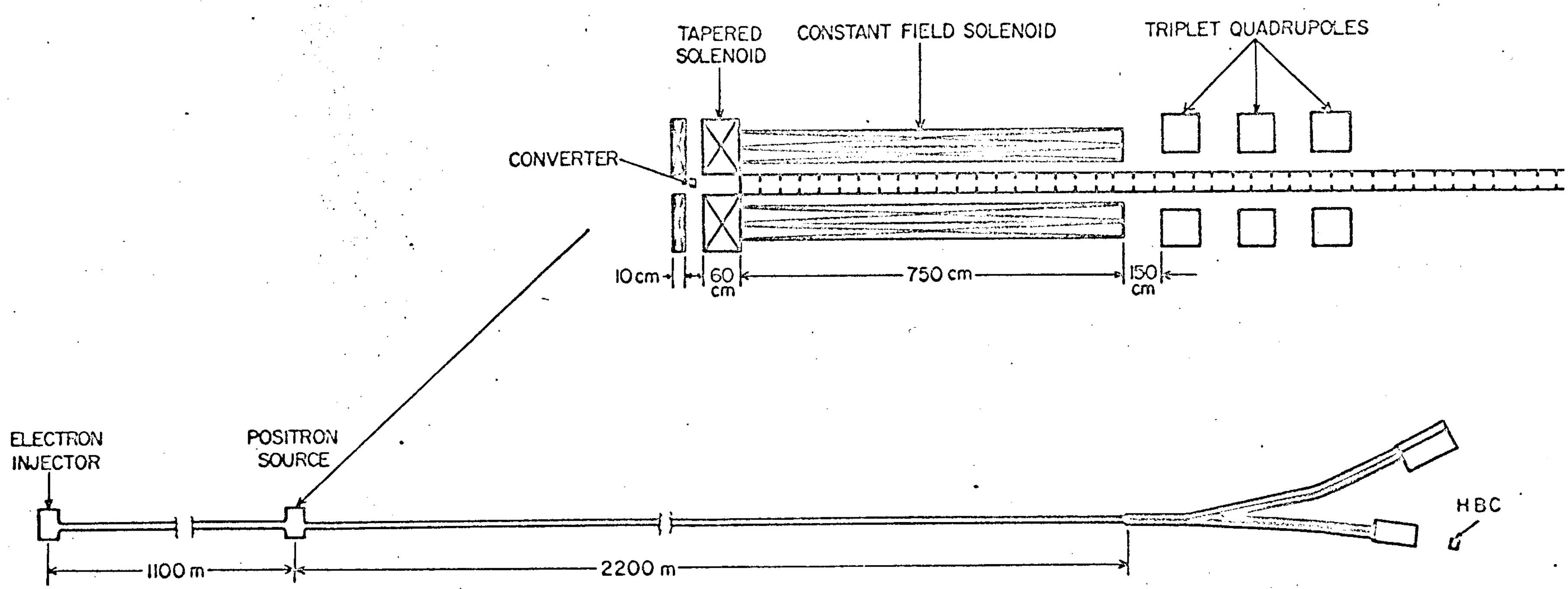


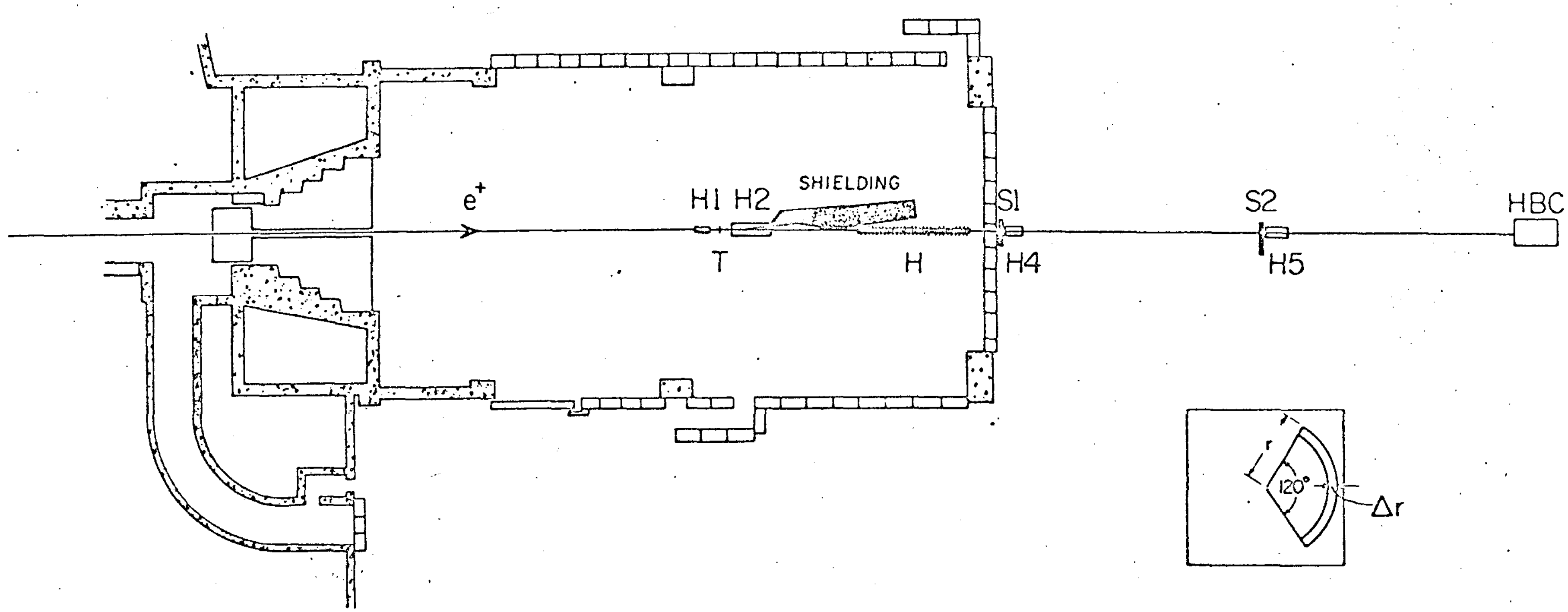
FIGURE 2

106-7-8



POSITRON ACCELERATION

FIGURE 3



0 10 50 10 meter

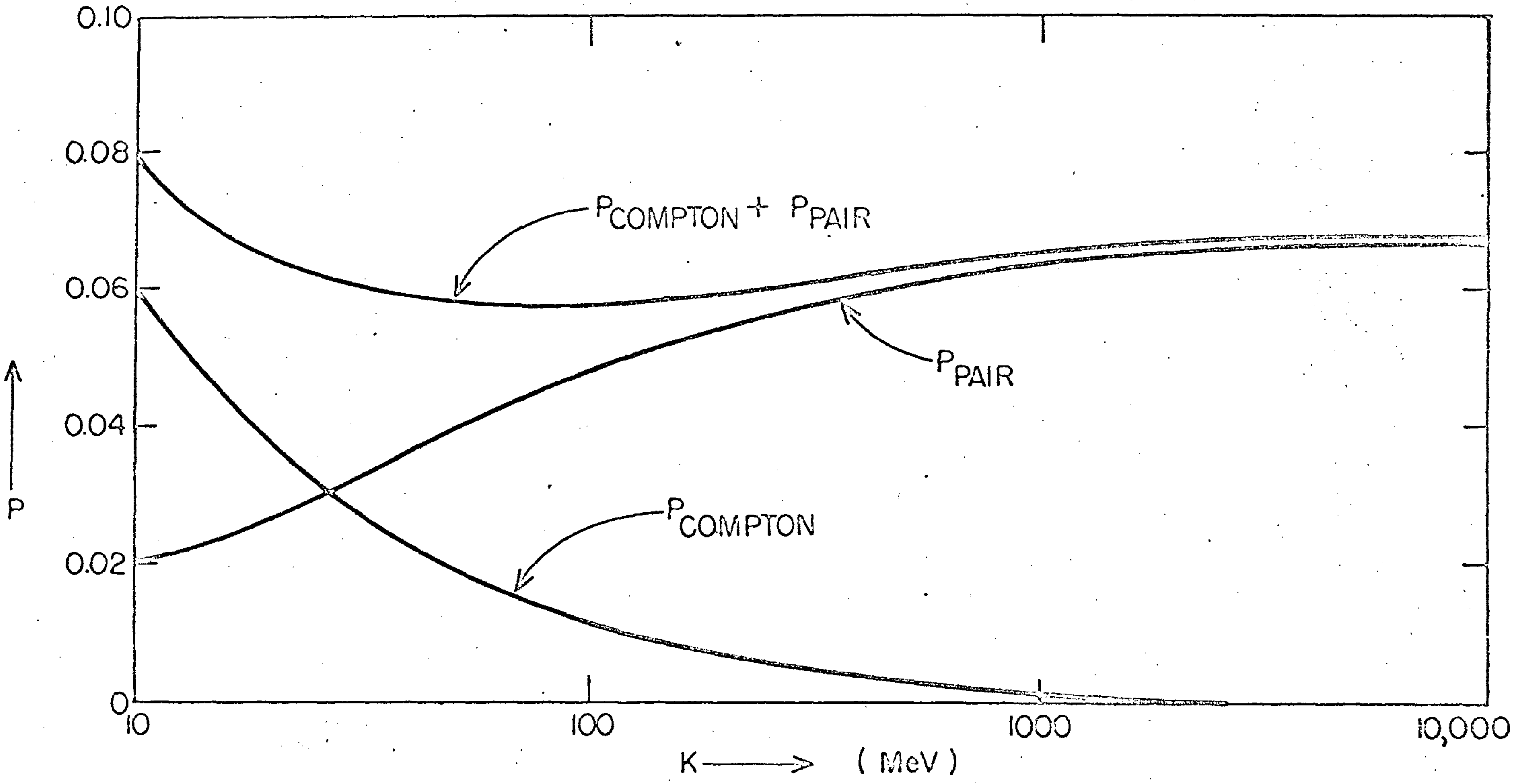
ALMOST MONOCHROMATIC PHOTON BEAM

T: LH_2 TARGET, 0.5 gm-cm^{-2}
H1 : e^+ STEERING MAGNET
H2 : e^+ DUMP MAGNET
H : 10 r.l. LH_2 PHOTON HARDENER

S1: SLIT, r = 17.4 cm Δr = 0.2 cm
S2: SLIT, r = 34.9 cm Δr = 0.4 cm
H4, H5 : SWEEPING MAGNETS
HBC : 1m. HYDROGEN BUBBLE CHAMBER, Be THIN WINDOW, 70 X 25 cm

106-2-C

FIGURE 4



P: PROBABILITY / INCIDENT γ – TOTAL PROBABILITY OF ELECTROMAGNETIC INTERACTIONS IN A 1.0m HYDROGEN BUBBLE CHAMBER

106-3-A

FIGURE 5